Nuclear Reactions

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Part 2. Transfer reactions

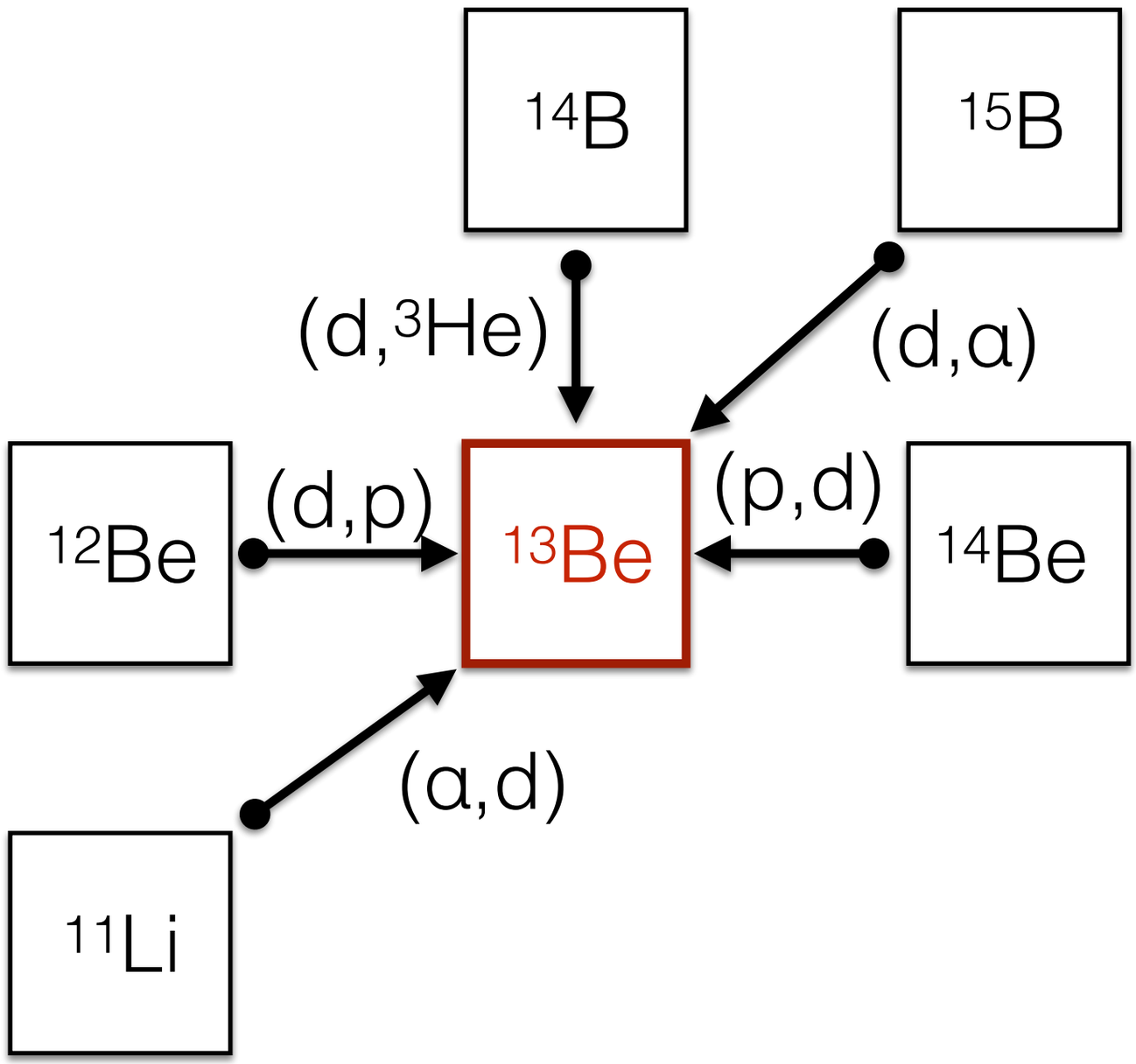
Transfer reactions

Simple nucleon transfer reactions with rare isotope beams at energies ~10 MeV/u or below are popular tools to study structure of exotic nuclei.

The most useful reactions are (d,p); (t,p); (d,^{3}He); (^{3}He,d); (p,d); (p,t); (^{6}Li,d); (^{7}Li,t); (α,d); (d;α)

Direct reactions: structure of exotic nuclei

(p,d)
(p,t)
(d,p)
(d,^{3}He)
(d,α)
(^{3}He,d)
(^{3}He,t)
(^{4}He,t)
(^{4}He,d)



Transfer reactions theory

^{16}O+d -> ^{16}O + d

^{16}O+d -> ^{16}O*+ d

^{16}O+d -> ^{17}O + p

^{16}O+d -> ^{15}O + t

^{16}O+d -> ^{14}C + α

^{16}O+d -> ^{17}F + n

Partitions:

$$\Psi^{M_{tot}}_{xJ_{tot}}(R_x,\xi_p,\xi_t) = \sum_{LI_pJ_pI_tM\mu_tM_a\mu_t} \phi^{xp}_{I_p\mu_p}(\xi_p)\phi^{xt}_{I_t\mu_t}(\xi_t) i^L Y^M_L(\vec{R_x}) \frac{1}{R_x}\psi^{J_{tot}}_{\alpha}(R_x)$$
$$< LM, I_p\mu_p | J_pM_a >< J_pM_a, I_t\mu_t | J_{tot}M_{tot} >$$

$$\psi^{J_{tot}\pi}_{\alpha\alpha_i}(R_x) = \frac{i}{2}\left[H^-_{L_i}(\eta_\alpha, k_\alpha R_x)\delta_{\alpha\alpha_i} - H^+_L(\eta_\alpha, k_\alpha R_x) S^{J_{tot}\pi}_{\alpha\alpha_i}\right]$$

$$S_{\alpha\alpha_i} = \delta_{\alpha\alpha_i} + 2iT_{\alpha\alpha_i}$$

$$\sigma_{\alpha\alpha_i}(\theta) = \frac{1}{(2I_{p_i}+1)(2I_{t_i}+1)} \sum_{\mu_p\mu_t\mu_{pi}\mu_{t_i}} |f^{\alpha\alpha_i}_{\mu_p\mu_t,\mu_{p_i}\mu_{t_i}}(\theta)|^2$$

$$f^{\alpha\alpha_i}(\theta) \sim T_{\alpha\alpha_i}$$

Transfer reactions theory

$$T^{PWBA}_{\alpha\alpha_i} = -\frac{2\mu}{\hbar^2 k} < \phi^{(-)}|U|\phi >$$

ϕ - plane wave

$$f^{PWBA}(\theta) = -\frac{\mu}{2\pi\hbar^2}\int dR e^{-iqR}U(R)$$

$$\vec{q} = \vec{k} - \vec{k_i} = 2k\sin\frac{\theta}{2}$$

$$T^{DWBA}_{\alpha\alpha_i} = -\frac{2\mu}{hbar^2 k} < \chi^-_\alpha|U|\chi_{\alpha_i} >$$

χ - distorted waves calculated using optical model potentials

Spectroscopic factors

The spectroscopic factor is the overlap between initial and the final state in a reaction channel. Cross section for the transfer reaction is proportional to the spectroscopic factor. For resonance state spectroscopic factor can be related to the reduced width.

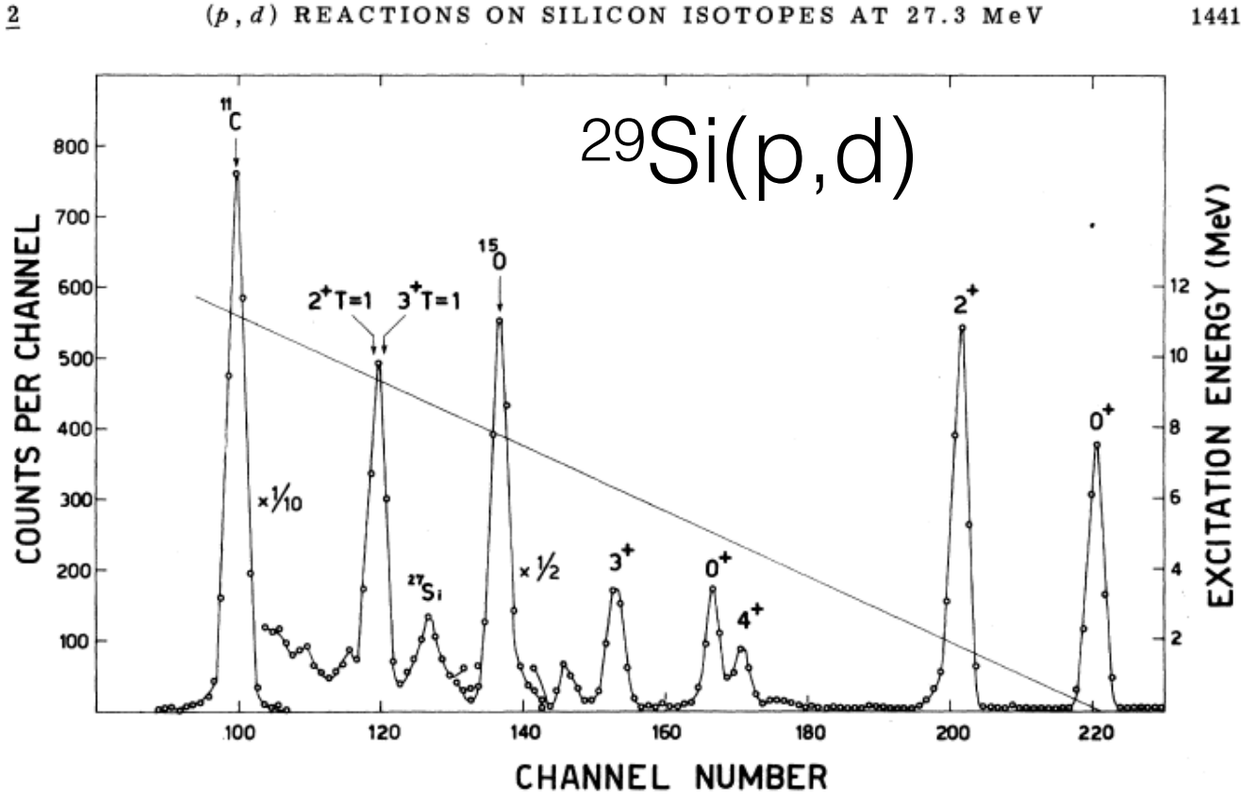
C* -> a+A

$$S \sim \int [\phi(a) \times \phi(A)] \phi(C^*) ds \qquad S = \frac{\gamma^2}{\gamma_{sp}^2}$$

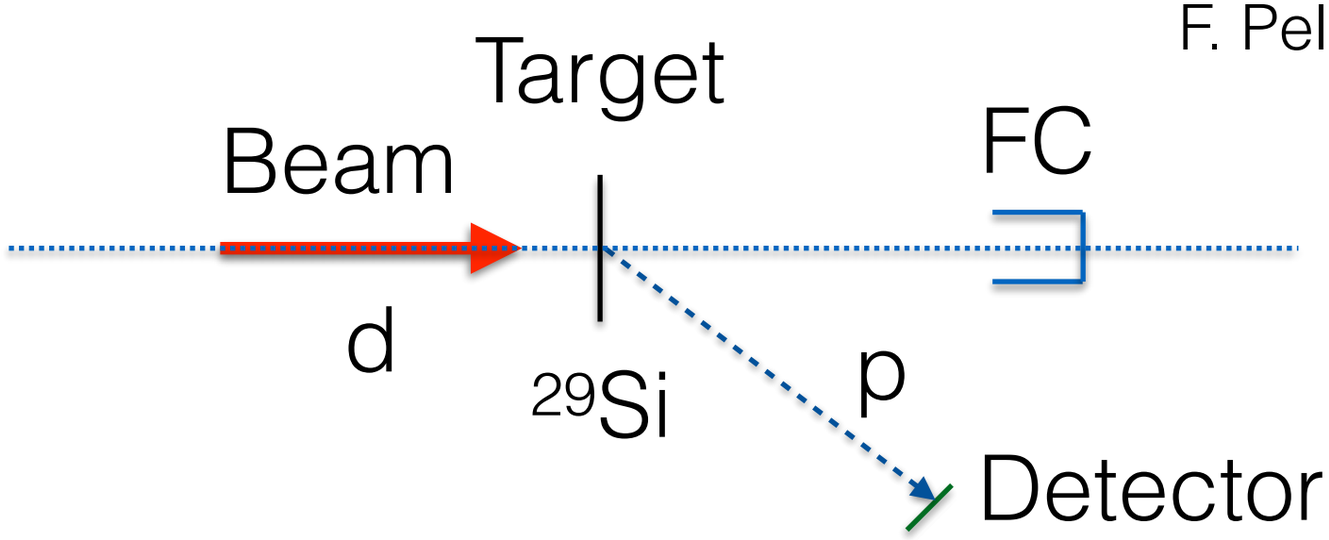
ad + A -> aA + d

$$\frac{d\sigma}{d\Omega}_{\exp} = S_{\alpha d} S_{\alpha A} \frac{d\sigma}{d\Omega}_{DWBA}$$

Missing mass method

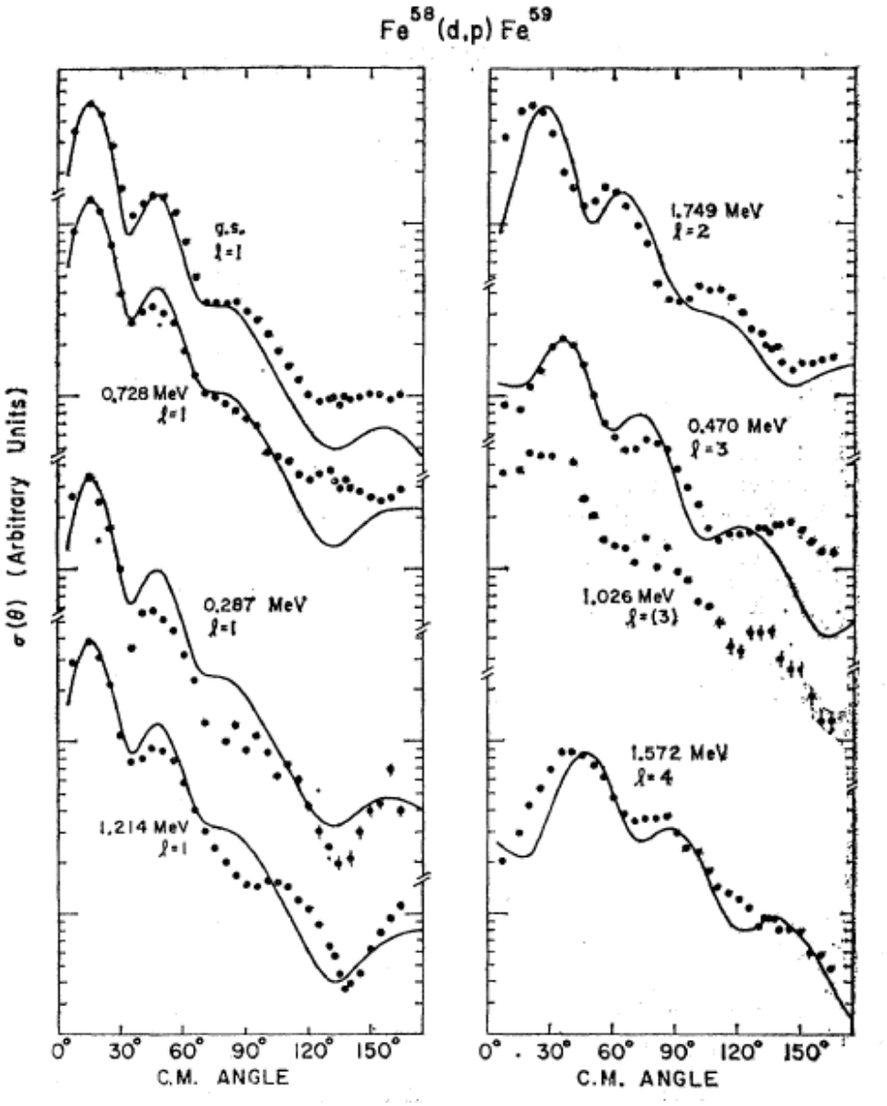


F. Pellegrini, et al., PRC 2 (1979)



Energy resolution - 100 keV

Angular distribution for the transfer reaction is determined by the momentum transfer - therefore l-value can be determined



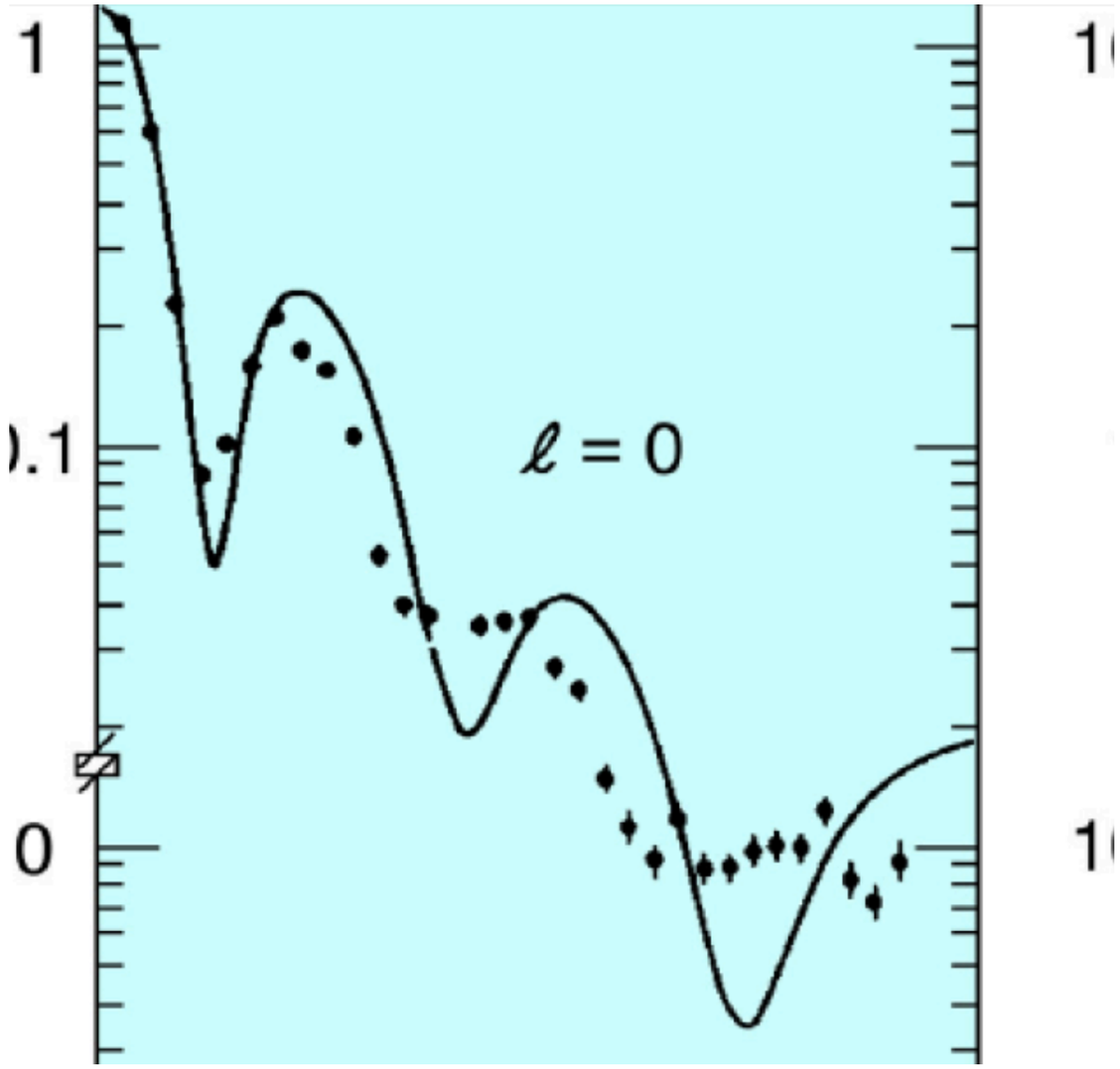
Klema, Lee, Schiffer Phys. Rev. 161 (1967)

$$q = |k_f - k_i| \approx 2k \sin(\theta/2) \sim \frac{\ell}{R}$$

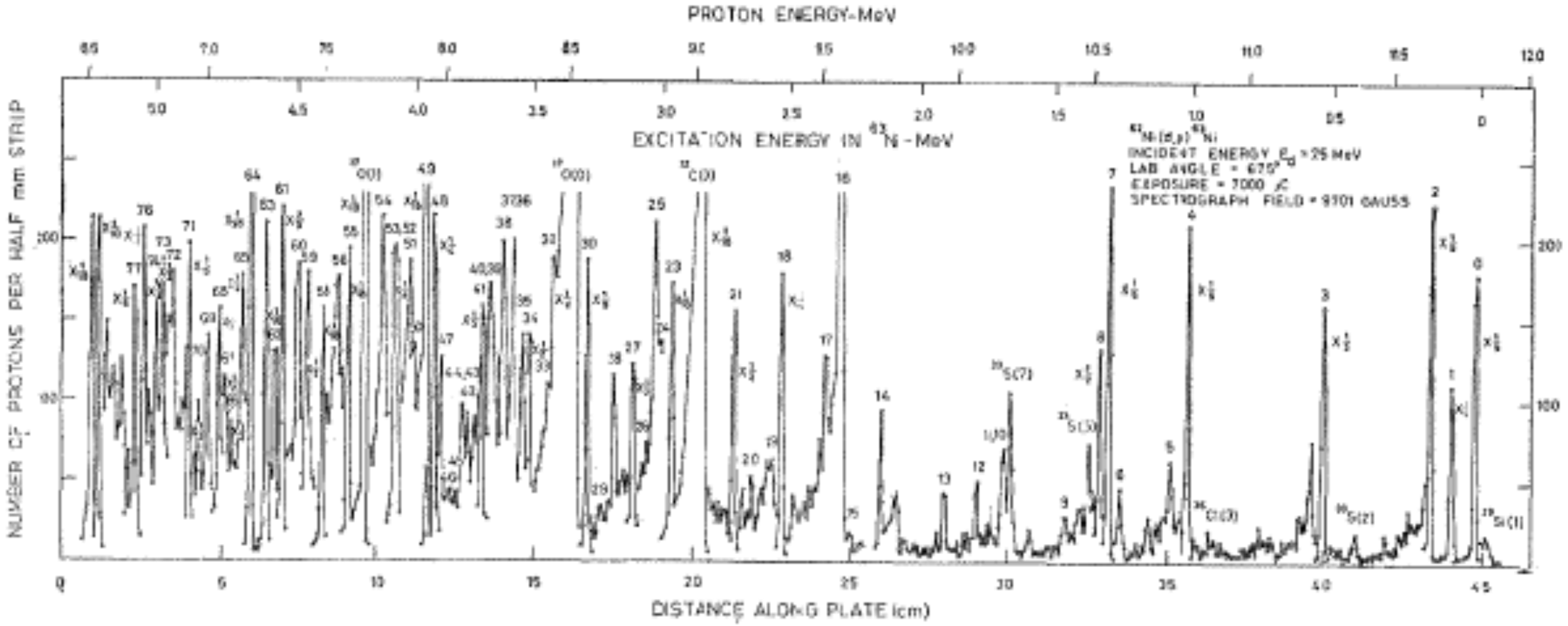
With l-value known the spin-parity can be determined (often not uniquely)

States with what spin-parities can be populated in L=2 transfer in ^{58}Fe(d,p) reaction?

At what angle the cross section maximum is expected for L=0 transfer?



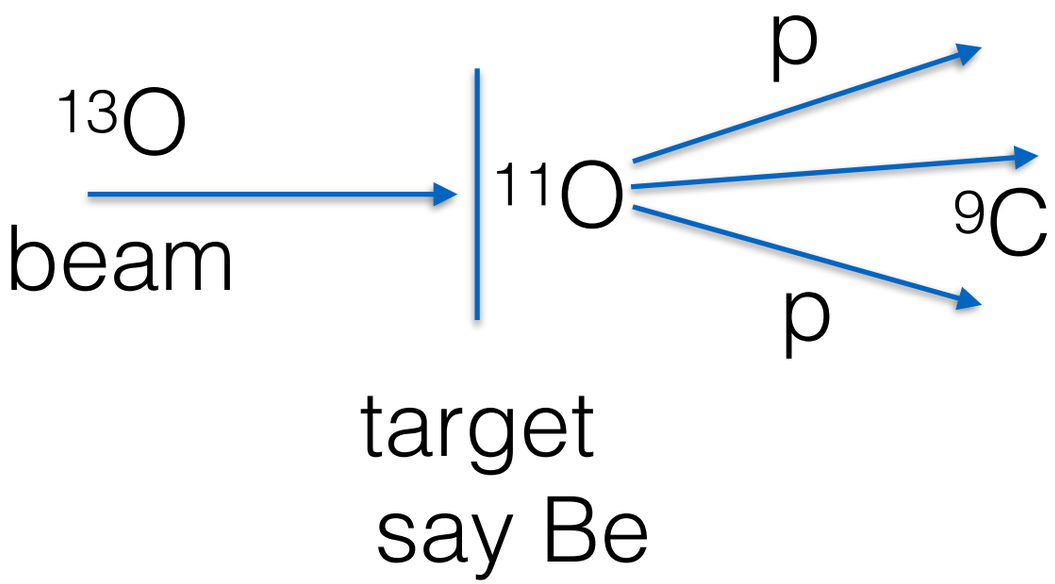
Missing mass method



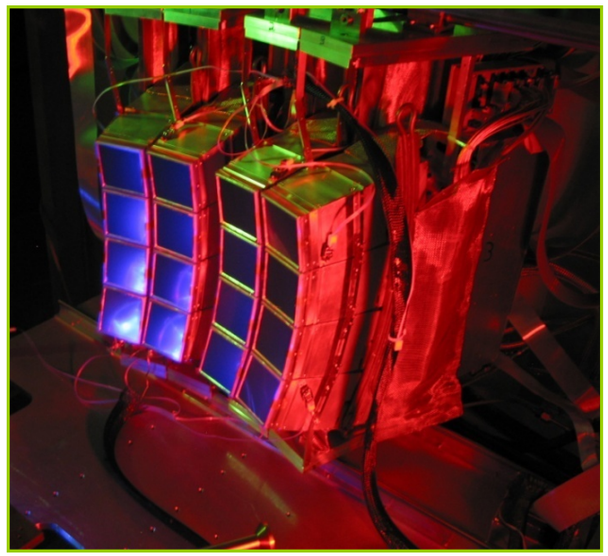
Use of spectrometers allows for much better resolution on the order of 10 keV!

T.R. Afinsen, et al.,NPA 157 (1970)

Invariant Mass



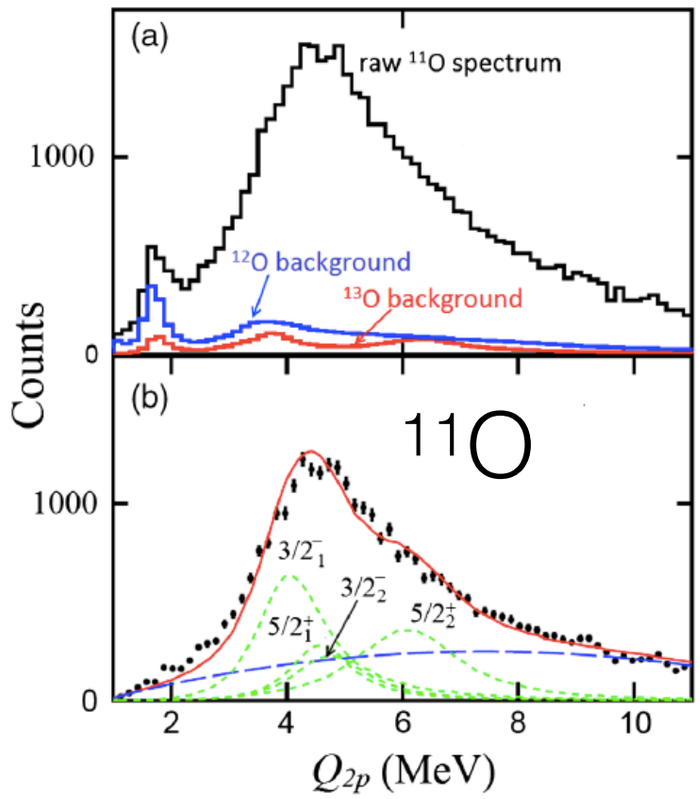
$$M^2_{^{11}O} = (\sum E_i)^2 - (\sum_i \vec{P}_i)^2$$



PHYSICAL REVIEW LETTERS **122,** 122501 (2019)

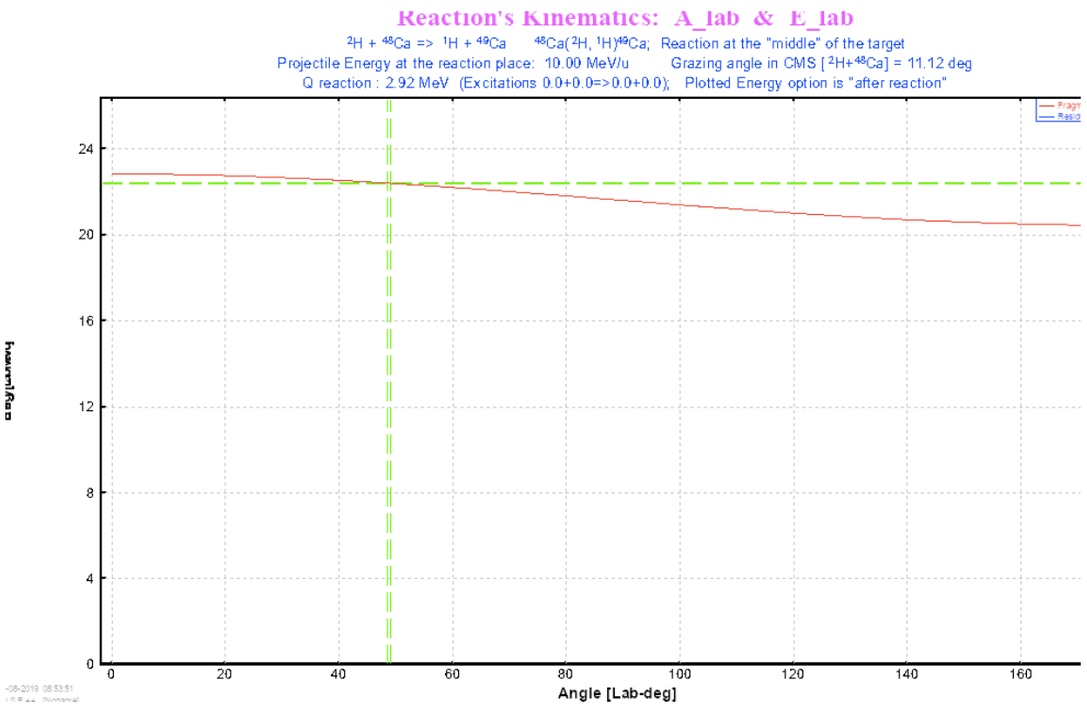
First Observation of Unbound ^{11}O, the Mirror of the Halo Nucleus ^{11}Li

T. B. Webb,[1,*] S. M. Wang (王思敏),[2] K. W. Brown,[2] R. J. Charity,[3] J. M. Elson,[3] J. Barney,[2] G. Cerizza,[2] Z. Chajecki,[4] J. Estee,[2] D. E. M. Hoff,[3] S. A. Kuvin,[5] W. G. Lynch,[2] J. Manfredi,[2] D. McNeel,[5] P. Morfouace,[2] W. Nazarewicz,[6] C. D. Pruitt,[3] C. Santamaria,[2] J. Smith,[5] L. G. Sobotka,[1,3] S. Sweany,[2] C. Y. Tsang,[2] M. B. Tsang,[2] A. H. Wuosmaa,[5] Y. Zhang,[2] and K. Zhu[2]

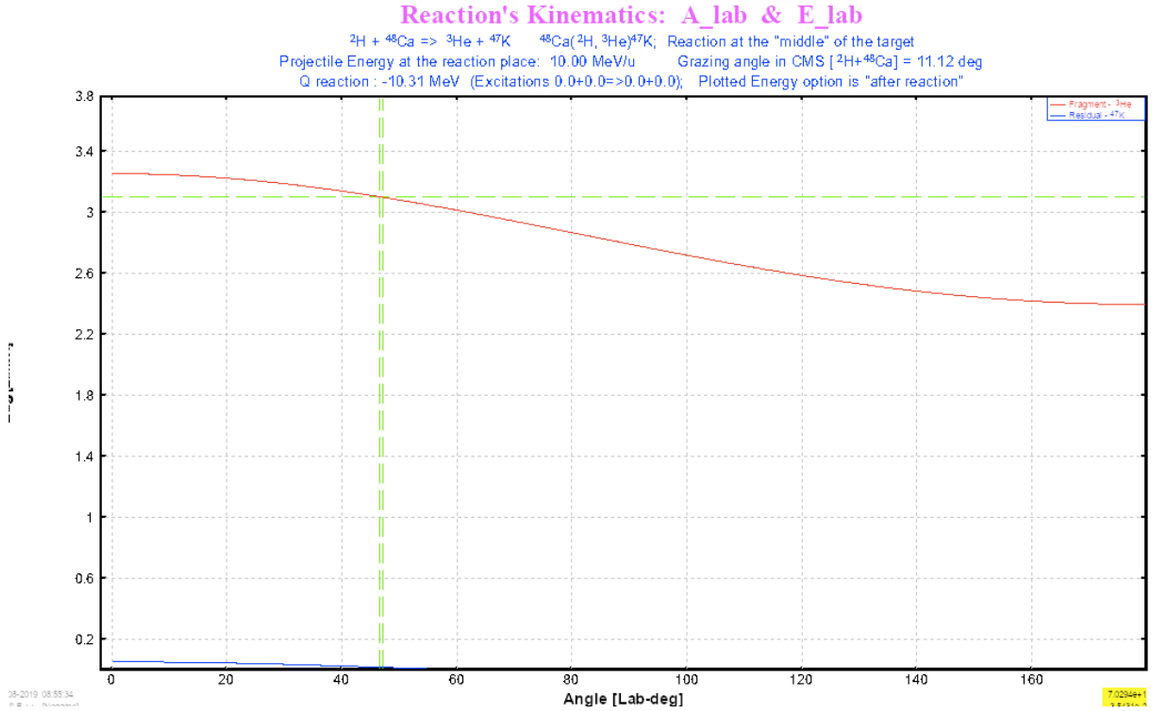


Transfer with radioactive beams

Direct kinematics - (d,p)



Direct kinematics - (d,^{3}He)

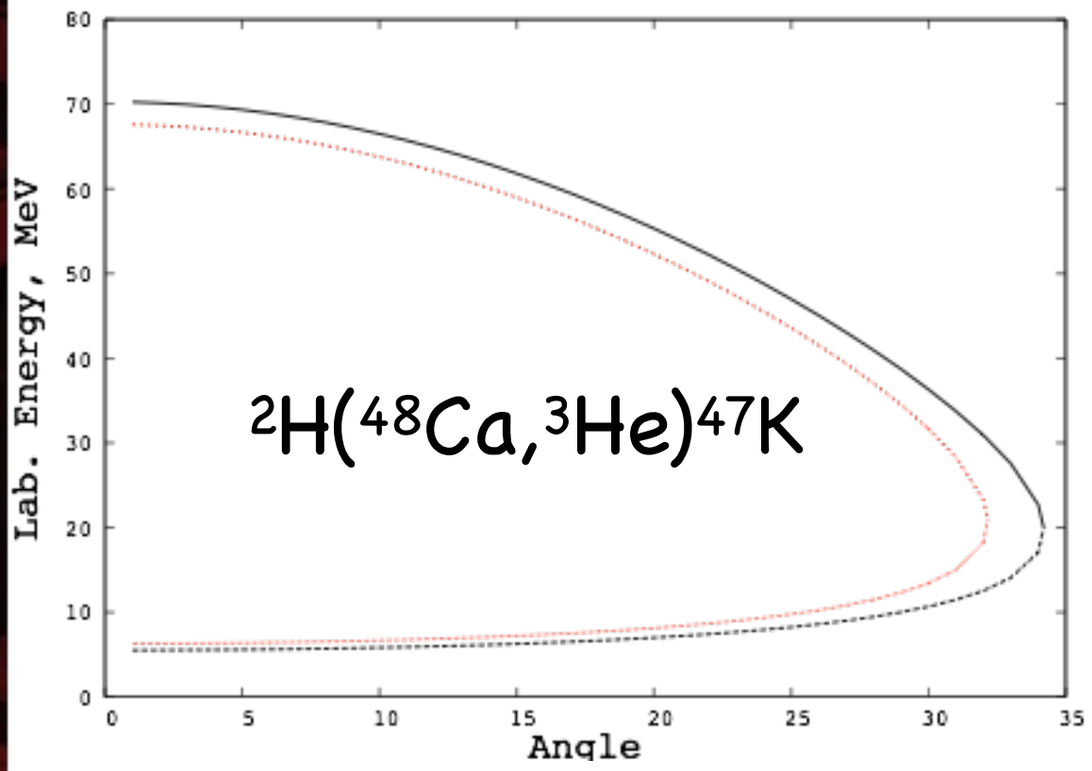


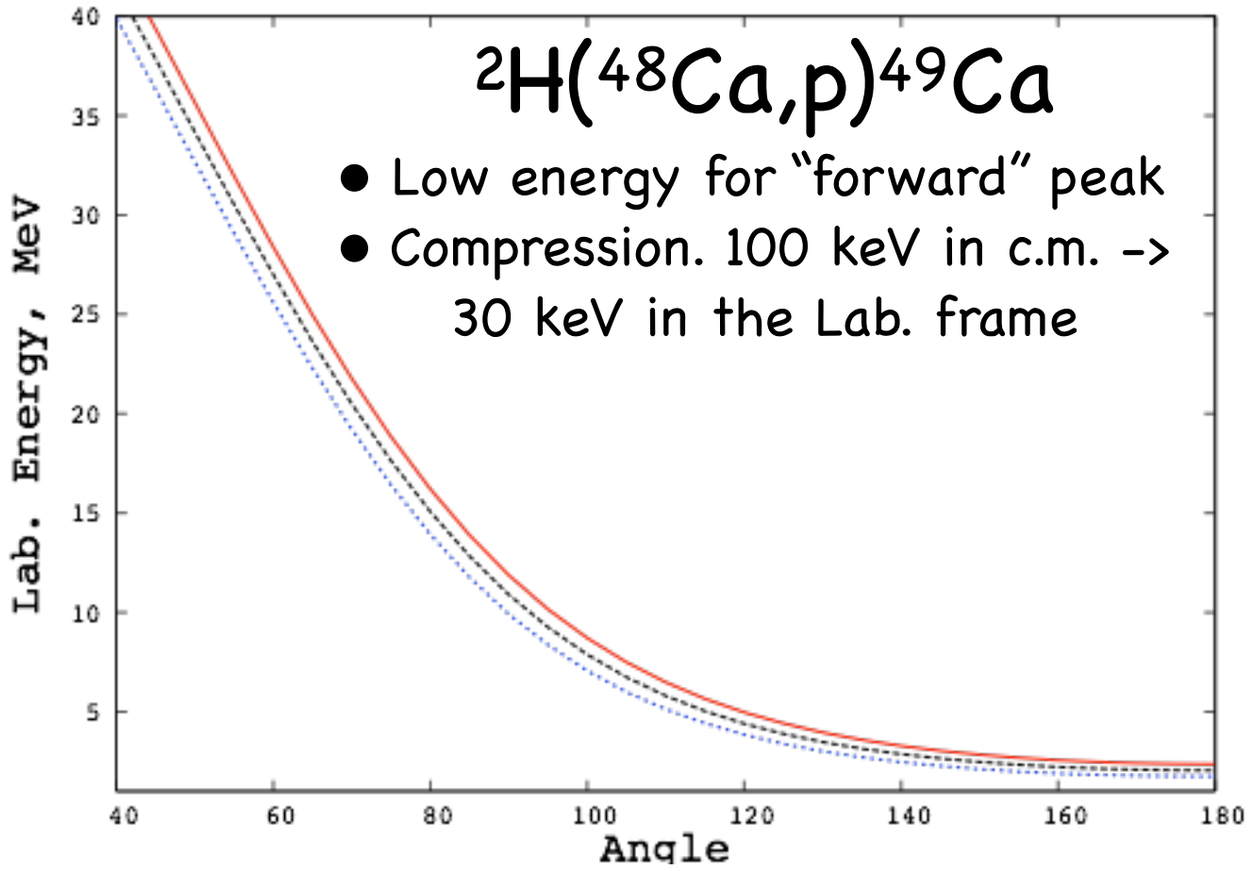
Transfer with radioactive beams

Inverse kinematics

HI nucleon(s) drop off

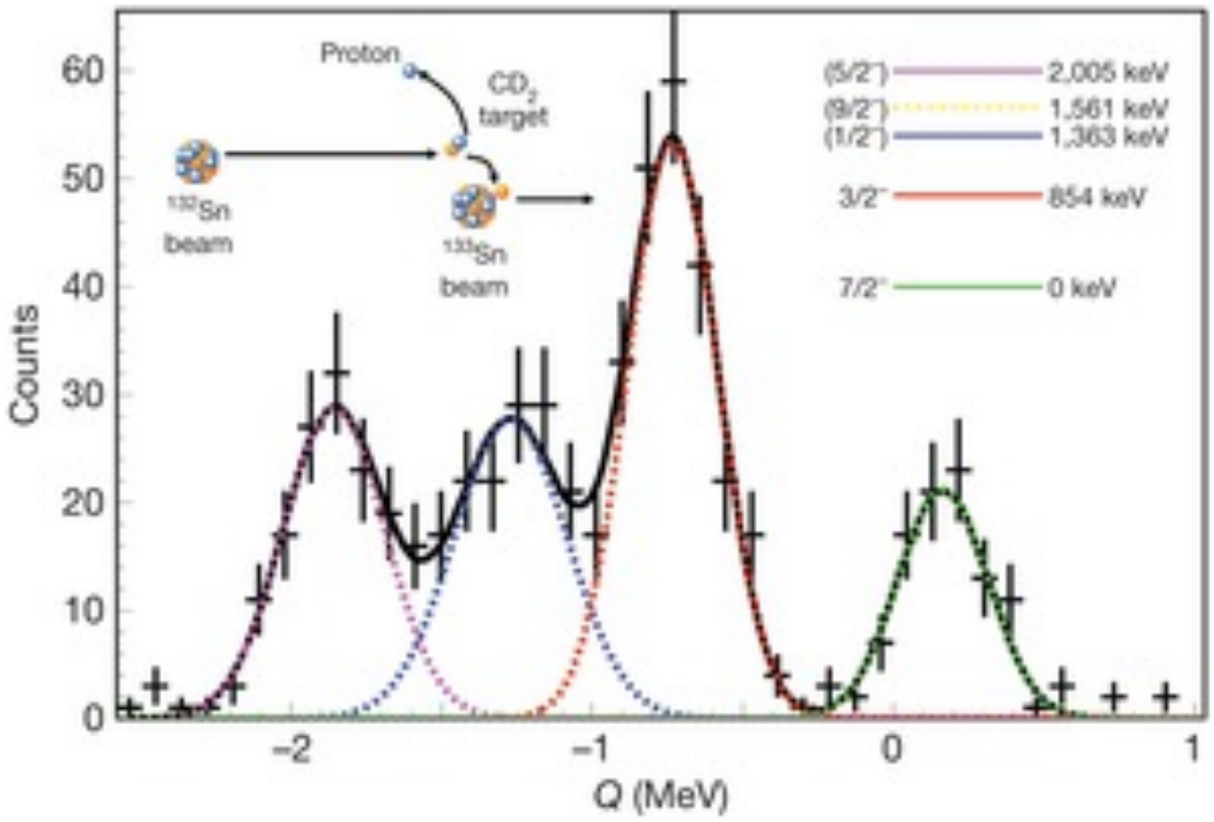
HI nucleon(s) pick up

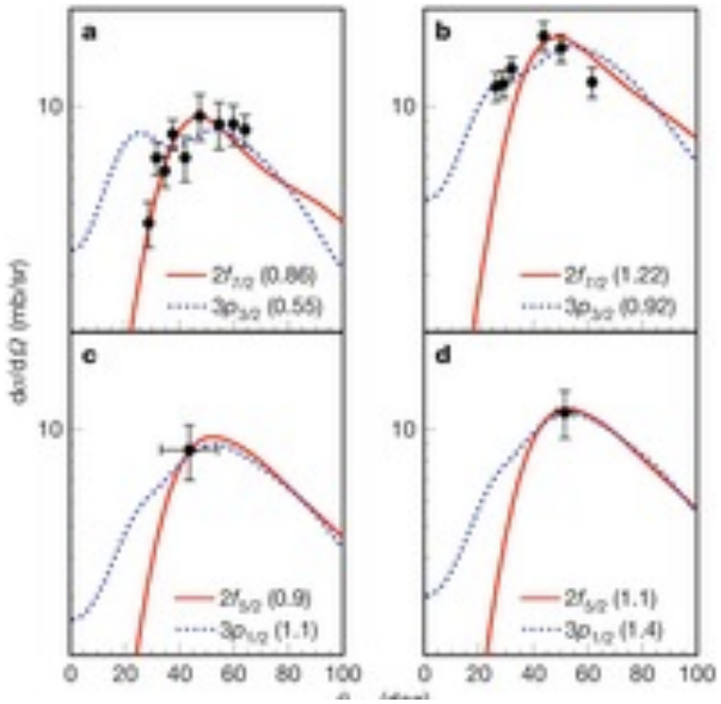




E_{beam} ~ 10 MeV/u

Doubly magic ^{132}Sn

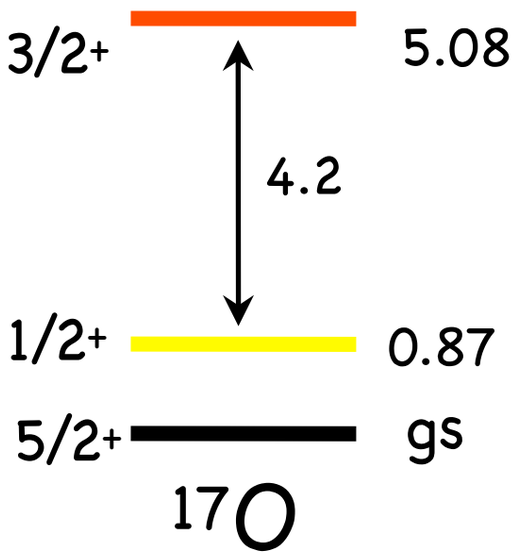


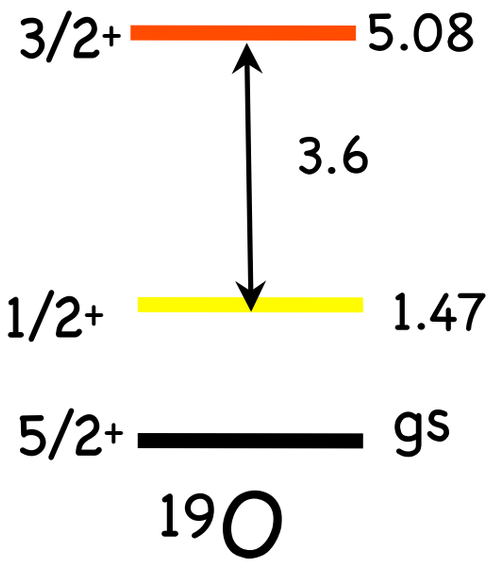


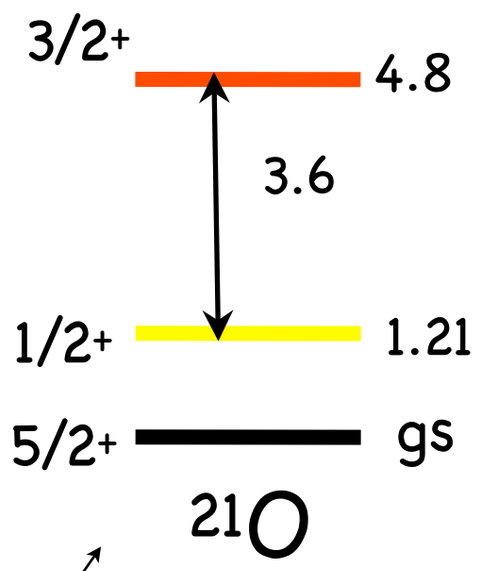
K. Jones, et al., *Nature* **465**, 454–457 (27 May 2010)

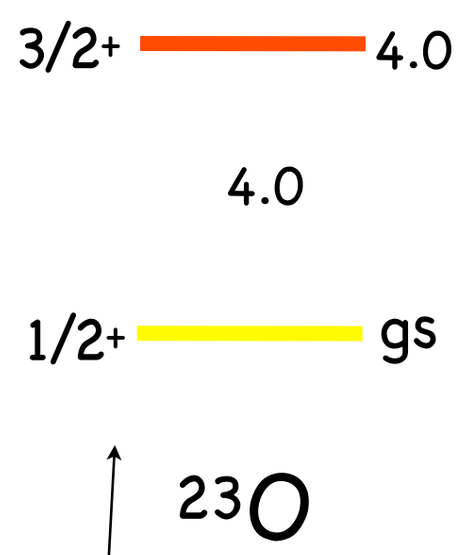
Typical energy resolution ~400 keV

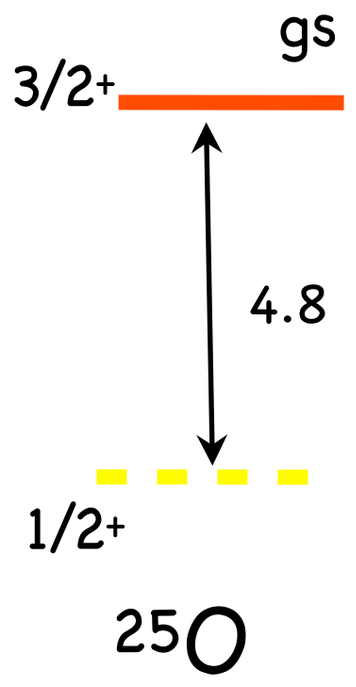
Emergence of N=16 shell gap





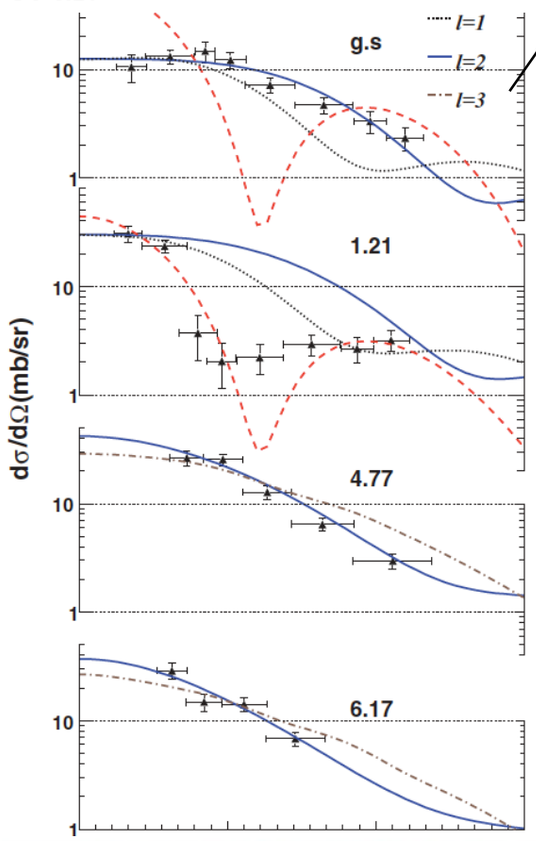




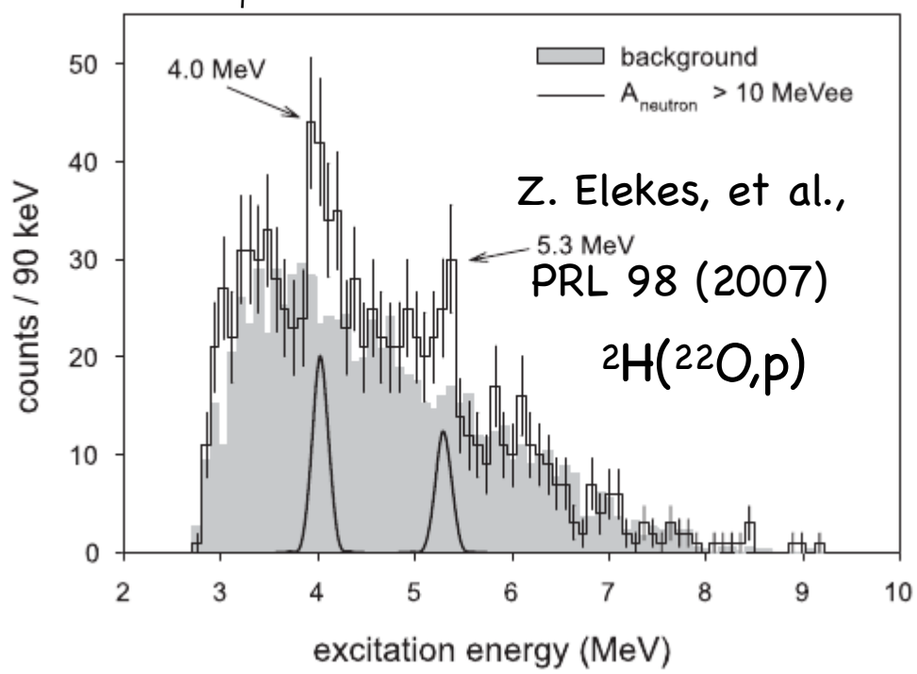


B. Fernandez-Domınguez, et al.
Phys. Rev. C 84,
011301(R) (2011)

$^{2}H(^{20}O,p)$



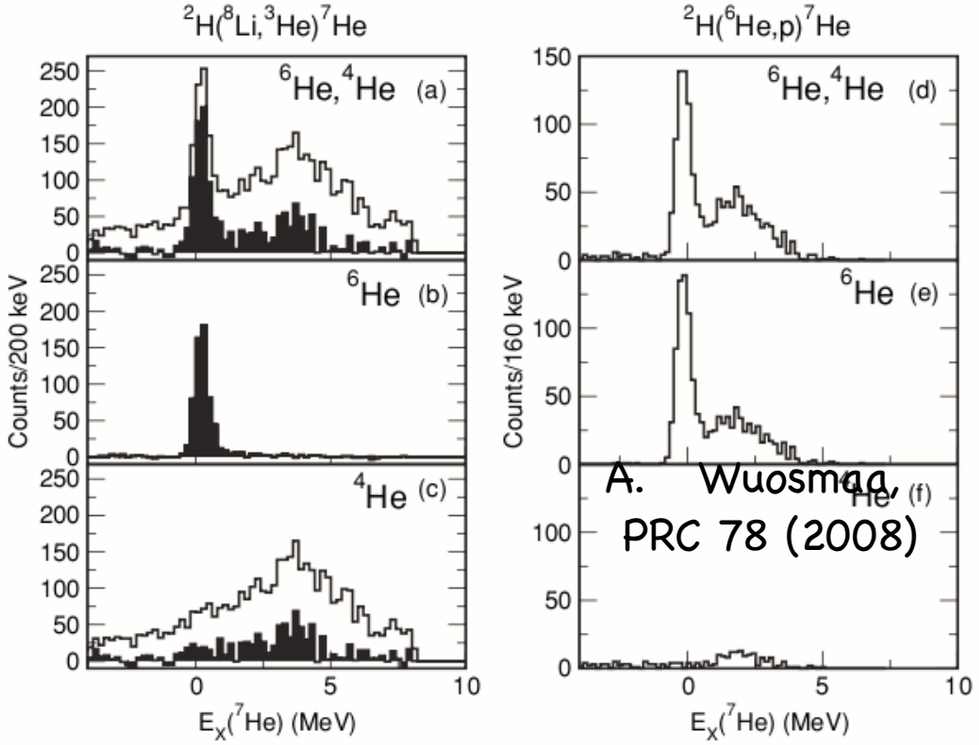
C. Hoffman, et al., PRL
100 (2008)



Z. Elekes, et al.,
PRL 98 (2007)

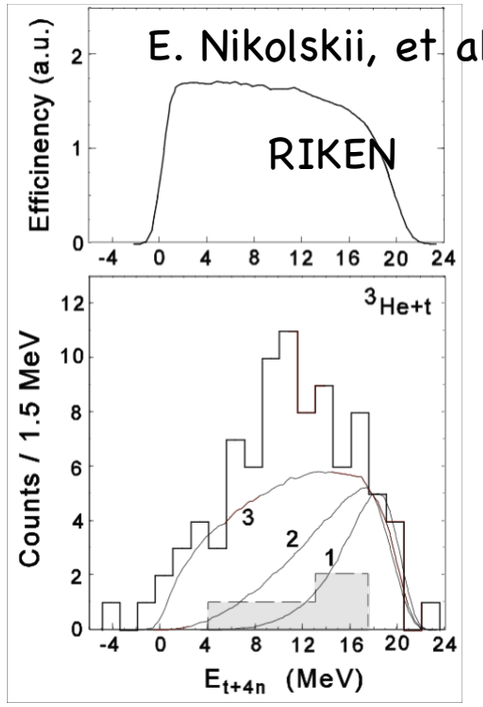
$^{2}H(^{22}O,p)$

Nuclear extremes



A. Wuosmaa, PRC 78 (2008)

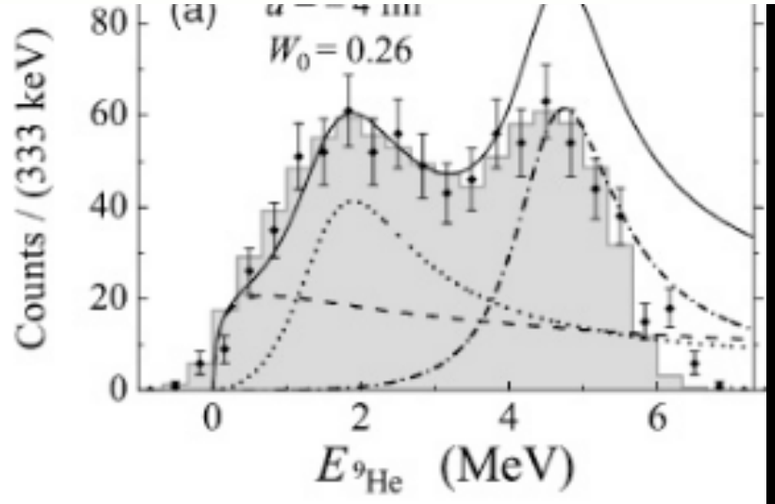
^{1}H(^{8}He,2p) A
^{2}H(^{8}He,^{3}He)
^{12}C(^{8}He,^{13}N
E. Ni



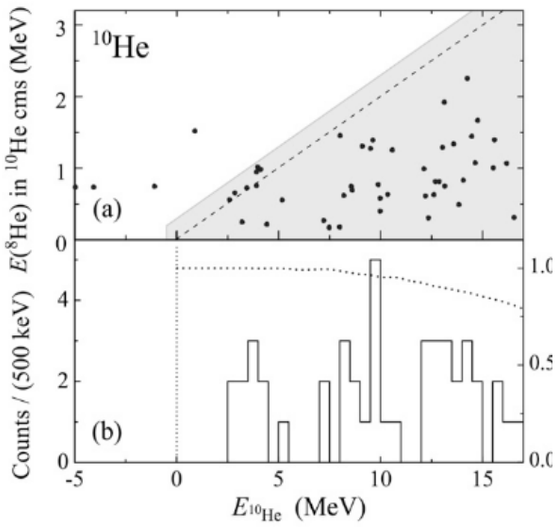
(2003)
2007)
007)

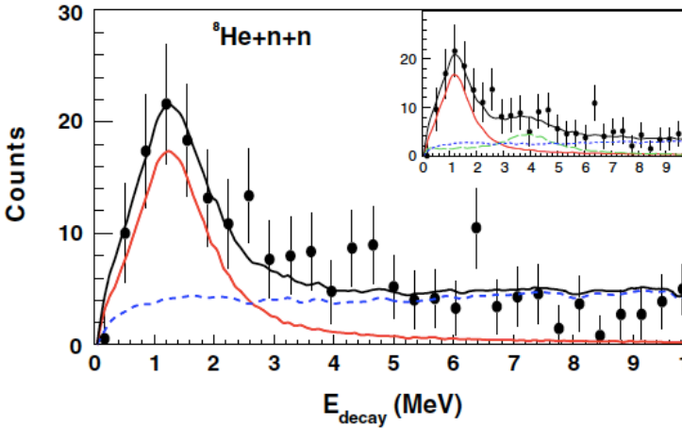
gs

^{1}H(^{8}He,
^{12}C(^{8}He
^{2}H(^{8}He,



^{2}H(^{8}He,p) M.S.Golovkov, et al., PRC 76 (2007)



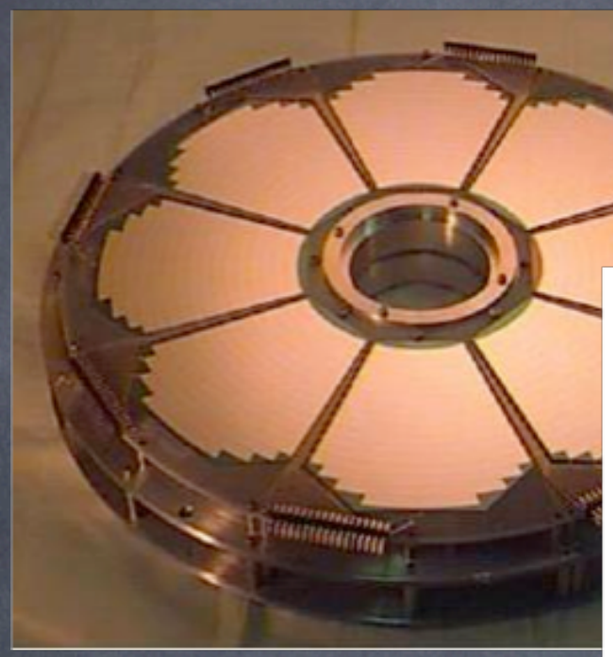


the GS?

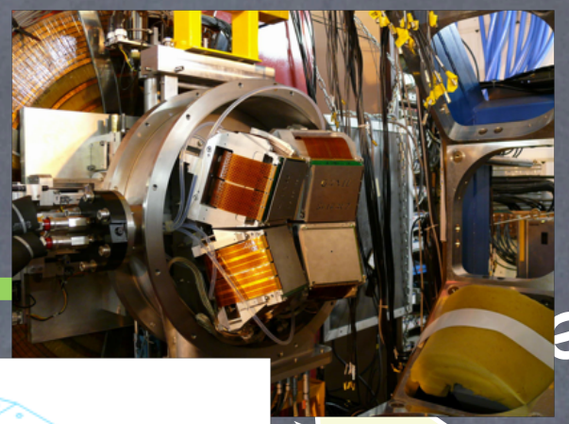
^{3}H(^{8}He,p)^{10}He M.S. Golovkov, et al., PL B 672 (2009)

"Typical" experimental setup for transfer reactions experiment with RIB

SIDAR (ORNL)



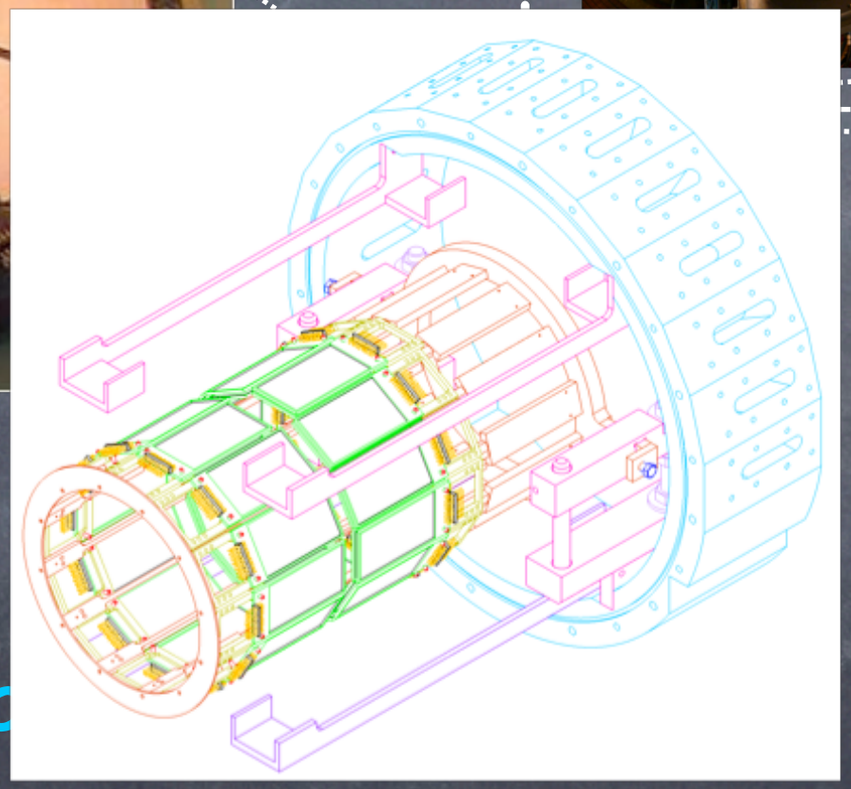
OTHER examples:
TIARA (GANIL)
LAMP; LEDA (CRC); TUDA (TRIUMF)

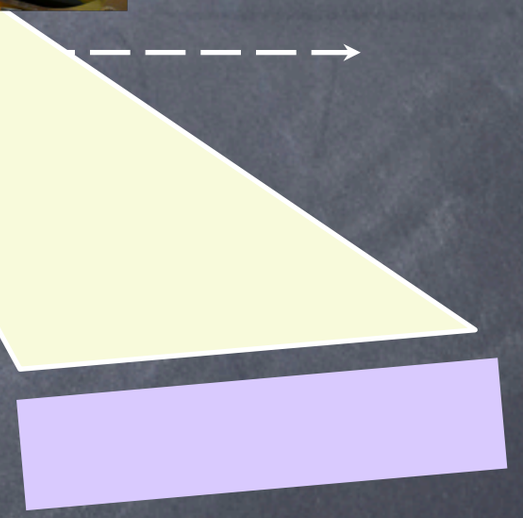


MUST2, GANIL

HiRa, MSU

ectrometer





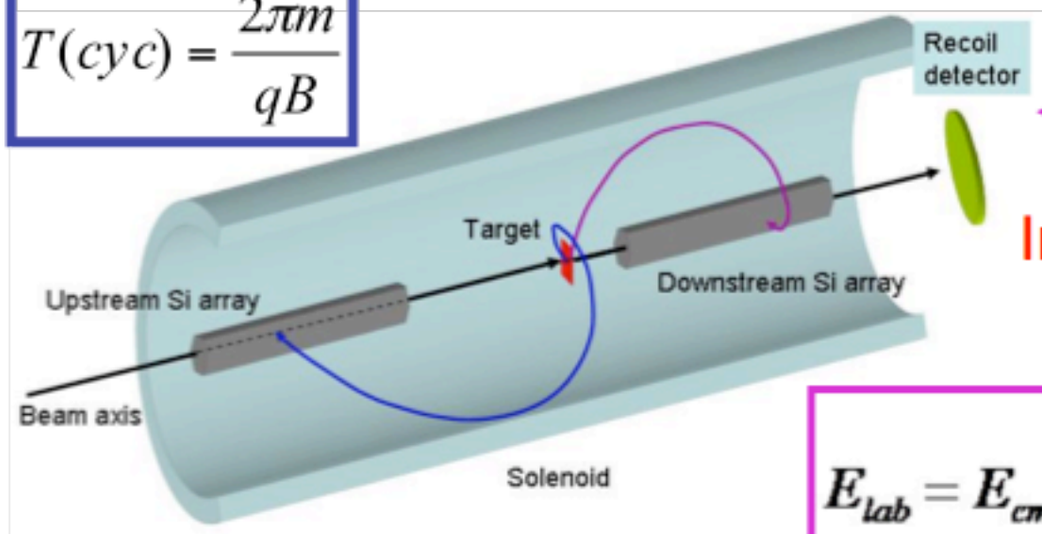
HI Ions detectors
ΔE, E, x, y, TOF, Bρ

Oak Ridge Rutgers U
Barrel Array

HELIOS: Spectrometer for Inverse-kinematic reactions

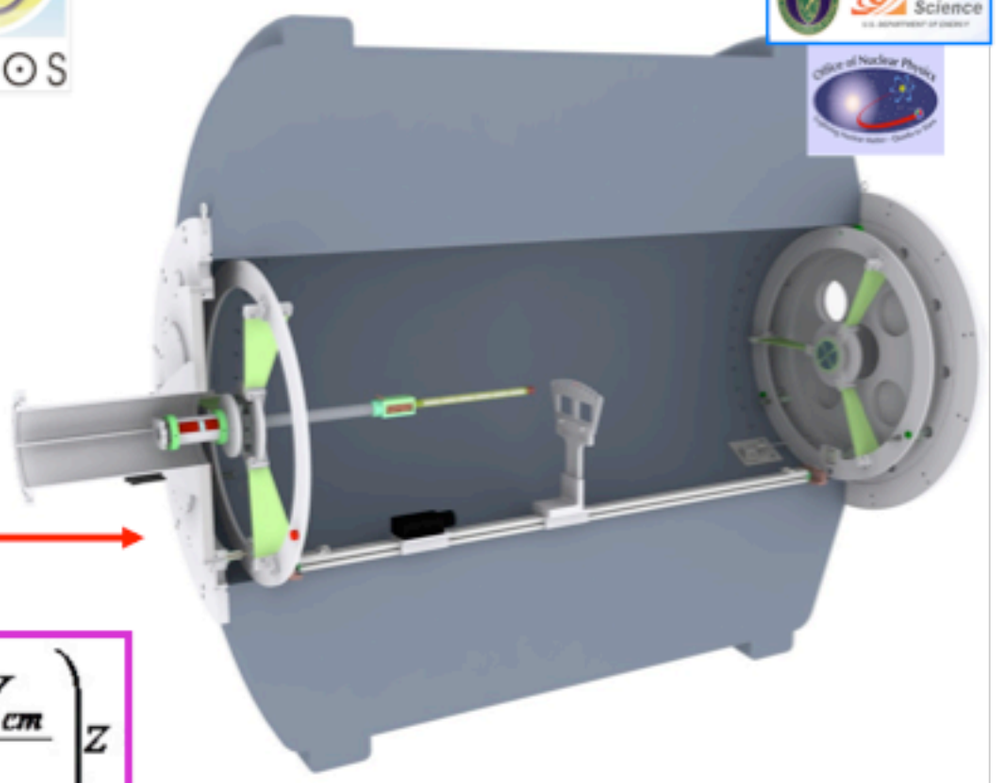
A. H. Wuosmaa et al, NIM A 580, 1290 (2007)

$$T(cyc) = \frac{2\pi m}{qB}$$



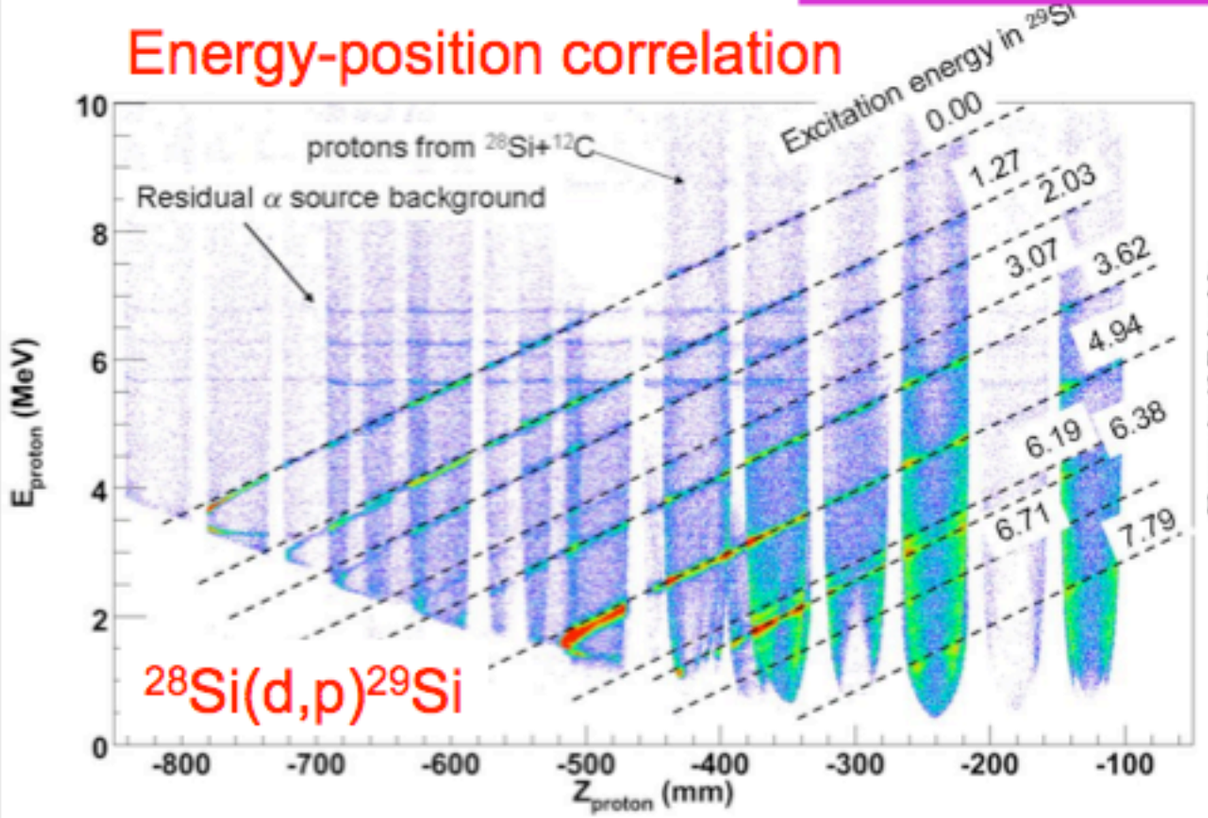
Concept

Implementation

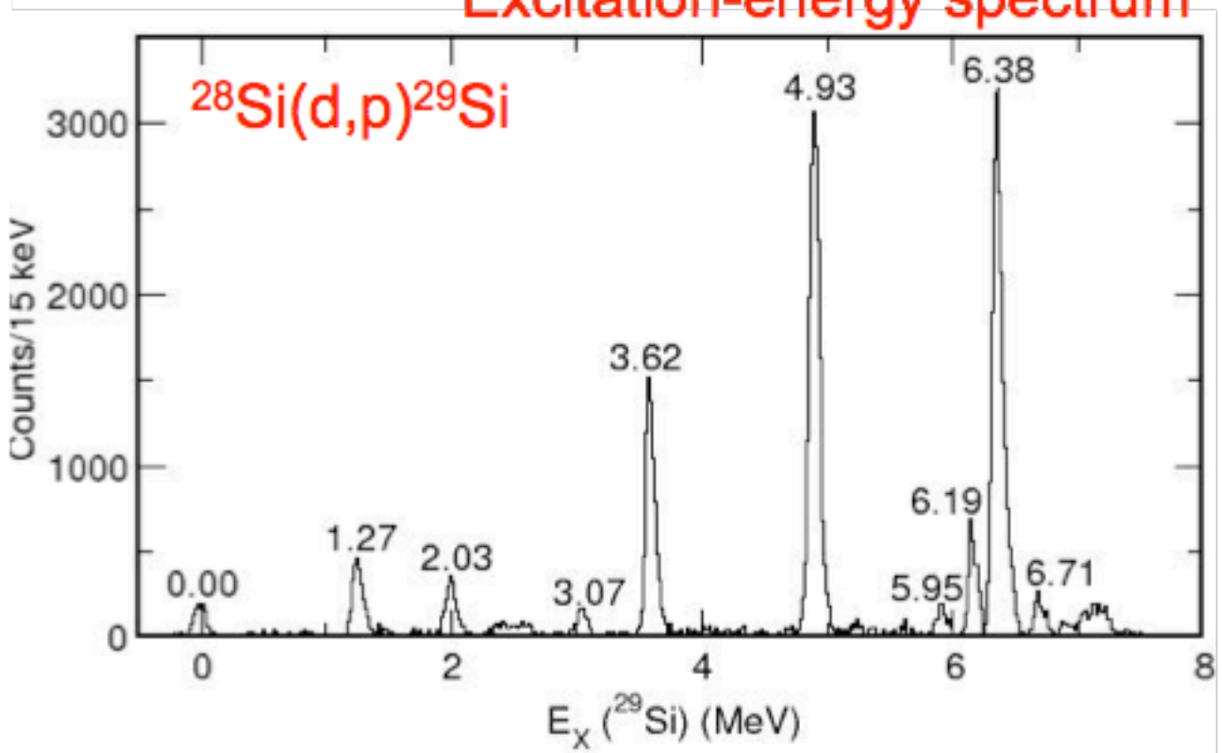


$$E_{lab} = E_{cm} - \tfrac{1}{2} m V_{cm}^2 + \left(\frac{m V_{cm}}{T_{cyc}}\right) z$$

Energy-position correlation



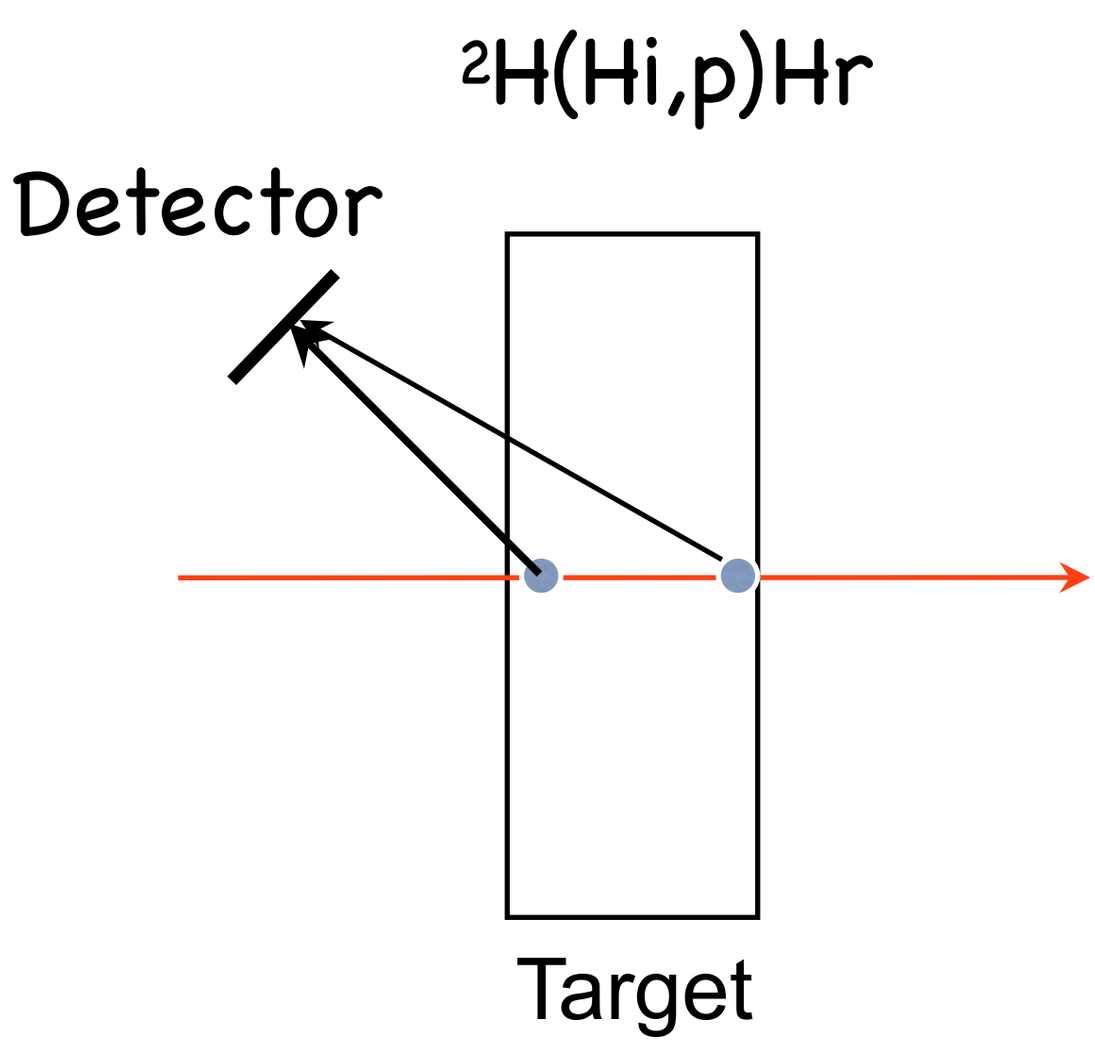
Excitation-energy spectrum



Slide is courtesy of A. Wuosmaa

Target thickness and resolution

- Target thickness is restricted by energy losses of light and heavy recoils
- To keep energy resolution <100 keV target should be <1 mg/cm^2
- With cross sections ≈1 mb beam intensity should be >10^3 pps

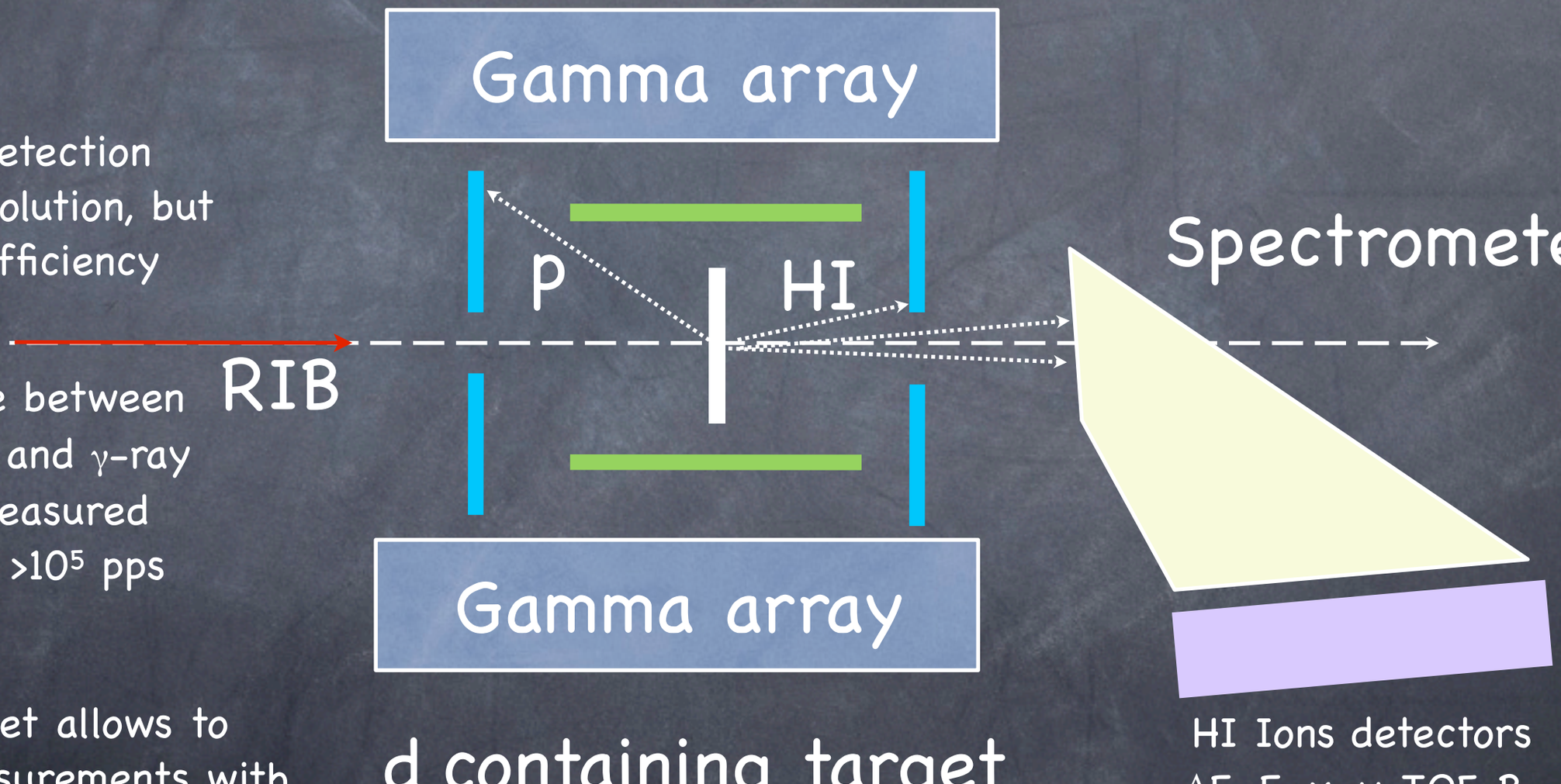


Si array + Gamma array + spectrometer

Gamma detection improves resolution, but reduces efficiency

Coincidence between light recoil and γ-ray can be measured with RIBs >10^5 pps

Thick target allows to perform measurements with beams >10^3 pps (no light recoil is measured)

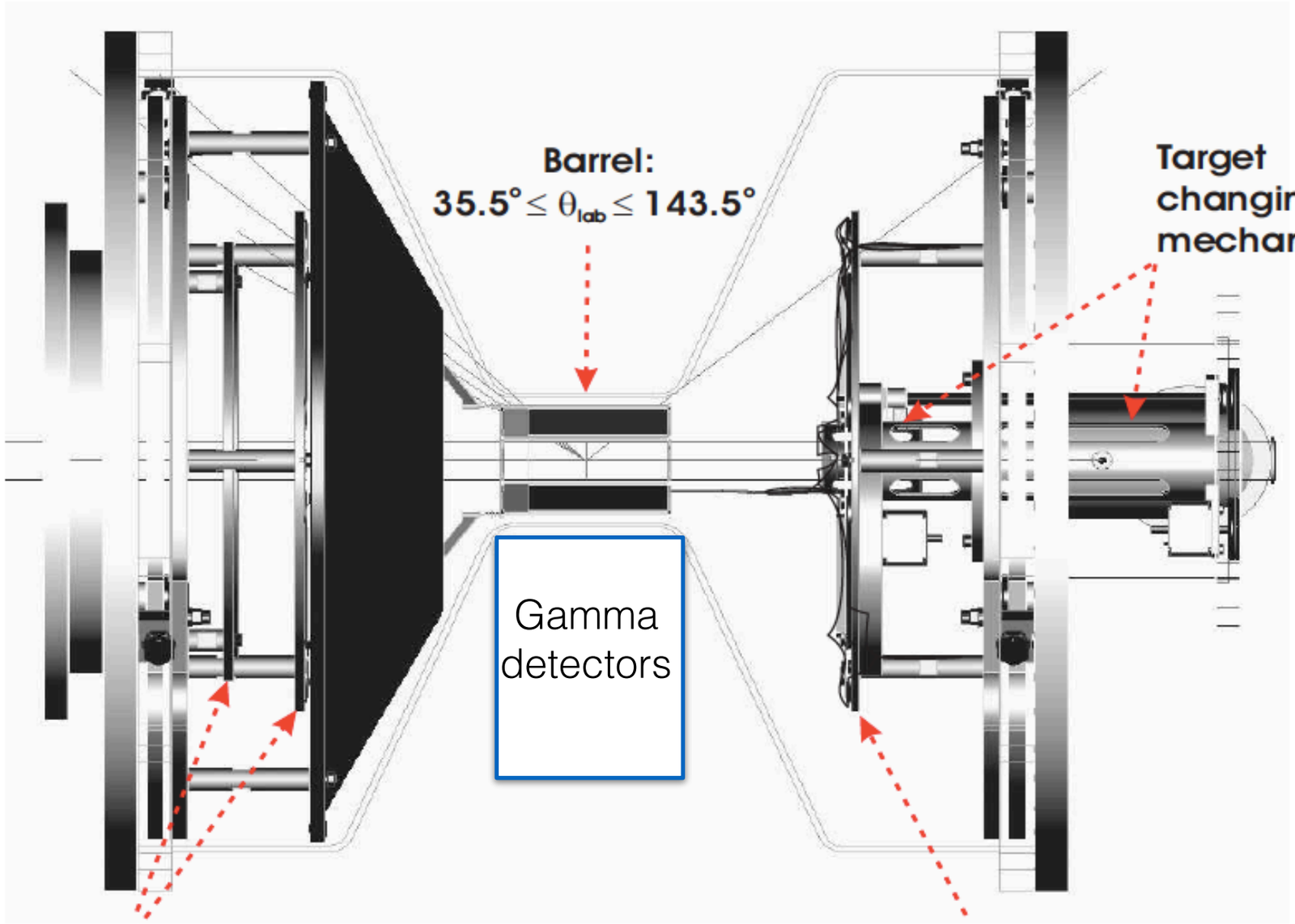


d containing target

side Si array

back/front Si array

TIARA


Barrel:
35.5° ≤ θlab ≤ 143.5°
Target changing mechanism
Gamma detectors
Forward annular detectors: 3.8° ≤ θlab ≤ 27.5°
Backward annular detector: 137° ≤ θlab ≤ 169.4°