Nuclear **R**eactions - **E**xperiment **I**

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Exotic Beam Summer School – 2014 ORNL

Outline

- Overview of nuclear reactions
  - Transfer reactions
- Observed and extracted information
- Techniques
  - Normal vs. Inverse kinematics
- Systematic test of the sum-rules
  - Start-to-finish example

Nuclear Reactions

- Which of the following is NOT a correct expression for a nuclear reaction?

1. $^{48}Ca(d,p)^{49}Ca$
2. $^{58}Ni(^{46}Ti,4n)^{100}Sn$
3. $^{16}O(p,p')^{15}N$
4. $^{9}Be(^{44}S,\ ^{9}Be)^{42}Si+2p$

Nuclear Reactions

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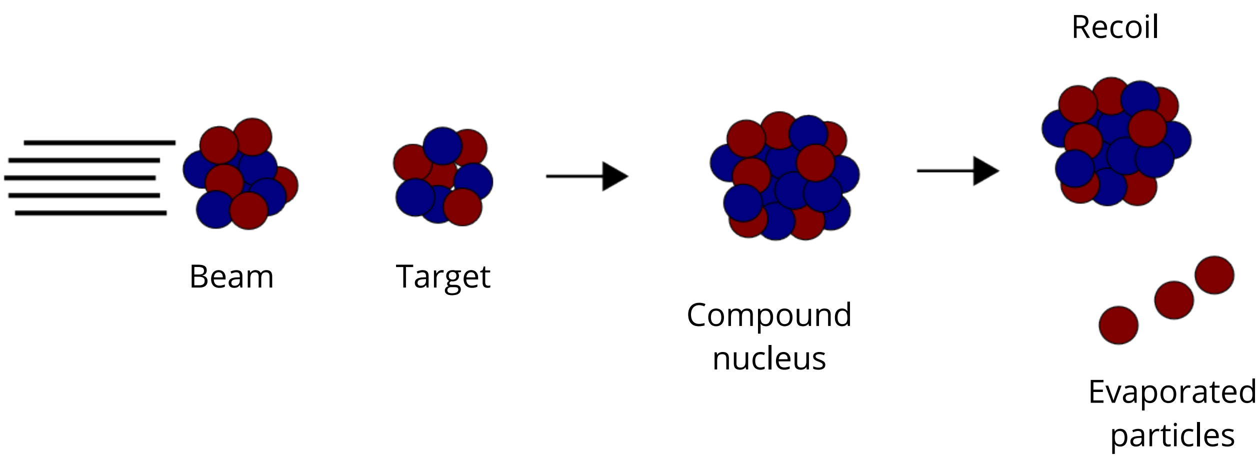
Answer: 3) → $^{16}O(p,p')^{16}O$

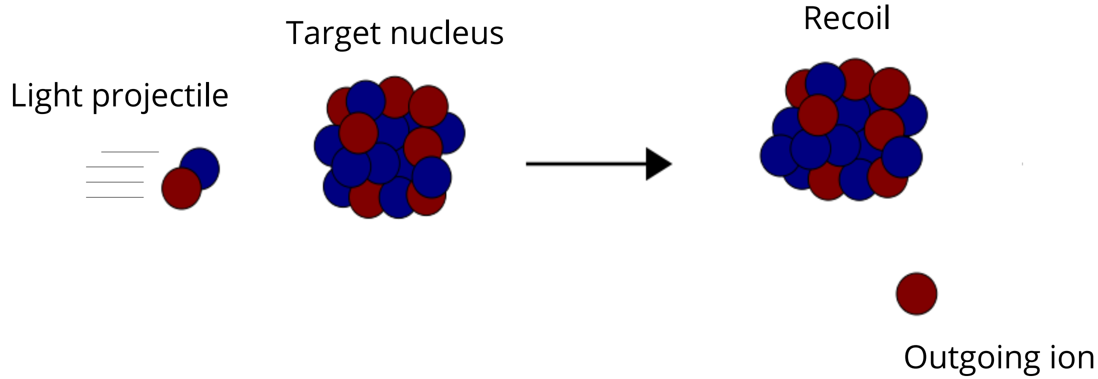
Selectivity of the Reaction Mechanism

- Low-energy (<1000 MeV/u) nuclear physics
  - Knock-out / nucleon removal
  - Fusion-evaporation
  - Transfer
  - Deep inelastic
  - Scattering (elastic / inelastic)
  - Capture

Fusion Evaporation vs. Direct Transfer

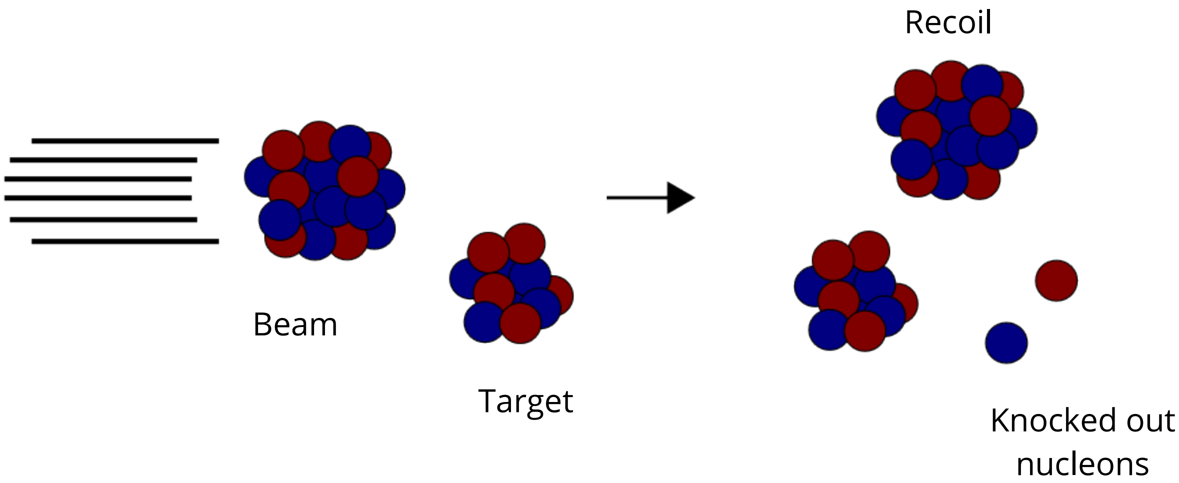


- A + b = C → D + X
  - $^{12}C(^{18}O,3n)^{27}Si^*$
- Compound system has NO memory of its formation
- Evaporated particle energies give excitation energies of final states

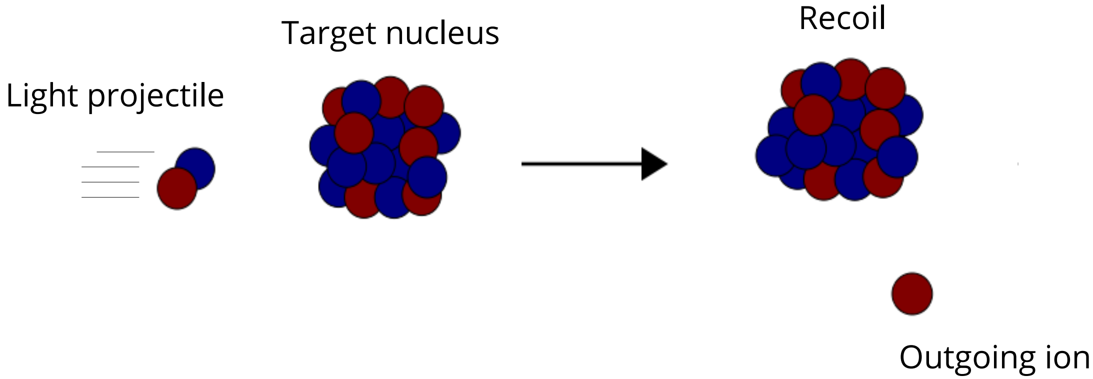


- Two-body A(b,c)D
  - $^{16}O(d,p)^{17}O^*$
- Outgoing particles DO retain knowledge of transferred particles

Knockout Reaction vs. Direct Transfer



- A + b = c – Xn -Xp
  - ^{9}Be(^{44}S,-1p1n)^{42}P*
- Momentum distribution of recoil reflects orbital momentum transfer



- Two-body A(b,c)D
  - ^{16}O(d,p)^{17}O*
- Outgoing particles DO retain knowledge of transferred particles

Transfer Reactions

Single-nucleon

[e.g., (d,p), (^{3}He,d), (α,t)]

- **Single-particle states**

Two-nucleon

[e.g., (t,p), (^{3}He,p), (α,d)]

- **Pair transfer (2n, d, etc.)**

Charge exchange

[e.g., (p,n), (^{3}He,t), (t,^{3}He)]

- **Gamow Teller Strengths**
- **Isobaric analog states**

Surrogate reactions

[e.g., (^{6}Li,d), (^{7}Li,t), (d,n)]

- **Mimics the analogous particle transfer**

Heavy Ion

[e.g., (^{13}C,^{12}C), (^{12}C,^{10}Be), (^{14}C,^{10}C)]

- **Highly selective**
- **Exploratory**

Transfer Reactions: Measured Quantities

- Momenta and angles of outgoing light particles [or heavy-ion recoils]

Reaction: A(b,c)D

[e.g., ^{208}Pb(^{3}He,d)^{209}Bi]

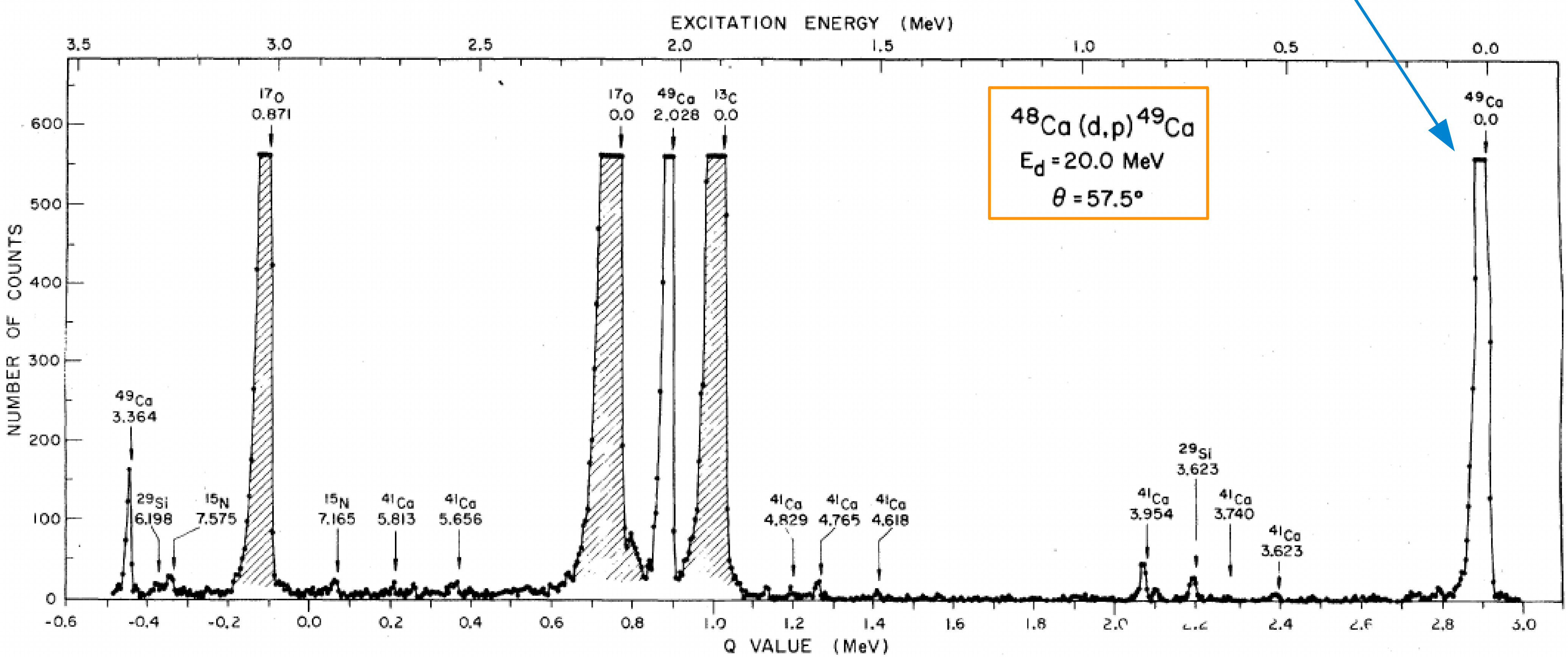
$$\mathrm{BE_D} = \mathrm{M_D} + \mathrm{E_D^*} = \sqrt{\mathrm{M}_c^2 + \mathrm{E}_{cm}^2 - 2 \cdot \mathrm{E}_{cm} \cdot \mathrm{E}_c'}$$

$$\mathrm{E}_c' = \mathrm{f}(\mathrm{E}_c, \theta_c)$$

$$\mathrm{Q} = (\mathrm{BE}_c + \mathrm{BE_D}) - (\mathrm{BE_A} + \mathrm{BE}_b)$$

Transfer Reactions: Measured Quantities

[Q(g.s) = +2.92 MeV]

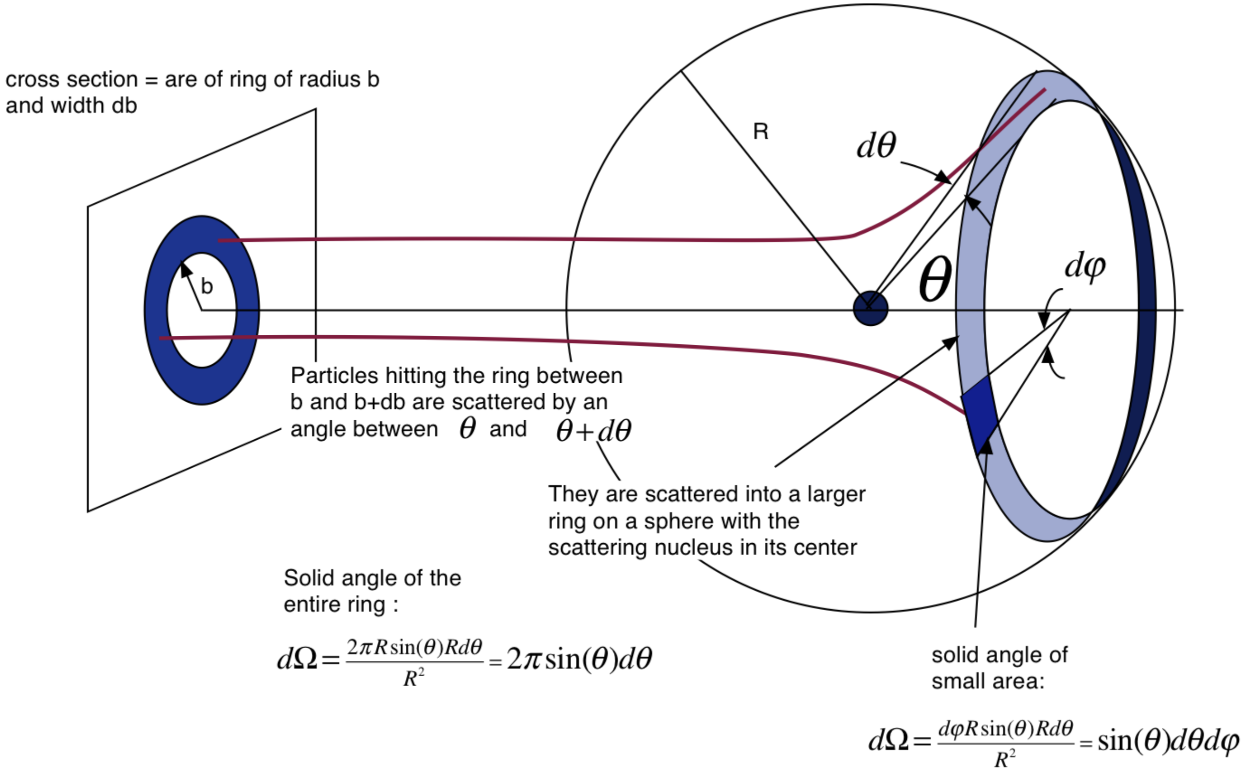


$$Q = (BE_c + BE_D) - (BE_A + BE_b)$$

Transfer reactions: Measured quantities

Cross sections – Yields as a function of angle

[differential cross section: millibarns per ster radians (mb/sr)]



Rutherford Scattering

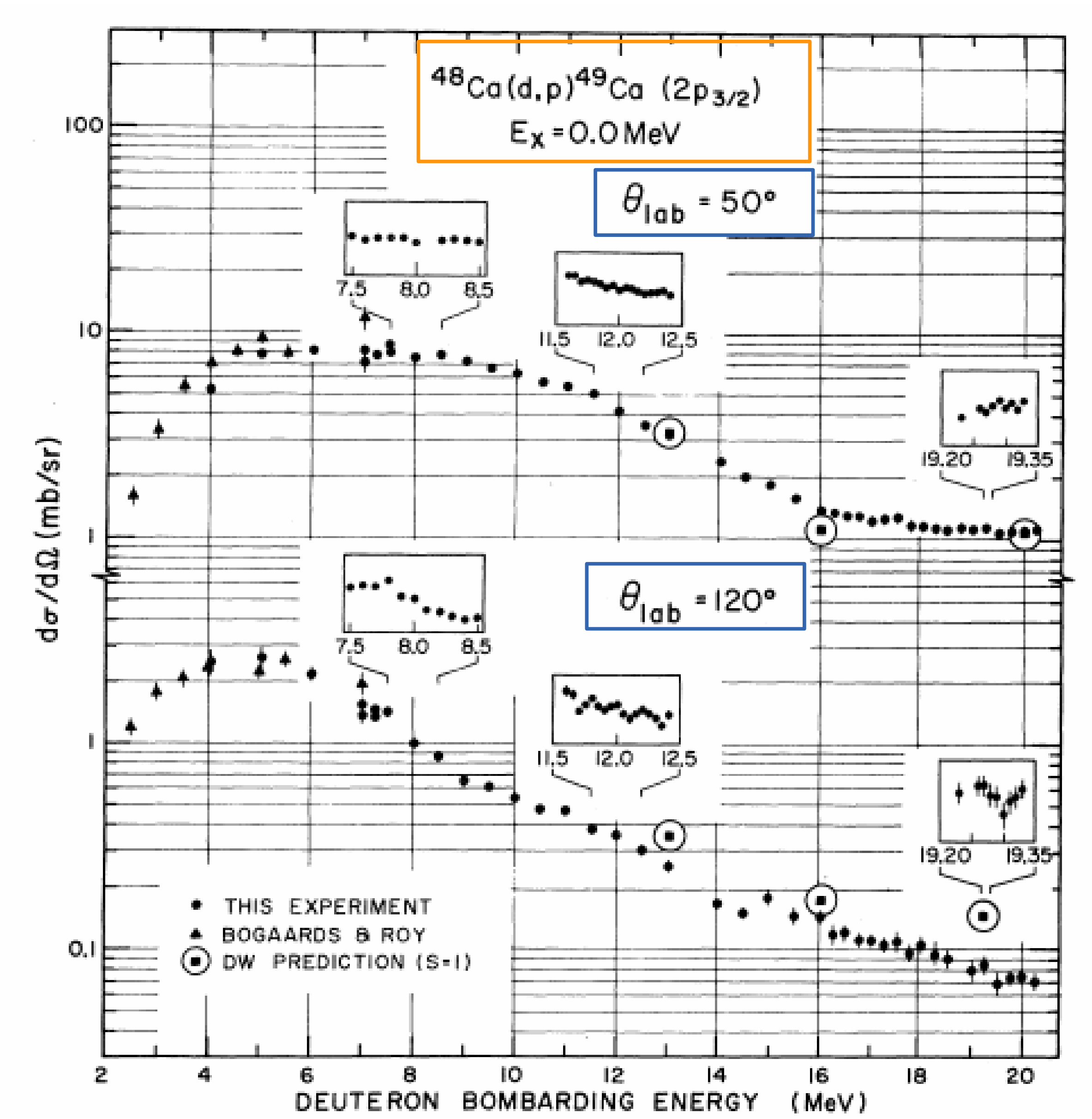
[V = Coulomb]

$$\frac{d\sigma}{d\Omega} = \frac{(zZe^2)^2}{(4\pi\varepsilon_0)^2 (4E_{kin})^2} \frac{1}{\sin^4\left(\theta/2\right)}$$

Transfer Reaction

[V = Nuclear + Coulomb]

Cross Section vs. Incident Beam Energy



Metz et al., PRC 12, 827 (1975)

Transfer reactions: Extracted quantities

Sensitivity of the differential cross sections to orbital angular momenta (*l*) of transferred nucleon(s)

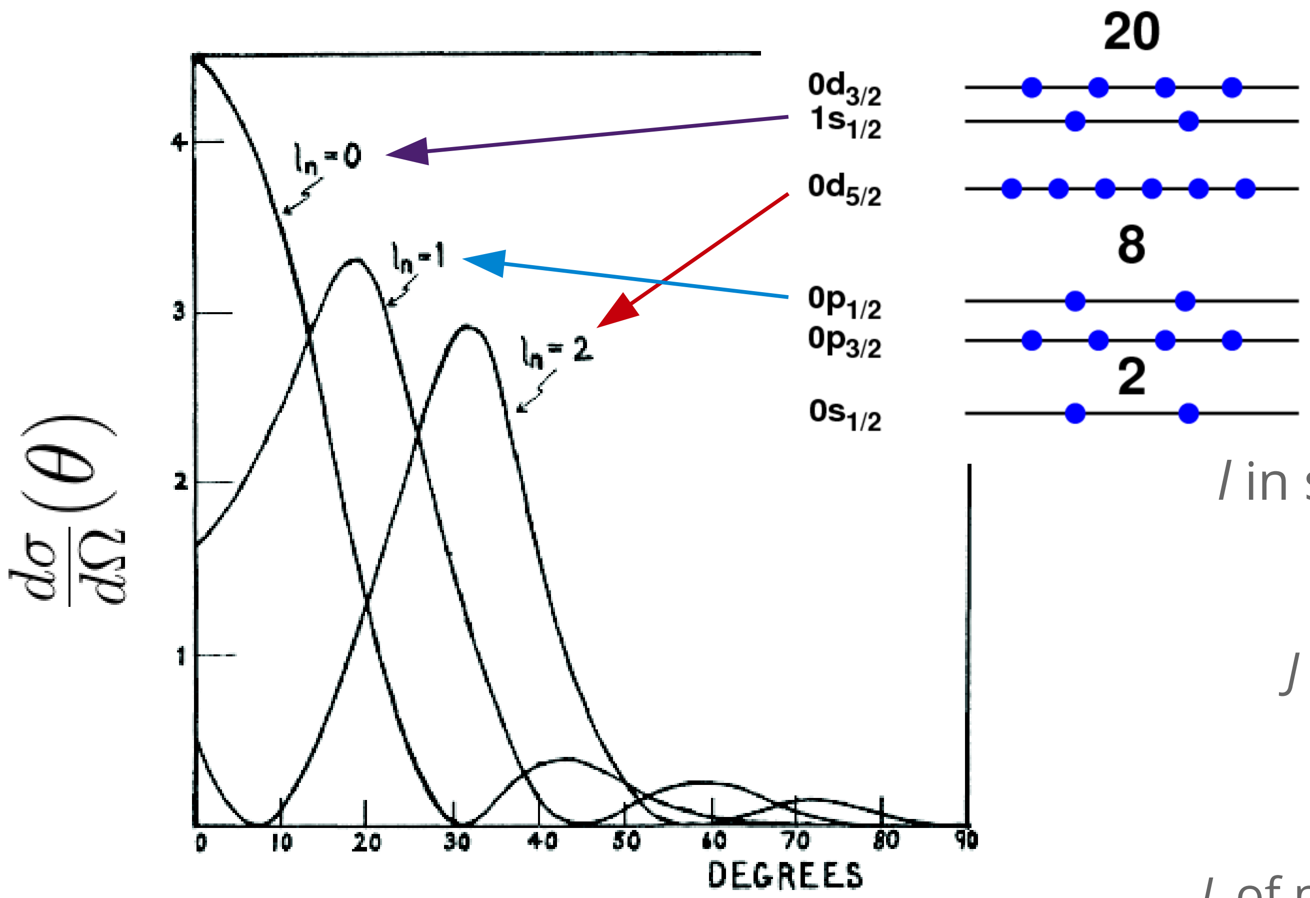


FIG. 1. Theoretical angular distributions for (*d*, *p*) and (*d*, *n*) reactions for different angular momentum transfers to the initial nucleus.

l in single-particle transfer
[e.g., (d,p)]

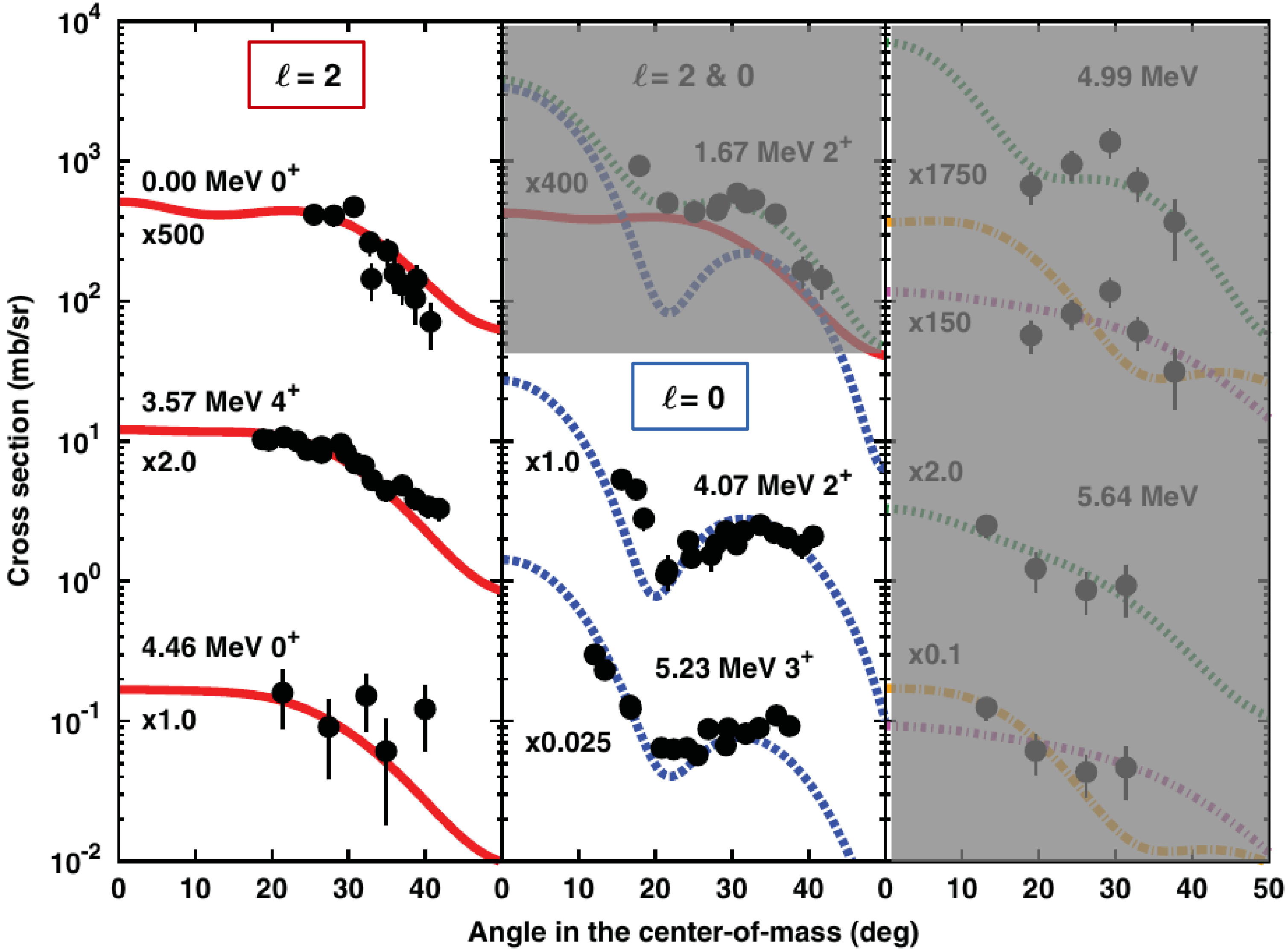
J if incoming particle is polarized
[analyzing power]

L of pair in two-particle transfer
[e.g., (t,p)]

S. T. Butler (1950), H. B. Burrows et al., (1950)

Examples of angular distributions

$^{19}O(d,p)^{20}O$ @ 6.6 MeV/u



Hoffman et al., PRC 85, 054318 (2012)

Momentum Matching

Nucleon transfer at the surface of the nucleus $\ell = r \times p$

$$\ell \leq qR$$

$$R = r_0 A^{1/3}$$

$$r_0 \approx 1.2 \text{ fm}$$

$$q = p_f - p_i$$

Determined largely by Q value of the reaction

[Small Q (d,p) → small l]

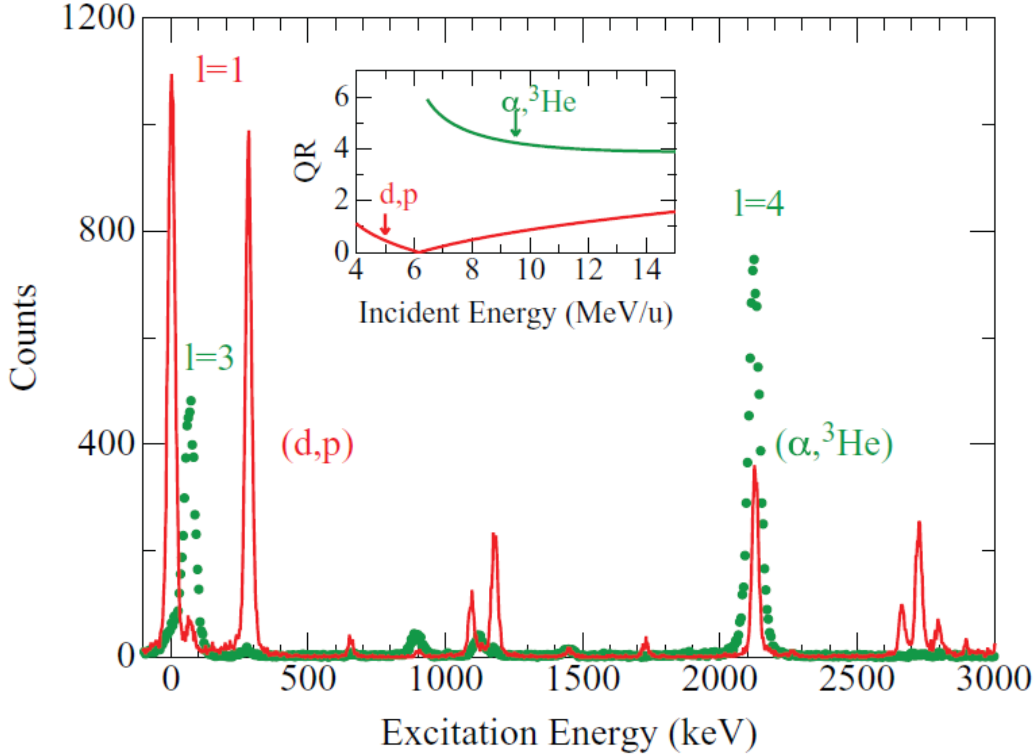
[Large -Q (^{4}He,^{3}He) → large l]

^{60}Ni Target

+5.6 MeV (d,p)

-12.8 MeV (^{4}He,^{3}He)

Good matching → more reliable calculations and extracted values



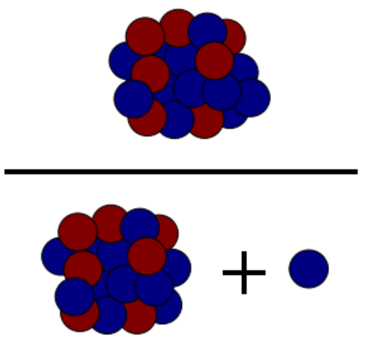
Transfer reactions: Extracted quantities

Experimental spectroscopic factor

[Relative values are typically reliable (<25%)]

[absolute values can be tricky (>30%)!]

S_{lj} =



Final state

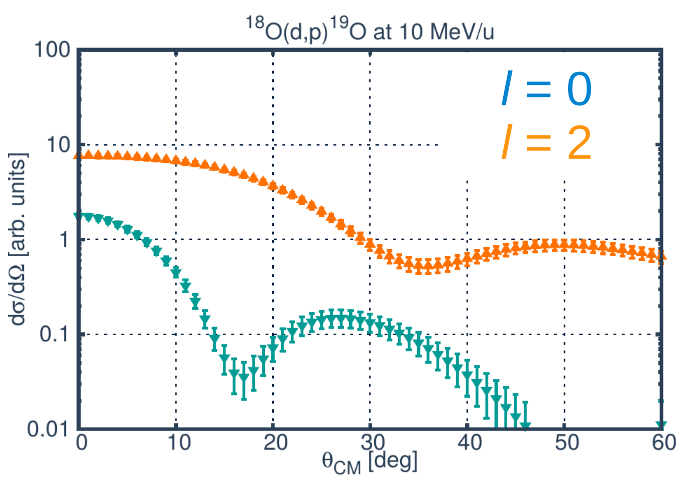
Initial state + nucleon

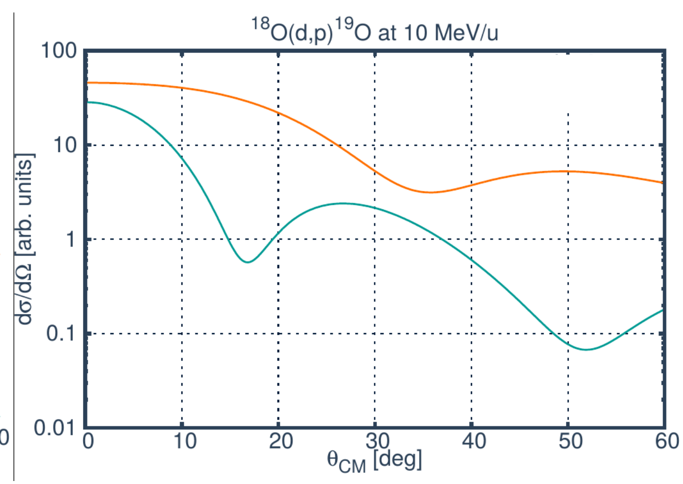
Statistical factor

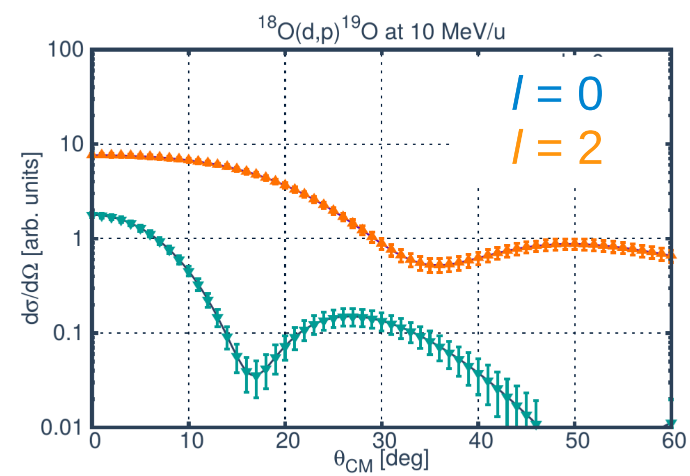
Calculated cross section for "pure" single-particle like state

$$\left.\frac{d\sigma}{d\Omega}\right|_{Measured} = g S_{lj} \left.\frac{d\sigma}{d\Omega}\right|_{DWBA}$$

Amount of overlap between initial and final states
Spectroscopic Factor







Transfer reactions: Extracted quantities

Methods for calculating the distributions

Distorted wave Born approximation (DWBA)

[e.g., PTOLEMY, etc..]

- Calculation using optical model, various parameter sets

Adiabatic wave approximation (ADWA)

[e.g., TWOFNR, etc...]

- Better handling of breakup channels and near/beyond threshold states

Coupled Channels (CC)

- Extension to the optical model through description of strongest channels

Continuum Discretized Coupled Channels (CDCC)

[e.g., FRESCO, etc...]

- Extension of CC to unbound states

Coupled Reaction Channels (CRS)

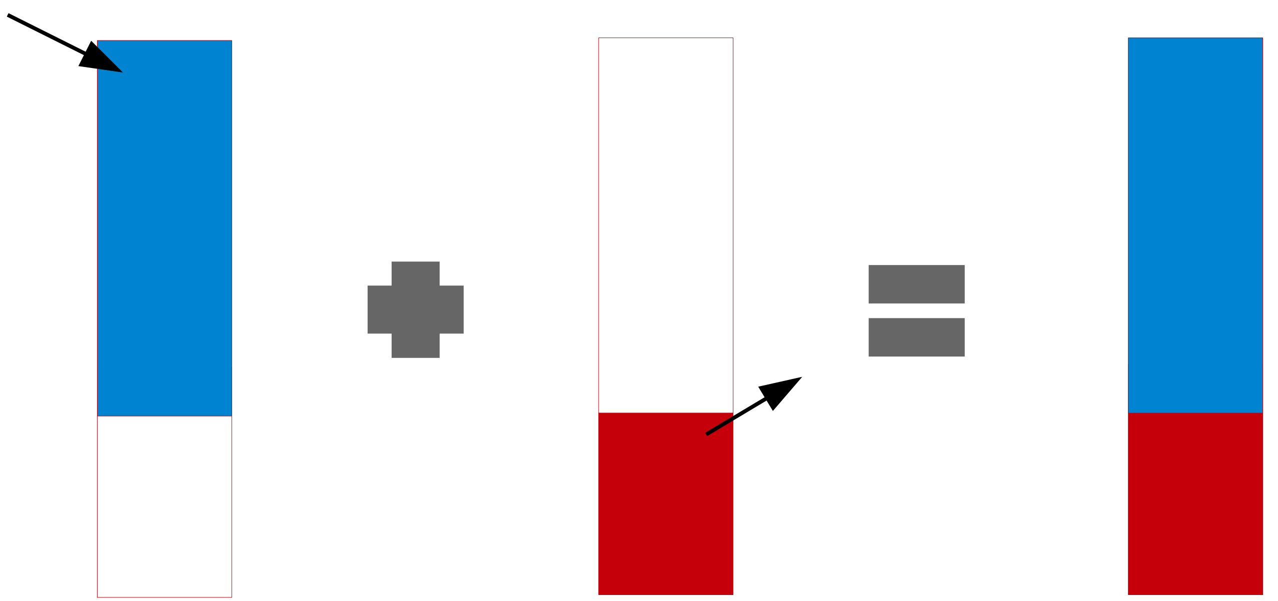
- Extension of CC include multiple nucleon or composite particle transfer

Keeley et al., Prog. Part. Nucl. Phys. 63, 396 (2009)

Transfer reactions: Extracted quantities

Normalized spectroscopic factors (Asymptotic Normalization Coeff. [ANC])

[Clear procedures must be followed]



Orbital (njl)

Vacant

Occupied

Neutron Adding probes vacancy [# of holes]

Neutron Removal probes occupation [# of particles]

Degeneracy:

V + **O** = 2j + 1

[$1p_{3/2}$ = 4]

Macfarlane & French SUM RULE

$$N \equiv \frac{1}{(2j+1)}[\Sigma(2j+1)C^2 S_{\text{adding}} + \Sigma C^2 S_{\text{removing}}]$$

Normalization [for single orbital]

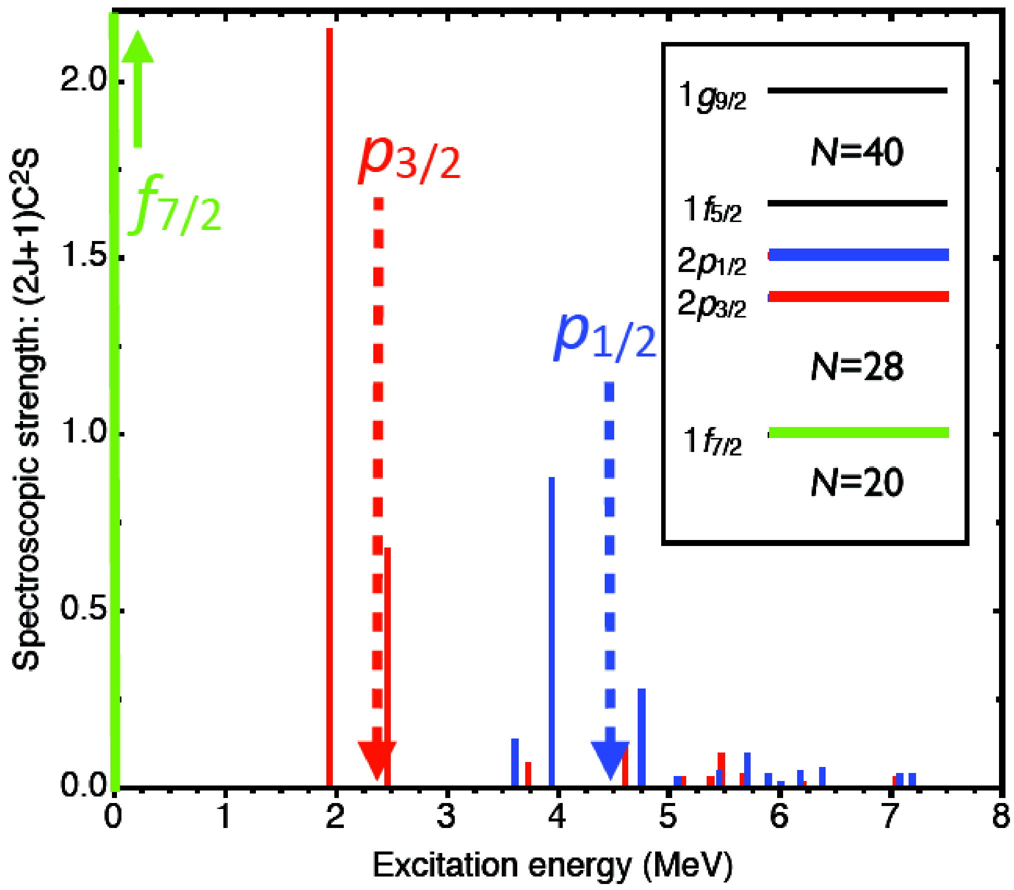
Macfarlane and French, Rev. Mod. Phys. 32, 567 (1960)

Transfer reactions: Extracted quantities

Single-particle energies

[Deduce locations of single-particle orbitals from single-nucleon transfer data]

^{40}Ca(d,p)^{41}Ca



S weighted center of gravity

$$\epsilon = \frac{\sum_f (E_o - E_f^-)C^2S_f^- + (2J_f+1)(E_f^+ - E_o)C^2S_f^+}{\sum_f C^2S_f^- + (2J_f+1)C^2S_f^+},$$

[formula in general requires both adding and removing reactions]

$$E_{cent} = \frac{\Sigma(2J+1)S\cdot E^*}{\Sigma(2J+1)S}$$

[outside a robust shell closure]

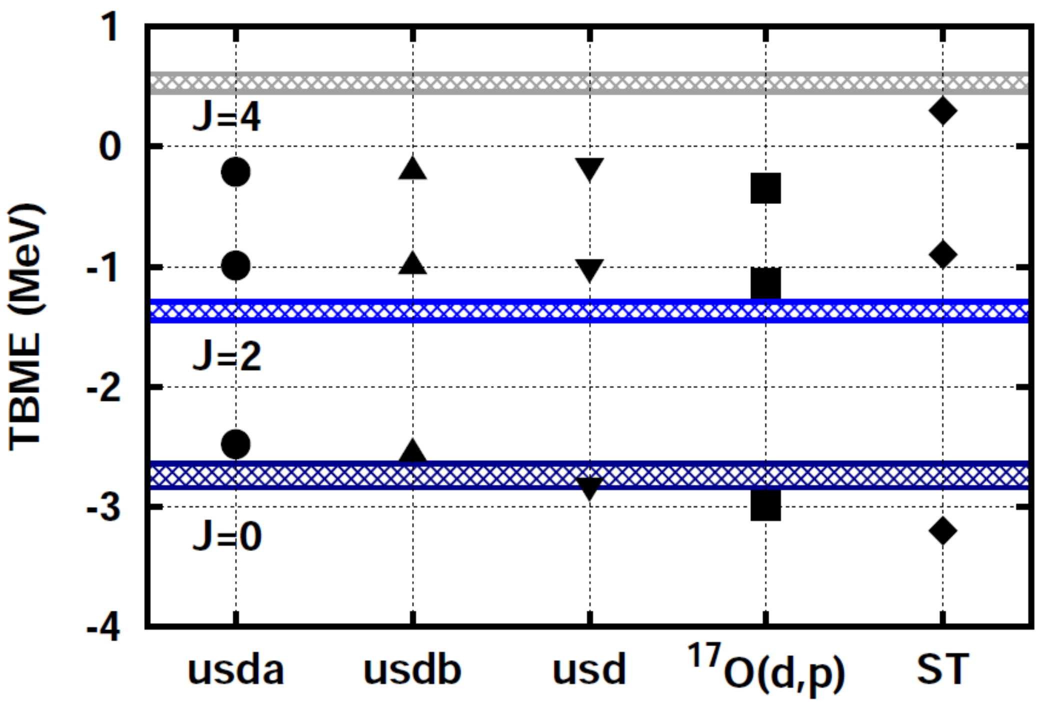
Transfer reactions: Extracted quantities

- Two-body matrix elements
- Analyzing powers
- Pairing strengths
- ANCs
- Etc…

Diagonal Two-Body Matrix Element

$$\langle (d_{5/2})^2 J | V | (d_{5/2})^2 J \rangle = E_0 + \frac{\sum (2J+1) C^2 S \cdot E^*}{\sum (2J+1) C^2 S}.$$

$$E_0 = 2B[^{21}\mathrm{O}] - B[^{20}\mathrm{O}] - B[^{22}\mathrm{O}] = -3.04(6)\ \mathrm{MeV},$$



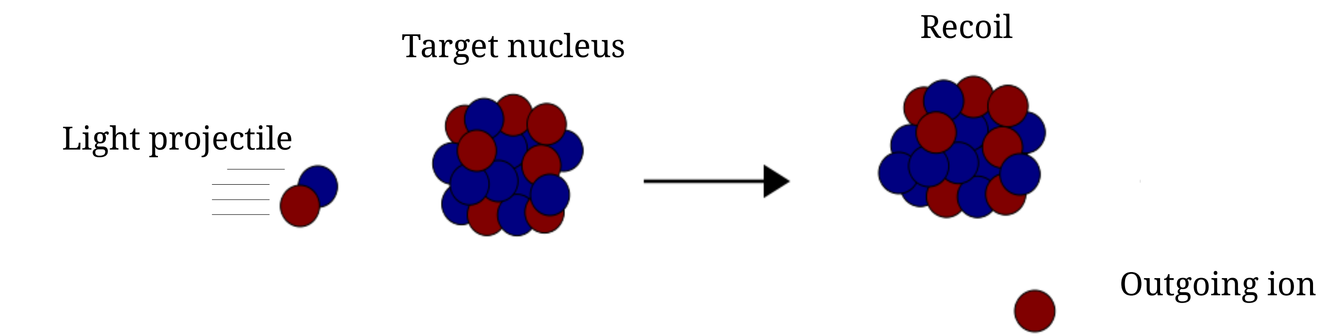
Schiffer and True, (1976)

Experimental Techniques

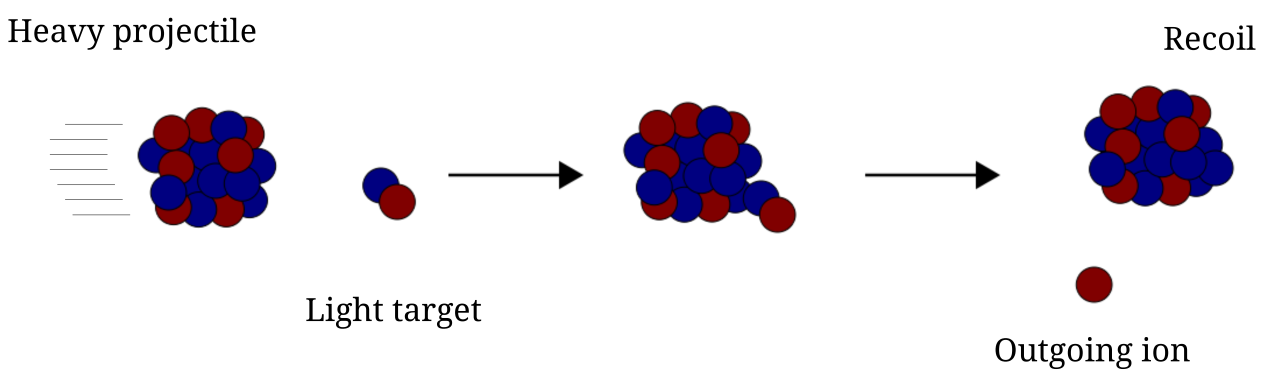
“Designing” a Transfer Measurement

- Physics interest → single-nucleon, pairing, astrophysics, etc…
- Reaction type and energy
  - Momentum matching, cross sections, etc…
- Region of interest → Stable or radioactive nuclei
- Beam energies → Analysis methods and applicability
- Detection options and challenges → inverse kinematics
- Beam rates → Limits techniques, sensitivity etc…

Transfer Reactions: Normal vs. Inverse

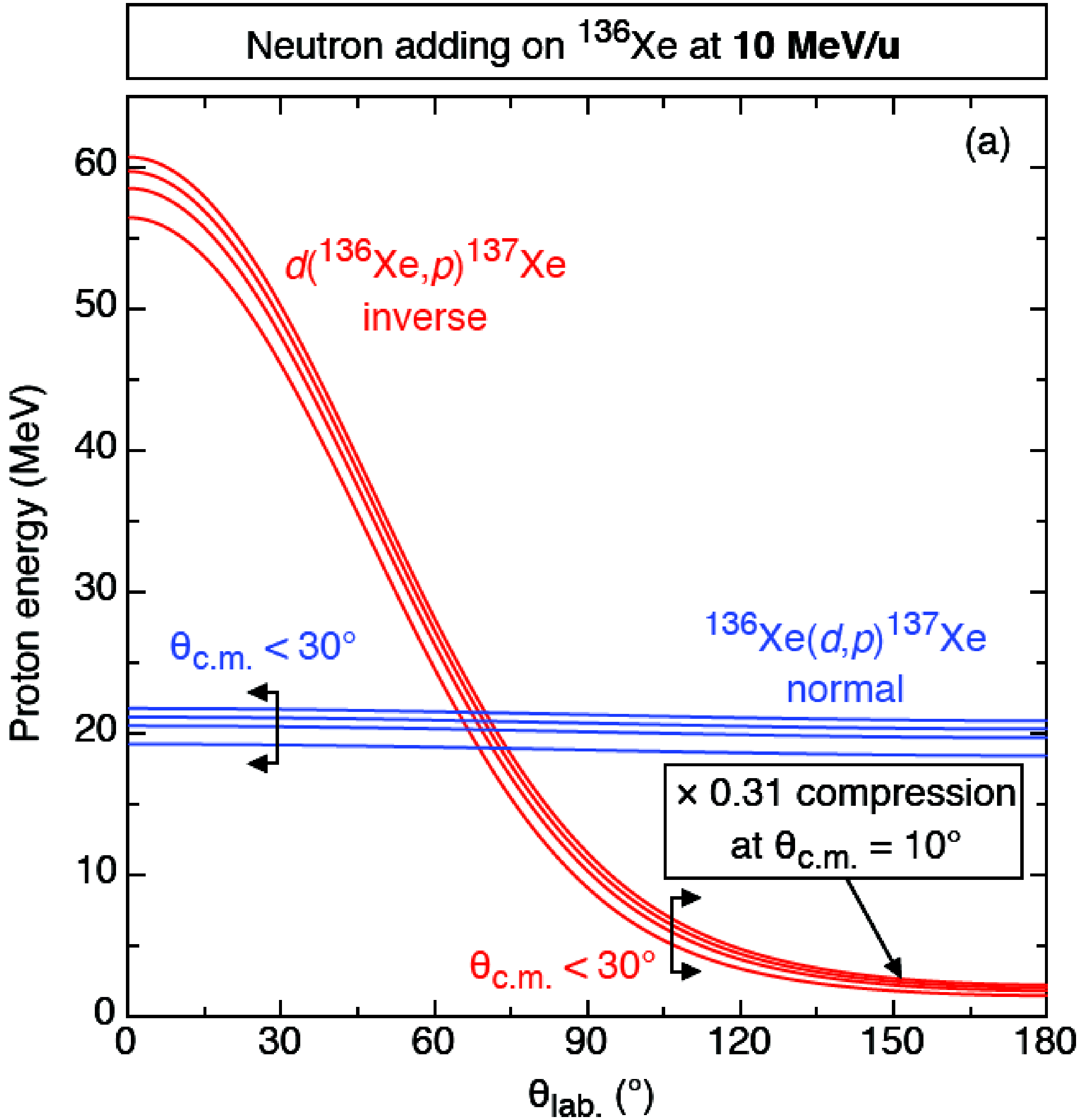


- A(b,c)D
- Moderate outgoing particle energies
- <50 keV resolution



- b(A,c)D
- Low particle energies (theta_cm <40 deg)
- 100 – 1000 keV resolutions

Transfer Reactions: Normal vs. Inverse



Magnetic Spectrographs

- Split-Pole (Enge) - ANL, formerly Yale U. etc…
- Q3D – Munich (TUM)
- Grand Raiden – RCNP

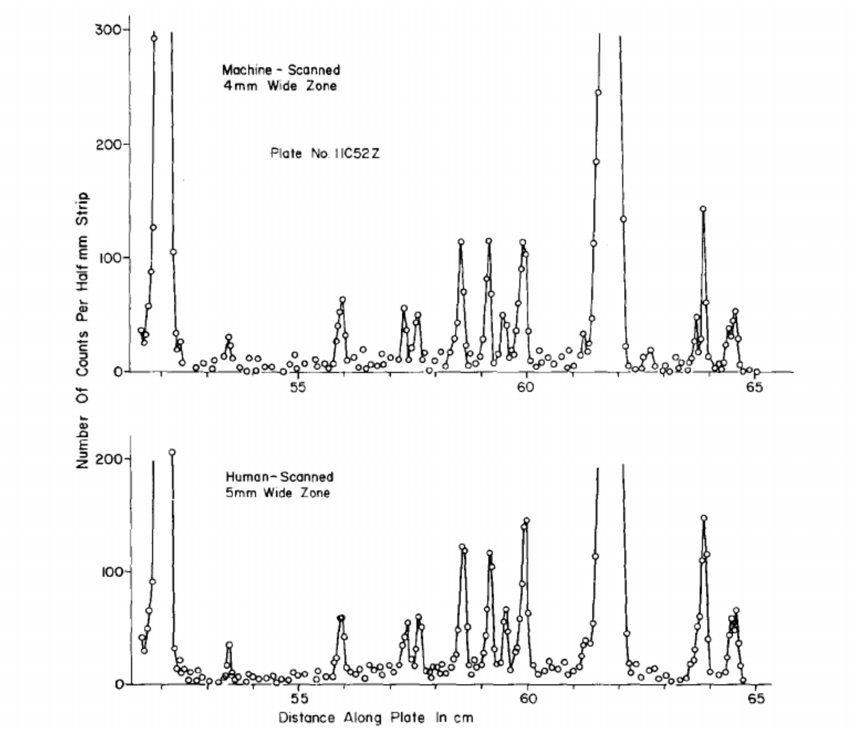
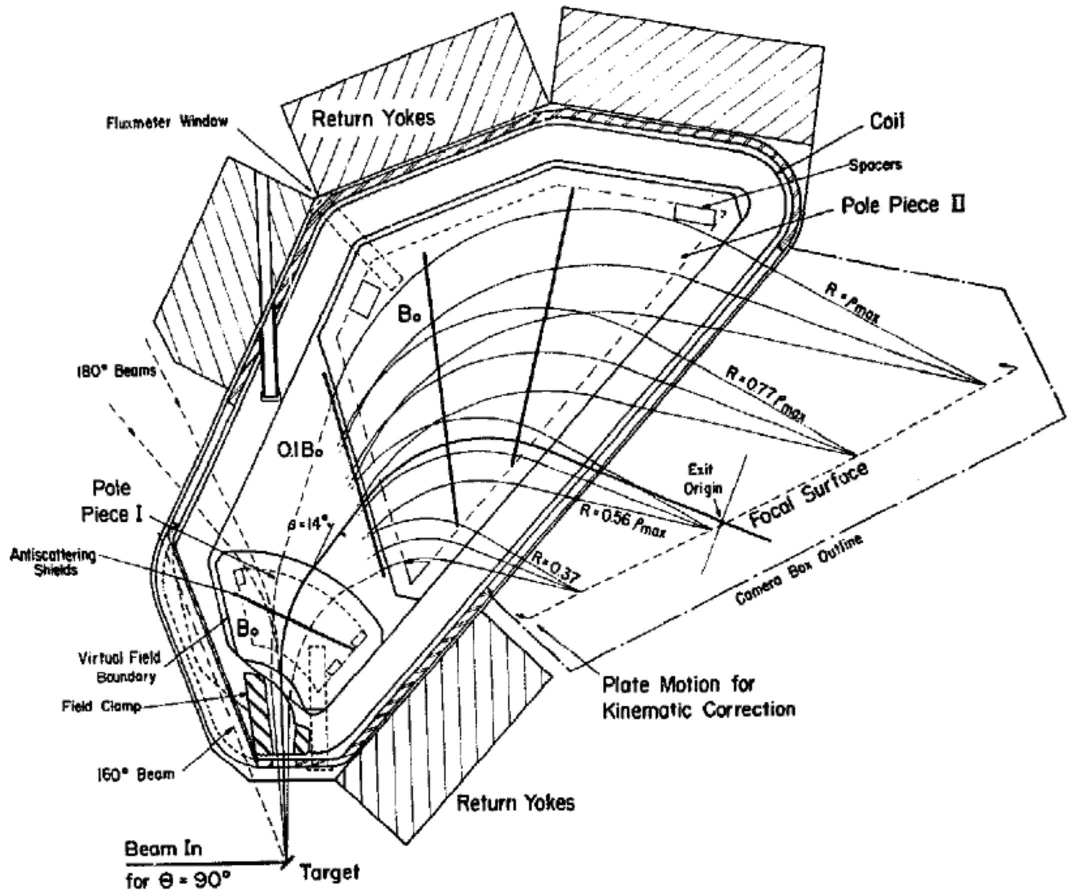


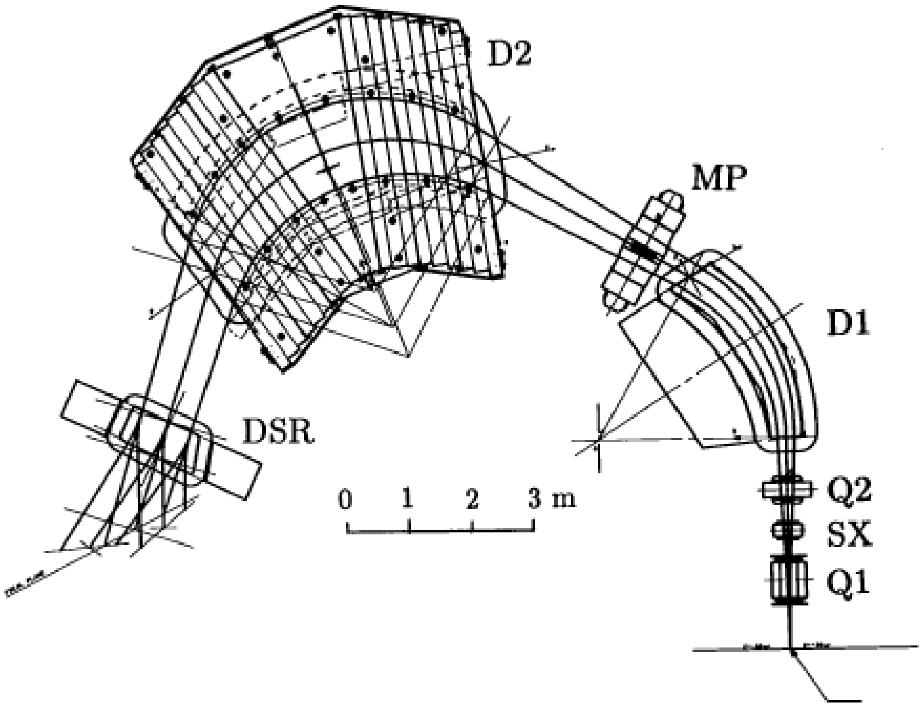
Fig. 9. Comparison of a spectrum counted by Cyclops, the M.I.T. automatic scanner and by Mr. W. A. Tripp.

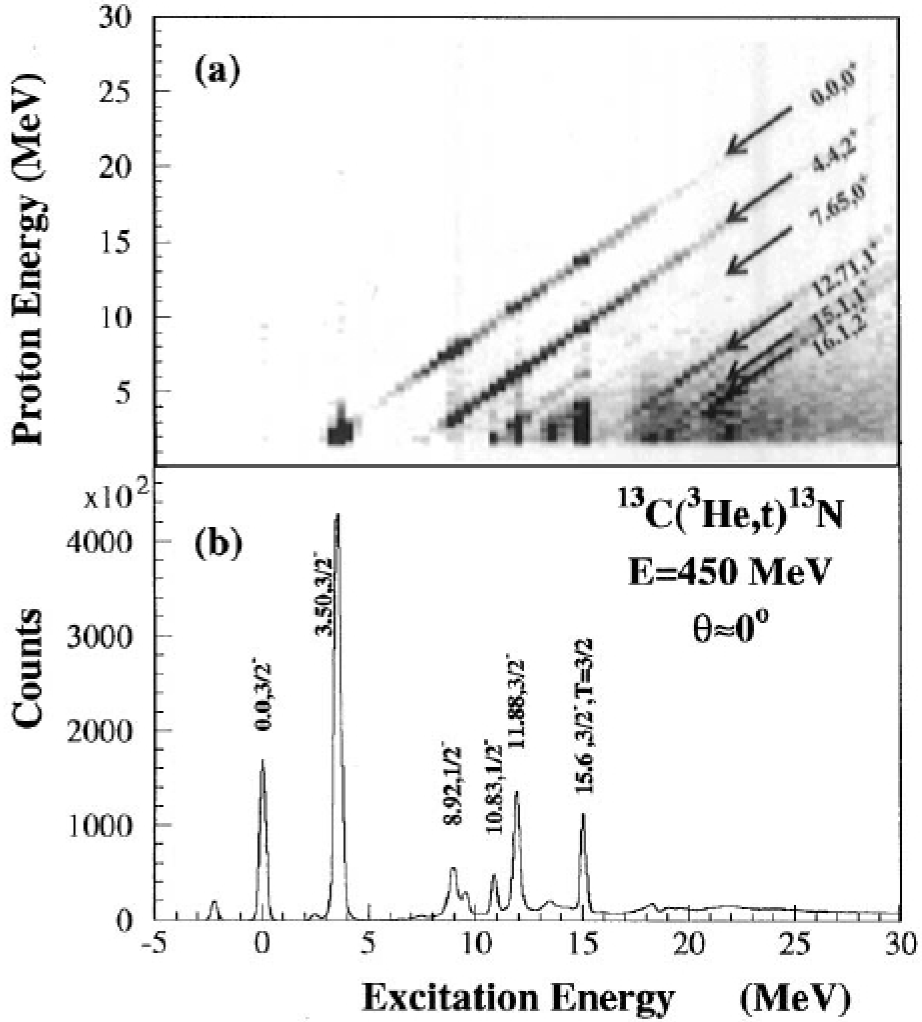


- Separate particle of varying momentum in space across the focal plane
- Fixed angle byte with good particle resolutions
- Can be used for heavy-ion measurements (gas-filled modes of operation)

Example Data from Magnetic Spectrograph

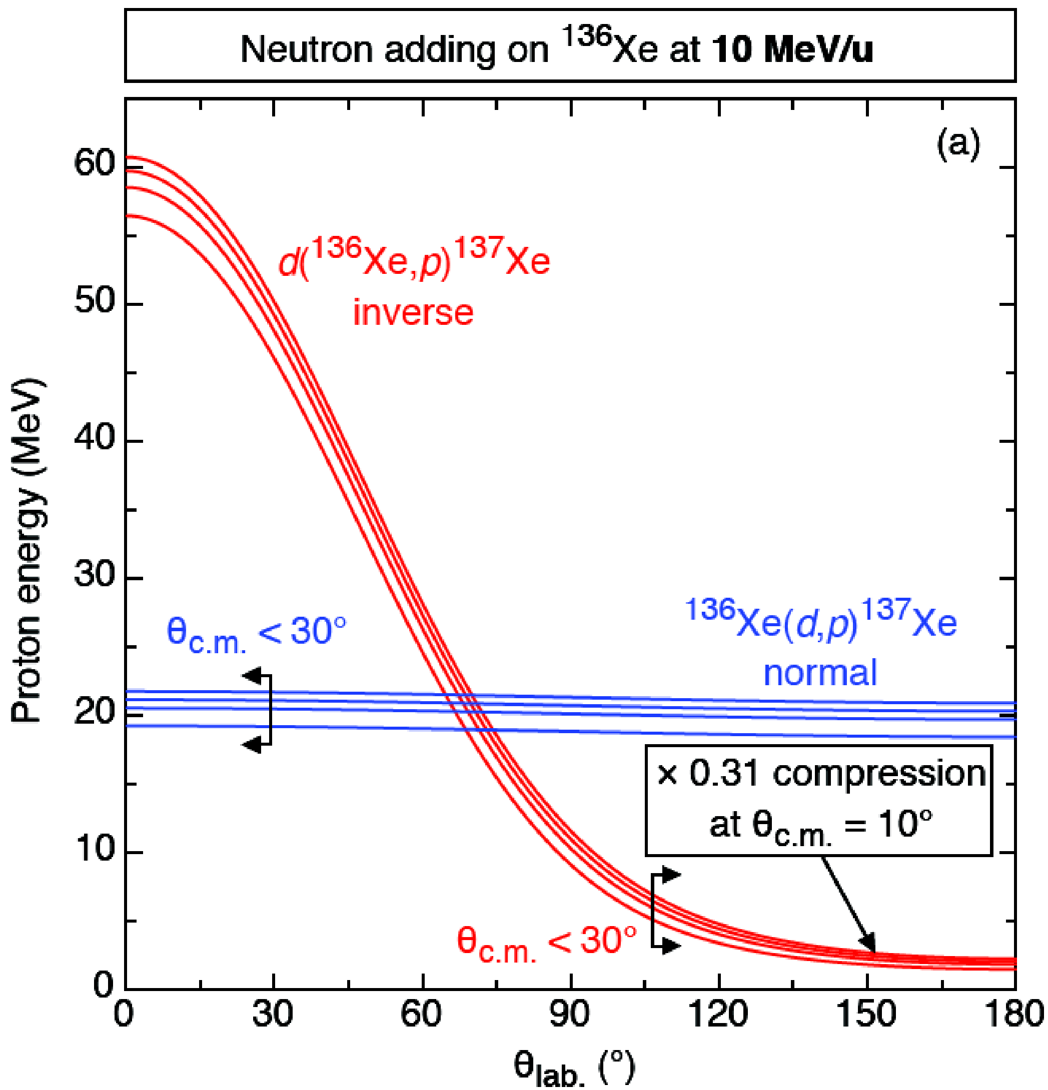
- Grand Raiden (Osaka, RCNP)
  - Zero-degree detection
  - High rigidity





Fujiwara NIMA 422, 484 (1999)

Transfer Reactions: Normal vs. Inverse



- Resolution factors
  - Larger energy losses in the target
  - Lower energy outgoing particles
    - Energy and angle straggling
  - Kinematic compression
  - Outgoing angles

Transfer Reactions: Normal vs. Inverse

Detect the heavy ion beam-like recoil

[Magnetic spectrometer]

For example: SPEG (GANIL) etc.

Measure the outgoing target-like light-particle

[Charged particle detector array]

For example: HiRA & AT-TPC (NSCL/MSU), MUST2 (GANIL), MAYA(GANIL/TRIUMF), Super ORRUBA (ORNL), HELIOS (ANL), IKAR (GSI), MSTPC (RIKEN), ANASEN (FSU/LSU/ReA3), ACTAR (GANIL) etc.

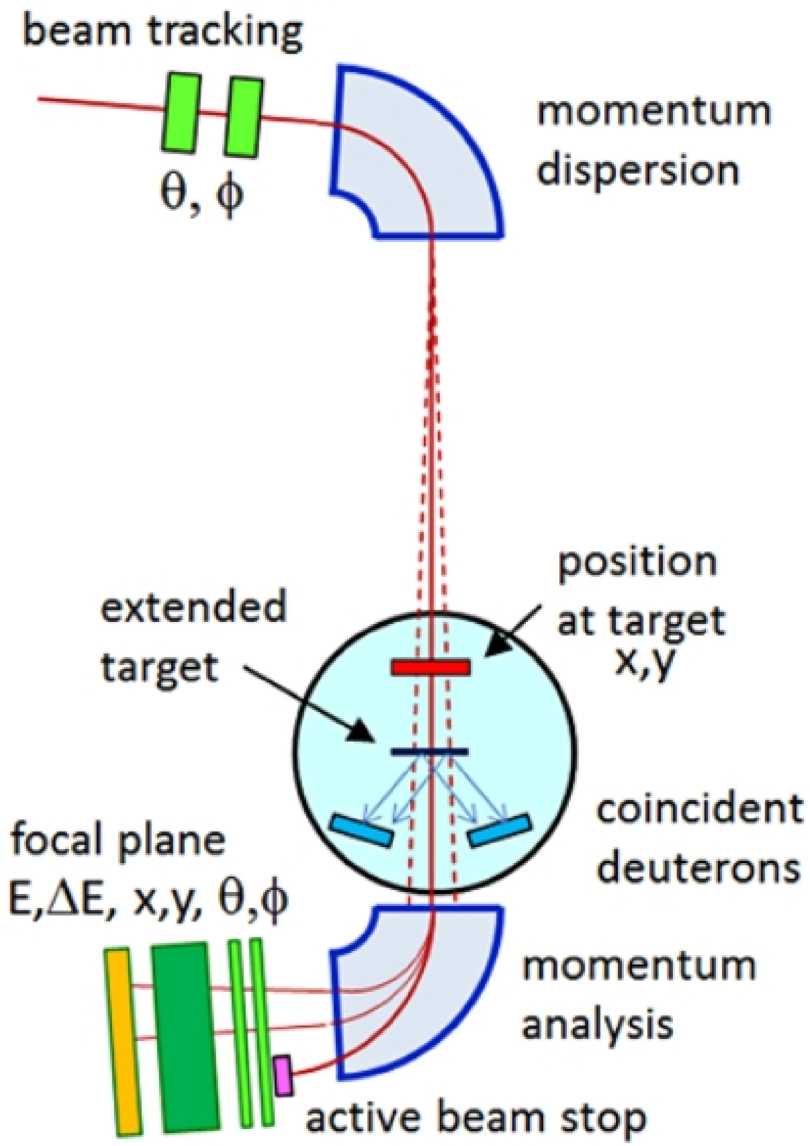
Observe γ-rays in coincidence with either of the above

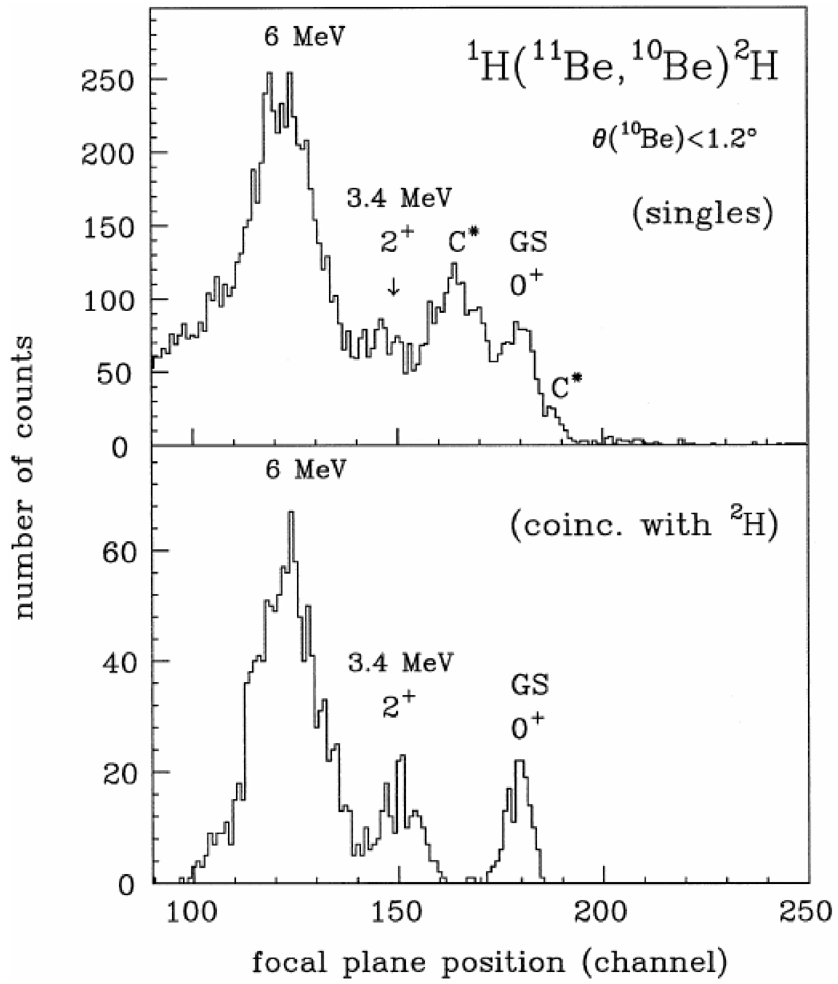
[γ-ray array + Si detector array/spectrometer]

GODDESS (ORNL), Hyall + CLARION (ORNL), T-REX+Miniball (ISOLDE), TIARA+MUST2+EXOGAM (GANIL), SHARC+TIGRESS (TRIUMF), GASPARD (SPIRAL2) etc.

Detect the heavy ion beam-like recoil

[SPEG/GANIL]





Fortier et al., PLB 461, 22 (1999)

Measure the outgoing target-like light-particle

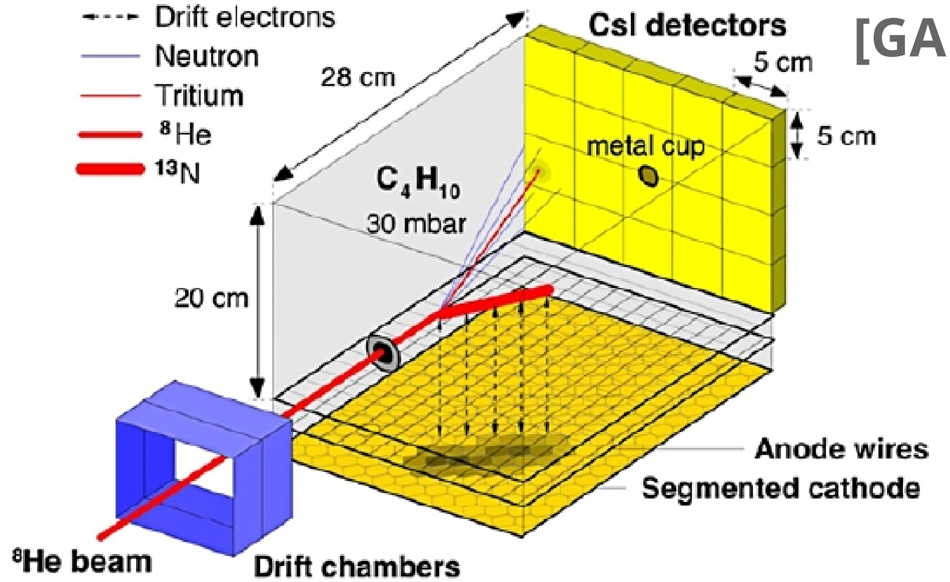
[Active targets]

Measure particle energies and tracks

- Excitation functions
- Thick target → excellent capabilities with weak beams

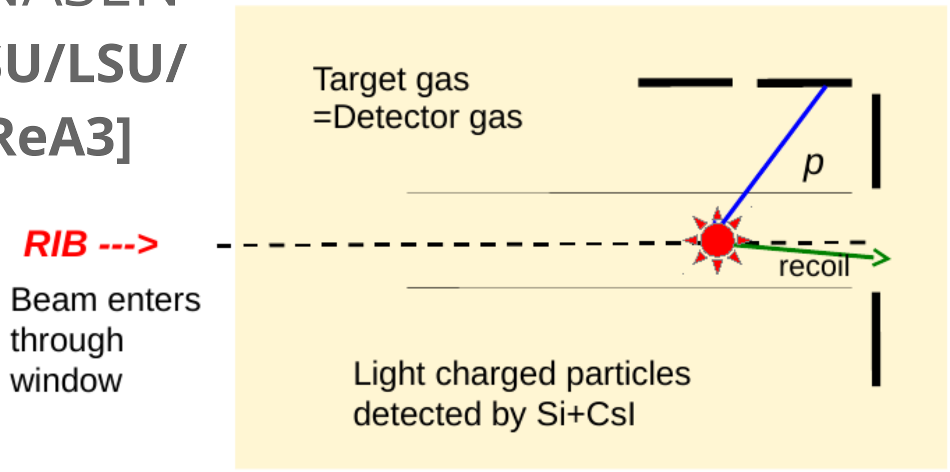
MAYA

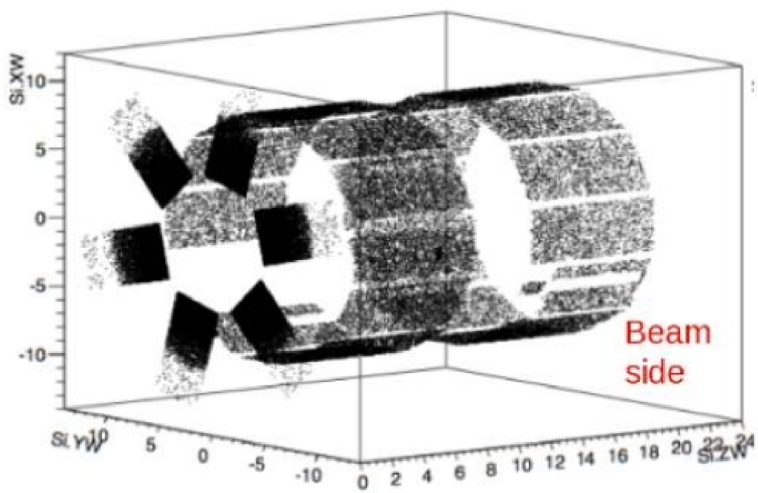
[GANIL]



ANASEN

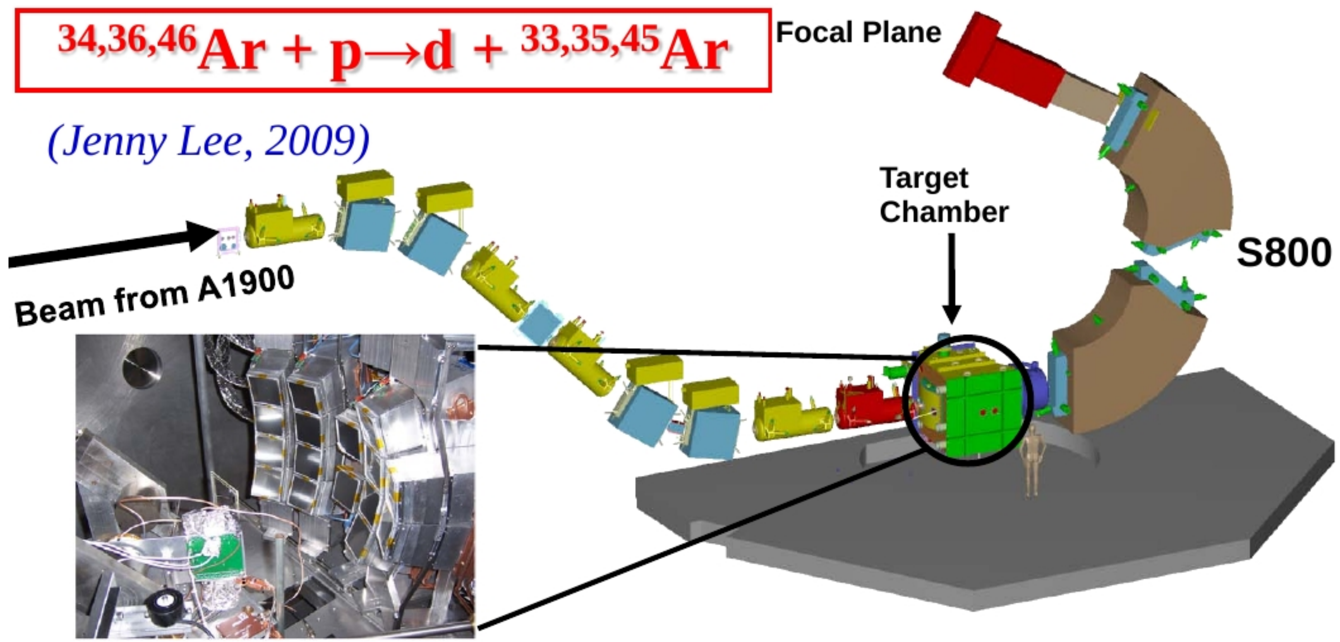
[FSU/LSU/ ReA3]

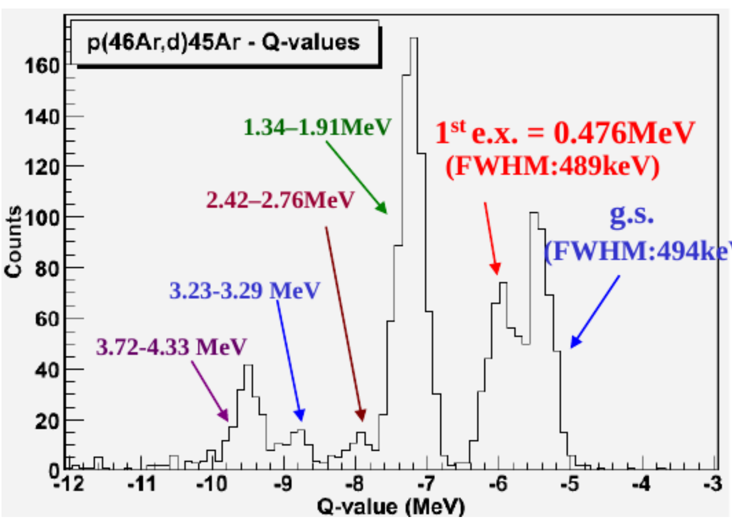


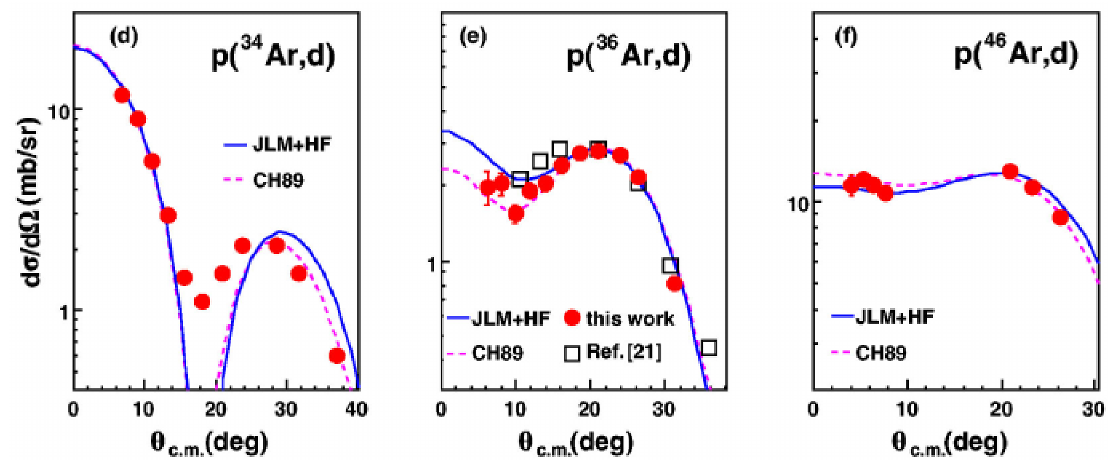


Measure the outgoing target-like light-particle

[Si and/or CsI Arrays: HiRA (NSCL/MSU)]



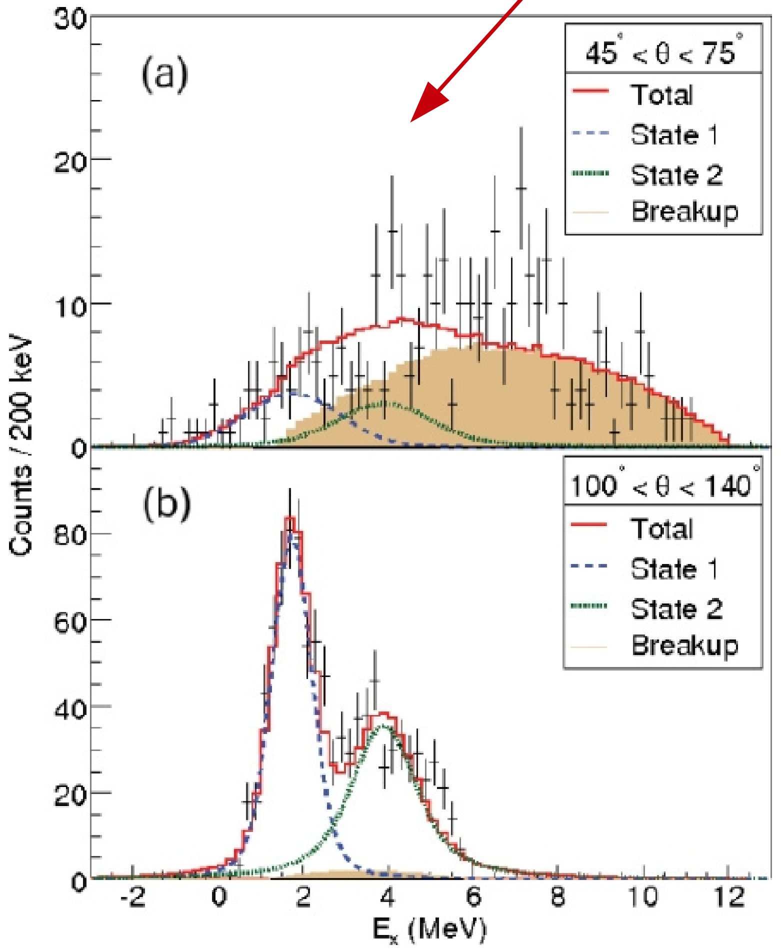




Lee et al., PRL 104, 112701 (2010)

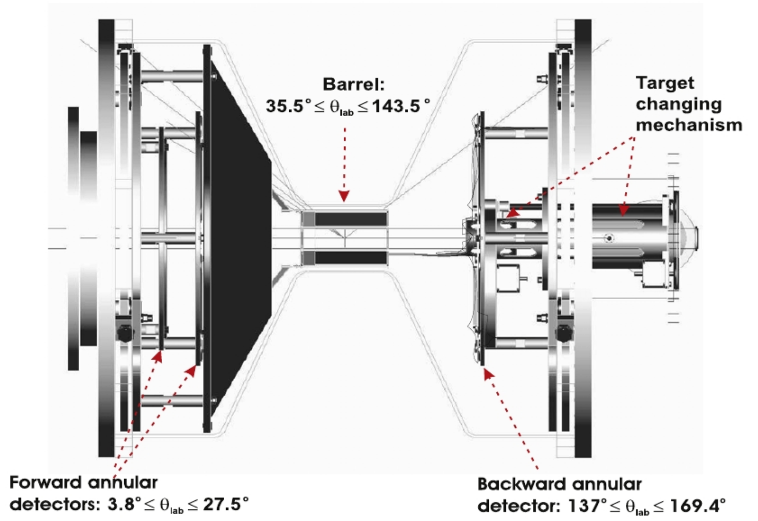
Measure coincidence γ-rays with charged particles/recoils

[TIARA+EXOGAM+VAMOS (GANIL)]

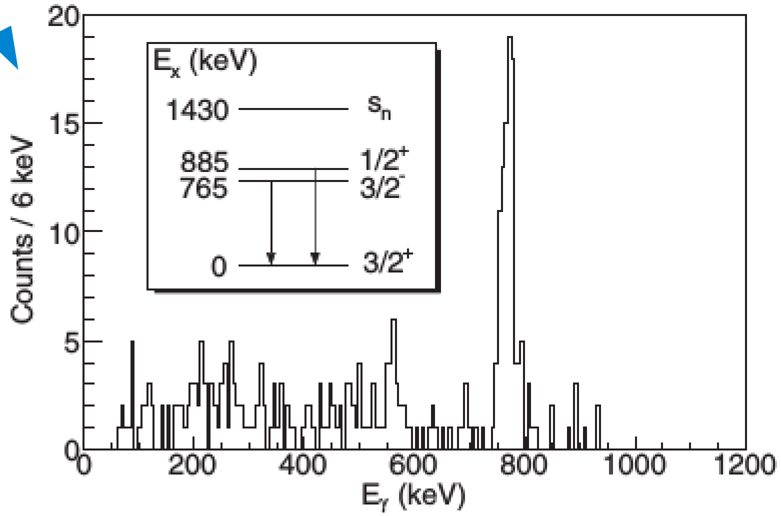


^{26}Ne(d,p)^{27}Ne @ 9.8 MeV/u

[GANIL]



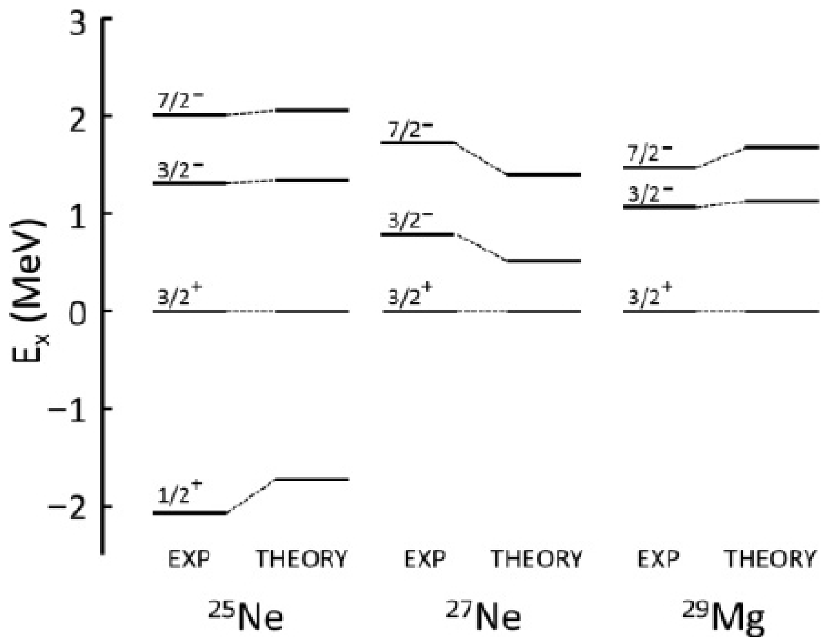
Labiche et al., NIMA 614, 439 (2010)

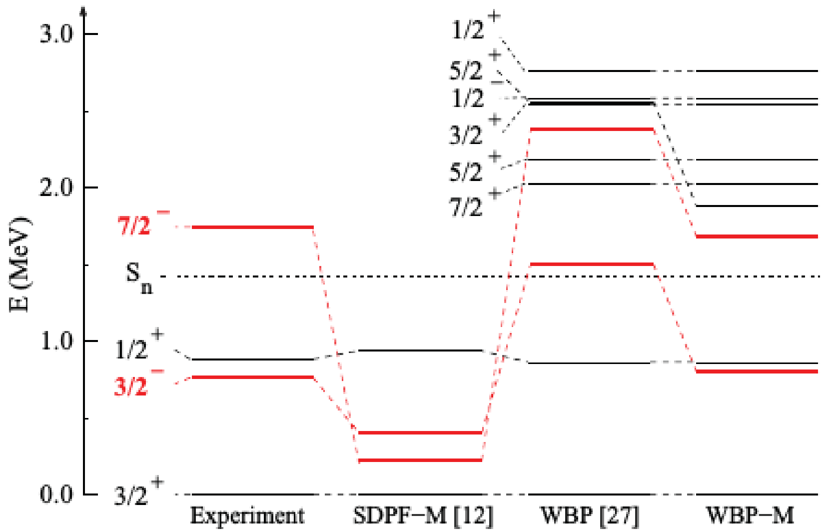


Simpson et al., Acta Phys. Hung. 11, 159 (2000)

Measure coincidence γ-rays with charged particles/recoils

[TIARA+EXOGAM+VAMOS (GANIL)]



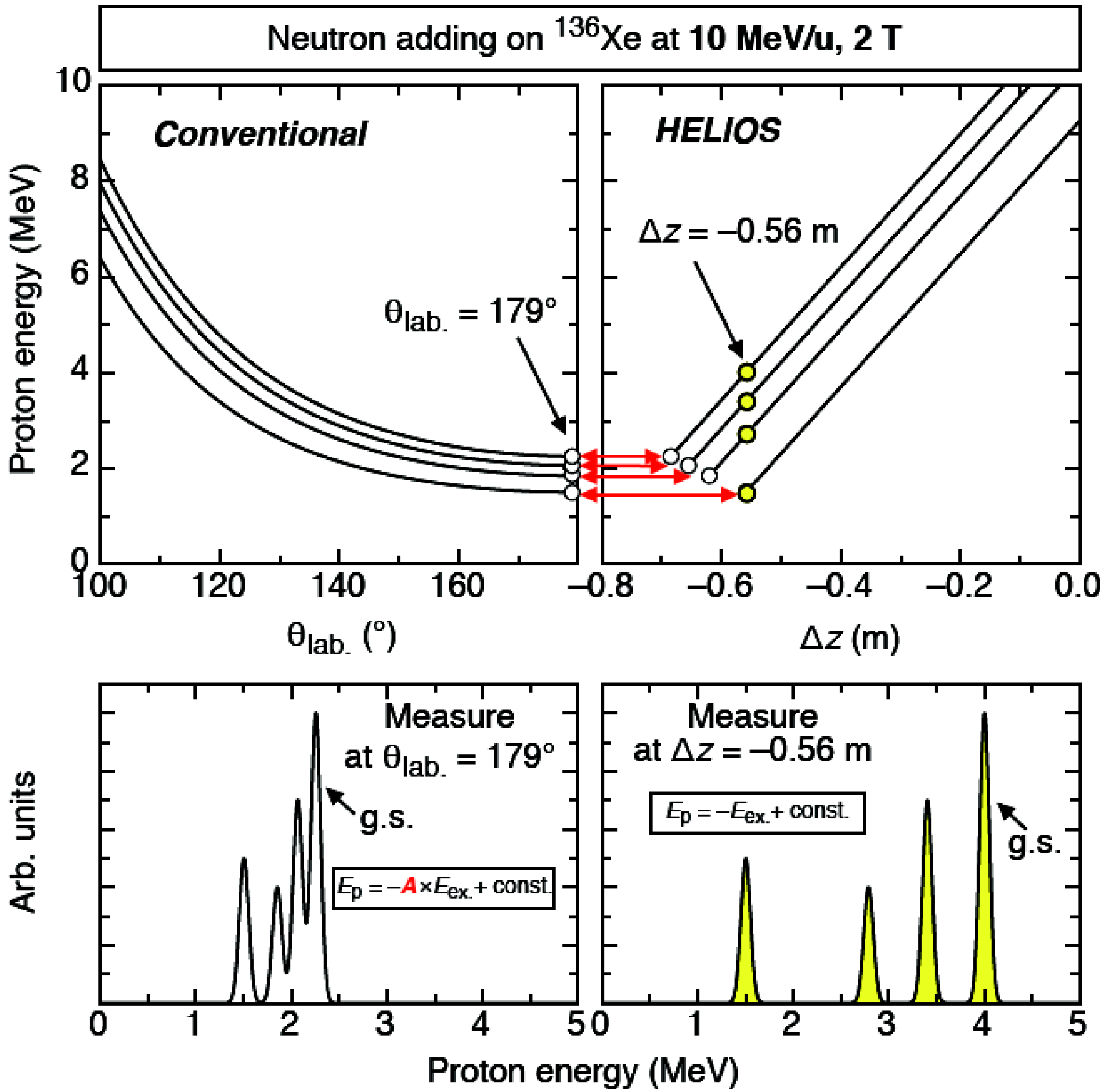


J^π	E^*_{exp} (MeV)	$E^*_{WBP\text{-}M}$ (MeV)	C^2S Ref. [10]	C^2S Present	C^2S WBP-M
$3/2^+$	0	0	0.2(2)	0.42(22)	0.63
$3/2^-$	0.765	0.809	0.6(2)	0.64(33)	0.67
$1/2^+$	0.885	0.869	0.3(1)	0.17(14)	0.17
$7/2^-$	1.74	1.686	–	0.35(10)	0.40

Brown et al., PRC 85, 011302(R) (2012)

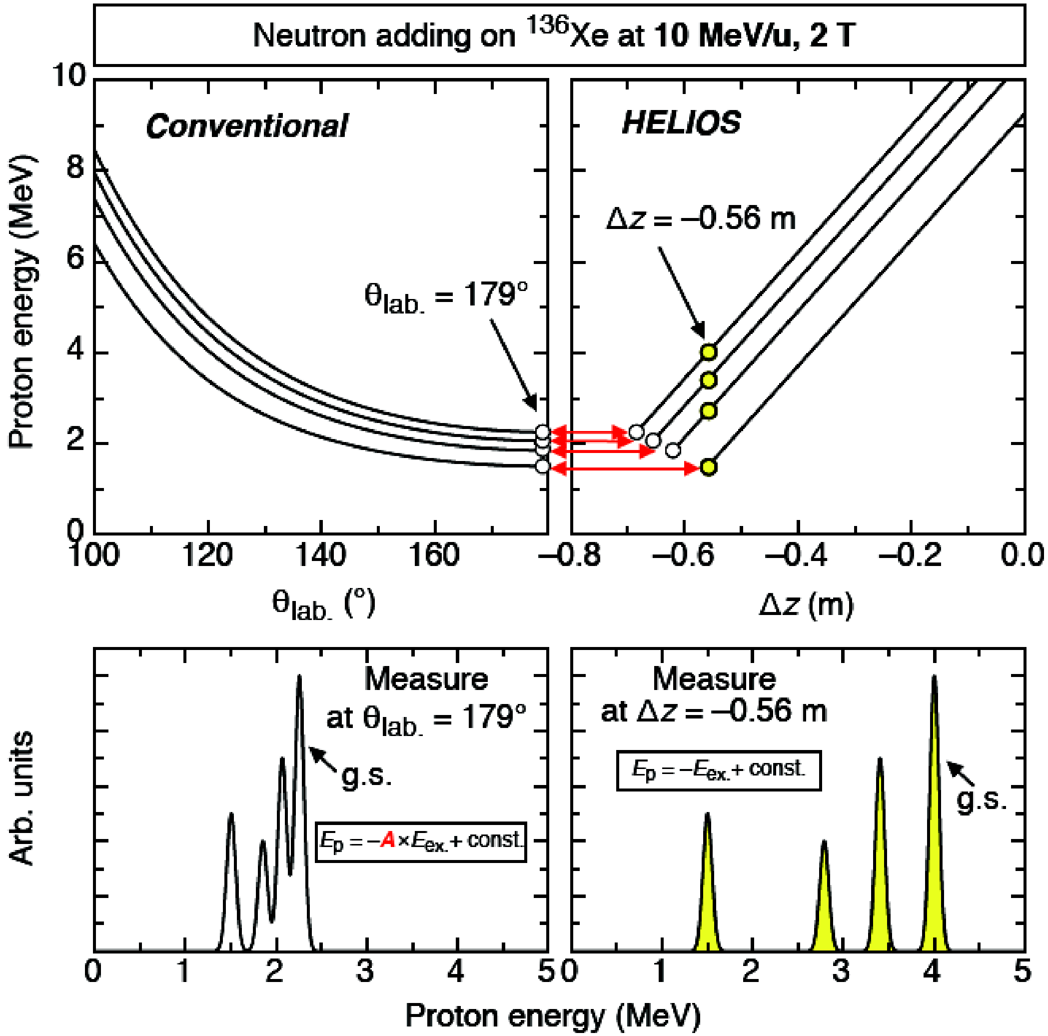
Measure the outgoing target-like light-particle

[New(ish) Approach]



Measure the outgoing target-like light-particle

[New(ish) Approach]



Measured quantities

Flight time: $T_{flight} = T_{cyc}$

Position: z

Energy: E_{lab}

Derived quantities

Part. ID: m/q

Energy: E_{cm}

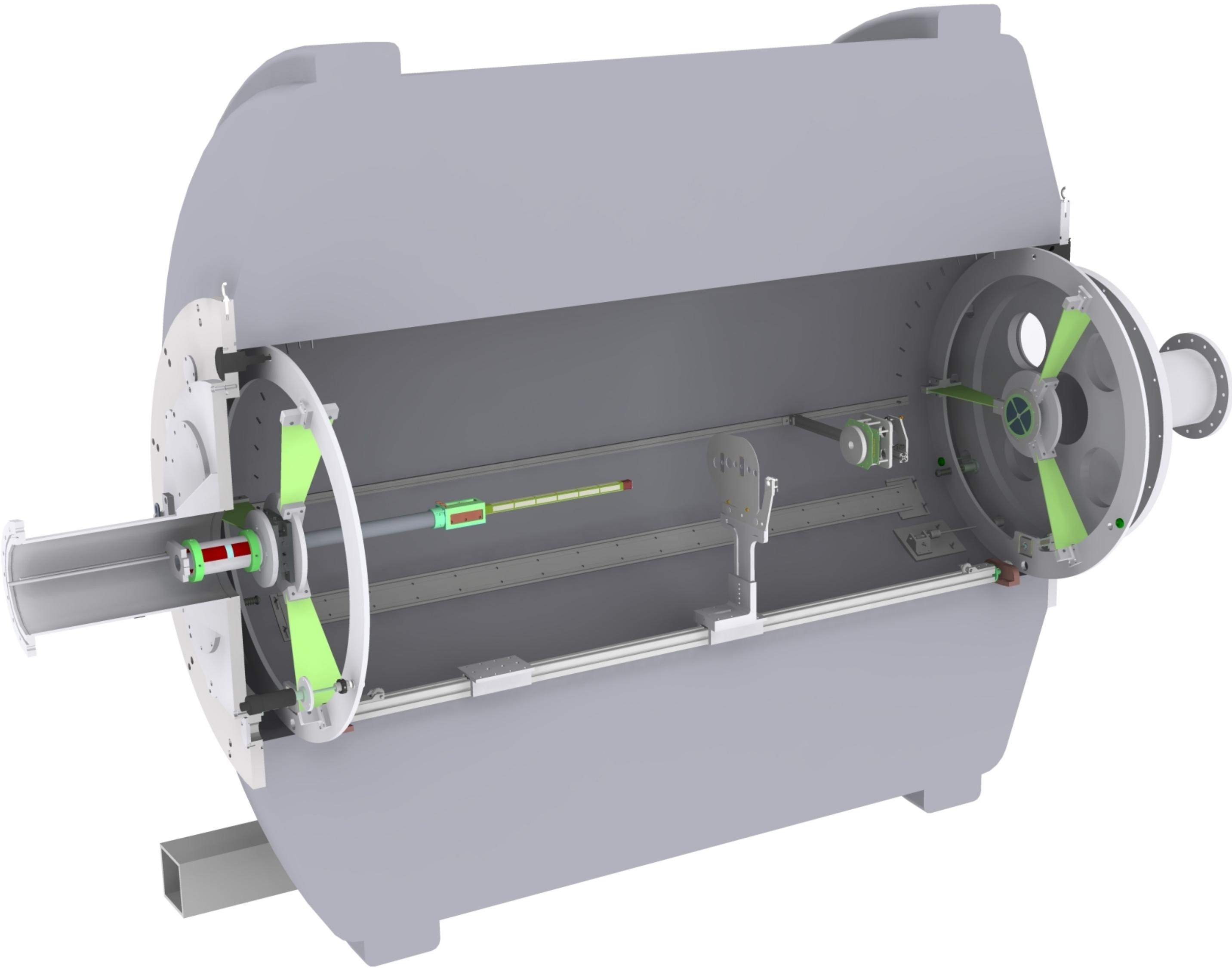
Angle: θ_{cm}

$$\frac{m}{q} = \frac{eB}{2\pi} \times T_{flight}$$

$$E_{cm} = E_{lab} + \tfrac{1}{2} m V_{cm}^2 - \frac{V_{cm} q e B}{2\pi} z$$

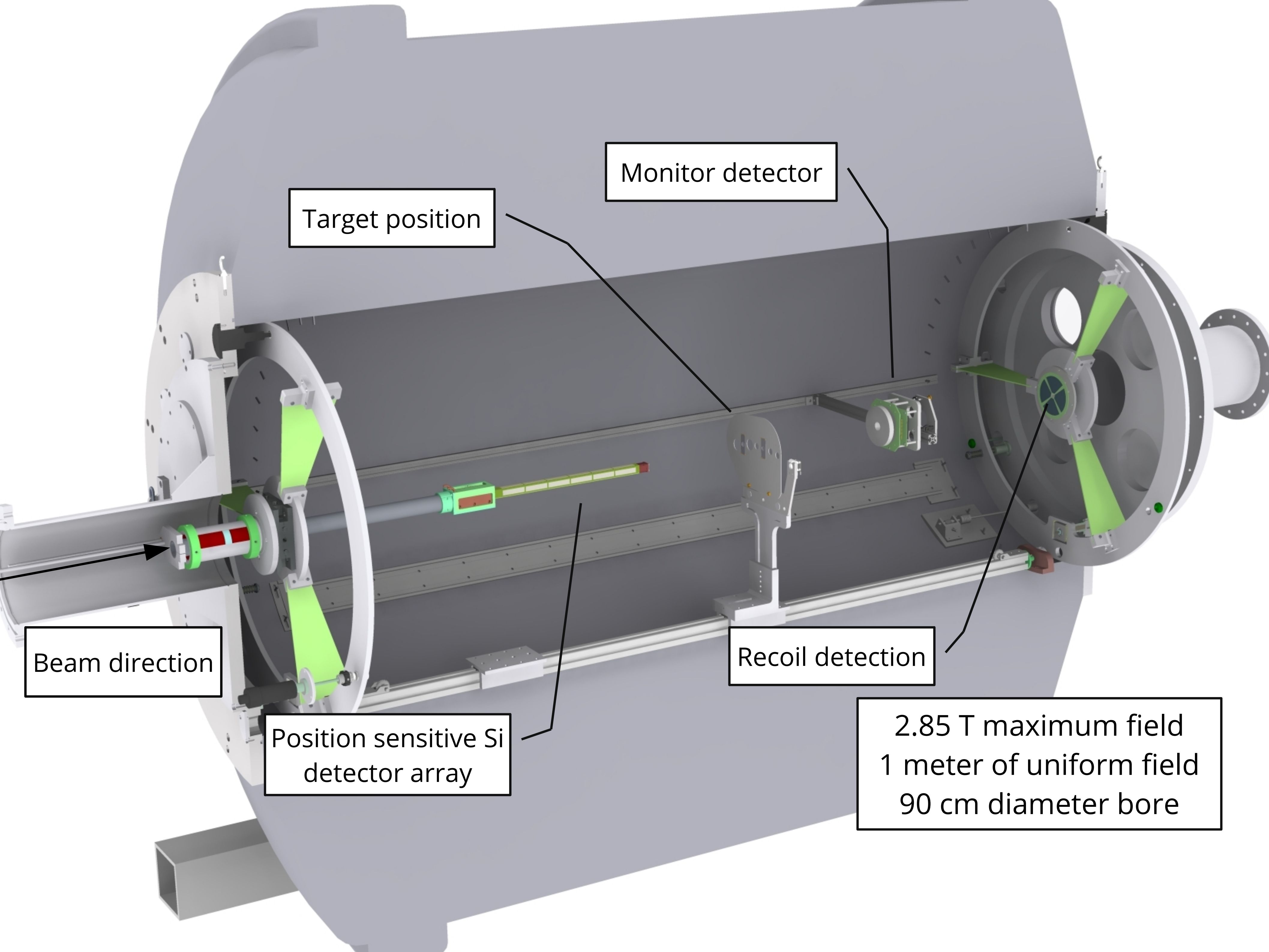
$$\theta_{cm} = \arccos\left(\frac{1}{2\pi} \frac{qeBz - 2\pi m V_{cm}}{\sqrt{2mE_{lab} + m^2 V_{cm}^2 - m V_{cm} qeBz / \pi}} \right)$$

HELIcal Orbit Spectrometer



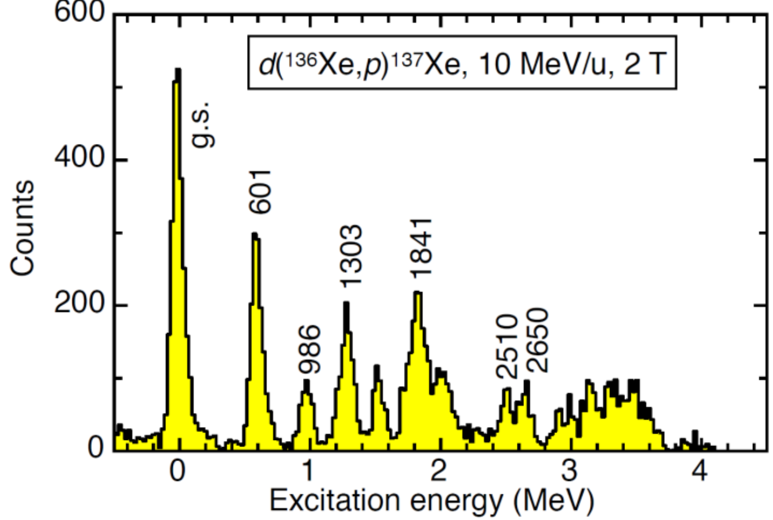
HELIOS

Wuosmaa et al., NIM (2007), Lighthall et al., NIM (2010)

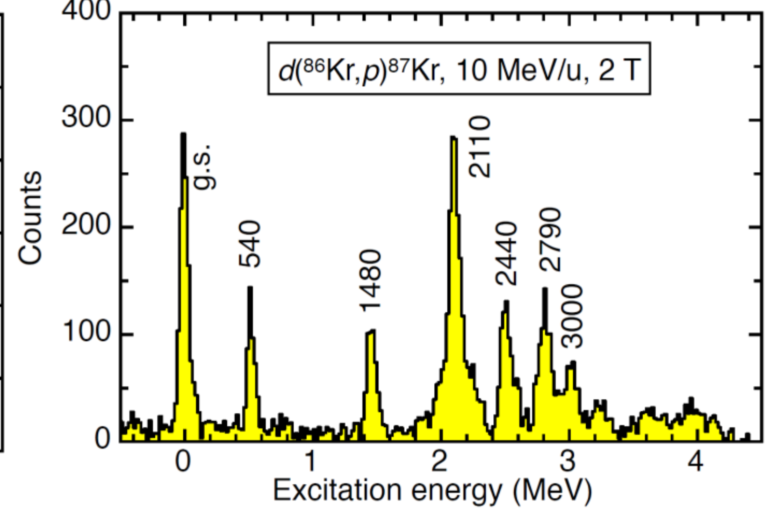

Monitor detector
Target position
Beam direction
Recoil detection
Position sensitive Si
detector array
2.85 T maximum field
1 meter of uniform field
90 cm diameter bore

Results from HELIOS

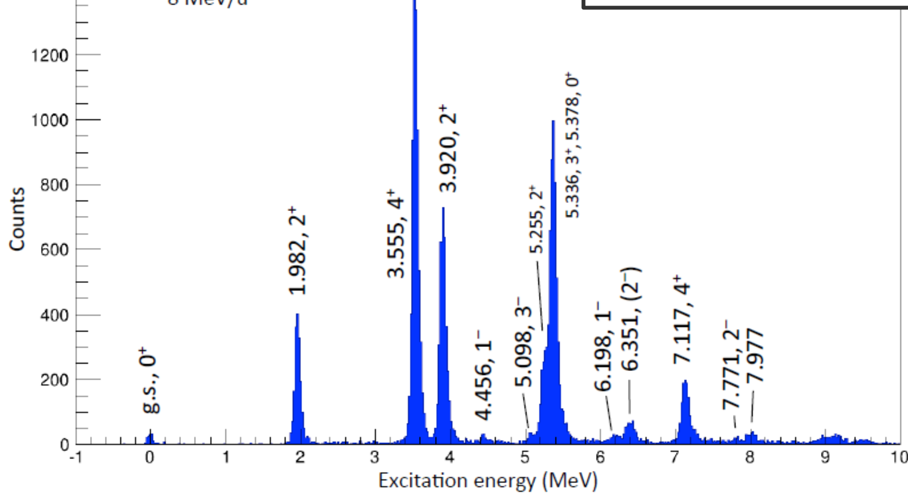
Resolution <100 keV



Resolution <70 keV



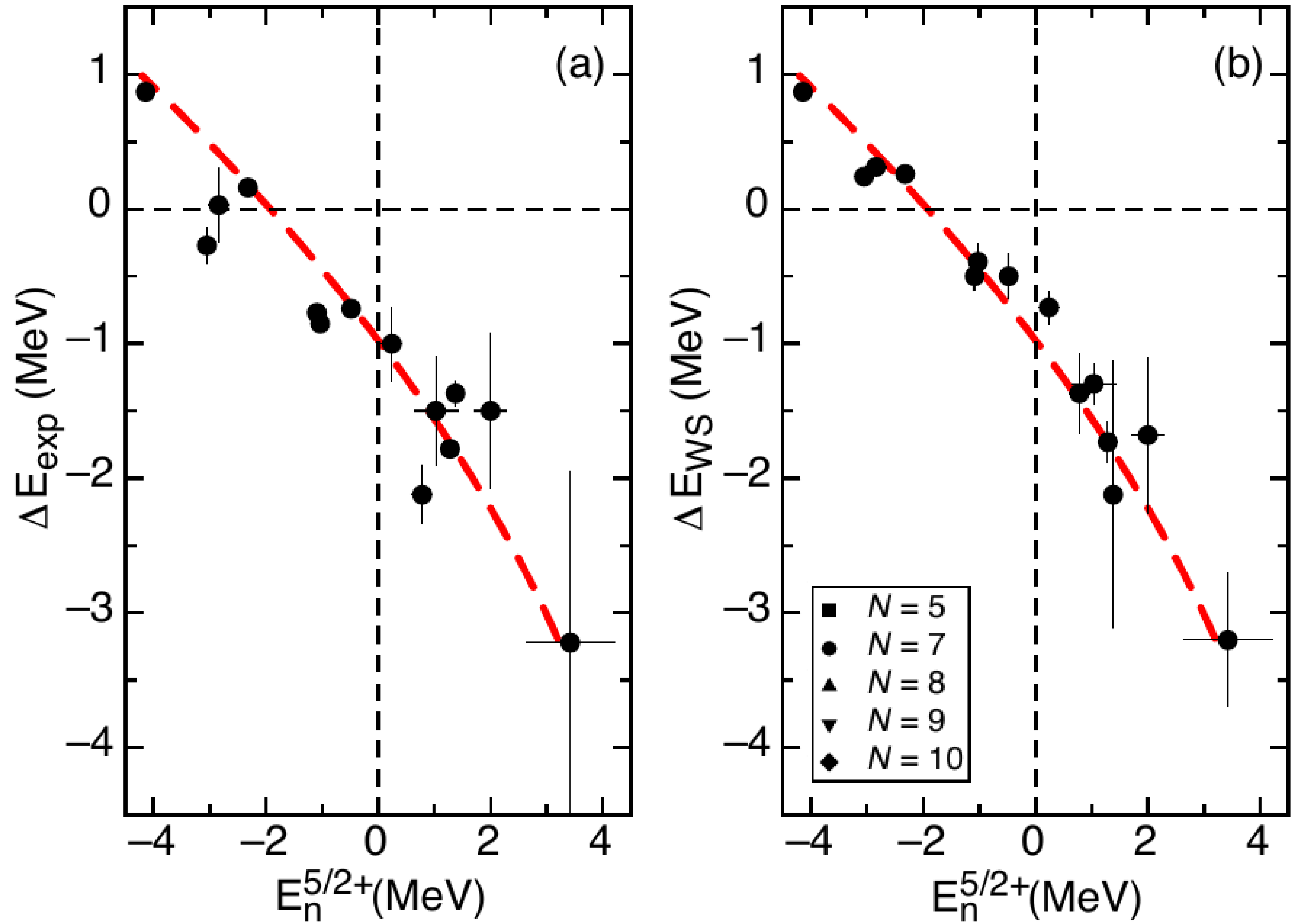
Resolution <60 keV



Ordering of the $1s_{1/2} - 0d_{5/2}$ neutron orbitals

Experiment

Calculation



Hoffman, Kay, Schiffer, PRC (2014)

Summary

- Choosing proper reaction for physics of interest is key
  - Selectivity of reaction, momentum matching, etc...
- Many key properties can be obtained from transfer reactions
  - Q-value, cross sections, spectroscopic factors & strengths, single-particle energies etc...
- Transfer in normal kinematics has been crucial for our understanding of nuclei
- Inverse reactions present a new set of problems
  - Various methods to overcome these challenges