

TRIUMF



THE TRIUMF-ISOL FACILITY

A PROPOSAL FOR AN INTENSE
RADIOACTIVE BEAMS FACILITY

MESON FACILITY OF:

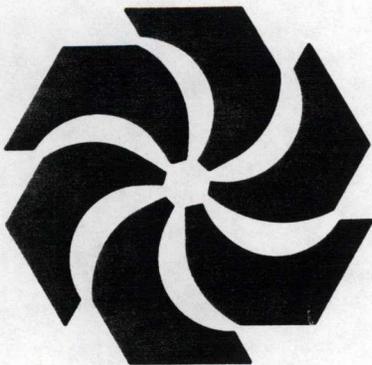
UNIVERSITY OF ALBERTA
SIMON FRASER UNIVERSITY
UNIVERSITY OF VICTORIA
UNIVERSITY OF BRITISH COLUMBIA

OPERATED UNDER A CONTRIBUTION FROM THE
NATIONAL RESEARCH COUNCIL OF CANADA

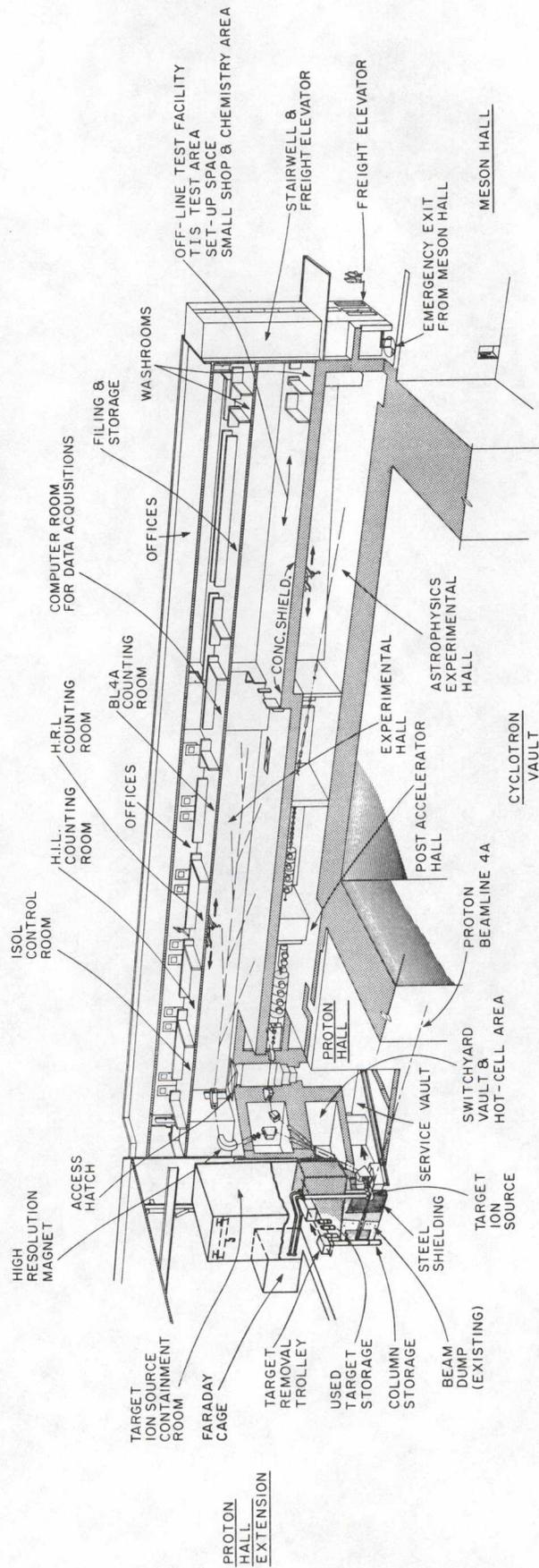
JUNE 1985

THE TRIUMF - ISOL FACILITY

**A PROPOSAL FOR AN INTENSE
RADIOACTIVE BEAMS FACILITY**



June 1985



**Proposed
 TRIUMF - ISOL
 Facility**

RÉSUMÉ

The TRIUMF-ISOL presented in this proposal is a radioactive beams facility. Isotopes produced in targets bombarded with the TRIUMF proton beam are transported as intense, mass-separated beams of variable energy to the experimental areas. The target assembly will be installed near the end of TRIUMF beam line 4A while most of the facility will be housed in a new building attached to the north wall of the present experimental proton hall.

The proposed facility will be unique. It will consist of a high yield on-line isotope separator (ISOL) and a post-accelerator with variable output energy. The isotope production rate will surpass that of any other ISOL in operation or actively planned in the world. The post-accelerated radioactive beam will itself be unique, offering new opportunities for research in fields ranging from medical physics and chemistry to nuclear astrophysics. In particular, it will permit for the first time the mounting of experiments of low intrinsic sensitivity, the production of radioactive targets of isotopically pure nuclides, and the investigation of nuclear reactions involving short-lived isotopes. The post-accelerator will be ideal for the investigation of nuclear reactions of particular interest for nucleosynthesis in stars. This will be the first, and for the foreseeable future, the only facility where such systematic studies can be carried out.

Although much of the technology for ISOLs and post-accelerators is well developed, the TRIUMF-ISOL will operate in very different conditions. The ISOL will be situated in a radioactively hostile environment which will be more severe than in any existing facility. The post-accelerator must be capable of efficiently accelerating a wide variety of low energy ions. Careful studies will be required and the testing of new design concepts may be necessary. In this proposal, we have presented in detail our approach towards the design and construction of a new-generation type of ISOL and a preliminary design for the post-accelerator, which is still currently under study. The total estimated capital cost is \$4.4 M for the ISOL and approximately \$4.5 M for the post-accelerator. The cost of the main building, including the necessary shielding requirements, will be \$4.6 M. A total manpower of 44 man-years will be required for its construction. When completed, the facility will be able to handle about 2000 h per year of proton-beam-on-target operation. A total staff of 31 personnel will be required for its operation and the annual operating budget (including salaries) is estimated to be \$3.0 M.

TRIUMF-ISOL will add a new dimension to the TRIUMF operation. It will offer new and unique opportunities for research in areas which are different from those of current TRIUMF principal interests. This will enhance TRIUMF's role as a national facility for a wider subatomic physics community. Its access will be sought by many scientists worldwide.

PREFACE

This is a proposal to install a radioactive beams facility at TRIUMF (abbreviated as TRIUMF-ISOL). The proposed facility consists of an on-line isotope separator (ISOL), capable of producing intense, mass-separated, radioactive beams, and a post-accelerator, for further acceleration of the separated ions. This proposal is the outcome of the initial efforts of the ISOL Study group, established in 1984 under the coordination of Professor J.K.P. Lee of McGill University. A workshop, attended by 50 participants, was held at Mt. Gabriel, Québec, June 13-16, 1984 and the proceedings have been published as a TRIUMF Report (TRI-84-1). A preliminary proposal for the installation of such a facility was presented to the TRIUMF Long Range Planning Committee in July 1984. That proposal was positively received and approval was given to examine, with the assistance of TRIUMF personnel, the details of various technical considerations and to arrive at a realistic cost estimate. Activities at TRIUMF were managed by Professor J.M. D'Auria of Simon Fraser University.

Experimental proposals, representing a collaboration of about 50 scientists, requiring such a radioactive beams facility were presented to the winter meeting of the TRIUMF Experimental Evaluation Committee (December 1984). Among these proposals were projects to address some of the important technical considerations for such a facility (namely ion source development and post-accelerator design studies). These projects are now in progress and for the current year, the main efforts will be directed towards the installation and use of an on-line, ion source testing facility at TRIUMF, and the organization of a workshop on accelerated radioactive beams to be held September 4-8, 1985. The proposal presented here is the result of the efforts of a large number of scientists and engineers. These include

<u>McGill</u>	<u>TRIUMF</u>	<u>Elsewhere</u>		
Buchinger F.	Bosman P.	Schmor P.	Buchmann L.	- Toronto
Crawford J.	Cameron W.	Stinson G.	D'Auria J.M.	- SFU
Dautet H.	Chutka F.	Thorson I.	Ewan G.	- Queen's
Lee J.K.P.	Emmons T.	Verma V.	Hagberg E.	- CRNL
Mark S.K.	Gurd D.	Vincent J.	Hardy J.C.	- CRNL
Moore R.B.	Mark C.	Yanden J.	Litherland A.E.	- Toronto
Nikkinen L.	Moritz L.		Morrison S.R.	- SFU
Oxorn K.	Otter A.		Reeder P.	- Batelle
Raut V.	Ruth T.		Sawicki J.	- CRNL
	Schneider H.		Schmeing H.	- CRNL

Also, acknowledgements are due to all the participants of the Mt. Gabriel Workshop and many others who have contributed in various forms during the course of our study. Special thanks are due to the ISOLDE and ISOCELE collaborations, particularly to Drs. H. Ravn and P. Paris. The assistance of the TRIUMF Design Office in the preparation of the figures in this proposal and the special efforts of I. Duelli, P. Stewart and M. White in the typing of this proposal are gratefully acknowledged. The study was sponsored by NSERC and TRIUMF. Direct financial contributions from McGill University and Simon Fraser University are gratefully appreciated.

C O N T E N T S

	page
I. INTRODUCTION	1
II. SCIENTIFIC MOTIVATION	3
1. Nuclear Properties	4
1.1 Nuclear Masses	4
1.2 Nuclear Structure: Conventional Spectroscopic Techniques	8
1.3 Nuclear Structure: Laser Spectroscopic Techniques	15
1.4 Exotic Decays	20
1.4.1 Proton-Rich Nuclei	20
1.4.2 Neutron-Rich Nuclei	25
1.5 Fundamental Physics	32
1.6 Nuclear Physics with Accelerated Radioactive Beams	33
2. Astrophysics using Accelerated Radioactive Beams	35
3. Condensed Matter Studies	45
4. Medical Physics	58
5. Other Applications	61
6. Summary	62
III. FACILITY DESCRIPTION	63
1. Desired Features of a Radioactive Beams Facility	64
2. Advantages of TRIUMF as a Site for a Radioactive Beams Facility	66
3. Major Technical Considerations	68
4. Outline of the Facility	71
5. Detailed Descriptions of the Major Design Features	74
5.1 Target and Ion Sources (TIS)	75
5.2 Beam Line 4A Upgrade and Modification	81
5.3 Target Ion Source and Extraction Electrode	86
5.4 Remote Handling and Operations	93
5.5 The Separator System and its Beam Optics	95
5.6 ISOL Ion Beam Line Components	99
5.7 Control Systems	106
5.8 Radiation Safety	111
5.9 Building	117
5.10 Off-Line Facilities	124
5.11 Post-Accelerator	125
6. Experimental Halls	128
IV. PROJECT MANAGEMENT	130
1. Cost Estimates	130
2. Implementation Schedule	130
3. Impact on TRIUMF Operation	135
V. FACILITY OPERATION	136
1. Steady State Operation	136
2. Scientific and Technical Support	136
3. Operating Cost Estimates	136
4. Evolution of the ISOL Group	138
5. Impact on TRIUMF Operation	139

APPENDICES

- A. Complete Set of (Larger Scale) Building Plans
- B. Proposals Submitted to Experiment Evaluation Committee (EEC)
- C. Design and Technical Notes related to the ISOL Facility
 - a. Specifications and Design Considerations of a Target-Ion Source System for a TRIUMF ISOL (TRI-TN-84-5 Rev)
 - b. An Interim Report on the Ion Beam Optics of the Proposed TRIUMF-ISOL Project (TRI-DN-84-68)
 - c. Initial Concepts of a Post-Accelerator for the TRIUMF-ISOL Facility (TRI-TN-85-1)
 - d. Beam Line 4A Operation for the Proposed Isotope Separator Facility (ISOL) (TRI-DNA-85-2)
- D. Details of Cost Estimates for Major Areas
- E. Miscellaneous
 - a. The Isochronator Project

I. INTRODUCTION

We propose that TRIUMF undertake a project to install a radioactive beams facility (referred to as TRIUMF-ISOL) in the near future. This facility will ultimately consist of a high-yield on-line isotope separator (ISOL), to be installed near the end of the TRIUMF beam line 4A, and a post-accelerator to be installed in a new building attached to the north wall of the present main experimental hall. The proposed ISOL will represent what we envisage as the next generation ISOL for a high current accelerator. It will be the only one of its kind in North America and its performance has the potential to surpass that of any other ISOL in operation (or in active planning) anywhere in the world. The post-accelerator will accelerate light ($A < 60$) singly charged radioactive ions to an energy of up to about 1 MeV/amu and provisions are made for further acceleration to higher energies at a later date. This will be a unique facility, particularly suited for the study of nuclear reactions of astrophysical interest. Such a facility would introduce a new and powerful capability to TRIUMF and would have a profound impact on the nuclear, astrophysical and other related scientific communities world-wide.

Since its introduction in 1965, numerous ISOL facilities have been installed at various accelerator and reactor sites, and their usefulness as research tools can be witnessed by the numerous contributions to the conferences on properties of nuclei far from stability [Con 66, Con 70, Con 76, Con 79, Con 81]. Among the ISOL facilities, the one that has had the most profound impact on the community is the ISOLDE facility located at the 600 MeV proton synchrocyclotron accelerator (SC) at CERN [Rav 75, CER 83]. The ISOLDE-2 has been operational since the mid '70s. The availability of intense and pure isotopes there has created a tremendous demand on its beam time. In 1983, an additional ISOL facility (ISOLDE-3) was approved to handle the increasing demand. This new facility is scheduled to be operational late this year or early in 1986, and intense preparations for the new generation of experiments are underway. Compared to these two facilities, our proposed ISOL will have a higher overall production rate for a larger variety of elements; a high resolution mass separator is incorporated to allow isobar separation for nuclei far from stability. These features alone will mean that much of the interesting work done at ISOLDE can be extended to more exotic regions of interest. Of more significance, perhaps, is the fact that the higher yield (expected to be more than one order of magnitude higher) of pure isotopes will allow an opportunity to produce radioactive targets of acceptable thickness to be used in various conventional nuclear reaction studies. These new studies will yield a wealth of information not accessible easily by other approaches. With a post-accelerated radioactive ion beam, many reaction studies can then be extended to short-lived nuclei. This will be of particular interest in nuclear astrophysics, where key reaction rates involving short-lived nuclides are totally unknown.

In addition to these areas, the availability of an intense and pure isotopic beam will find many applications in other fields. This is evidenced by the variety of proposals presented at the ISOLDE-3 workshop [Wor 84]. No doubt, a similar situation will evolve at TRIUMF, emulating the previously profitable symbiosis of nuclear physics, material science, chemistry and medical physics already in existence.

Our main scientific motivation for the TRIUMF-ISOL facility is

described in Chap. II of this proposal. In Chap. III, we outline the desirable features for a future radioactive beams facility and explain why TRIUMF is the most appropriate and perhaps the only suitable site to house such a facility. Details of our proposed ISOL are given, but only preliminary specifications for the post-accelerator are presented. The cost estimate of the project is given in Chap. IV, together with a proposed time schedule for its implementation. The envisaged steady-state operation of the facility is described in Chap. V, and the projected operating cost is given. The impact of this project to the TRIUMF operation is analyzed for both the construction and operation phases. They are described in Chaps. IV and V. It should be mentioned that in Chaps. III to V, description and estimates for the post-accelerator are given in a preliminary fashion. A detailed study is currently underway and a more updated report will be available late this year. However, we believe that the description given at present will not be significantly different from the final version.

The proposal consists of two parts, the main body and the Appendices. We have included in the main body all the pertinent information from our study to support our proposal. Other relevant information, such as the proposals submitted and defended to the TRIUMF Experiments Evaluation Committee (EEC), detailed design notes and technical notes, and details of the cost estimates, are included as Appendices. Copies of the Proceedings of the Mt. Gabriel Workshop are available from the TRIUMF library.

REFERENCES

- [CER 83] "ISOLDE-3 Project", CERN 83-27 (1983).
- [Con 66] Lysekil Conference 1966, Nuclides Far off the Stability Line, Ark. Fys. 36, (1967).
- [Con 70] Leysin Conference 1970, Proc. of Int. Conf. on the Properties of Nuclei Far From the Region of β Stability, CERN 70-30 (1970).
- [Con 76] Cargèse Conference 1976, Int. Conf. on Nuclei Far From Stability, CERN 76-13 (1976).
- [Con 79] Nashville Symposium 1979, Proc. Sym. on Future Directions in Studies of Nuclei Far From Stability, ed. J.H. Hamilton et al., North-Holland (1980).
- [Con 81] Helsingør Conference 1981, Proc. 4th Int. Conf. on Nuclei Far From Stability, CERN 81-09 (1981).
- [Rav 75] H.L. Ravn et al., Nucl. Instr. and Meth. 123, 131 (1975).
- [Wor 84] ISOLDE-3 Workshop, Zinal 1984.

II. SCIENTIFIC MOTIVATION

It is becoming increasingly clear that to further our understanding of the complex interaction of the nuclear constituents, it is necessary to carry out both the systematic studies of the nuclear properties and specific experiments where particular aspects of the interaction may manifest themselves. These systematic studies should be performed with nuclei pushed to extreme conditions, such as very high angular momentum or excitation energies, or far off the valley of stability towards the proton or neutron drip lines. In the last category, the contributions of ISOL facilities in general have been well recognized. However, with the exception of the light mass region, our knowledge of nuclear properties near the drip lines is still very limited. With the prospect of much higher yields of pure isotopes and the provisions for low background areas, the proposed ISOL will make a definite contribution in these studies.

The second category (specific experiments) involves the study of specific characteristics of certain nuclei or the study of reactions between specific particles under controlled conditions. In these studies, the high yield characteristics of the proposed ISOL will offer new opportunities not available before. When a certain radioactive nuclide can be produced in sufficient quantity, experiments with low intrinsic sensitivities can be applied and precision measurements may be made. If appropriate targets can be prepared, then much more specific experiments become possible. We believe that the proposed ISOL will have adequate yield for many isotopes such that these studies will become feasible.

Our knowledge of nuclear properties has been the basis for our understanding of the evolution of the universe. In the specific area of nucleosynthesis of elements and isotopes, knowledge of the nuclear reaction rates among various stellar constituents is essential. For reactions involving stable nuclei, rates can be measured in the laboratory. However, for reactions involving radioactive nuclides, very little is known, even for those reactions involving the most abundant radioactive species. This lack of knowledge has hampered progress in the development of models dealing with stellar nucleosynthesis and other evolutionary processes. It is felt that the research in nuclear reactions involving radioactive nuclei will soon become, if it is not already, the priority area for concentrated efforts. The high yield capability of the proposed ISOL, combined with a post-accelerator, offers, for the first time, the unique opportunity to tackle this field in a systematic manner.

These areas of research are the primary motivations behind this proposal. However, it is recognized that the availability of a large variety of pure isotopes in abundant quantity will have many applications in other nuclear related disciplines. This is particularly relevant for TRIUMF since there already exist at TRIUMF research programs that can benefit from the proposed facility.

Details of the scientific interests are presented in the following Sections.

1. NUCLEAR PROPERTIES

1.1 NUCLEAR MASSES

One of the most basic properties of a nucleus is its mass or total energy. This quantity is the ground state eigenvalue of the Hamiltonian of the nuclear system under consideration. The determination of the mass of a nucleus thus provides one way of studying the fundamental inter-nucleon forces.

The study of atomic masses has historically been of great importance for our understanding of the properties of the atomic nucleus and for the development of theories to account for these properties. Early systematic studies of atomic masses provided the first information on shell structures, nuclear binding energies and the strength and range of nuclear forces. Over the years, new or improved mass-measurement techniques have evolved, with the result that our knowledge of precise masses for stable nuclides is extensive. There are few stable nuclides whose masses have not been determined with sufficient precision for nuclear structure studies.

In contrast to the situation for the stable nuclides, masses of most radioactive nuclides have never been measured. Furthermore, those that have are generally not known very precisely. Up to now, various techniques such as studies of reaction energies or thresholds, (n,γ) reactions and α - and β -decay energies, have been used to determine the masses of radioactive nuclides. Unfortunately, all these techniques have their limitations; no single one is generally applicable to a majority of unstable nuclides.

The present status of the masses of radioactive nuclides is not an indication of a lack of interest in this field but rather reflects the difficulties inherent in the precise mass measurements of such nuclides. A high intensity ISOL facility coupled to a mass spectrometric device [Bar 84] or a high resolution ISOL facility on its own [Sha 84] are both capable of direct mass measurements, particularly for nuclei far from stability. Such facilities will play an increasing role in the future.

Examples of areas of physics interest, where significant progress has been made because of recent mass measurements follow.

Atomic Masses and Nuclear Structure

The currently known body of data on atomic masses provides a striking manifestation of shell structure effects in the atomic nucleus. Indeed, the quantitative determination of shell effects is most directly achieved through systematic studies of nucleon binding energies. An extension of our knowledge of atomic masses to many more nuclides will refine our understanding of the physical properties responsible for the emergence of shell structure.

Systematic comparisons of nucleon binding energies have recently proved that proton and neutron shell strengths are correlated [Sch 80]. Both types of shells show maximum strength at doubly magic nuclides. For neutron shells, the strength is found to decrease rapidly with increasing number of protons or proton holes, and the same behaviour is also found for proton shell strengths as a function of neutron number. The effects of such 'mutual magicities' are normally not included in shell model calculations where a constant shell strength is assumed. The determination

of the masses of many nuclides in the vicinity of single shell closures is therefore necessary to establish the general behaviour of shell strength.

Studies of subshell closures through the systematics of nucleon binding energies are also of interest. The locations and strengths of the subshells provide another challenge for the present theoretical models. For instance, much interest has recently been focussed on the shell strength variation along the $Z=64$ subshell, especially in the region of the $N=82$ shell closure. The nuclides under consideration are not very far from stability and are certainly accessible with a versatile on-line mass spectrometer.

It is well-known that the nuclear mass surface is split into four different sheets because of the effects of nucleon pairing. Studies of the mass difference between these four sheets directly reflects the neutron and proton pairing energies as well as the interaction between an odd neutron and an odd proton. These pairing energies are often taken to have constant values, independent of which specific nuclide is under consideration. Detailed systematic studies of the splitting of the nuclear mass surface do, however, reveal evident trends in the proton, neutron, and neutron-proton pairing energies that must originate from nuclear structure effects. Of special interest here would be the study of the pairing strengths in nuclides with abnormal proton-to-neutron ratios. At present such information is almost non-existent.

Atomic Masses and Nuclear Shapes

A knowledge of the broad outlines of the nuclear mass surface for a wide range of nuclides is a very useful source of information on the shapes of nuclei. Evidence of nuclear deformations is obtained from the systematic behaviour of double proton or neutron separation energies as a function of N and Z . The general trend is a slow decrease in the separation energy with increasing particle number [Wap 77, Bar 64, Duc 69]. A sudden change in the two-particle separation energy occurs at a shell closure, and it is consequently visible as a discontinuity in the trend that otherwise has the same slope on either side of that shell closure. Regions of deformed nuclides, on the other hand, manifest themselves through a gradual change of slope, creating a broad hump in the two-particle separation energies.

Recent on-line mass measurements by Epherre et al. [Eph 79] of isotopes of Rb and Cs have made possible the determination of a long series of double-neutron separation energies. For the Rb case, the trend of the separation energies clearly delineates the $N=52$ shell closure and the onset of deformation around $N=60$, a region that is expected to be heavily deformed. Indications are also seen of a new deformed region around ${}^{78}\text{Zr}$. A minor break in the separation energy slope at $N=56$ is caused by the closure of the $d_{5/2}$ neutron subshell. For the Cs case, the $N=82$ shell closure is indicated and the probable onset of deformation at $N=90$ is also seen.

In another excursion away from the line of β -stability the masses of neutron-rich sodium nuclides were measured with on-line mass spectrometry [Thi 75]. The resulting two-neutron separation energies show a sharp change at $N=20$ indicating a sudden onset of a large deformation. In this case such a behaviour was not expected since $N=20$ corresponds to a well-known spherical closed shell.

Considerable new insight into the field of nuclear deformations has been gained through these three on-line mass measurements even though the experimental techniques used were only applicable to alkali metals. A mass measuring system that does not have this limitation would naturally be very exciting.

Atomic Mass Formulas

Improvement of the quality of semi-empirical atomic mass formulas depends on new and better information on atomic masses. The masses of stable nuclides have already played their role in determining the parameters of these formulas, so that differences between the results of various mass formulas for the masses of stable nuclides are very small and usually well within the stated uncertainties. Stringent tests of atomic mass formulas, and hence of their inherent assumptions on fundamental nuclear structure, can at present only be made through the determination of masses of highly unstable nuclides.

The accuracy of the atomic mass formulas is of importance since they often provide the only information that is available on very remote nuclides. The limits of stability against nucleon emission, for instance, are almost entirely based on such predictions, as are also the suggestions of an island of long-lived, super-heavy elements.

Many nuclear processes of astrophysical interest occur far from stability. Nucleosynthesis, through the r-process, proceeds along a narrow band of extremely neutron-rich nuclides. The masses and half-lives of nuclides in this band are not, and may never be, known. Consequently these properties, which are essential for r-process calculations, have to be taken from predictions. It is therefore of interest to measure the masses of neutron-rich nuclides as far as possible. If the atomic mass formulas cannot correctly predict the measured masses of those nuclides, as is often the case, then their predictions for the even more neutron-rich nuclides involved in the r-process are of no value.

Comparisons between predictions of atomic mass formulas and experimental masses are also of interest for nuclear structure studies. Such systematic comparisons have revealed areas of the chart of nuclides where the differences between theory and experiment are quite large. In addition to such slowly varying deviations between theory and experiment, there are other abrupt, local variations, which are interpreted as signatures of nuclear structure. The unexpected onset of deformation or the prediction of deformation that is not actually present give rise to such signatures. The regional variations in the accuracy of atomic mass formula predictions thus serve to probe the basic physical assumptions built into the formula.

Improvements in the Reliability of Presently Known Masses

Most of the known masses of radioactive nuclides have been determined through α - or β -decay Q-value measurements. However, these methods of mass determination have the disadvantage that they are reliable only if the decay pattern of the nuclei under investigation is well-known [Key 81]. This concern becomes especially worrisome for nuclides far from stability since, generally, very little is known about their decay schemes. Furthermore, the absolute mass of a particular nuclide far from stability may be deduced from a long series of decay energy measurements connecting it eventually to the mass of a stable nuclide. As a result of

the cumulative effects of errors in each decay- energy measurement, the masses determined through such a procedure may not be reliable.

The confirmation of the masses of some selected nuclides far from stability with an independent technique would improve our confidence in earlier decay energy measurements. Direct mass measurements are especially valuable for such corroborations since they can be selected so as to provide mass connections along isotopic or isotonic lines and are thus complementary to the α - or β -decay energy measurements. Through these complementary techniques, closed loops of nuclides can be constructed where the mass differences between all neighbouring nuclides in the loop have been measured. Such closed loops allow important consistency checks to be made on the deduced masses, and would clearly identify areas where mistakes have been made in the earlier determinations.

REFERENCES

- [Bar 64] R.C. Barber, H.E. Duckworth, B.G. Hogg, J.D. Macdougall, W. McLatchie and P. Van Rookhuysen, Phys. Rev. Lett. 12, 597 (1964).
- [Bar 84] R.C. Barber, H.E. Duckworth, K.S. Sharma, E. Hagberg, J.C. Hardy and H. Schmeing, AECL-8188 (1984) 1.
- [Duc 69] H.E. Duckworth, R.C. Barber, P. Van Rookhuysen, J.C. Macdougall, W. McLatchie, S. Whineray, R.L. Bishop, J.O. Meredith, P. Williams, G. Southon, W. Wong, B.G. Hogg and M.E. Kettner, Phys. Rev. Lett. 23, 592 (1969).
- [Eph 79] M. Epherre, G. Audi, C. Thibault, R. Klapisch, G. Huber, F. Touchard, and H. Wollnik, Phys. Rev. C19, 1504 (1979).
- [Key 81] U. Keyser, F. Münnich, B. Pahlmann and B. Pfeiffer, 4th Int. Conf. on Nuclei Far from Stability, Helsingør, 1981, eds. P.G. Hansen and O.B. Nielsen, CERN report 81-09, p. 116.
- [Sch 79] K.H. Schmidt and D. Vermeulen, in Atomic Masses and Fundamental Constants 6, East Lansing 1979, eds. J.A. Nolen and W. Benenson (Plenum Press, 1980) 119.
- [Sha 84] K.S. Sharma, H. Schmeing, H.C. Evans, E. Hagberg, J.C. Hardy and V.T. Koslowsky, Mt. Gabriel, 1984, eds. J. Crawford and J.M. D'Auria, TRIUMF report TRI-84-1 (1984) p. 70.
- [Thi 75] C. Thibault, R. Klapisch, C. Rigaud, A.M. Poskanzer, R. Prieels, L. Lessard and W. Reisdorf, Phys. Rev. C12, 644 (1975).
- [Wap 77] A.H. Wapstra and K. Bos, Atomic Data and Nuclear Data Tables 19, 177 (1977).

1.2 NUCLEAR STRUCTURE: CONVENTIONAL SPECTROSCOPIC TECHNIQUES

INTRODUCTION

The preceding Section has stressed the importance of wide-ranging systematic studies of ground state properties over the mass surface. Likewise, spectroscopic studies of nuclear excited states have yielded their richest dividends in systematic investigations over regions of neighbouring isotopes or isotones. There are two complementary tools for this sort of study: in-beam spectroscopy with heavy ion beams yields rich information on high spin states and nuclear band structure. However, this information, by itself, is often incomplete. A detailed understanding, particularly of low spin states, is often only possible with decay studies.

SPECTROSCOPY NEAR MAGIC NUMBERS

Nuclei with small numbers of valence nucleons outside closed shells have always provided critical tests of nuclear models. Regions near the five stable doubly-magic nuclei have been particularly closely studied. With modern techniques, it has been possible to carry out some investigations at (or close to) the remaining candidates. Of these, all except ^{56}Ni lie very far from the valley of stability, and it is clearly important to know what aspects of the nuclear shell model remain valid in the unstable region. The most-studied candidates so far are ^{132}Sn and its neighbours. This nuclide lies approximately 10 nucleons from stability, so conventional reaction studies are essentially impossible. Nevertheless, actinide fission has produced mass-separated samples which have sufficient activity for spectroscopic work. The information on ^{132}Sn itself comes from the β^- decay of ^{132}In [Bjo 82] and from the decay of the $^{132}\text{Sn}(8^+)$ isomer [Lau 78]. With a first excited 2^+ level at 4 MeV, this nucleus appears to have the strongest shell closure in nuclei above ^{16}O . Blomqvist [Blo 81] has done shell-model calculations using techniques similar to the ^{208}Pb case; more detailed calculations require knowledge of single-particle and single-hole energies in the neighbouring nuclei. A series of experiments have established proton levels in ^{133}Sb [Bor 73, Sis 78] and neutron-hole levels in ^{131}Sn [Fog 84], and plans are underway to establish proton-hole levels in ^{131}In from ^{131}Cd decay [Bjo 84]. The neutron-particle information remains unknown, since ^{133}Sn is a β -delayed neutron emitter. Nevertheless, the level scheme, β and γ branching ratios, and transition probabilities determined thus far are essentially consistent with Blomqvist's calculations. Experimentally much more work remains to be done in this important region, and this may be possible when purer, more intense sources of ^{132}In beams become available at ISOL facilities.

On the proton-rich side of stability, there has been equal interest in the $^{100}_{50}\text{Sn}_{50}$ doubly-magic region, although the experimental difficulties in producing a nucleus some 14 nucleons from stability are formidable. Nevertheless, fusion evaporation reactions at the GSI mass-separator have produced nuclei close to ^{100}Sn , and from these, some aspects of this new region are becoming clearer. For example, the β -delayed γ -rays from the decay of ^{96}Ag have been observed, yielding information on the ground state band in ^{96}Pd [Kur 82]. The Gamow-Teller transition probabilities from

$g_{9/2}$ proton to $g_{7/2}$ neutron states from ^{96}Pd - ^{96}Rh decay have been measured (with $\log ft$ values of 3.75 and 3.61 to the 939 and 1275 keV levels, respectively, in Rh). This represents a strong hindrance, compared to shell-model predictions; this has been ascribed to effects of configuration mixing, and particle-hole and Δ -hole excitations [Har 84]. Similar hindrances have been observed in the $^{104}\text{Sn} \rightarrow ^{104}\text{In}$ decay [Rat 85], and in the corresponding $\pi h_{11/2} \rightarrow \nu h_{9/2}$ transitions of $N=82$ nuclei [Hab 84]. The ^{104}Sn experiment was done with beams of 10^3 ions/s, and the calculated cross section for ^{102}Sn production is two orders of magnitude lower, suggesting that the available beam will have an intensity of only 10 ions/s with more severe isobaric contamination.

Doubly magic effects are also of interest in the region near ^{146}Gd at the proton subshell closure. These effects are revealed both by an anomaly in the α -decay energy at $Z=64$, and by a 2_1^+ level which lies significantly higher in energy than in the ^{144}Sm and ^{148}Dy neighbours. There has therefore been considerable interest in the use of ^{146}Gd as a core for the shell model calculations [Kle 84]. Consequently, as for the ^{132}Sn region, recent experiments have focused on several Gd neighbours; the initial effort has been directed to the accurate measurement of ground state masses. At GSI, studies of the β -delayed protons from ^{149}Er and ^{107}Dy show distinct peaks at low energy; an autocorrelation analysis [Jon 76] reveals an average level spacing of ~ 1.3 keV in ^{147}Tb at $E^* = 5.4$ MeV, much larger than the 0.6 keV value predicted by the Gilbert-Cameron formula [Gil 65, Tru 70]. This is believed to reflect the influence of the strong ^{146}Gd core shell closure [Roe 85]. Radioactive ^{148}Gd targets have also been recently used for studies in this region (see later discussion).

Gamma spectroscopy on ^{146}Gd neighbours has revealed some aspects of shell structure which have never been observed in the ^{208}Pb core. A recent spectroscopic "first" was the observation of a 2-phonon octupole state [$\nu f_{7/2} \times 3^- \times 3^-$] in ^{147}Gd [Kle 81]. Here, the one-phonon 3^- state in ^{146}Gd lies at approximately 1.6 MeV, much lower than in the ^{208}Pb case (about 2.6 MeV).

The lightest magic-number region which has been systematically investigated in recent years has been the set of Na isotopes near $N=20$. The surprise in this region was the observation of an abrupt increase in the two-neutron separation energy [Thi 75, Thi 80], and the observation of a very low energy first excited 2^+ level in ^{32}Mg [Det 79, Gui 81], indicating a departure from the usual magic number expectation: an onset of a new region of deformation near $Z=11$, $N=20$. Recently, Hartree-Fock and Strutinski calculations indicated that the observed deformation arises from strong shell and pairing effects.

SPECTROSCOPIC STUDIES OF NUCLEAR SHAPE

In nuclei away from closed shells, much attention has been directed to deformed regions, with recent emphasis placed on the study and theoretical modelling of the "transitional" nuclei--these lie between the spherical nuclei at closed shells, and the highly deformed rotors. One such region includes the nuclides from Os to Bi, at the upper (high Z) edge of the rare earth deformation; here, the complexities observed are well illustrated by studies of mercury isotopes. Figure II.1 shows the observed bands in Hg (see [Woo 84], and references therein), together with the

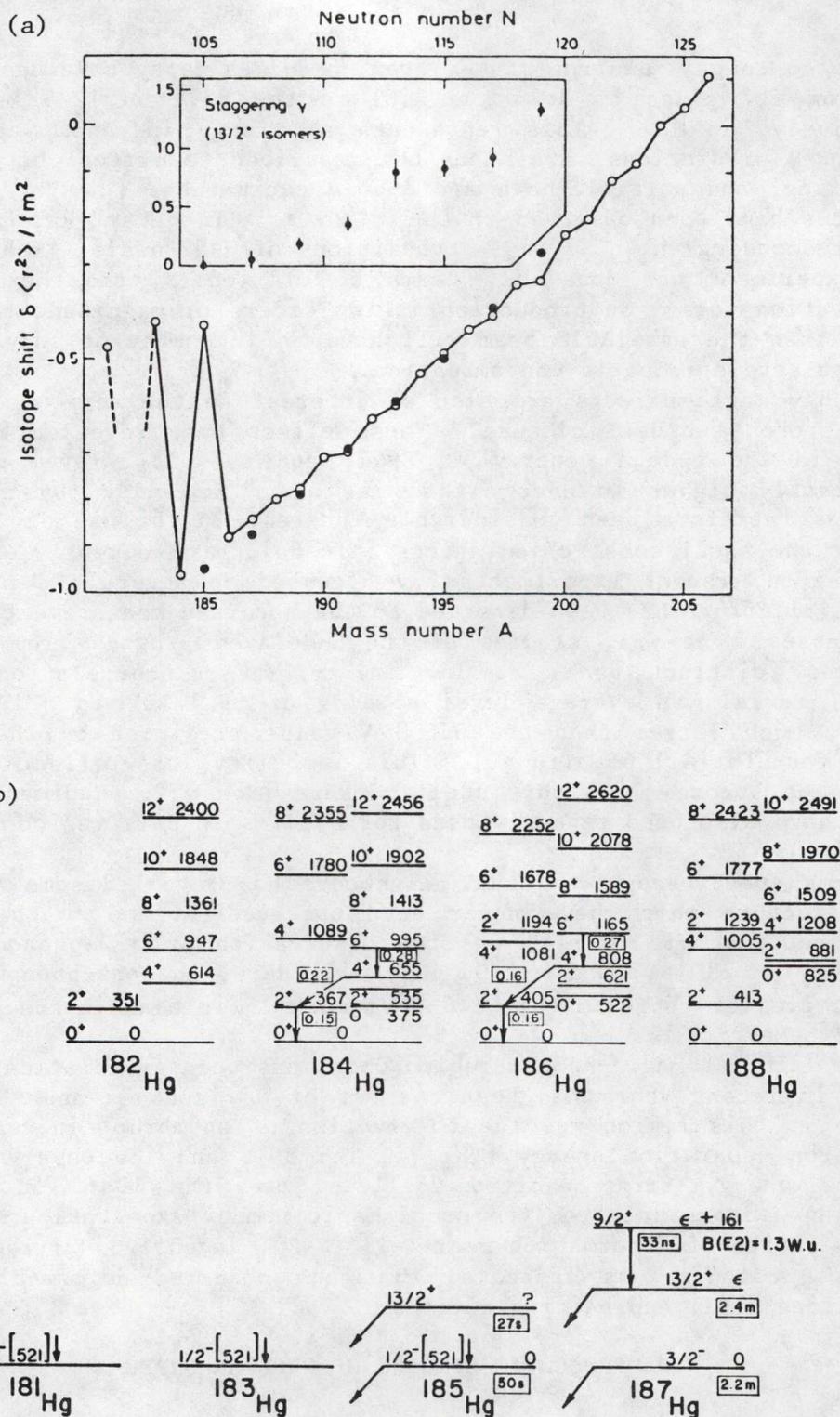


Fig. II.1. (a) Changes of mean square charge radii of Hg isotopes relative to ^{204}Hg . Open circles indicate ground states, solid circles are isomers, (from ([Klu 82])). (b) Low-lying structure of $^{181-188}\text{Hg}$, showing coexisting bands (from [Woo 84]).

β -RADOP measurements of changes in mean square charge radius for these isotopes [Bon 76]. The hyperfine spectroscopy studies indicate the rapid shape fluctuations between neighbours, and also clearly show the shape isomers in ^{185}Hg . The band structures show the coexistence of two bands, with the strongly deformed one built on a low-lying 0^+ state. Similar structures are seen in the nearby Au, Tl and Bi isotopes. The present interpretation is that such coexistence near closed shells involves the excitation of both valence protons and neutrons across shell gaps; it is the p-n residual force which is responsible for the energy decrease of the intruding configurations. These studies have been extended to odd-mass nuclei (for an extensive review see [Hey 83]), and systematics have now been collected which show many such instances of coexistence for odd proton nuclei in both the Z=50 and 82 regions. It has been pointed out [Woo 84] that in the Z=82 region, transfer reaction data are lacking; the coexisting bands only appear at low energy near N=104, and stable targets for particle transfer studies are rare or non-existent. Similarly, the experimental picture near N = 28, 50, 82 and 126 is very limited, since shell-model intruder states lie at energies higher than in the Z = 50, 82 cases. It is clearly important to have detailed knowledge along extended isotope chains, and it is inevitable that much coincidence sorting, on cleanly prepared sources from ISOLs, must be done. Less labour would be required if bent crystal spectrometers could be used to resolve complex multiplets. However, this sort of work is only possible if very intense sources can be collected.

Perhaps the most surprising and dramatic spectroscopic result in recent years has been the growing evidence for a mirror asymmetric ground state--a stable octupole deformation--in ^{225}Ra and ^{227}Ra . It is believed that such deformation arises through polarization of the core by the extra nucleon. The signature of this sort of deformation is the structure of rotational bands built on close-lying parity doublets, with characteristic mixing ratios; additional evidence has been provided by magnetic moment measurements [Ahm 83]. Very recently, similar spectroscopic studies have been made of ^{227}Ac , with new level assignments, and magnetic moment measurements done by the perturbed angular-correlation technique. For low spin states ($3/2^{\pm}$), the analysis is consistent with the existence of a permanent octupole deformation [Mar 84]. Many studies must still be done in this region to confirm the present interpretation, and to map its occurrence in the actinides.

RADIOACTIVE TARGETS AND BEAMS

For many years, the idea of collecting microscopic quantities of radioisotopes to use as targets in other spectroscopic studies has been considered seriously. In 1976, a pilot experiment was done at ISOLDE to prepare a sample of ^{84}Rb , which was then used in (n,p) studies [And 76], and in 1980, letters of interest were submitted for the SIN-ISOLDE proposal [Har 80, Kle 80]. The Rb sample consisted of $\sim 10^{14}$ atoms, which represents a minimum target size for many classes of nuclear experiments (e.g. transfer and pickup reaction studies). An alternative scheme - to use a stable target and radioactive beam - requires beam intensities of $\sim 10^9$ atoms/s. Recent estimates [Hag 84] suggest that for typical experiments, beams generally are advantageous in cases where the activity has a half-life less than ~ 1 h. Some of the nuclear spectroscopic studies already

mentioned could clearly benefit from the availability of such beams and targets; the doubly-magic $^{56}_{28}\text{Ni}_{28}$ ($T_{1/2} = 6$ d) would be an excellent candidate as a target material, and isotopes near $^{100}_{50}\text{Sn}_{50}$ might be synthesized using targets of ^{44}Ti , or beams of ^{34}Ar [Nit 84]. Very recently, targets of ^{148}Gd ($T_{1/2} \sim 75$ y) in microgram quantities have been prepared by chemical separation, electrodeposition and isotope separation, and have been used in a determination of the ground state mass of ^{147}Gd , and in studies of single proton states of ^{149}Tb by a transfer reaction [Lan 84, Man 84, Dec 84]. A specific experiment (#309) to perform transfer reaction studies on radioactive targets, in particular ^{56}Ni , prepared at the TRIUMF-ISOL facility, has been presented to the TRIUMF EEC and a copy is included in the Appendix of this proposal. A second study (#314), requiring targets of ^{188}Pt , has also been submitted. The greatest motivation, however, for the development of radioactive beam facilities is for the study of nucleosynthesis in astrophysical processes. This will be discussed in detail in Sect. 2.

REFERENCES*

- [Ahm 83] S.A. Ahmad, W. Klempt, R. Neugard, E.W. Otten, K. Wendt, K. Ekstrom, Phys. Lett. 133B, 4 (1983).
 [And 76] G. Anderson, M. Asghad, A. Emsallem, E. Hagberg, B. Jonson, Phys. Lett. 61B, 234 (1976).
 [Bjo 82] T. Bjornstad, J. Blomqvist, G.T. Ewan, B. Jonson, K. Kawade, A. Kereck, S. Mattsson, K. Sistemich, Z. Phys. A306, 95 (1982).
 [Bjo 84] T. Bjornstad, J. Blomqvist, R.D. van Dinkelge, G.T. Ewan, P. Hoff, B. Jonson, K. Kawade, A. Kereck, O. Klepper, G. Lövhöjden, S. Mattsson, G. Nyman, H.L. Ravn, D. Schardt, and K. Sistemich, Zin 84, C9.
 [Blo 81] J. Blomqvist, Hel 81, 536.
 [Bon 76] J. Bonn, G. Huber, H.-J. Kluge, E.W. Otten, Z. Phys. A276, 203 (1976).
 [Bor 73] S. Borg, G.B. Holm, B. Rydberg, Nucl. Phys. A212, 187 (1973).
 [Dec 84] D.J. Decman, L.G. Mann, T.N. Massey, G.L. Struble, D.H. Sisson, C.M. Henderson, K.E. Thomas, H.A. O'Brien, Jr., H.J. Scheerer, P. Kleinheinz, LLL 84, 6-68.
 [Det 79] C. Detraz, D. Guillemaud, G. Huber, R. Klapisch, M. Langevin, F. Naulin, C. Thibault, L.C. Carraz, F. Touchard, Phys. Rev. C19, 164 (1979).
 [Fog 84] B. Fogelberg and J. Blomqvist, Phys. Lett. 137B, 20 (1984).
 [Gil 65] A. Gilbert and A.G.W. Cameron, Can. J. Phys. 43, 1446 (1965).
 [Gui 81] D. Guillemaud, C. Detraz, M. Langevin, F. Naulin, Hel 81, 368.

*In these references the following abbreviations are used:

- Hel 81: Proceedings of the 4th Int. Conf. on Nuclei Far From Stability, Helsingør, 1981 eds. P.G. Hansen and O.B. Nielsen (CERN 81-09).
 LLL 84: Nuclear Chemistry Divison Ann. Rept. FY-84, UCAR 10062-84/1, Lawrence Livermore Natl. Lab. 1984.
 TRI 84: Proceedings of the TRIUMF-ISOL Workshop, Mt. Gabriel, 1984, eds. J. Crawford and J.M. D'Auria, TRI-84-1.
 Zin 84: Abstracts from the Workshop on the ISOLDE programs, Zinal, 1984.

- [Hab 84] W. Habenicht, L. Spanier, G. Korschinek, H. Ernst, E. Nolte, Proc. 7th Int. Conf. on Atomic Masses and Fund. Const. AMCO-7 (1984) 244.
- [Hag 84] E. Hagberg, J.C. Hardy, H. Schmeing, G. Audi, Proc. of Workshop on Prospects for Research with Radioactive Beams, Washington, 1984, LBL-18187, p. 81.
- [Har 80] J.C. Hardy, E. Hagberg, Lett. of Interest, SIN-ISOLDE Proposal (1980) PSSC/80-68.
- [Har 84] J.C. Hardy and I.S. Towner, Jour. de Phys. C4, 417 (1984).
- [Hey 83] K. Heyde, P. van Isacker, M. Warozquier, J.L. Wood, and R.A. Meyer, Phys. Rep. 102, 293 (1983).
- [Jon 76] B. Jonson, E. Hagberg, P.G. Hansen, P. Hornshøj and P.T. Tidemand-Petersson, Proc. Int. Conf. Nucl. Far from Stability, Cargèse, 1976; CERN Report 76-13 (1976) 277.
- [Kle 80] P. Kleinheinz, O. Schult, Lett. of Interest, SIN-ISOLDE Proposal (1980) PSSC/80-59.
- [Kle 81] P. Kleinheinz, J. Styczen, M. Piiparinen, M. Kortelbahti, J. Blomqvist, Hel 81, 542.
- [Kle 84] P. Kleinheinz, Zin 84, C10.
- [Klu 82] H.-J. Kluge, Proc. Conf. on Lasers in Nuclear Physics, Oak Ridge, 1982, ed. C.E. Bemis, Jr. and H.K. Carter, Nucl. Sci. Res. Conf. Series Vol. 3, (Harwood Acad. Publ., New York, 1982) p. 137.
- [Kur 82] W. Kurcewicz, E.F. Zganjar, R. Kirchner, O. Klepper, E. Roeckl, P. Komninos, E. Nolte, D. Schardt, P. Tidemand-Petersson, Z. Phys. A308, 21 (1982).
- [Lan 84] R.G. Lanier, T.N. Massey, E.A. Henry, D.H. Sisson, C.M. Henderson, LLL 84, 6-62.
- [Lau 78] W.D. Lauppe, K. Sistemich, T.A. Khan, H. Lavin, G. Sadler, H.A. Selic, O.W.B. Schult, Proc. Int. Conf. on Nuclear Structure, Tokyo, 1977, J. Phys. Soc. Japan Suppl. 44, (1978) 335.
- [Man 84] L.G. Mann, D.J. Decman, T.N. Massey, G.L. Struble, D.H. Sisson, C.M. Henderson, B. Rubio, P. Kleinheinz, J.L. Tain, G.P.A. Berg, C.J. Meissburger, J.G.M. Romer, G. Hlawatse, D. Paul, B. Brinkmole, P.V. Rossen, H.J. Scheerer, K.E. Thomas, H.A. O'Brien, Jr., LLL 84, 6-65.
- [Mar 84] H.E. Martz, D.J. Decman, G.L. Struble, D. Burke, and R. Naumann, LLL 84, 6-109.
- [Nit 84] J.M. Nitschke, TRI 84, 230.
- [Rat 85] G.-E. Rathke, K. Rykaczewski, R. Kirchner, O. Klepper, V.T. Koslowsky, E. Roeckl, D. Schardt, I.S. Grant, P.O. Larsson, A. Plochocki, J. Zylicz, P. Tidemand-Petersson, GSI Preprint 85-12 (1985) to be submitted to Z. Phys. A.
- [Roe 85] E. Roeckl, D. Schardt, to be published.
- [Sis 78] K. Sistemich, W.D. Lauppe, T.A. Khan, H. Lawin, H.A. Selic, J.P. Bocquet, E. Monnard and F. Schussler, Z. Phys. A285, 305 (1978).
- [Thi 75] C. Thibault, R. Klapisch, C. Rigaud, A.M. Poskanzer, R. Prieels, L. Lessard, W. Reisdorf, Phys. Rev. C12, 644 (1975).
- [Thi 80] C. Thibault, M. Epherre, G. Audi, R. Klapisch, G. Huber, F. Touchard, D. Guillemaud, F. Naulin, Proc. 6th Int. Conf. on Atomic Masses and Fund. Const. AMCO-6 (1980) 291.

- [Tru 70] J.W. Truran, A.G.W. Cameron, and E. Hilf, Proc. Int. Conf. Nucl. Far From Stability, Leysen, 1970, CERN Report 70-30 (1970) 275.
- [Woo 84] J.L. Wood, TRI 84, 87.

1.3 NUCLEAR STRUCTURE: LASER SPECTROSCOPIC TECHNIQUES

INTRODUCTION

The electromagnetic interaction between the atomic shell and the nucleus is expressed through the hyperfine splitting (hfs) and isotope shift (IS) of atomic levels. Nuclear spins, magnetic moments and electric quadrupole moments are obtained from the hfs [Kop 58]. Changes in nuclear mean square charge radii and changes in nuclear deformation in isotopic sequences are derived from the IS [Hei 74, Ull 75].

Since the early days of nuclear physics, optical experiments investigating the hfs and IS of stable isotopes have contributed to the understanding of the nucleus, and have provided results which were of crucial importance in establishing the cornerstones of nuclear models. The extension of hfs and IS measurements to isotopes far from stability, possible through the marriage of sensitive optical experiments and powerful isotope production facilities, has opened up a new dimension in the study of nuclear ground state properties.

ON-LINE OPTICAL SPECTROSCOPY

Different optical methods have been used to exploit the capabilities of ISOL systems. The first experiments yielding results about the hfs and IS in long isotopic series were based on the optical pumping method, which combines optical excitation with RF-induced transitions between hfs or Zeeman states in atoms. Measurements in Hg [Hub 76], Rb and Cs [Bon 78] were carried out using radiation detected optical pumping (RADOP), where the β -decay asymmetry of a radioactive nucleus polarized by optical pumping is used as a resonance monitor. Conventional light sources (e.g. spectral lamps) were used for the optical excitation. The replacement of these conventional light sources by tunable dye lasers with their high spectral purity, perfect collimation and high-power density triggered the development of the new generation of optical experiments at ISOL systems. The work of the Mainz group at the ISOLDE mass separator, using pulsed lasers for UV spectroscopy in Hg [Dab 79], can be considered as a continuation of their RADOP work and was motivated mainly by the interest in the behaviour of changes in mean square charge radii of the even-even Hg isotopes (see Fig. II.1a, Sect. 1.2). The method was based on laser excitation and fluorescence detection of atoms prepared as an atomic vapour in a cell, and was later also applied for measurements in Cd [Buc 81]. The relative low resolution, a result of the large Doppler broadening and the laser linewidth (both of the order of 1 GHz), could be tolerated since the hfs and IS are larger (Hg) or comparable (Cd) to the observed linewidths.

Doppler-free spectroscopy and CW lasers with bandwidths of the order of MHz must be used where more resolution is required. Spectroscopy on collimated atomic beams excited by laser light at right angles is the most straightforward Doppler-free technique. The Karlsruhe group [Reb 82, Tho 82] has investigated the elements Ba, Ca and Pb using this direct approach. A French collaboration from Aimé Cotton and René Bernas laboratories adopted a more sophisticated version of the crossed beam technique for hfs and IS measurements of alkalines [Thi 82]: the laser optical pumping of an atomic beam with a Stern-Gerlach analyser. Here, hyperfine

pumping by the laser changes the relative population of the hfs levels of the atomic ground state. This change of population is detected by a Stern-Gerlach analyser which focuses only one group of Zeeman levels with $m_j = \pm 1/2$ onto a hot wire detector, where they are ionized and counted. The requirement of the presence of a Stern-Gerlach force ($J \neq 0$) and a low ionization potential of the elements has limited this laser optical pumping method to the investigations in the alkaline metals.

Until now, the most productive and versatile on-line laser spectroscopic method applied for hfs and IS measurements of radioactive species has been collinear laser spectroscopy on fast beams [Kau 76]. This method avoids the drawbacks of thermal beam or in-cell experiments. For example, no intermediate collection and re-evaporation steps are required for the preparation of a spectroscopically useful sample. There are no collimation losses of the sample as in the crossed beam techniques, and the chemical properties of the element under investigation, which play a crucial role in in-cell techniques, are of no importance. High resolution is achieved by superimposing a fast ion beam ($E \approx 50$ keV) and a laser beam in collinear geometry. The velocity distribution of the ion beam is dynamically compressed, and this results in a strong suppression of the Doppler broadening. The method has been used for spectroscopy on fast ion beams [Wen 84] and fast atomic beams [Neu 82], where the latter are efficiently produced by charge exchange collisions in an atomic vapour. The charge exchange can also be used for the population of metastable atomic levels which then serve as the initial state for subsequent excitation by laser light [Buc 82]. Collinear fast beam laser spectroscopy should be applicable for the investigation of all elements which are obtained as beams from ISOL systems.

The collinear technique is obviously limited to those elements which can be produced by target-ion sources. However, it should be noted that spectroscopy on decay products is also possible. Here, a mass-separated radioactive beam is collected, transferred to an optical cell, and studied by some sensitive in-cell technique (e.g. polarization spectroscopy). The spectroscopy of Au isotopes, produced by Hg decay, is an example of this approach [Klu 82].

FUTURE GOALS

Recent progress in this field has been rapid and impressive. Systematic information on long isotopic chains of 19 elements with over 200 isotopes and 20 isomers complement the data on nuclei in or near the valley of β -stability. Besides providing systematic information about the gross behaviour of nuclear matter in isotopes spanning a large fraction or even a complete neutron shell, the new data have revealed new regions of deformation, the breakdown of magic numbers far from stability, new semi-magic neutron and proton numbers and nuclear shape transitions and coexistences. Optical methods have also been used for the identification of new isotopes, which are often hidden from classical nuclear spectroscopy experiments because of background from radioactive isobars [Klu 84].

Despite this progress, the field of optical spectroscopy on short-lived species is still wide open. More systematic studies are necessary in order to find the answers to many questions raised by the previous experiments. Some recent developments are:

- (1) The Hg studies [Bon 76] have prompted attempts to locate in the neighbouring transitional nuclei other examples of shape transitions and coexistences.
- (2) Experiments in the rare earth region (between $Z=56$ and $Z=70$) are continuing the study of the influence of the $N=82$ shell closure on nuclear ground state properties as well as their Z -dependence near the $Z=64$ subshell closure and the onset of deformation at $N=90$ [Ahm 84].
- (3) Work has started in the Ra region [Ahm 84] where static intrinsic octupole deformations are expected and where other examples of changes in the nuclear shape from nearly spherical to strongly deformed (at $Z > 82$, $N > 126$) can be studied.
- (4) Experiments are planned near $Z=38$ where strong nuclear deformation (around $M \approx 100$) has been indicated by laser spectroscopy experiments in Rb [Thi 82] and nuclear level structure studies in Sr [Azu 79].
- (5) Problems in light elements, where nuclear properties can be studied over ranges covering complete neutron shells and mirror nuclei as well as nuclei with high N/Z ratios, have barely been attacked.
- (6) Information about short-lived isomeric states is completely missing.

Some of the reasons for the present gaps in our explorations of these nuclear systematics are related to limitations in ISOL isotope production while others have to do with difficulties in the optical spectroscopic methods. Currently, for example, only about 74 elements have been produced at ISOL systems [Rav 84]; of these, not all are produced at levels sufficient to meet the spectroscopic sensitivities required ($\sim 10^6/s$ for beam methods, $10^4/s$ for RADOP, and $\sim 10^{12}$ collected atoms in the case of in-cell methods). Even with sufficient isotopic yield the laser spectroscopy may not be straightforward, since most of the ions and light elements have ground state transitions in the ultraviolet (UV).

Until now, the most convenient way to generate UV was by frequency doubling the output of a pulsed dye laser. This implies low duty cycles and large linewidths; the linewidths present no problem for isotope shift measurements of heavy atoms, but are unacceptable for measurements on light elements. In summary, new optical spectroscopy experiments at ISOL systems will require advances in (a) ISOL capability and yield, and (b) spectroscopic sensitivity, resolution, and versatility.

Most of the ISOL developments centre on the improvement of target-ion sources. These include not only the modification of sources to produce a wider variety of elements, but also the development of sources which can bunch the beam, concentrating the maximum available yield into brief bursts. Intense pulsed proton beams may be useful for bombardment of sources having fast release times; also, techniques of collection and timed release through laser heating appear promising and may be combined with techniques of laser isotope separation [Lee 84]. With such bunching, a new generation of Doppler-free pulsed spectral techniques should be possible. Even CW laser experiments would benefit from the increased signal-to-noise ratio possible if bunched atomic beams were available.

Current efforts in the improvement of the spectroscopic methods are directed mainly towards CW ultraviolet techniques. Intense UV sources will simplify spectroscopy of both light elements and ions. Improved detection methods using ion counting are also under study and include multiphoton ionization, field ionization of Rydberg states, and ionization by charge exchange [Neu 84, Lib 84, ASU 84]. Combining such detection techniques with existing experimental methods (e.g. collinear laser spectroscopy) should improve the achievable sensitivity by about two orders of magnitude.

Other novel methods presently under development include the combination of collinear laser spectroscopy and RADOP [Arn 84]. Here, atom beams that are optically pumped by laser light are implanted into a cubic crystal, and the nuclear orientation is detected by the asymmetry in the β -decay of the implanted nucleus. Measurements of short-lived isomeric states could possibly follow the lines indicated by Feld et al. [Bur 77]. A short-lived state of a nucleus is populated by the radioactive decay of a parent isotope collected and contained as a vapour in a cell. The isomer is polarized by optical pumping methods and the polarization detected by the asymmetry in the β -decay. A pilot (off-line) experiment investigating the 1 μ s isomer ^{85}Rb , produced from the decay of ^{85}Kr , is currently under way [Fel 82] and promises to be adaptable to on-line use at an ISOL system.

CONCLUSION

Optical spectroscopy at on-line mass separators has contributed to a more profound understanding of the interplay between neutrons and protons in nuclei. The results provide systematic information about changes in both single particle and collective properties of nuclear matter. Despite the amount of data already available, questions remain which will provide a challenge for optical spectroscopy at ISOL systems for coming decades. Progress in ISOL systems and experimental techniques will be necessary to allow more systematic studies and an extension of the measurements towards the limits of nuclear stability.

REFERENCES

In the following references, LNP 82 refers to Proceedings of the Conference on Lasers in Nuclear Physics, Oak Ridge, 1982, ed. C.E. Bemis Jr., and H.K. Carter, Nuclear Science Research Conference Series, Vol. 3 (Harwood Academic Publ., New York, 1982); Zin 84 refers to the collection of abstracts from the workshop on the ISOLDE programme held at Zinal (1984); TRI 84 refers to the TRIUMF Proceedings (TRI-84-1) of the TRIUMF-ISOL Workshop, eds. J. Crawford and J.M. D'Auria, Mont Gabriel, Québec (1984).

- [Ahm 84] S.A. Ahmad, C. Ekström, W. Klempt, R. Neugart, E.W. Otten, K. Wendt, Zin 84, B11.
- [Arn 84] E. Arnold, D. Bauer, J. Bonn, R. Gegenwart, F. Kuhn, E.W. Otten, T. Reichelt, K.P.C. Spath, Zin 84, B3.
- [ASU 84] Inst. of Spectroscopy, Acad. Sci. USSR, Zin 84, B8.
- [Azu 79] R.E. Azuma, G.L. Borchert, L.C. Carray, P.G. Hansen, B. Jonson, S. Mattsson, O.B. Nielsen, G. Nyman, I. Ragnarsson, H.L. Ravn, Phys. Lett. 86B, 5 (1979).

- [Bol 84] G. Bollen, H.J. Kluge, W. Kronert, F. Lindenlauf, W. Neu, G. Passler, J. Streib, K. Wallmeroth, G. Wolf, Zin 84, B7.
- [Bon 76] J. Bonn, G. Huber, H.-J. Kluge, E.W. Otten, Z. Phys. A276, 203 (1976).
- [Bon 78] J. Bonn, F. Buchinger, P. Dabkiewicz, H. Fischer, S.L. Kaufmann, H.J. Kluge, H. Kremmling, L. Kugler, R. Neugart, E.W. Otten, L. von Reisky, J.M. Rodriguez-Giles, H.J. Steinacher, K.P.C. Spath, Hyperfine Interactions 4, 174 (1978).
- [Buc 81] F. Buchinger, P. Dabkiewicz, H.J. Kluge, A.C. Mueller, E.W. Otten, Hyperfine Interactions 5, 165 (1981).
- [Buc 82] F. Buchinger, A.C. Mueller, B. Schinzler, K. Wendt, C. Ekström W. Klempt, R. Neugart, Nucl. Instr. Meth. 202, 159 (1982).
- [Bur 77] M. Burns, P. Pappas, M.S. Feld, D.E. Murnick, Nucl. Instr. Meth. 141, 429 (1977).
- [Dab 79] P. Dabkiewicz, F. Buchinger, H. Fischer, H.J. Kluge, H. Kremmling, T. Kühl, A.C. Mueller, H.A. Schuessler, Phys. Lett. 82B, 199 (1979); P. Dabkiewicz Thesis (Mainz, 1980).
- [Fel 82] M.S. Feld, LNP 82, p. 1.
- [Hei 74] K. Heilig, A. Steudel, Atomic Data and Nuclear Data Tables 14, 613 (1974).
- [Hub 76] G. Huber, J. Bonn, H.J. Kluge, E.W. Otten, Z. Phys. A276, 187 (1976).
- [Kau 76] S.L. Kaufmann, Opt. Comm. 17, 309 (1976).
- [Klu 82] H.J. Kluge, LNP 82, p. 137.
- [Klu 84] H.J. Kluge, TRI 84, p. 196.
- [Kop 58] H. Kopfermann, Nuclear Moments (Academic Press, N.Y. 1958).
- [Lee 84] J.K.P. Lee, private communication.
- [Lib 84] S. Liberman, J. Pinard, P. Juncar, J.L. Vialle, C. Thibault, F. Touchard, Zin 84, B1.
- [Neu 82] R. Neugart, LNP 82, p. 231.
- [Neu 84] R. Neugart, W. Klempt, K. Wendt, Zin 84, B2.
- [Rav 84] H. Ravn, TRI 84, p. 19.
- [Reb 82] H. Rebel, G. Schatz, LNP 82, p. 197.
- [Thi 82] C. Thibault, F. Touchard, LNP 82, p. 113.
- [Tho 82] R.C. Thomson, A. Hauser, M. Anselment, S. Göring, G. Meisel, H. Rebel, G. Schatz, LNP 82, p. 227.
- [Ull 75] S. Ullrich, E.W. Otten, Nucl. Phys. A248, 173 (1975).
- [Wen 84] K. Wendt, S.A. Ahmad, F. Buchinger, A.C. Mueller, R. Neugart, E.W. Otten, Z. Phys. A317, 125 (1984).

1.4 EXOTIC DECAYS

1.4.1 PROTON-RICH NUCLEI

With the high production rates anticipated from an ISOL on-line to TRIUMF, it will be possible to increase enormously the number of isotopes available for study (see Fig. II.1). Indeed, among neutron-deficient nuclei, isotopes at or near the drip line should be available over much of the nuclear chart.

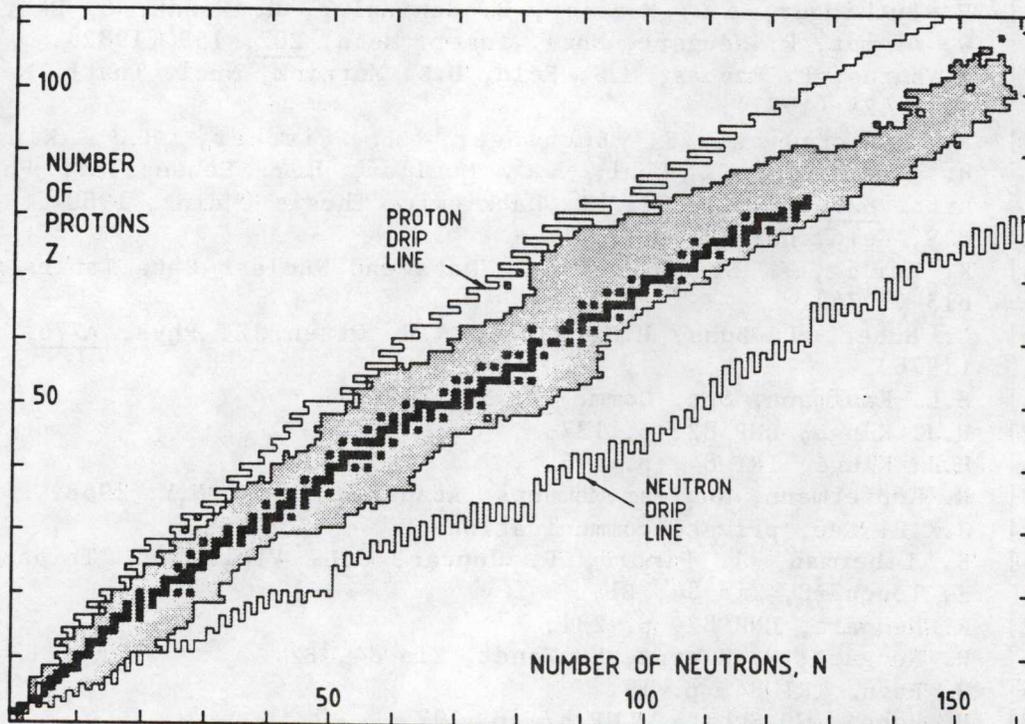


Fig. II.2. Chart of the nuclides. The stable isotopes are represented by black squares. Moving out from the stable isotopes are areas representing isotopes that have already been synthesized and identified, isotopes that calculations indicate could exist for an observable period of time but have not yet been produced and, finally, combinations of neutrons and protons not expected to adhere. The peninsula of observable nuclei undoubtedly extends for a short distance beyond the figure frame to the upper right. Predictions in this "superheavy" region are tenuous at best.

Why is the drip line an important goal? It is, of course, the most extreme condition we can impose on an unexcited nucleus, and as such it provides a demanding test of the predictions of nuclear theory. But there are more superficially exciting reasons as well. The further away nuclei are from the stable isotopes, the more energy they have available for decay, and the more exotic are the decay processes that can occur. Novel processes are inherently interesting, but some of those already studied

have also proven their usefulness in yielding nuclear-structure information that could not have been obtained by conventional means even with nuclei nearer stability. The search for nuclei near the drip lines attacks a genuine frontier where new phenomena are to be observed and new insights gained.

Figure II.3 illustrates the energetic changes that occur with remoteness from stability; it is a plot of the masses for a series of nuclei,

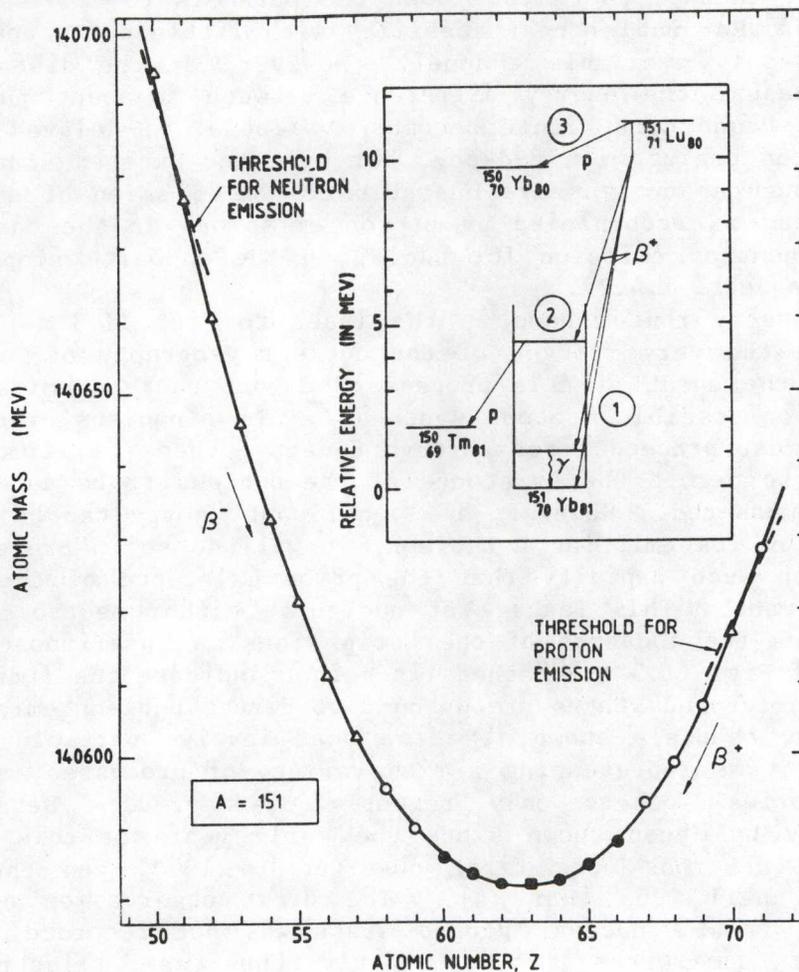


Fig. II.3. Atomic masses of a series of isotopes that have 151 nucleons in their nuclei. The masses are given in MeV to emphasize the energy released by decay between neighbouring nuclei. The only stable isotope, $^{151}_{63}\text{Eu}_{88}$, is shown as ■; the other isotopes whose masses have been measured appear as ●. All remaining masses come from predictions, with ○ representing nuclei that have been observed and Δ those that have not. The dashed lines show the approximate threshold at which a neutron or proton becomes energetically unbound by the nucleus. The inset illustrates three possible decay channels for the very neutron-deficient nucleus ^{151}Lu . Only the one labelled "1" is the "normal" β -decay channel leading down the $A=151$ mass parabola; the other two connect to an equivalent $A=150$ parabola.

all with the same total number of nucleons--in this example, 151. Only one corresponds to a stable isotope, ${}_{63}^{151}\text{Eu}_{88}$, shown as a black box at the bottom of the parabola. The farther $A = 151$ isobars are from this stable valley, the greater is their β -decay energy, with values approaching 20 MeV possible near the drip line.

The inset in Fig. II.3 displays a few of the possible decay channels available to the very neutron-deficient nucleus ${}_{71}^{151}\text{Lu}_{80}$. The first is the "normal" β -decay channel that leads down the parabola to ${}^{151}\text{Yb}$ and ultimately to ${}^{151}\text{Eu}$. For nuclei near stability with little decay energy this is usually the only available channel. However, as the distance from stability increases, the energy difference between adjacent nuclei increases, and a second decay route becomes available: β -delayed particle emission. It too begins with β -decay, but here the excited states populated in the daughter nucleus are unstable to the emission of a nucleon. Thus, the β -decay is accompanied by proton emission, in the case illustrated, or by neutron emission for nuclei on the opposite slope of the mass valley (see Sect. 1.4.2).

The third decay route shown in the inset to Fig. II.3 is one that only appears at the very fringes of the nuclear geography of Fig. II.2. In fact, it is the onset of this process of direct nucleon emission that sets the limit on possible isotope synthesis. If a nucleus' radioactive transformation must proceed first through β -decay, then its lifetime will be long enough to permit the existence of the nucleus to be detected and its properties measured. However, if significant energy can be released from a nucleus by its emitting a nucleon, it will do so in preference to β -decay and with such rapidity that the prior existence of the nucleus itself becomes moot. This leakage of nucleons, either neutrons or protons, establishes the location of the "drip lines". Superimposed on the mass parabola of Fig. II.3 are dashed lines that indicate the limit beyond which the nuclear ground states are unbound to direct nucleon emission.

Of the decay channels shown, the two that involve particle emission can be thought of as representing a rich variety of processes, some with venerable histories, others only recently discovered. Beta-delayed α -particle decay has been known since the early years of this century, while β -delayed neutrons were first observed in 1939, and the proton equivalent not until 1963 [Har 74]. The first observation of direct proton emission from a nuclear ground state was not recorded [Hof 82] until 1982; it came from ${}^{151}\text{Lu}$, exactly the case illustrated in Fig. II.2.

These possibilities are only the beginning. Excited states in ${}^{151}\text{Yb}$, or in any other nucleus like it, even on the opposite side of the valley of stability, can be unbound to the emission of nuclear fragments other than a single nucleon. Alpha particles have already been mentioned. Two protons [Cab 83] two and three neutrons [Azu 79, Azu 80] and even tritons [Lan 84] have all been observed, accompanying β -decay, for the first time during the past five years. Even direct fragment emission, without the preceding β -decay, can lead to exotic possibilities. The naturally occurring radioactive isotope ${}^{223}\text{Ra}$, long known to decay by α -particle emission, was discovered just last year to emit a ${}^{14}\text{C}$ nucleus for every 10^9 α particles. Never before, outside of the fission process, has a nuclear fragment heavier than $A=4$ been observed emitted in a radioactive decay.

The significance of these exotic decay modes extends, of course,

beyond their mere observation, although it frequently takes some years to realize the full extent of their usefulness. Delayed proton decay provides a good example. In the two decades since its discovery, the number of nuclei known to decay by proton emission has grown to over 60. Evidently β -delayed proton (and neutron) emission has become one of the important classes of radioactivity. Its study has yielded important results for: (1) nuclear mass differences among remote nuclei; (2) spectroscopic information on low-spin high-excitation energy levels in light nuclei; (3) statistical information on such levels in medium and heavy nuclei; (4) lifetimes of excited states in the range of 10^{-16} s (rarely accessible even for nuclei near stability); (5) allowed and first-forbidden β -decay transition strengths; (6) Gamow-Teller giant resonance and strength functions; (7) isospin mixing and Fermi β -decay; and (8) β - v angular correlations.

Beta-delayed multi-nucleon decay, though relatively new, is expected to become an especially rich source of information yielding, over and above the usual nuclear data, extra insight into the low-energy interactions between the emitted particles themselves. This can be demonstrated by the β -delayed two-proton decay of ^{22}Al , recently observed and studied at Berkeley [Cab 83]. Here, the question--as yet not definitively answered--is whether the two protons are emitted together, presumably as a ^2He nucleus that subsequently breaks up, or in a sequential two-step process in which the first proton leads to a definite state of ^{21}Na before the second proton is released. The energy distribution of individual protons and the correlation between them should be indicative: simultaneous two-proton emission gives rise to angularly correlated protons with a broad distribution of energies, while sequential decay leads to specific proton energy groups, each distributed isotropically. The most recent results [Jah 85] indicate a predominantly sequential decay mechanism, although a 15% admixture of correlated di-proton (^2He) emission cannot be excluded. Other multi-particle decays might be expected to contribute to resolving the ambiguity, but so far this has not happened. Only one other isotope has been observed to decay by β -delayed two-proton emission, namely $^{26}_{15}\text{P}_{11}$, and it is a rather special case: the protons are forced by angular momentum conservation to sequential emission, a consequence confirmed by the individual proton spectra. Beta-delayed multi-neutron emitters are known in greater profusion and they too have the option of decaying by paired or sequential emission. Unfortunately, to date, the mechanism in that case is no better understood. Experimental difficulties with the efficient, prompt detection of neutrons have effectively precluded the necessary measurements.

By the time that an ISOL at TRIUMF is functioning to capacity, such specific problems will undoubtedly be superceded by others, and some of the decay modes that are novel now will be yielding detailed nuclear properties, while yet more exotic modes--such as β -delayed fission perhaps--take the limelight. This brief survey of the current status can serve to illustrate the richness of the field and hint at its future direction. Much remains to be done in probing nuclear properties, two dimensionally in N and Z , over the entire nuclear chart with the sophistication now possible in the measurement of particle decays. The dividends will come from a greater understanding not only of nuclear structure generally but also of specific properties required in astrophysical models. In this context decay studies with an ISOL complement well the thrust of a

radioactive beam facility, while retaining a strong base in nuclear structure physics.

REFERENCES

- [Azu 79] R.E. Azuma, L.C. Carraz, P.G. Hansen, B. Jonson, K.-L. Kratz, G. Mattsson, G. Nyman, H. Ohm, H.L. Ravn, A. Schröder and W. Ziegert, *Phys. Rev. Lett.* 43, 1652 (1979).
- [Azu 80] R.E. Azuma, T. Björnstad, H.A. Gustafsson, P.G. Hansen, B. Jonson, S. Mattsson, G. Nyman, A.M. Poskanzer and H.L. Ravn, *Phys. Lett.* 96B, 31 (1980).
- [Cab 83] M.D. Cable, J. Honkanen, R.F. Parry, S.H. Zhou, Z.Y. Zhou, and J. Cerny, *Phys. Rev. Lett.* 50, 404 (1983).
- [Har 74] For an outline of the history and a description of the properties of β -delayed particle decay see J.C. Hardy in "Nuclear Spectroscopy and Reactions, Part C" (Academic Press, New York, 1974) p. 417.
- [Hof 82] S. Hofmann, W. Reisdorf, G. Münzenberg, F.P. Hessberger, J.R.H. Schneider and P. Armbruster, *Z. Phys.* A305, 111 (1982).
- [Jah 85] R. Jahn, R.L. McGrath, D.M. Moltz, J.E. Reiff, X.J. Xua, J. Aystö, and J. Cerny, to be published.
- [Lan 84] M. Langevin, C. Détraz, M. Epherre, D. Guillemaud-Mueller, B. Jonson, and C. Thibault, in *Proc. 7th Int. Conf. on Atomic Masses and Fundamental Constants*, O. Klepper, ed. (Darmstadt, 1984) p. 36.

1.4.2 EXOTIC DECAY OF NEUTRON-RICH NUCLEI

INTRODUCTION

If one considers all combinations of neutrons and protons which form nucleon stable nuclides, there are many more possibilities among the neutron-rich nuclides than among the proton-rich ones. The neutron "drip" line is the limit beyond which the binding energy of an additional neutron is negative. This limit is much farther from the valley of β -stable nuclides than the corresponding limit for protons on the opposite side of the valley (see Fig. II.2). Studies of proton-rich nuclides have reached the limit of proton stability in many cases, but there are broad regions of unknown neutron-rich nuclides.

These neutron-rich nuclides are of great interest because it is through these nuclides that the astrophysical r-process occurs, which builds up stable elements heavier than Fe. These nuclides are also important because they are products of nuclear fission. Thus, they affect such practical issues as reactor kinetics, waste disposal, and decay heat. Another reason for studying neutron-rich nuclides is their importance in understanding nuclear structure. The models developed for nuclei close to beta stability should be tested over as wide a range of nuclides as possible.

The energy available for β -decay (Q_β) increases and the binding energy (B_n) of the least bound neutron decreases as one proceeds away from the valley of stability on the neutron-rich side. These trends lead to some exotic new decay modes which occur only for very neutron-rich nuclides. In the rest of this Section, we will emphasize some of these exotic decays as well as some nuclear structure effects in very neutron-rich nuclides. At the same time, we hope to show how the proposed TRIUMF-ISOL can contribute to the study of these exciting problems.

BETA-DELAYED NEUTRON EMISSION

(a) Beta-Delayed One-Neutron Emission

When the energy available for β -decay exceeds the one-neutron binding energy, the process of β -delayed neutron emission becomes energetically allowed. If the β -decay populates an excited state of the daughter nucleus that is above the neutron binding energy, the neutron will be ejected on a time scale shorter than the time for γ -ray de-excitation. Delayed neutrons are the key to controlling nuclear reactors. Much effort has gone into identifying the individual nuclides which are delayed neutron precursors, measuring the delayed neutron emission probabilities (P_n), and measuring delayed neutron energy spectra for fission product precursors. The present status of delayed neutron data is given in Refs. [Eng 83, Man 84, Ree 83, Ree 84, Gre 83].

Beta-delayed neutron emission occurs in all regions of the nuclidic chart; however, facilities for producing non-fission product precursors have been limited primarily to the SC and PS accelerators at CERN [Gui 84, Bjo 81]. On-line mass separators with positive surface ionization sources have been coupled to these high energy proton accelerators to give very neutron-rich isotopes of Li, Na, and K, as shown in Fig. II.4. These nuclides were produced by fragmentation reactions of protons on heavy mass targets such as $^{191,193}\text{Ir}$ and ^{238}U . Figure II.4 shows that there are

many other nuclides in this mass region that are expected to be delayed neutron precursors. Counting delayed neutrons is often the easiest way to identify new nuclides which are very neutron-rich [Lan 84a, Ree 85]. The TRIUMF-ISOL will make a major contribution to the production and study of these delayed neutron precursors below the fission product mass region.

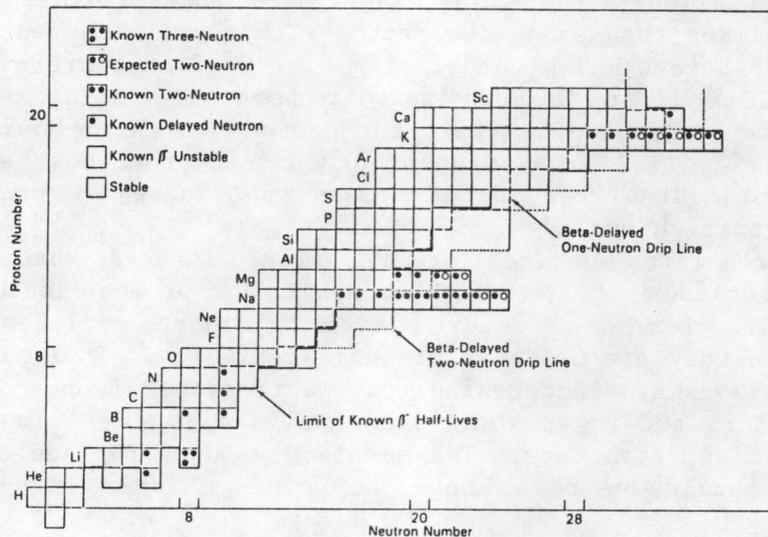


Fig. II.4. Partial chart of the nuclides showing neutron-rich nuclides from $Z = 1-21$. Limits of known β^- half-lives, β -delayed one-neutron drip line, and β -delayed two-neutron drip line are shown by solid, long-dashed, and short-dashed lines, respectively. See code in figure for known nuclides which are β -delayed i -neutron precursors.

(b) Beta-Delayed Two-Neutron Emission

Beta-delayed two-neutron emission has been observed in ${}^1\text{Li}$ [Azu 79], ${}^{30-33}\text{Na}$ [Det 80], ${}^{98}\text{Rb}$ [Ree 81], and ${}^{100}\text{Rb}$ [Jon 81]. The predicted location of the nuclides that are energetically allowed for this decay process is indicated in Fig. II.4 as the region to the right of the line called the beta-delayed two-neutron "drip" line. Mass formula predictions indicate that the fission product nuclides ${}^{83,84}\text{Ga}$, ${}^{86,87}\text{As}$, ${}^{91}\text{Se}$, ${}^{92}\text{Br}$, ${}^{101,102}\text{Rb}$, ${}^{136}\text{Sb}$, ${}^{142}\text{I}$, and ${}^{148}\text{Cs}$ should also be β -delayed two-neutron precursors.

A prime interest in studies of this decay mode is the possibility of observing effects due to the "dineutron". The only bound state of two nucleons is the ${}^3\text{S}$ state of the deuteron. However, it may be possible for two neutrons to be emitted from a nucleus in a virtual ${}^1\text{S}$ state (dineutron). The two neutrons will break apart outside the nucleus; however, the momentary existence of the dineutron may have effects which can be observed experimentally. These effects would provide a unique way of studying neutron-neutron interactions.

The emission of two neutrons as a correlated pair competes with the emission of two successive neutrons. Calculations show that the latter process dominates in nearly every case [Lyu 83]. The dineutron emission mechanism is more probable among lighter mass precursors than among

heavier mass precursors. The calculations suggest that 11% of the two-neutron emission from ^{32}Na should go by dineutron emission. The two mechanisms may be distinguished from each other by their characteristic angular distributions. The angular correlation of the two neutrons from dineutron emission should be less than 40° for typical cases, whereas the angular correlation for successive neutron emission should be symmetric about 90° . The TRIUMF-ISOL facility would be ideal for producing $A=11-52$ precursors where the dineutron emission is most favourable.

(c) Beta-Delayed Three-Neutron Emission

Beta-delayed three-neutron emission has been observed in the decay of ^{11}Li [Azu 80]. This nuclide has an unusually high Q_β (20.7 MeV) which is well above the threshold for three-neutron emission at 8.888 MeV. The three-neutron emission was identified by the time correlation between successive neutron counts in a paraffin moderated neutron counter. The known isotopes $^{31-35}\text{Na}$ are expected to be three-neutron precursors also. The lightest mass three-neutron precursor among the K isotopes should be ^{55}K , but the heaviest known K isotope at present is ^{54}K . These and other three-neutron precursors among odd Z elements should be available from the TRIUMF-ISOL.

For these very neutron-rich nuclides, delayed neutron emission becomes the dominant decay mode. Total delayed neutron emission probabilities approach and even exceed 100% due to multiple neutron emission [Ree 83]. The experimental P_{1n} , P_{2n} , and P_{3n} values can be compared to values calculated from theoretical models and thus they define the allowable input parameters for these calculations. The nature of energy spectra for three-neutron emission is an open question.

BETA-DELAYED TRITON EMISSION

The possibility of β -delayed ^3H emission was discussed in theoretical papers in 1969 and 1970 [Ber 69a, Ber 70a]. This decay mode is possible for very neutron-rich nuclides in which the β -decay energy is of the order of 15-30 MeV. The list of presently known nuclides which are energetically allowed for this decay mode includes ^8He , ^{11}Li , ^{14}Be , ^{15}B , ^{17}B , ^{17}C , ^{19}C , ^{20}C , ^{27}F , ^{29}Ne , and ^{35}Na . The calculations of [Ber 69a] give predicted branching ratios for β -delayed ^3H emissions (P_t) for Ca isotopes of mass 55-60. ^{55}Ca is just two neutrons beyond the presently known ^{53}Ca and its P_t was estimated to be about 5%.

Experimental observation of this decay mode in ^{11}Li was recently announced [Lan 84b]. For this nuclide the $Q_\beta = 20.70$ MeV, the $B_t = 15.72$ MeV, and the $P_t = (0.010 \pm 0.004)\%$. The ^3H were detected by a relatively simple ΔE -E detector consisting of a silicon surface barrier E detector in a gas proportional ΔE detector.

The study of all types of β -delayed particle emission is important for establishing the parameters of the mass formulas. Our predictions for the limits of nucleon stable nuclides depend on extrapolation of mass formulas far beyond the known regions, and it is desirable to reduce the uncertainties in these extrapolations. Delayed particle emission is also of interest because it sometimes populates states in the final nucleus which are not accessible by ordinary β -decay (due to spin and angular momentum selection rules). Study of these decays can provide information on the structure of these excited levels.

BETA-DELAYED FISSION

On both sides of the valley of β -stability, β -decay can populate excited states which have fission rates comparable to other modes of de-excitation [Ber 70a, Ber 69b]. Calculations of the probability for β -delayed fission are complicated by the need to use poorly known fission barriers [Kla 83]. However, the problem can be inverted and experimental probabilities for β -delayed fission can be used to study the fission barriers for "cold" nuclei far from the β -stability line.

On the proton-rich side, positron-delayed fission must compete with α -decay and spontaneous fission so only a few examples of this decay are expected. Beta-minus delayed fission should occur among a few hundred nuclides in the neutron-rich mass region from $Z = 89-99$. Experimentally, positron-delayed fission branching ratios have been measured for $^{232,234}\text{Am}$, $^{240,242}\text{Bk}$, $^{244,246,248}\text{Es}$, and $^{248,250}\text{Md}$. β^- delayed fission branching ratios are known for ^{232}Ac and $^{234,236,238}\text{Pa}$. More positron examples are known because of the ease of producing them by heavy ion induced reactions. However, a small portion of the β^- delayed fission nuclides could be produced by spallation from protons on a ^{238}U target. Some 7 nuclides produced by $(p, xpyn)$ reactions are estimated to have branching ratios greater than 1% for this decay process. If $(p, xp\pi^+)$ reactions are considered, then 9 more nuclides could be produced at TRIUMF-ISOL. Studies of β^- delayed fission would be quite exciting because of the importance of this process in terminating nucleosynthesis by the r-process and in cosmochronology.

GROUND STATE TWO-NEUTRON DECAY

As one approaches the neutron "drip" line, the binding energy of the last neutron generally decreases. However, the energy gained by neutron pairing can, in some cases, more than offset this trend. It is thus possible to have a nuclide with an odd number of neutrons for which the last neutron is not bound, yet the neighbouring nuclide with one more neutron can be bound. Examples of this situation already are known, e.g. ^5He and ^7He are unbound, yet ^6He and ^8He are bound. Likewise, ^{10}Li is unbound whereas ^{11}Li is bound.

The ^6He , ^8He , and ^{11}Li ground states are bound with respect to both one-neutron and two-neutron emission. However, as one goes even farther from β -stability, mass formulas predict that there will be many examples of nuclides which are bound with respect to one-neutron emission and unbound with respect to two neutron emission. The possibility then exists of observing two-neutron decay from the ground state of a very neutron-rich nuclide.

This decay mode would be identified by observing coincident neutrons which were correlated in energy and angle. The predicted decay energies are small (<3 MeV). Thus, many of the techniques for identifying β -delayed two-neutron emission would apply here also. Pure ground state two-neutron emission is more likely to be observed if the neutrons must penetrate a centrifugal barrier [Ber 70a, Ber 70b]. The probability of preforming a dineutron inside the barrier may also serve to slow down the emission process. These effects should increase the lifetime for the two-neutron decay, but it is not clear whether the lifetimes are long enough to allow the nuclide to be separated in an ISOL system. The cross sections for

producing candidates such as ^{21}B are very small, so traditional types of studies of this process will be difficult. A new approach, using neutron transfer reactions with accelerated radioactive species (like ^8He in the proposed post-accelerator, as discussed in later Sections), will be explored.

DOUBLE BETA DECAY

The probability for double β -decay near stability is very small with lifetimes of the order of 10^{21} years. This probability increases dramatically as the available energy increases. Calculations show that lifetimes of about 10^2 years are possible for nuclides with a Q_β of 20-25 MeV [Ber 70a, Ber 70c]. The ratio of double β -decay to single β -decay is about 10^{-11} to 10^{-15} which makes the observation of this process in very neutron-rich nuclides a very difficult problem.

BETA STRENGTH FUNCTIONS

For nuclei far from beta stability, the Q_β is very large so that β -decay can populate high excitation regions in the daughter nucleus where the density of states is very high. In these circumstances, it is convenient to describe the β -decay by average quantities.

We define the β -decay rate constant (λ) as:

$$\lambda = k \int_0^{Q_\beta} \rho(E) \cdot M^2 \cdot f(Z, Q_\beta - E) dE$$

where

- k = combined constants,
- $\rho(E)$ = density of levels at excitation energy E ,
- M^2 = average β -decay matrix element,
- $f(Z, Q_\beta - E)$ = Fermi integral function .

The Fermi function is well known, but the level density and matrix elements are not. The β -strength function S_β is therefore defined as the product of the level density and the average matrix elements. It is possible to determine β -strength functions by very careful beta, gamma and delayed neutron spectroscopy experiments. However, the β -strength function is critical for a wide range of problems, and must be estimated for unknown nuclides in the neutron-rich region. The β -strength function is required in such issues as [Kla 83]:

1. Synthesis of heavy elements in astrophysical processes.
2. Dynamics of the gravitational collapse of stars.
3. Determination of the age of the galaxy by r-process chronometers.
4. Efficiency of solar and galactic neutrino detectors.
5. Reactor neutrino spectra (which affects reactor neutrino oscillation experiments and neutrino mass).
6. Fission barriers of cold nuclei far from stability.
7. Practical problems in reactor decay heat and emergency cooling systems.
8. Fast breeder reactor dynamics (via delayed neutron emission probabilities and spectra).

Although theoretical estimates of the β -strength function have been invoked to solve these problems, it is essential to continue measurements of S_{β} on nuclei far from stability to provide the basis for extrapolating into unknown regions. These experiments can only be done at ISOL facilities.

NUCLEAR STRUCTURE

The standard shell model was developed for nuclides close to β -stability. As one moves away from stability, the shell structure changes, sometimes in unexpected ways. A new region of deformed nuclei was found among the very neutron-rich Na isotopes by mass measurements, laser spectroscopy, and beta/gamma spectroscopy [Gui 84]. The large deformation of ^{32}Mg ($N=20$) is surprising since $N=20$ gives a strong spherical closed shell for nuclides near stability. The experimental result has stimulated several theoretical calculations which have given greater understanding of the nuclear structure in this mass region.

Another new region of strong deformation has been identified around ^{100}Sr and ^{100}Y [Key 84]. A subshell closure occurs at $Z=40$ and $N=56$, but for $N > 60$ the nuclides have become deformed. This is an unusually rapid transition from spherical to deformed shape.

Knowledge of the shape of nuclides influences the mass surface. Present mass formulas do not account for these shape changes and thus incorrectly predict the masses. This has serious consequences for calculating β -decay properties of unknown nuclides. There is thus a continuing need for more and better studies of the mass surface of neutron-rich nuclides far from β -stability.

REFERENCES

- [Azu 79] R.E. Azuma, L.C. Carraz, P.G. Hansen, B. Jonson, K.-L. Kratz, S. Mattsson, G. Nyman, H. Ohm, H.L. Ravn, A. Schroder, and W. Ziegart, *Phys. Rev. Lett.* 43, 1652 (1979).
- [Azu 80] R.E. Azuma, T. Bjornstad, H.A. Gustafsson, P.G. Hansen, B. Jonson, S. Mattsson, G. Nyman, A.M. Poskanzer, and H.L. Ravn, *Phys. Lett.* 96B, 31 (1980).
- [Ber 69a] E.Ye. Berlovich and Yu.N. Novikov, *Bulletin of the Academy of Sciences USSR-Physical Series* 33, 626 (1969).
- [Ber 69b] E.Ye. Berlovich and Yu.N. Novikov, *Phys. Lett.* 29B, 155 (1969).
- [Ber 70a] E.Ye. Berlovich, *Proc. of the Int. Conf. on the Properties of Nuclei Far From the Region of Beta Stability*, Seysin, Aug. 31-Sept. 4, 1970, CERN report 70-30, p. 497.
- [Ber 70b] E.Ye. Berlovich, O.M. Golubev, and Yu.N. Novikov, *JETP Lett.* 12, 195 (1970).
- [Ber 70c] E.Ye. Berlovich and Yu.N. Novikov. *Sov. Phys. Doklady* 14, 986 (1970).
- [Bjo 81] T. Bjornstad, L.C. Carraz, H.A. Gustafsson, J. Heinemeier, B. Jonson, O.C. Jonsson, V. Lindfors, S. Mattsson, and H.L. Ravn, *Nucl. Instr. Meth.* 186, 391 (1981).
- [Det 80] C. Detraz, M. Epherre, D. Guillemaud, P.G. Hansen, B. Jonson, R. Klapisch, M. Langevin, S. Mattsson, F. Naulin, G. Nyman, A.M. Poskanzer, H.L. Ravn, M. de Saint-Simon, K. Takahashi, C. Thibault, and F. Touchard, *Phys. Lett.* 94B, 307 (1980).

- [Eng 83] T.R. England, W.B. Wilson, R.E. Schenter, and F.M. Mann, Nucl. Sci. Eng. 85, 139 (1983).
- [Gre 83] R.C. Greenwood and A.J. Caffrey, NEANDC Specialists Meeting on Yields and Decay Data of Fission Product Nuclides, Oct. 24-27, 1983, BNL 51778, p. 365.
- [Gui 84] D. Guillemaud-Mueller, C. Detraz, M. Langevin, F. Naulin, M. de Saint-Simon, C. Thibault, F. Touchard, and M. Epherre, Nucl. Phys. A426, 37 (1984).
- [Jon 81] B. Jonson, H.A. Gustafsson, P.G. Hansen, P. Hoff, P.O. Larsson, S. Mattsson, G. Nyman, H.L. Ravn, and D. Schardt, Proc. 4th Int. Conf. Nuclei Far From Stability, Helsingør, June 7-13, 1981; CERN, Geneva, 1981, 81-09, p. 265.
- [Key 84] U. Keyser, F. Munnich, B. Pahlmann, M. Graefenstedt, H. Faust, H. Weikard, and B. Pfeiffer, Proc. of the 7th Int. Conf. on Atomic Masses and Fundamental Constants AMCO-7, Darmstadt-Seeheim, Sept. 3-7, 1984 (Technische Hochschule Darmstadt, Schriftenreihe Wissenschaft und Technik 26) p. 148.
- [Kla 83] H.V. Klapdor, Progress Particle Nuclear Physics, Vol. 10, D. Wilkinson, ed. (Pergamon Press, Oxford, 1983) p. 131.
- [Kra 82] K.-L. Kratz, H. Ohm, H. Gabelmann, G.I. Crawford, G. Jung, and B. Pfeiffer, Z. Phys. A305, 93 (1982).
- [Lan 84a] M. Langevin, C. Detraz, D. Guillemaud-Mueller, A.C. Mueller, C. Thibault, F. Touchard, and M. Epherre, Nucl. Phys. A414, 151 (1984).
- [Lan 84b] M. Langevin, C. Detraz, M. Epherre, D. Guillemaud-Mueller, B. Jonson, C. Thibault, and the ISOLDE Collaboration, Proc. of the 7th Int. Conf. on Atomic Masses and Fundamental Constants AMCO-7, Darmstadt-Seeheim, Sept. 3-7, 1984, (Technische Hochschule Darmstadt, Schriftenreihe Wissenschaft und Technik 26) p. 36.
- [Lyu 83] Yu.S. Lyutostanskii, I.V. Panov, and V.K. Sirotkin, Sov. Nucl. Phys. 37, 274 (1983).
- [Man 84] F.M. Mann, M. Schreiber, R.E. Schenter, and T.R. England, Nucl. Sci. Eng. 87, 418 (1984).
- [Ree 81] P.L. Reeder, R.A. Warner, T.R. Yeh, R.E. Chrien, R.L. Gill, M. Schmid, H.I. Liou, and M.L. Stelts, Phys. Rev. Lett. 47, 483 (1981).
- [Ree 83] P.L. Reeder, NEANDC Specialists Meeting on Yields and Decay Data of Fission Product Nuclides, Oct. 24-27, 1983, BNL 51778, p. 337.
- [Ree 84] P.L. Reeder and R.A. Warner, Nucl. Sci. Eng. 87, 181 (1984).
- [Ree 85] P.L. Reeder, R.A. Warner, R.M. Liebsch, R.L. Gill, and A. Piotrowski, Phys. Rev. C (to be published).

1.5 FUNDAMENTAL PHYSICS

The nucleus may be used as a laboratory to study fundamental symmetry properties such as parity conservation, time reversal invariance and CP conservation. It can also be used to test the predictions of quark models in nuclei. Experiments to study such fundamental properties often require nuclei with specific properties, such as closely spaced doublets of levels with the same spin whose wave functions may be mixed. An example is the 0^+ , 0^- doublet in ^{18}F , which has been used to test parity non-conservation in the strong interaction. Other examples include specific cases for testing time reversal invariance.

The choice of nuclei that can be studied is limited especially if radioactive nuclei are required. The possibility of obtaining intense clean beams of a large variety of nuclei of half-lives down to approximately 10 ms greatly expand the possibility of finding a suitable case to test a specific conservation law. There is also the possibility of implanting the beams in a suitable environment, catching them in traps or storage rings, and polarizing the beams.

An example of the type of experiment that can be considered with an ISOL facility is a proposal by F. Calaprice for "Nuclear Orientation Studies and Measurements of Magnetic Moments of Radon Isotopes" to be done at ISOLDE [Cal 84]. The long-term objective of the experiments is to find a suitable case in which the atomic electric dipole moment can be measured with a sensitivity of better than 10^{-25} e-cm. The observation of such an electric dipole moment would indicate a violation of T-invariance. The sensitivity would be comparable to that obtained in present measurements of the electric dipole moment of the neutron and could possibly be better. The principle of the method involves nuclear orientation of the radon isotopes by the spin exchange optical pumping method. Narrow resonance techniques are used to measure magnetic dipole moments and if very narrow line-widths are obtained, a test of the effect of the electric dipole moment becomes possible. Calaprice has done such experiments with ^{131}mXe , ^{133}Xe and $^{133\text{m}}\text{Xe}$, but there is an advantage in using the heaviest possible atoms.

The existence of very clean, isotopically pure beams of a large range of radioactive nuclei makes other experiments possible. For example, beams with $T_z \leq 3/2$ in light nuclei are being used to study β -transitions to the Gamow-Teller resonance, which gives information on spin-isospin transitions. If the beams are sufficiently free of contamination, it could become possible to measure weak effects with small branching ratios. There may be cases in which parity forbidden decays can be studied. No detailed proposals have yet been made for such experiments as they depend on knowledge of the level structure of specific nuclei which are not known but could be studied with the proposed ISOL facility.

REFERENCES

- [Cal 84] F.P. Calaprice, in Abstracts of the Workshop on the ISOLDE Programme, Zinal, 1984, G3.

1.6 NUCLEAR PHYSICS WITH ACCELERATED RADIOACTIVE BEAMS

INTRODUCTION

The intensity of the radioactive beams available from the proposed TRIUMF-ISOL facility will allow a new field of nuclear physics to open. It will now be possible and practical to accelerate these low energy, radioactive ion beams to (conceivably) any useful energy, bombard a target, and thus perform standard nuclear structure and nuclear reaction studies for projectile-target systems previously inaccessible. As there exist some hundreds of unstable nuclei with half-lives greater than 10 ms (approximate transit time of an ISOL including diffusion in the thick target) which could now serve as heavy ion projectiles, a wealth of new nuclear information becomes available using this facility. This concept of accelerating the separated isotopic ion beam to usable energies is not new, but nevertheless the combination of the proposed high intensity TRIUMF-ISOL with a post-acceleration stage would be unique and would allow studies impossible with other approaches.

The most pressing need for studies with radioactive beams is in the field of nuclear astrophysics, which involve mainly fusion or transfer reactions at 1 MeV/amu or less on hydrogen or helium gaseous targets; this area of study is covered in Sect. 2.2 which follows. But, in fact, a wide field of heavy ion reactions would become accessible, involving reactions both with very neutron-rich and proton-rich projectiles, and indeed, also with long-lived isomers. These would be of interest both from a nuclear reaction and a nuclear structure point of view. The intention of this Section is not to review the entire area of heavy-ion physics, a field now commanding a great deal of attention in nuclear physics, but rather to illustrate only a few of the interesting kinds of studies that could be performed. The emphasis here is not necessarily technical feasibility, but rather scientific interest, though some of these studies are certainly within the range of the facility proposed.

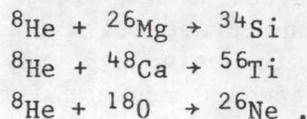
A more complete review of prospects for research with accelerated radioactive beams was given by J.M. Nitschke [Nit 84].

POTENTIAL AREAS OF INTEREST

All nuclear reactions that were feasible with stable species could, in principle, now be performed with radioactive species, depending upon the energy of the post-accelerator and the transmitted beam intensity. In fact, the use of radioactive beams can be advantageous, and the examples selected below are given only to illustrate some of these advantages, with particular emphasis on the use of lower projectile energies, a more realistic situation for the initial operation of this facility. Interesting areas of study include:

- a. Isotopes in a long-lived isomeric state can be produced and transported in an ISOL facility and used as projectiles in nuclear reactions. This would give the first opportunity to study reactions starting from excited states, rather than ground states. Of particular interest to the area of astrophysics are simple fusion reactions using such isomers as $^{26\text{m}}\text{Al}$ [Fow 84], but such new data are also of interest in the determination of the global optical model parameters used in various models.

- b. The use of neutron-rich, radioactive species as projectiles would provide a good method, in many cases the only method, of producing very neutron-rich isotopes for further measurement. For example, a TRIUMF-ISOL produced projectile of ^8He , accelerated to about 12 MeV (or 1.5 MeV/amu), could be used to initiate such reactions as



While the projected intensity of ^8He is not high ($\sim 10^9$ atoms/s), the expected high fusion cross section can give reasonable yields ($\sim 10^3$ c/s) of these products. An alternate method to produce interesting new isotopes for study is to take advantage of neutron and charged particle transfer reactions, again using such heavy neutron-rich projectiles as ^8He or $^9,^{11}\text{Li}$.

- c. Simple Coulomb excitation of the accelerated radioactive projectiles could provide a novel method of obtaining new information about the radioactive projectile itself. In any case, since nuclei that are now accessible only in nuclear reactions can serve as projectiles, such information as quadrupole (nuclear) moments, magnetic moments (g-factors) and lifetimes of excited states will be easier to determine for these nuclei. Such simple means as elastic scattering could, for example, provide phase shift analysis of excited states, thus determining angular moments as well as mixing between several states.

One area of initial interest could be the light neutron-rich helium and lithium isotopes, exploring the neutron p-shell built up in this region. While some information is available regarding levels in ^5He , the situation deteriorates as one proceeds to the heavier species out to ^{10}He . Since these are simple systems, they represent essentially pure neutron matter outside of a strong alpha core, and information on neutron-neutron interactions (e.g. pairing energies) could be accessible.

- d. Fusion reactions just above or below the barrier involving very neutron-rich projectile/target combinations could give another approach in the search for super-heavy elements. For example, the use of a projectile like ^{50}Ca on ^{248}Cm can be shown theoretically to give an increase of 10^6 in the predicted lifetime of the super-heavy product [Nit 84]. Such a study would require energies of the order of 5 MeV/amu and intensities around 10^{10} atoms/s.

REFERENCES

- [Nit 84] J.M. Nitschke in Proceedings of the TRIUMF-ISOL Workshop, Mt. Gabriel, Quebec, 1984, eds. J. Crawford and J.M. D'Auria, p.230.
 [Fow 84] W.A. Fowler, Rev. Mod. Phys. 56, 149, (1984).

2. ASTROPHYSICS USING ACCELERATED RADIOACTIVE BEAMS

It is now widely recognized [Fow 84, Hoy 65, Wal 81, Hil 82] that in numerous astrophysical environments, nuclear burning is expected to occur at sufficiently high temperatures and densities that reactions of unstable, radioactive nuclei with charged particles begin to compete with their natural decay. Hence, there is considerable interest in obtaining rates of simple fusion reactions involving nuclei with relatively short (greater than a few seconds) half-lives. The importance of such studies to nuclear astrophysics is illustrated by the following quote from William Fowler's 1983 Nobel Prize lecture:

"It is my view that continued development and application of radioactive ion-beam techniques could bring the most exciting results in laboratory nuclear astrophysics in the next decade" [Fow 84].

The intensity of the wide range of radioactive beams available from the proposed TRIUMF-ISOL facility should provide the opportunity to meet this challenge. In a limited number of cases, reasonably intense targets of radioactive materials can be produced for use at low energy, light ion accelerators elsewhere. This approach suffers from certain severe limitations such as half-life restrictions, high radiation fields, inefficient product detection, and handling problems. Of greater interest is the possibility of accelerating these radioactive beams and using them as projectiles in reactions with appropriate targets, such as hydrogen and helium.

The following Sections will cover a general review of the nuclear reactions of interest in astrophysical phenomena, aspects of this novel experimental approach for obtaining rates of important reactions and a brief description of the specifications of an ISOL post-accelerator device based upon nuclear astrophysics requirements.

NUCLEAR REACTIONS IN ASTROPHYSICAL PROCESSES

It is the aim of nuclear astrophysics to understand the nuclear processes that occur in stars. Thus, reaction networks can be devised based upon known nuclear measurements which show how the elements and isotopes are formed; an example is displayed in Fig. II.5, i.e. the cold CNO cycle. Explosive stellar burning at temperatures of 10^8 to 10^{10} K is believed to occur in many astrophysical environments such as supernovae, novae, accreting neutron stars and supermassive stars (10^5 - 10^7 solar masses). As opposed to the low temperature, static stellar burning, these "hot" events include nuclear reactions which involve radioactive species. Displayed in Fig. II.6 is the reaction network of the "hot" CNO cycle, believed to occur in some of these explosive burning situations.

The main parameters needed to calculate isotopic concentrations are the Q values and the reaction rates, $\langle\sigma v\rangle$, of each reaction indicated. These parameters are then used in extensive computer modeling of stellar processes. The rates $\langle\sigma v\rangle$ result from a folding of the Maxwell-Boltzmann

velocity distribution $[M(v)]$ of the colliding gases with the nuclear cross section $[\sigma(v)]$, namely,

$$\langle \sigma v \rangle = \int_0^{\infty} M(v) v \sigma(v) dv . \quad (1)$$

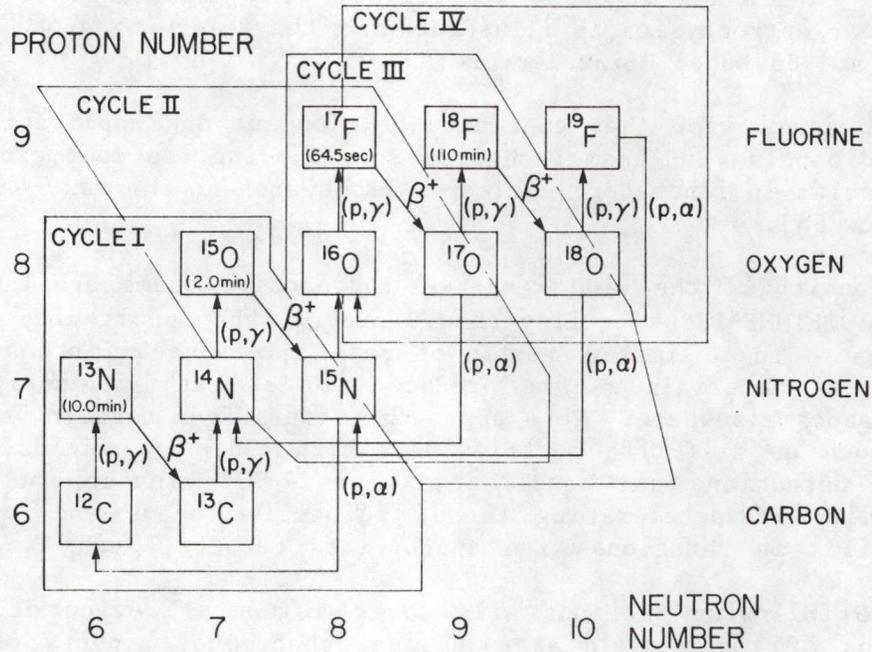


Fig. II.5. The nuclear reaction network for the cold CNO cycle.

In principle, the energy dependence of the reaction cross section should be known over a wide range of energies. In practice, due to the experimental decrease of the velocity distribution, $M(v)$, and the corresponding increase in $\sigma(v)$ due to the penetration factor through the Coulomb barrier, a peak (called the Gamow peak at one stellar temperature) results in the integrand, around a narrow energy region. The Gamow energy region around which σ should be determined is normally quite low for static stellar burning, e.g. around 10 keV in the sun. Thus, extrapolations of measured reaction rates from relatively high energy regions must be performed. Indeed, such extrapolations can lead to very large uncertainties, especially when low-Z elements are involved [Fow 84]. Here, for example, narrow but intense unknown reaction resonances at low energies can play a major role. This point will be expanded upon later; for more background, consult [Cla 68] and [Buc 84].

In the case of explosive burning, this extrapolation may not be necessary due to the higher temperatures involved. It may be possible to measure nuclear cross sections directly for the particular radioactive species. The energy range of interest is from about 100 keV/amu to at least 1000 keV/amu.

The first reaction of interest involving unstable species in the "hot" CNO cycle (see Fig. II.6) is $^{13}\text{N}(p,\gamma)^{14}\text{O}$. Using this as an illustration, the strength of this reaction determines the cycle speed as well as the relative occurrence of ^{13}C , a primary neutron source for the build up of heavy elements (s-process).

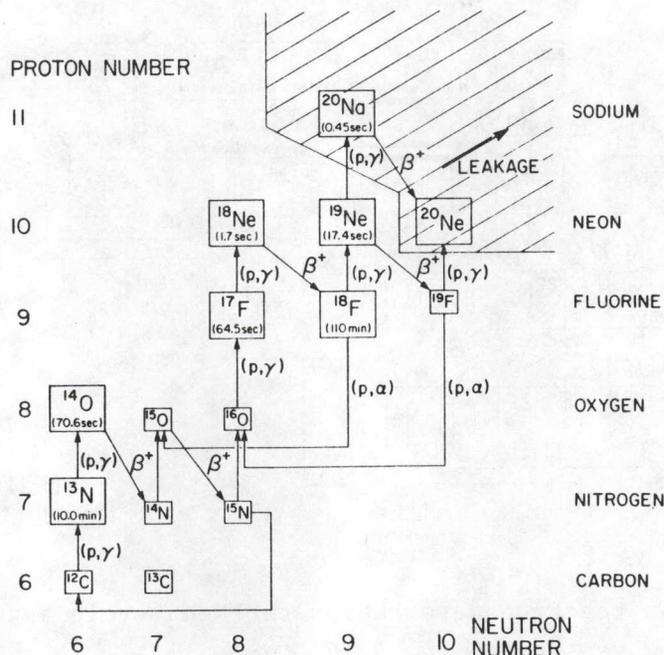


Fig. II.6. The reaction network for the "hot" CNO cycle.

In general, this hot CNO cycle could lead to a change in the isotopic concentration of the final products relative to the cold CNO-cycle, and could also cause a leakage of catalytic material from the cycle by the $^{18}\text{F}(p,\gamma)^{19}\text{Ne}(p,\gamma)^{20}\text{Na}(\beta^+)^{20}\text{Ne}$ -chain, thus drying out the cycle by the loss of catalytic agents, e.g. ^{12}C . Indeed, even a small leakage or loss of these catalytic agents can cause serious disruptions of the cycles. The hot CNO-cycle may also explain the relative abundances of such rare isotopes as ^{15}N , ^{17}O , ^{18}O , ^{19}F , ^{21}Ne , and ^{22}Ne (in the NeNa-cycle) [Aud 73, Nør 77].

As a result of some isotopic anomalies found in meteorites [Was 82], as well as the discovery of ^{26}Al in cosmic γ -ray observations, there has been increased interest in the higher NeNa- and MgAl-cycles. These cycles, shown in Fig. II.7, occur mainly in explosive hydrogen burning processes. The NeNa-cycle starts with the normally (second generation star) abundant ^{20}Ne , goes via proton captures and some β -decays to ^{23}Na , and then returns to ^{20}Ne by (p,α) . Also for relatively cold cases, which are suspected to be found in the hydrogen burning cores of massive stars, the $^{22}\text{Na}(p,\gamma)^{23}\text{Mg}$ reaction is crucial, because of the relatively long half life (2.6 y) of this isotope.

For higher temperatures, which are reached in nova and supernova explosions, reactions with the radioactive isotope ^{21}Na ($t_{1/2} = 23$ s)

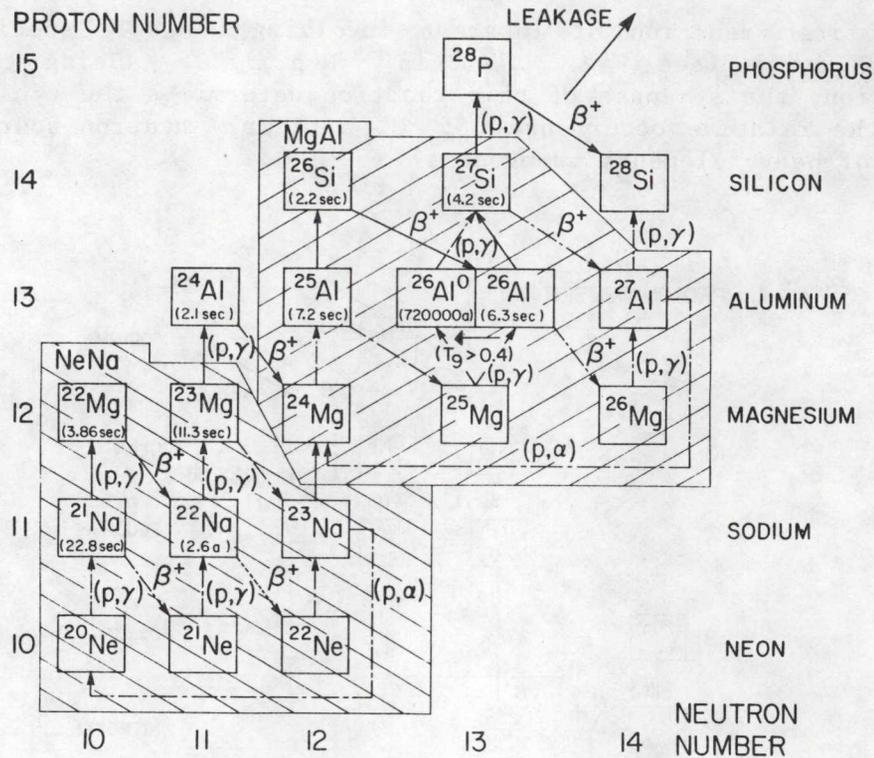


Fig. II.7. The reaction network for the NeNa cycle and the MgAl cycle.

also become important. For these temperatures, there is an outlet to the MgAl-cycle which occurs at about 30% with respect to the $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$ reaction (see Fig. II.7). In that cycle, radioactive isotope reactions like $^{25}\text{Al}(p,\gamma)^{26}\text{Si}$, $^{26}\text{Al}^m(p,\gamma)^{27}\text{Si}$ and (as a main leakage) $^{27}\text{Si}(p,\gamma)^{28}\text{P}$ become important. For further information about that cycle see [Hil 82] and references therein. From a nuclear point of view, it could also be interesting to compare proton capture from the ground state as well as from the isomeric state of ^{26}Al .

Wallace and Woosley [Wal 81] have proposed the so-called rp-process in which rapid capture of protons on unstable nuclei can lead to the ^{56}Ni region and higher, in competition with the "hot" CNO cycle and at somewhat higher temperatures. This proposed break-out process from the "hot" CNO cycle is based (for lower temperatures) only upon estimated rates for the $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$ and the $^{19}\text{Ne}(p,\gamma)^{20}\text{Na}$ reactions (see Fig. II.6); thus, actual measurements would be invaluable. Other similar reactions in this break-out path are of equal importance in helping to decide whether the rp-process is a valid model. This process is also of interest to model calculations as it would lead to an output of energy a hundred times greater than in the "hot" CNO. If it turns out that the rp-process is a valid process in nucleosynthesis, the determination of mainly proton capture rates for about 70 radioactive, proton-rich isotopes from ^{15}O to ^{70}Ge (including some isomeric states) would be desirable. Both the "hot" CNO cycle and the rp-process are believed to occur in hydrogen material accreting on the surface of neutron stars as well as white dwarfs (novae).

ASPECTS OF A NOVEL EXPERIMENTAL APPROACH

As indicated, one method of obtaining rates of reactions involving radioactive species of importance to nuclear astrophysics is to perform the reaction using the heavy species as the projectile, interacting with appropriate targets, e.g. gaseous hydrogen and helium. The generation and use of radioactive beams for such cross section measurements is in its infancy, but some efforts (not using an ISOL device) have been made by Boyd [Boy 83] and Haight [Hai 83] in very specific and limited cases.

An alternate approach of producing very energetic, fast-moving reaction products with a very high energy, heavy ion beam and slowing them to the appropriate region of interest is being considered elsewhere [Nit 84]. This and other approaches are analysed to a greater extent in a TRIUMF Technical Note (TRI-TN-85-1) in the Appendix.

A more viable approach from both a scientific and financial point of view is the one proposed here. An ISOL facility at TRIUMF should generate large quantities ($\sim 10^{12}$ atoms/s) of different and useful radioactive projectiles, which then need to be accelerated to the energy region of interest with some post-accelerator. A high intensity, good quality beam of essentially any projectile of interest would then be available to perform reaction studies.

Experimenters have been attempting for many years to measure stellar reaction rates using stable species. Because such reactions take place far below the Coulomb barrier, these studies require intense beams, stable targets, good beam qualities, and a great deal of patience. As discussed earlier, the energy region of interest for explosive nucleosynthesis is higher than for static situations, and the determinations of cross sections from 100 to 1000 keV (in the c.m. system) would be desirable.

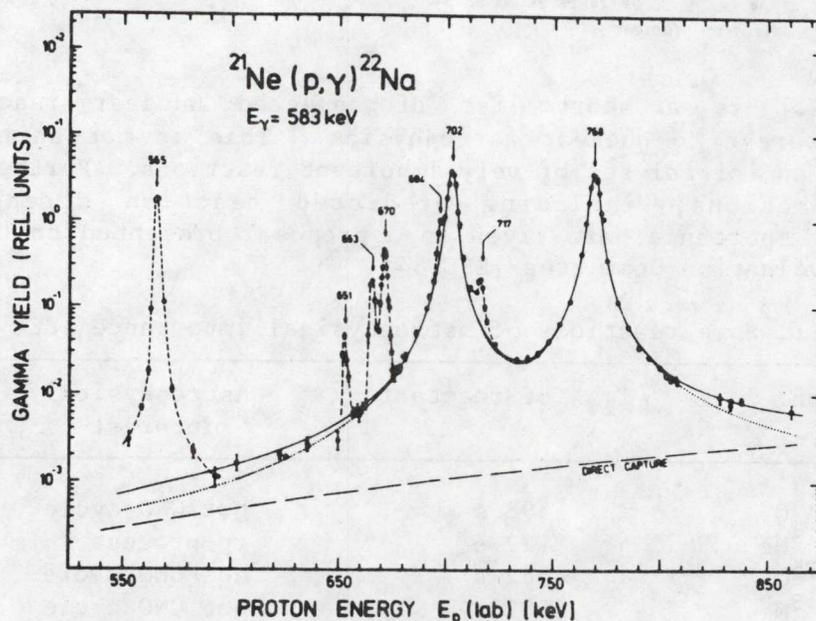


Fig. II.9. Excitation function for broad resonances in the $^{21}\text{Ne}(p,\gamma)^{22}\text{Na}$ -reaction [Gör 83]. The width of the 565, 651, 663, 670, 694 and 717 keV resonances reflects the target thickness.

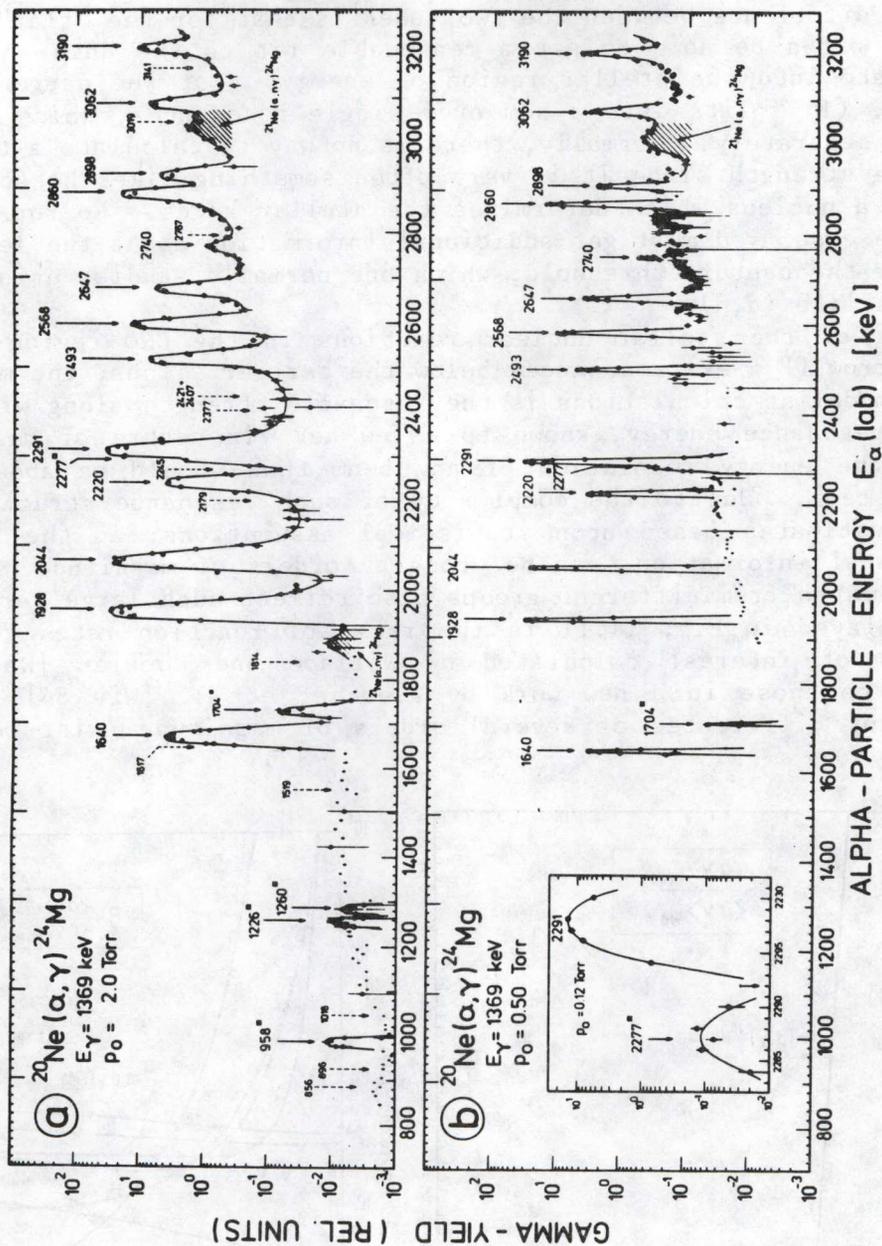


Fig. II.10. Excitation function for the $^{20}\text{Ne}(\alpha, \gamma)^{24}\text{Mg}$ reaction [Sch 83]. Shown are figures for two target thickness (gas-cell pressure). Clearly the width of most resonances is due to the target thickness.

In the course of excitation function measurements, one observes mainly two different cases for different reactions: a "flat" cross section caused either by broad resonances or by non-resonant direct processes or, in the other case, narrow resonances whose width is much less than the target thickness. Figs. II.9 and II.10 show these two cases for reactions involving two stable nuclei.

The difference between the two cases is that for the "flat" case, one may very often be able to get a reasonable fit to the data and thus can extrapolate into the stellar region of energy. For the narrow resonance case, Eq. (1) splits into a sum over single resonances, which have to be measured separately. Normally, there is no way to calculate a theoretical resonance strength since it is very often something like the 43rd excited state in a nucleus which determines the stellar rates. So for the narrow resonance case, you must get additional information about the level structure near the capture threshold, which one normally studies using transfer reactions like (d,n).

Most of the stellar nuclear reactions in the CNO region pass over many, narrow ($\Gamma \sim \text{eV}$) resonances below the barrier. Thus, the main parameter in modeling calculations is the resonance strength along with a well-defined resonance energy, known to a few keV (in centre of mass). As a result, the energy resolution of any beam thus should be about 1-2 keV (c.m. system). Due to the complexity of such resonance structure, theoretical estimates based upon statistical assumptions, in the absence of experimental information, can be wrong by orders of magnitude. Theoretical estimates from different groups also reflect such large variations.

Displayed in Fig. II.11 is the ratio of reaction rates for various reactions of interest calculated by Wallace and Woosley [Wal 81], as compared to those in a new work by Wiescher et al. [Wie 84]. Clearly, significant differences of several orders of magnitude exist between the

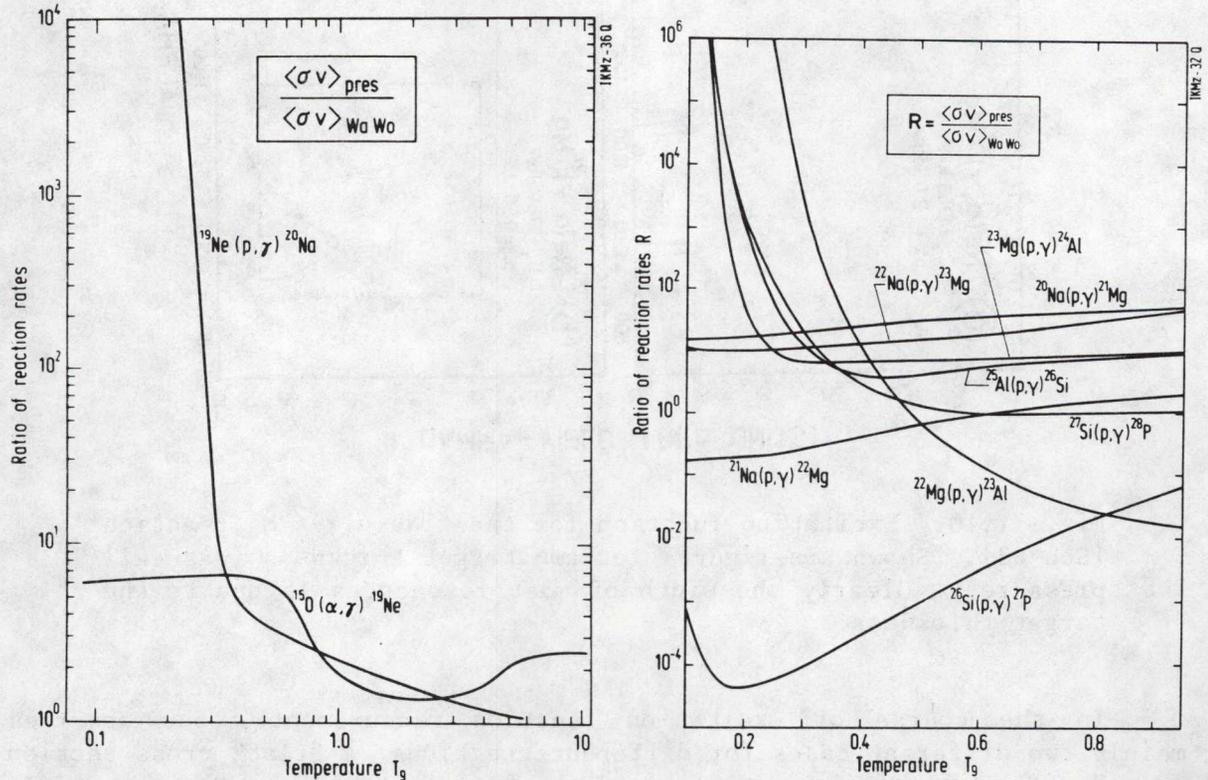


Fig. II.11. Ratio of stellar reaction rates from Wiescher [Wie 84] as compared to those of Wallace and Woosley [Wal 81]; (a) for $^{19}\text{Ne}(p, \gamma)$ and $^{15}\text{O}(\alpha, \gamma)$; (b) for reaction involving species with $A = 20-27$.

rates estimated by the two different approaches. Both theoretical works use gross properties of the states involved as input parameters. But because of unknown resonance states or an "abnormal" behaviour of a particular state, large variations can occur. Similarly, large differences can occur between experimental data and theoretical predictions. From a different perspective, experiments with large experimental errors are still of great value in elucidating the reaction paths in explosive stellar burning processes.

SUMMARY

In summary, there is a great deal of interest in measuring reaction rates at sub-barrier energies for many simple fusion reactions involving low-Z, radioactive reactants. The best approach is to accelerate the intense, separated isotopic heavy-ion beam from the TRIUMF-ISOL and react it with either a helium gaseous target [for (α, γ) and (α, p) reactions] or a hydrogen gaseous target [for (p, γ) reactions]. The desired specifications of such a post-accelerator based upon the requirements of nuclear astrophysics are given in Table II.2. Initially, the intention is to study the reactions listed in Table II.1 and discussed in more detail in [EEC 84]. Such a facility would be unique in the world, and these kinds of measurements would be difficult to perform elsewhere.

Table II.2. Specifications of a TRIUMF-ISOL Post-Accelerator

Parameter	Value	Comments
Projectile ion	$A \leq 60$	singly charged (\pm) ions from ISOL
Energy range	100 keV/amu to ≥ 1000 keV/amu	continuously variable
Energy spread	$\Delta E/E \leq 10^{-3}$	map narrow resonances
Transmission	high ($\sim 50\%$)	ISOL currents are normally low
Beam current	$\geq 10^{10}$ particles/s	required since small cross sections

REFERENCES

- [Aud 73] J. Audouze, J.W. Truran, B.A. Zimmerman, Ap. J. 184, 493 (1973).
- [Boy 83] R.N. Boyd, L. Rybareyk, M. Wiescher, and H.J. Hausmann, 1983, IEEE Trans. Nucl. Sci., NS 30, No. 2. 1387.
- [Buc 84] L. Buchmann, in Proc. of the TRIUMF-ISOL Workshop, Mt. Gabriel, Québec, eds. J. Crawford and J.M. D'Auria, June, 1984; TRI-84-1.

- [Cla 68] D.D. Clayton, "Principles of Stellar Evolution and Nucleosynthesis", (McGraw-Hill, New York, 1968).
- [EEC 84] L. Buchmann and J. D'Auria, 1984, proposal submitted to the Experiment Evaluation Committee at TRIUMF, Exp. 311.
- [Fow 84] W.A. Fowler, Rev. Mod. Phys. 56, 149 (1984).
- [Gri 76] J. Grindley, H. Gursky, H. Schnopper, D.R. Parsignault, J. Heise, A.C. Brinkman and J. Schrijver, Ap. J. Lett. 205, 1127 (1976).
- [Gör 83] J. Görres, H.W. Becker, L. Buchmann, C. Rolfs, P. Schmalbrock, H.P. Trautvetter, A. Vlieks, J.W. Hammer and T.R. Donoghue, Nucl. Phys. A408, 372 (1983).
- [Hai 83] R. Haight, G.J. Mathews, R.M. White, L.A. Aviles and S.E. Woodward, Nucl. Instr. Meth. 212, 245 (1983).
- [Hil 82] W. Hillebrandt and F.K. Thieleman, Ap. J. 255, 617 (1982).
- [Hoy 65] F. Hoyle and W.A. Fowler in "Quasi-stellar sources and gravitational collapse", eds. I. Robinson, A. Schild, E.L.S. Auckling (Univ. of Chicago Press, Chicago, 1965) 62.
- [Mah 84] W.A. Mahoney, J. Ching, W.A. Wheaton and A.S. Jacobson, Ap. J., in press (1984).
- [Nit 84] J.M. Nitschke 1984, in: Proceedings of the TRIUMF-ISOL Workshop p. 230.
- [Nør 77] H. Nørgaard, Ap. J. 215, 200 (1977).
- [Sch 83] P. Schmalbrock, H.W. Becker, L. Buchmann, J. Görres, K.U. Kettner, W.E. Kieser, H. Kräwinkel, C. Rolfs, and H.P. Trautvetter, Nucl. Phys. A398, 279 (1983).
- [Wal 81] R.K. Wallace and S.E. Woosley, Astrophys. J. Suppl. 45, 389 (1981).
- [Was 82] J. Wasserburg, 1982, in: "Essays in Nuclear Astrophysics", C.A. Barnes, D.D. Clayton, D.N. Schramm (eds.), Cambridge University Press, Cambridge.
- [Wie 84] M. Wiescher, 1984, private communication, to be published.

3. CONDENSED MATTER STUDIES

INTRODUCTION

The study of the interaction between nuclei and solid matter is a vast and fertile field of basic and applied research commonly known as nuclear solid state physics. The rapidly growing activity in this field during the past decade has resulted in discoveries of new effects in solids, in the development of new experimental techniques, and the collection of a wealth of nuclear data. Various nuclear solid state methods, such as ion implantation and channelling, Rutherford backscattering and nuclear reaction analysis, Mössbauer spectroscopy, NMR, ESCA, PIXE, EXAFS, positron annihilation, and neutron scattering, have matured to play a decisive role in expanding the frontiers of today's high technologies to the realm of submicron dimensions. According to general expectations [Fey 79], the investigations of submicronic low-dimensional solid objects such as surfaces, interfaces, thin films, implanted and intercalated structures, will constitute a field of extremely challenging discoveries in the coming years.

Isotope separation on-line (ISOL) of unstable nuclei [Rav 79] is now sufficiently well developed to be considered an important tool for materials research. The next generation of ISOL facilities will provide new attractive opportunities for solid state physics using short-lived nuclear probes, which will enter a new phase of expansion and vigorous international collaboration.

Various possible applications of radioactive ion beams in surface physics and chemistry were recently discussed by S.R. Morrison during the TRIUMF-ISOL workshop [Mor 84]. The topics of special interest listed there included sputtering, surface diffusion, condensation, implantation, channelling, ion neutralization, adsorption/desorption kinetics, catalysis and surface composition analysis. The techniques of low energy ion scattering (LEIS) and modulated beam reaction spectroscopy (MBRS) using radioactive beams have been discussed in detail as some of the suggested research methods. The subject has also been considered during the recent workshop at Zinal by E. Recknagel [Zin 84], who pointed to interesting applications such as defect studies in metals, lattice location of impurities, surface studies and internal tracer diffusion.

This Section will emphasize several other applications and techniques, among them mainly the studies of nuclear hyperfine interactions and conversion electron spectroscopy of implanted short-lived nuclei.

ION IMPLANTATION

Ion implantation, regarded initially as an obscure phenomenon obstructing nuclear reaction experiments, has itself become a subject of intense study. Additionally, it has become a powerful tool for materials science, being now more and more widely applied in non-equilibrium micro-metallurgy and in the manufacture of sophisticated semiconductor and optoelectronic components (e.g. Ref. [Pic 84, Pic 85]).

Ion implantation has several very attractive features as a tool for the carefully controlled introduction of radioactive impurities in solid materials. Using ion beams, one can create extraordinary new materials or new phases, very often with drastically modified properties, regardless of

the usual solubility limits and alloying rules. Practically all elements can be intermixed. In contrast to conventional thermal alloying, the solid solubility can be exceeded by several orders of magnitude. Both the location and depth of implantation, as well as the ion dose and resultant concentration in the matrix, can be defined with a high degree of precision. At commonly used isotope separator energies (10-100 keV), the ion range in solids is of the order of 100-1000 Å. Ion implantation introduces much damage to the target, and therefore creates new phenomena and defect structures often characteristic of the materials used in a nuclear reactor environment.

MÖSSBAUER SPECTROSCOPY

Mössbauer spectroscopy is an efficient method for studying ion implantation, radiation damage and modifications of materials by ion beams. Mössbauer spectra permit the study of hyperfine structure. As mentioned in Sect. 1.3, this permits the determination of three useful parameters: (i) the isomer shift, which is proportional to the density of electrons at the nucleus, (ii) quadrupole splitting, which measures the electric field gradient at the nucleus, and (iii) magnetic hyperfine splitting, which measures the effective magnetic field at the nucleus. The analysis of these parameters provides information about the electronic structure of the implanted atoms, their positions in the matrix and the configuration of nearby lattice defects, as well as the magnetic properties of the materials.

The applications of Mössbauer spectroscopy in ion implantation studies have been extensively discussed [Saa 81, Sai 85, Waa 75, Nie 83, Rus 73, Wey 81]. Four techniques are used at present:

1. Conversion electron Mössbauer spectroscopy (CEMS) for the investigation of stable isotopes (mostly ^{57}Fe , ^{119}Sn , ^{151}Eu and ^{197}Au) implanted by the isotope separator at high fluences (from 10^{14} to 10^{17} ions/cm²). CEMS also makes it possible to investigate various beam-modified materials and surface effects in materials containing the isotopes listed above. The technique has been largely developed by the Cracow group, see e.g. [Saa 81, Sai 85].
2. Emission Mössbauer spectroscopy (EMS) of long-lived radioactive isotopes ($T_{1/2} \sim 1$ d) implanted with the isotope separator (e.g. ^{57}Co , ^{83}Kr , ^{119}Sn , ^{119}Sb , ^{119}Te , ^{125}Te , ^{129}Te , ^{133}Xe , ^{153}Sm , ^{161}Tb , ^{169}Er). Fluences are from 10^{11} to 10^{13} ions/cm². The investigations have been carried out mostly in Groningen, Leuven and Aarhus and are reviewed in [Waa 75, Nie 83].
3. Coulomb recoil implantation Mössbauer effect (CRIME), as introduced in Stanford [Rus 73], makes it possible to investigate excited nuclear states in nuclei which have been recoil-implanted through a vacuum into various solid targets. Reaction recoils can be used as well. Nuclei studied were e.g. ^{57}Fe , ^{170}Yb , ^{174}Yb , ^{178}Yb .
4. Mössbauer spectroscopy with the isotope separator on-line (MSISOL) for short-lived nuclei (10^{-3} s to 1 d) produced by an accelerator and implanted with the ISOL facility. Extremely low doses (10^8 - 10^{10} ions/cm²) can be investigated. The technique has been pioneered at CERN by the Aarhus group, [Wey 81]. A mass-separated beam of 5×10^8 $^{119}\text{In}^+$ /sec ($T_{1/2} = 2.1$ min), produced at ISOLDE by proton-induced fission in a uranium-carbide target, has been used to study lattice

defects in semiconductors and in metals. Alternatively, ^{119}Sb (83.5 h) was used. Figure II.12 shows a sectional view of the equipment used at CERN.

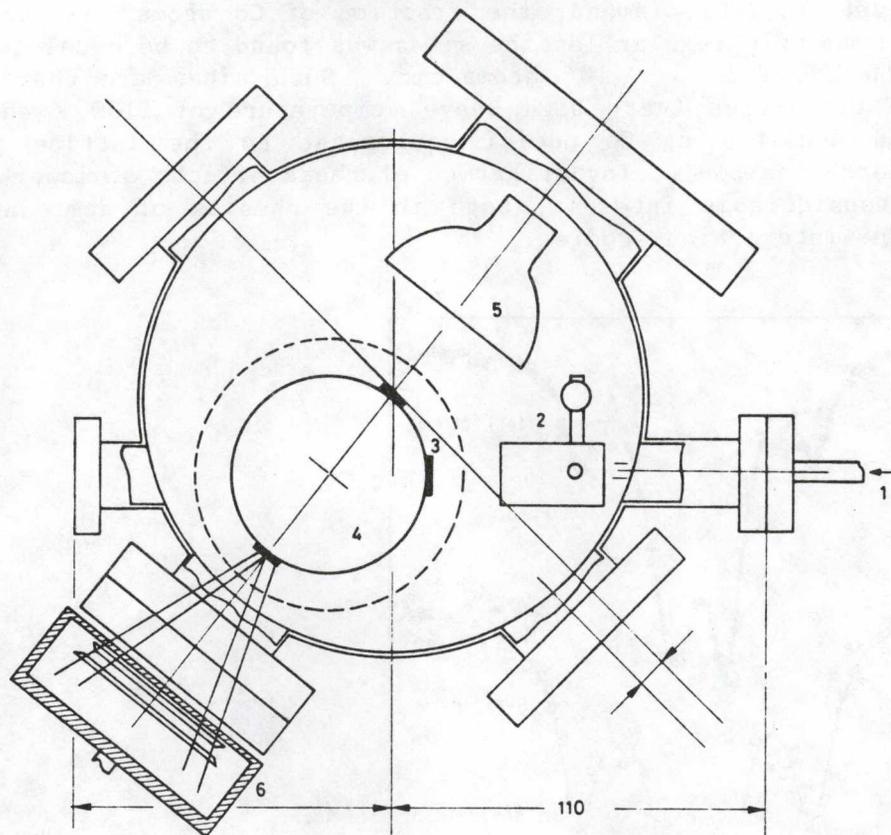


Fig. II.12. Schematic sectional view of the implantation chamber for on-line Mössbauer experiments at ISOLDE. (1) Beam entrance port; (2) movable Faraday cup; (3) target crystal; (4) liquid nitrogen cooled target holders; (5) lamp for annealing experiments; (6) resonance detector (from [Wey 81]).

By using the ISOL for the rapid extraction and implantation of isotopes, one can considerably extend the range of applications of Mössbauer spectroscopy in nuclear solid state physics, chemistry and materials science. Intense beams of short-lived isotopes ($T_{1/2} < 1$ d), obtained by separation of nuclear reaction products directly from a target, yields source strengths of 10^{-3} - 10^{-1} Ci, sufficient to measure the Mössbauer spectra of many isotopes on a time scale of minutes to hours. In addition, the use of short-lived isotopes permits the investigation of samples at very low doping levels ($\sim 10^8$ - 10^{10} ions/cm²). Particularly attractive would also be the measurements of the 14.4 keV resonance in ^{57}Fe using a ^{57}Mn source with $T_{1/2} = 2.1$ m; this is short compared with $T_{1/2} = 270$ d for ^{57}Co , the source presently used in ^{57}Fe measurements.

Lowering the doping level is particularly important in the studies of semiconductors. An example of such studies, taken from [Lan 84], is

given in Fig. II.13. It shows that the character of the residence sites of ^{57}Co implanted in silicon drastically changes when the doping dose is lowered to about 10^{12} - 10^{13} atoms/cm², that is, below the limit for matrix amorphization. In diamond, the fraction of Co atoms that can reside in highly symmetric regular lattice sites was found to be equal to about 25%, below the dose of 5×10^2 atoms/cm². Such sites are characterized by extreme properties (very high Debye temperature of 1100 K and very high electron density) at Co nuclei equivalent to the lattice pressure of 1500 kbars [Saa 81b]. Investigation of these effects at lower doses would be of considerable interest, both in the physics of semiconductors and hyperfine interaction studies.

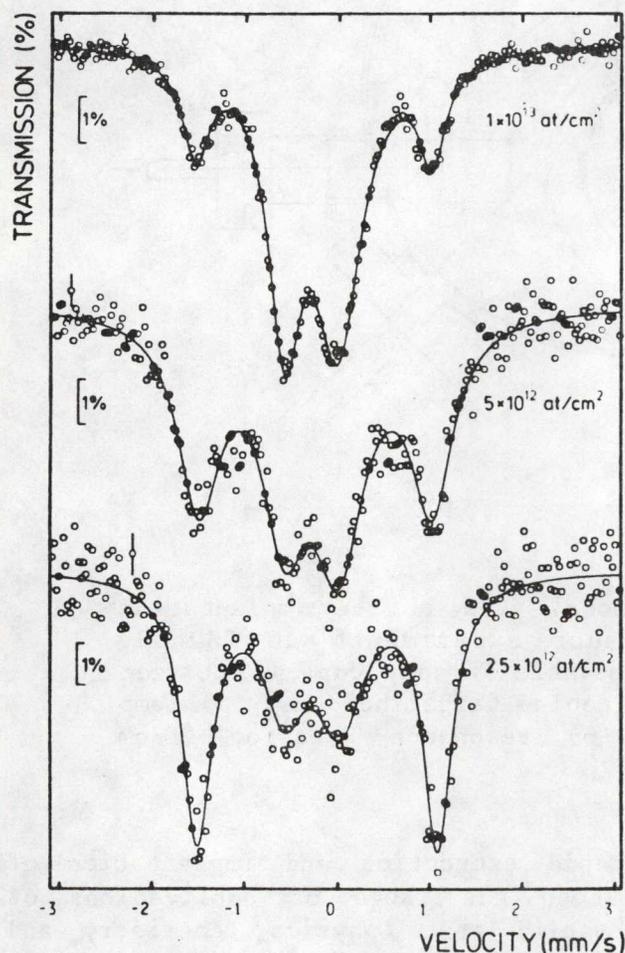


Fig. II.13. Mössbauer spectra from ^{57}Co sources implanted into n-type Si with various doses and annealed to 475°C. The central quadrupole doublet corresponds to Co-silicide, whereas the outer doublet corresponds to Co-Co dimers formed during the recrystallization of the silicon lattice (from [Lan 84]).

Mössbauer spectroscopy is particularly well suited for studies of the residence sites and valence states of implanted ions. It is often used to follow the annealing processes and chemical transformations near the surface of implanted matrices. It also finds many applications in characterization of magnetic properties of various materials. As examples of possible research topics, the following subjects are suggested:

1. Studies of low doping effects in silicon, diamond and in other semiconductors; elucidation of lattice defects in such systems [Saa 81b, Sai 82].

2. Studies of impurity states and defects in ionic crystals, oxides and minerals [Per 83].
3. Studies of residence sites and non-equilibrium alloying processes in implanted transition metal-rare earth alloys.
4. Characterization of radiation damage in steels and other materials applied in fission and thermonuclear fusion reactors [Saa 85].

Solid State Gamma-Ray Laser

The concept of the solid state γ -ray laser has been discussed for many years [Bal 81] but laser action has not yet been achieved due to many experimental difficulties. One of the necessary conditions is a large density of excited resonant nuclei (Mössbauer states) in some crystalline low-Z solid, e.g. beryllium. In this connection, it may be worth considering the possibility of activation, separation and implantation of short-lived isomers ($\leq 1 \mu\text{s}$), using ultra-fast isotope separation techniques [Arj 85].

OTHER HYPERFINE INTERACTION TECHNIQUES

Nuclear Orientation

The measurements of the anisotropy of the angular distribution of α -, β -, and γ -radiation from oriented nuclei have, in the past, supplied a considerable volume of data on spins, multipolarities and nuclear moments of isotopes with long and medium half-lives. The technique is also used to measure hyperfine magnetic fields and electric field gradients at the nuclei, and to study many related effects, e.g. Knight shifts, large hyperfine anomalies or vacancy trapping and recombination. Solid state applications also include studies of spin-lattice relaxation in metals, semiconductors and insulators. The capabilities of nuclear orientation have been considerably increased by combining with NMR (NMRON) and Mössbauer techniques (MSOM) and, most recently, by introducing the method of "level-mixing" [Ber 83].

In the case of γ -detection, considering the normal case of the β -decay of a parent nucleus followed by a γ -cascade, the nuclear orientation method is applicable if the spin of the parent nucleus is ≥ 1 , and the decay proceeds via the state of spin $\leq 1/2$. Thus, though technically complex, the method is generally applicable to a very large class of nuclei, including those far from stability. A high-performance ^3He - ^4He dilution refrigerator, with a continuous base temperature as low as 5 mK, allows for on-line operation of the nuclear orientation setup. Nuclear orientation/ISOL facilities are already operational in Leuven [Van 81, Van 83] and Daresbury [Gre 83] and a similar program is being organized at CERN. The scheme of the setup in Leuven is shown in Fig. II.14. The focused beam of separated isotopes, accelerated through about 100 keV, is implanted directly into a polarized ferromagnetic foil target cooled to a temperature below 20 mK. Such a method permits the study of nuclei far from stability, with the lifetime limited only by the nuclear spin-lattice relaxation time T_1 which for many elements, e.g. in iron lattice, is 10-100 s at 10 mK. One can further enlarge the range of nuclei studied with the NO/ISOL method by shortening the relaxation time possible by the appropriate doping of crystals, by introducing lattice defects or by so-called magnon cooling in ferromagnets.

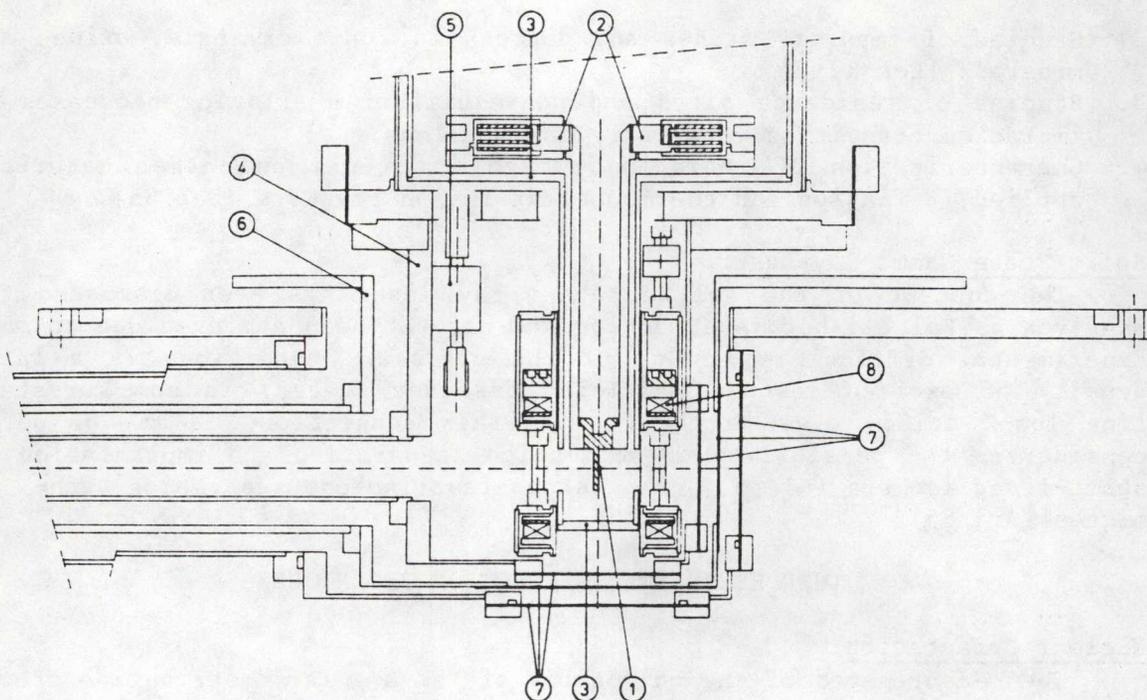


Fig. II.14. Dilution refrigerator tails and connected side access. (1) sample holder; (2) mixing chamber and dilution unit; (3) 0.6 K shield; (4) 4 K shield; (5) 4 K baffle driver; (6) 77 K shield; (7) demountable window; (8) 5 kG split pair magnet (from [Van 81]).

Fundamental limitations to low temperature orientation by the spin-lattice relaxation time can probably also be circumvented by the adoption of an immediate "on-line" orientation mechanism, for instance, by channelling of implants or scattering at grazing incidence on the magnetized single ferromagnetic crystals. Considerable solid state studies would be required to better understand this nuclear orientation mechanism and to find appropriate catcher foils that would hold their polarization for times as long as several hours.

As with other hyperfine interaction techniques, on-line nuclear orientation yields information for small activity production, and at very small doping levels. Ion implantation will permit the introduction of nuclear probes into systems which have not yet become accessible and to measure hyperfine fields in cases of very small or zero solubility (e.g. Bi, In or Ag in Fe). In addition, it was possible to show that in certain systems (InFe and AgFe) almost completely substitutional implantations are possible at low temperature, and below a certain dose limit (22) (Fig. II.15). It is supposed that due to the immobility of vacancies at low temperatures, the formation of impurity-vacancy complexes is possible only during the collision cascade and is therefore highly depressed, which results in the high substitutional fraction.

Perturbed Angular Distributions and Correlations (PAD-PAC)

These techniques are used to determine the interaction of the nucleus in an excited state with the hyperfine magnetic field and the electric

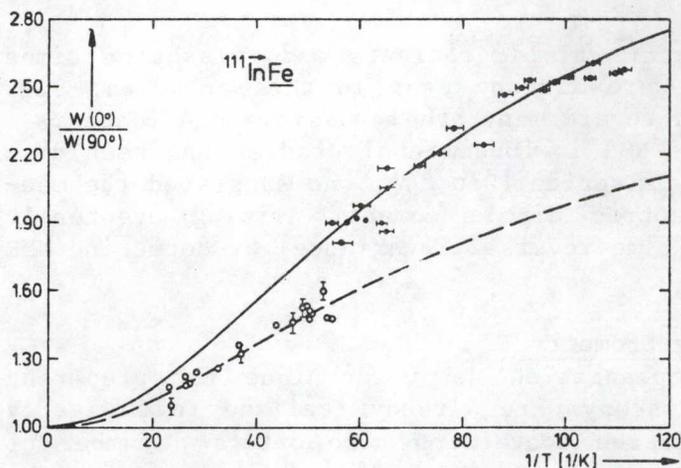


Fig. II.15. Anisotropy of the 171 keV fraction of ^{111}In after implantation into Fe; the solid points represent data taken after cold implantation, the others after RT implantation. The solid curve is the theoretical anisotropy (from [Van 83]).

field gradient [HIR 83], from which both nuclear moments and the structure of solids is determined. PAC experiments have been carried out for several years at ISOLDE at CERN. A recent survey of hyperfine interaction studies with PAC on pulsed heavy ion beams is given in [Rag 84].

Unlike Mössbauer spectroscopy, PAC can be studied at high temperatures and in both solids and liquids. In addition, it is not limited to nuclei close to stability: any nucleus with suitable γ - γ or β - γ cascades, having an intermediate state spin $I \geq 1$ and a lifetime in the range of 10^{-9} - 10^{-6} s, are suitable. Because they permit the determination of components of the electric field gradient tensor, the measurements of perturbed γ - γ or β -gamma correlations are most often employed in studies of radiation damage in materials. The PAC method is particularly suitable for identification of impurity-defect configurations; combined with the change of the relative populations in the annealing stages, it provides information on the nature of the defect (vacancy or interstitial) released or mobile at the particular annealing temperature.

NMR Techniques

The application of β -emitters and isomeric γ -emitters as NMR probes in condensed matter presents a wide class of experimental possibilities (see survey [Ack 83]). Most of the experiments have so far been carried out in-beam with the probe nuclei having lifetimes in the range of 10^{-5} - 10^3 s. The method is best explained by means of Fig. II.16 published by Sugimoto et al. [Sug 66]. An ISOL may help to extend the range of nuclei investigated by this technique especially in the region of highly deformed nuclei with large spins. Using NMR techniques, both solids and liquids can be studied.

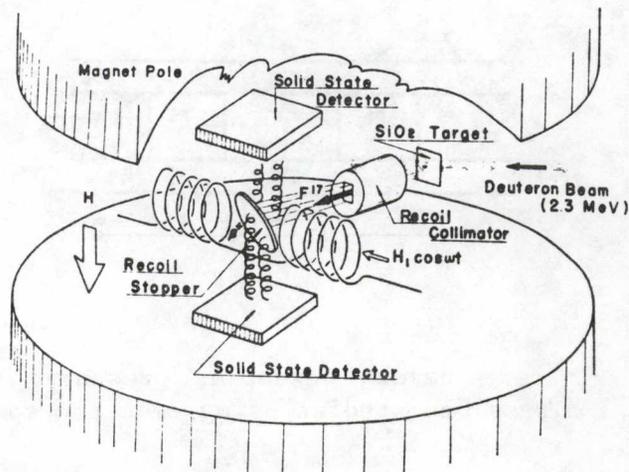


Fig. 5. Experimental setup for NMR measurements on ^{17}F produced via the reaction $^{16}\text{O}(d,n)^{17}\text{F}$ (from [Sug 66]).

Hyperfine magnetic fields, electric field gradients and relaxation times can be measured. Many probes were already used in these studies, e.g. ^8Li , ^{11}B , ^{12}C , ^{25}Al , ^{31}P , and there are many other possible candidates.

Interesting application of NMR in fundamental studies has been discussed at the Zinal workshop by Calaprice [Zin 84], who suggested the measurements of the non-zero electric dipole moment (arising eventually through violation of parity and time reversal invariance) by detecting NMR on oriented radon nuclei.

Beta and Conversion Electron Spectrometry

The advantages of ion implantation as a technique for preparing radioactive sources of β -spectroscopy were already realized in the early 1960's [Ber 63]. Internal electron conversion also offers a number of possibilities in studying condensed matter [Dra 83], although so far the determination of transition multipolarities and particularly the examination of electric monopole transitions and transitions of very low energy remain the domain of conversion electron spectroscopy. The solid state environment influences both electron binding energies and the density of electrons at the nucleus. This, in turn, results in changes of the conversion electron energies and intensities, and influences the lifetime of the transitions. Measurements of these effects could provide unique information on the electronic structure of condensed matter. From the energy losses of outgoing conversion and Auger electrons, one can learn about the depth distribution of radioactive nuclei, and, in particular, about their diffusion in solids. The investigation of low energy conversion electrons (10 keV), due to their low range in the matter (10-100 nm), would be especially useful in the studying of near-surface regions, whereas electrons with high energies (1000 keV) would provide insight into bulk properties of materials.

There exists a variety of magnetic, electrostatic and semiconductor spectrometers for measuring the energies and intensities of conversion and Auger electrons emitted in both radioactive decays and nuclear reactions, but to the author's knowledge, none of them has been used in the ISOL mode. The best energy resolution (FWHM) reported so far is close to 1.0 eV [Dra 83]. A simple double cylindrical-mirror analyzer shown in Fig. II.17, built in Orsay and in Dubna [Bri 84], could easily be adapted to an ISOL program.

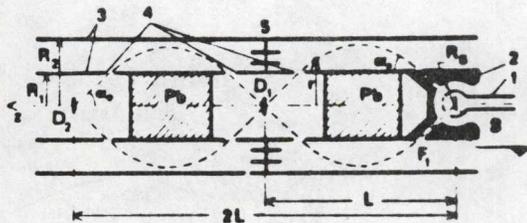


Fig. II.17. Schematic view of the electrostatic conversion electron spectrometer with an electron retarding device in series with a double cylindrical mirror analyzer. (S) source; (1) and (2) concentric spherical electrodes; (3) inner and outer cylinders; (4) adjustable slits (from [Bri 84]).

Several examples presented below can illustrate the directions of possible studies using electron spectrometry.

Valence State of Trace Amounts of Radioactive Atoms

Figure II.18 shows the M_4 and M_5 conversion lines of the 2.17 keV transition in ^{99m}Tc ($T_{1/2} = 6$ h) measured in several different chemical environments by Dragoun et al. [Dra 83b]. From binding energy shifts, it was possible to determine the valence states of as few as 10^{-11} g of ^{99m}Tc , with a sensitivity about three orders of magnitude better than the sensitivity of the ESCA method. The investigation of trace amounts of ^{99}Tc is of particular interest in nuclear medicine. With the use of isotopes of shorter lifetimes, one can think of developing ESAC-ISOL techniques with even better sensitivity limits.

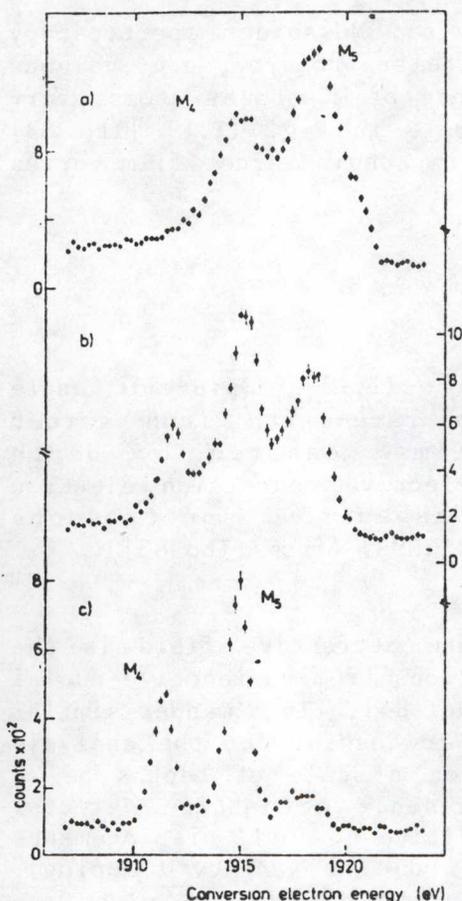


Fig. II.18. The conversion electron lines of the 2.17 keV transition corresponding to various chemical states of ^{99m}Tc . (a) Original deposit (mainly $\text{Tc}\cdot 2\text{H}_2\text{O}$); (b) after partial oxidation (a mixture of $\text{TCO}_2\cdot 2\text{H}_2\text{O}$ and NH_4TCO_4), (from [Dra 83b]).

Changes of Nuclear Lifetimes

Precise measurements of lifetimes of highly converted transitions provide information on the chemical environment of radioactive nuclei. The largest variation in the lifetime has been found in the 77 keV transition ($T_{1/2} = 30$ m) which depopulates the isomeric level in ^{235}U : (half-lives of ^{235m}U measured for $^{235m}\text{UO}_2$ and for ^{235m}U implanted into Ag metal differ by $9.8 \pm 1.1\%$). Owing to the exceptionally low transition energy, the conversion of this transition proceeds only in the outermost P and Q shells and thus is extremely sensitive to chemical effects. Further investigations of ^{235m}U lifetimes could be particularly useful for reactor fuel technology. More studies of this type with an ISOL would be feasible.

Observation of Diffusion Processes

By analyzing the conversion electron line shapes, one can determine the depth at which the radioactive nuclei are deposited in matter and can establish their diffusion behaviour in various materials [Ple 78]. The possibility of using radioactive isotopes with much shorter lifetimes such as can be delivered by an ISOL (≤ 1 s), could considerably extend this field of study. In particular, it would be very interesting to investigate the mechanism of radiation-enhanced diffusion and fast diffusion processes at high temperatures.

Depth Profiling of ^{57}Fe

The combination of conversion electron and Mössbauer spectroscopy (CEMS) makes it possible to trace how a particular property, e.g. valence state, chemical composition or magnetic moments of Mössbauer atoms, vary with the depth below the surface. An example in Fig. II.19 [Ito 83] shows how the spin-tilt angle of iron atoms in a thin garnet film varies as a function of the depth.

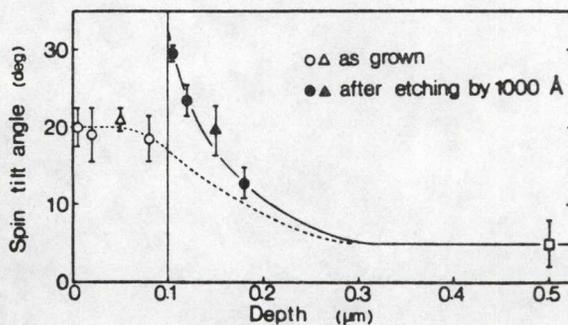


Fig. II.19. Spin-tilt angle in rare-earth iron garnet films measured by depth selective conversion electron Mössbauer spectroscopy (DSCEMS) (from [Ito 83]).

Conversion electron channelling. Another new attractive field is the application of channelling of conversion electrons from radioactive nuclei for analysis of atomic structures in solids [Hof 84]. In a manner similar to ion channelling, electron channelling is very useful for the analysis of changes in the atomic lattice structure on a scale of tenths of an angström as, for example, caused by the presence of lattice defects. Electron channelling turns out to be most sensitive to small displacements of impurities from substitutional sites (e.g. due to vacancy trapping). Because ion channelling is most successful in the determination of displacements to interstitial positions (e.g. due to self-interstitial trapping or formation of larger vacancy agglomerates), each method complements the other. Additionally, since electron emission channelling can be measured simultaneously with PAC or Mössbauer spectra, a location of implanted radioactive probes in the lattice can be determined in a complementary manner and with a high precision (0.1 \AA). An example of the experimental data is shown in Fig. II.20. Experiments of this type have recently begun at ISOLDE at CERN.

RBS, Ion Channelling and Other Techniques

Rutherford backscattering spectroscopy and channelling of light ions are very efficient means of characterization of thin films, implanted impurities and their localization in the matrices, as well as in the study of lattice defects [Dav 83, Swa 82, How 83]. Measurements of this type

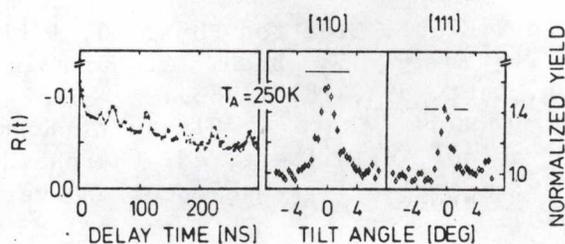


Fig. II.20. PAC time spectrum $R(t)$ for 171 keV-245 keV γ - γ cascade in ^{111}In ($T_{1/2} = 2.8$ d) (left) and channelling effects measured for 219 keV (K conversion) electrons around a [110] and [111] axis (right) at a Cu crystal implanted with ^{111}In after H^+ irradiation and annealing to 250 K (from [Hof 84]).

could be performed in situ on the implanted targets but many valuable data could also be obtained for samples fabricated in an ISOL and transported to other laboratories (in Canada and abroad). In particular, measurements of electrical conductivity and optical absorption can supply valuable data about lattice defects in materials investigated, electron microscopy can characterize structural modifications, measurements of microhardness can give information about mechanical modifications, and the magneto-optic Kerr-effect can give data about surface magnetism. Therefore, a high yield ISOL could greatly extend existing programs.

Other Possibilities

A whole range of the subjects belonging to surface physics in the strictest sense that can be conveniently investigated by using decelerated ion beams have not been discussed here. However, advances can be anticipated in future studies of solid state effects in α -decay and in more exotic decay modes via neutrons, protons, tritons, ^{14}C or fission.

REFERENCES

- [Ack 83] H. Ackerman, P. Heitjans and H.J. Stöckmann, *Hyperfine Interactions of Radioactive Nuclei*, Topics in Current Physics, Vol. 31, J. Christiansen, ed. (Springer, 1983) p. 291.
- [Arj 85] J. Arje, J. Aystö, H. Hyvönen, P. Teslienen, V. Koponen, J. Honkanen, A. Hautojärvi and K. Vierinen, *Phys. Rev. Lett.* **54**, 99 (1985).
- [Bal 81] G.C. Baldwin, L.C. Solem and V.I. Goldanskii, *Rev. Mod. Phys.* **53**, 687 ((1981)).
- [Ber 63] I. Bergström, F. Brown, J.A. Davies, J.S. Geiger, R.L. Graham and R. Kelly, *Nucl. Instr. Meth.* **21**, 249 (1963).
- [Ber 83] I. Berkes, G. Marest, J. Sau, H. Sayouty, P. Put, R. Coussement and G. Scheveneels, *Hyperfine Interactions* **15/16**, 233 (1983).
- [Bri 84] Ch. Briancon, B. Legrand, R.I. Wallen, Ts. Vylov, A. Minkova and A. Inoyatov, *Nucl. Instr. Meth. in Phys. Research* **221**, 547 (1984).
- [Dav 83] J.A. Davies, *Physica Scripta* **28**, 294 (1983).

- [Dra 83] O. Dragoun, Adv. Elect. Electron Phys. 60, 1 (1983).
- [Dra 83b] O. Dragoun, M. Fiser, V. Brab, A. Kovaoik, A. Kuklik, P. Mikusik, Phys. Lett. 99A, 187 (1983).
- [Fey 79] R.P. Feynman, lecture "There is Plenty of Room at the Bottom", in 'Miniaturization', H. Gilbert, ed. (Reinhold, New York, (1-961), chap. 16; see also 'Microscience: an Overview', Physics Today 32 (1979).
- [Gre 83] V.R. Green, W.D. Hamilton, S.J. Robinson, N.J. Stone and P.M. Walker, Hyperfine Interactions 15/16, 979 (1983).
- [HIR 83] Hyperfine Interactions of Radioactive Nuclei, Topics in Current Physics, Vol. 31, J. Christiansen, ed. (Springer, 1983).
- [How 83] L.M. Howe, M.L. Swanson and J.A. Davies, Methods of Experimental Physics, 21, 275 (1983).
- [Hof 84] H. Hofsaess, G. Linder, E. Recknagel and Th. Wichert, Nucl. Instr. Meth. in Phys. Research B230, 13 (1984).
- [Ito 83] J. Itoh, Y. Yonekura, T. Toriyama, H. Miyasaka and K. Histake, Hyperfine Interactions 15/16, 771 (1983).
- [Lan 84] G. Langouche, M. de Potter and D. Schroyen, Phys. Rev. Lett. 53, 1364 (1984).
- [Mor 84] R. Morrison, in Proceedings of the TRIUMF-ISOL Workshop, Mont Gabriel, June 13-16, 1984, J. Crawford and J.M. D'Auria, eds., TRI-84-1, p. 244.
- [Nie 83] L. Niessen, Hyperfine Interactions 13, 65 (1983).
- [Per 83] A. Perez, G. Marest, B.D. Sawicka, J.A. Sawicki and T. Tyliczszak, Phys. Rev. B28, 1227 (1983).
- [Pic 84] S.T. Picraux, Physics Today (1984); Ann. Rev. Mater. Sci. 14, 335 (1984).
- [Pic 85] S.T. Picraux and P.S. Percy, Scientific American 252, 102 (1985).
- [Ple 78] F. Pleiter and H. de Waard, in "Mössbauer Isomer Shifts", G.K. Schenoy and F.E. Wagner, eds. (North Holland, Amsterdam, 1978) p. 253.
- [Rag 84] P. Raghavan and R.S. Raghavan, Proc. International Workshop on Hyperfine Interactions, Kanpur, India, 1984; Hyperfine Interactions, in print.
- [Rav 79] H.L. Ravn, Phys. Rep. 54, 201 (1979).
- [Rus 73] P.B. Russell, G.L. Latshaw, S.S. Hanna and G. Kaindl, Nucl. Phys. A210, 133 (1973).
- [Saa 81] B.D. Sawicka and J.A. Sawicki, in Topics in Current Physics, Vol. 25, U. Gonser, ed. (Springer, 1981).
- [Saa 81b] B.D. Sawicka, J.A. Sawicki and H. de Waard, Phys. Lett. A85, 303 (1981).
- [Saa 85] B.D. Sawicka, J.A. Sawicki and R. Behrish, Mat. Sci. and Engineering 69 (1985).
- [Sai 82] J.A. Sawicki and B.D. Sawicka, Nucl. Instr. Meth. 194, 465 (1982).
- [Sai 85] J.A. Sawicki, Mater. Sci. and Engineering 69, 501 (1985).
- [Sug 66] K. Sugimoto, A. Mizobuchi, K. Nakai and K. Matuda, J. Phys. Soc. Japan 21, 213 (1966).
- [Swa 82] M.L. Swanson, Rep. Progr. Phys. 45, 47 (1982).
- [Van 81] D. Vandeplasche, L. Vanneste, H. Pattyn, I. Geenen, C. Nuytten and E. Van Walle, Nucl. Instr. Meth. 186, 211 (1981).

- [Van 83] L. Vanneste, C. Nuytten, K. Vandeplassche, E. Van Valle and J. Wouters, *Hyperfine Interactions* 15/16, 947 (1983).
- [Waa 75] H. de Waard, *Phys. Scr.* 11, 157 (1975).
- [Wey 81] G. Weyer, *Nucl. Instr. Meth.* 186, 201 (1981).
- [Zin 84] Workshop on the ISOLDE programme, "On-line in 1985 and beyond", Zinal, June 18-22, 1984, Abstracts, unpublished.

4. MEDICAL PHYSICS

INTRODUCTION

For the 20 or 25 years which followed the 1939-1945 war, radionuclide production for biomedical applications was mostly centered at major nuclear reactor installations [MRP 66, RPQ 71, Pog 74]. The last decade has, however, witnessed a rapid growth in the use of particle accelerators for this purpose, as extensively reviewed by Silvester and Waters in 1979 [Sil 79], following from certain favourable characteristics of accelerator-produced, neutron-deficient radionuclides.

Both commercial radionuclide producers and research workers have added accelerators to their armamentarium. The machines most used have been cyclotrons [Mar 79], of compact "industrial" or "medical" design [Wol 83].

In addition, the BLIP facility [Ric 73] at Brookhaven National Laboratory in the US, as well as other major accelerator laboratories including LAMPF in the US [Obr 73], TRIUMF in Canada [Pat 79] and SIN in Switzerland [Hus 81], have engaged in significant radionuclide production.

The broad objectives of the Radiopharmaceutical group in the Applied Program Division at TRIUMF are: (i) to design and develop new radiopharmaceuticals that would lead to a better understanding of physiological processes, provide improved methods for diagnostic and therapeutic applications and minimize the radiation dose burden to the patient; (ii) to evaluate production modes for the established radionuclides to obtain the most efficient and economical route to large scale routine production, and (iii) to participate in collaborative research on the use of new radionuclides/radiopharmaceuticals with the medical community.

Often the limitations associated with the evaluation of a radionuclide for medical purposes is the inability to acquire this nuclide in sufficient purity by standard irradiation-separation techniques. This can result in the inability to study the decay scheme sufficiently well so that radiation dosimetry to patients can be calculated. On a more fundamental level, if the radionuclide cannot be produced with sufficient purity, in vivo experiments with animals and humans will be greatly curtailed.

Thus it is not difficult to envision a continuing program of high purity radionuclide production studies that can be used with an isotope separator (ISOL). Some of the difficulties mentioned above could be circumvented by using the isotope separator off-line during non-running periods for target enrichment.

In order to illustrate how the radiopharmaceutical group would use an ISOL, the following examples are put forward as representative experiments.

PROPOSED EXPERIMENTS

We have recently developed a method of synthesizing 6-fluorodopa by the destannylation of a tin derivative of dopa [Ada 84]. This was a direct application of the technique developed at TRIUMF for the synthesis of aryl fluorides [Ada 81, Ada 84b]. This tin chemistry has been extended by us to include bromine labelling [Ada 82]. Seitz et al. [Sei 80] have

used tin compounds in iodine labelling. The next halogen to be tried is astatine (At). Since there are no stable isotopes of At, its chemical and physical properties are not well characterized. However, what is known is that ^{211}At is a potential source of directed radiation for cancer therapy [Car 40]. The α particles emitted in the process of the radioactive decay of ^{211}At (i) are directly ionizing, (ii) have an average E_α of 6.7 MeV, (iii) have a range of 60 μm in water (the range of a few cell diameters), and (iv) have an average linear energy transfer of 113 keV/ μm which results in high specific ionization. It has been shown that ^{211}At -tellurium colloids have a curative effect on tumour-bearing mice [Blo 81]. This radiocolloid is not site specific; therefore, it can not be used in treating tumours in humans. However, if ^{211}At could be bound to a biologically active compound with site specificity, we could have a very powerful tool in cancer therapy. The PET chemistry group lacks a source of ^{211}At since its formation in a radionuclidic and radiochemical pure state requires α particles of ~ 29 MeV [$^{209}\text{Bi}(\alpha, 2n)^{211}\text{At}$]. A potential clean source of ^{211}At is a $^{211}\text{Rn}/^{211}\text{At}$ generator. If ^{211}Rn as produced in an ISOL could be trapped and allowed to decay it would yield a very pure ^{211}At source for chemistry development with the tin chemistry. The production of ^{211}Rn should be straightforward in an ISOL.

The medical physics group at TRIUMF is also interested in developing generator systems that have long-lived parents and short-lived daughters. These generators would provide positron-emitting radionuclides to centres without an accelerator. One such system is the $^{82}\text{Sr}/^{82}\text{Rb}$ generator [Yan 79]. The half-life of ^{82}Sr is 25 d and that of ^{82}Rb is 76 s. At present such a system is being tested at Berkeley for studies of the human blood brain barrier [Yan 81]. However, one of the biggest drawbacks is assaying the ^{85}Sr content from the spallation of the Mo metal target [Hor 81]. The principal γ -ray in ^{85}Sr is 514 keV - too close in energy to be resolved from the 511 keV line from the β^+ annihilation. Also, the abundance of the 777 keV γ -ray of ^{82}Rb is uncertain with reported values varying between 9-13% [Led 67, Led 78]. Therefore, an ISOL could be helpful in preparing a clean source of ^{82}Sr for establishing the characteristics of a $^{82}\text{Sr}/^{82}\text{Rb}$ generator.

Recently Beyer et al. [Bey 84] have demonstrated a useful technique for producing a $^{81}\text{Rb}/^{81\text{m}}\text{Kr}$ generator at the ISOLDE collaboration. They used ion implantation in plastic foils which resulted in a generator with high elution efficiency and low breakthrough. While the chemical species in the Rb/Kr generator are ideal for separation, it would be interesting to try this technique on other generator systems like the aforementioned $^{82}\text{Sr}/^{82}\text{Rb}$ and $^{68}\text{Ge}/^{68}\text{Ga}$.

The Atomic Energy of Canada Ltd. (AECL) Radioisotope Production group located here at TRIUMF have been making ultrapure ^{123}I from the $^{124}\text{Xe}(p, 2n)^{123}\text{Cs} \rightarrow ^{123}\text{Xe}$ plus $^{124}\text{Xe}(p, pn)^{123}\text{Xe}$ reactions [Gra 84] using highly enriched ^{124}Xe . The natural abundance of ^{124}Xe is 0.10% thus making their target system quite expensive. They have expressed interest in investigating the possibilities of using the separator off-line to maintain their stock of ^{124}Xe .

It has recently been suggested that ^{186}Re [Wes 84] may be among the best therapy radiolabels since it possesses a sufficiently long half life necessary for tumor localization, γ -radiation suitable for imaging, intermediate β -energy, a stable daughter nucleus and has a reasonable chance to form a stable chelate with an antibody system. The production of ^{186}Re

from an enriched ^{186}W target may not be of sufficient radionuclidic purity: therefore its production from a spallation reaction and isolation with an ISOL could produce samples of ^{186}Re that are required for testing its efficacy as an anti-tumor agent.

REFERENCES

- [Ada 81] M.J. Adam et al., J. Chem. Soc., Chem. Commun., 733 (1981).
 [Ada 82] M.J. Adam et al., J. Chem. Soc., Chem. Commun., 625 (1982).
 [Ada 84] M.J. Adam et al., J. Label. Cpd. Radiopharm. 1984 (in press).
 [Ada 84b] M.J. Adam et al., J. Fluorine Chem. 25, 322 (1984).
 [Blo 81] W.D. Bloomer et al., Science 212, 340 (1981).
 [Bey 84] G.J. Beyer et al., Int. J. Appl. Radiat. Isot. 35, 1075-76 (1984).
 [Car 40] D.R. Carson et al., Phys. Rev. 58, 672 (1940).
 [Gra 84] D. Graham et al., J. Nucl. Med. 25, P32 (1984).
 [Hor 81] P.L. Horlock et al., J. Radioanal. Chem. 64, 257 (1981).
 [Hus 81] I. Huszar and E. Loepfe, Production of Cyclotron Isotopes for Medical Purposes at SIN/EIR, SIN Physics Report No.3 (April 1981), Swiss Inst. for Nuclear Research, 5234 Villigen, Switzerland.
 [Led 67] C.M. Lederer et al., Table of Isotopes, 6th ed. (Wiley, New York, 1967).
 [Led 78] C.M. Lederer and V.S. Shirley, eds., Table of Isotopes, 7th ed. (Wiley, New York, 1978).
 [Mar 79] J.A. Martin, Cyclotrons-1978, Proc. Eighth Int. Conf. on Cyclotrons and their Applications, IEEE Trans. Nucl. Sci. NS-26, 2443-2651 (1979).
 [MRP 66] Manual of Radioisotope Production, Technical Report Series No.63, Int. Atomic Energy Agency, Vienna (1966).
 [Obr 73] H.A. O'Brien, Status of the Los Alamos Meson Physics Facility for Radionuclide Production, Sci. Sem. of Nucl. Med., DHEW Publication 74-8012 (FDA) 14-19, U.S. Gov. Printing Office (1973).
 [Pat 79] B.D. Pate, Medical Radioisotope Production at TRIUMF, Proc. 27th Conf. on Remote Systems Tech., American Nuclear Soc., 283-284 (1979).
 [Pog 74] J.K. Poggenburg, The Nuclear Reactor and its Products, Sem. Nucl. Med. 4, 229-243 (1974).
 [Ric 73] P. Richards, Status of the BLIP Facility for Radionuclide Production, Sci. Sem. of Nucl. Med., DHEW Publication 74-8012 (FDA) 22-26, U.S. Gov. Printing Office (1973).
 [RPQ 71] Radioisotope Production and Quality Control, Technical Report Series No.128, Int. Atomic Energy Agency, Vienna (1971).
 [Sei 80] D. Seitz et al., J. Organomet Chem. 186, C33 (1980).
 [Sil 79] D.J. Silvester and S.L. Waters, Radionuclide Production, Proc. Second Int. Symp. on Radiopharmaceuticals 727-744 (1979).
 [Yan 79] Y. Yano et al., J. Nucl. Med. 20, 961 (1979).
 [Yan 81] Y. Yano et al., J. Nucl. Med. 22, 1006 (1981).
 [Wes 84] B.W. Wessels and R.D. Rogers Med. Phys. 11, 638 (1984).
 [Wol 83] A.P. Wolf, W.B. Jones, Radiochemica Acta 34, 1 (1983).

5. OTHER APPLICATIONS

With well separated, high intensity ion beams, ISOLs become attractive for a number of studies which have not been mentioned in the preceding Sections. Experiments either carried out recently or proposed at existing facilities give some idea of the range of possibilities. Atomic physics--considered an extensively studied field--provides a recent, remarkable example. The element francium, the heaviest alkali metal, was discovered in 1939 [Per 39], and the wavelengths of its principal series were predicted even earlier, in 1931 [Yag 31]. Yet, it was only in 1978, when a sufficient yield of Fr atoms became available at ISOLDE that the first resonant lines were observed [Lib 78]. In 1983 [Ben 84] and 1984, collinear fast beam laser spectroscopy permitted the measurement of the second members of the principal series.

In the list of SIN-ISOLDE proposed activities, a proposal was presented for another type of study in atomic physics: the precision measurement of K-X-ray energies [Bor 80]. Earlier experiments at ISOLDE 2 revealed energy shifts arising from a number of nuclear and atomic origins [Bor 77, Bor 78, Bor 78b]. The study of these effects requires measurements of a precision of about 10^{-3} of the natural linewidth, which is possible only by bent-crystal spectrometry. The sources must be geometrically precise, but the required deposited activity (~ 1 Ci) was obtained at ISOLDE, and would be easily within the capabilities of TRIUMF-ISOL.

REFERENCES

- [Ben 84] N. Bendali, H.T. Duong, O. Juncar, S. Liberman, J. Pinard, M. de Saint-Simon, J.C. Vialbe, S. Buttgenbach, C. Thibault, F. Touchard, A. Pesville, A. Mueller, and the ISOLDE Collaboration, C.R. Acad. Sci. 299, II, 1157 (1984).
- [Bor 77] G.L. Borchert, O.G. Hansen, B. Jonson, H.L. Ravn, O.W.B. Schult, O. Tidemand-Petersson, Phys. Lett. 63A, 15 (1977).
- [Bor 78] G.J. Borchert, P.G. Hansen, B. Jonson, I. Lindgren, H.L. Ravn, O.W.B. Schult, P. Tidemand-Petersson, Phys. Lett. 65A, 297 (1978).
- [Bor 78b] G.L. Borchert, O.G. Hansen, B. Jonson, I. Lindgren, H.L. Ravn, O.W.B. Schult, P. Tidemand-Petersson, Phys. Lett. 66A, 374 (1978).
- [Bor 80] G.L. Borchert, P.G. Hansen, B. Jonson, H.L. Ravn, and O.W.B. Schult, Lett. of Interest for the SIN-ISOLDE Proposal PSSC 80, 4-45.
- [Lib 78] S. Liberman, J. Pinard, H.T. Duong, P. Juncar, J.C. Vialle, P. Jacquinet, G. Huber, F. Touchard, S. Buttgenbach, A. Pesnelle, C. Thibault, R. Klapisch, and the ISOLDE Collaboration, C.R. Acad. Sci. 286D, 253 (1978).
- [Per 39] M. Perey, C.R. Acad. Sci. 208, 97 (1939).
- [Yag 31] H. Yagoda, Phys. Rev. 38, 2298 (1931).

6. SUMMARY

In the preceding Sections, we have presented many interesting fields in which the proposed TRIUMF-ISOL will be able to make important contributions. In some areas, interesting programs that are currently being carried out at other ISOL sites can be extended to new regions of interest. In some other areas, totally new opportunities will be presented to the scientific community. We have identified two particularly advantageous areas: nuclear structure and reaction studies using radioactive targets, and nuclear reaction studies using a post-accelerated radioactive ion beam. In addition, we have mentioned other pure and applied fields where this facility is likely to play an increasingly important role. The rich possibilities of using radioactive probes in a wide range of nuclear solid state techniques has only begun to be exploited. The production of radionuclides of interest in medical research can be initiated very quickly. Applications in other areas such as atomic physics and industrial research have good potential, but are yet to be fully exploited.

We have presented the diverse fields that could benefit from a facility such as the TRIUMF-ISOL. At present, it is difficult to project the likely initial experiments that would be performed with TRIUMF-ISOL when it becomes operational. Based on the experimental proposals submitted to the TRIUMF Experiment Evaluation Committee in 1984, it appears that a wide range of research programs can be expected. The list of the proposals are given in Table II.3 and the proposals are included in the Appendices.

Table II.3. List of Experimental Proposals for TRIUMF-ISOL.

Expt.	Title	Spokesperson
309	Transfer Reaction Studies with Radioactive Targets	E. Hagberg
310	Production of a $^{211}\text{Rn}/^{211}\text{At}$ Generator for Radiochemical Experiments	T.J. Ruth
311	Nuclear Reactions of Astrophysical Interest with Radioactive Beams	L. Buchmann J.M. D'Auria
312	Low-Energy Ion Scattering Using ISOL	S.R. Morrison
313	Delayed Neutron Studies at TRIUMF-ISOL	P.L. Reeder
314	Production of Radioactive Targets for Nuclear Structure Studies	J. Sauvage-Tessier
315	Development of a Laser-Based Ion Source	J.K.P. Lee
316	Collinear Laser Spectroscopy of Radioactive Beams	F. Buchinger
317	Spectroscopic Studies of Nuclear Properties	Foster Radiat. Lab.
—	Mass Spectroscopy at ISOL	A.E. Litherland L. Kilius

III. FACILITY DESCRIPTION

The radioactive beams facility that we propose for TRIUMF will be unique in the world. It is based on what we believe will be the next generation of on-line isotope separators for high current accelerators. Furthermore, it will be the first adaptation of existing accelerator technology to the problem of accelerating a variety of radioactive ions. In this Chapter, we describe the proposed facility, present arguments for TRIUMF as an ideal site, outline a number of major technical problems which must be solved during development, and present conceptual designs to indicate that feasible solutions do exist.

1. DESIRED FEATURES OF A RADIOACTIVE BEAMS FACILITY

HIGH BEAM CURRENTS OF RADIONUCLIDES

The desire for a high current of radionuclides is perhaps the easiest to understand. With more intense beams, less sensitive experimental techniques can be applied. A stronger radioactive source will give a distinct advantage for certain classes of experiments such as the study of rare decay branching ratios, the detection of small deviation from theoretical prediction, high precision measurement, etc. If the beam current is more than $\sim 10^{10}$ ions/s, the production of useful radioactive targets for conventional nuclear reaction experiments becomes feasible. This will present a new and powerful technique for nuclear structure studies. If targets of very proton-rich or very neutron-rich nuclides of appropriate thickness can be obtained, their use at heavy ion accelerators such as the TASCC at Chalk River may offer a new opportunity to explore the region near the limit of particle emission stability. Finally, for many reaction studies using accelerated radioactive beams such as those of interest in astrophysics, an intense ion beam is indispensable. We consider the capability to produce an intense radioactive ion beam the most important feature for a future generation ISOL.

HIGH PURITY OF DELIVERED ISOTOPES

One of the greatest difficulties in many experiments proposed for an experimental facility based on a present generation ISOL is contamination of the delivered beam of radioactive ions. In the search for particularly exotic nuclei, the vast flux of ions from the target source presents a problem of discrimination, sometimes of the order of 1 part in 10^{12} . For some elements, careful design of the target material and the ionization mechanism may provide some chemical selection. However, for the majority of cases, an intense and pure isotope beam still remains to be realized. For a modern ISOL, provisions should be made to introduce additional chemical selection capabilities along with a magnetic mass analyzing stage of higher resolution than available elsewhere.

A LARGE VARIETY OF DELIVERED ELEMENTS

Many experiments planned for a radioactive beams facility involve selecting an element best suited for studying a particular phenomenon, be it magnetization of a crystal site or a progression in nuclear deformation with changing nuclear type. The wider the variety of elements available, the greater the power of the facility for scientific experiments.

HIGH RADIOACTIVE BEAM BRIGHTNESS

Beam brightness is a technical term expressing the concentration to which a beam can be focused by a given transport system. A high beam brightness can, of course, be achieved by a high beam current, but it can also be achieved by a small beam emittance which allows the beam transport system to focus the beam to a small spot. With a good beam brightness, experiments using the radioactive beam directly (such as collinear laser spectroscopy) will be easier to perform. Also, injection of this beam

into post-accelerators, storage rings or ion traps can be accommodated with better efficiencies. The desire for high beam brightness also comes from the desire for more concentrated collections of radionuclides into storage rings and post-accelerators.

VARIABLE RADIONUCLIDE BEAM ENERGY AND TIME STRUCTURE

Variable radionuclide ion energy is desired for a wide variety of experiments ranging from condensed matter physics where ion energies as low as 1000 V are desired, to astrophysics where energies of 1 MeV per nucleon are desired for ions of mass A up to 60. The energies of interest in condensed matter physics can be achieved by DC deceleration (or acceleration) to a high voltage pedestal, providing the output beam of the ISOL has sufficiently good emittance characteristics. A post-accelerator is required to produce the higher energy beams needed in nuclear physics and astrophysics studies.

2. ADVANTAGES OF TRIUMF AS A SITE FOR A RADIOACTIVE BEAMS FACILITY

HIGH USABLE BOMBARDING BEAM CURRENT

The beam current available at TRIUMF for high energy particle bombardment of targets considerably exceeds that available at any present ISOL facility. The properties of the beam along beam line 4A and at the proposed ISOL target position are described in an Appendix. It is estimated that a bombarding beam of only a few millimeters in diameter could be achieved if required. Steady beams of 10 μA of 500 MeV protons would be routinely usable and up to 150 μA of such protons could be available for fractions of a second with very little development work. By upgrading the beam line to the ISOL and the beam dump after the target, beam currents of up to 100 μA could be routinely available. Coupled with the use of thick targets, this means higher production rates for many radioisotopes that are higher than at any present ISOL facility and possibly higher extraction efficiencies for short-lived radioisotopes.

In the western world, there are three proton accelerators that can have comparably high bombarding energies and intensities, namely, the meson production facilities located at TRIUMF, LAMPF at Los Alamos, and SIN at Zürich. In the late 70's, the feasibility of moving the ISOLDE operation from CERN to SIN was considered. This option was abandoned in favour of the current plan of adding a second ISOL (ISOLDE-3) at the SC of CERN. At LAMPF, there is no active plan for a major ISOL facility, although an isotope separator based on a helium-jet transport system is being considered (see W. Talbert in Proceedings of Mt. Gabriel Workshop). This leaves TRIUMF as the only high-current accelerator available and an ISOL installed there will yield a large variety of ion beams with intensities that can surpass any other ISOL facility, in existence or planned for the foreseeable future.

FLEXIBILITY AND STABILITY OF BOMBARDING CURRENT INTENSITY

The bombarding beam current at TRIUMF can be easily and reliably controlled over a range from at least 0.1 to 100 μA . This allows the experimenter on an ISOL to adapt the bombarding current to a particular specialized target and to particular experimental requirements. More importantly, the proton beam is quite stable in intensity and position, minimizing large fluctuations in the heat deposited in target systems. This is particularly important if proton beam current density control is used to regulate the target ion source operating temperature.

FLEXIBILITY IN BOMBARDING ENERGY

One of the unique features of TRIUMF is that the energy of the proton beam used for target bombardment can be easily varied from 185 to 505 MeV. This is a distinct advantage for some cases, since one may maximize the production of a desired radioisotope relative to that of other contaminating radioisotopes by this means.

CONTINUOUS BEAM

A major feature of TRIUMF, advantageous for the operation of a high resolution ISOL facility is the external, continuous beam (DC on a time

scale outside the RF cycle of the cyclotron). The reason is the large current load placed on the high voltage power supply for the ion source when a large pulse of current from a short duty cycle accelerator passes through the target. For the ultimate in resolution from a modern ISOL, the ion source potential must be kept to within a few volts at a potential of up to 60,000 V. Such control is difficult when there are large peaks in the demand from the power supply due to a pulsed primary proton beam bombardment.

TECHNICAL EXPERTISE ON-SITE

The design, construction, and maintenance of a radioactive beams facility will require the support of highly skilled personnel. The regular high proton beam operation will generate a fair amount of radioactive waste and contaminated components. The availability of expertise in high radiation level work and of equipment to handle radioactive material at TRIUMF is a very significant advantage for an ISOL there. The design and construction of the ion beam transport and the post-accelerator can draw on the resources of the existing TRIUMF accelerator group. Also, the experience of the ion source development group at TRIUMF will be beneficial for the target ion source development program for the TRIUMF-ISOL project. It is certainly advantageous that there already exists at TRIUMF most of the necessary expertise for the design and construction of various components of the TRIUMF-ISOL facility, and this ensures rapid, early process.

EXISTING INTERDISCIPLINARY PROGRAMS ON-SITE

The research at a radioactive beams facility at TRIUMF will be interdisciplinary and the facility will accommodate a wide variety of specialists from medicine to astrophysics. Satisfactorily serving such a disparate clientele requires skills which can only be developed by experience. In this regard, TRIUMF has the distinct advantage that there already exist strong programs in many of these areas. Besides the sub-atomic physics research, TRIUMF has many on-going interdisciplinary programs such as isotope production, medical physics, chemistry and condensed matter physics. This presence at TRIUMF will ensure that the potential applications of radioactive beams in various fields will be exploited at the earliest stage of operation.

3. MAJOR TECHNICAL CONSIDERATIONS

To fulfill the scientific research demands, the radioactive beams facility must be a next generation ISOL coupled to a highly efficient and versatile post-accelerator. In considering various technical problems, we have relied heavily on the operating experience of ISOLDE-2 and ISOCELE and the existing heavy-ion accelerator technology. However, in the present study, we have had to extrapolate the existing technology to regions where no (or little) working experience is available. We have examined many of the key areas and believe that we have come up with solutions that are technically feasible. Some of the details of the design will require rigorous tests before they can be implemented. On the other hand, some other technical problems, such as the target ion source (TIS) design, will require a continuous development effort to meet the demands of the experiments. In this Section, we outline the major technical problems that we have considered. More detailed analysis of these considerations are presented in the form of design notes included as Appendices.

HIGH BOMBARDMENT INTENSITIES

One of the greatest technical challenges for our proposed facility is to overcome the problems associated with the passing of extreme levels of proton currents through a thick target in sometimes very complicated ion sources. The levels of activities induced in the target material, the radiation damage to components in the immediate vicinity of the target and the heat load from the primary proton beam will impose very severe design constraints on all the components near the target area. For example, a radiation-hard turbomolecular pump at the vicinity of the target will sustain only one month of continuous running at extreme conditions! All the components near the target should be removable by remote control and, as much as possible, all the delicate and expensive components should be placed away from the target area. It is imperative that adequate remote handling and safety equipment be in place from the very beginning of operation of the facility.

The energy deposited by the primary proton beam in the target material will impose a totally new problem in TIS design. At the operating level of ISOLDE and ISOCELE (proton beams of $<4 \mu\text{A}$), the targets are usually heated by the Joule effect to facilitate the diffusion of radioisotopes from the target material. At about $10 \mu\text{A}$ beam current, the energy deposited by the beam will be adequate to maintain the desired target operating temperature. Further increase in beam current will actually require cooling of the target. In addition, sudden changes in the proton beam will also have to be adequately compensated to minimize TIS damage. This will impose a difficult technical problem, but at the same time, it will present an opportunity to explore new concepts of ion source design not accessible at other accelerator facilities.

PROVISIONS FOR A WIDE VARIETY OF ION SOURCE DESIGNS

It is clear that different TIS designs will be required to optimize the production and ion beam quality for different elements, and sometimes even for different isotopes. Therefore, the TIS system should be flexible enough to accommodate a wide variety of ion sources. These must include

the capabilities to adapt to both slit and spot extraction geometries, to handle high ion beam current of stable isotopes, and to provide reactive gases for the release of particular elements. In addition to the existing types of ISOL ion sources, the TIS region should be designed to accommodate novel ion sources which may have very different geometrical and physical needs. At least two such types should be examined: a laser-based ion source, which may provide the element selection capability, and an electron cyclotron resonance (ECR) source, which seems to have a relatively high efficiency for producing both singly and multiply charged ions.

BEAM CLEAN-UP AND EMITTANCE CONTROL

To arrive at a pure isotopic ion beam, it is most desirable to achieve the selective ionization of a particular element (or elements) at the ion source position. However, for a more general application, it will be desirable to install a high resolution mass separator system to physically remove the contaminant isobars. With the possible high ion current from the source and the presence of a wide variety of radioactive elements that will be produced by a typical bombardment with the TRIUMF proton beam, a careful design for the ion source emittance control and ion transport system will be required. The vacuum around the ion source exit port and the extraction electrode should be as low as reasonably feasible. Fine control of at least five degrees of freedom for the positioning of the extraction electrode will be necessary. Also, the separator system, particularly in the sections immediately down-stream from the ion sources, must be designed with magnetic transport elements and simple beam pipe interiors. Adequate magnet tuning capabilities must be provided to achieve an overall high resolution capability.

FACILITY LAYOUT AND EXPERIMENTAL AREAS

In the planning of the facility layout, many factors have to be taken into consideration. Essentially, one will be searching for a solution that can meet the demands of the primary goals of the scientific interest while minimizing the cost of the project. The facility should be installed at the available site with minimal disturbance of the overall planned research programs at TRIUMF. Adequate experimental space should be provided, together with the necessary off-line supporting facilities. Provisions for possible future expansions should also be taken into consideration.

The detailed planning of the experimental area is perhaps somewhat premature. However, careful consideration must be given to some of the more pertinent demands of the experiments. The preparation of radioactive targets would mean a very hot area, and the possibility of contaminating the other experimental positions must be considered. In particular, some experiments may require very low radiation background. Nuclear reaction studies using the accelerated radioactive beams will likely require prolonged, continuous running. Its interference with the preparation of other experiments should be minimized. The overall radiation safety measures and the accessibility of various areas should be planned so that the normal work can be carried out with minimal interruption.

POST-ACCELERATOR DESIGN

An accelerator for radioactive ions would be essentially a heavy ion accelerator, but one having to deal with comparatively very low beam currents. Although heavy ion accelerator technology is highly developed, the design of an accelerator for radioactive ions presents some new problems. In particular, the accelerator must be able to accelerate a very large fraction of the ions injected into it. This is not only because of desired beam intensity but also because of possible contamination of the accelerator structure by radionuclides lost during acceleration. In addition, a system capable of transmitting equally well either positive or negative ions would be extremely useful.

Another problem presented by an ISOL as a source of ions is that the usual approach in heavy ion accelerator design of using a high charge state ion is not available. So far, ISOL ion sources have been designed to ionize a very large fraction of the radionuclides produced in a target. The ions produced with this high efficiency are singly charged. It is difficult to see how these ions can be efficiently stripped to high charge states without, in fact, having them accelerated to a limited extent initially. Thus, what is needed is a heavy ion accelerator which is capable of accelerating very low charge-to-mass ratio ions very efficiently.

A third problem is the very low velocity that the ions have when emitted from the ISOL. The total energy of these singly charged ions is at most 60 keV. At present, in standard heavy ion systems, ions have injection energies higher than about 10 keV/amu. This would only allow species with $A \leq 6$ to be accelerated, which is hardly very useful. Final output energies of course depend upon the experimental studies planned. For nuclear astrophysics, a continuously variable energy accelerator from about 100 to 1000 keV/amu, at least for species with values of A up to 60, would be quite useful. A related problem is the question of the required energy resolution of the final heavy ion beam. Again, for nuclear astrophysics a resolution of 10^{-4} is desirable, although 10^{-3} is acceptable.

4. OUTLINE OF THE FACILITY

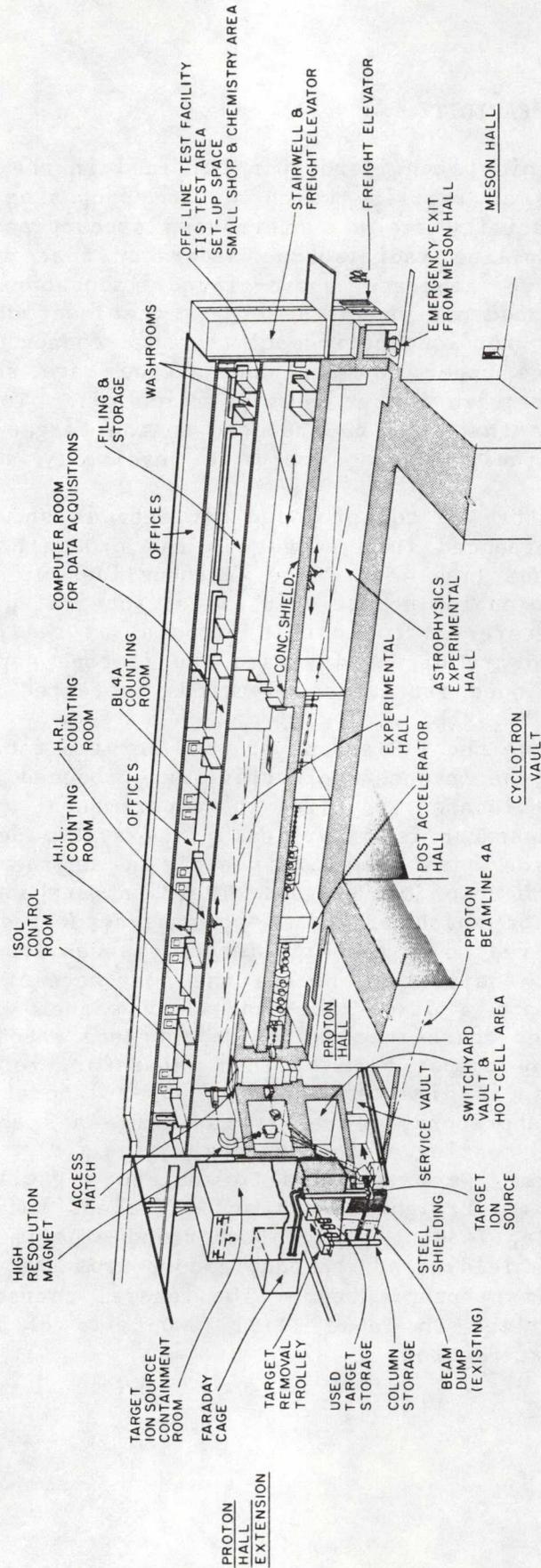
The major technical considerations outlined in the previous section led us to the type of facility which we are proposing. The essential features of this facility are a subterranean production site for radionuclides with an on-line radioisotope separator that delivers beams of radionuclides to two separate above-ground laboratories. These two laboratories are placed one above the other, the lower designed to handle high intensity beams for long periods of time and to accommodate the post-accelerator, and the upper to make use of the rare species of radionuclides that may require higher beam purification. To handle the high levels of activities that will be produced in the target area, we include a remote handling facility that would be physically separate from the laboratory areas.

The basic geometry of the proposed facility is shown in Fig. III.1. Radionuclides are produced in a target in the proton hall basement near the beam dump on beam line 4A. These radionuclides are rapidly released from the target into an ion source which is an integral part of the target ion source system (referred to in this proposal as the TIS). The radioactive ions produced are directed toward the isotope separator system by an accurately positioned extraction electrode (referred to as EE in this proposal).

Immediately above the TIS and EE are the service facilities for these systems. Because of the intense radioactivities produced in these systems, these facilities are located away from the experimental areas.

The isotope separator is a vertical plane system designed to transport the radionuclide beam to ground level in as short a distance as possible, and is made up of two stages. The first stage is a medium resolution mass separator which provides two mass-separated radioactive ion beams. One is referred to as the high intensity beam and is directed into the lower laboratory hall which houses the post-accelerator. The other beam is injected into a dispersion-cancelling magnet which creates the high-brightness image source necessary for entrance into the high resolution separator. The output beam of this separator, referred to as high resolution ion beam, is directed into the upper laboratory. At the far end of the upper laboratory, we reserve as large a space as is feasible for the assembly and testing of ion sources.

In general terms, we have tried to achieve a facility layout which accommodates the most straightforward and efficient radionuclide separation system possible, leading to low background experimental areas while providing adequate shielding at reasonable cost from the intense radiation produced by the primary proton beam. The general characteristics of the facility are summarized in Table III.1. Details of the facility are presented in the next Section.



**Proposed
TRIUMF - ISOL
Facility**

Fig. III.1. A conceptual layout of the proposed TRIUMF-ISOL facility.

Table III.1 General characteristics of proposed TRIUMF-ISOL facility ion source.

Ion Source

- horizontal slit or circular extraction port
- up to 10 mA ion current
- 60 kV ionization voltage, stabilized to ± 2 V
- provisions for various types of ion sources
- target thickness, ≤ 100 g/cm²
- design proton beam current, 10 μ A generally, 100 μ A for some TIS

First Stage Mass Separator

- two 4 in. quadrupoles and one dipole (QQD)
- resolution 635 for 30π mm/mrad emittance or 3900 for 3π mm/mrad emittance
- dispersion 3.86 cm/percent momentum change

Zero Dispersion System

- a mirror image of the first stage system (DQQ)

High Resolution Mass Separator

- resolution of up to 30,000

Two Simultaneous Ion Beams Extracted

- high intensity ion beam (after the first stage separation), delivered to the lower experimental hall where the post-accelerator is located
- high resolution ion beam (after high resolution mass separator), delivered to upper experimental hall

Post-Accelerator (Preliminary)

- RFQ-LINAC combination accelerator
 - injecting energy, ≥ 1.0 keV/amu
 - mass range, up to A=60
 - exit energy variable, ≥ 1.0 MeV/amu
 - exit energy resolution, $\leq 0.1\%$
 - one stripping station
 - high transmission efficiency
 - one stripping station
-

5. DETAILED DESCRIPTIONS OF THE MAJOR DESIGN FEATURES

Clearly at this early stage, it is premature and unwise to suggest that such a complex facility can be easily designed in detail. It is more important to demonstrate that reasonable and feasible conceptual designs can be suggested that meet or appear to solve the identifiable technical problems. During the process of arriving at such conceptual designs, those areas that clearly will require more concentrated engineering research and design can be identified. The approach taken in this proposal was to divide this facility into its major components, to attempt to arrive at feasible solutions to the required specifications, and then to use these concepts to arrive at realistic cost estimates.

Given the general specifications indicated in Sects. 1 to 4, the following major areas are identified, namely:

- Target and Ion Source
- Beam line 4A Upgrade and Modifications
- Target and Ion Source Services
- Remote Handling and Operation
- The Separator System and Its Beam Optics
- Ion Beam Line Components
- Control Systems
- Radiation Safety
- Building
- Off-Line Facilities
- Post-Accelerator
- Experimental Halls

A summary of each of these areas will be given, sufficient to explain the general concepts involved in the final design, and hopefully sufficient to explain and justify the final cost estimates in the next Chapter. It should be noted that detailed design notes included in the Appendices do present a more complete view of some of the desired specifications of these areas.

5.1 TARGET AND ION SOURCES (TIS)

INTRODUCTION

This Section gives a broad review of the Target Ion Source (TIS) situation in order to project the needs in that area for a TRIUMF-ISOL.

An ion beam of nuclear reaction products results from the combined effects of three parts: a target, an ionization chamber, and an extraction electrode. For each of these components, there exists a variety of different designs, and separators around the world have used various combinations (in addition, new concepts have surfaced during the last few years that are still in need of further research and development). Although there is a large number of possible combinations, one is often limited either by the type of facility at which the separator is installed, by the characteristics of the elements that one wishes to produce, or by the compatibility of the various components. These will now be considered in more detail.

THE TARGET

The target is composed of a material from which the nuclear reaction products can be extracted and directed to the ionization chamber. This is the most complex part of the TIS. Some of the important parameters on which the proper operation of the facility depends are: the target material, its operating conditions (temperature, admixture of chemically reactive compounds), and the environment (boat, transfer of radioactivity to the ion source). Furthermore, these parameters are not always independent.

The first criterion in choosing a target material is a sufficiently high cross section for the production of the isotopes of interest. The second criterion is the ability to extract these isotopes from the target matrix in a time short enough that a significant fraction of the nuclei to be extracted have not decayed before reaching the ionization chamber. Satisfying the first condition is usually simple (when possible), however, satisfying the second is complex. In the case of thick targets, unless the target matrix is brought to a high temperature, the release of reaction products is very slow, resulting in poor yields of short-lived products. It has been shown, for example, [Car 78], that increasing the temperature of a Ta foil target from 1600°C to 2000°C results in an order of magnitude decrease in the release time of Yb isotopes. This is critical for the efficient production of nuclei with shorter half-lives. In general, temperatures of approximately 2000°C (or above) have been found satisfactory [Car 79]. Presently, many facilities run at very high temperatures [Brü 85, Pio 84, Kir 81a, Bjo 81, Mün 81]. The situation depends, however, on the matrix itself (thin foils, powder and molten target will have different release properties for the same element [Fuj 81, Car 79]) and its chemical composition. If the target material cannot stand the required temperature (for example, too low a melting point or too high a vapor pressure of a powder target), one has to use more refractory compounds of the chosen element [Hof 84]. In particular, this is the case with oxides of Cr, Zr or carbides of the elements of period IV (U, V, Ti). Mixtures such as alloys have also been used.

Alternatively, one can produce on-line, molecular compounds of the element of interest that have a lower boiling point, by introducing chemical reagents such as CF_4 [Sau 84]. This on-line chemistry has the added advantage of chemically separating the various isobars in the selected mass, since different elements will have different affinities for the reagent [Sau 84, Hof 81] (in this case, fluorine). In some cases, there is no choice but to operate in conditions such that the target material itself evaporates (consumable target) [Sau 84]. The above considerations would be eased in the case of a heavy-ion based facility, since in this case the products usually recoil from a thin target and can be collected, either directly [Kir 81b] or by means of a gas-jet system [Oka 81, Tal 84, Shm 84], on a catcher foil kept at high temperature to vaporize the caught recoils. In the case of a high energy proton beam, the target is usually fairly thick (up to several hundred grams per cm^2), to optimize production of the isotopes of interest.

ION SOURCES

The reaction products drift into a small chamber where they may be ionized. The ionization techniques fall into two main categories. A more detailed description of various classical ion sources may be found in [Kir 81a].

i. Gaseous Discharge Ion Sources

Gaseous discharge ion sources achieve ionization by electron bombardment of the vapor in the chamber. There are many sources of this type. They are, in general, reasonably efficient for a broad range of elements. Those most often employed at ISOL facilities are:

- (a) FEBIAD (forced electron bombardment induced arc discharge). This is an efficient source that operates best at low pressure ($\sim 10^{-4}$ Torr). It is the ion source most often used at ISOLs [Kir 85, Gil 84].
- (b) Bernas-Nier [Put 81, Sau 84, Sch 84]. This source operates at a higher pressure than the FEBIAD. This can be an advantage if one operates with a high vapor pressure target material or if a substantial amount of reactive gas has to be added. However, the advantage exists only if the separator is designed to handle high ion currents. It also has the advantage of good plasma properties combined naturally with a slit geometry for the exit orifice, leading to an efficient and fast release of the ions from the source as well as a small beam emittance. It has, however, the disadvantage of requiring a large volume of support gas, causing a greater demand on the vacuum pumping system.
- (c) Hollow Cathode. This is an efficient source but does not have the advantages of the previously mentioned types. It operates with a high pressure and has poor emittance characteristics.

ii. Thermal Ion Source

- (a) Surface Ionization. This technique is particularly useful for ionizing the alkalines and elements of period II. It presents the advantage of providing element selectivity, but is restricted in

the number of elements that can be ionized efficiently. However, recent progress with so-called negative surface ion source have extended the range of the elements to the halogens [Vos 81, Shm 81, Rav 84].

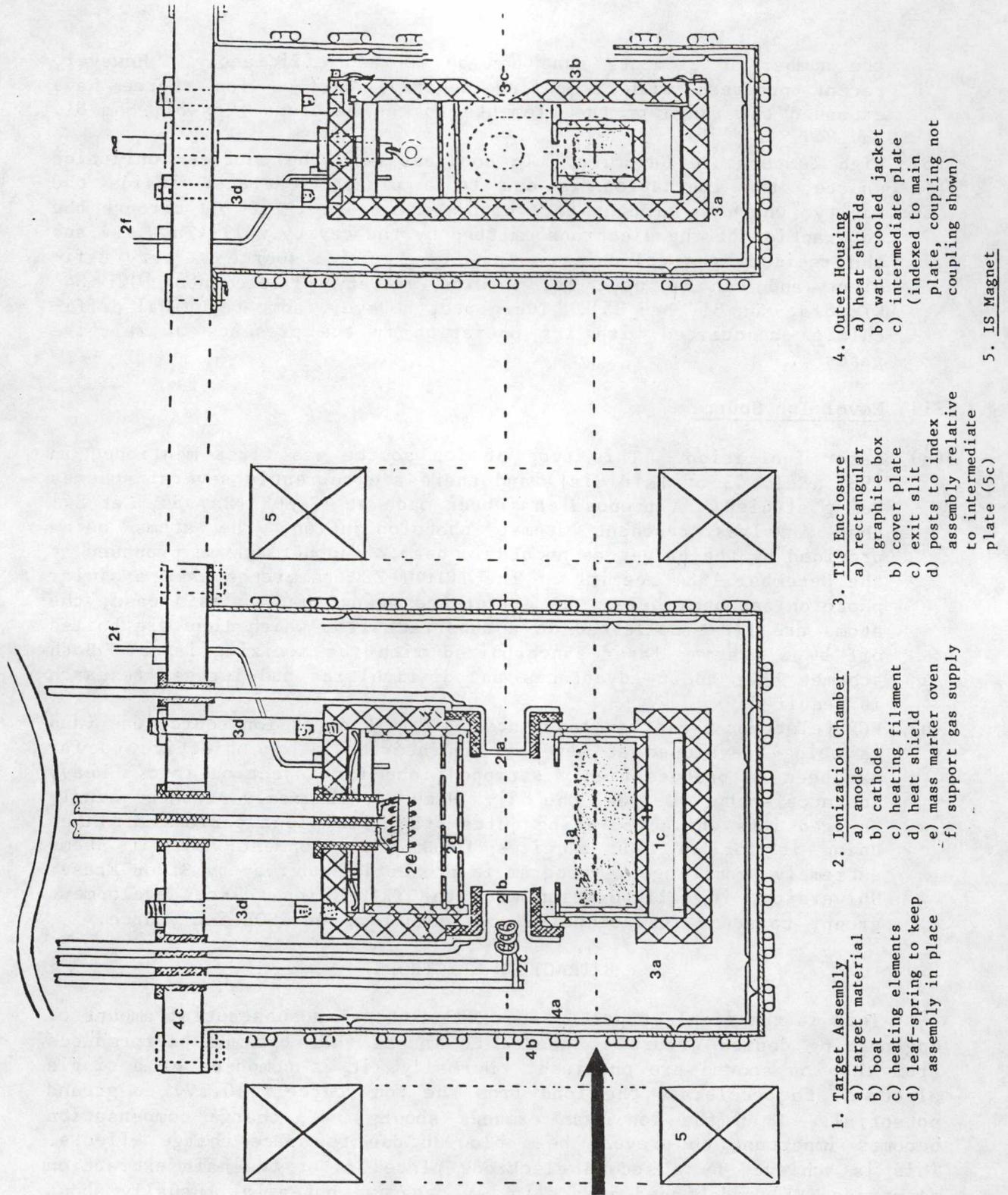
- (b) High Temperature Cavities. In contrast with the surface ionization source, the ionization is due to a plasma generated inside the cavity, which is brought to a high temperature ($>2500^{\circ}\text{C}$) through the interaction of the electrons emitted by the cavity wall (Ta,W,Re) and the residual gas molecules. This type of ion source is very efficient and can be used for a wide variety of elements [Gil 84, Kir 81a, Mün 81, Brü 85]. There are, however, some technical difficulties associated with its operation in the presence of reactive gases.

iii. Novel Ion Source

- (a) Laser Ionization. This type of ion source was first mentioned in 1981 (Ref. 43 of [Kir 81a]) and there are currently several schemes being studied. A proposal has been made at ISOLDE [Rav 84, Let 84] that involves resonant atomic photoionization, the atoms being provided by the target as an atomic beam. Another scheme proposed at the December 1984 meeting of the TRIUMF-EEC committee uses a similar photoionization scheme, the difference being that in this case, the atoms are first collected on a substrate from which they are boiled off by a heating laser synchronized with the ionizing laser. Both schemes have their advantages and difficulties and further research is required.
- (b) ECR (electron cyclotron resonance). This kind of ion source was (and is being) developed at several laboratories. The objective so far has been to produce highly stripped ions for injection into a heavy ion accelerator [Gel 84, Che 84]. However, it easily produces singly charged ions while operating quite stably for long periods of time. Using it for an ISOL requires further development, but it seems extremely promising. A program is presently underway by Simon Fraser University, in collaboration with the TRIUMF ion source development group, to study its potential application as an ISOL ion source.

EXTRACTION ELECTRODE

This is the simplest part of the TIS although a substantial amount of engineering design effort is needed to insure that optimum performances from the ion source are obtained. Normally, it is composed of a single electrode to accelerate the ions from the ion source (~ 60 kV) to ground potential. When the ion beam exceeds about 1 mA, charge compensation becomes important to prevent beam blow-up due to space charge effects. This is achieved by a second electrode placed after the main extraction electrode (EE) and biased at a slightly negative potential (usually about -100 V) which repels the electrons. In view of the desired high resolution, it is important that the EE be adjustable with five degrees of freedom of motion to shape the beam profile as it exits from the ion source. Also, it must compensate for any misalignment (or slight change due to, for example, sagging of the ion source after hours of heating) of the TIS as well as the slight transverse momentum imparted to the ions by the TIS magnetic field.



- 1. Target Assembly
 - a) target material
 - b) boat
 - c) heating elements
 - d) leaf-spring to keep assembly in place
- 2. Ionization Chamber
 - a) anode
 - b) cathode
 - c) heating filament
 - d) heat shield
 - e) mass marker oven
 - f) support gas supply
- 3. TIS Enclosure
 - a) rectangular graphite box
 - b) cover plate
 - c) exit slit
 - d) posts to index assembly relative to intermediate plate (5c)
- 4. Outer Housing
 - a) heat shields
 - b) water cooled jacket
 - c) intermediate plate (indexed to main plate, coupling not shown)
- 5. IS Magnet

Fig. III.2. A schematic representation of a possible target/ion source.

A TRIUMF-ISOL SOURCE

The preceding considerations have indicated the availability of a large range of ion sources. Clearly none is truly universal although some produce many elements and a TRIUMF-ISOL will require different combinations depending on the elements of interest. Designing an ion source for optimum performance (resolution, yield, release time) is already a challenge in itself. Designing one for operation with a 100 μ A proton beam presents difficulties that need further research. The most critical problem is excessive heating due to the power deposited in the target by the primary proton beam. A target with a thickness of the order of 100 g/cm² would absorb about 150 MeV of the beam energy, which corresponds to 15 kW. Such power would have to be dissipated very quickly to prevent vaporization of the target material. At this time, it is not clear how this may be done effectively.

In the present proposal, the TIS described is a conventional one except that a horizontal extraction slit is used. A schematic diagram is shown in Fig. III.2. The design can be based on one of those already used extensively at ISOLDE or ISOCELE. With this approach, proton beam currents of up to about 10 μ A can be used. The geometrical layout of the EE and TIS is such that most of the conventional types of sources mentioned can be accommodated. In addition, the target vacuum chamber can be remotely removed from its normally imbedded position to allow the installation of other novel ion source designs that may require radically different geometrical arrangement. Details of the vacuum chamber, the EE and the provision of the necessary services will be presented in Sect. 5.3, while a more complete description of specifications of the TRIUMF ISOL source are found in the Appendix (TRI-TN-84-5 Rev).

REFERENCES

- [Bjo 81] T. Bjørnstad, L.C. Carraz, H.A. Gustafsson, J. Heinemeier, B. Jonson, O.C. Jonsson, V. Lindfors, S. Mattssons and H.L. Ravn, Nucl. Instr. Meth 186, 391 (1981).
- [Brü 85] M. Brügger, N. Hildebrand, T. Karlsewski, N. Trautmann, A.Z. Mazundar, and G. Herrman, Nucl. Instr. Meth. 234, 218 (1985).
- [Car 78] L.C. Carraz, I.R. Haldorsen, H.L. Ravn, M. Skarestad, and L. Westgaard, Nucl. Instr. Meth. 158, 217 (1970).
- [Car 79] L.C. Carraz, S. Sundel, H.L. Ravn, M. Skarestad, and L. Westgaard, Nucl. Instr. Meth. 158, 69 (1979).
- [Che 84] A. Chetioui, M. Delaunay, S. Dousson, R. Geller, B. Jacquot, D. Hitz, and D. Vernet, Nucl. Instr. Meth. 227, 6 (1984).
- [Fuj 81] M. Fujioka and Y. Arai, Nucl. Instr. Meth. 186, 409 (1981).
- [Gel 84] R. Geller and B. Jacquot, Nucl. Instr. Meth. 219, 1 (1984).
- [Gil 84] R.L. Gill, in Proc. of the TRIUMF-ISOL Workshop (1984), ed. J. Crawford and J.M. D'Auria, TRI-84-1, p. 99.
- [Gil 85] R.L. Gill and A. Piotrowski, Nucl. Instr. Meth. A234, 213 (1985).
- [Hof 79] P. Hoff, O.C. Jonsson, E. Kugler, and H.L. Ravn, Nucl. Instr. Meth. 221, 313 (1984).
- [Hof 81] P. Hoff, L. Jacobson, B. Johansson, P. Aagaard, G. Rudstam, and H.U. Zwicky, Nucl. Instr. Meth. 186, 381 (1981).
- [Hof 84] P. Hoff, O.C. Jonsson, E. Kugler, and H.L. Ravn, Nucl. Instr. Meth. 221, 313 (1984).
- [Kir 81a] R. Kirchner, Nucl. Instr. Meth. 186, 275 (1981).

- [Kir 81b] R. Kirchner, K.H. Burkard, W. Hüller, and O. Klepper, Nucl. Instr. Meth. 186, 295 (1981).
- [Kir 85] R. Kirchner, D. Mark, O. Klepper, V.T. Koslowsky, T. Kühl, P.O. Larson, E. Roeckl, K. Rykaczewski, D. Schardt, J. Eberz, G. Huber, H. Lochmann, R. Menges, and G. Ulm, Nucl. Instr. Meth. A234, 224 (1985).
- [Let 84] V.S. Letokov, in Proc. of the Workshop on the ISOLDE programme, Zinal (1984).
- [Mün 81] J. Münzel, H. Wollnik, E. Pfeiffer, and C. Jung, Nucl. Instr. Meth. 186, 343 (1981).
- [Oka 81] K. Okano, Y. Kawase, K. Kawade, H. Yamamoto, M. Hanada, T. Katoh, and I. Fujiwara, Nucl. Instr. Meth. 186, 115 (1981).
- [Pio 84] A. Piotrowski, R.L. Gill and D.G. McDonald, Nucl. Instr. Meth. 224, 1 (1984).
- [Put 81] J.C. Putaux, J. Obert, L. Kotfila, B. Roussiere, J. Sauvage-Letessier, C.F. Liang, A. Peghaire, P. Paris, and J. Giroux, Nucl. Instr. Meth. 186, 321 (1981).
- [Rav 84] H. Ravn, in Proc. of the TRIUMF-ISOL Workshop (1984), ed. J. Crawford and J.M. D'Auria, TRI-84-1, p. 19.
- [Sau 84] J. Sauvage, C. Bourgeois, A. Caruette, P. Kilcher, J. Obert, J. Oms, J.C. Putaux, B. Roussiere, A. Ferro, J. Fournet, L. Kotfila, C.F. Liang, P. Paris, M.G. Porquet, and G. Cornudet, in Proc. of the TRIUMF-ISOL Workshop (1984), ed. J. Crawford and J.M. D'Auria, TRI-84-1, p. 161.
- [Sch 84] H. Schmeing, E. Hagberg, and J.C. Hardy, in Proc. of the TRIUMF-ISOL Workshop (1984), ed. J. Crawford and J.M. D'Auria, TRI-84-1, p. 148.
- [Shm 81] M. Schmid, G. Engler, I. Yoresh, and E. Skurnik, Nucl. Instr. Meth. 186, 349 (1981).
- [Tal 84] W.L. Talbert, Jr., M.E. Bunker, and J.W. Starnner, in Proc. of the TRIUMF-ISOL Workshop (1984), ed. J. Crawford and J.M. D'Auria, TRI-84-1, p. 179.
- [Vos 81] B. Vosicki, T. Björnstad, L.C. Carraz, J. Heinemeier, and H.L. Ravn, Nucl. Instr. Meth. 186, 307 (1981).

5.2 BEAM LINE 4A UPGRADE AND MODIFICATIONS

GENERAL

It is proposed that the target of the ISOL be located at the end of beam line 4A, approximately 2 m before the beam enters the beam dump wall (see Fig. III.1). This is the best location for several reasons. First, this position can receive unpolarized beam at the same time as beam line 1, the major user of unpolarized beam at present. Second, this location is not heavily used by experimenters and would require only minimal disruption to other users of this beam line. Third, this beam line can presently be used for intensities as high as 10 μA , a current much higher than that available to users at other ISOL facilities, and with minimal modifications can be upgraded to handle 100 μA (see discussion below). Also, the extracted ion beam can be brought quickly outside the proton beam hall, thus minimizing the disturbance of the other experimental setups in that area.

MODIFICATIONS

Figure III.3 shows a plan view of the revised beam line 4A layout at beam level (268.5 ft) with the TIS and the first stage mass separator installed.

A beam blocker will be installed upstream of 4AB2 to be used in the area access control safety interlock system. This will allow access to the ISOL area when beam line 4B is in operation. Beam line monitor 4AM7 will be relocated upstream of the ISOL target shielding and a pair of quadrupoles will be required to achieve an achromatic focus at the target location (see TRI-DNA-85-2 in Appendix). As it is not anticipated that there will be a target at the liquid deuterium target location when the 4A line is in operation, it should not be necessary to make the beam line upstream of the new facility radiation hard.

The 4A shielding at the existing beam dump was rated at 10 μA when it was installed and it is assumed that this will be adequate with a 100 μA beam. It is estimated that about 25% of the beam will be lost at the ISOL target and the downstream collimator. Radiation measurements made by the TRIUMF Safety Group (TSG) at ground level with 10 μA beam into the dump did not reveal any radiation hazards. An additional layer of concrete (3-1/2 ft) thick could be installed above the dump without raising the floor level, if necessary.

The beam stop in the dump is a 1 m by 30 cm, water-cooled, carbon block. It is located at the centre of the beam dump and will be retained. It will not be kept under vacuum but will be vented into the air space surrounding the target so that any active gases will be measured by the target region air handling system. The isolation window will be moved upstream to facilitate replacement.

The position of 4AB2 was changed during installation: it lies off the centerline of the beam dump by about 5 mrad. This will be corrected so that the dump and beam line axes are coincidental by using a standard steering magnet downstream of 4AB2. Collimators upstream and downstream of the ISOL target built into the steel shielding will ensure that the beam is aligned onto the target and that backscattering is minimized.

The installation of new shielding and remote handling facilities

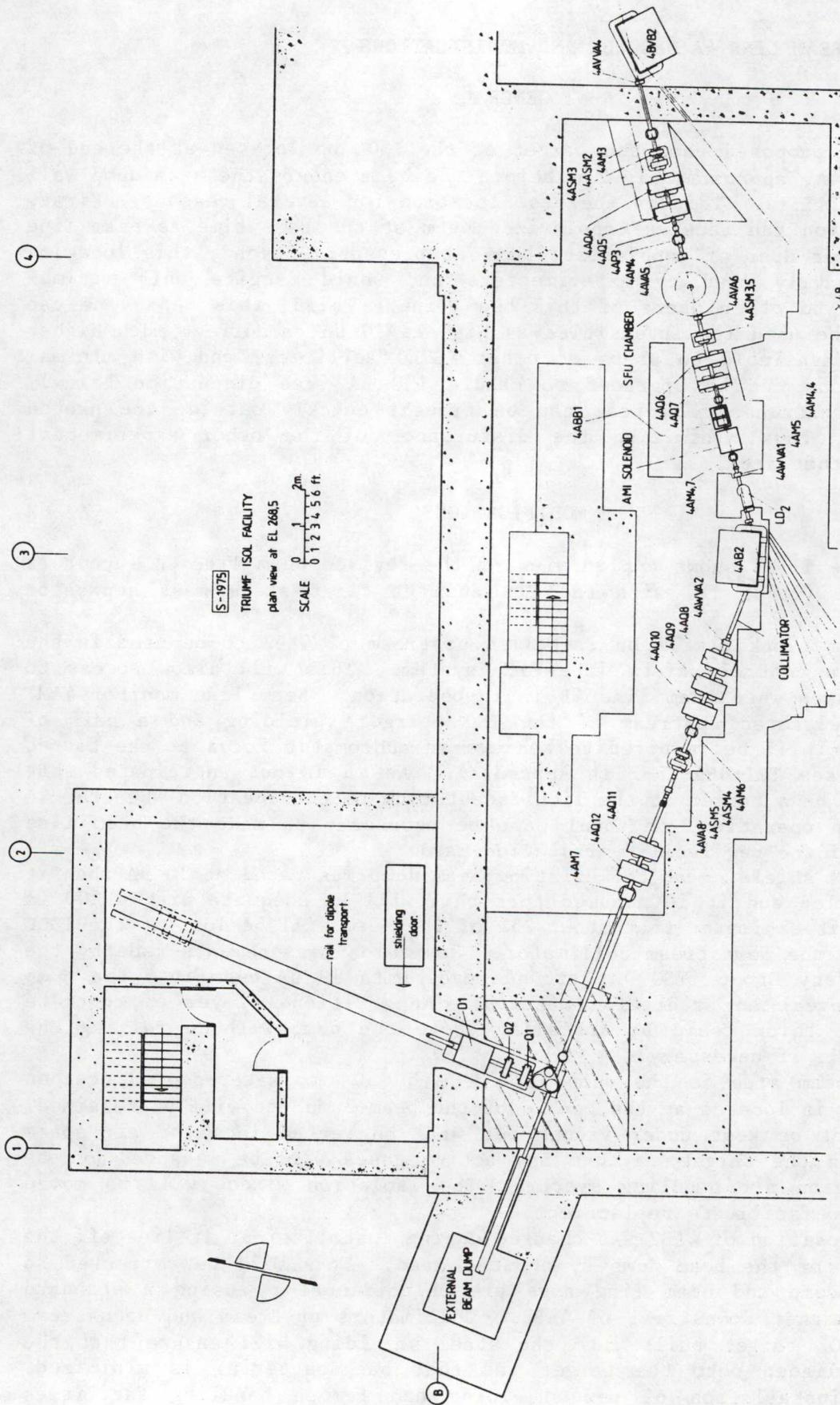


Fig. III.3. Displayed here is a plan view at beam level of a revised beam line 4A layout with TRIUMF-ISOL installed.

above the target (described in later Sections) will mean that the shielding at the end of the beam line will be completely rebuilt. Some of the present access controls will be changed and some services will have to be modified. The power supplies located on a wooden platform at the ends of the P-area and the extension will be relocated onto a new mezzanine on the north wall (see building plans).

The beam line tunnel and shielding surrounding the target and the ISOL beam line will be sealed to provide a local region of isolated air which will be exhausted through a duct system and filters. In this way, the target region will be maintained at a negative pressure and activated air will be prevented from diffusing into the Proton Hall.

TARGET SHIELD

Figures III-4 and III-5 show plan and elevation views of the proposed ISOL target array shielding. The reference case for the maximum amount of shielding required was 100 μ A beam, into a 100 g/cm² target of uranium. A detailed discussion of radiation levels is presented in an Appendix (TRI-TN-84-5 Rev.). It was required that the fast neutron field at the shield surface be less than 0.01 mSv/h (1 mrem/h). Local inner steel shielding, 1.83 m in thickness, is used for the first few radiation lengths to reduce the assembly size. This casing of removable blocks is surrounded by modular, reinforced concrete about 2.43 m in thickness, to complete the shielding requirements. The combined shielding would ensure minimal encroachment onto usable experimental space in the 4B area, i.e. maintain the present situation. Two collimators will be incorporated into the steel shields to minimize scattering of the beam into unshielded parts of the downstream beam line. Water cooling will be used to remove heat from the collimators and the steel adjacent to the target ion source. Additional steel may be needed in the upstream section to reduce backscattering. A vertical tube will allow access to the proton beam immediately upstream of the TIS for target protect and position monitors. A vertical access will also be made at the junction of the beam line and the wall for access to beam dump services. Existing thermocouples and cooling lines from the 4A dump pass through this access route.

The shield assembly shown in Fig. III.5 will form the base for the remote handling facilities described in Sects. 5.3 and 5.4.

The ISOL ion beam line will exit from the shield at the lower level as shown in Fig. III.3, at an angle of 21° to the north wall.

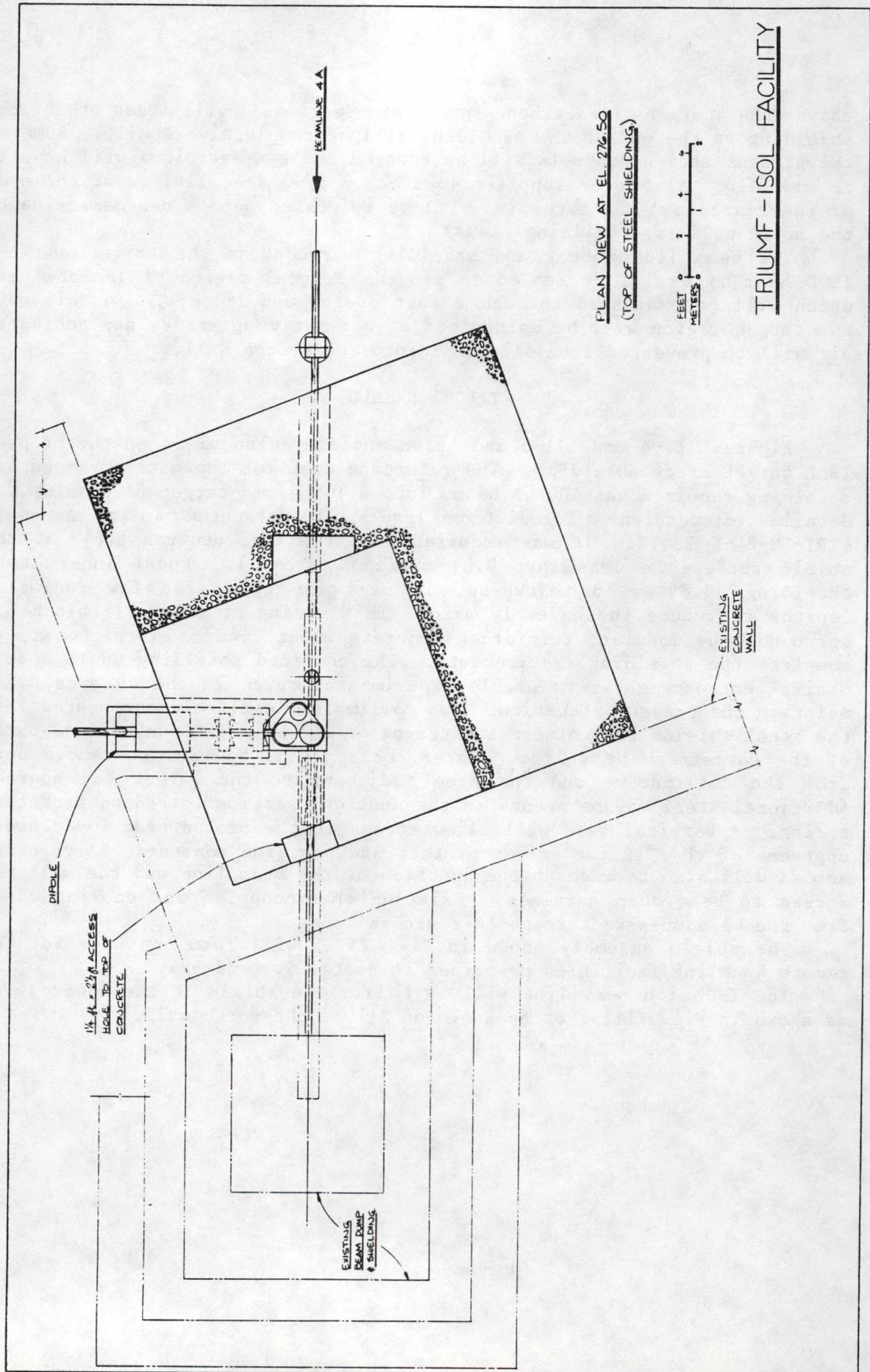


Fig. III-4. Plan view of target array shielding.

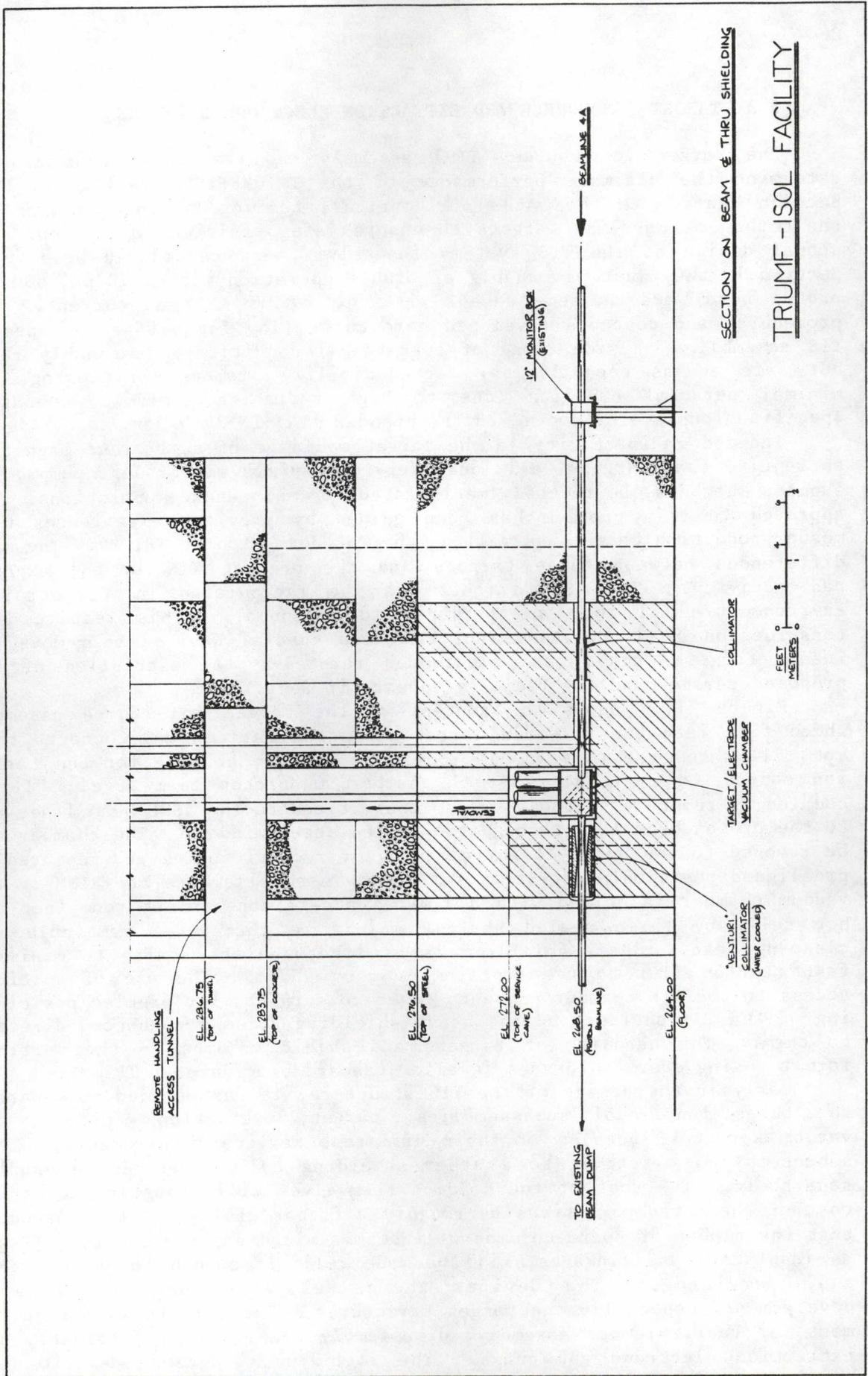


Fig. III-5. Elevation view of target array shield and revised beam line 4A.

shhl eld anisedseam beam lline 4A.etar et

5.3 TARGET ION SOURCE AND EXTRACTION ELECTRODE SERVICES

The target ion source (TIS) assembly and its associated services determine the ultimate performance of the TRIUMF-ISOL facility. This Section deals with the vacuum, electrical, heating/cooling services and the method of handling targets to ensure safe, efficient operation. The actual design of the TIS systems themselves were considered briefly in Sect. 5.1; they must be capable of stable operation with a 10 μ A, 500 MeV proton beam, and in some cases, with up to 100 μ A beam current. The procedures and concepts developed here must allow for different types of TIS assemblies, a wide range of operational conditions, reasonably rapid but safe access capabilities, reproducibility, remote positioning, and minimal personal handling (due to high radiation fields). Detailed specifications are presented in an Appendix (TRI-TN-84-5 Rev.).

Induced radioactivity in the target would be of sufficient magnitude to require that targets, all local services, viz. electrodes, pumps, and exposed chambers, be remotely manipulated for maintenance operations. The approach to this problem has been guided by previous experiences with meson production targets as well as the TNF beam stop at TRIUMF. The main differences between these targets and the present TIS is the exposed radioactivity. The ISOL targets must be manipulated in a controlled environment until they are packaged for disposal. This requires the construction of a contiguous hot cell and special devices to remove and insert targets, pumps, and electrodes remotely. A description of the proposed remote handling facility appears in Sect. 5.4.

Figure III.6 shows the concept of the target ion source assembly which fits into the shielding array discussed earlier and connects to a hot cell through a containment room. The vacuum housing for the target ion source is a stainless steel chamber at proton beam level. It is coupled by remotely operable vacuum connections to the ISOL beam line, and to the proton beam line through two cooled steel windows. The chamber can be removed to the hot cell for cleaning or reconditioning and replaced on prealigned positioning devices of the type used elsewhere at TRIUMF. The vacuum chamber is joined with a limited access containment room (not the hot cell) by three sealed shafts, which are themselves removable for cleaning, etc. Steel shielding is used between the shafts to minimize fast neutron flux to the containment room above. The use of vertical access to the TIS chamber presents fewer constraints for precise positioning of the TIS devices and the heavy shielding columns connected directly to them. The handling of targets and shield columns in the vertical format using overhead cranes is also standard procedure at TRIUMF.

Early in the design of the TIS structure, it was decided to separate the three functional subassemblies: target, extraction electrode and vacuum services, because of their different service requirements. Each subassembly is attached to a steel shielding column and can be handled separately. The cost of the columns themselves will probably exceed the cost of the attached devices by roughly a factor of 10, so it is expected that the number of spare columns will be minimized and the internals, such as insulators and linkages, will be made reliable enough to avoid extensive servicing. The devices themselves will undergo extensive development, especially the target structures. Thus, there is a requirement for facile remote assembly, disassembly and testing of targets, the extraction electrode and pumps. The following paragraphs describe the properties of the individual subassemblies.

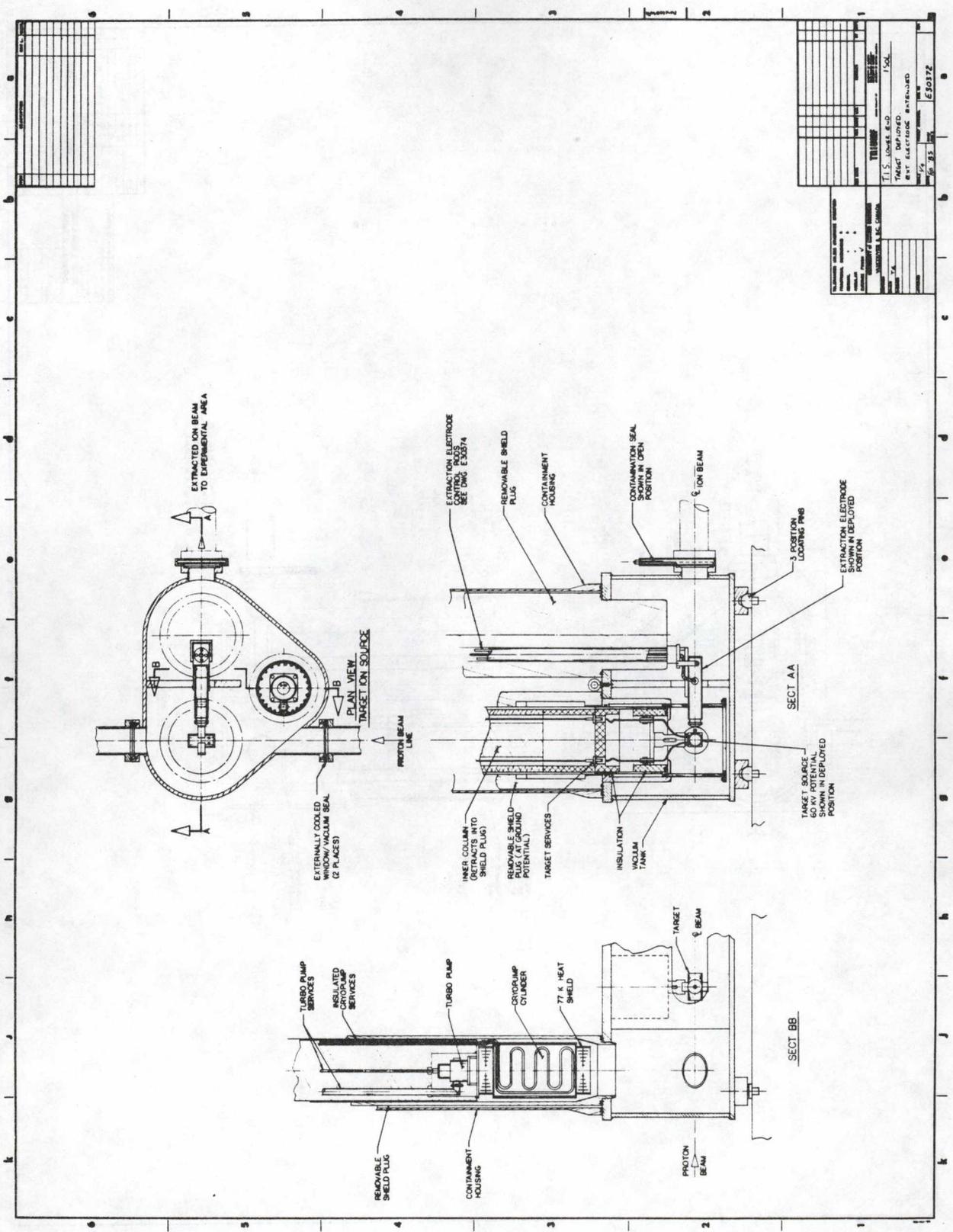
The target column performs these functions: target assemblies can be attached remotely to the bottom end, tested for leaks and electrical connections, evacuated and stored in vacuum continuously until exposed to proton beam. Figure III.7 shows the end of the target column, partially inserted into the vacuum chamber, but with the target sealed in its vacuum transfer container. Note that this position allows the proton beam to pass below the target for beam line tuning or use by non-ISOL personnel. The target module connects to the column electrical, gas and water services at the plugs directly above. Details of the remote disconnects remain to be developed. Figure III.6 shows the target deployed for proton beam bombardment. This is accomplished by moving a separate inner column core with respect to an outer column as shown in the top assembly, Fig. III.8. It is expected that target assemblies will be serviced at least once a week, so that elastimer seals may be used for the transfer chamber and bottom column-to-vacuum chamber interface. Containment housing (Fig. III.7) and beam line seals, however, must be radiation hardened, probably using a TRIUMF indium seal design. The target column must contain a minimum of 2 m of steel shielding. The column core and target are insulated for 60 kV potential with the minimum leakage to ground. It is expected that this column will require more frequent service than the other two. The procedure for extraction, following removal of the proton beam and structure down of TIS services, is to seal the target, vent the TIS vacuum chamber, retract the extraction electrode as shown in Fig. III.7, and hoist the TIS column. A discussion of target handling in the change area (for disposal and storage) is discussed in a later Section.

The extraction electrode column contains the mechanism for positioning the electrode precisely with respect to the ion source. Figure III.9 shows a typical assembly which might be used for a more conventional ion source. The electrode itself may consist of more than one lens depending on the beam requirements, but all assemblies will be required to position themselves accurately with respect to the ion source, and follow its changes in position during normal operation. One mechanism which might accomplish this task is shown schematically in Fig. III.9. Motion is transmitted to the extraction electrode through three double shaft assemblies. Three ball joints at the end of these assemblies couple to sockets in the electrode bracket, as shown in the elevation sections of the figure. The assemblies consist of an inner shaft with one of the balls mounted eccentrically at the electrode end, and a second shaft which holds the inner shaft eccentrically. This combination of shafts and the ball form a double eccentric. The plan view shows how the electrode mounting can be moved in a plane by rotating inner and second shafts in a synchronized way. This motion obviously includes rotations as well as translations. Tilting is accomplished by moving the second shafts longitudinally. Tilting the electrode will require rotations of the eccentrics as well as longitudinal shaft motions to maintain the constraint of the ball joints. The limits of translation and tilt are given in the table labelled "FUNCTIONS" in Fig. III.9 for a design which fits easily on the 30 cm diameter shield column. Finally, the three shaft assemblies are mounted within a single outer shaft which can be rotated 180 degrees to retract the electrode for removal. As shown in Fig. III.7, the principal advantage of this design is direct coupling of the electrode to the external actuators. We believe that this design will permit reasonably

precise positioning. However, the shaft assemblies will have to be temperature controlled to limit thermal expansion over their 3 m length. The main disadvantage is that the nine actuators required to provide the desired motions will have restraints on their synchronization to satisfy the constraint of the ball joints on the electrode bracket.

The third column shown in Fig. III.6, provides access for vacuum pumps. A 25 K cryopanel is proposed for pumping 0.01 Torr-litre/s target sweep gas, so that a vacuum of 10^{-7} Torr may be achieved in the ion beam line. It is assumed that the sweep gas will be argon or some other condensible with a similar vapour pressure curve. A 350 litre/s turbo pump is also provided for ubiquitous hydrogen. There is uncertainty as to the deployment of the cryopanel. The local vacuum will be lower if the pump is located beneath and between the extraction electrode and the TIS, but beam power thermal loads in this position will exceed the gas thermal loads. A position in the throat of the pump column is more hospitable but sufficient pumping speed may not be available.

A Faraday cage is needed to house the 60 kV and other ion source power supplies. This cage will be placed at the ground floor level in the corner of the proton hall extension (see building plans in Sect. 5.9). The cage itself will be patterned after three other ion source cages at TRIUMF. A 3 x 4 x 3 m aluminum room will be supported on appropriate insulators. This room will require a 4 x 5 m floor space of limited access. The 60 kV supply is required to have short-term stability of 3 parts in 10^5 at currents up to 50 mA, however, better stability may be achieved. Other specifications are given in an Appendix (TRI-TN-84-5 Rev.). Within the cage, there are nine auxiliary power supplies, six equipment racks for controls, and switchgear. Two cooling circuits and three target gas sources are also required. The cage room must be air-conditioned to control temperature and humidity. Control problems are discussed in a later Section. There are, however, two outstanding hardware problems seen at this time in the application of electrical services. The first is the return of activated cooling water (from the target) to the cage at HT. One solution to this problem is to have a shielded heat exchanger running at HT in the new containment room above the columns. There are obvious problems with this arrangement which will have to be solved. The second problem is the development of the umbilical cable, (see Fig. III.8), to connect electrical, gas and water services to the target. This cable would be at least 20 cm in diameter and 10 m long and there might be some difficulty insulating it. The cost estimates on the umbilical, the cooling systems and the HT power supply reflect some uncertainty which can only be resolved by engineering studies.



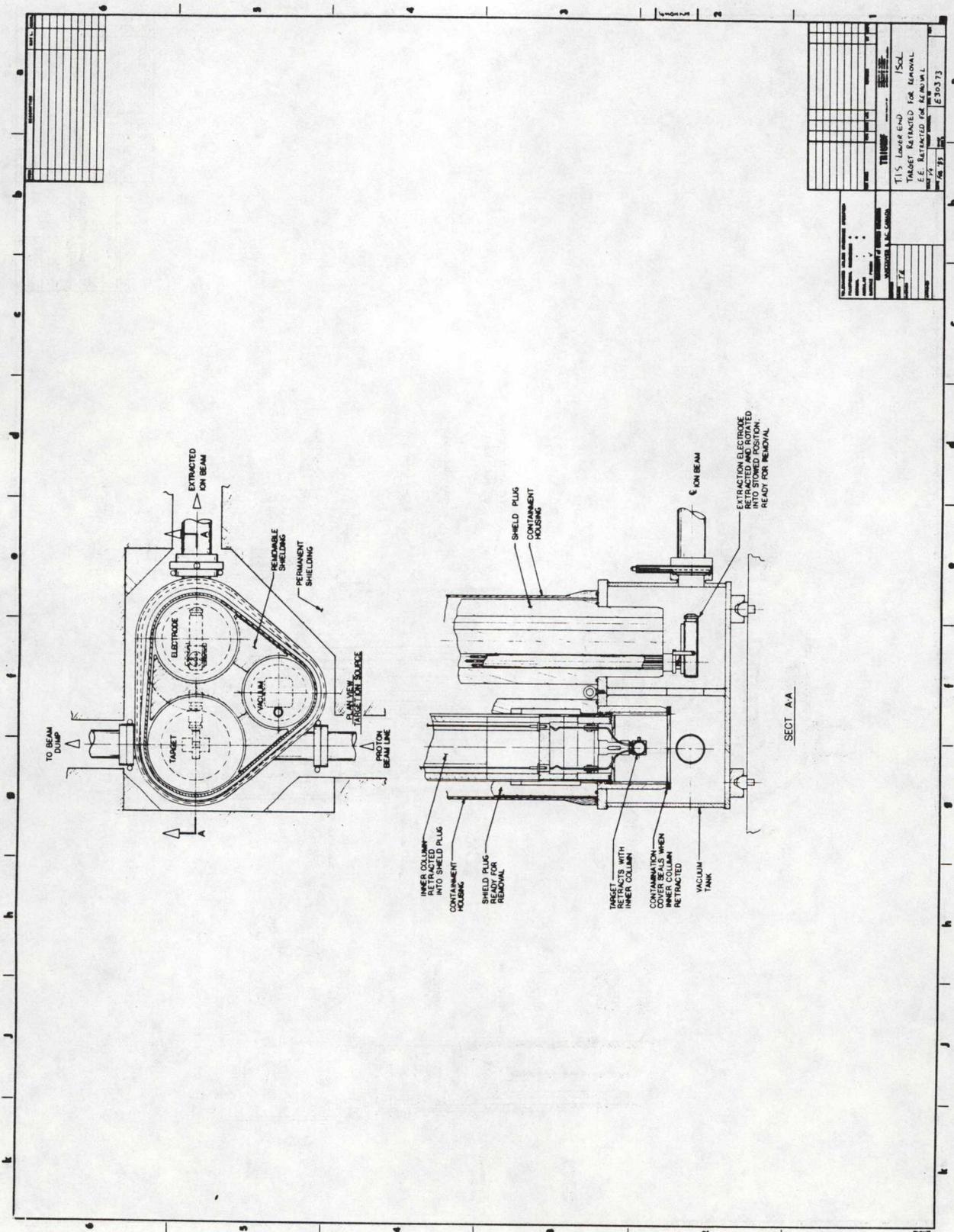
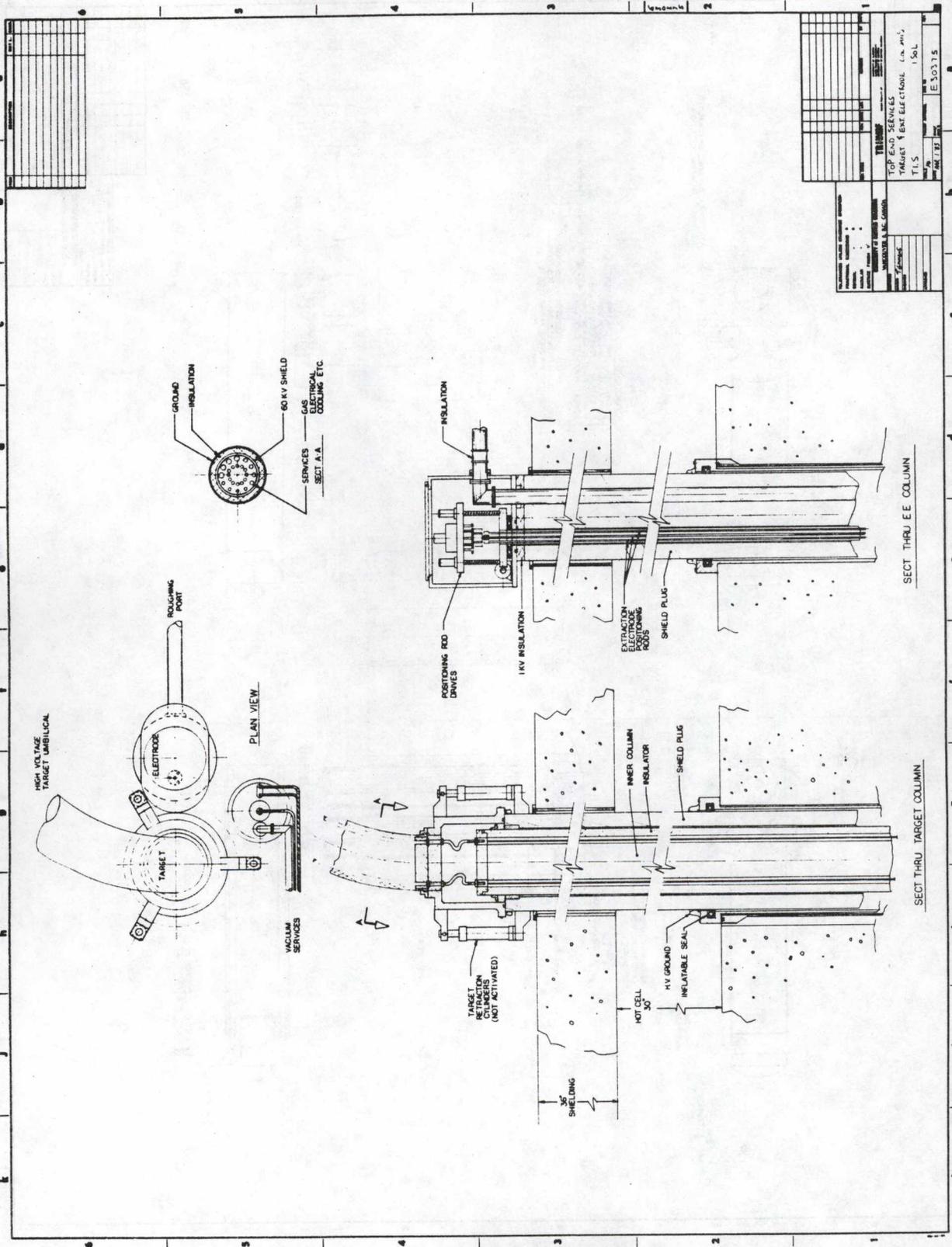


Fig. III.7. Bottom of TIS and EE columns with EE ready for extraction and TIS in upper position.



TOP END SERVICES	DATE	BY
TARGET & EXT ELECTRODE	1.2.61	PH
T.I.S.	1.5.61	PH
E 50375		

Fig. III.8. Top end of TIS/EE columns indicating service connections.

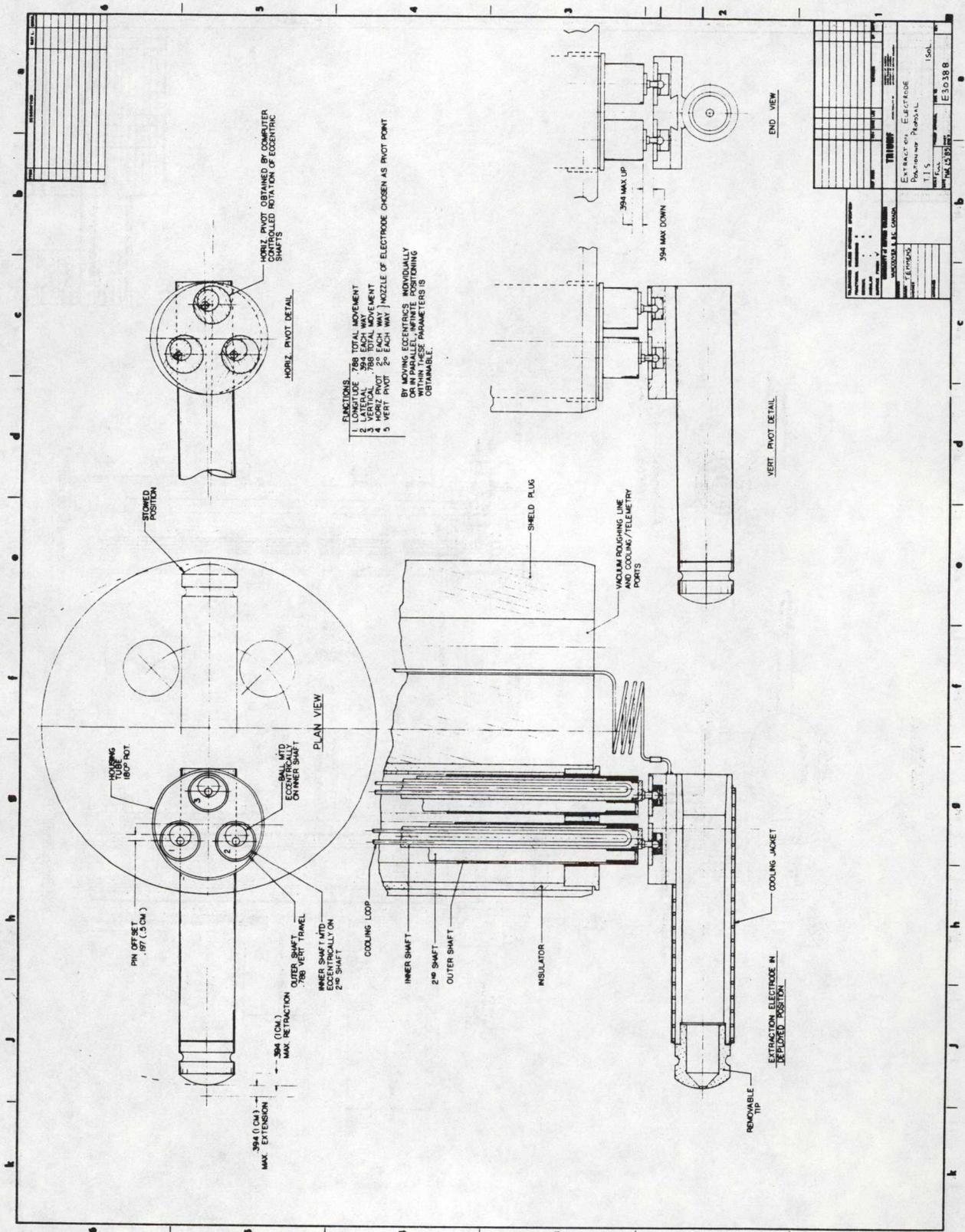


Fig. III.9. A schematic representation of a novel method of accurately positioning (five degrees of freedom) extraction electrode, remotely.

5.4 REMOTE HANDLING AND OPERATIONS

As indicated earlier, remote handling and operation of the TIS, EE and other components of the ISOL facility is absolutely necessary due to the high radiation fields involved, coupled with the specification to allow reasonably fast (~2 h) changes of the TIS and EE. In the previous Section, a general description of the three service columns for the TIS, EE and pumps was presented. Presented in Fig. III.10 is a three-dimensional conceptual view of the remote handling system.

An overhead crane, located in a new containment room above the TIS columns, is used to lift the designated column. TIS and EE columns may be raised sufficiently (~3 m) to bring the components to the level of the remote handling access tunnel (see Figs. III.5, III.8, III.10). A remotely controlled trolley, not unlike other devices designed at TRIUMF and used in the vault of the main cyclotron, with specially designed mechanical tools, may be used to decouple the TIS container (or EE nozzle). These would then be transferred to the indicated storage holes or, if necessary, to the hot cell indicated (Fig. III.10). Similarly, new TIS systems and EE nozzles could be routinely installed and the columns precisely repositioned. Non-routine servicing could be performed directly by personnel, under controlled access, with the columns fully removed in the containment room, or if required by radiation levels, in the hot cell, through the top. Access to the containment room (above TIS) is restricted with the proton beam on 4A, but the hot cell personnel area is accessible. It should be noted that the entire TIS vacuum chamber can be removed vertically for maintenance in the hot cell, if necessary.

The indicated hot cell (see Fig. III.10 and building plans) is intended to be used for many functions. A short list follows:

- a) Tests on used "hot" ion sources, including leak testing, electrical circuit testing, exchange target material.
- b) Salvaging valuable components from used ion sources. Remount old sources to allow reuse of components.
- c) TIS vacuum chamber - decontaminate, repair seal surface.
- d) Repair/replace proton window assembly, TIS vacuum chamber.
- e) Extraction electrode - decontaminate, adjust, repair, test.
- f) Cryo/turbo - decontaminate, repair, replace, dispose.
- g) Switchyard components - decontaminate, dismantle, salvage package for disposal.
- h) Expensive ion beam line components - decontaminate, repair, salvage.
- i) Inexpensive ion beam line components - package for disposal.
- j) Radiochemistry assays, isotope encapsulation.
- k) Preparation of packages of "hot" disposal items for removal from TRIUMF.
- l) Availability of hot cell services for decontamination and repairs of experimental apparatus.

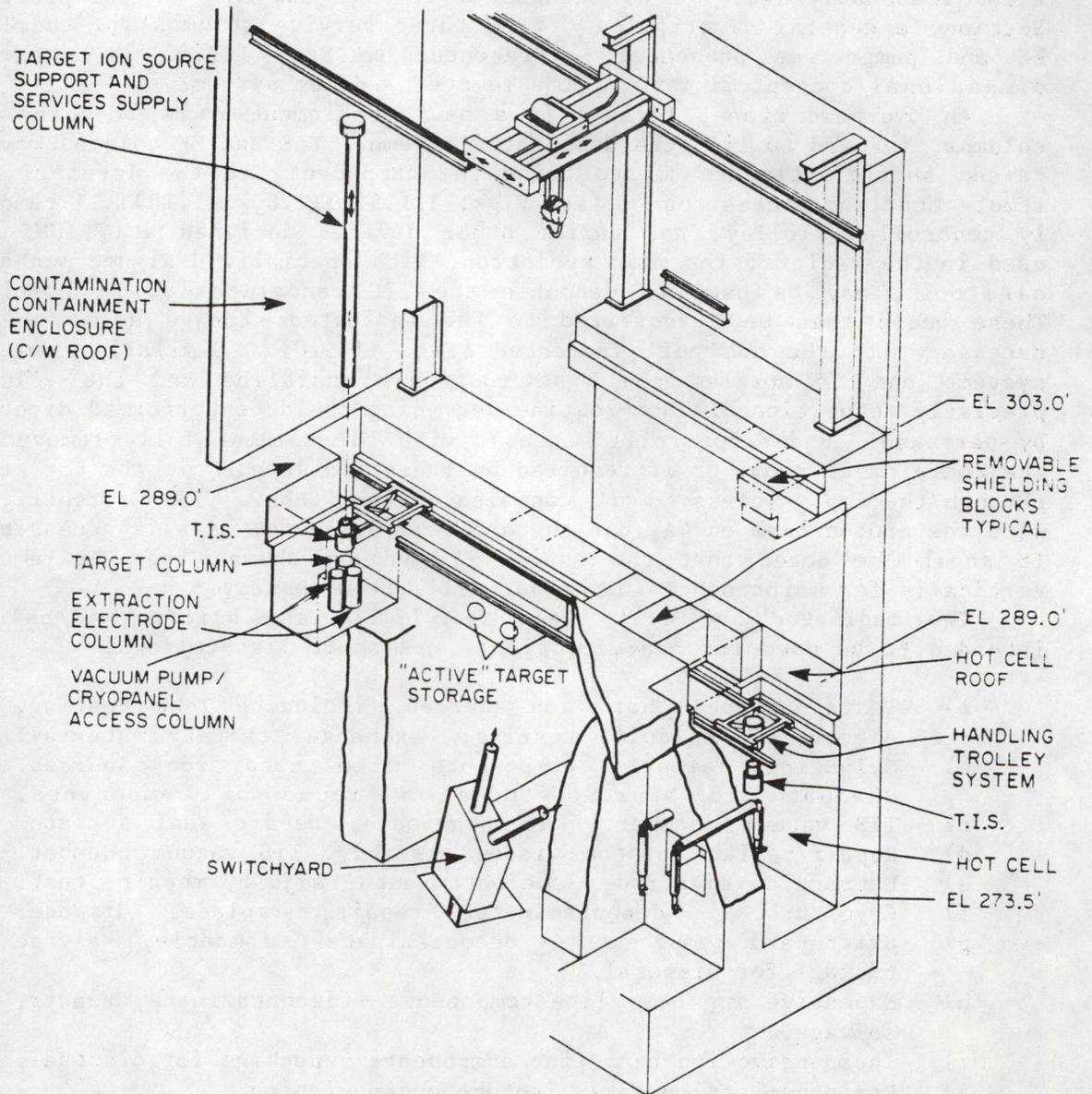


Fig. III.10. A three-dimensional conceptual view of the remote handling area above columns into the new ISOL building.

5.5 THE SEPARATOR SYSTEM AND ITS BEAM OPTICS

This Section summarizes the detailed analysis of the mass separator and its beam optics to be found in an Appendix (TRI-DN-84-68). In order to produce a state-of-the-art isotope separator, high resolution, high beam intensity and high beam purity must be achieved. Once an appropriate dipole magnet has been designed, the bend-plane emittance determines the resolution. Thus, in order to achieve high resolution, the emittance, in general, must be reduced by placing an aperture at a waist that has a sharply peaked intensity distribution. Finally, high purity may be achieved if the system includes elements which correct for aberration (second and higher order optics), which tends to skew and put tails on the intensity distribution.

As a solution to these problems, a separator system has been designed which includes a zero-dispersion clean-up stage (see Fig. III.11). The beam from the ion source passes through the first (dispersive) stage, capable of high resolution in atomic mass. At the intermediate focus, the beam is slit to remove unwanted A's (mostly stable target material). The beam then passes into the dispersion-cancelling stage, which is a mirror image of the first stage about the intermediate focus, and returns the beam to a zero-dispersion (ZD) focus which has a sharply peaked intensity distribution. At this point, a narrow aperture may be placed which trims the emittance while maintaining high transmission intensity (good beam brightness). Then the beam passes into a high dispersion stage (Dipole D3) to a high resolution focus, capable of achieving a mass resolution of up to 1 part in 30,000.

The first stage is made up of two magnetic quadrupoles and one magnetic dipole, and is called the QOD. It was decided to have quadrupoles do the focusing since this facilitates changes in the focal properties. In addition, magnetic quadrupoles were chosen so that they may be moved along the beam axis to accommodate different ion sources, and so that there is no charge build-up, as in the case of electrostatic elements in the vicinity of an intense beam. The dipole has been equipped with pole face windings which introduce a second-order field gradient, and pole edge curvatures. These are sextupole elements which correct for aberration.

This first stage is tuned to give a double-focus 4 m from the exit of the dipole. The resolution varies between 635 for an ion source with a bend plane emittance of 30π mm-mrad (the worst test case) to 3900 for 3π mm-mrad (the best test case). Without aberration correcting elements, the resolution for both emittances is about 200, which may severely reduce the purity. The largest second-order aberration terms at the intermediate focus are the two which propagate the effect of the divergences of the beam on the width of the spot (T_{122} and T_{144}). These two terms are made zero by the proper choice and tuning of correcting elements. It is important that the first stage has high brightness (resolution and transmission) since it may feed both the second stage and the high intensity beam line (see Fig. III.13). The magnet specifications may be found in Table III.2 in the next Section.

The second stage is a mirror image of the first and returns the beam to a second double-focus, which has zero dispersion and is a low current copy of the ion source, except for the effects of aberration. In a symmetrical system, certain aberration terms are zero. In the present case, the ZD focus is not inverted and thus $T_{122} = T_{144} = 0$ at the ZD focus.

Thus, the dominant second order term is the T_{134} term, which propagates the combined effect of the ion source slit length (y-plane size) and the y-plane divergence, on the spot width. Without third order corrections, the ZD waist is about 1 cm short of the ZD focus. For the largest test phase space ($30\pi, 100\pi$), about 92% of the desired beam intensity falls within the bounds set by the ion source emittance. In this case, the effect of aberration is minimal. For the smallest test phase space ($3\pi, 10\pi$), 48% of the desired intensity falls within the ion source image. The losses are mostly due to third order terms, particularly the one which propagates the effect of the bend-plane divergence. For the ($3\pi, 100\pi$) phase space, where the effects of aberration are most pronounced, 38% falls within the ion source image. The beam envelope (half the transverse extent of beam as a function of the propagation distance) for the ($3\pi, 10\pi$) test emittance is given in Fig. III.12.

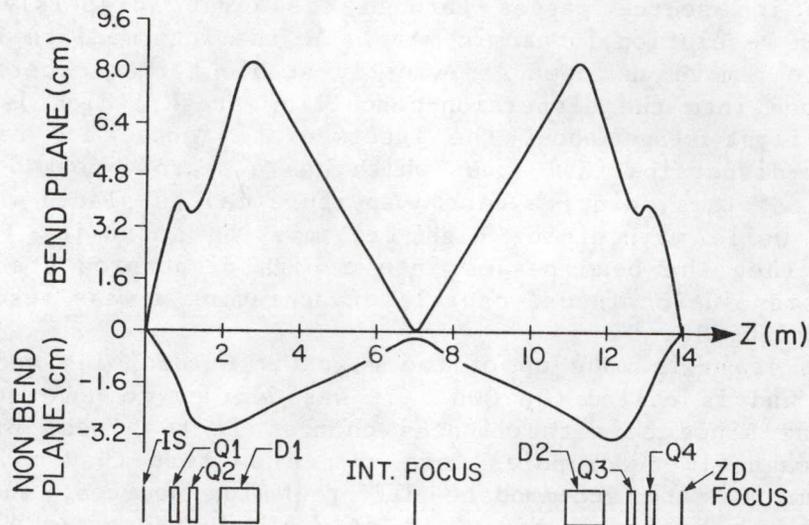


Fig. III.12. Calculated ion beam envelope in the TRIUMF-ISOL as a function of propagation distance for a ($3\pi, 10\pi$) test emittance.

Some preliminary analyses have been performed with a ray-tracing program which allows the introduction of third order correcting elements (such as pole face windings which introduce a third order field gradient). The results indicate that such a correcting element should bring most of the intensity at the ZD focus within the ion source image, even for the smallest emittance.

The effects of misalignments of the ion source and magnetic elements have also been investigated. It was found that misalignments on the order of 2 mm and/or 2 mrad may be easily compensated by adjusting the dipole fields (see TRI-DN-84-68 in Appendix).

Secondary ion beams, within $\pm 10\%$ of the mass of the primary ion beam, are also focused in the switchyard (see Fig. III.11), along a plane inclined 20° to the primary beam path. The primary beam or any of the secondary beams may be sent to the high intensity beam line by means of an

electrostatic bend which may be moved along the focal plane with the secondary beam slit (see Fig. III.12). The secondary beams have approximately the same brightness as the primary beam. This is important since the post-accelerator requires a reasonably good emittance.

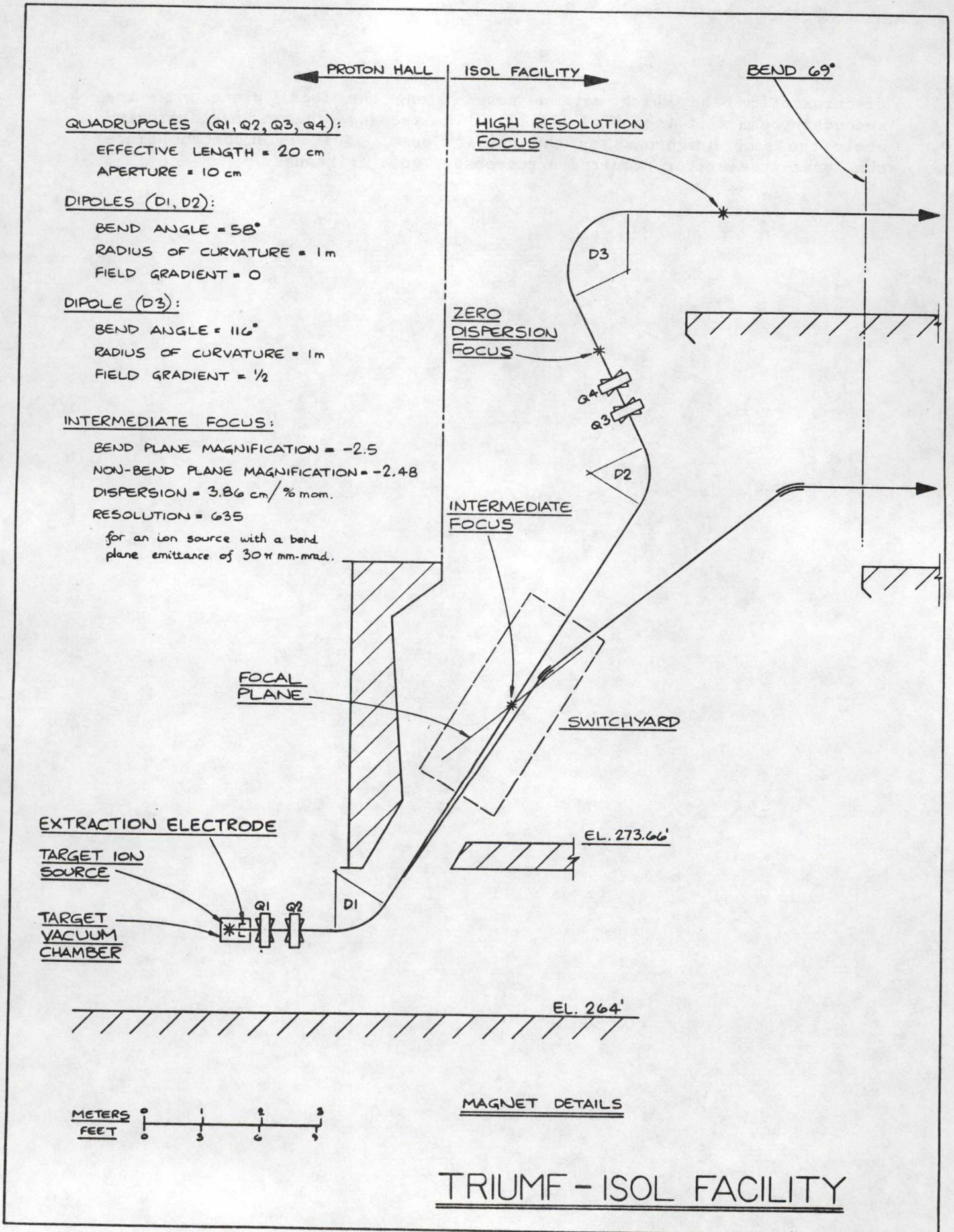


Fig. III.11. A schematic representation of the TRIUMF ISOL separator system including beam optics information.

5.6 ISOL ION BEAM LINE COMPONENTS

PRIMARY TRANSPORT SYSTEM

The ISOL ion beam line layout is shown in Fig. III.11. At the target the radiation levels will be intense and the magnets (D1,Q1,Q2) must be radiation hardened. They will be conservatively designed and protected to avoid maintenance. The quadrupoles and dipole will be placed onto a common stand, mounted on rails so that all three magnets can be withdrawn for servicing into the basement level of the ISOL facility. The cooling water and power connections will be radiation hard and capable of remote connection. This technology has been used at TRIUMF for the triplet downstream of LAT2 (Fig. III.3) and for the combination magnets in the cyclotron vault.

The magnet parameters are listed in Table III.2. We propose to use indirectly cooled Pyrotenax with stainless steel cooling tubes embedded in lead tin solder. This technique is used on the vault combination magnets and at the SIN facility in Switzerland. It avoids the cooling line blockage problem that has been evident with directly cooled magnets both at TRIUMF and at (LAMPF) Los Alamos. The magnets beyond the switchyard probably need not be fully radiation hard. This will be decided at the design stage based on the economics of the coil and design costs. The yoke sizes for the magnets would not be changed.

The dipole correction coils will be made from air cooled pyrotenax conductors fastened between the poles and the vacuum chamber. A study will be made to determine the conductor position and current requirements to achieve the required changes to the field parameters as specified in an Appendix (TRI-DN-84-68). It will not be possible to use the printed circuit board technique as was done at Chalk River (CEF) unless a large board with a ceramic substrate is available.

The high resolution magnet D3 has not been designed in detail. It will bend the beam to the horizontal plane and will be similar to the 58° bends. It also will have correction windings and a field gradient of $n=1/2$. Its cost estimate is an extrapolation from the 58° bends.

The horizontal beam line will be bent horizontally by 69° to bring its axis parallel to the wall. This bend has been costed as an electro-magnet.

At the design stage, a study will be made to see if an electrostatic bend is more economical, and the cheaper version will be chosen.

Focusing elements and bends in the experimental areas have not been specified as a detailed layout has not been finalized.

THE SWITCHYARD

The switchyard is a part of the central section of the vacuum chamber between the first two dipole magnets in the separator system (Fig. III.11) and fulfills several functions in a mass separator. Unwanted beams of separated isotopes are blocked and those chosen for experiments are distributed to the available beam lines. This can best be done in or near the focal plane of the first magnet where the ion beams are spatially well separated. Furthermore, the analysis of the ion beams in the focal plane (in the switchyard) offers a check of the performance of the first part of the separating system. Thus, in the switchyard, the separated ion beams

Table III.2. Magnet Parameters

Quadrupoles Q1, Q2, Q3, Q4

Aperture	10 cm
Effective length	20 cm
Maximum Pole Tip Field	2.5 kG
Conductor	0.25 in. square solid Pyrotenax
# turns/pole	60
Current	105 A
Voltage/magnet	23.7 V
Magnet resistance	0.226 Ω
Cooling	water - indirect
Flow	0.4 IEPM/coil
Pressure drop	5 psi/coil
Constant temperature rise	5°C
Conductor temperature rise	$\approx 25^\circ\text{C}$
Overall width	55.9 cm
Overall height	55.9 cm
Overall length	31.8 cm
Magnet weight	≈ 182 kg

Dipoles D1, D2Parameters

Maximum field	5.6 kG
Gap (horizontal)	12 cm
Bend angle	58°
Nominal bend radius	1 m
Conductor	0.53 in. square solid Pyrotenax
Coil array	12 \times 14 = 160 turns/coil
Current	175 A
Resistance/coil	0.31 Ω
Magnet voltage	108 V
Magnet power	20 kW approx.
Conductor weight	395 kg/coil
Steel weight	6374 kg

High Resolution Dipole D3

Bend angle	116°
Bend radius	1 m
Gap	12 cm
1st order gradient	$n = 1/2$

are either blocked (unwanted beams), distributed (wanted beams), or analyzed (intensity, shape).

The design of the switchyard is closely connected to the design parameters of the separating system. Its dimensions are derived from the tilt of the focal plane of the first magnet and the range of masses which one wants to accept for simultaneous use with the primary ion beam.

In the present separator system, we intend to serve two beam lines, either separately or simultaneously, with ion beams: the "primary" beam line, which leads to the high resolution stage of the separator, and a "secondary" beam line, which serves the high intensity area. The tilt of the focal plane in the bend plane of the first magnet is 20° . The separating system is laid out so that in the switchyard, ion beams with masses 10% greater or lower than the mass of the isotope in the primary beam line are focused. Thus, the minimum length of the switchyard is roughly 1.5 m and its minimum width is about 40 cm.

The selection of the ion beams that are fed into the two beam lines is done by slits. The slits are movable along a plane parallel to the focal plane about $1\frac{1}{2}$ cm beyond it. The primary beam (which is sent to the high resolution beam line) is selected by a "fixed" slit. Although the slit is fixed, in principle, at an optimum position given by the design parameters of the separator system, adjustment of its position for the initial setup is desirable. The primary beam travels without deflection towards the high resolution system. The slit for selecting the secondary beam (or the high intensity beam) should travel on both sides of the fixed slit of the primary beam. Since the secondary beam is deflected into a second beam line, the translation of the slit will be correlated with the movement of an electrostatic deflector. For optimum transmission into the second beam line, the deflector's orientation will be adjustable. Both slits will have variable openings (up to 30 mm) and will be electrically floated in order to control cut-offs of the ion beams. A conceptual layout of the switchyard is shown in Fig. III.13.

The beam analysis, i.e. the measurement of the intensity and profile of the ion beams, might be done by a system of scanners and Faraday cups moving along the focal plane. The requirements for the beam analysis equipment is a function of the beam intensity expected. Since the separator is laid out as a high current machine, beam currents in the switchyard might reach the mA level for stable species. On the other hand, radioactive beams with intensities only up to 10^{12} s are delivered, and it is desirable to measure beam intensities down to the lowest level possible. At the present stage, we are considering a combination of conventional Faraday cups and wire scanners for high and medium intensity beams. The conventional scanner can be a single or multiple pin array (wire matrix), which should be able to scan all or part of the focal plane. Also, the Faraday cup must be movable along the entire focal plane. All components that require a motion will be driven by a remotely controlled device suitable for performance in a high radiation environment.

The switchyard is a major item and will require considerable design effort to accommodate the seven variable position devices requested. The chamber is mounted vertically and the drives will be mounted at an angle to the vertical. Ball screw and chain drives operated from ferrofluidic feedthroughs will be used. The drive motors, either synchronous or stepping, will be operated via a computer control system with position feedback outside of the chamber. Access to the chamber will be limited due to

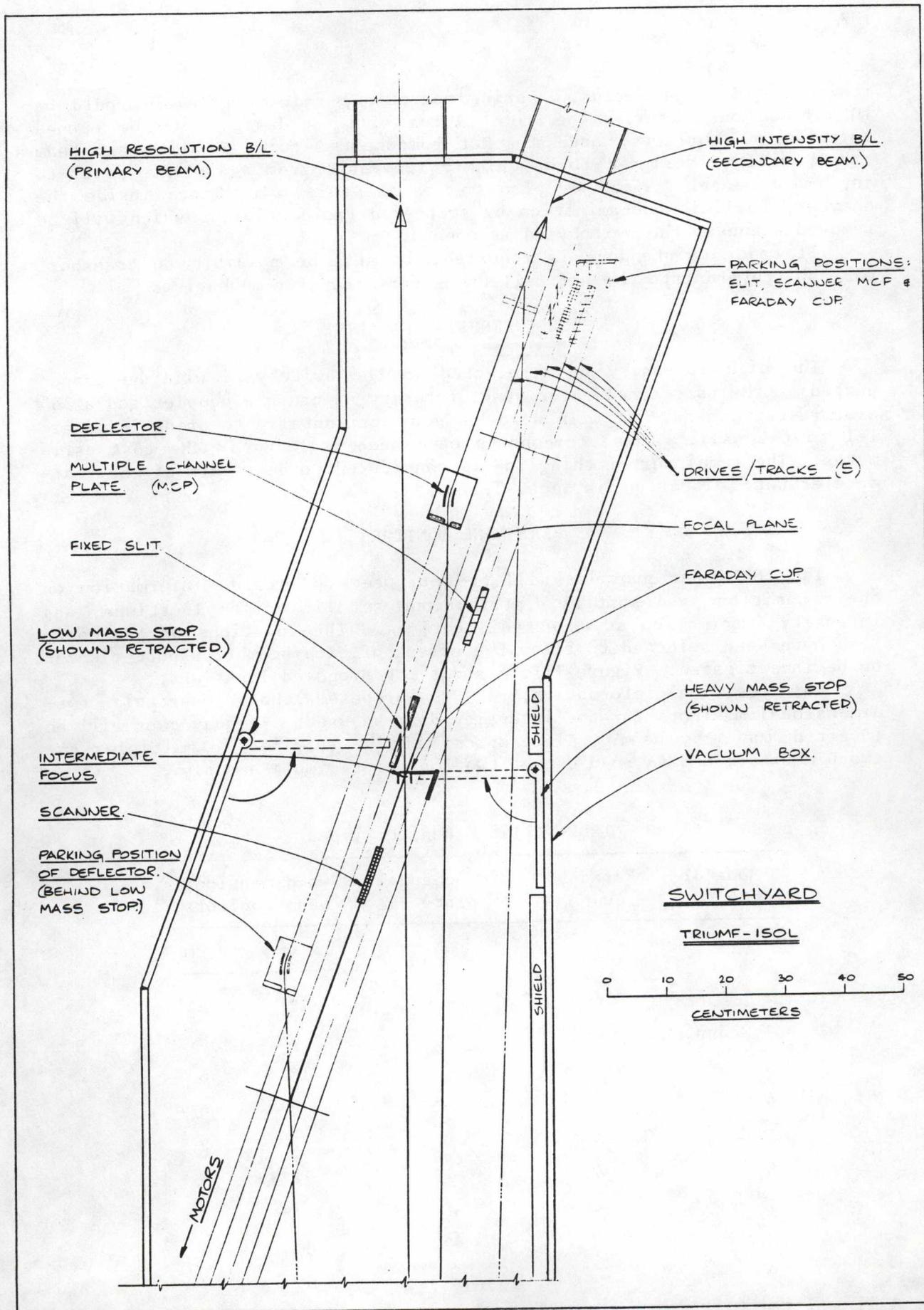


Fig. III.13 The ISOL switchyard

residual radiation fields. During operation, radiation levels could be 10 R/h at one meter. The side plates will be designed to be opened quickly to allow easy access. Hot components, such as slits and beam stops, will be designed to be quickly removable from a distance prior to any maintenance. Also, we plan to install throwaway liners inside the chamber, to limit contamination by sputtered radioactivity, which will be removed whenever the switchyard is opened.

If major maintenance is required, it will be possible to transport the switchyard into the hot cell using some transfer mechanisms.

HIGH INTENSITY BEAM LINE

The high intensity beam selected in the switchyard will be transported to the post-accelerator via a focusing quadrupole doublet and a 38° electrostatic bend. It will also be bent horizontally to bring it parallel to the wall. These components have been included in the cost estimates. The remainder of this line is considered to be a part of the post-accelerator, discussed in Sect. 5.11.

BEAM LINE MONITORS

The ISOL beam profiles will be monitored to provide information on their positions and spatial distributions at all monitor locations, and intensity information at selected locations. The locations of the monitors have been selected to allow the effect of each beam transport element to be investigated. Figure III.14 shows the proposed locations.

For position information, it is proposed that insertable two-dimensional monitors for the intensity data be used. Faraday cups will be inserted into the beam. Electronics will be supplied to multiplex the two-D monitors and to read out at two locations simultaneously.

Table III.3. Monitor Types

Monitor No.*	Faraday cup	Microchannel plate	Two-dimensional beam monitors	
			x cm	y cm
1	✓	-	12	6
2 Scanning	✓	-	2	6
3	✓	-	12	6
4	✓	-	8	6
5	✓	-	2	2
6	✓	-	12	6
7	-	✓	2	2
8	✓	-	12	6
9	-	-	12	6

*See Fig. III.14.

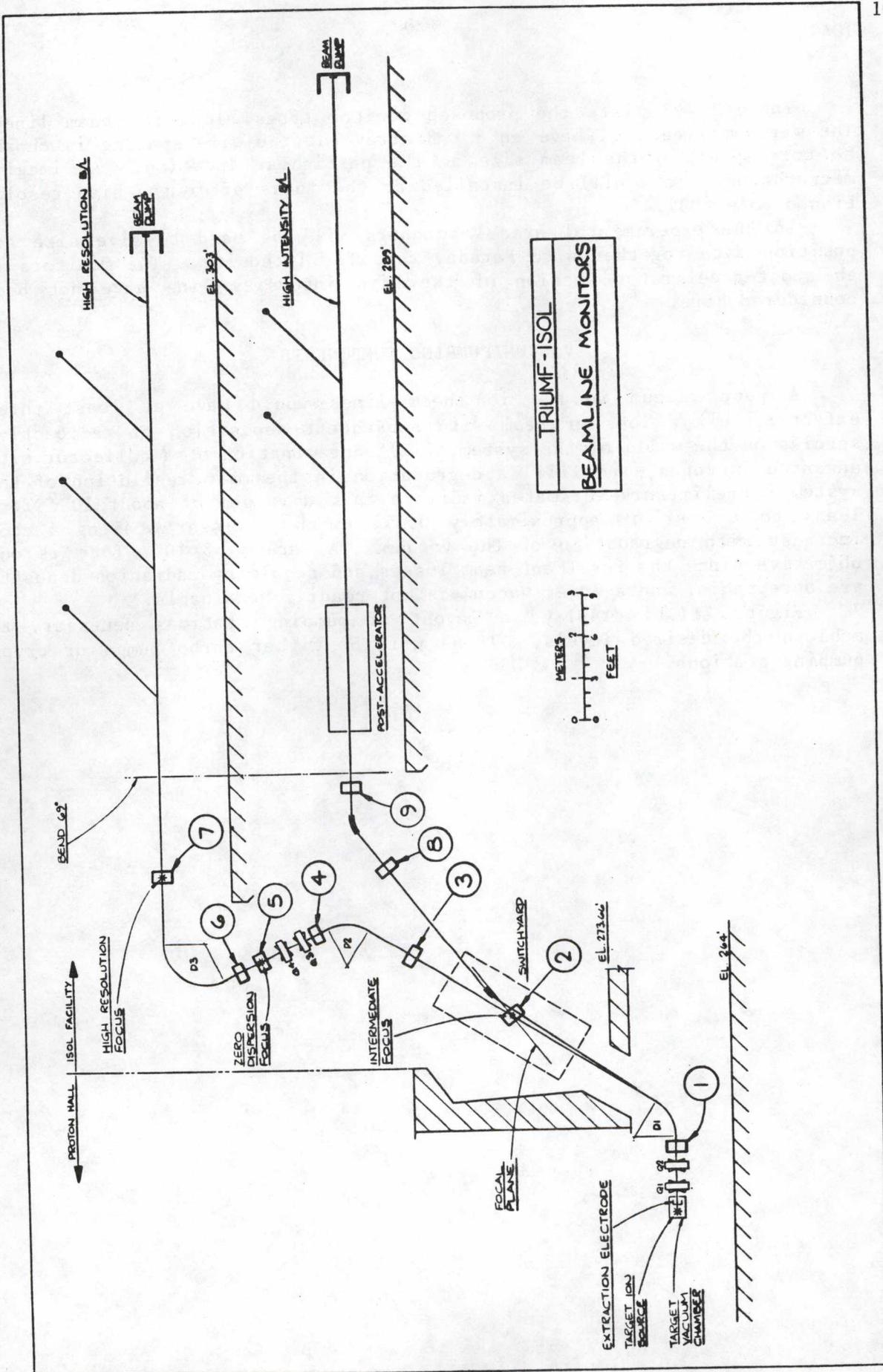


Fig. III.14. Layout of beam monitors

Fig. 14. Layout of beam monitors

Table III.3 lists the proposed monitor types along the beam lines. The wire matrices all have an 8×8 array but the wire spacing is chosen to correspond to the beam size at the particular location. An imaging microchannel plate will be installed at the focus after the high resolution dipole (D3).

In the experimental area V-scanners will be used to give size and position data together with Faraday cups for intensity. The monitors in the post-accelerator section of the high intensity line have not been considered here.

VACUUM/PUMPING COMPONENTS

A poor vacuum in the ion beam lines would have at least three effects: (i) a loss of beam with subsequent deposition of radioactive species on the walls of the system, (ii) contamination of a collector with unwanted isotopes, and (iii) a degradation in the main resolution of the system. Preliminary estimates indicate that a vacuum of about 10^{-7} Torr leads to a loss of approximately 0.15%, with a linear scaling factor increase with degradation of the vacuum. A vacuum of 10^{-7} Torr is our objective since the resultant beam losses and resulting radiation deposits are acceptable, and a lower vacuum is not readily attainable.

Figure III.15 displays a layout of pumping stations necessary to achieve the desired levels. These will be either turbo pumps or cryo-pumping stations.

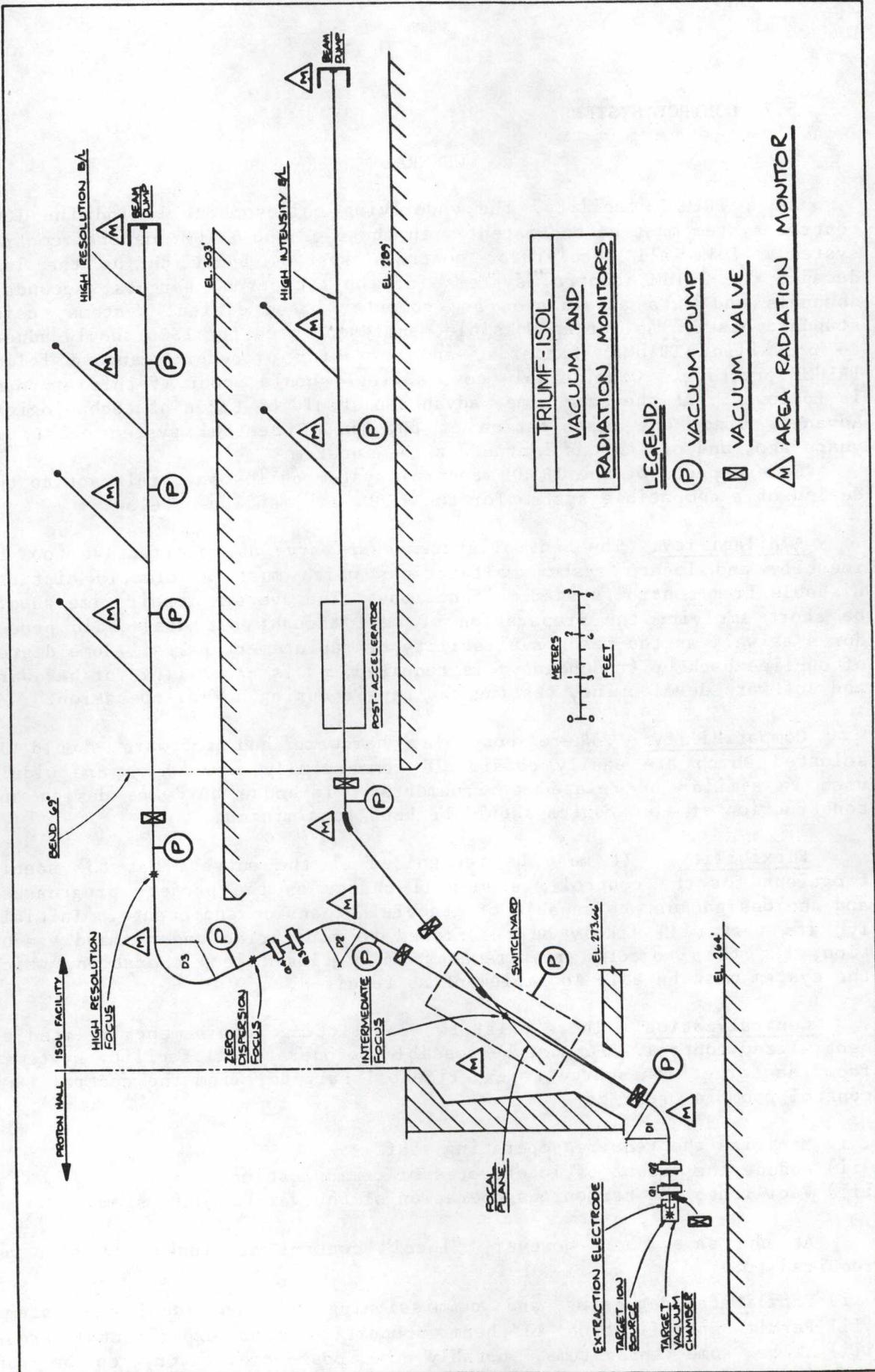


Fig. III.15. Layout of vacuum and radiation monitors on the ISOL beam lines

5.7 CONTROL SYSTEMS

GENERAL

As a TRIUMF facility, the underlying philosophies behind the ISOL control system must be consistent with those of the TRIUMF central control system. Like all accelerator controls systems built during the last decade, the TRIUMF control systems for the cyclotron, targets, secondary channels and data acquisition are computer based digital systems, using standard buses. As far as possible, equipment used for ISOL should adhere to prevailing TRIUMF standards, and operating procedures should follow TRIUMF practice. Considerable cost savings should occur if this approach is followed. At the same time, advantage should be taken of technological advances since the installation of the TRIUMF central system nearly 15 years ago, and of lessons learned in the interim.

Some aspects of the TRIUMF control system philosophy, relevant to the design of a compatible system for the ISOL, are mentioned below.

Availability: The control system must serve as an effective tool to identify and locate system malfunctions which must be clearly distinguishable from control system malfunctions. The average repair time should be short implying the preparation of well thought out diagnostic procedures as well as the ready availability of replacement parts. Some degree of on-line back up (redundancy) is required, as is capability for hardware and software development, testing and repair during normal operation.

Compatibility: Where possible, hardware and software should be selected which are easily obtainable commercially, and which are widely used in similar or related environments. In-house hardware design and construction of electronics should be kept to a minimum.

Flexibility: It must be recognized at the outset that the specifications for the control system will change as the project progresses, and the design must be capable of graceful expansion and change. Initially, its task will likely be restricted to monitoring and command execution, but the projected requirements imply closed loop operation, which the system must be able to implement as required.

Centralization: There exist two conflicting requirements related to centralized control. It must be possible to operate all facility systems, from the target ion source to experimental targets, from the central ISOL control room in order to:

- i) Minimize the required operating staff
- ii) Reduce the amount of interprocessor communication
- iii) Facilitate the harmonious operation of the various subsystems

At the same time, however, "local" control stations will also be required to:

- i) Facilitate debugging and commissioning of individual subsystems
- ii) Permit specification of beam properties from experimental areas
- iii) Allow some subsystems, notably the post-accelerator, to be run independently.

The system design must accommodate both sets of requirements.

Safety: The personnel safety system must operate independently of the central control system, and use techniques that minimize the risk of program corruption. A proposal for such a system is outlined elsewhere in this report.

The objectives outlined above can all be achieved most effectively by using a computer based system compatible with TRIUMF practice and experience. The additional requirement of close coupling to the TRIUMF central control and safety systems also implies that approach. The application of these considerations should be apparent in the discussion which follows.

SYSTEM CONFIGURATION

The system configuration shown in Fig. III.16 is only representative of a large number of possible valid configurations. The final arrangement can be expected to differ markedly in detail, but is likely to resemble the following proposal in its main features. It is even more premature to select vendors or to specify a data bus at this time, because market conditions and equipment capabilities change very quickly in this field. Mention of specific types of equipment is made simply to give an indication of the capabilities required and provide a basis on which to make cost estimates. Such mention should not be interpreted as indicating that the named equipment has been chosen. Opportunity for competitive bidding for the various parts of the system should be provided.

A byte serial, optical, CAMAC Branch Hyway system has been used for the purposes of cost estimation. Although many other data bus systems are possible, this system was chosen because of the large number of CAMAC crates it can accommodate, the built-in immunity of the system to a failure in a single crate (loop collapse), and the immunity to EMI noise provided by the exclusive use of fibre optic transmission systems.

The CAMAC specification permits multiple sources of intelligence at the crate level by using crate controllers incorporating an 'auxiliary controller bus' (ACB). The proposal makes extensive use of this possibility by placing microprocessors at the crate level, and the estimated cost per crate includes this possibility.

A number of CAMAC compatible microprocessor modules are commercially available, with varying levels of complexity and software support. The one chosen for use at ISOL should be software compatible with all other levels of the system.

At the next level, the proposed system shows a small number of 32 bit microcomputers. These would be located in the central control room area, and each would be responsible for a well defined part of the ISOL facility or a well defined task. Their task would be to coordinate all activities relating to a subsystem group, route messages, and provide local autonomy at the subsystem level for commissioning and maintenance. A more fully configured microVAX computer is proposed for the top level. It would coordinate the activities of all subsystems, download programs and data to lower level systems as required, and perform complex numerical computations. Isotope selection, for example, would be coordinated by the main computer.

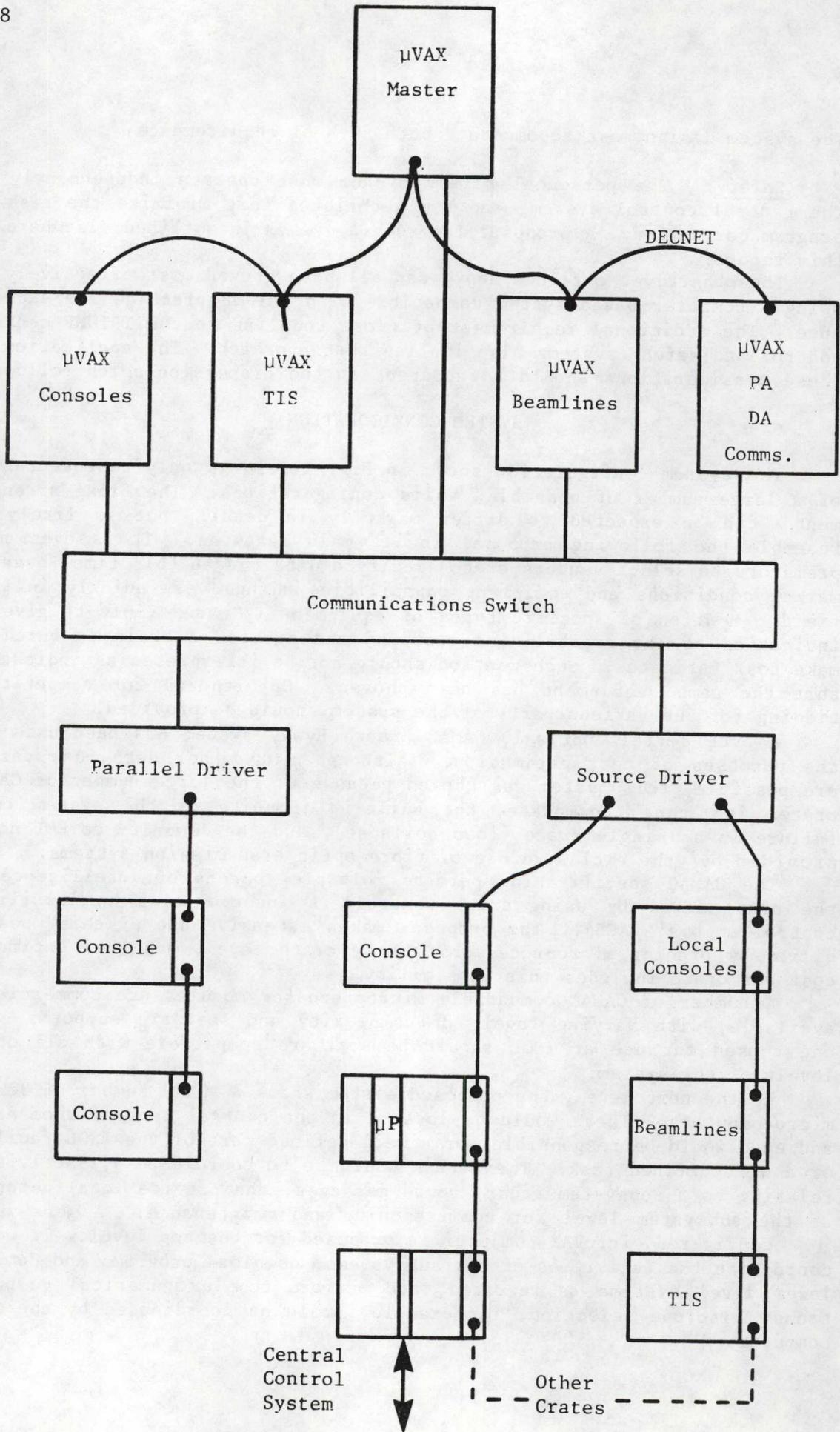


Fig. III.16. Possible configuration for ISOL

Software: It is to be anticipated that the major control system effort and expense will be for software development. To minimize these costs, the vendor's operating system should provide the majority of system services required. One serious concern with the use of the typical vendor supplied operating system is its inherent slowness. However, LAMPF now has experience with VMS (the VAX operating system supplied by DEC) in a controls application and VAX ELAN, available for real time applications on the microVAX, has been installed in the TRIUMF central control room. Thorough design and documentation procedures must be established and enforced at the outset. System programming should be restricted to the provision of a library of subroutines and utilities, carefully specified at the earliest stages of the project, which will permit applications programs to be written easily in a familiar, high level language. Communications protocols between the various levels of intelligence should be transparent to the applications programmer.

DEVICE INTERFACING

Standard techniques are well established at TRIUMF for the interfacing and control of power supplies, vacuum equipment and motor control system, and no special problems are anticipated in controlling similar devices in an ISOL.

Two areas requiring special attention will be beam diagnostics and the target ion source.

Beam Diagnostics: Beam diagnostics is a costly item, but the costs in operating efficiency can be great if care is not taken to insure detailed understanding of beam behaviour. In general, as many monitors as are consistent with space constraints (one per steering or focusing group) should be the objective. Beam profile and SEM monitors can be similar to those used at TRIUMF, although requirements differ for highly ionized beams of heavy isotopes.

Target Ion Source: The ISOL target ion source is of comparable complexity to one of the TRIUMF ion sources, although involving many new developments. Over 50 analogue readbacks, 16 set points, 200 digital status readbacks, gas handling systems, as well as a complex motor control system for the extraction electrode are required. Two CAMAC crates will be needed, and space for two racks of controls and interlock equipment should be provided. A facility for fast logging of parameters in a ring memory for diagnostic purposes in case of target ion source failure may be required. Some control equipment will be floating at 60 kV, and is subject to potential damage due to sparking. TRIUMF has had considerable experience in dealing with this problem in the two 300 kV ion sources, and is at present dealing with an even greater sparking hazard, given the 70 joules of energy stored in the third ion source. Very careful grounding and isolation strategies must be followed, but experience at TRIUMF indicates that these problems can be solved.

CENTRAL CONTROL ROOM

The main control room is the focus of operational activity. It is essential that it be large enough to house comfortably the main console

and associated equipment, and to provide an efficient working environment for the operation crew. For this reason, and to minimize noise in the control room, the control system computers should be placed in a separate room adjacent to the main control room which houses the control consoles. Both rooms should have computer (raised) flooring. The computer room must be equipped with a substantial air conditioning system as the proposed equipment dissipates approximately 200,000 BTU/h. "Clean" electrical services will also be required, possibly on no-break power. TRIUMF costs are approximately \$2.5K/KVA of no-break power.

Nearby space must also be provided to house control system spare parts at the CAMAC module and controller level, as well as test facilities for maintenance and development of both hardware and software.

The total space provided for these three rooms should be 800-1000 ft². In addition, it is extremely important that office space for controls personnel be located as closely as possible to the main control and computer rooms, and to the offices (if any) of the operations group. Smooth operation of the accelerators requires a close relationship between operations and controls personnel, which is best encouraged by physical proximity.

5.8 RADIATION SAFETY

The success of the ISOL facility in meeting its full potential will to some extent depend on how well one can deal with the substantial radiation hazards. There is a considerable experience at TRIUMF in dealing with both the direct radiation from intense proton beams and the hazard from the induced radioactivity produced by these beams. However, in the ISOL facility, there will be the new aspect of radioactive ion beams and the possibility of depositing large amounts of radioactivity on beam line components.

POLICIES

Any facility located at TRIUMF is subject to a variety of constraints in the design of its radiation protection program. These are imposed both by external agencies, such as the Atomic Energy Control Board (AECB) through its regulations and licencing authority, and by an internal safety organization. The TRIUMF Safety Advisory Committee (TSAC) scrutinizes all proposals for new facilities before they may be submitted to the AECB for approval.

The design of any procedures for handling radioactivity or for working in the high radiation areas must take these constraints into account. First among these is the AECB requirement that the exposure to ionizing radiation of any individual and the collective dose shall be kept as low as reasonably achievable. This is known as the ALARA principle and is accepted policy in most western countries. A maximum individual annual dose of 50 mSv* is also imposed by the AECB. In order to show compliance with the ALARA principle, and to reserve a personnel exposure pool for contingencies or unavoidable non-recurring procedures, TSAC has set an internal action level of 10 mSv annual dose which may only be exceeded under special circumstances. It has been the experience at TRIUMF that if personnel are required to keep their dose below 0.5 mSv a day, this ensures that the annual action level is not exceeded. A dose of 0.5 mSv per day should therefore be taken as a guide to designing any procedures for the handling of radioactive material or for working in high radiation areas.

In addition, the AECB imposes special restrictions through its licences. Although the radioactive beams facility will most likely be initially licenced as a separate facility until commissioned, there is no reason to expect that the licencing constraints will be different from those imposed on TRIUMF as a whole.

From a practical point of view, the most restrictive constraints are those that set the maximum dose-rates in unsupervised and uncontrolled areas (i.e., those without boundary definition or information signs):

- | | |
|-----------------------------------|--|
| i) Low occupancy areas (<10%) | 25 μ Sv/h averaged over one day or
10 μ Sv/h averaged over one month. |
| ii) Medium occupancy areas (<30%) | 6 μ Sv/h averaged over one day or
2.5 μ Sv/h averaged over one month. |
| iii) High occupancy areas (>30%) | 2.5 μ Sv/h averaged over one day or
1.0 μ Sv/h averaged over one month. |

*1 mSv = 100 mrem (old units).

The environmental impact is also of some concern both in terms of the direct radiation and the possibility of radioactive emissions. The AECB also has set limits on the operating levels at the TRIUMF boundary in terms of the integrated dose at the exclusion area fence. This dose is limited to less than 2.5 mSv over any three month-period and to less than 5.0 mSv per year. Radioactive emissions are restricted in terms of the annual dose to the "critical group", i.e. the nearest population which is likely to be exposed. The annual dose to this group must be less than 0.05 mSv. The report "Derived Release Limits for the TRIUMF Site" outlines a method for calculating the environmental impact of such emissions.

ESTIMATES OF DEPOSITED ACTIVITY LEVELS

The activity deposited by the ion beam has been estimated for a 100 g/cm² target of ²³⁸U and a proton beam current of 100 μA. This is considered to be the worst case situation because of the broad range of nuclides which will be produced in the target. In general, lighter mass targets will produce lower overall levels of activity.

Radiation levels due to deposition from the radioactive ion beams will depend largely on how well the beam transport system and separator are tuned. Because of the narrower range of isobars present and the smaller number of long-lived radionuclides, light mass ion beams will deposit less long-lived radioactivity than postulated in the worst case. Activity beyond the switchyard will arise from ion beam losses due to scattering from the residual gas molecules in the beam pipe and from diffusion of material from the switchyard, slits and ion beam dumps. In order to maintain high transmission and reduce the deposited radioactivity levels, it will be necessary to maintain a vacuum of 10⁻⁷ Torr.

Although the high resolution beam line can accept the full output of the separator at a particular mass, it is expected that this line will generally be operated at considerably reduced ion currents because of experimental requirements and the desire to limit the contamination of the line. The excess ion beam current will be deposited on slits.

Table III.4. Estimates of Deposited Radioactivity

Target ion source	200 TBq	(5000 Ci)
Extraction electrode	200 TBq	(5000 Ci)
Target chamber	40 TBq	(1000 Ci)
TIS to first bend	4 TBq/m	(100 Ci/m)
First bend to switchyard	2 TBq/m	(50 Ci/m)
Switchyard	200 ~ 400 GBq/m ²	(5 ~ 10 Ci/m ²)
High current beam line	200 MBq/m	(5 mCi/m)
Slits S-3	700 GBq max	(20 Ci)
Dipole D-3	40 KBq/m	(1 μCi)
Slits S-4	100 MBq	(3 mCi)
High resolution beam line	40 KBq/m	(1 μCi/m)
High resolution beam dump	100 MBq	(3 mCi)
High current target or beam dump	700 GBq	(20 Ci)
Maximum local due to failure	700 GBq	(20 Ci)

Estimates for the worst case situation of the deposited activity at various points in the TIS and in the ion beam transport system are presented in Table III.4. It was further assumed that the average production cross section per radionuclide will be approximately 10 mb and that the TIS extraction efficiency for the desired radionuclide will be 20%. Other radionuclides of the same mass were assumed to increase the overall yield by a factor of two.

These estimates assume saturation values for all activities. In fact, only those activities with half-lives shorter than the running time will build up to an appreciable fraction of the saturation levels. The dose-rates calculated from these estimates assuming Co^{60} -like activity are shown in Fig. III.17.

INTERLOCKS

Those areas in which chronic exposure rates are above $25 \mu\text{Sv/h}$ will be designated as exclusion areas controlled by the interlock system. The design of the safety interlock system will be based on the same philosophy used in both the TRIUMF 500 MeV and the 42 MeV facilities. In both cases, the Safety System is separate from the Control System. Interlock signals to and from the Safety System must be in the form of isolated contact closures from remote relays, limit switches, position switches, etc. All signals from devices must be taken in a fail-safe manner. A contact closure is used to imply a device is off or in the "safe" condition. Cable disconnects, shorts to ground or a power failure in the device then imply it is on or "not safe" and the Safety System acts accordingly. Critical devices require redundant signals, eg. "in" and "not out". All safety related wiring must be separate from the wiring for the Control System. The control logic for the Safety System will be resident in Erasable Programmable Read Only Memory (EPROM) and executed by a microprocessor located in a CAMAC system. This allows simple re-programming from time to time without, at the same time, allowing unauthorized tampering with the interlock logic.

Local microprocessor-based Area Safety Units near the entrance to each interlocked area will perform the logic for the access control and communicate with the central Safety System. For access to any of the areas where the radiation fields are determined primarily by the proton beam, there must be three devices in place, each of which will independently prevent the proton beam from entering the area. For secondary channels, such as the radioactive beam lines in the ISOL, two independent devices are needed. The Safety System will disable these devices once access has been permitted.

Five interlock areas have been identified:

- (i) Hot cell area/containment room
- (ii) Switchyard area
- (iii) High intensity line, front end
- (iv) Two low intensity experimental areas
- (v) High intensity experimental area

Each of these areas will require its own lock-up chain consisting of a series of watchman stations laid out in a predetermined search pattern. For the first three areas, the watchman stations will also incorporate emergency "panic" buttons which will shut down the proton beam in the

event of a search failure. Each door accessing these areas will require a set of microswitches for status information as well as emergency break-bolts to allow emergency egress.

RADIATION MONITORING

Many of the radiation monitoring techniques used now at TRIUMF will find direct application at the radioactive beams facility. However, there will be some unique problems associated with the handling of the large quantities of radioactivity in the beams. Beam either lost or intentionally scraped will manifest itself as local deposits of radioactivity which may build up substantial radiation fields (Fig III.17). The time constant which governs the buildup is largely determined by the half-life of the radioactivity involved and therefore will be highly variable. This radioactivity will pose a major hazard due to the direct radiation fields. In addition, there is the possibility of spreading loose radioactivity (which may be ingested) during servicing.

Monitors to detect the buildup of radioactivity in the ion transport system will be based on the TRIUMF beamspill monitor design. These monitors consist of 50 mm diameter NE102 plastic scintillators mounted on photomultiplier tubes. The anode current is taken as a measure of the ambient radiation field. This design yields a large dynamic range which allows these monitors to be used both as 'beamspill' monitors and as area monitors during access. The range switching is accomplished through the automatic adjustment of the PMT bias voltage by the access control system. For operating fields in excess of ~ 10 Gy/h, the plastic scintillators suffer excessive radiation damage and a simpler air ionization chamber design can be used. The present concept would have approximately 12 of these "spill" monitors deployed along the ion transport system (Fig. III.15).

Although it is expected that few neutrons (except the short-lived delayed neutrons from some nuclides) will be generated along the ion transport system or any of the target stations, there will need to be some monitoring of the neutron leakage through the shielding from both the TIS location and from the 500 MeV cyclotron. Three neutron monitors of the Anderson-Braun type would be sufficient to monitor the neutron fields in the areas normally occupied.

The monitoring of the exhausts from the ventilation systems will be accomplished using the present design of the TRIUMF stack monitors. It is envisioned that there will be at least two separate ventilation systems. One system for the proton beamline will exhaust activity induced by the high neutron flux generated at the TIS. This activity will be largely composed of short-lived β^+ emitters and ^{41}Ar , similar to that generated in the 500 MeV cyclotron vault and high intensity beamlines. The other system will ventilate the front end of the ion beam separator and the hot cell. Both systems will require HEPA filtration, the latter will also require charcoal filtration with a "bag in-bag out" system for handling what will possibly be highly contaminated filters.

Due to the potentially large amounts of loose activity deposited in the ion beam line components, it will be necessary to monitor the air activity in the experimental areas on a continuous basis and in the hot cell area during hot cell operations. Such monitoring is, at present, not done elsewhere on the TRIUMF site, and will require the acquisition or design of new monitors.

Both the ion source and the post-accelerator will use high voltage power supplies which may be sources of X-radiation, especially when not operating under optimum conditions. At least three X-ray monitors will have to be installed.

In addition to the fixed area and other monitors described previously, there will be a need for contamination monitoring of personnel and equipment. At least one or possibly two hand and foot monitors (depending on the final layout) will be required for the entrance to the high radiation areas. In addition, a variety of hand held monitors and survey meters will have to be permanently available for radiation surveys and contamination monitoring. A whole body scanner may also be necessary.

All the fixed monitoring equipment should have remote readouts in the control room. Some of the area monitors will also require local readouts. In addition, to aid in predicting future radiation levels and in order to satisfy compliance reporting for licencing purposes, it will be necessary to log many of the radiation monitor readings on a more or less continuous basis. Both these functions can be performed by a small microcomputer-based display and logging system similar to the one installed in the 500 MeV facility. It may in fact be desirable to link the two systems via some network to avoid duplication of some of the data reduction.

ADDITIONAL SAFETY REQUIREMENTS

In addition to the monitoring and interlock requirements, there will be a need for some other safety-related facilities. These have largely to do with ensuring the safe handling of the loose radioactivity during servicing of the TIS and the ion beam transport system. It is recommended that in order to ensure that all openings from the areas containing the largest amounts of radioactivity be sealed from those of high occupancy, the flow of air through any remaining penetrations be into the high activity areas. In addition, the floors in the hot cell area as well as the switchyard must be sealed so as to be easily decontaminated. There should be curbs around penetrations to lower floors and sills at the entrances. All drains must be plumbed to a holding tank whose capacity should not be less than 2000 litres. Preferably, this holding tank should be accessible during running in order that samples may be taken for assaying the radioactivity. It will also be required that there be a dilution system for this holding tank so that any radioactive effluents may be safely disposed of in the sanitary sewers.

Space will be reserved at the entrances to the high radiation areas for safety-related equipment such as hand and foot monitors, step-over barriers, protective clothing, contamination monitors and decontamination supplies. A minimum of 10 m² is required at each entrance for this purpose.

Although the operating radiation fields from the high resolution ion beam line are expected to be small, there will be local "hot spots" due to radioactivity deposited at experimental stations, slits, etc. The intention is that these will be locally shielded using lead bricks and concrete blocks. This approach should obviate the need for extensive shielding of the experimental areas.

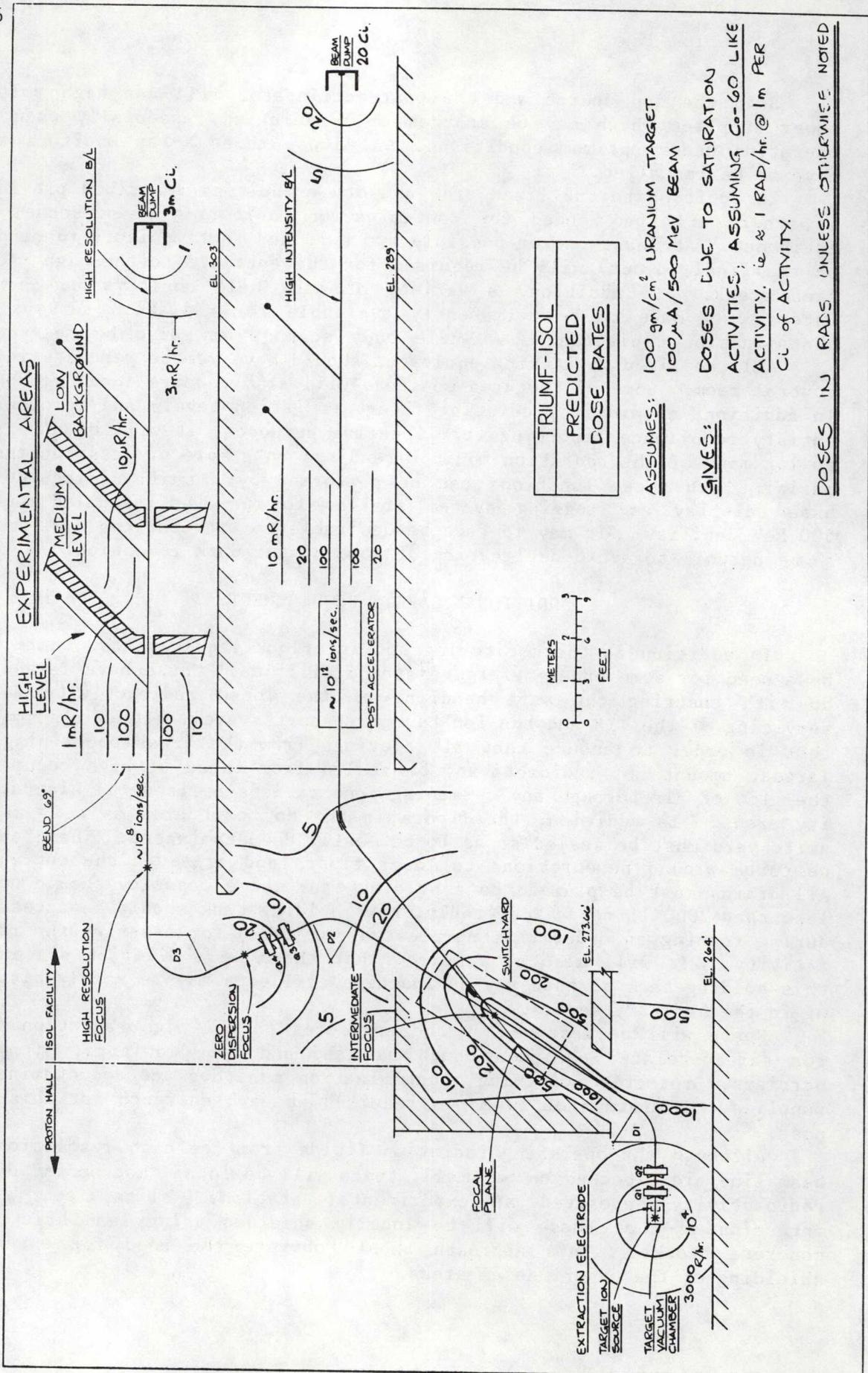


Fig. III.17. Calculated dose rates along the ISOL ion beam line assuming a worst case situation.

5.9 BUILDING

BUILDING DESCRIPTION*

Location: The proposed ISOL building will be located on the TRIUMF site, immediately north of the existing main accelerator building as indicated in Fig. III.18 (D-16675). The site would have to be cleared by relocating several experimental trailers, gas tank storage pads, and by removing the large amount of the earthfill mound which presently shields the north side of the 500 MeV cyclotron. This will be replaced by cement shielding (see section A.A on Fig. III.19, D-16677). The length of the building is limited in the west by the underground 4A beam dump and above ground, by the required road clearance, and in the east by the existing exit stairwell and access road to the meson hall loading bay. The building width is essentially limited to the width of the existing earth shielding of 40 ft (12 m) to preserve the important access road between the accelerator building and the remote handling building. The width of this road is 20 ft (6 m) as required by the Fire Marshall.

Layout: The design requirements of the post-accelerator and adjacent experimental layouts result in a long building of approximately 225 ft by 40 ft wide (70 m by 12 m). The main floor, which houses the post-accelerator, will be placed at ground level for easy access of large equipment. The above-ground location was also dictated by the 500 MeV cyclotron access tunnel, which passes under the proposed building and requires shielding of about 14 ft (4.3 m) of concrete or equivalent. A further consideration is the possibility of a future underground beam tunnel from the 500 MeV cyclotron to a future Kaon Factory. A suggested detailed layout of the post-accelerator hall and related experimental hall A is shown in Fig. III.18 (D-16675).

Above the post-accelerator floor is the high resolution beam experimental hall B with adjacent off-line test facility, TIS test and development area, a chemistry lab, a small workshop, and a space for assembling experimental apparatus prior to installation on the beam line (Fig. III.20, D-16676).

The third floor comprises various control and counting rooms, computer terminals and offices (Fig. III.20, D-16676).

An incursion inside the main TRIUMF experimental hall, at ground level, is shown in Fig. III.18. This is in addition to the beam line changes. It is for the containment room described in Sect. 5.4 (see Figs. III-1 and III-10) and an overhead crane for lifting the TIS, EE and pump columns. The Faraday cage at the extreme west side is also indicated inside the main building.

Structural design: As the building is placed partially on backfill, part of the foundation will most likely have to be supported by concrete piles down to bearing ground. The ground floor (with the post-accelerator hall) is surrounded by a 3 ft. (0.9 m) thick concrete perimeter shielding wall and a 3 ft (0.9 m) thick concrete ceiling slab to provide radiation

*Note: all dimensions in this section are in imperial rather than metric for consistency with TRIUMF site planning.

protection for the surrounding areas. The floor consists of a 12 in (30 cm) thick reinforced concrete slab on grade to provide support for the heavy beam line components and movable concrete shielding blocks.

The two upper storeys will consist of structural steel framing with corrugated sandwich metal panels as wall cladding, similar to all other TRIUMF buildings. Figure III.21 (D-16678) shows the vertical elevation of the building.

The new building will have to be separated from the existing main building by a 12 in thick concrete block fire wall providing a 2 h fire rating, and extending above the roof of the main building to comply with the 1980 National Building Code of Canada (NBC).

The shielding door at the proton beam level (shown at elevation 264 ft in Fig. III.18) will be designed to be essentially closed while the beam is on to minimize radiation levels in the hot-cell area.

Access and communication: Personnel access to the post-accelerator floor is restricted to the east and west ends of the building. Both entrances are protected by radiation mazes and served by decontamination rooms. Initial access for large beam line components will be through a temporary opening in the north wall which will be closed by shielding blocks later. The experimental end of this floor (east half) will be served by a five ton overhead crane. The western half of the floor, where no frequent equipment moves are anticipated, is served by an overhead access hatch through which equipment can be entered or removed by the ten ton overhead crane on the experimental floor above. Temporary overhead moving devices can also be installed as needed.

Both floors, and the deep underground area housing the dipoles and switchyard equipment, are served by a loading bay on the buildings west side, which is under the ten ton overhead crane range. Removable hatch covers allow crane access to all four levels. The entire experimental hall (at floor elevation 303 ft) is also under the range of the same ten ton crane.

Access for smaller equipment to the second and third floor is facilitated by the freight elevator at the east end of the building.

Personnel entry to and exit from the upper floors is provided by three stairwells located at the east end, centre, and west end of the building. These three stairwells must be provided to comply with NBC regulations because the building is over 200 ft in length.

Exterior views from different points are provided in Fig. III.22 (D-16678).

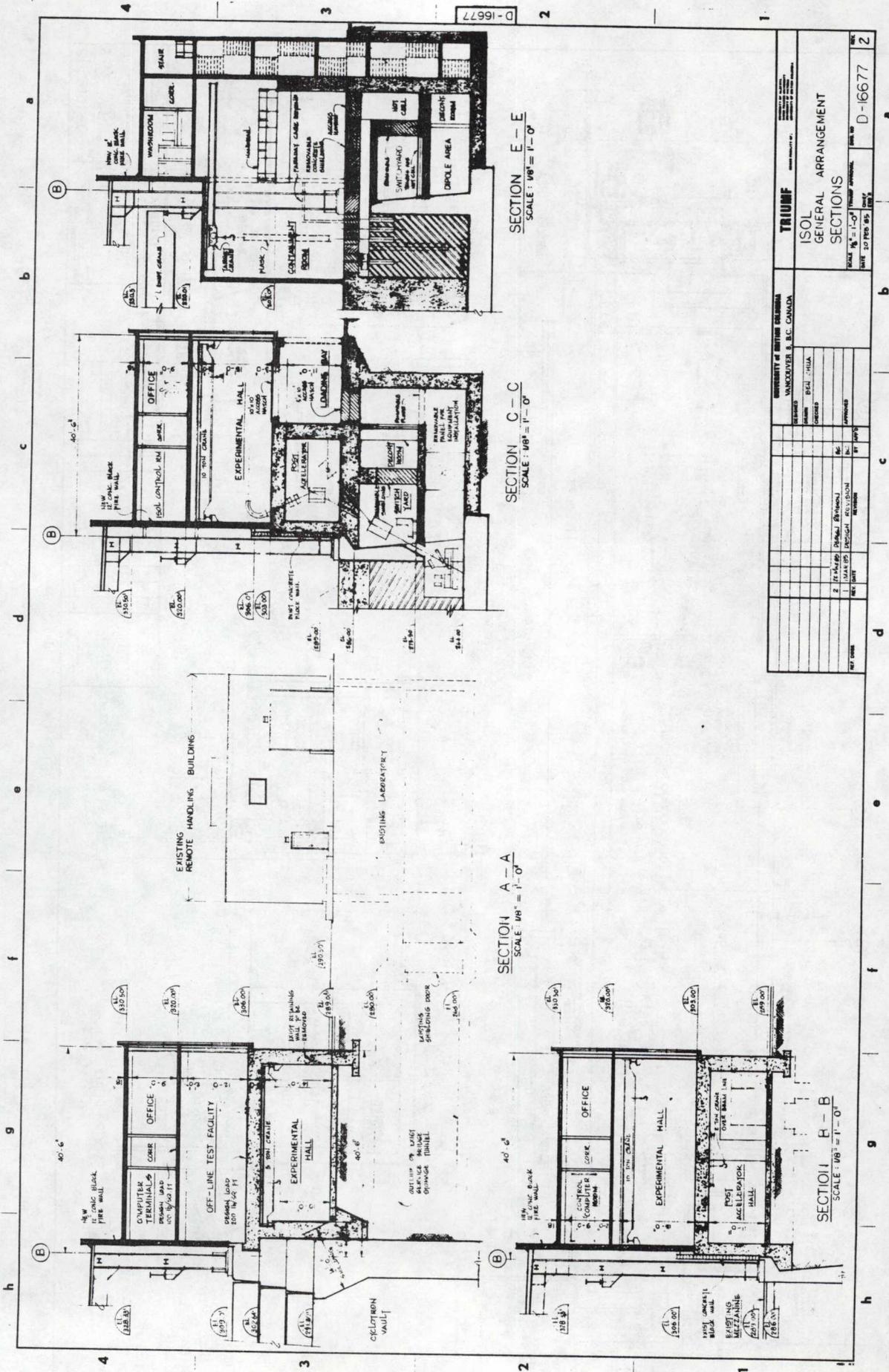


Fig. III.19. Elevation views of different sections of the proposed ISOL building (see III.18).

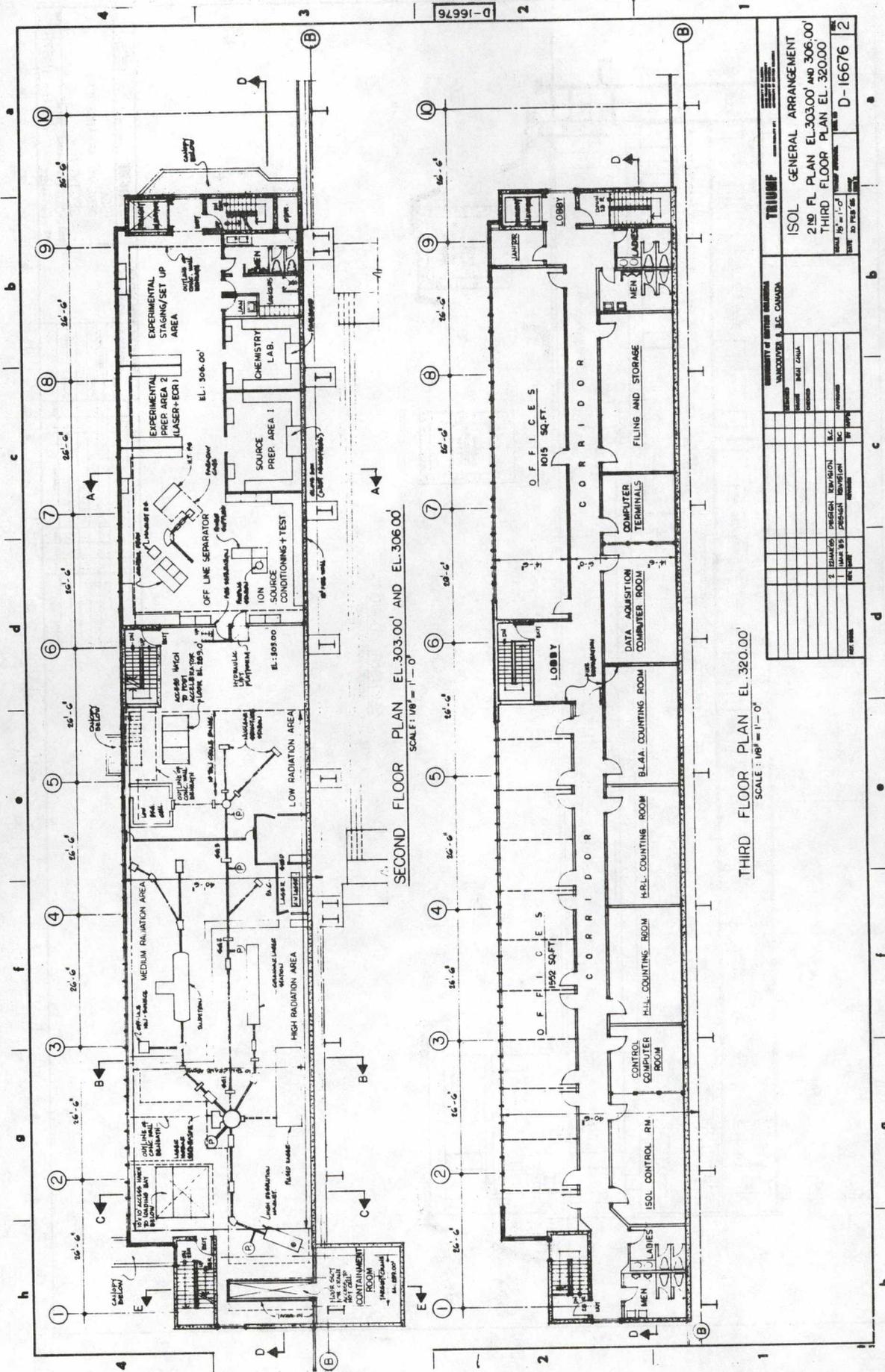
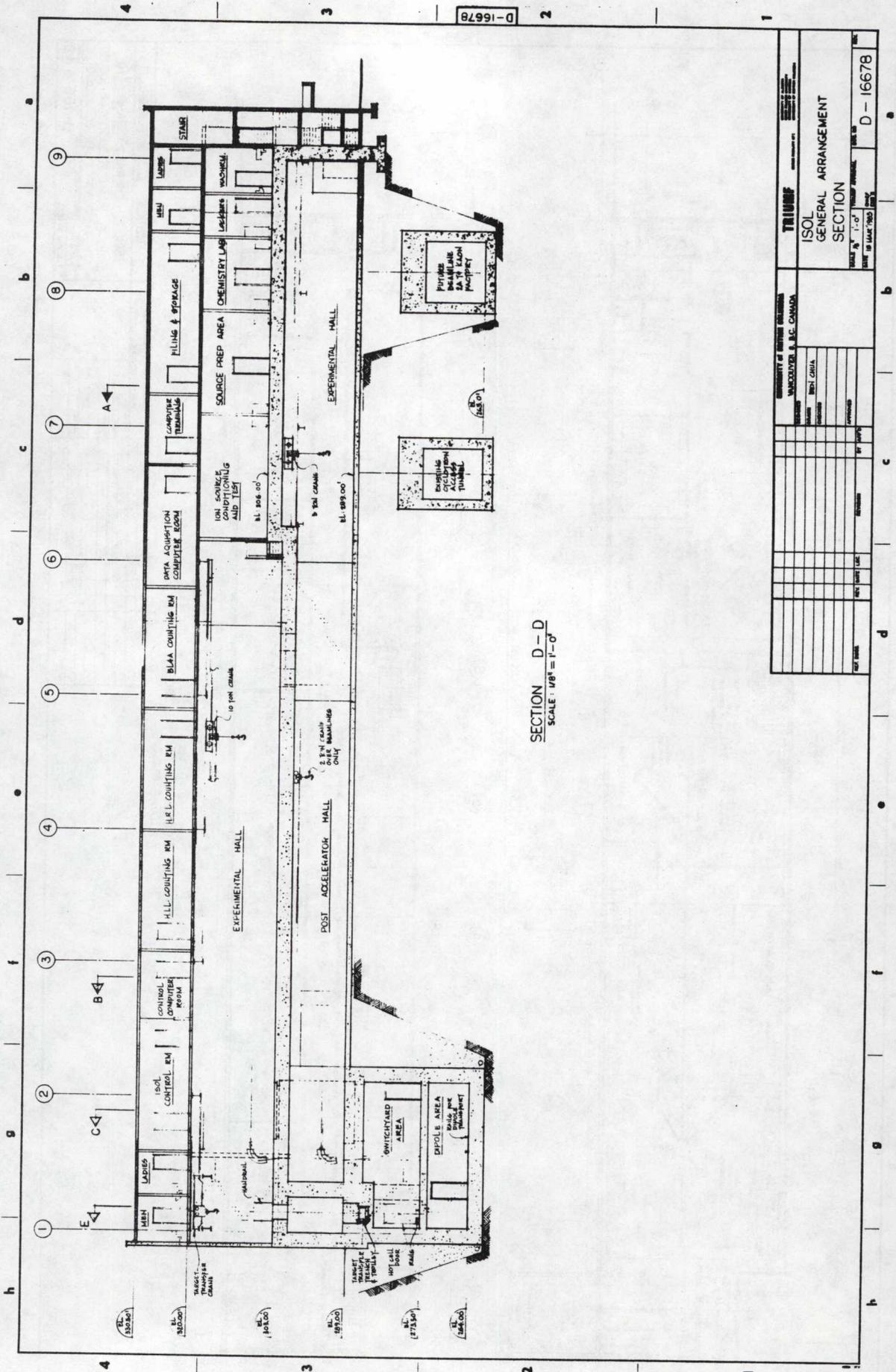


Fig. III.20. Layouts of the high resolution beam line (second) floor and the top floor of the proposed ISOL building.



SECTION D-D
SCALE: 1/8" = 1'-0"

Fig. III.21. Vertical elevation of the entire ISOL building including locations of the existing cyclotron access tunnel and the beam line to the proposed Kaon Factory.

5.10 OFF-LINE FACILITIES

It should be clear from the preceding discussions that the feasibility of any new experiments depends largely on the development of TIS systems capable of producing and delivering the required beams with sufficient intensity. We have also seen that this requirement leads to the development of extremely complicated TIS systems. At the heart of such developmental activities is obviously an off-line ion source testing facility. The test facility consists of several components: a mass separator to measure the relative production of various species, a station for testing the other features of the TIS systems (such as HT bias, heating and cooling systems, etc.), and a chemistry laboratory for radiochemical and physio-chemical needs (such as testing the diffusion and release of the radioisotopes from the target matrix). Also, space is required in a non-radioactive environment for the testing of experimental apparatus prior to installation on the ion beam line. A preliminary layout of the off-line facility area is shown in Fig. III.20.

5.11 POST-ACCELERATOR

Various options of accelerator configurations to accelerate efficiently the 60 keV beam from the ISOL to a useful output energy range have been examined. Based upon the requirements of the experimental program for studies in nuclear astrophysics this accelerator should produce external beams of ions up to an A value of at least 60, with energies in the range from about 100 keV/amu to at least 1 MeV/amu, continuously variable with a resolution of 10^{-3} or better. Transmission efficiencies should be high so that useful beam intensities in the nA region are available; acceptance of either positive or negative ions from the ISOL would be a desirable feature. Based upon these specifications as well as the technical problems discussed in Sect. 3, a LINAC solution was considered more suitable than other means of acceleration including cyclotrons and Tandem accelerators.

A critical part of the post-accelerator is the first stage which must capture, bunch, and accelerate the singly charged (+/-), very low velocity ($\beta > 0.0015\%$), dc beam from the ISOL, with good efficiency. This is best accomplished by some form of radiofrequency quadrupole (RFQ) such as one built at GSI for $q/A > 1/130$ [Mül 84], or a low frequency version (~23 MHz) of the Los Alamos four vane structure. A preliminary design of the latter version, done at CRNL for $q/A > 1/40$, a peak field of 1.5 Kilpatrick, and an operating frequency of 23 MHz, has a calculated capture efficiency of 94% for a 0.1π cm-mrad (normalized emittance) ISOL beam [Mac 85]. At some point between 60 and 100 keV/amu the beam may be stripped and injected into a post-stripper section. This latter section can be based on existing LINAC designs such as the UNILAC, HILAC or RILAC.

As an illustration a possible post-accelerator layout, initiated following discussions with H. Klein [Kle 84], is shown in Fig. III.23, along with the associated experimental area. A foil stripper is inserted at 100 keV/amu to increase the charge-to-mass ratio and minimize the length of the accelerator. The single gap sections shown can be switched on or off individually as well as adjusted by their relative RF phases to give the required ion energy variation. A debuncher is also provided to tailor the beam to meet the required energy resolution. This system, operating at CW, would require an estimated 4 MW of RF power. Other similar solutions can be envisaged which use less power but may not meet all of the specifications. A more complete discussion of such initial concepts of the TRIUMF-ISOL post-accelerator can be found in a TRIUMF report (TN-85-1) in the Appendix.

Two separate beam lines are planned to accommodate two different experimental set-ups. At a later date, one of the beam lines may be replaced by additional LINACS or other types of accelerators if ions of higher energies are required for the experimental program. Acceleration up to 6 MeV/amu can be accommodated. However, if additional experimental space or higher energies are required, further expansion of the building would be necessary.

At present, a detailed examination of the LINAC configuration is being carried out. This includes a realistic estimate of the RFQ accelerator efficiency, the detailed arrangement of the subsequent linac sections including intertank matching, the positioning (in energy), the type and efficiency of the stripper, and the energy resolution that can be

expected. This will be followed by preparation of realistic cost estimates and an implementation schedule. The results of this study, supplemented by the proceedings of the planned TRIUMF Radioactive Beams Workshop to be held this September, will be available late this year 1985. In the present proposal, we have included only the preliminary result of our study, but the final solution is not expected to be significantly different.

REFERENCES

- [Mül 84] R.W. Müller, U. Kopf, J. Bolle, S. Arai, P. Spädtke, Proceedings of the 1984 LINAC Conference, ed. N. Angert; GSI-report 84-11.
- [Mac 85] G. MacMichael and B. Chidley, 1985, CRNL, private communication.
- [Kle 84] H. Klein, University of Frankfurt, 1984, private communication.

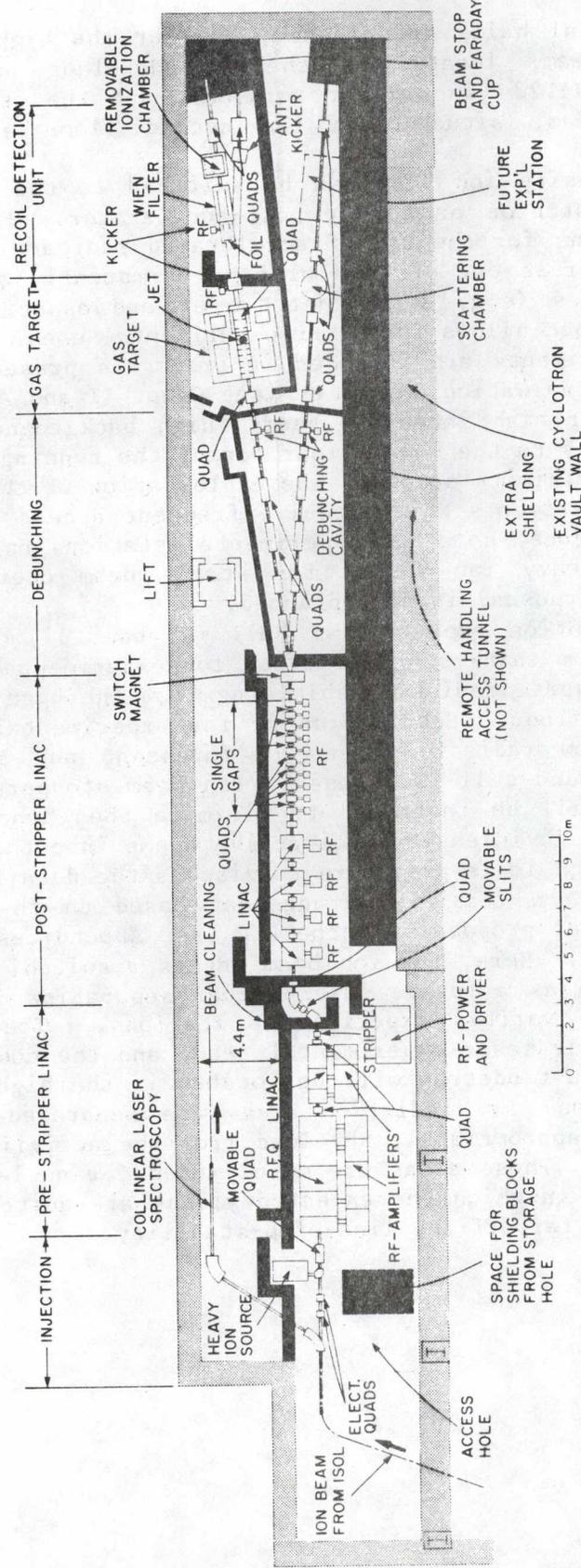


Fig. III.23. A schematic representation of a possible layout of an ISOL post-accelerator based upon suggestions of H. Klein [Kle 84].



6. EXPERIMENTAL HALLS

Two experimental halls are planned, one for the high intensity, accelerated ion beam, located on the ground floor as shown in Figs. III.18 and III.23 (an earlier version), and the other for the high resolution beam, situated on the second floor as shown in Fig. III.24.

The high intensity ion beam can be switched to the radioactive target collection station or to the post-accelerator. Further, two experimental stations for the use of accelerated radioactive isotopes are available. Whereas one of them will be permanently occupied for astrophysics purposes (e.g. a gas jet target and associated components), the second one allows for other experimental uses. Details of some of these experiments are included in proposals presented to the TRIUMF Experiments Evaluation Committee (see Chap. II and Appendices). The extensive use of high intensity beams (high background area) and the restricted access to the lower floor during the running periods of the post-accelerator limits somewhat the exploitation of the remaining space for other experiments which require frequent access for testing and service. Therefore, no other experimental stations on this floor are planned. A heavy ion source for static beam operation (for testing and other purposes) is also planned.

The high resolution experimental hall is about 11 m \times 35 m in size, and has a 0.9 m thick concrete floor for experimental equipment loading and for adequate radiation shielding from the high background area of the ground floor. Subdivision of the experimental area into high, medium and low radiation areas is foreseen, and a specially shielded low background cell is planned. Ion beam stoppers and automatic gate valves will be installed to minimize the chance of accidentally injecting high intensity radioactive beams into the low background area. Although it is premature to discuss the detailed allocation of floor space, a feasible arrangement based on the currently submitted experimental proposals to the EEC (see Appendices) is indicated in Fig. III-24. Here, the ion beam enters a switching station, which can also serve as a future laser isobar separation device, and is directed towards various experimental stations. The switching station, the collinear laser experimental setup and the double charge exchange cell for the tandetron will be located in the high radiation area. The medium and low radiation areas are separated from each other, and are also appropriately shielded from the activities in the high radiation area. These areas are mainly used for nuclear physics counting experiments in which the expected yields are quite low, e.g. the study of species far off the line of β -stability.

IV. PROJECT MANAGEMENT

1. COST ESTIMATES

The concept of work breakdown structure (WBS) into its components was used for the project-management cost estimate. Figure IV.1 shows an overall organizational picture of the TRIUMF-ISOL facility divided into nine subprojects, each further subdivided into smaller, well defined tasks. This approach helped to organize the planning of this project by defining tasks that must be performed within the conception, design, development, fabrication and test stages of the project. In this way, the required cost and other resources, for the entire project can be reached more reliably. Also, the proposed schedule and the related flow of resources can be estimated realistically.

The cost estimate procedure used is identical to those adopted for other TRIUMF projects. The required material and supply, and professional and technical support are estimated separately for each task. They are then summarized under the headings of the various subjects and are presented in Table IV.1. Detailed estimates of each of the sections are included in the Appendices. The TRIUMF cost center manpower indicated in Table IV.1 includes only those personnel from the TRIUMF design office, the machine shop and the electronics services. The costs are in 1985 Canadian dollars and where US data have been used, a 0.75 exchange rate was assumed. No contingencies are included.

The estimated cost presented here represents the actual resources required for the installation of the isotope separator, including the necessary engineering development studies. The total estimated cost is \$4.74 M for materials and supplies plus 44 man-years of professional and technical support. This amount does not include the cost of installing the post-accelerator, but does include the cost of its engineering development study. Detailed study of a post-accelerator system is currently in progress. A preliminary estimate for the cost of a combination of RFQ and other LINAC sections is \$4.5 M, or about the same amount as required for the ISOL system itself.

The building costs presented include \$891 K of material and supply required for ISOL related services (\$397 K) and PA services (\$494 K). The planned capability will be adequate to support the operation of a RFQ-LINAC type of post-accelerator.

2. IMPLEMENTATION SCHEDULE

Figure IV.2 shows an overall plan and schedule for the entire project, including the expected progress of all the subprojects. It is assumed that this proposal will be approved by TRIUMF late in 1985 so that an intense engineering development plan can be initiated in early 1986. The major commitment of resources will start in 1987. The building can be completed in two years (by April 1989) and the isotope separator installed by the end of the third year (April 1990). Radioactive isotope beams would be available to the experimentalists six months later. Assuming that the post-accelerator will be ready by then, the injection of the radioactive beam into the accelerator can be accomplished towards the end of the fourth year (April 1991). With this general schedule, the estimated flow of capital and manpower requirements for the isotope separator

TRIUMF-ISOL FACILITY INSTALLATION

(Cost Estimates)

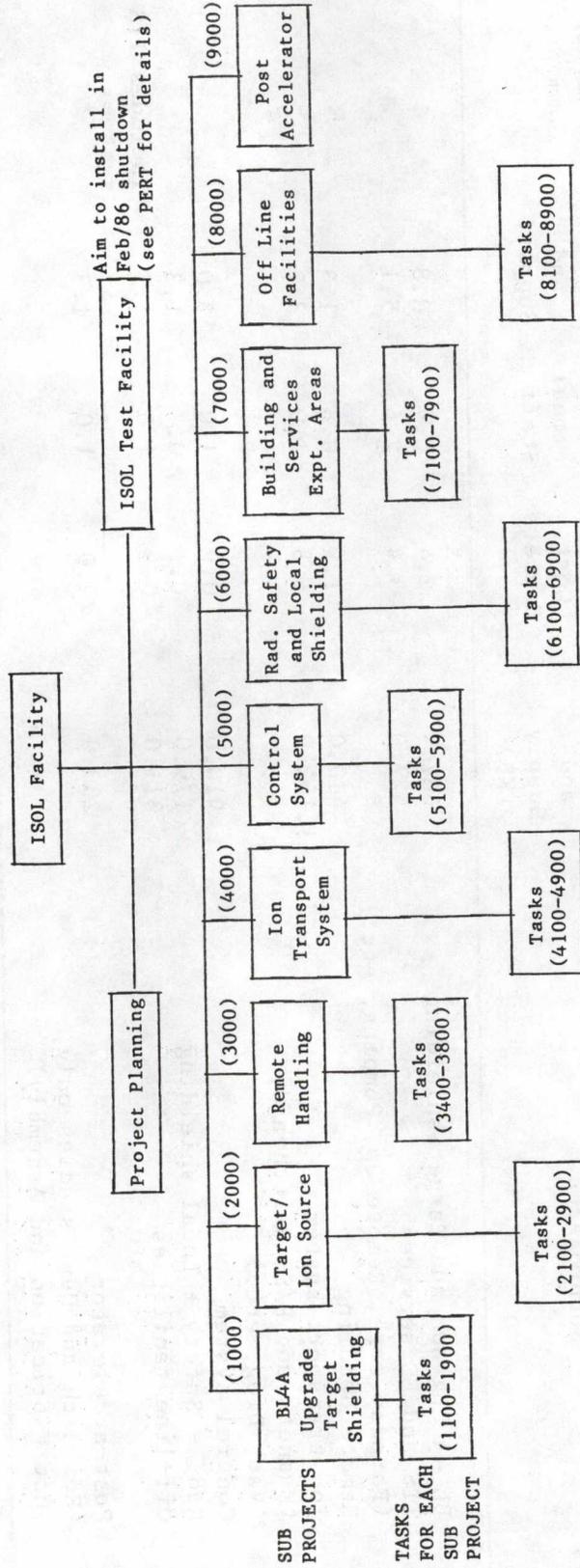


Fig. IV.1. Organizational chart for the TRIUMF-ISOL study.

Date: April 22/85

Table IV.1. Cost Estimates - Summary for the TRIUMF-ISOL Facility*
(for details, consult Appendices)

WBS Series #	Subprojects	Material and Supply (K\$)	Manpower Estimates (man-years)				Remarks/Comments
			TRIUMF Cost Centers	Professional Staff	Tech. and Support		
1000	BL 4A Upgrade and Target shielding	667.9	2.4	0.4	0.8		
2000	TIS and EF services (Faraday cage, Remote Op, Pumping, etc.)	527.0	3.4	2.6	5.1		
3000	Remote handling	410.0	1.9	0.8	1.3		
4000	Ion transport system (Magnets and P/S, Switchyard, Vac, Diag, etc.)	1,152.0	6.8	1.0	3.2		
5000	Control system	910.0	0.9	1.0	3.0		
6000	Rad. + Safety + Local shielding	179.0	0.1	0.7	1.3		
8000	Off-line facilities	311.0	0.9	1.0	1.3	Includes TIS systems	
9000	Post-accelerator (Research and Dev. studies only, not Fabrication and Assembly)	200.0	2.0	1.0	1.3		
TOTAL (for ISOL major components)		4,356.9	18.4	8.6	17.3		
7000	Building and Services	4,551.0	—	4.83†	—	Includes 397 K for ISOL related services and 494 K for PA services	
xxxx	Post-accelerator (preliminary estimates)	(4,500)	(20)	(10)	(20)		

*No contingencies have been included but a 15-20% range should be reasonable; all costs are in 1985 dollars. †4.83 man years for buildings and services refer to outside consultants (professionals).

portion of the project are shown in Figs. IV.3 and IV.4, respectively. Details of the time schedule for the post-accelerator are not included. However, it is expected that an RFQ-LINAC combination can be designed and installed within the time frame proposed here.

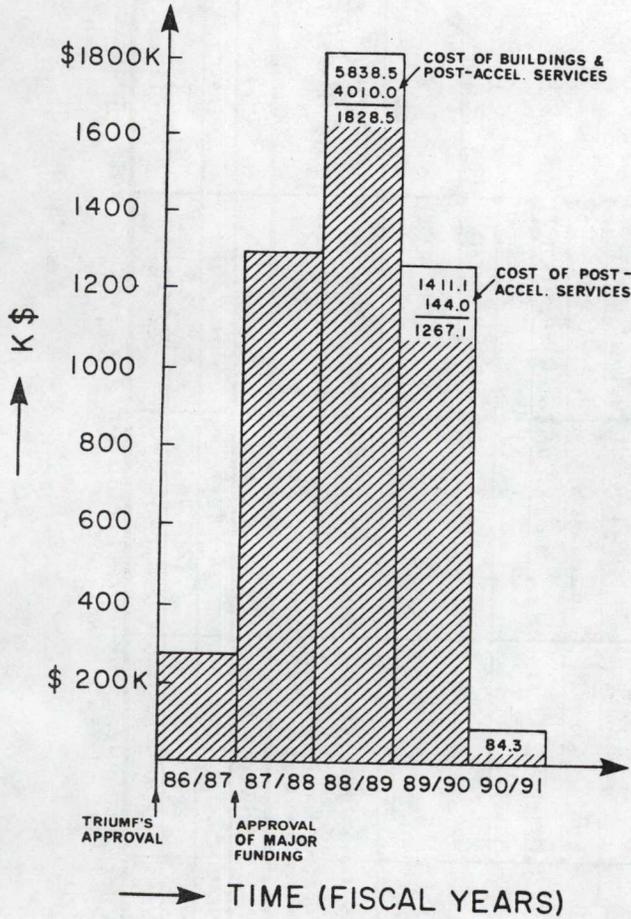


Fig. IV.3. Commitment flow excluding cost of buildings and post-accelerator services.

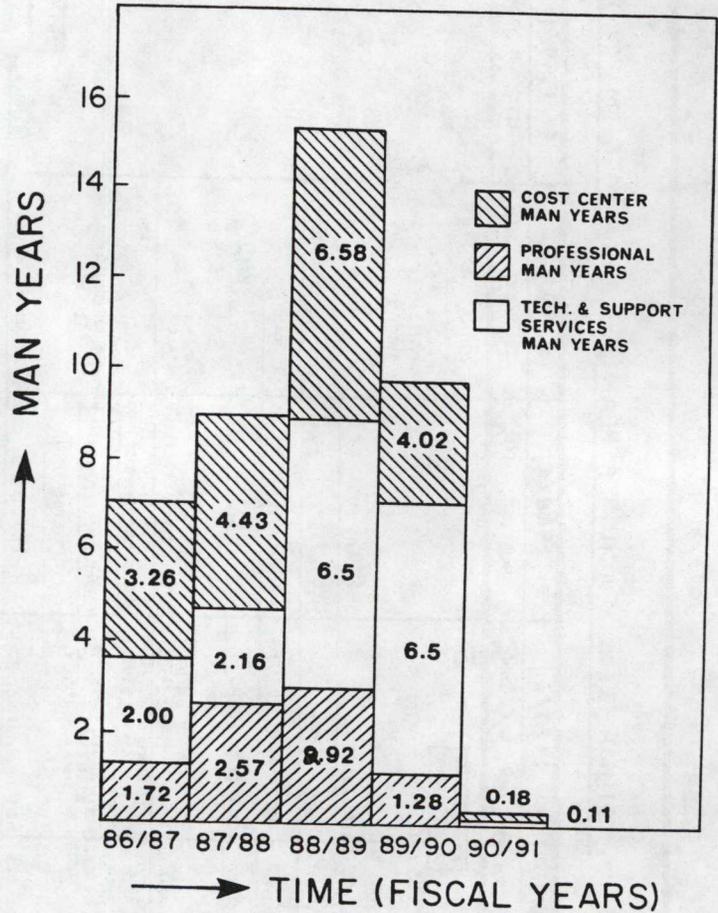


Fig. IV.4. Manpower projection for installation of the ISOL facility only.

While the time schedule for the entire project covers a five-year period (1986-1991), development work and studies related to the project during the current year (1985-86) are also indicated in Fig. IV.2. This work includes the design and construction of an on-line ion source testing facility to be installed on beam line 4A, a moderate program of ion source development, and an effort toward the preliminary design and cost estimates of the post-accelerator. A workshop on accelerated radioactive beams is to be held in September 1985. The budget allocated for the current year for these efforts, and the operating cost of the ion source testing facility in the subsequent years, is not included in the cost estimates.

3. IMPACT ON TRIUMF OPERATION

The TRIUMF-ISOL project will rely heavily on TRIUMF resources during all stages of its progress. Its impact on the present mode of the TRIUMF operation will be substantial, and careful planning will be required to accommodate its implementation. Such a process will involve various divisions of the TRIUMF operation and should be addressed at an early stage of the project implementation.

The construction of a building, 10 m by 65 m in size, along the north wall of the present building, will have some immediate impact. The existing structures along the north wall, including the liquid nitrogen tanks and SFU trailers, have to be moved to other locations, and some ongoing experimental programs will be affected. At the early stages of excavation and building construction, potential safety hazards due to the radiation from the cyclotron vault may require the shut-down of the cyclotron, or restricting it to low-level operation, for a six month period. The installation of the TIS system on beam line 4A, with its shielding blocks and remote control facilities, will mean the interruption of operations using beam line 4A and some restrictions in activities using beam line 4B. This interference will last about three to six months. These interruptions to ongoing activities should be kept to a minimum and this particular phase of implementation of the project can be scheduled to coincide with the regular TRIUMF accelerator maintenance periods as indicated in Fig. IV.2.

V. FACILITY OPERATION

1. STEADY STATE OPERATION

Under steady operating conditions, the proposed facility should be able to take full advantage of the TRIUMF beam capability and handle up to 2000 h/yr of (unpolarized) beam-on-target operation, with each operating cycle lasting a period of about 2 weeks. During the operation, two simultaneous radioactive ion beams may be extracted. In principle, the high intensity ion beam can always be injected into the post-accelerator. However, other experiments will require the production of nuclear species which are not useful for experiments using the post-accelerator. Thus, the actual operating time for the acceleration of radioactive ions will be reduced. Naturally, the post-accelerator can always operate with an off-line ion source for ion beams of stable or long-lived isotopes.

2. SCIENTIFIC AND TECHNICAL SUPPORT

In addition to the normal support for the maintenance, operation and development of the facility, there should be support for an in-house scientific team and a strong TIS development program. The scientific team should be charged with the responsibility of coordinating the various scientific research programs, and to assist and collaborate with the visiting groups. The TIS development team should have a program to meet the continuous demands from the experimentalists for new isotopes, higher intensities and purities, and more durable TIS systems.

The estimated level of manpower is summarized in Fig. V.1, which shows an outline of a possible organizational chart. A team of six scientists, five professionals, and twenty technical and administrative support staff will be required specifically for the ISOL facility, although integration of these positions with present TRIUMF groups can occur, especially where there exists an overlap of seniority of job characteristics (e.g. safety). This team will be supplemented by visiting groups, some of which should have personnel stationed at TRIUMF on a long-term basis.

3. OPERATING COST ESTIMATES

The proposed facility will be the first of its kind in the world and it is difficult to estimate a precise operating cost for it. Our estimate is based on the operating cost of ISOLDE, and modified to account for higher proton beam current operations, the need for TIS development, and the technical assistances for experimental programs. The material and supply required for the ISOL operation will be about \$700 K. A similar amount will also be required for the operation of the post-accelerator. The total estimated operating cost is then:

Material and supply	\$1.4 M
Salary for 31 persons	\$1.3 M
Other TRIUMF support	\$0.3 M
Total	\$3.0 M

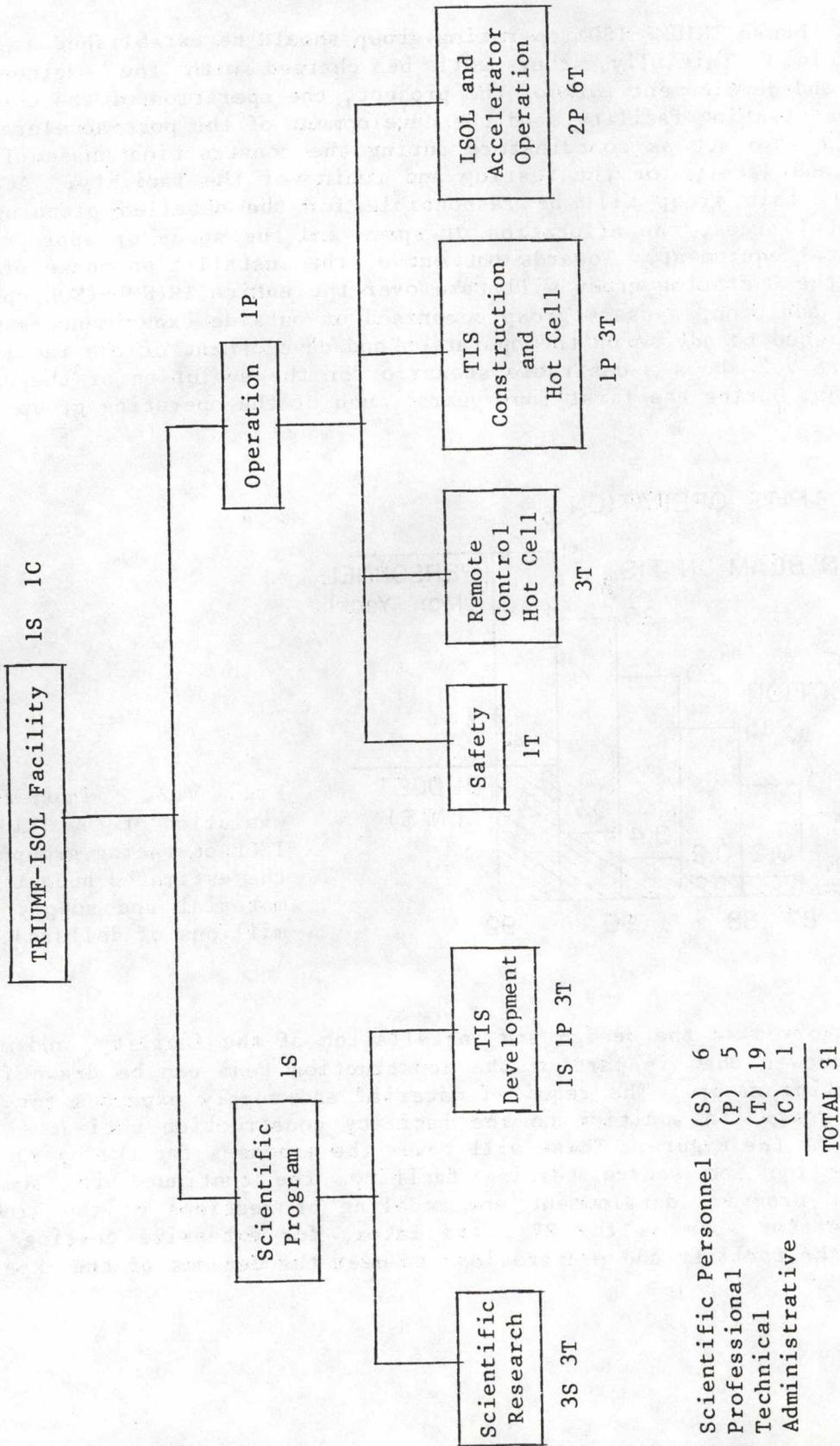


Fig. V.1. A possible organizational chart for the TRIUMF-ISOL operating group.

4. EVOLUTION OF THE ISOL GROUP

An in-house TRIUMF-ISOL operating group should be established as soon as possible. Initially, they will be charged with the engineering research and development work of the project, the operation of the on-line ion source testing facility, and the development of the post-accelerator. They could also act as coordinators during the construction phase of the facility and later, for the testing and tuning of the facility. At the same time, this group will be responsible for the detailed planning of experimental areas, the allocation of space and the setup of appropriate experimental equipment. Towards the end of the installation phase of the project, the operating group will take over the entire TRIUMF-ISOL operation. In addition, a users group comprised of outside experimenters will be established to advise on the operation and development of the facility.

Figure V.2 shows a desirable scenario for the evolution of the operating group. During the first four years, much of the operating group will

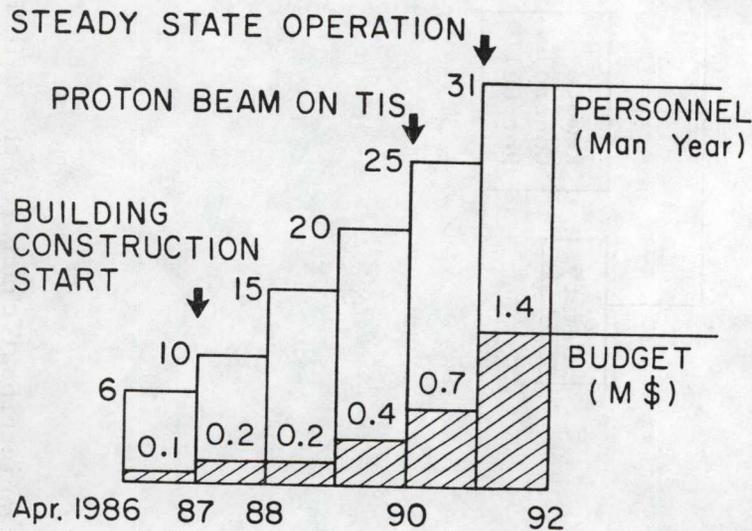


Fig. V.2. Projected evolution of the TRIUMF-ISOL operating group and the estimated budget for material and supply (in millions of dollars).

also be involved in the design and installation of the facility, and much of the manpower that is part of the construction team can be drawn from this operating group. The required material and supply expenses for the operating group (in addition to the facility construction estimates) is also shown in the Figure. These will cover the expenses for the operation of the on-line ion source testing facility, the continued ion source development program, development and modeling of sections of the linear post-accelerator such as the RFQ, and later, for extensive testing and tuning of the facility and preparations to meet the demands of the experiments.

5. IMPACT ON TRIUMF OPERATION

We have projected that the facility may handle up to 2000 h/yr of proton-beam-on-target operation. The beam current normally required can vary from 1-10 μA . For certain experiments, up to 100 μA proton beam may be desired, with the cyclotron beam delivered in d.c. or pulsed modes. The high beam current (100 μA), particularly in pulsed mode operation, will affect the experimental conditions in the meson hall, and careful planning will be necessary before implementing these running modes. The proton hall activities will be affected since the present 4A beam dump will not always be available due to TIS change and maintenance work conducted in that area. The radiation level from the TIS should not hinder the normal activities in the rest of the proton beam hall (4B). Sufficient shielding and interlock systems are proposed to allow access to 4B while 4A is in operation. The projected 2000 h/yr operation may impose a limit on the beam time available to the other research projects using beam lines 4A or 4B. In this case, beam line 5 could be installed to send an independent proton beam to the area normally served by beam line 4B.

The TRIUMF-ISOL facility has the potential to serve large and diversified disciplines in science. The isotope separator will be the only one of its kind in North America and the accelerated radioactive ion beam facility will be unique. We believe that it will attract many scientists from all over the world. These scientists will come mainly from fields that differ from the present main-stream research areas of TRIUMF. This will mean many more visiting scientists to TRIUMF and will put pressure on the existing TRIUMF resources. Hopefully, this will be met by a corresponding adjustment in the regular TRIUMF operating budget.

