nuclear astrophysics – lecture 3

Alan Chen

McMaster University, Canada

rare isotopes in stars: gamma-ray astronomy (^{26}Al, ^{44}Ti)

- **<u>observations</u>: γ-ray emission from ^{26}Al decay**
  - **diagnostic of ongoing nucleosynthesis**
  - **constraint on galactic chemical evolution**

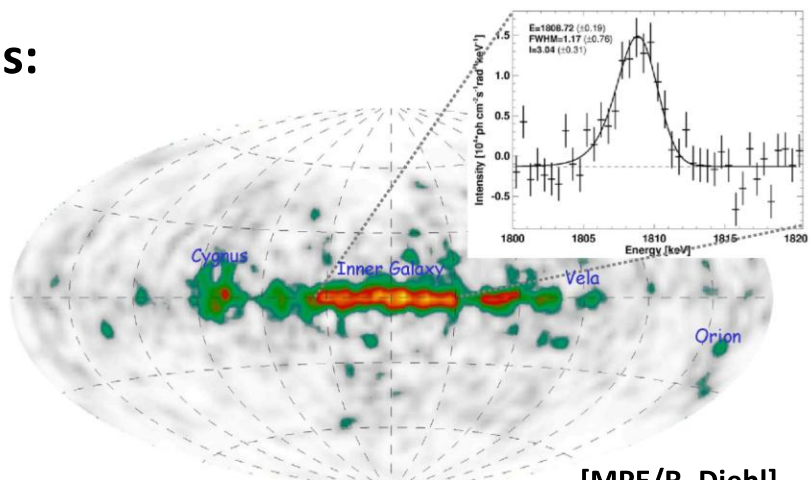
[Cassiopeia A]

- **<u>models</u>: need ^{26}Al yield predictions for different stars (e.g., supernovae, classical novae, AGB stars)**

- **important <u>reactions</u> affecting ^{26}Al synthesis:**

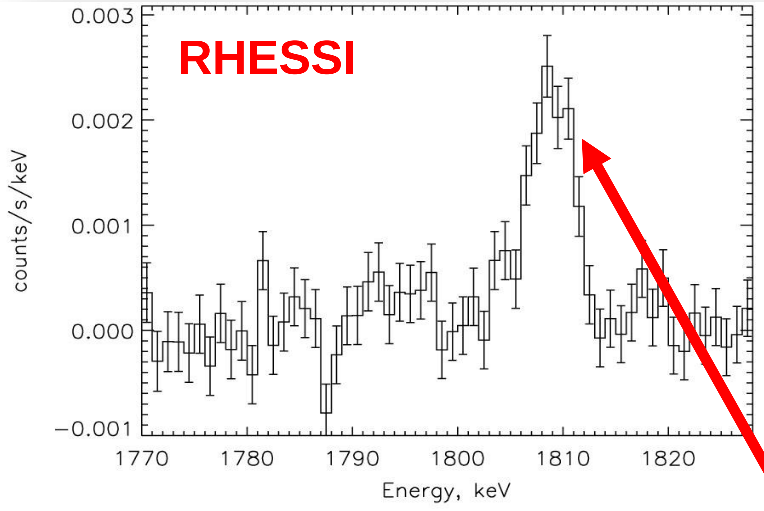
  $^{25}Al(p,\gamma)^{26}Si$

  $^{26}Al(p,\gamma)^{27}Si$

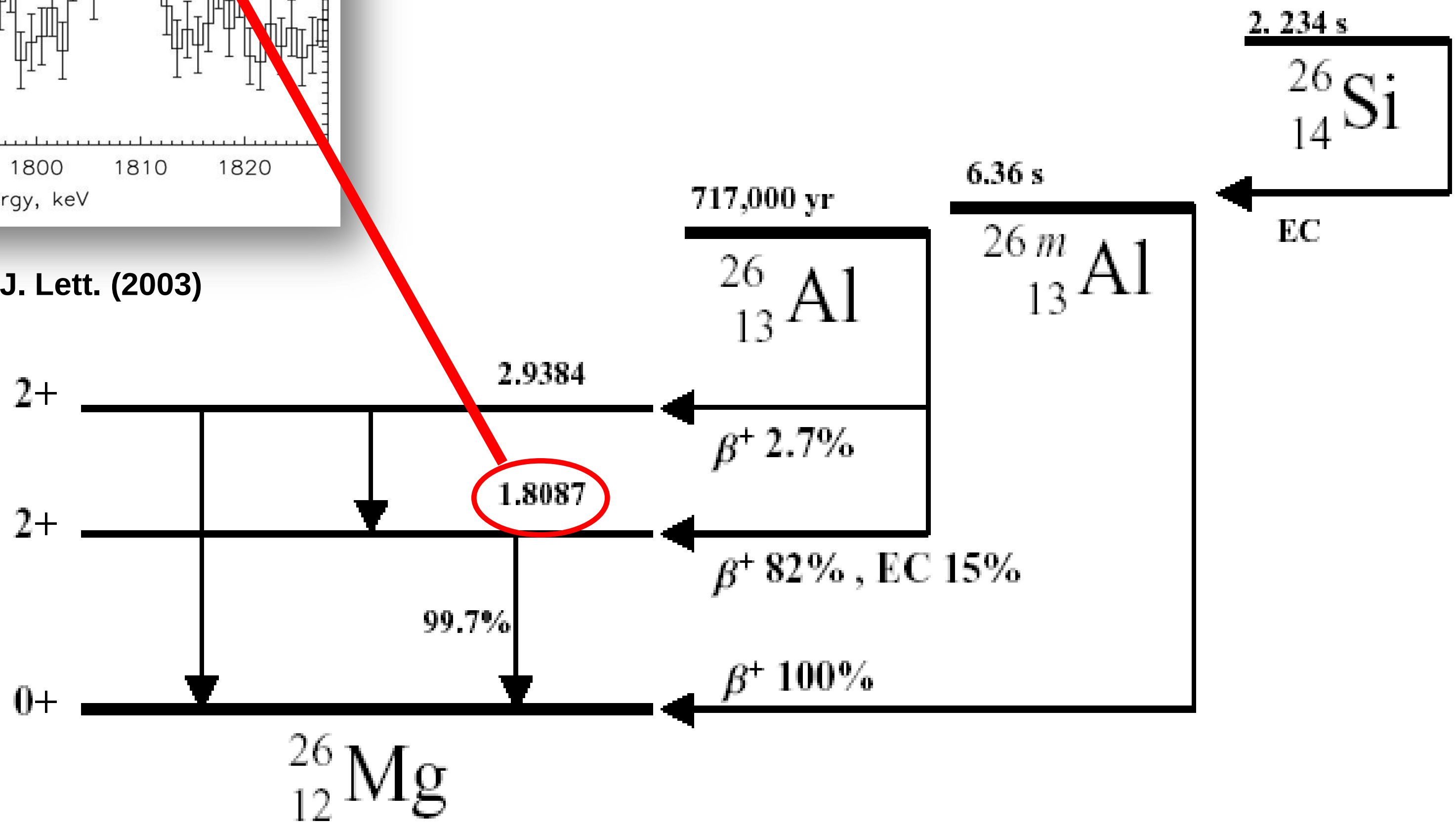


[MPE/R. Diehl]

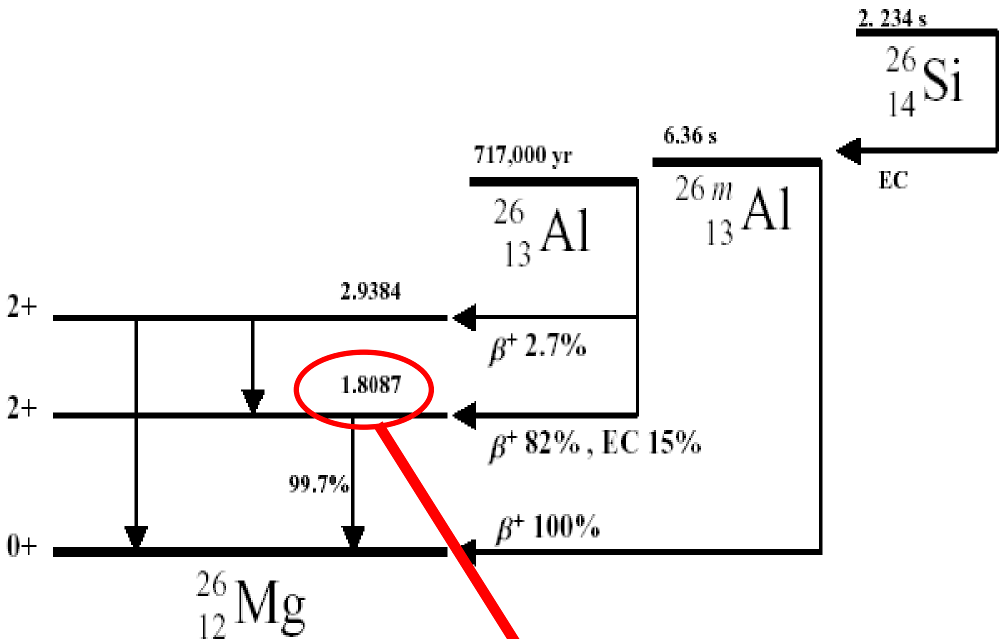
the nuclear origin of galactic ^{26}Al

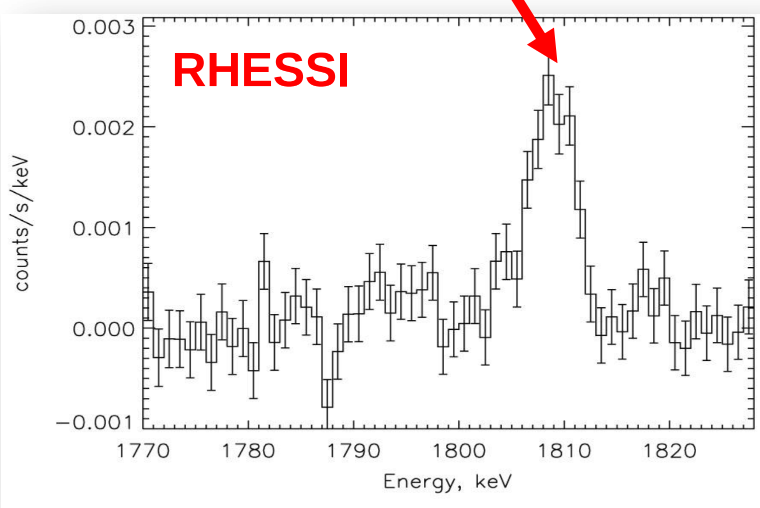


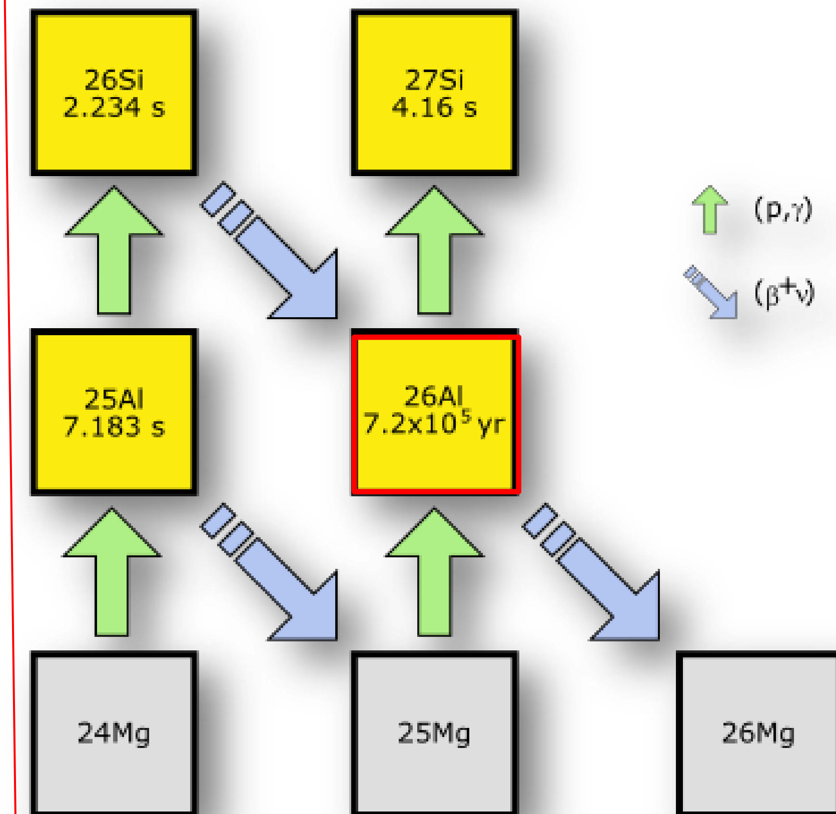
D.M. Smith, Ap. J. Lett. (2003)



the nuclear origin of galactic ^{26}Al







important reactions:

$^{26}Al(p,\gamma)^{27}Si$

$^{25}Al(p,\gamma)^{26}Si$

[Iliadis et al. Ap. J. (2002)]


Beaufort Sea
Baffin Sea
Greenland
NU
AK
YT
NT
Canada
Hudson Bay
Gulf of Alaska
AB
MB
BC
SK
NL
ON
QC
TRIUMF
WA
MT
ND
MN
NB
PE
VT
ME
NS
WI
MI
OR
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SD
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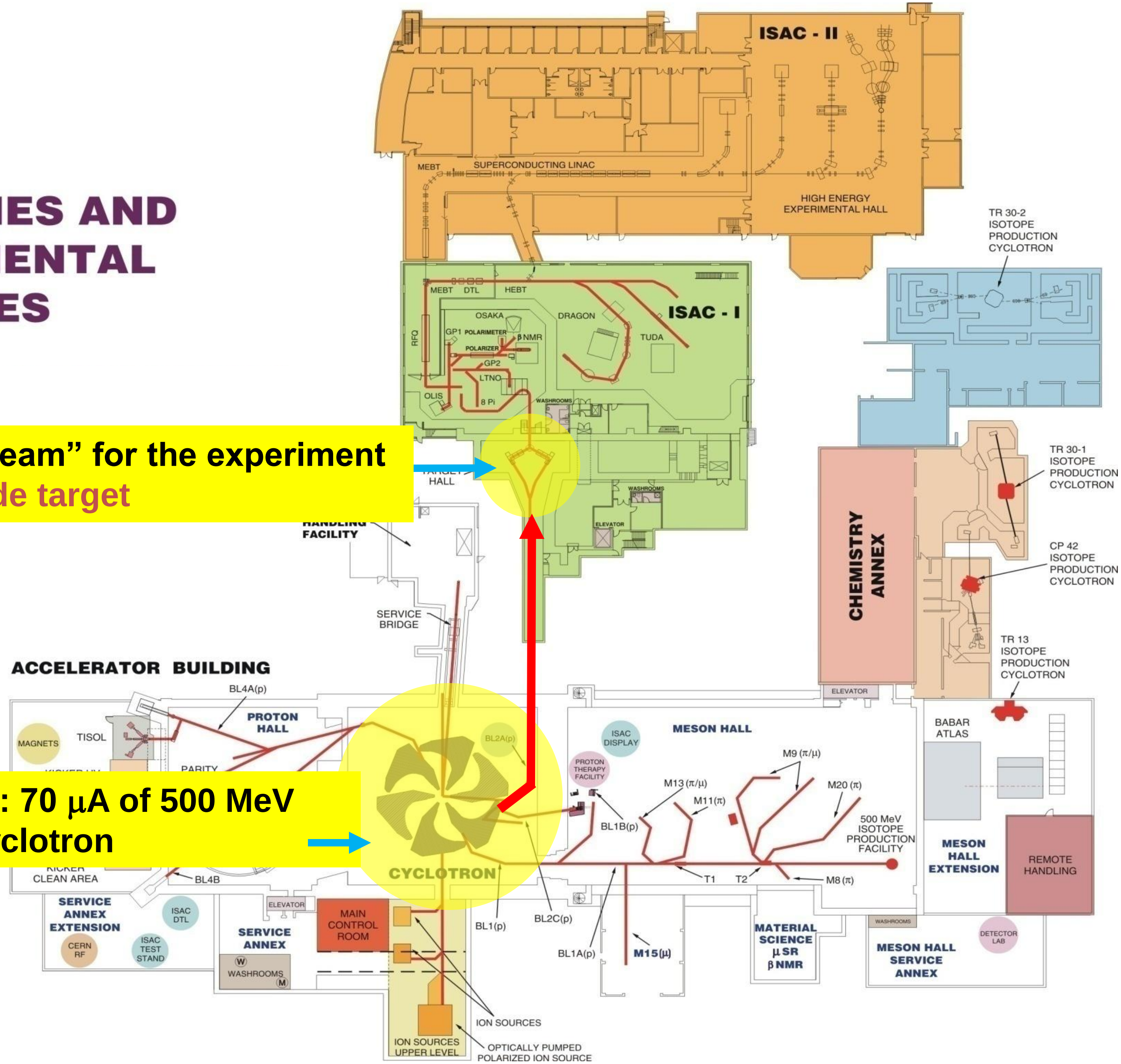
TRIUMF

Measurement of $^{26}Al(p,\gamma)^{27}Si$ at TRIUMF-ISAC

- **Goal: determine the (p,γ)-strength of the E_{cm} = 188 keV resonance**
    - **$E_{beam}(^{26}Al)$ ~ 200 keV/u**
    - **Need ISAC beam intensity > 10^9 ions per second**

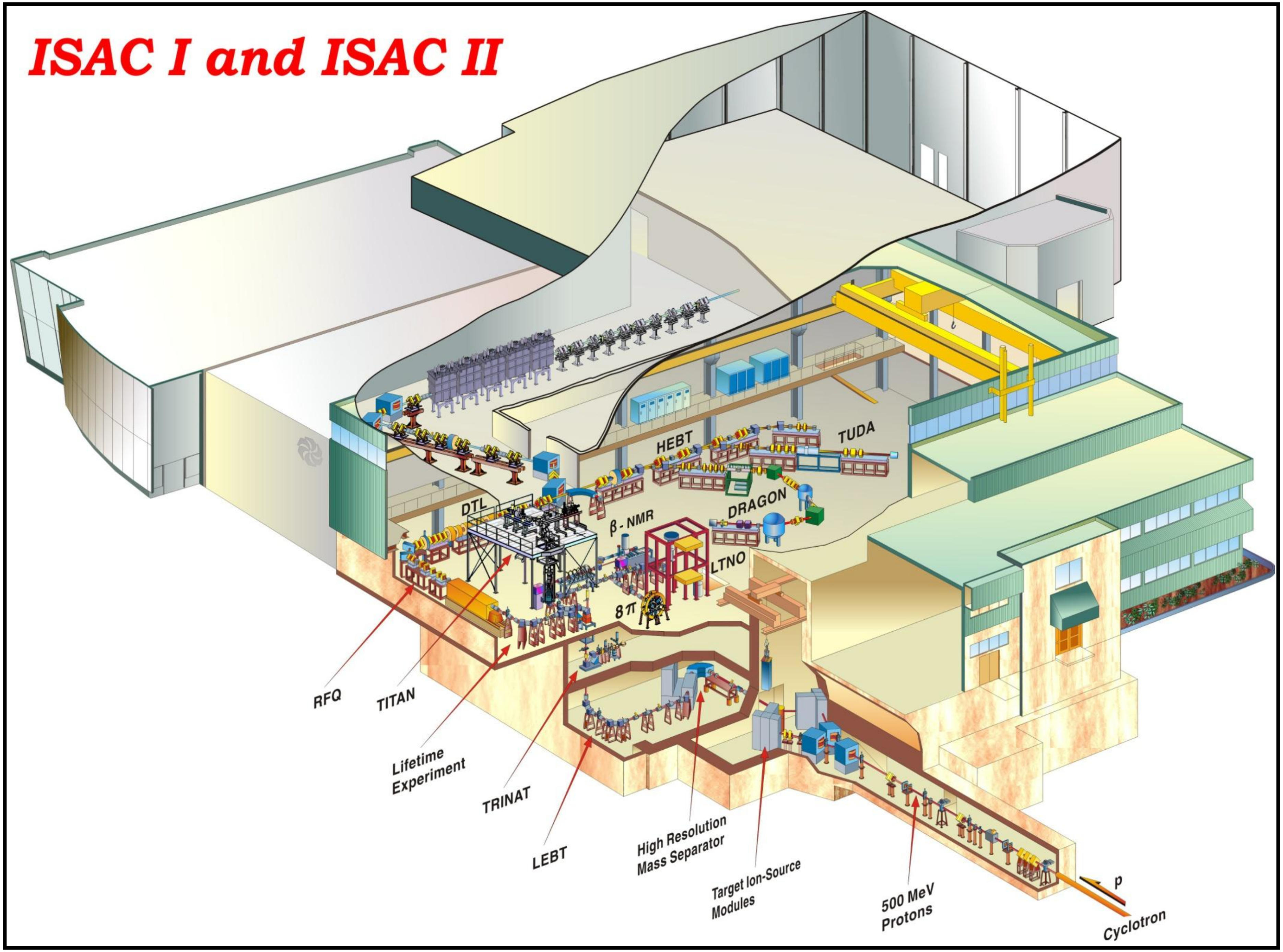
TRIUMF BEAMLINES AND EXPERIMENTAL FACILITIES



^{26}Al "secondary beam" for the experiment
Silicon Carbide target

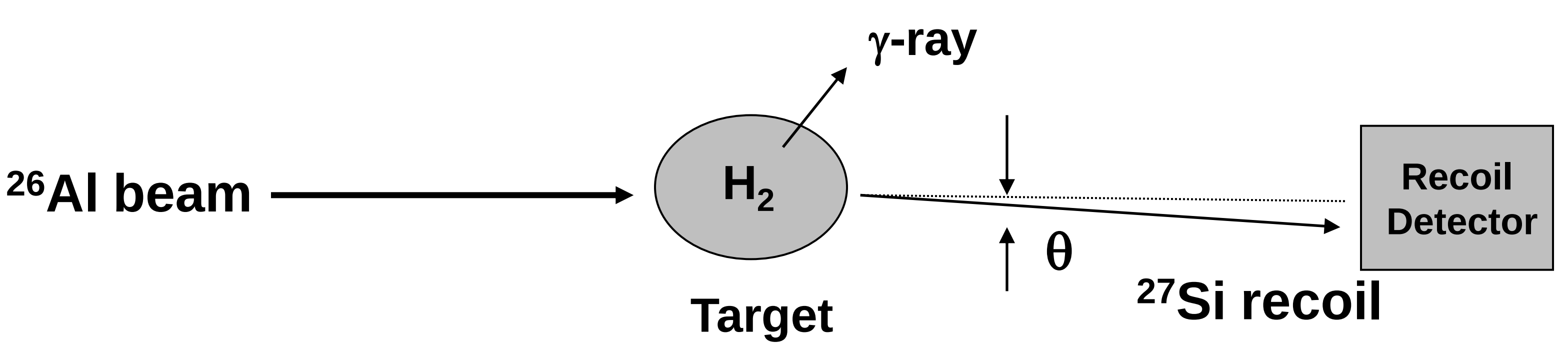
"primary beam": 70 μA of 500 MeV protons from cyclotron

ISAC I and ISAC II

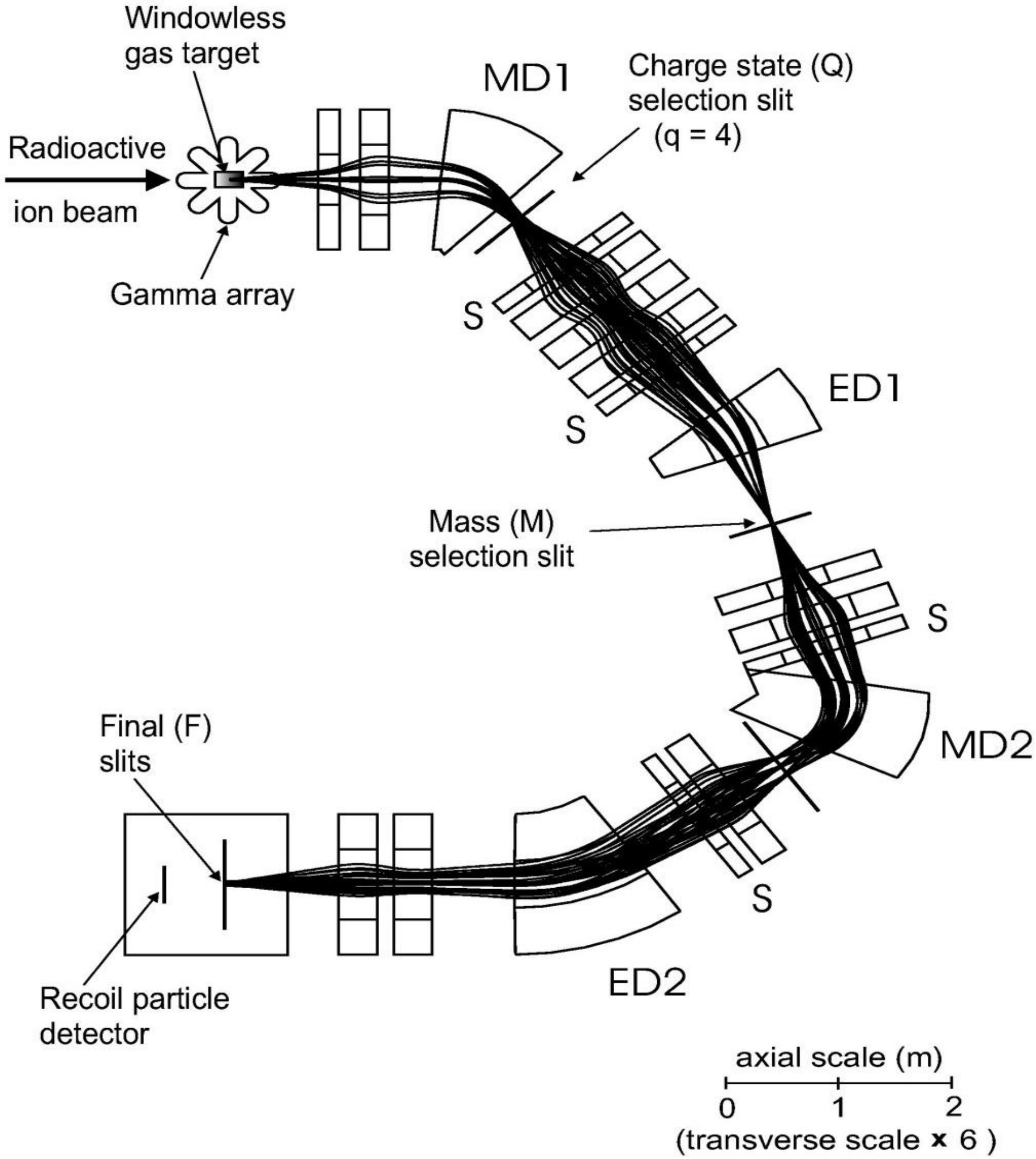


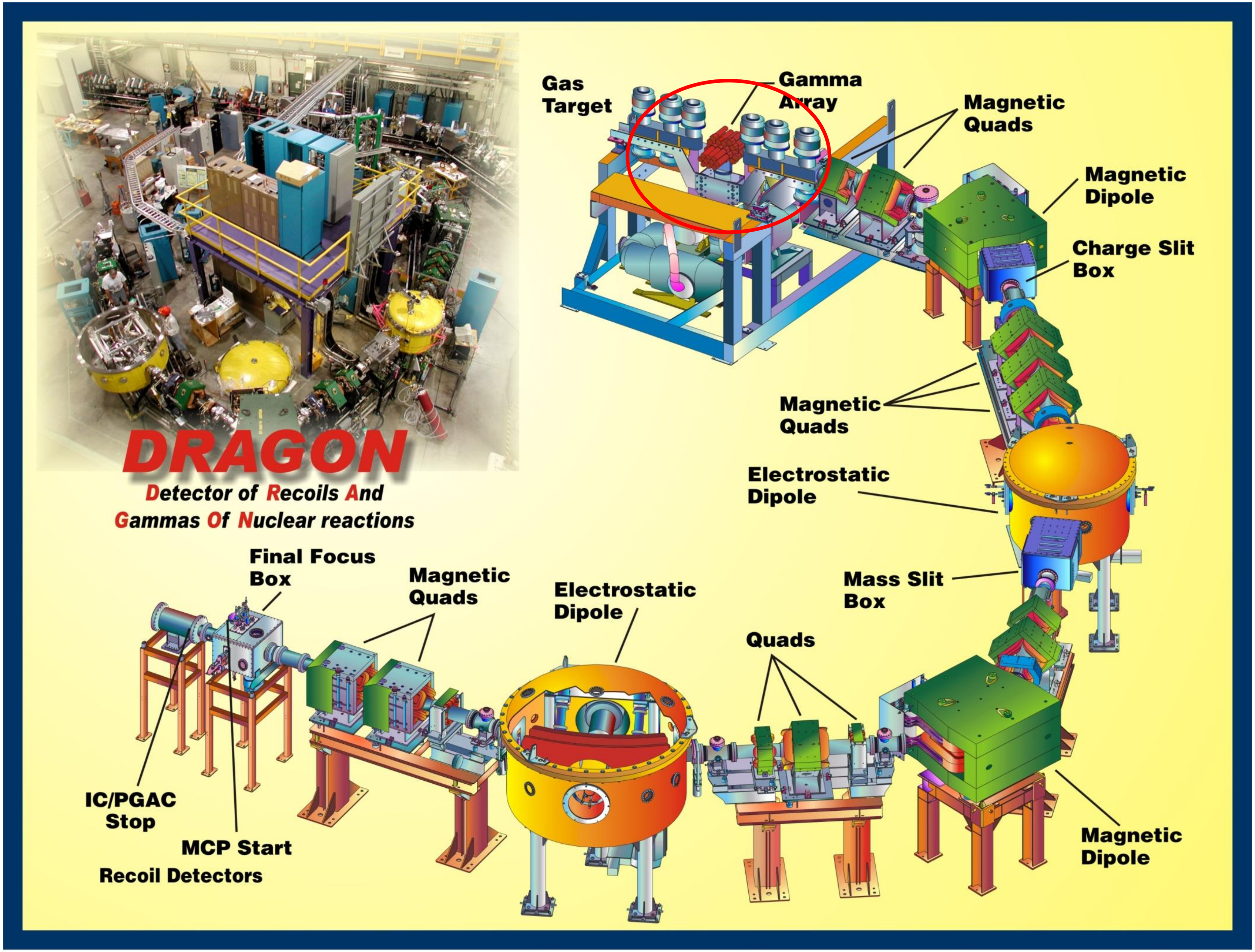
Measurement of $^{26}Al(p,\gamma)^{27}Si$ at TRIUMF-ISAC

- **Goal: determine the (p,γ)-strength of the E_{cm} = 188 keV resonance**
  - **$E_{beam}(^{26}Al)$ ~ 200 keV/u**
  - **Need ISAC beam intensity > 10^9 ions per second**
  - **Measure the yield of ^{27}Si recoils with DRAGON recoil separator (coincidence with prompt gamma rays)**

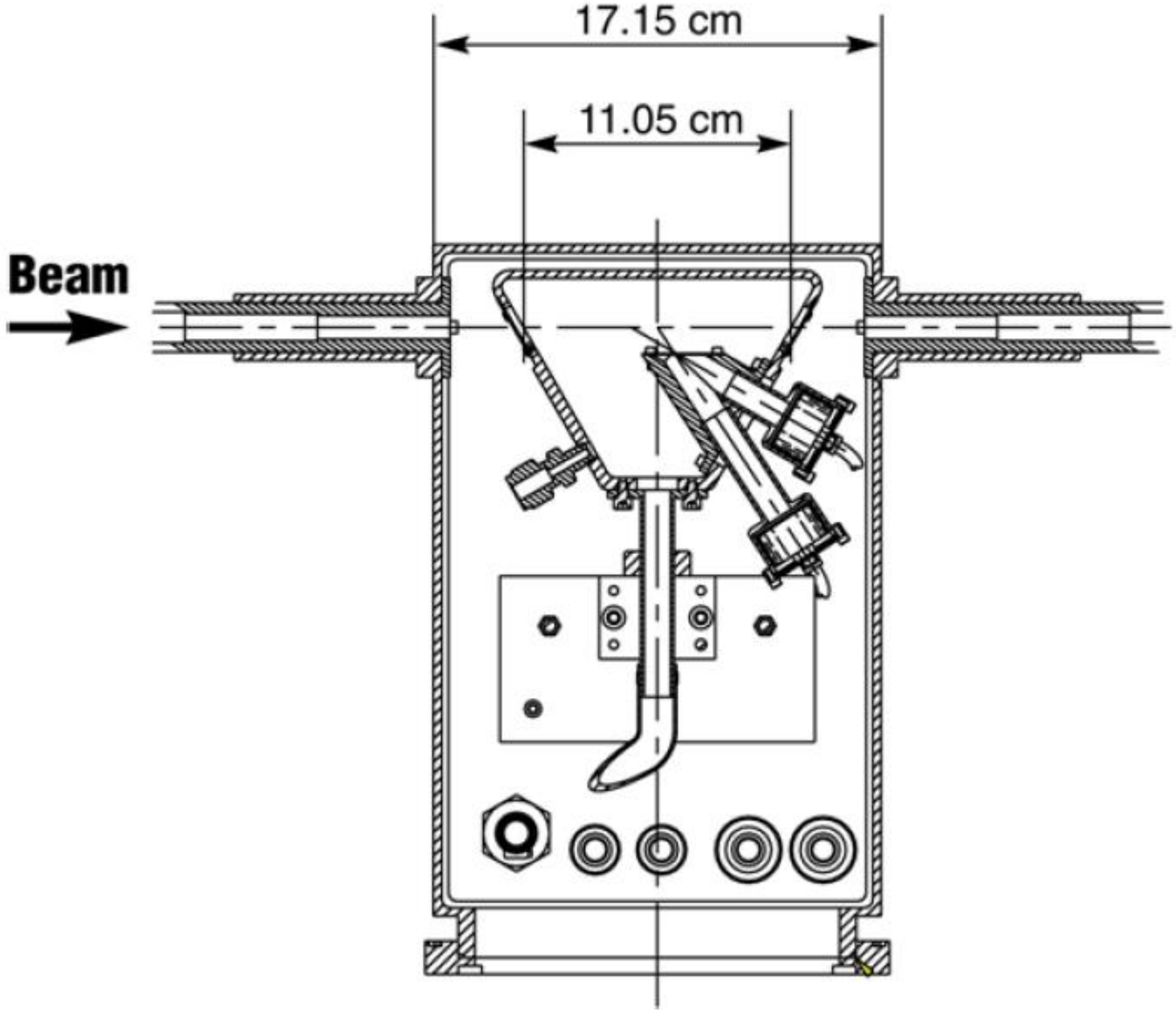


The DRAGON facility

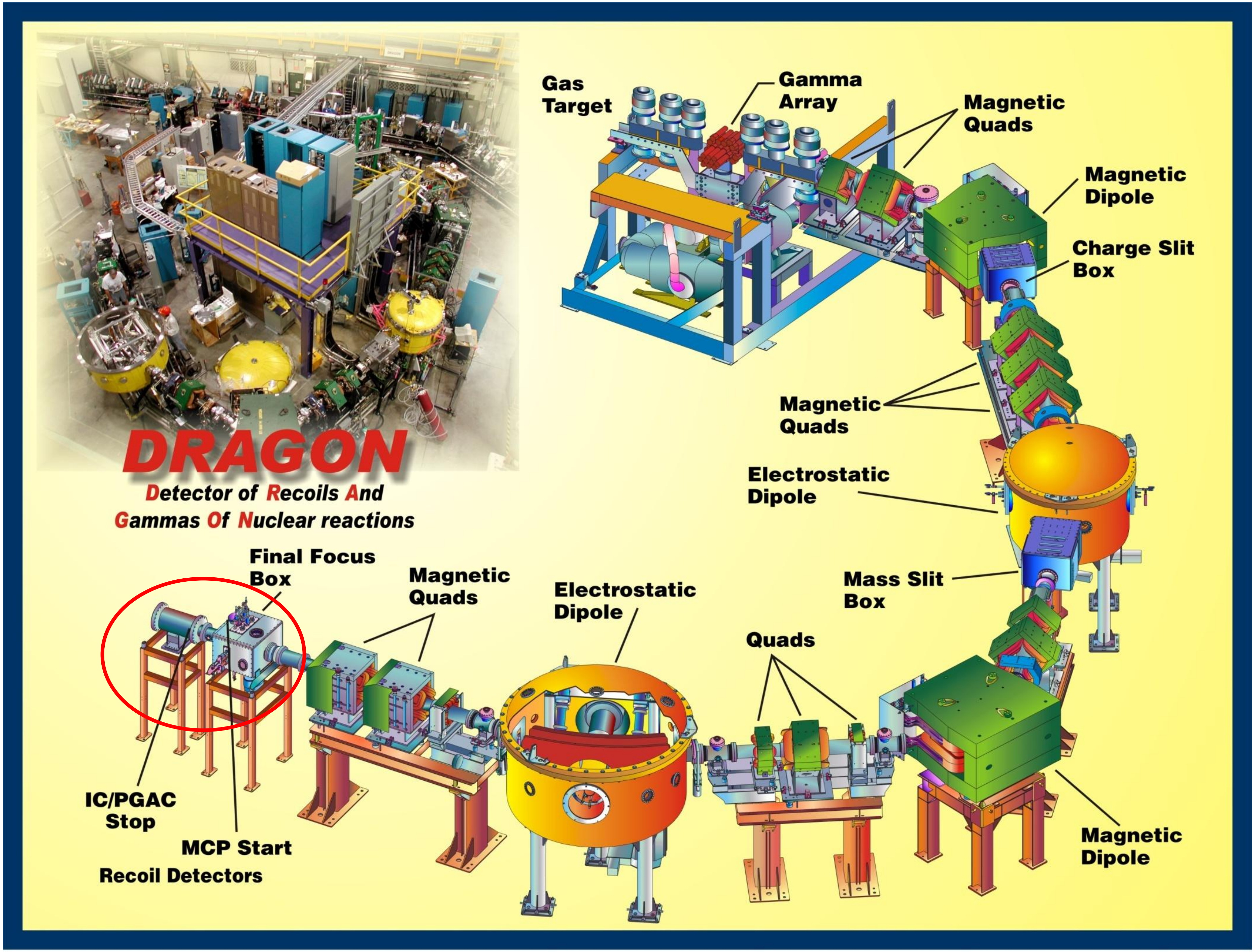



DRAGON
Detector of Recoils And
Gammas Of Nuclear reactions
Gas
Target
Gamma
Array
Magnetic
Quads
Magnetic
Dipole
Charge Slit
Box
Magnetic
Quads
Electrostatic
Dipole
Mass Slit
Box
Quads
Magnetic
Dipole
Electrostatic
Dipole
Magnetic
Quads
Final Focus
Box
IC/PGAC
Stop
MCP Start
Recoil Detectors

DRAGON: gas target

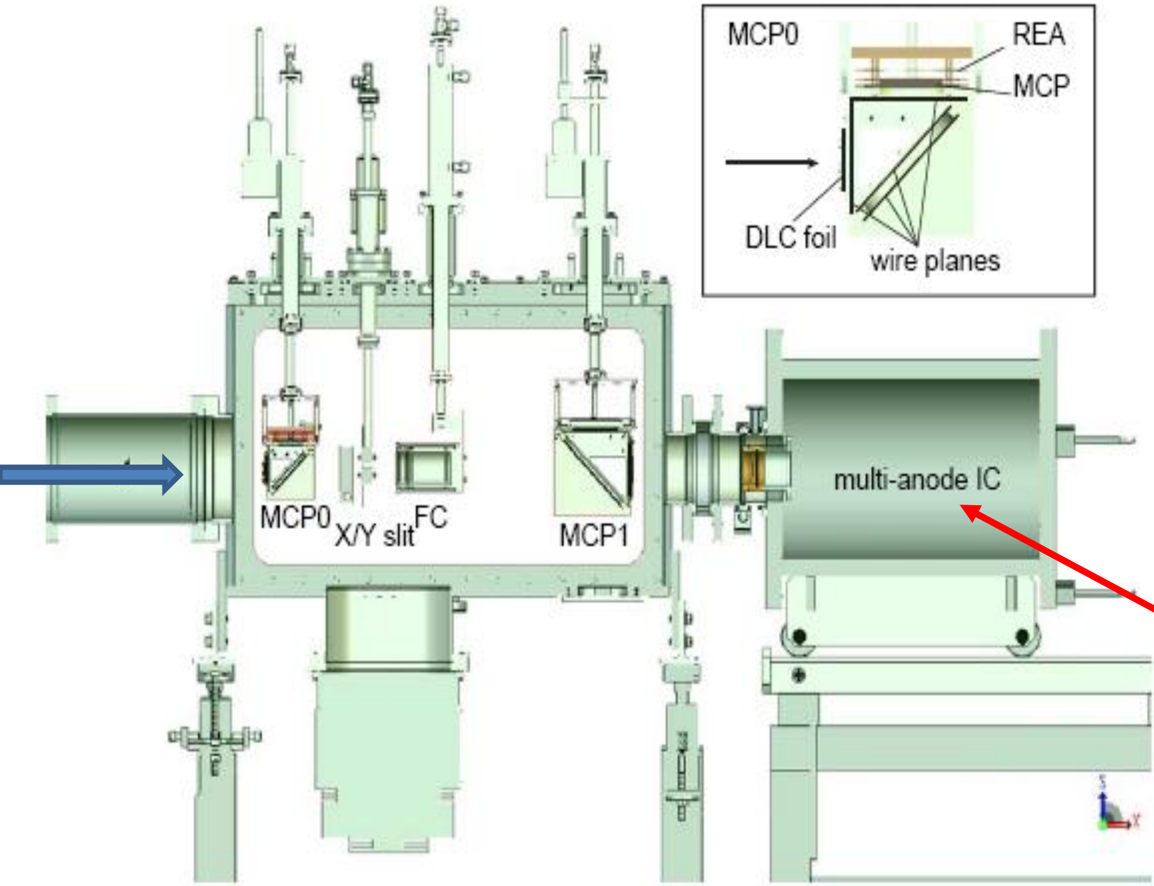


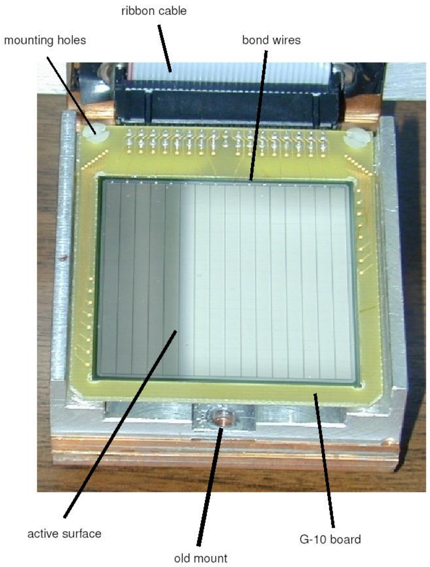
DRAGON: BGO array

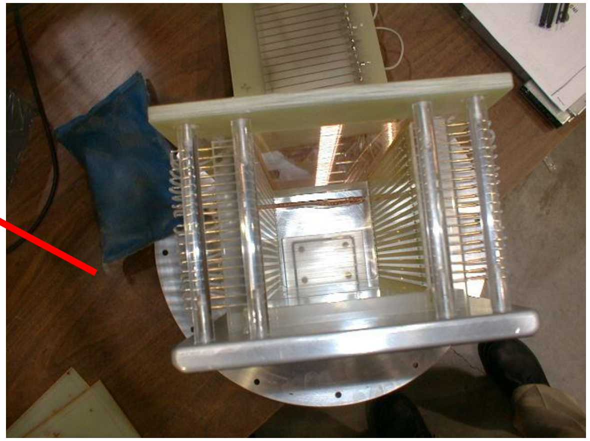


DRAGON
Detector of Recoils And
Gammas Of Nuclear reactions
Gas
Target
Gamma
Array
Magnetic
Quads
Magnetic
Dipole
Charge Slit
Box
Magnetic
Quads
Electrostatic
Dipole
Mass Slit
Box
Quads
Magnetic
Dipole
Electrostatic
Dipole
Magnetic
Quads
Final Focus
Box
IC/PGAC
Stop
MCP Start
Recoil Detectors

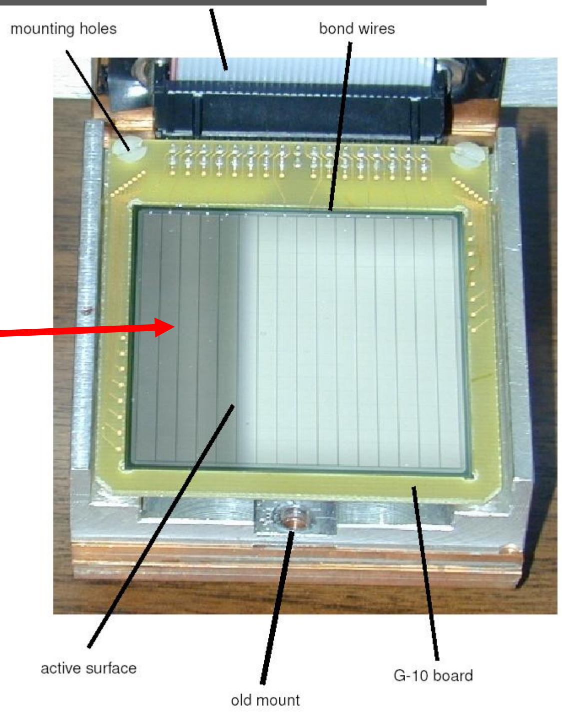
DRAGON end-detectors: local time-of-flight







DRAGON end-detectors

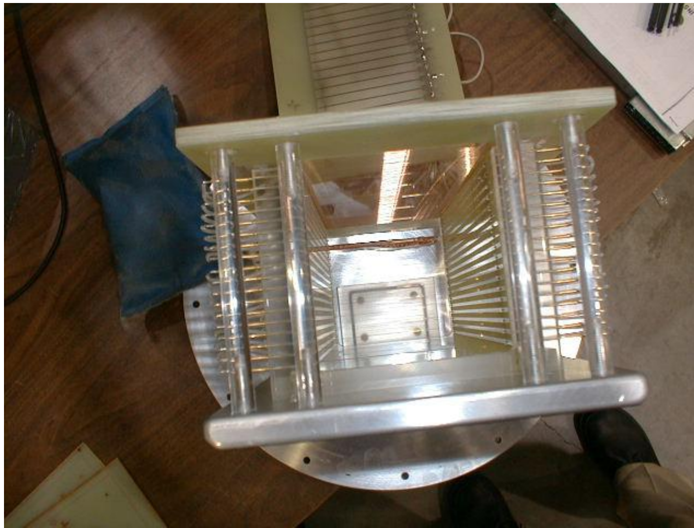


silicon strip detector ("DSSD")

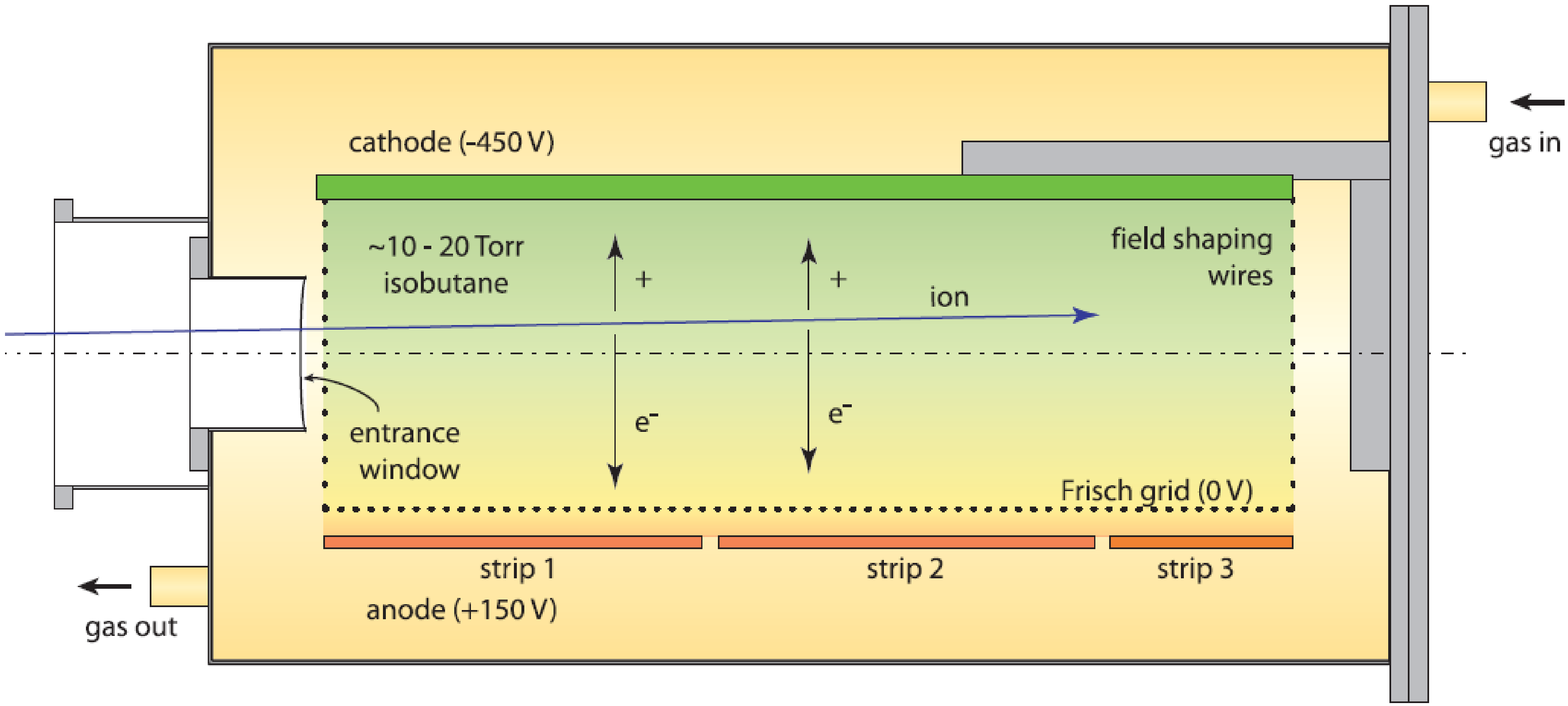
- time, position, energy
- $^{26}Al(p,\gamma)^{27}Si$

ionization chamber

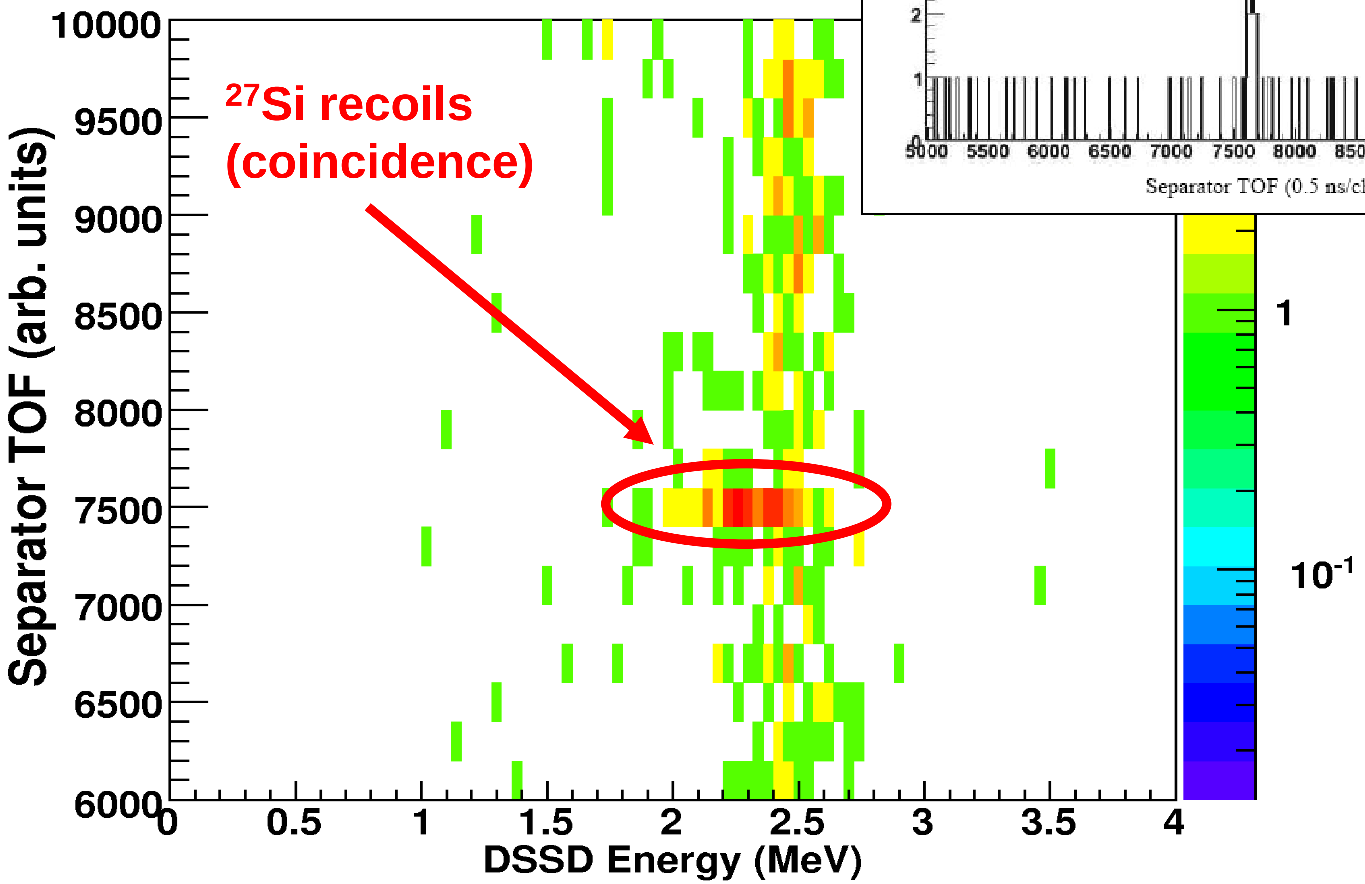
- energy for E-ΔE particle identification
- $^{40}Ca(\alpha,\gamma)^{44}Ti$

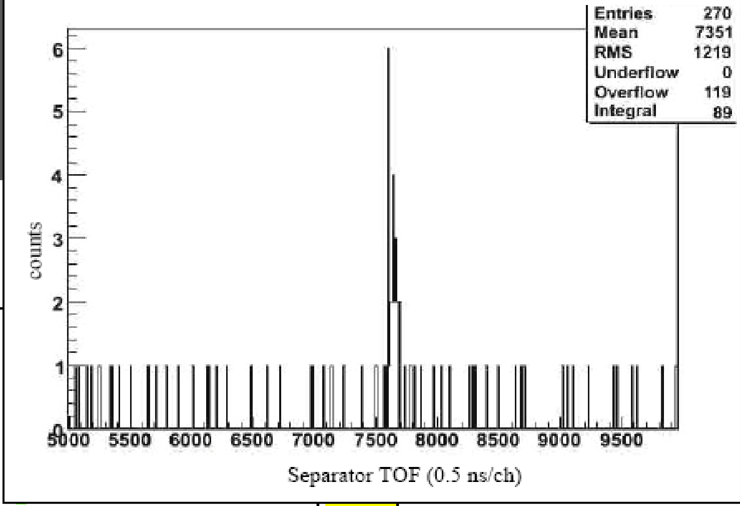


DRAGON: ionization chamber



$^{26}Al(p,\gamma)^{27}Si$ with DRAGON: ^{27}Si yield





^{27}Si time-of-flight through DRAGON vs. ^{27}Si energy

[Ruiz et al., PRL (2006)]

$\omega\gamma = 35 \pm 7\ \mu eV$

Recently: $^{23}Mg(p,\gamma)^{24}Al$ with DRAGON

(*L. Erikson et al., PRC 2010*)

Focused on important resonance of energy E_R ~ 473 keV:

- **^{23}Mg beam from ISAC**: 5 x 10^7 pps

  (strong contamination of **^{23}Na**, 20:1 -1000:1)

- **resonance energy**: 486 ± 2 keV

  (higher than previous value by 13 keV)

- **resonance strength**: $\omega\gamma$ = 38 ± 20 meV

PRL 110, 262502 (2013) PHYSICAL REVIEW LETTERS week ending 28 JUNE 2013

Measurement of Radiative Proton Capture on ^{18}F and Implications for Oxygen-Neon Novae

C. Akers,[1,2] A. M. Laird,[2] B. R. Fulton,[2] C. Ruiz,[1] D. W. Bardayan,[3] L. Buchmann,[1] G. Christian,[1] B. Davids,[1] L. Erikson,[4] J. Fallis,[1] U. Hager,[5] D. Hutcheon,[1] L. Martin,[1] A. St. J. Murphy,[6] K. Nelson,[7] A. Spyrou,[8,9] C. Stanford,[10] D. Ottewell,[1] and A. Rojas[1]

The rate of the ^{18}F$(p,\gamma)^{19}$Ne reaction affects the final abundance of the γ-ray observable radioisotope ^{18}F, produced in novae. However, no successful measurement of this reaction exists and the rate used is calculated from incomplete information on the contributing resonances. Of the two resonances thought to play a significant role, one has a radiative width estimated from the assumed analogue state in the mirror nucleus, ^{19}F. The second does not have an analogue state assignment at all, resulting in an arbitrary radiative width being assumed. Here, we report the first successful direct measurement of the ^{18}F$(p,\gamma)^{19}$Ne reaction. The strength of the 665 keV resonance ($E_x = 7.076$ MeV) is found to be over an order of magnitude weaker than currently assumed in nova models. Reaction rate calculations show that this resonance therefore plays no significant role in the destruction of ^{18}F at any astrophysical energy.

PRL 102, 152502 (2009) PHYSICAL REVIEW LETTERS week ending 17 APRIL 2009

First Direct Measurement of the ^{17}F$(p,\gamma)^{18}$Ne Cross Section

K. A. Chipps,[1,*] D. W. Bardayan,[2] J. C. Blackmon,[3] K. Y. Chae,[4] U. Greife,[1] R. Hatarik,[5] R. L. Kozub,[6] C. Matei,[7] B. H. Moazen,[4] C. D. Nesaraja,[2,4] S. D. Pain,[2,4] W. A. Peters,[5] S. T. Pittman,[4] J. F. Shriner, Jr.,[6] and M. S. Smith[2]

The rate of the ^{17}F$(p,\gamma)^{18}$Ne reaction is important in various astrophysical events. A previous ^{17}F$(p,p)^{17}$F measurement identified a 3^+ state providing the strongest resonance contribution, but the resonance strength was unknown. We have directly measured the ^{17}F$(p,\gamma)^{18}$Ne reaction using a mixed beam of ^{17}F and ^{17}O at ORNL. The resonance strength for the 3^+ resonance in ^{18}Ne was found to be $\omega\gamma = 33 \pm 14(\text{stat}) \pm 17(\text{syst})$ meV, corresponding to a γ width of $\Gamma_\gamma = 56 \pm 24(\text{stat}) \pm 30(\text{syst})$ meV. An upper limit on the direct capture of $S(E) \leq 65$ keV b was determined at an energy of 800 keV.

future plans with DRAGON

Reaction	Importance	Experiment
$^{17}F(p,\gamma)^{18}Ne$ *(Chen et al.)*	production of gamma-emitter ^{18}F in novae; break out from the Hot-CNO cycle in x-ray bursts	Need 10^{7-8} ions per sec.
$^{25}Al(p,\gamma)^{26}Si$ *(Chen et al.)*	production of gamma-emitter ^{26}Al in explosive hydrogen burning	Need 10^{8-9} ions per sec.

future plans with DRAGON

Reaction	Importance	Experiment
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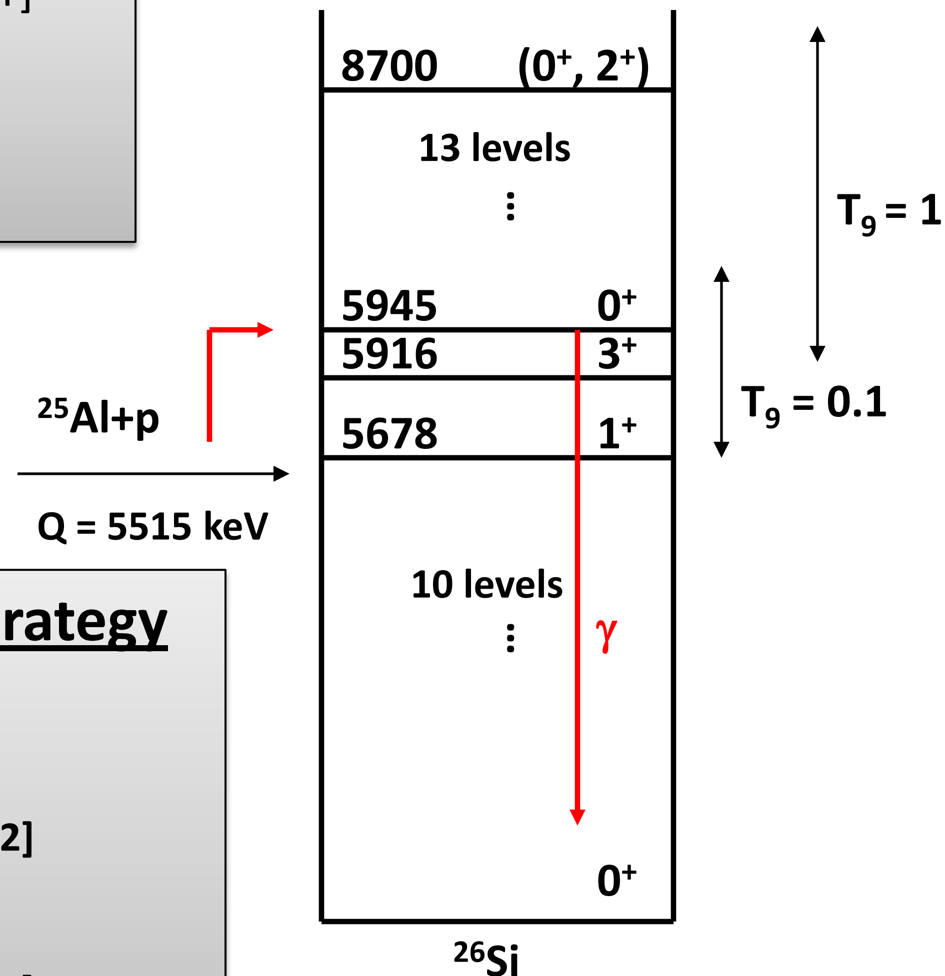
Good candidate for "indirect" approaches...

$^{25}Al(p,\gamma)^{26}Si$, indirectly

Stellar reaction rate:

$N_A\langle\sigma v\rangle = 1.54\times10^{11}\,(\mu T)^{-3/2}\,\omega\gamma\,\exp\,[-11.605\,E_R / T]$

where E_R = resonance energy
$\omega\gamma$ depends on J^π and $\Gamma_p\,\Gamma_\gamma / \Gamma_{total}$



$^{25}Al(p,\gamma)^{26}Si$, indirectly: two-part strategy

in-beam γ-ray spectroscopy (NSCL)

[J. Chen *et al.*, PRC 045809 2012]

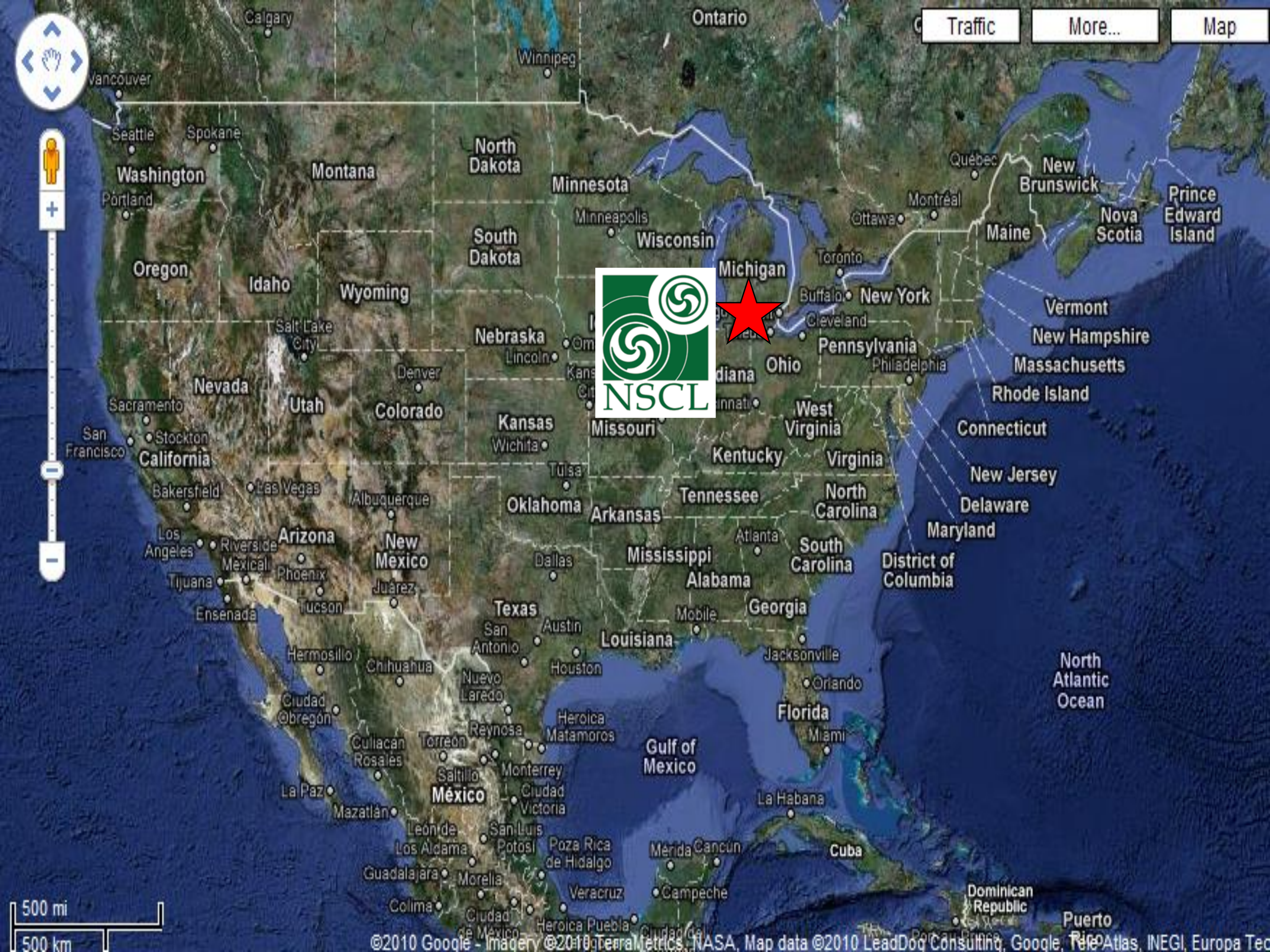
elastic proton scattering (RIKEN)

[J. Chen *et al.*, PRC 015805 2012]

the $^{25}Al(p,\gamma)^{26}Si$ reaction: indirect approaches

- ***Direct measurement:***
  - need beam with more than 10^8 ions per second: ISAC? REX-ISOLDE?
- ***Indirect studies:***
  - (^3He,^6He) Caggiano et al. 2002
  - (^3He,n) Parpottas et al. 2004
  - ^{26}P decay Thomas et al. 2004, Wrede et al. 2013
  - ^{26}Si mass Parikh et al. 2005 + Eronen et al. 2009 + Kwiatkowski et al. 2010
  - (^4He,^6He) Kwon et al. 2006
  - (p,t) Bardayan et al. 2006
  - (^{16}O,2n) Seweryniak et al. 2007
  - (d,n) Peplowski et al. 2009
  - (^3He,nγ) Komatsubara et al. 2010 + de Séréville et al. 2010

McMaster: (*p,d*) with rare isotope beams at the NSCL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Colima
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500 mi
500 km
NSCL
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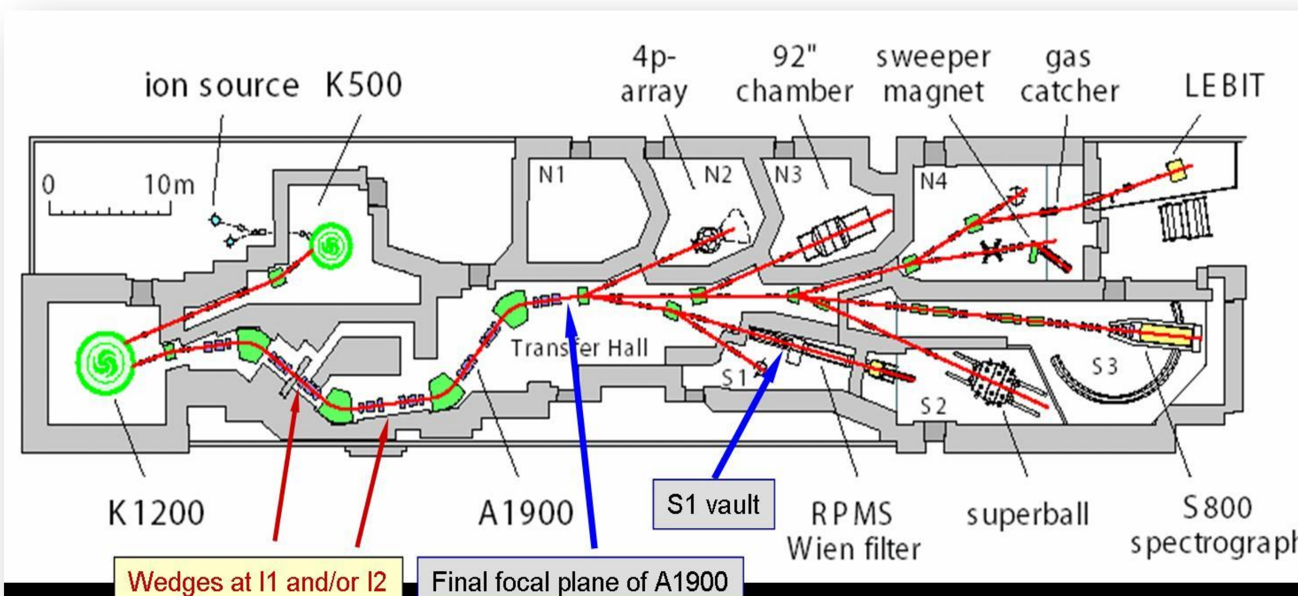
studying ^{26}Si at the NSCL with ^{27}Si(p,d)^{26}Si

Jun Chen
Ph.D. Thesis



MICHIGAN STATE UNIVERSITY

NSCL

p(^{27}Si,^{26}Si)d at NSCL: experiment details

– ***single neutron removal:*** easy beam intensity, large cross-section

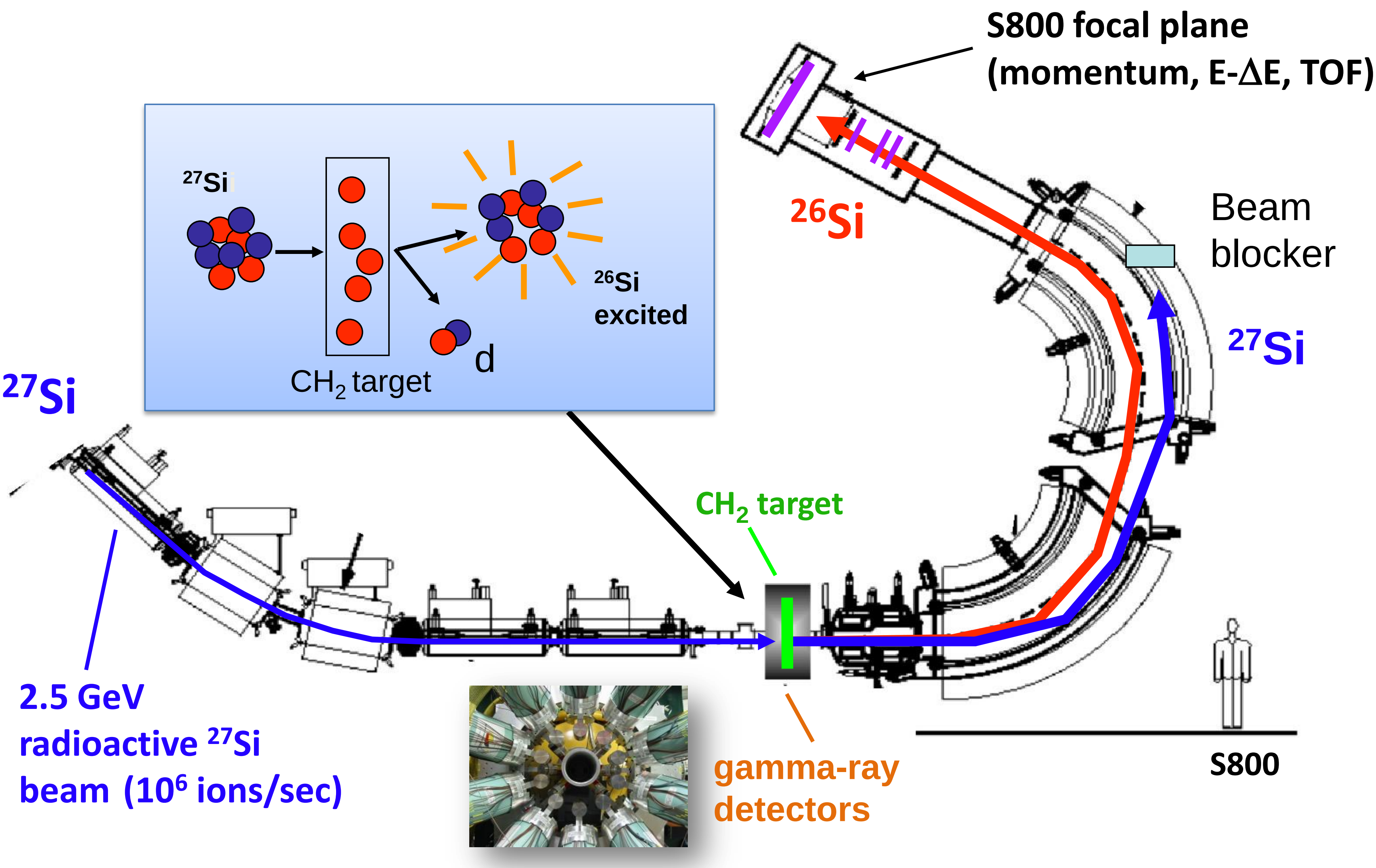
– ***^{27}Si beam*** ($T_{1/2}$ = 4.2 sec)
  – ^{34}Ar beam (150 MeV/u) + Be target → fragmentation
  – selection of ^{27}Si ions with the S1900 spectrometer

→ 10^6 ions/sec, 50% purity, 92 MeV/u

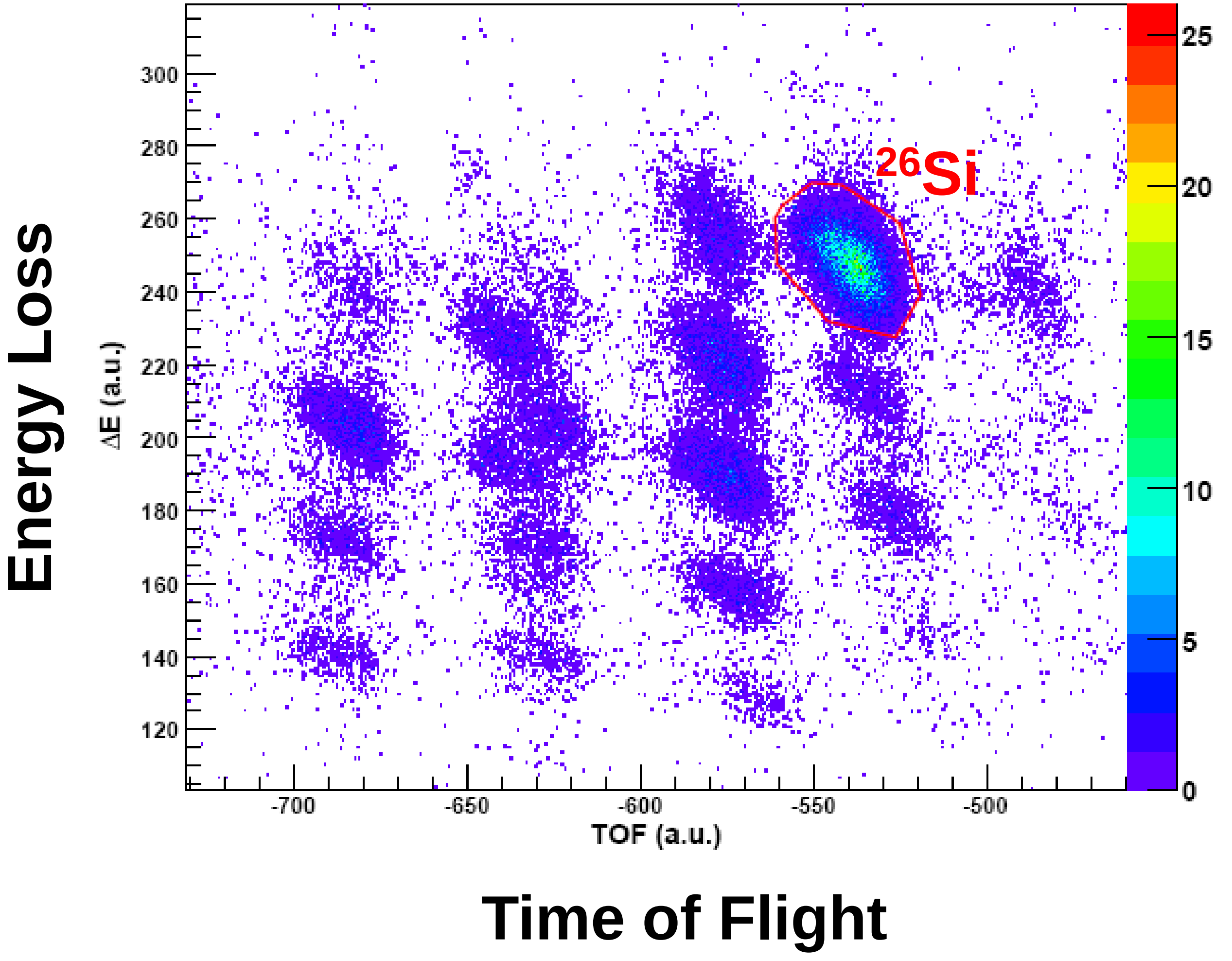
– ***proton target:*** CH_2 foil, ~ 2 mm thick, at the entrance to the S800 spectrometer

– ***goals:***
  – populate excited states of ^{26}Si
  – measure decay gamma rays
  – search for the 3^+ and 0^+ proton-unbound states

^{27}Si(p,d)^{26}Si: experiment setup

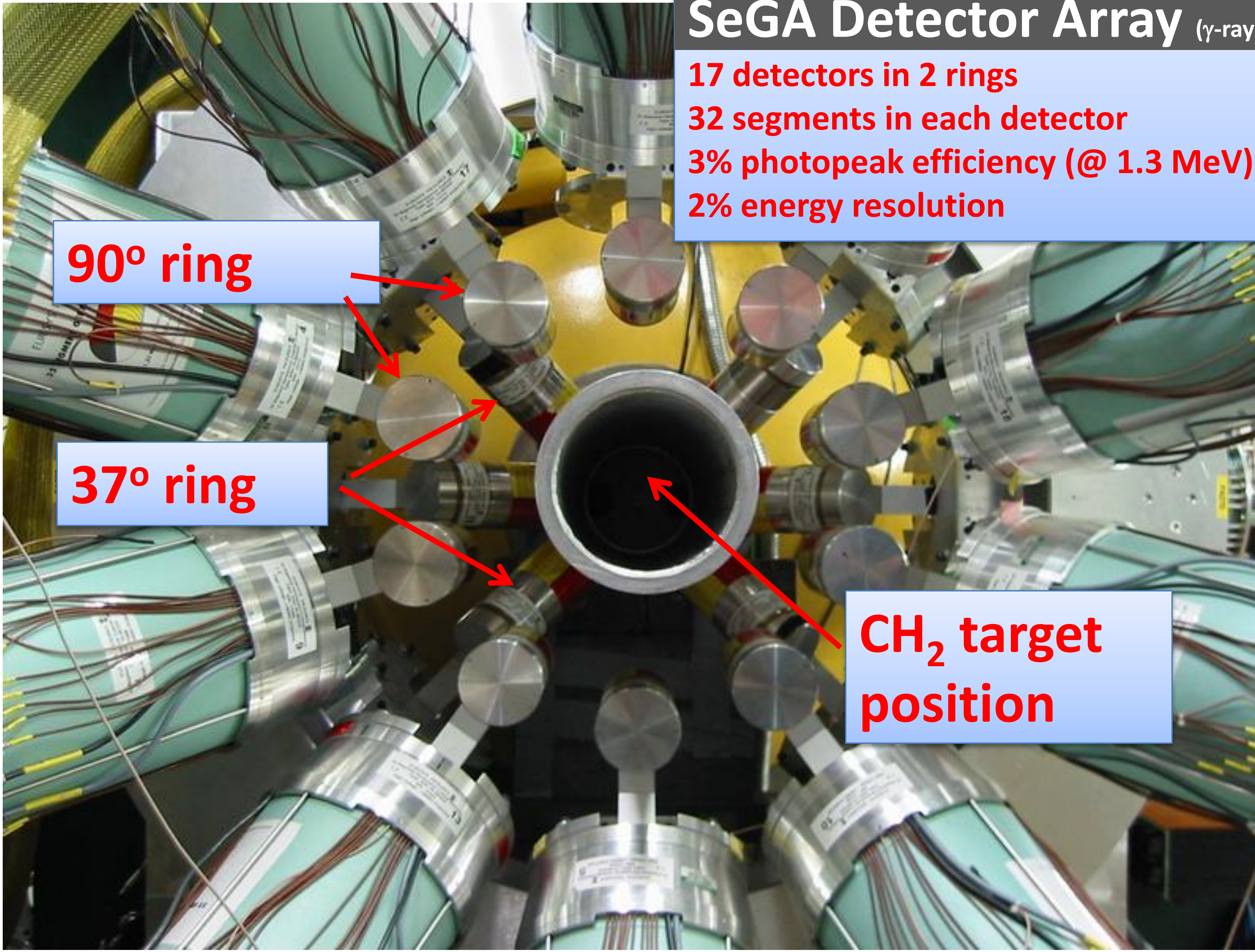


silicon-26 in the S800

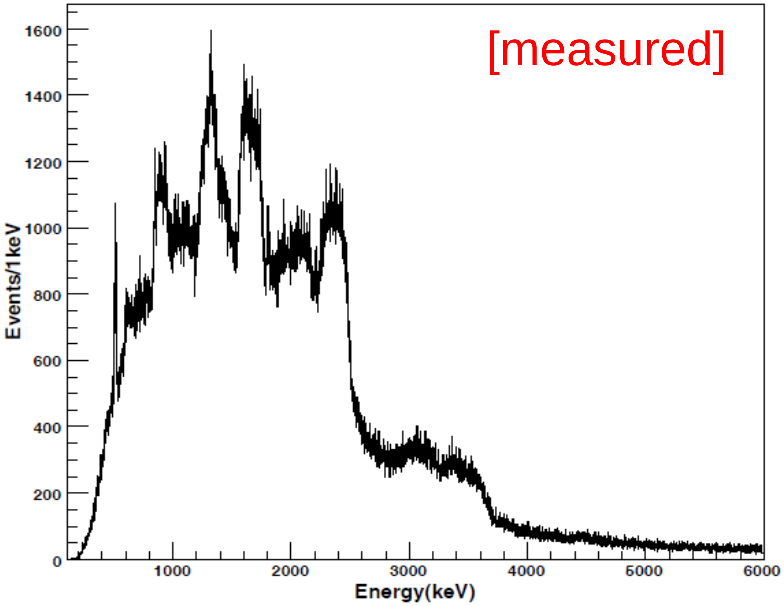


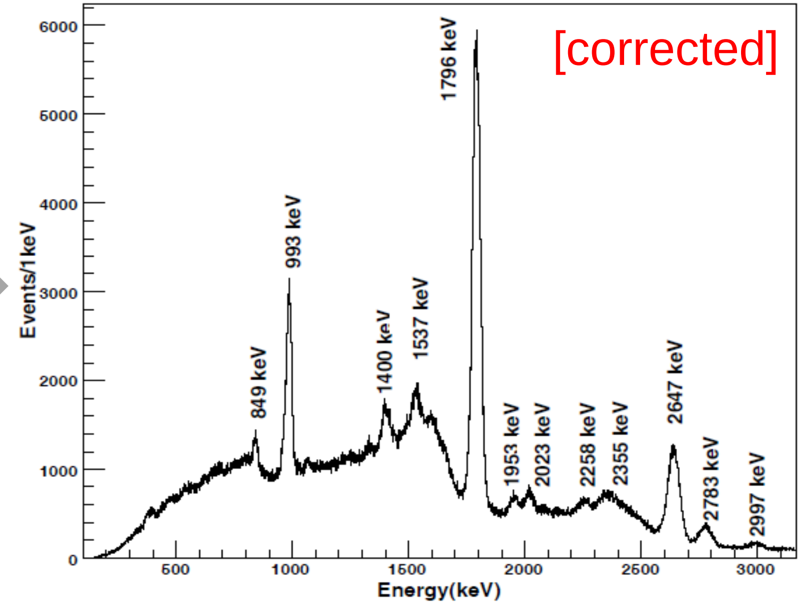
SeGA Detector Array (γ-rays)

- 17 detectors in 2 rings
- 32 segments in each detector
- 3% photopeak efficiency (@ 1.3 MeV)
- 2% energy resolution



γ-rays in SeGA: doppler broadening correction

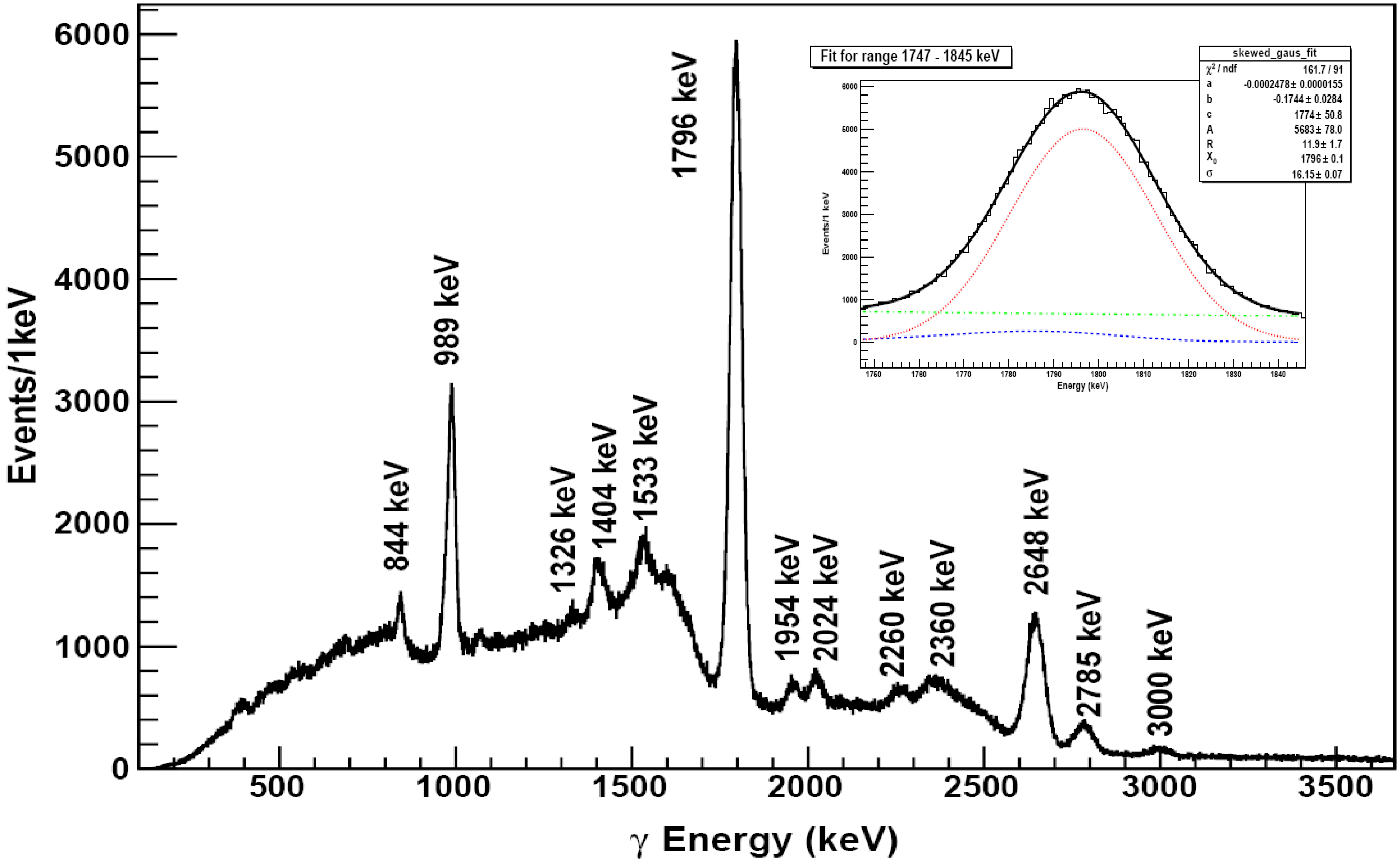




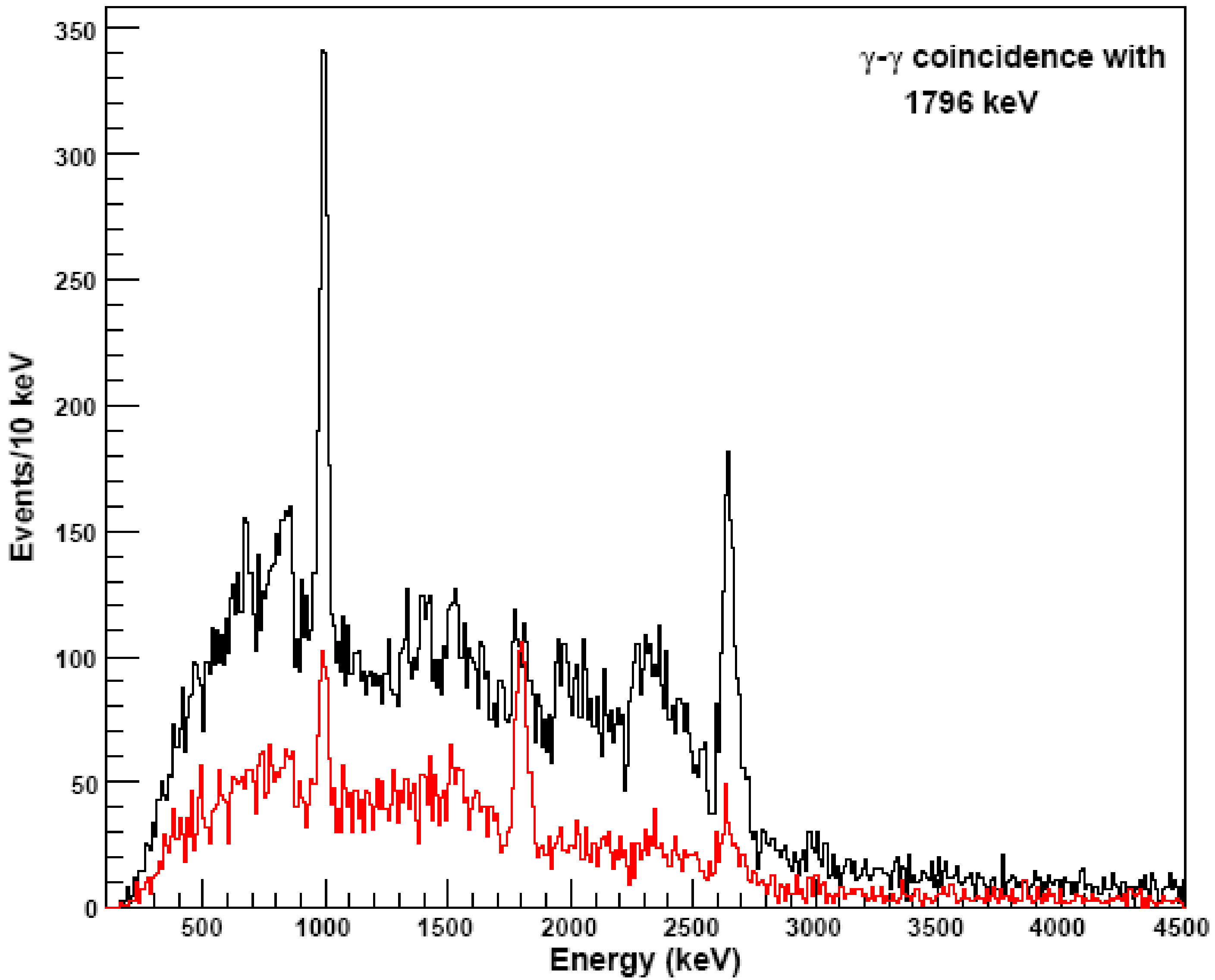
$$E_{corrected} = \frac{1-\beta\cos\theta}{\sqrt{1-\beta^2}} E_{measured}$$

$$\text{where } \beta = \frac{v}{c} \text{ and } v = \text{velocity of } {}^{26}\text{Si} \, (\sim 0.4\,\text{c})$$

γ-rays from ^{26}Si excited nuclear states



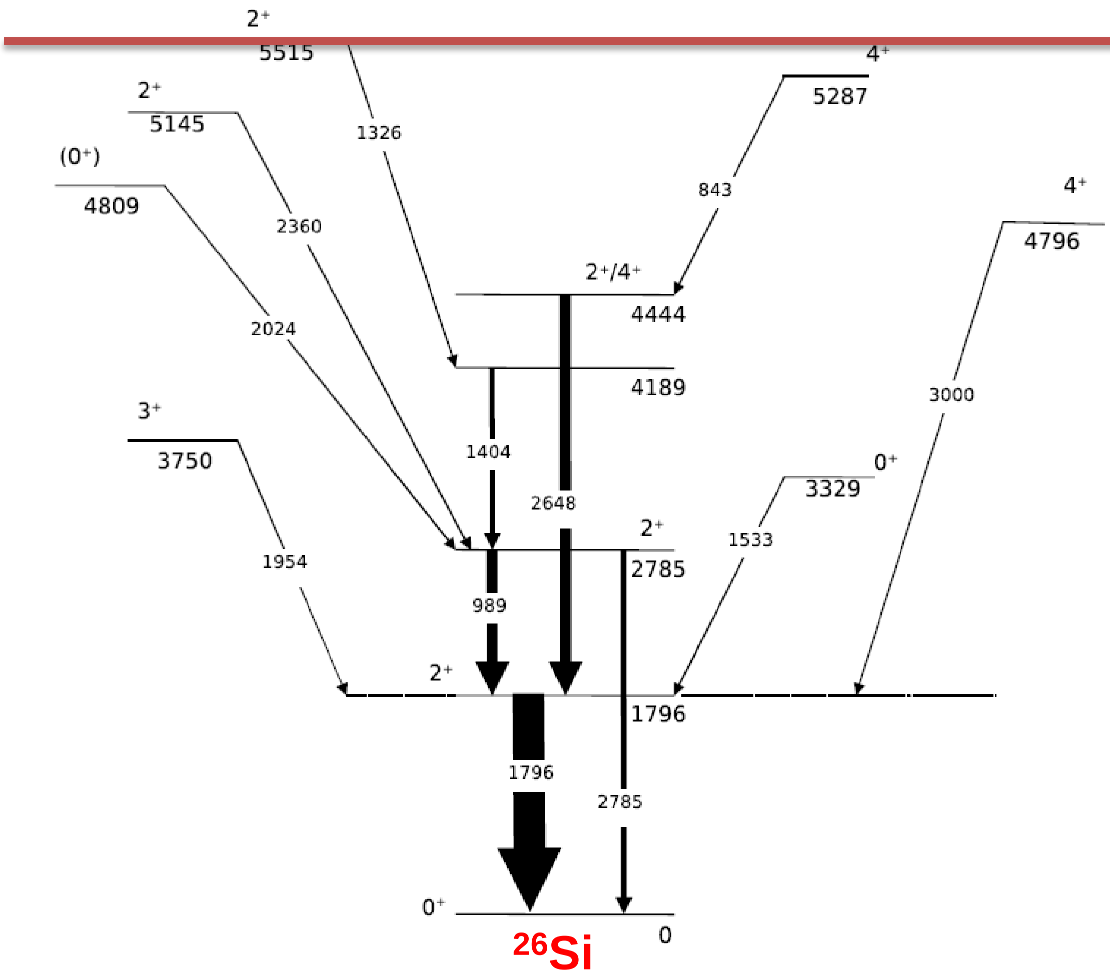
γ-γ coincidence analysis



^{26}Si level scheme

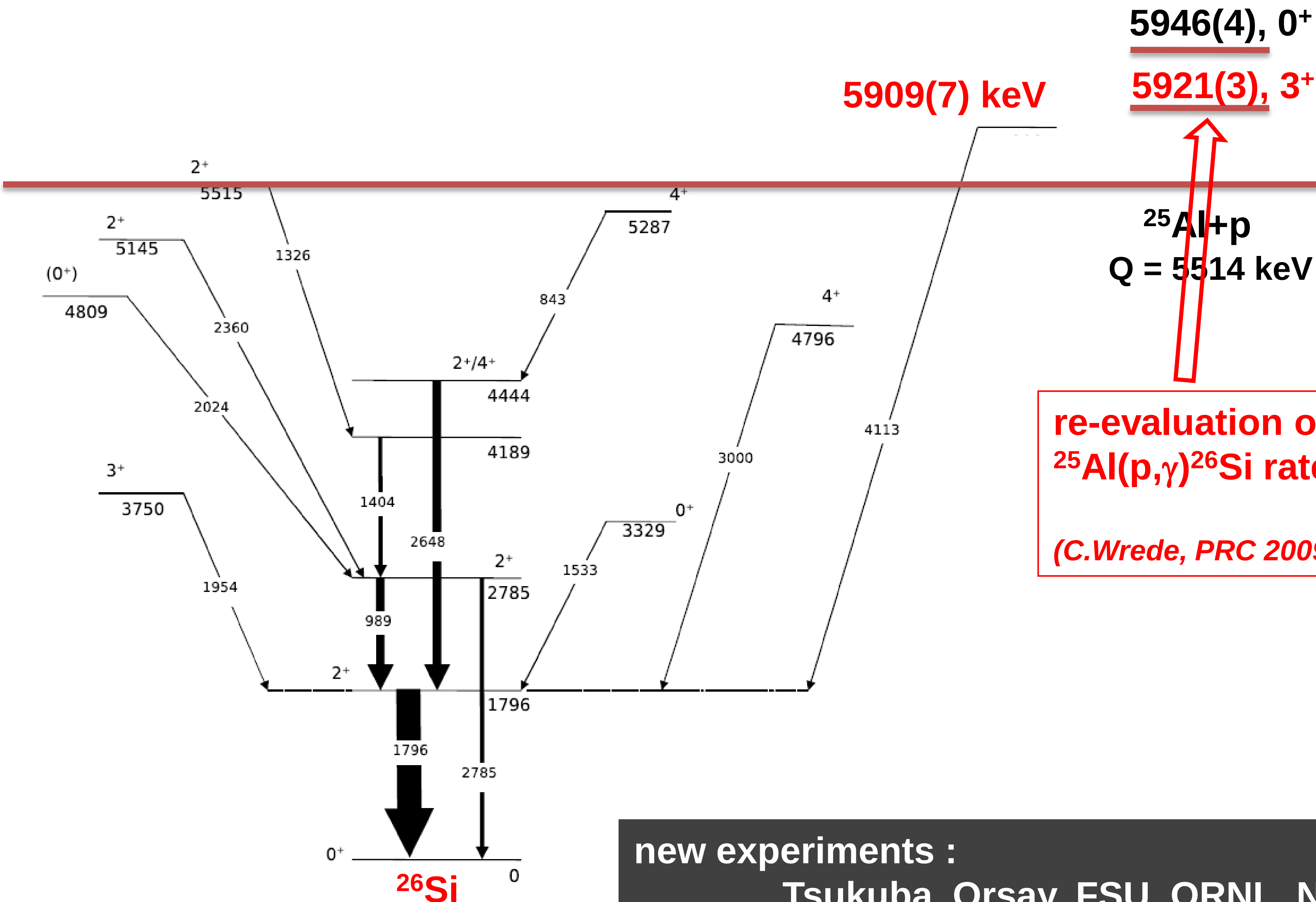
5946(4), 0$^+$

5914(3), 3$^+$



^{25}Al+p
Q = 5514 keV

^{26}Si level scheme



re-evaluation of ^{25}Al(p,γ)^{26}Si rate

(C.Wrede, PRC 2009)

new experiments :

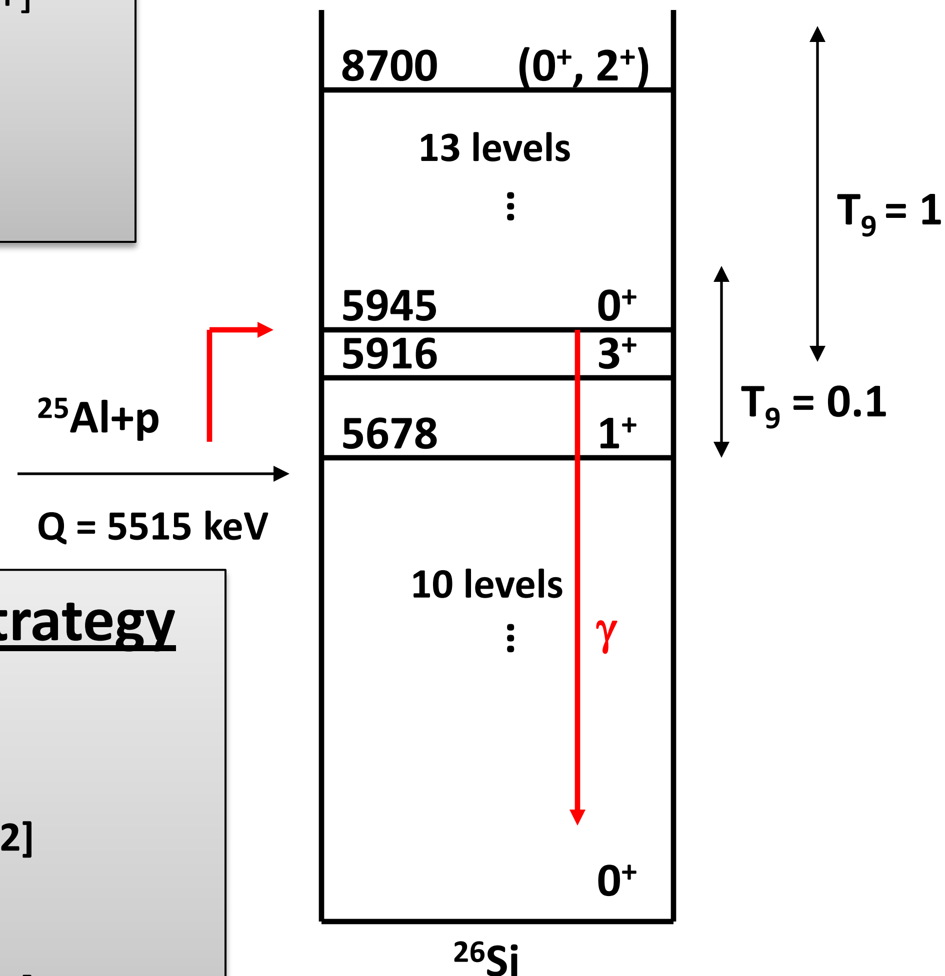
Tsukuba, Orsay, FSU, ORNL, NSCL

$^{25}Al(p,\gamma)^{26}Si$ with $^{25}Al+p$ elastic scattering

Stellar reaction rate:

$N_A\langle\sigma\nu\rangle = 1.54\times10^{11}\,(\mu T)^{-3/2}\,\omega\gamma\,\exp\,[-11.605\,E_R\,/\,T]$

where **E_R = resonance energy**
$\omega\gamma$ depends on J^π and $\Gamma_p\,\Gamma_\gamma / \Gamma_{total}$



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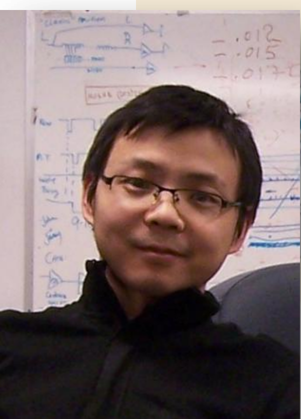
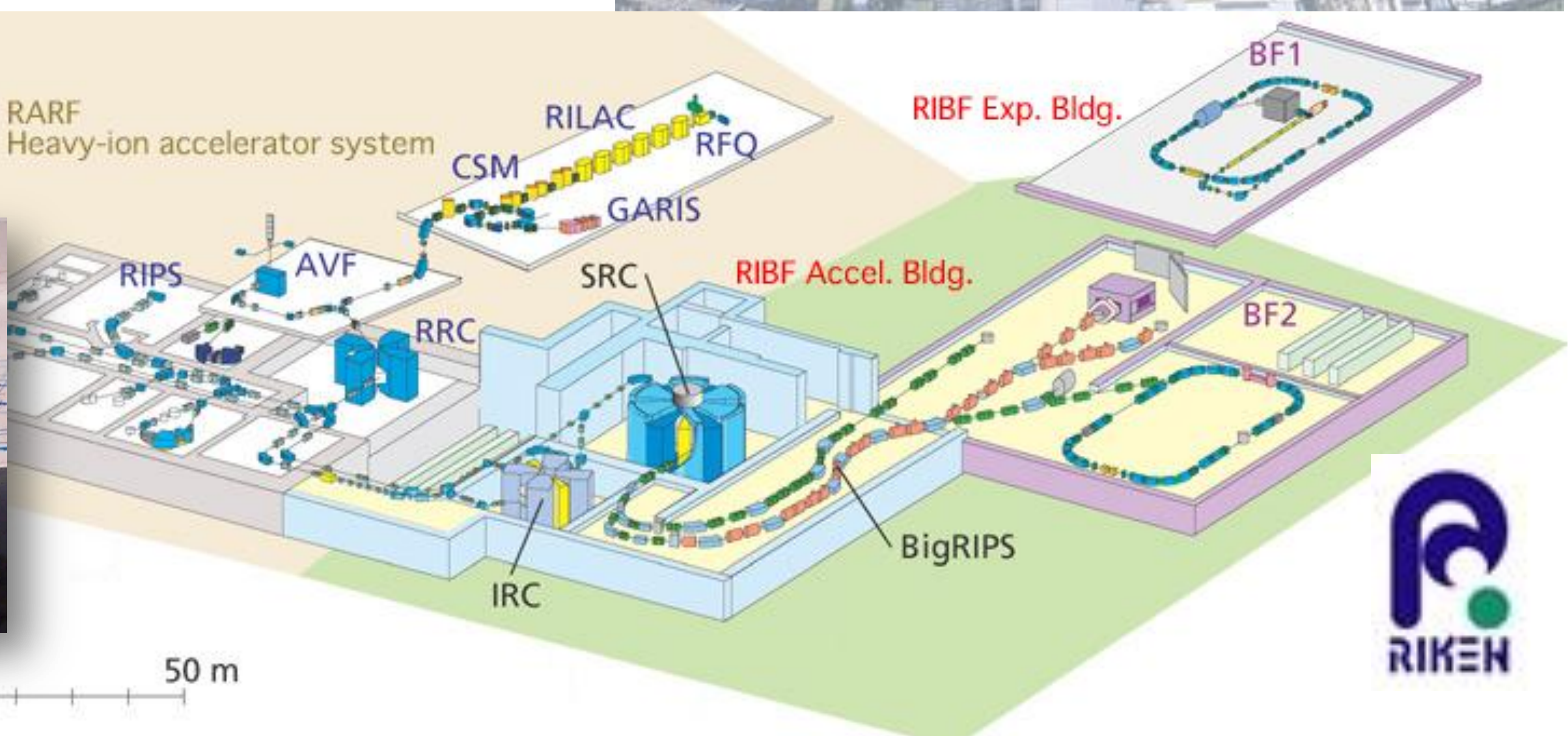
千葉
Okayama
岡山
Osaka
大阪
Tsu
津
Shizuoka
静岡
Hiroshima
広島
Takamatsu
高松
Fukuoka
福岡
Yamaguchi
山口
Matsuyama
松山
Kochi
高知
Kumamoto
熊本
Oita
大分
Nagasaki
長崎
Kagoshima
鹿児島
Miyazaki
宮崎
RIKEN
Google
100 mi
200 km
Imagery ©2010 TerraMetrics, Map data ©2010 SK M&C, Geocentre Consulting, NFGIS, ZENRIN - Terms of

p(^{25}Al,p)^{25}Al with CRIB at CNS (RIKEN)

Local collaborators: S. Kubono and team, Center for Nuclear Study, University of Tokyo

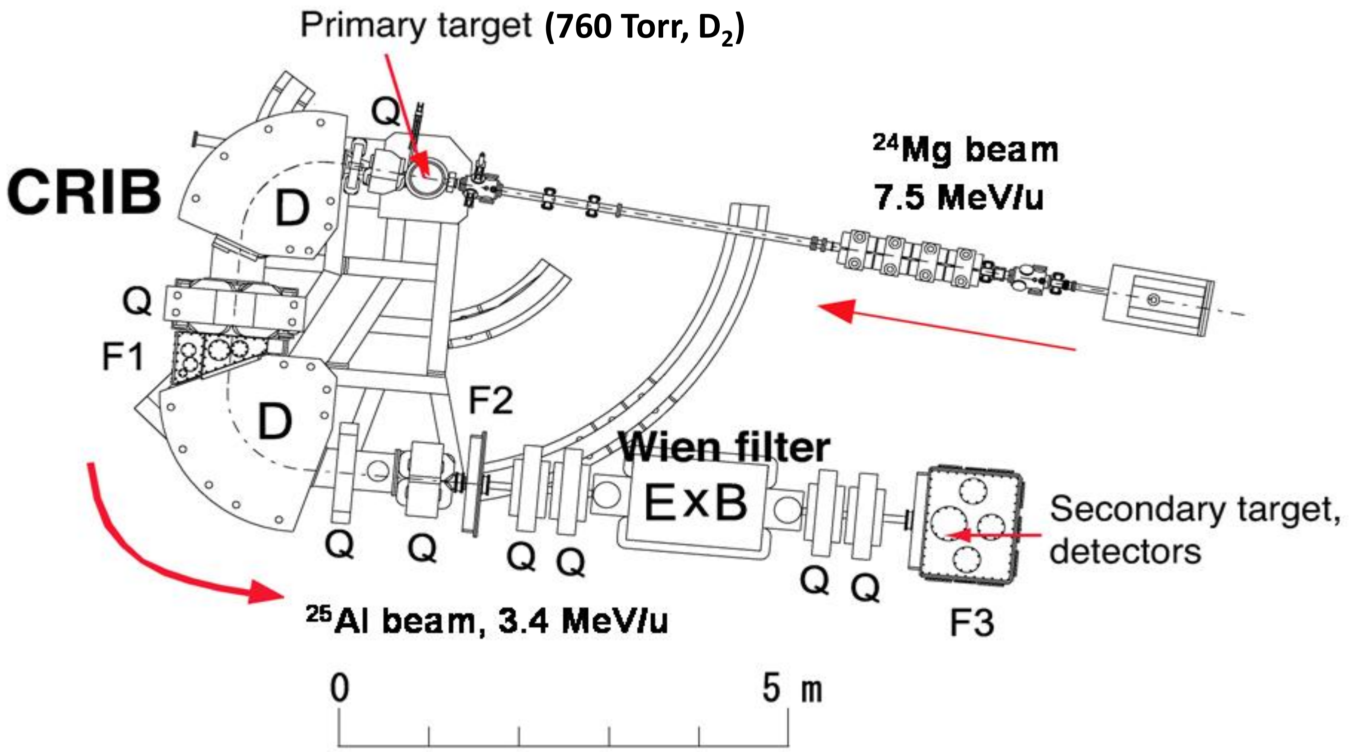
Jun Chen
Ph.D. thesis
Part I





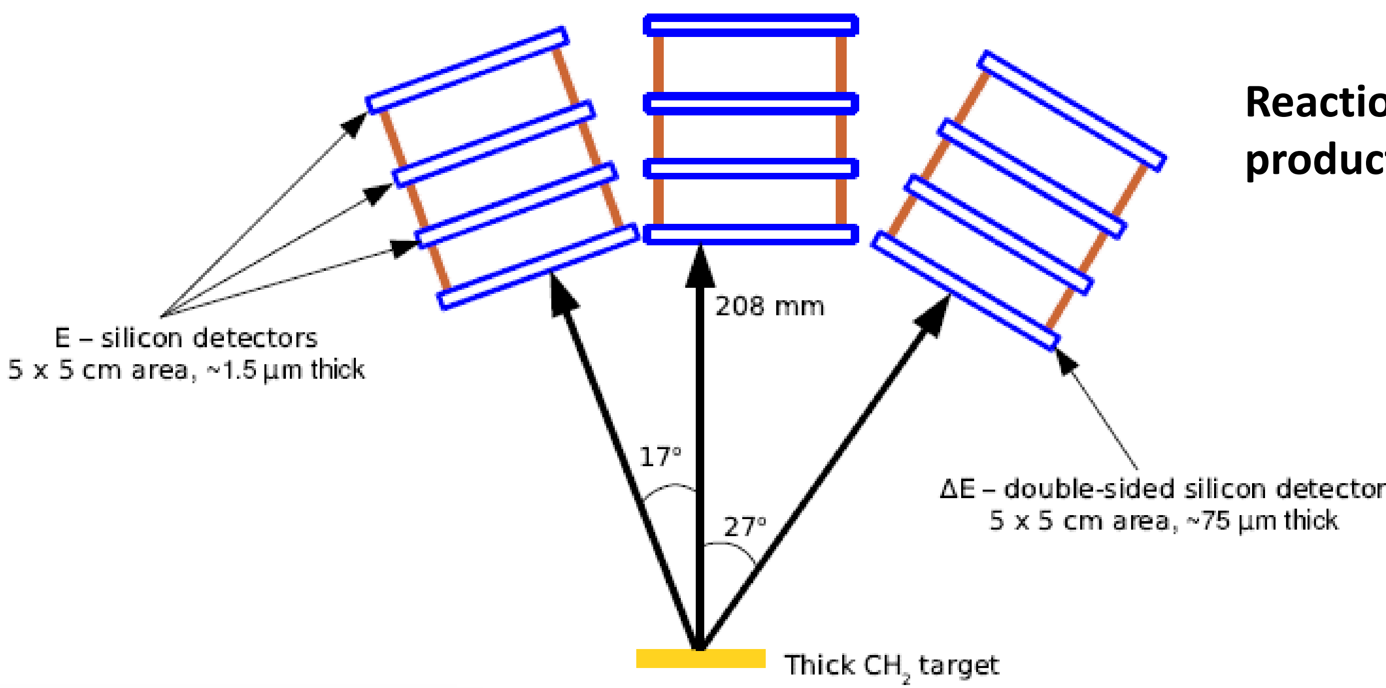
$p(^{25}Al,p)^{25}Al$ at CNS – beam production

- ^{24}Mg primary beam from cyclotron, ~ 25 nA
- ^{25}Al secondary beam produced using $^{2}H(^{24}Mg,n)^{25}Al$ reaction,
  ~ 10^{6} ions per second

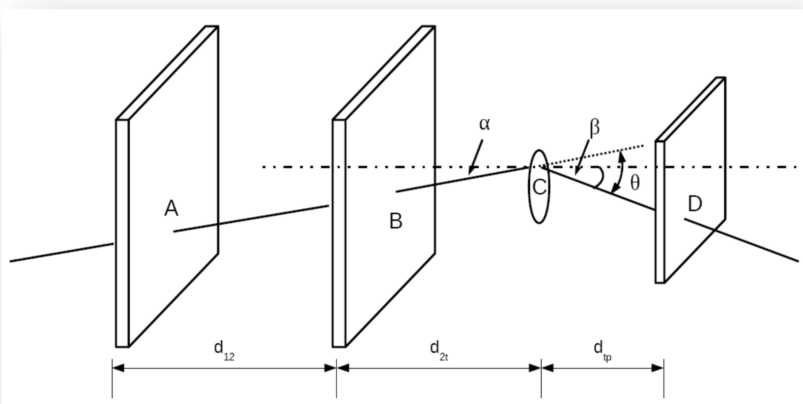


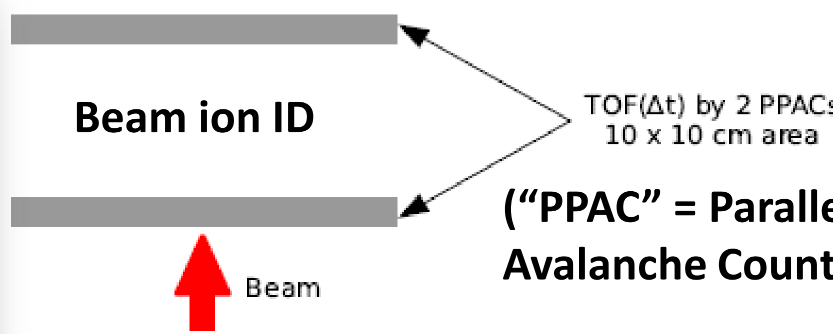
detection system setup (top view)

3 identical ΔE-E telescopes

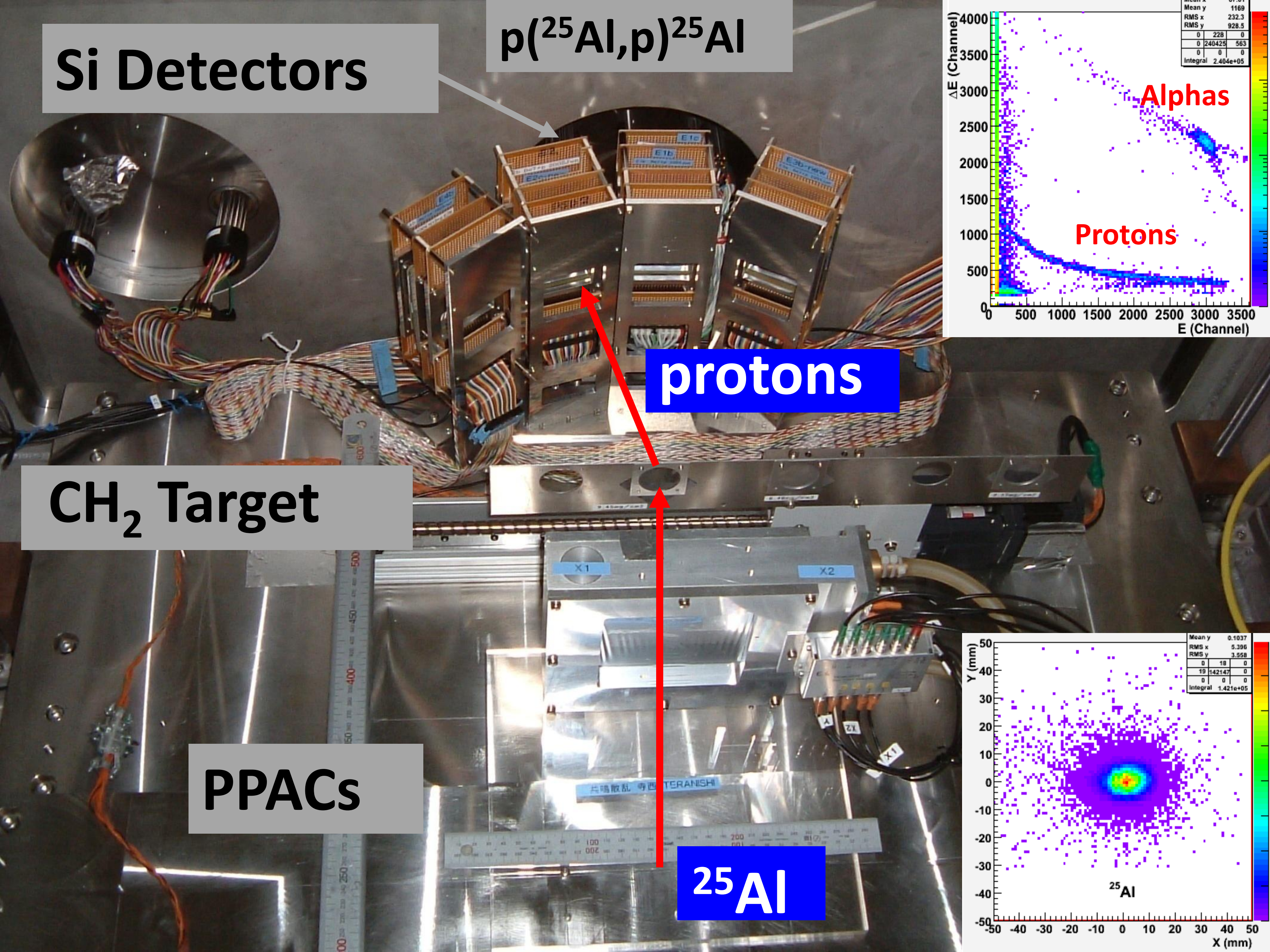


Reaction product ID

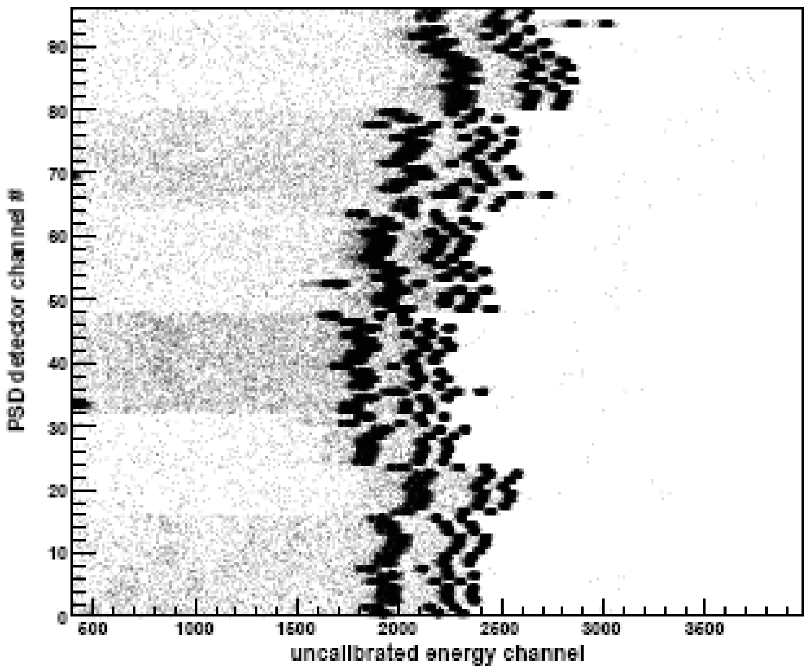


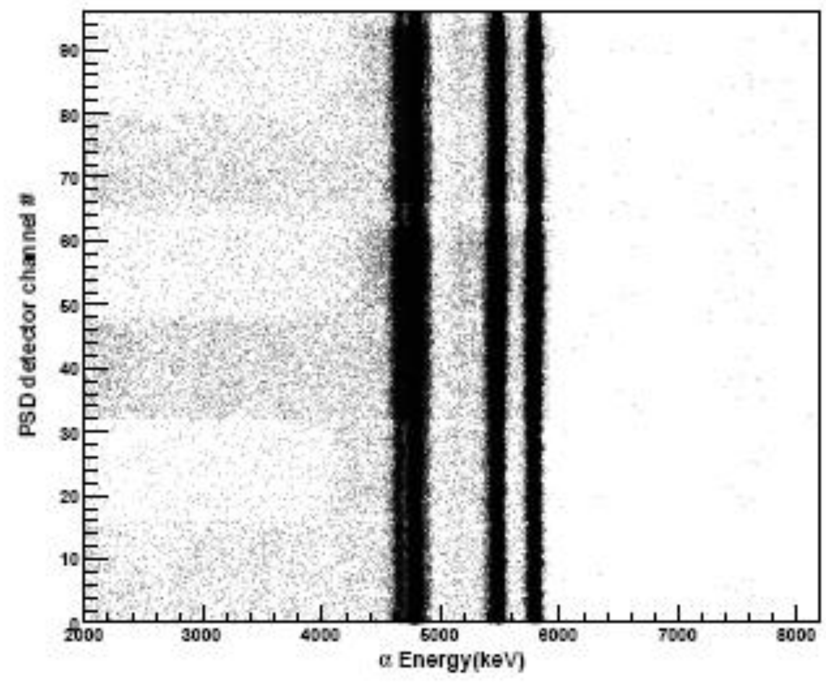


(“PPAC” = Parallel Plate Avalanche Counter)


Si Detectors
p(25Al,p)25Al
CH2 Target
PPACs
protons
25Al
ΔE (Channel)
E (Channel)
Alphas
Protons
Y (mm)
X (mm)
25Al
E1c
E1b
X1
X2
TERANISHI

ΔE-E telescope: "gain-matching"





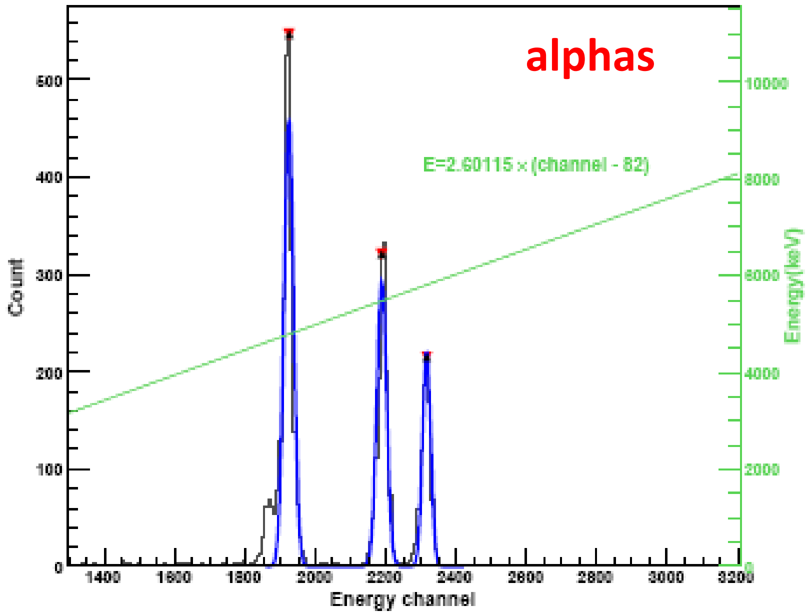
ΔE-E telescope: energy calibration

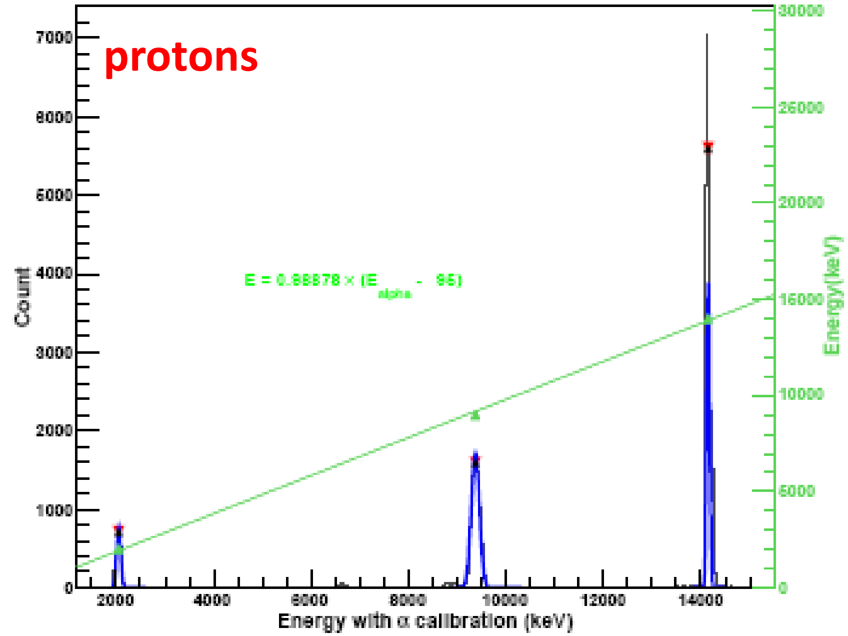
- with α-sources:

  ^{244}Cm, ^{241}Am, ^{237}Np (4.8 – 5.8 MeV)

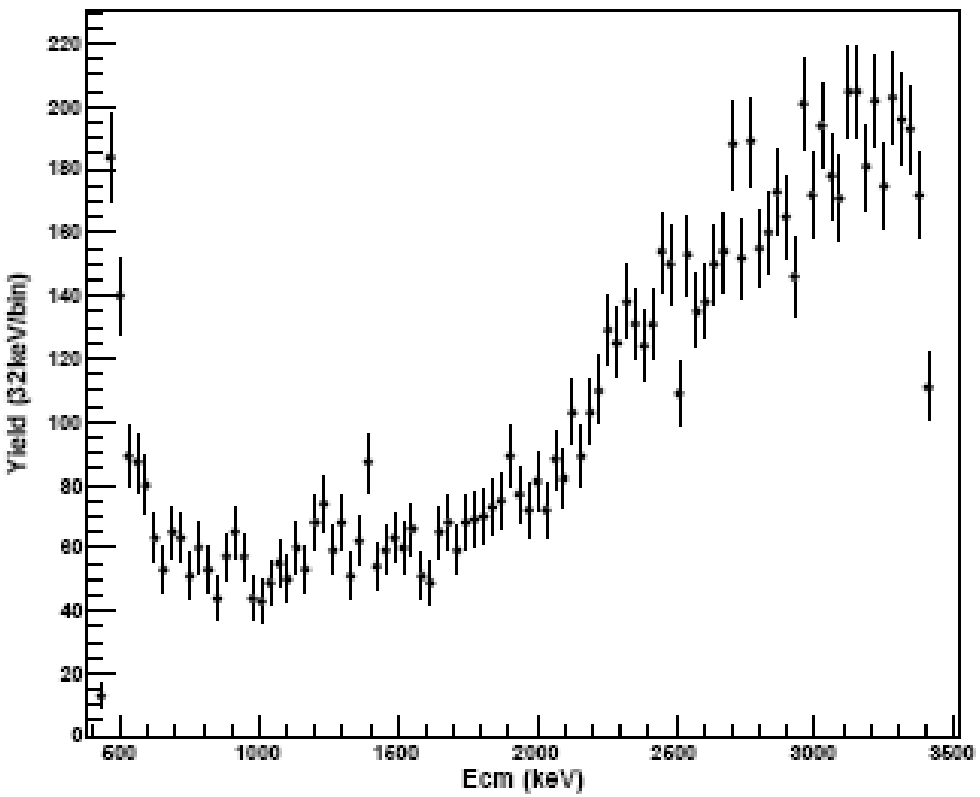
- with proton beams:

  Energies : 5, 9 and 14 MeV





background determination and subtraction

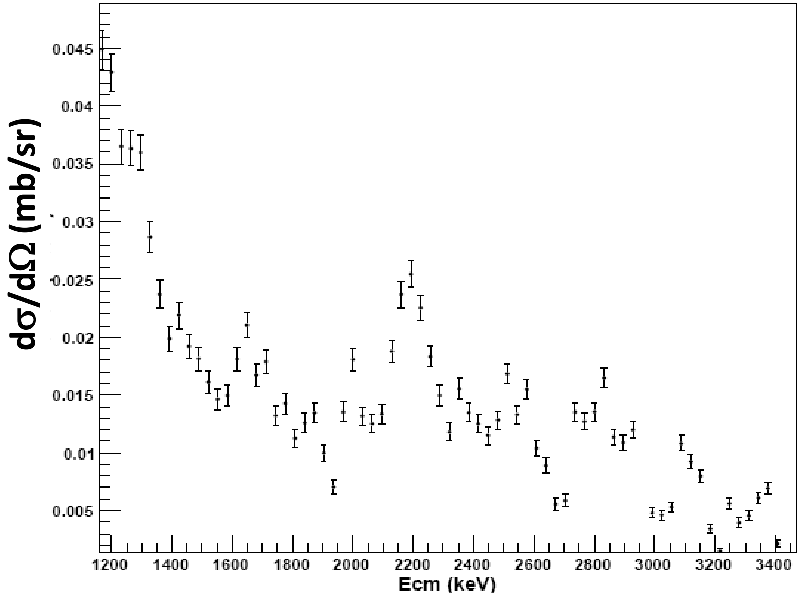


Some of the detected protons are not from ^{25}Al+p elastic scattering

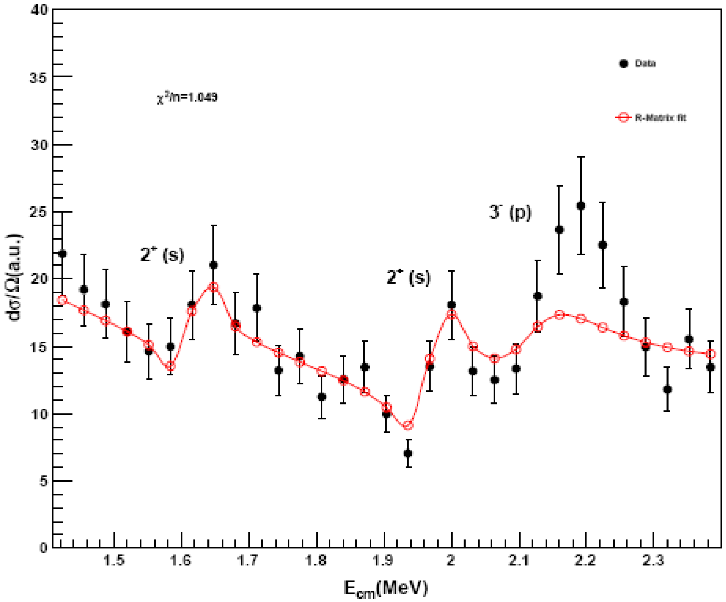
∴ replace CH_2 target with ^{12}C foil to detect protons from ^{12}C

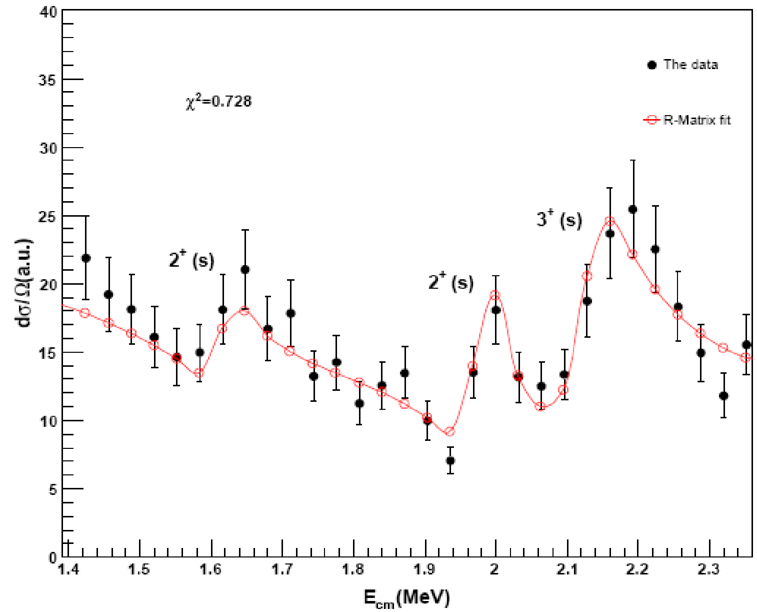
$p(^{25}Al,p)^{25}Al$ excitation function

After calibration, background subtraction, energy loss corrections



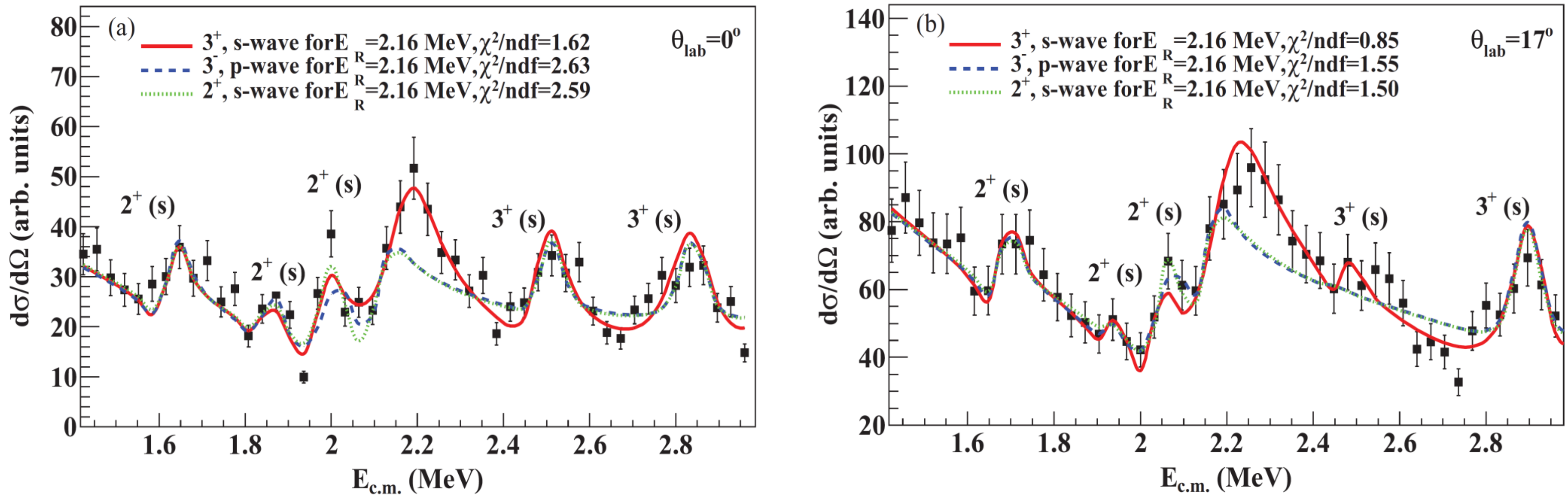
s-wave resonances in ^{26}Si from R-Matrix theory





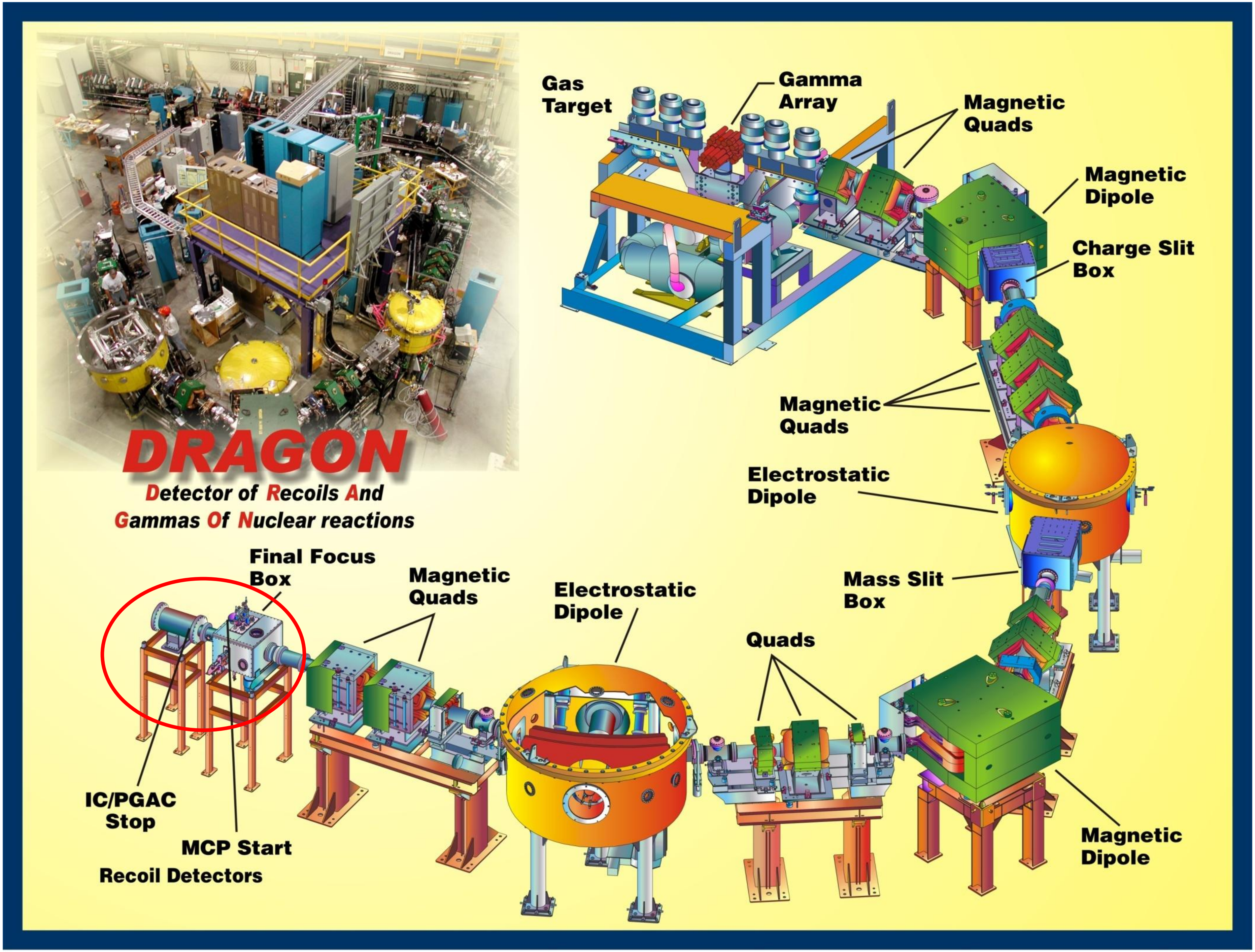
^{26}Si resonance parameters

s-wave resonances in ^{26}Si from R-Matrix theory [J. Chen *et al.*, PRC 2012]



This work	(p, t) [20][a]	(p, t) [6]	(p, t) [13][a]	β^+ decay [16][d]	(^{3}He, n) [15][b]	(^{4}He, ^{6}He) [19]	(^{3}He, n) [21][a]	(p, t) [22][a]
7.162(14), 2^+	7.157(4), 2^+	7.151(5)	7.160(5)		7.152(4), 2^+	7.161(6)	7.150(30), 2^+	7.150(15)
7.402(40), 2^+	7.439(6), (2^+)	7.4152(23), (4^+)[a]	7.425(7), (2^+)		7.425(4), 0^+	7.429(7)	7.390(30), (0^+)	
7.484(13), 2^+	7.512(8), (2^+)	7.479(12)	7.498(4)	7.501(5), 2^+	7.493(4), 2^+	7.480(20)	7.480(30), 2^+	7.476(20)
				7.606(6)				
		7.522(12), (5^-)[c]						
	7.672(2), 3^-	7.661(12), (2^+)[c]	7.687(22), 3^-		7.694(4), 3^-	7.676(4)		7.695(31)
7.704(13), 3^+		7.701(12)						
	7.875(2), 1^-	7.874(4)	7.900(22), 1^-		7.899(4), 1^-	7.885(4)	7.900(30)	7.902(21)
				7.962(5)				
8.015(14), 3^+								
				8.156(21), 2^+			8.120(30), (2^+)	
		8.222(5), (1^-)[c]						
		8.269(4), (2^+)[c]		8.254(5)				
8.356(12), 3^+								

next: <u>direct</u> ^{25}Al(p,γ)^{26}Si measurement?



DRAGON
Detector of Recoils And
Gammas Of Nuclear reactions
Gas
Target
Gamma
Array
Magnetic
Quads
Magnetic
Dipole
Charge Slit
Box
Magnetic
Quads
Electrostatic
Dipole
Mass Slit
Box
Quads
Magnetic
Dipole
Electrostatic
Dipole
Magnetic
Quads
Final Focus
Box
IC/PGAC
Stop
MCP Start
Recoil Detectors

Conclusions

Small sample of experiments aimed at improving our understanding of stellar explosions
– benefiting from interactions with astronomers and theorists/modellers

Future: FAIR, FRIB, RIKEN, TRIUMF – radioactive beams

Experiments at smaller accelerator labs:

these complement – and guide – those at bigger places

Thanks to...

- **Collaborators:**
  - **DRAGON collaboration (TRIUMF)**
  - **Hendrik Schatz's group (NSCL – Michigan State University)**
  - **Shigeru Kubono's group (CNS – U. of Tokyo, RIKEN)**

- **Technical staff at these labs**

- **and :**

NSERC CRSNG

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