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DIRECT NUCLEAR REACTIONS EXPERIMENT

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OUTLINE

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- Introduction to direct reactions
- Single-particle energies and spectroscopic factors
- Observables and non observables

- Nucleon transfer reactions
- Optical potentials
- Instrumentation for transfer reactions

- Quasifree scattering
- Nucleon removal induced from light-ion target
- Instrumentation for quasifree scattering

MISSING MASS METHOD

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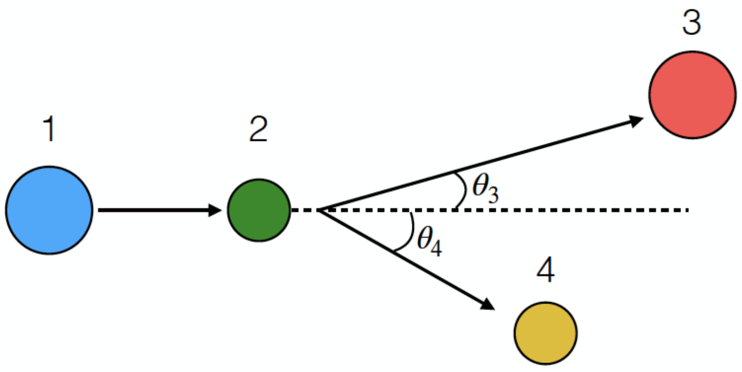
- **Two-body kinematics:** all information about the residue (4) can be obtained by measuring the momentum p3 and using the known mass m_3 of the second outgoing particle (3).



- The **excitation energy E^*_4** of particle (4) is given by:

$$E_4^* = \sqrt{E_4^2 - p_4^2 c^2} - m_{4,gs} c^2$$

with $E_4 = m_c c^2 + T_4$ total energy

- It can be expressed from energy conservation (EC) and momentum conservation (MC)

$E_4 = T_1 + m_1 + m_2 - (T_3 + m_3)$ (EC) $\quad$ $p_4^2 = p_1^2 + p_3^2 - 2 p_1 p_3 \cos(\theta_3)$ (MC)

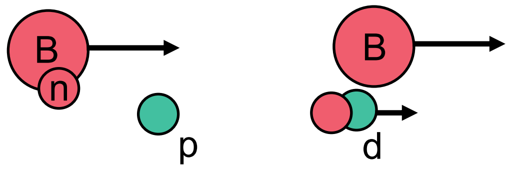
T_1, m_1, m_2, m_3 are known, T_3 (i.e. also p_3 after identification) and θ_3 are measured.

TRANSFER IN INVERSE KINEMATICS

- Momentum conservation implies a **strong constrain on the kinematics of transfer reactions.**

$$p_4^2 = p_1^2 + p_3^2 - 2p_1p_3\cos(\theta_3)$$

Representation of (p,d)



- In **inverse kinematics,** the stripping and pickup reaction kinematics lead to a light target-recoil in the forward and backward hemisphere, respectively :

- one nucleon **stripping at forward angles**: (p,d), (d,^{3}He), (d,t), (p,t)
- nucleon **pickup at backward angles**: (d,p), (t,p)
- **Elastic scattering around 90 degrees**: (p,p), (d,d)

^{16}C + p,d @ 35 A MeV, inverse kinematics

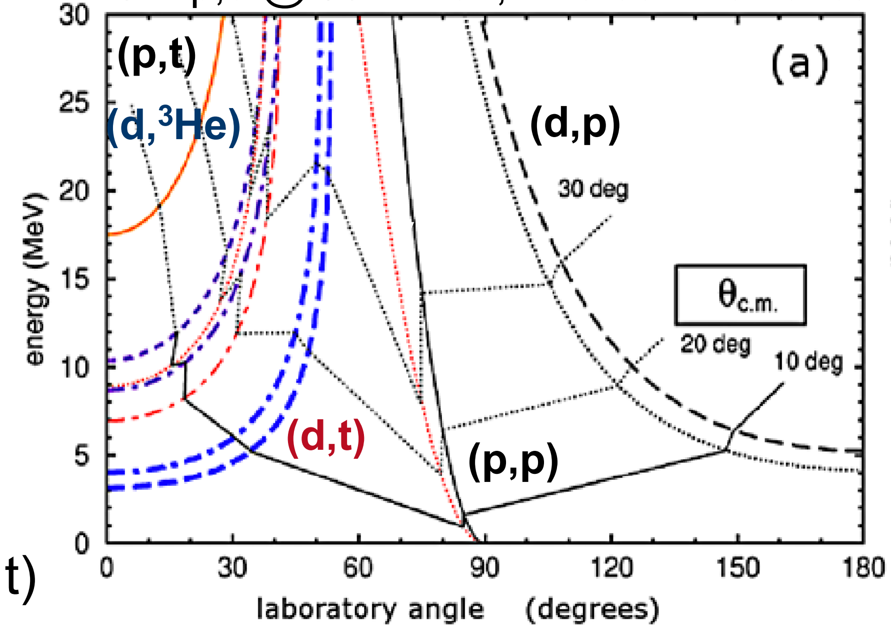


Figure adapted from W. Catford, Lecture

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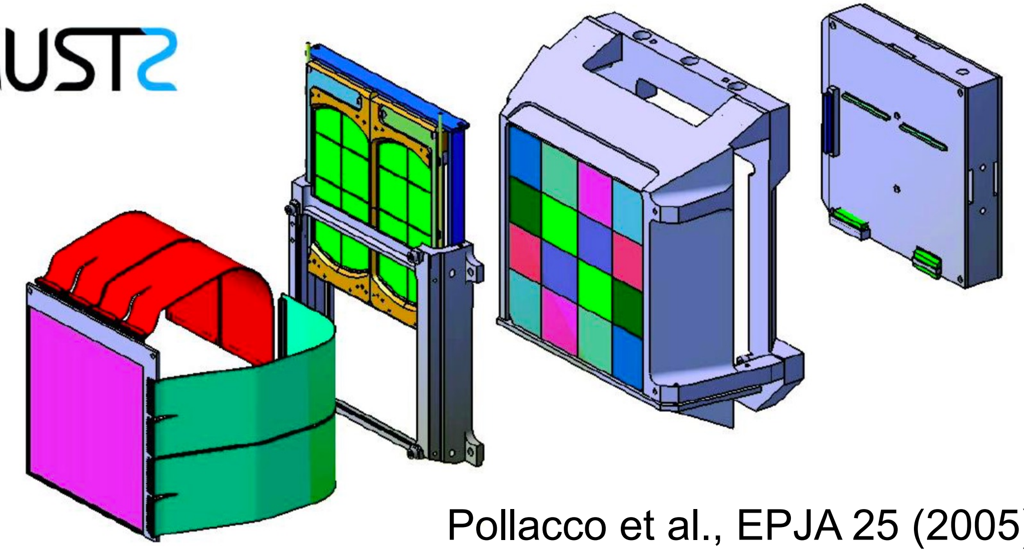
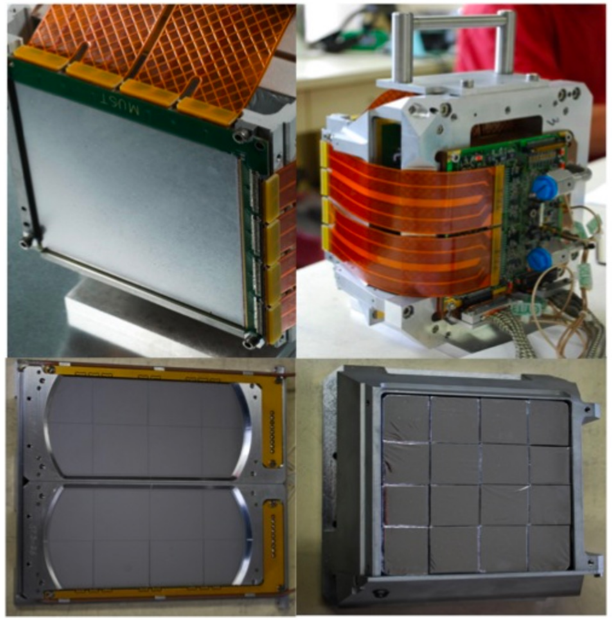
MUST2 CHARGED-PARTICLE DETECTOR

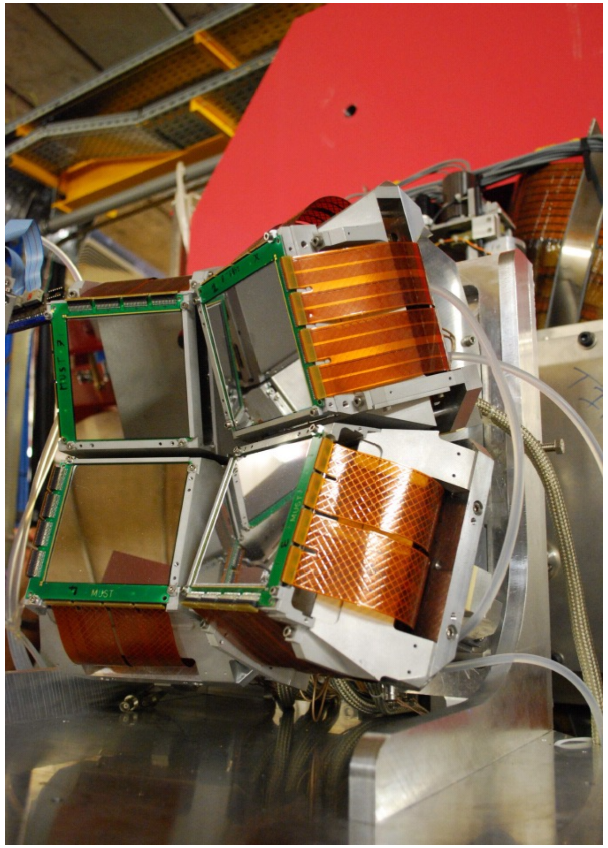
- 3 stage telescopes:
  - doubled-Sided Silicon detectors (DSSD): 128X, 128Y. Thickness 300 microns
  - depleted semiconductors
  - Si(Li): thickness 4.5 mm
  - CsI crystals: thickness 40 mm
- Dedicated electronics: ADC (energy) and TDC (time) for each channel

MUST2



Pollacco et al., EPJA 25 (2005)





PARTICLE IDENTIFICATION (PID)

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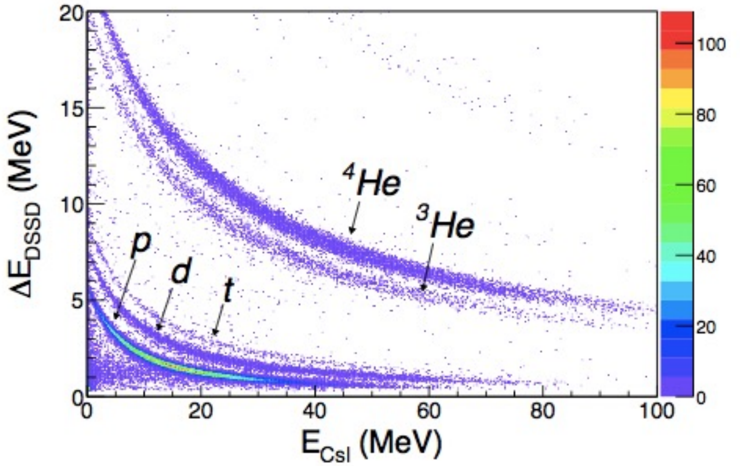
- Mean energy loss via ionization: **Bethe-Bloch formula**

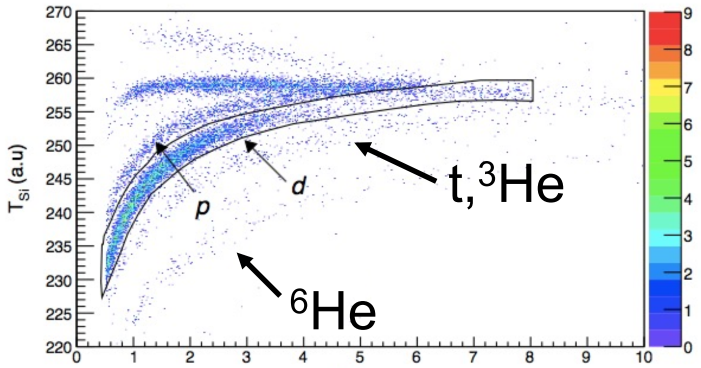
$$-\left\langle \frac{dE}{dx} \right\rangle \propto \frac{\rho Z q^2}{M\beta^2}\left[\ln\left(\frac{2m_e c^2\gamma^2\beta^2}{I}\right) - \beta^2 - \text{corrections}\right]$$

$$E\Delta E \propto Mz^2$$



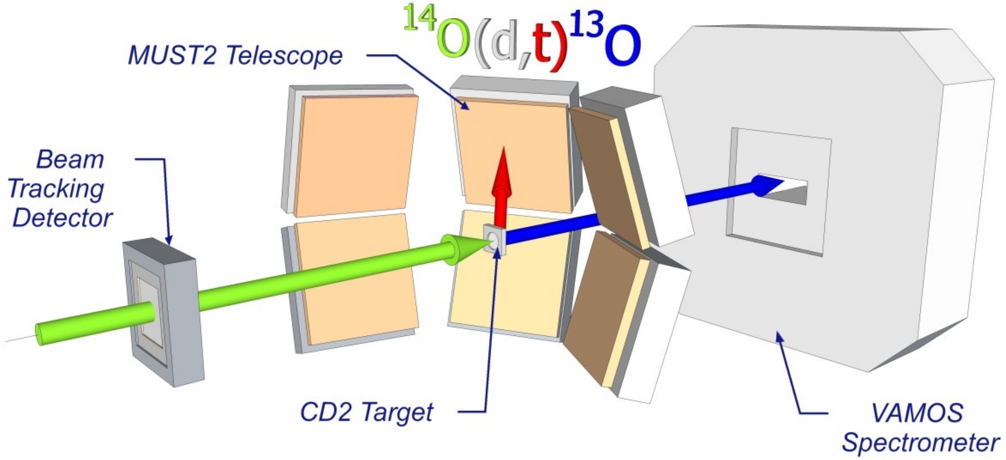
- Low-energy particles do not punch through the first layer (no ΔE)
- In these cases, time of flight (ToF) and total kinetic energy (E) of are used to determine the mass M

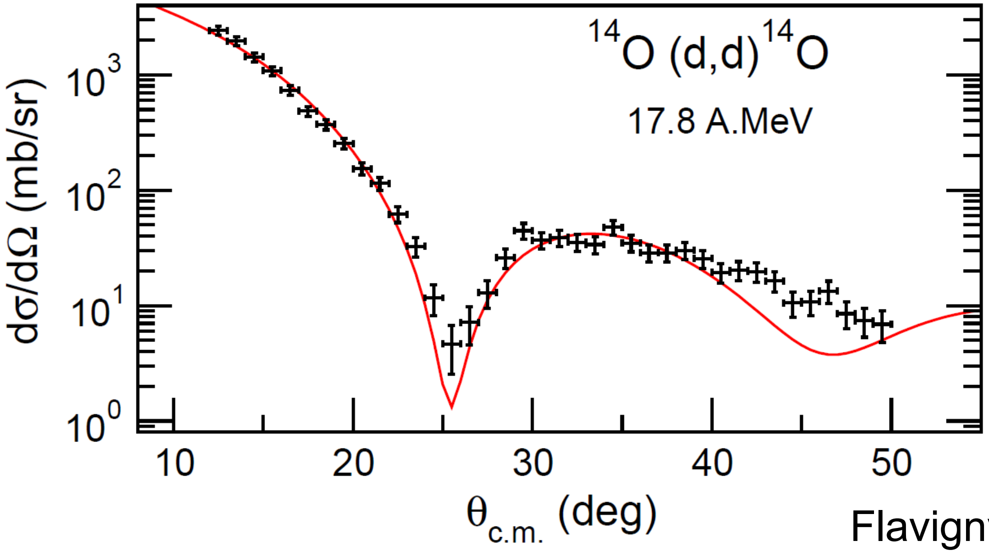
$$E = \frac{1}{2}Mv^2 \propto \frac{M}{ToF^2}$$

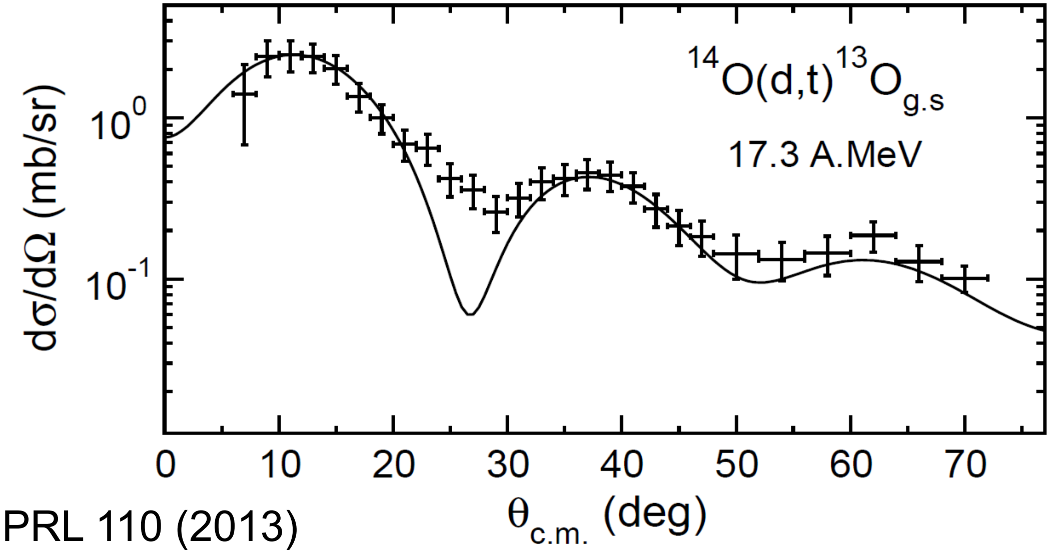


AN EXAMPLE

- ^{14}O pure beam, 18 MeV/n, 5. 10^4 pps, SPIRAL (GANIL)
- Target: CD_2
- Reactions: (d,d), (d,^{3}H) and (d,^{3}He) MUST2 array
- VAMOS spectrometer for recoil identification







Flavigny et al., PRL 110 (2013)

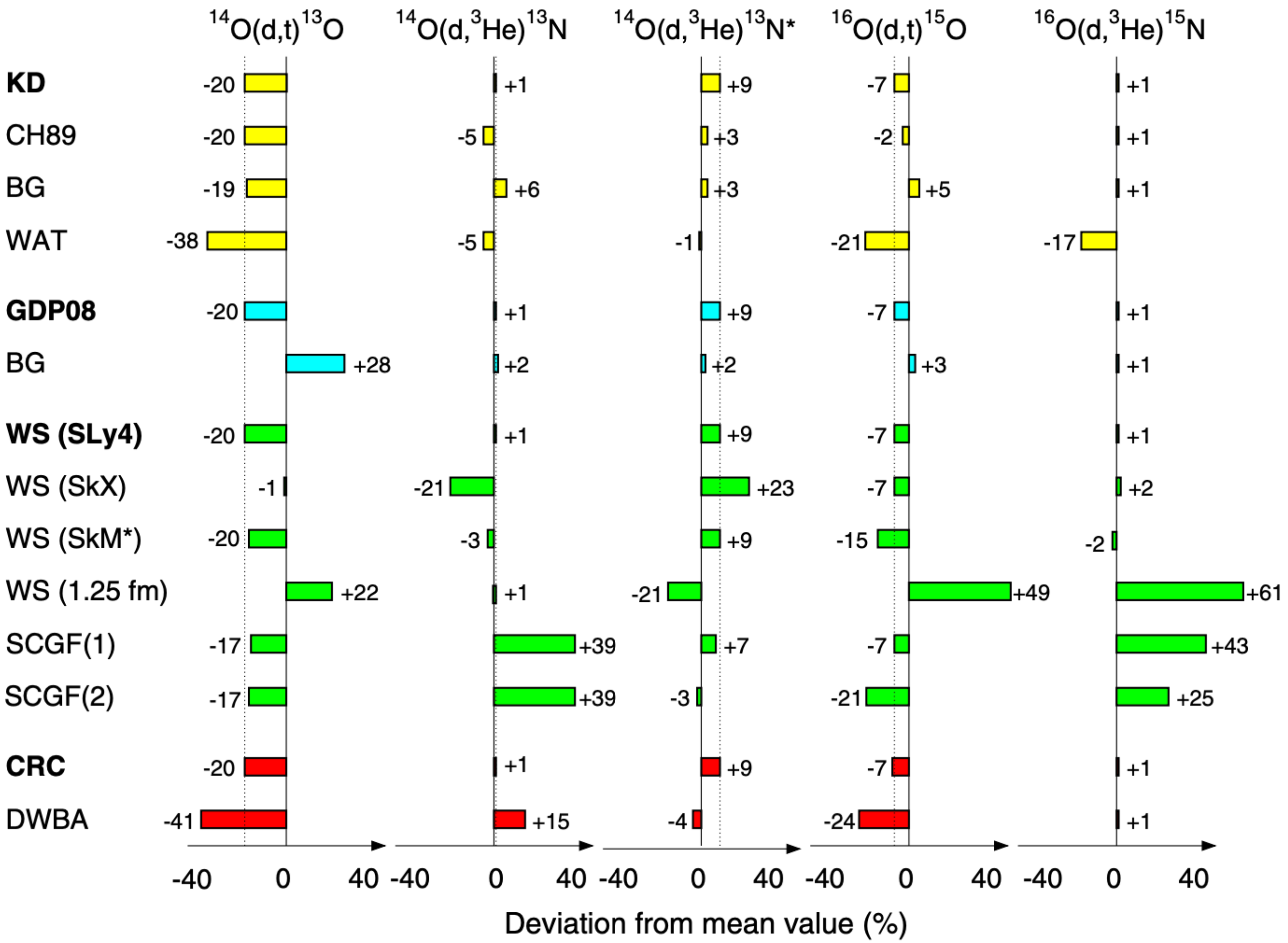
MODEL UNCERTAINTIES

Entrance channel optical potential

Exit channel optical potential

Wave function

Reaction model



Flavigny et al., PRC 97 (2018)

γ-PARTICLE SPECTROSCOPY

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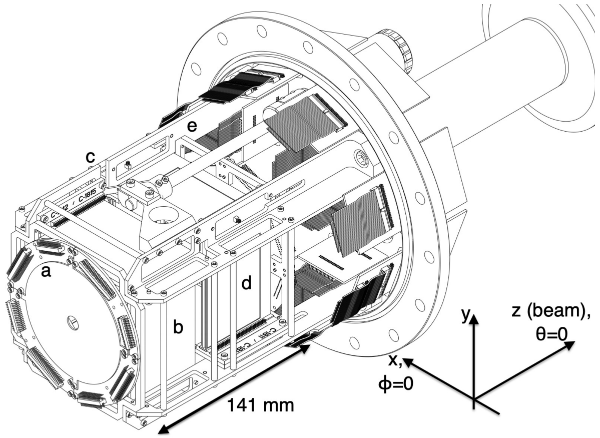
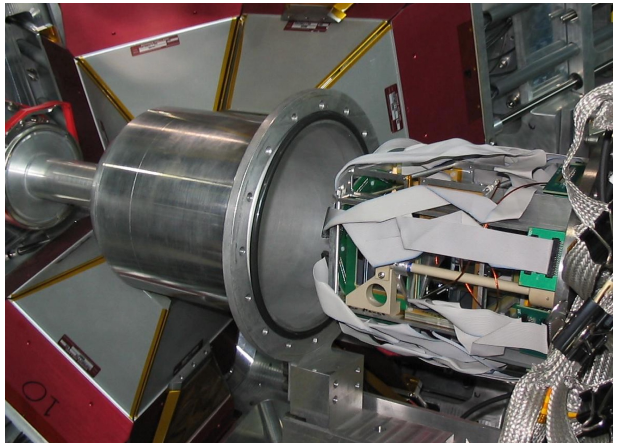
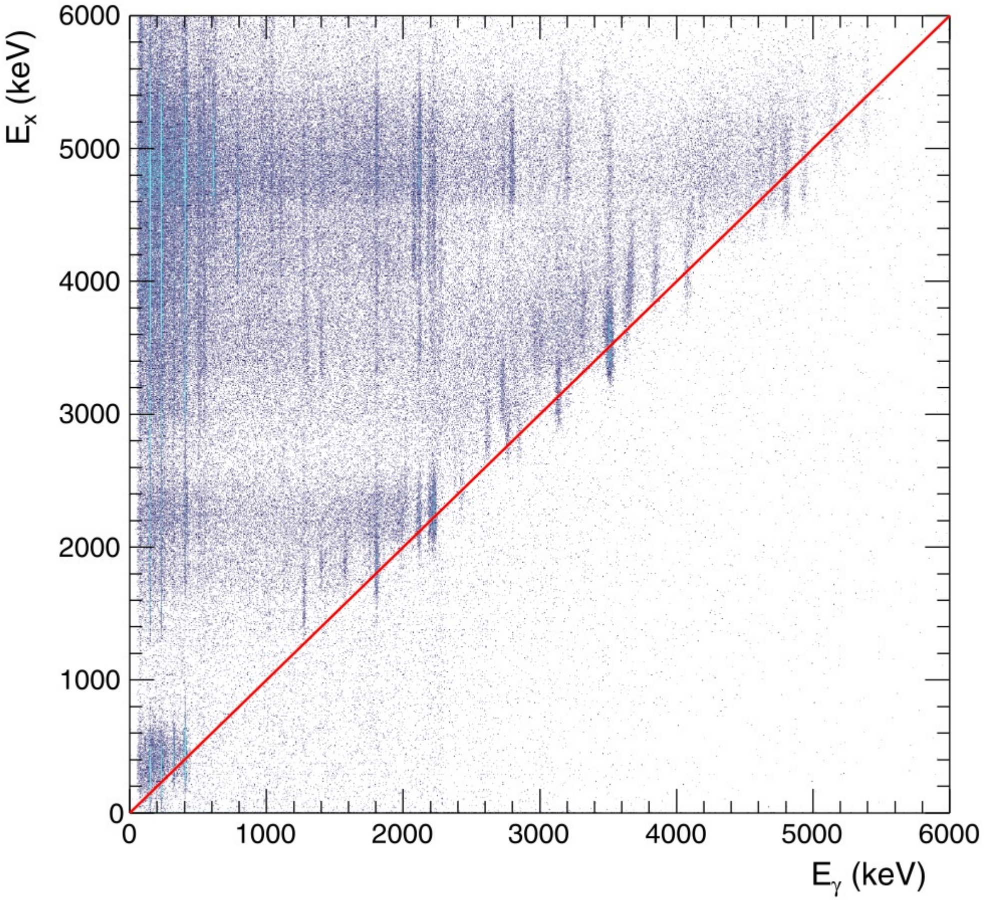




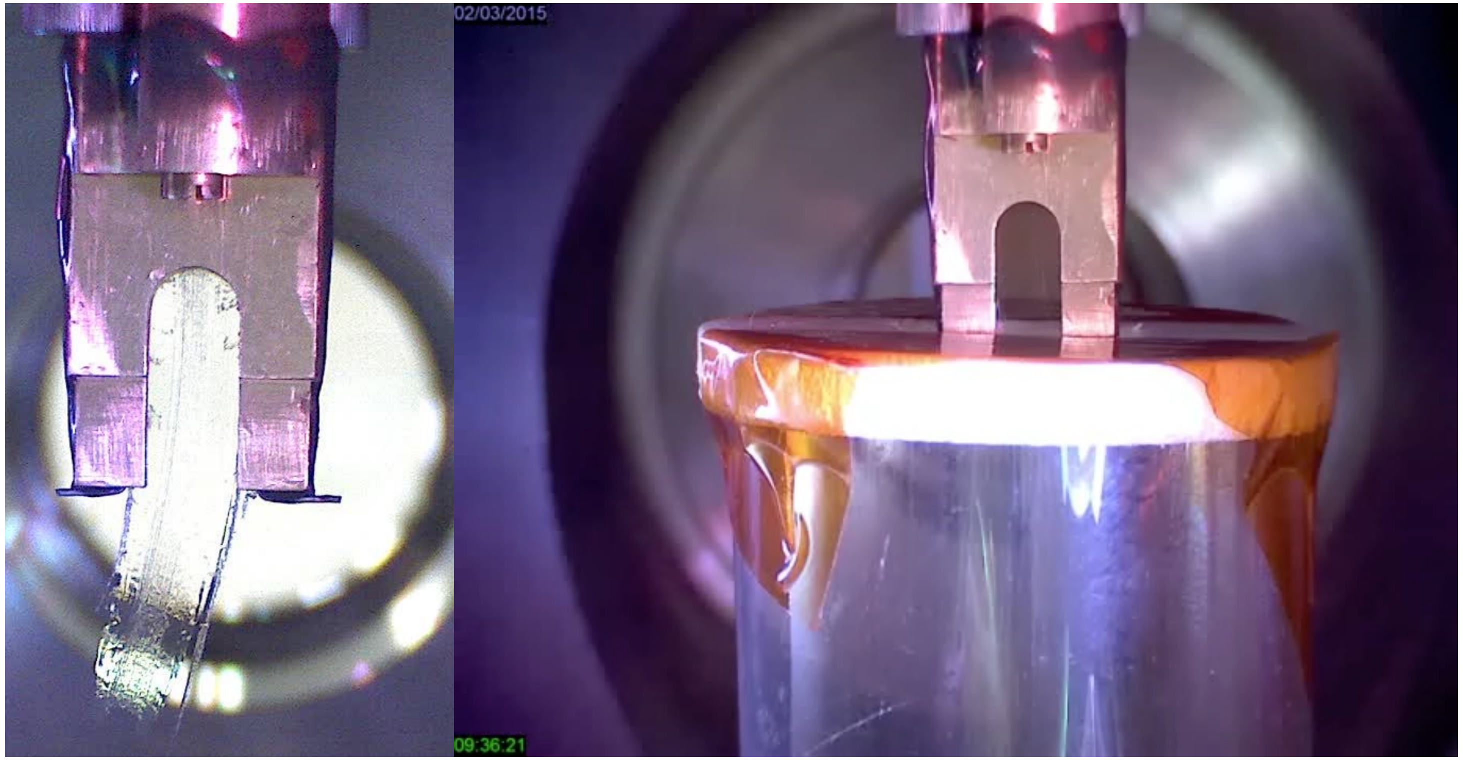
C. A. Diget et al., J. Instr. 6 (2011)



G. L. Wilson et al., PLB 759 (2016)

- Compact silicon arrays combined with γ-ray spectrometers
- Ex. SHARC with TIGRESS Ge array at TRIUMF, Canada
- $^{25}Na(d,p\gamma)^{26}Na$ at 5 MeV/n
- 3 challenges:
  - photon absorption
  - efficiency
  - particle identification

CHYMENE PURE HYDROGEN TARGET



- Ideal hydrogen target:
  - solid and thin
  - pure and windowless

- From fusion technology
- About 100 bars, 16 K
- Thickness down to 30 microns
- 5 – 10 mm radius
- R&D and prototype at CEA Saclay
- Challenge:
  - vacuum
  - thickness homogeneity

Cible d'Hydrogène Mince pour l'Étude des Noyaux Exotiques (fr.)
Thin hydrogen target for the study of exotic nuclei (en.)

Gillibert et al., EPJA 49 (2013)

TIME PROJECTION CHAMBERS (TPC)

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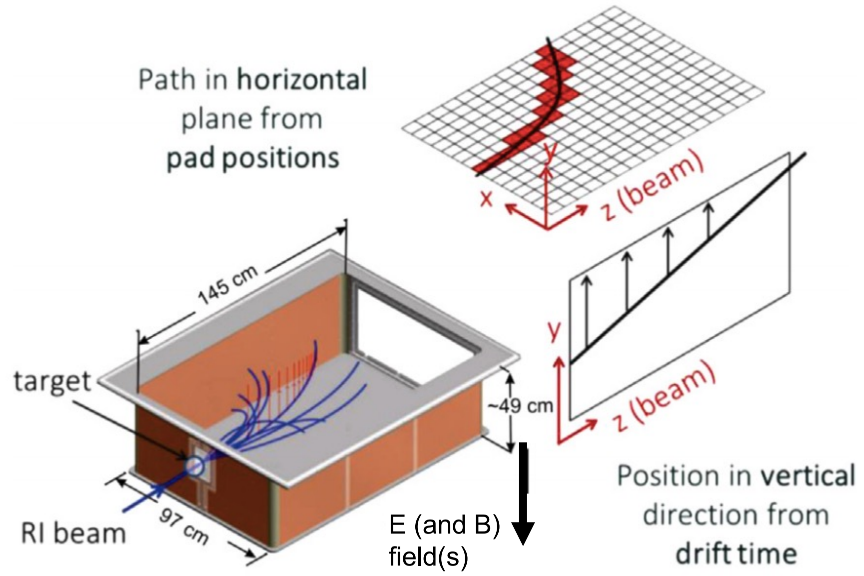
- The spectroscopy of unstable nuclei might suffer from low luminosity.
- The use of a thick target might not be possible due to too large recoil energy loss inside the target
- **TPCs used as active targets** can lead to a **gain in luminosity up to a factor 10**



A TPC is composed of the following three key elements:

1) a **drift region** with a constant E field of about 100-300 V/cm,
2) an **amplification region** with an E field > 10 kV/cm,
3) a **pad plane** where induced signals are measured. The tracks are reconstructed in 3D based from **drift time**.

R. Shane et al., NIMA 784 (2015)

AT-TPC

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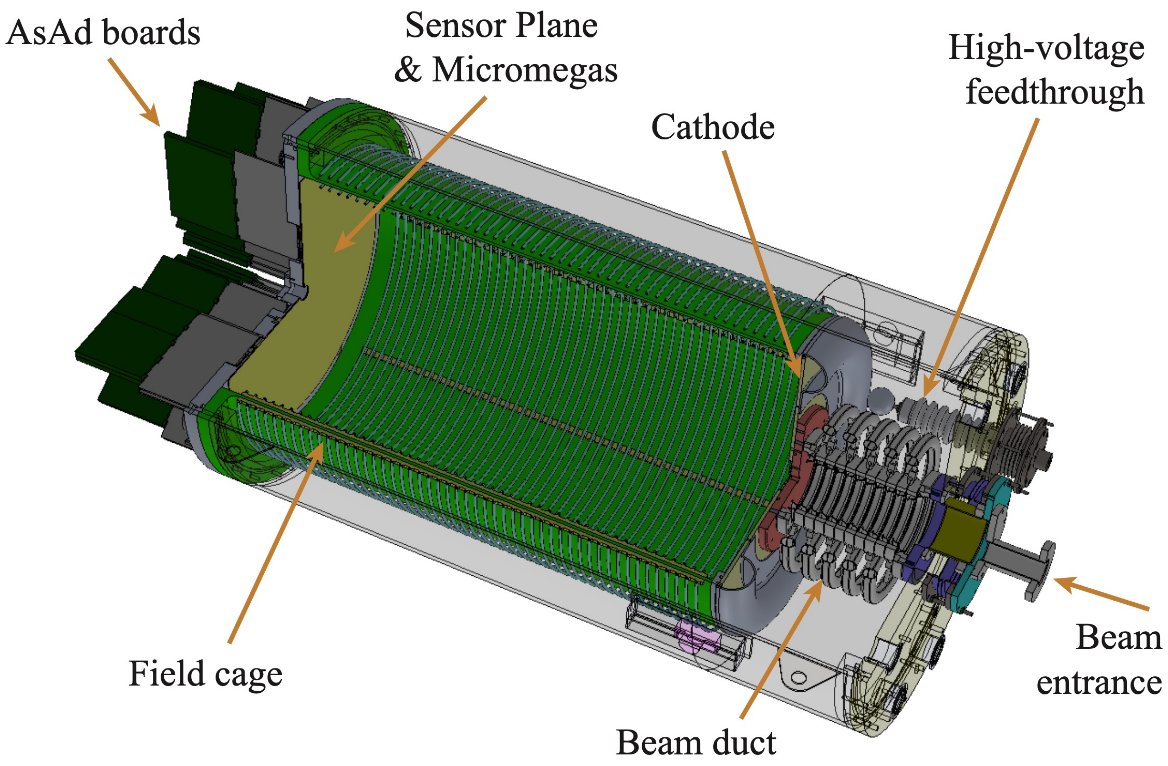
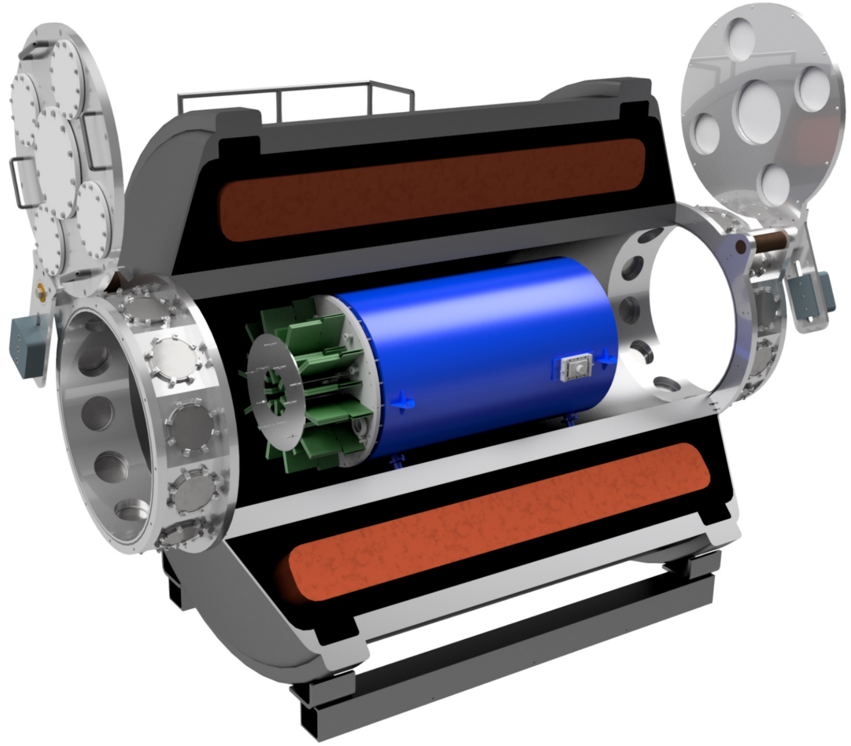
Active Target Time Projection Chamber



Solenoidal Spectrometer Apparatus for Reaction Studies

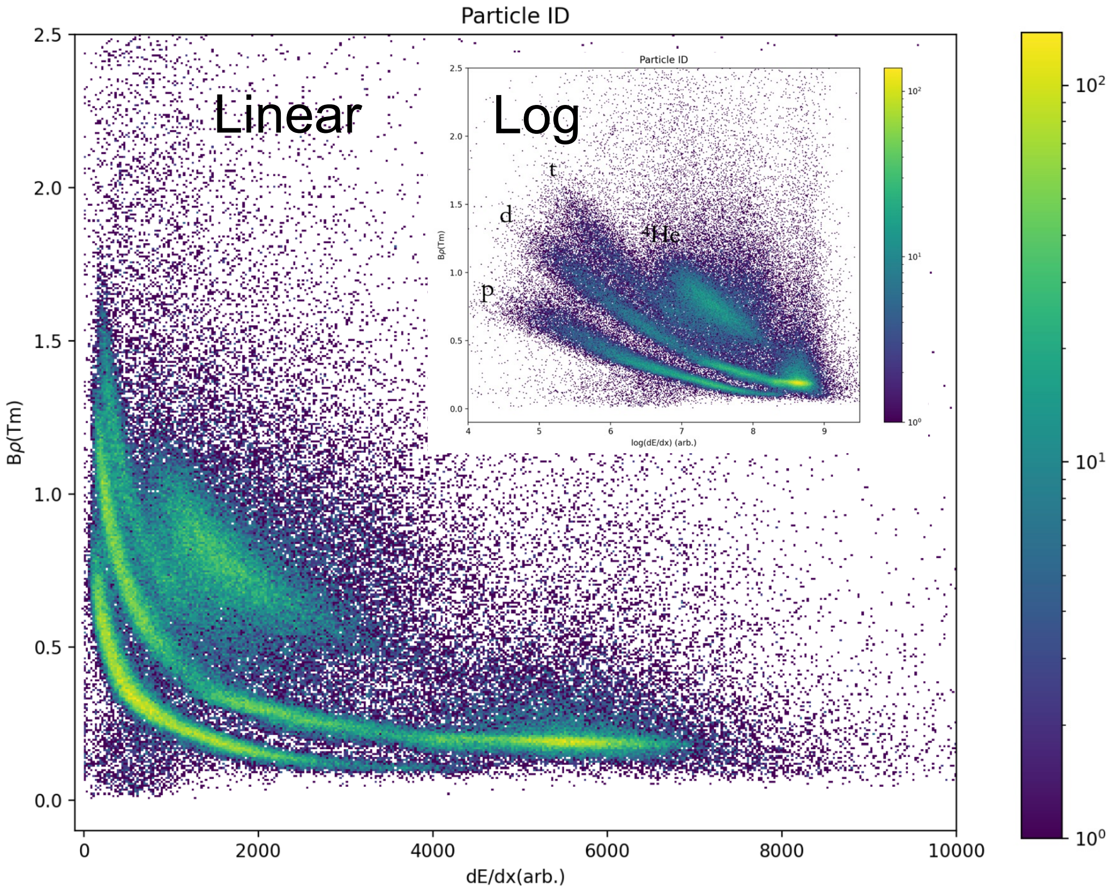


Courtesy: D. Bazin, FRIB

PARTICLE IDENTIFICATION

- Magnetic rigidity
  From curvature of track & polar angle
  $B\rho = {}^{p}/_{q} = \frac{\gamma M v}{q}$

- Energy loss
  From charge deposit along track
  Bethe-Bloch formula
  $-\left\langle \frac{dE}{dx} \right\rangle \propto \frac{\rho Z q^2}{M\beta^2}\left[\ln\left(\frac{2m_e c^2\gamma^2\beta^2}{I}\right) - \beta^2 - \text{corrections}\right]$



Courtesy: D. Bazin, FRIB; DREB2024

^{12}BE+P AT 12 MEV/NUCLEON

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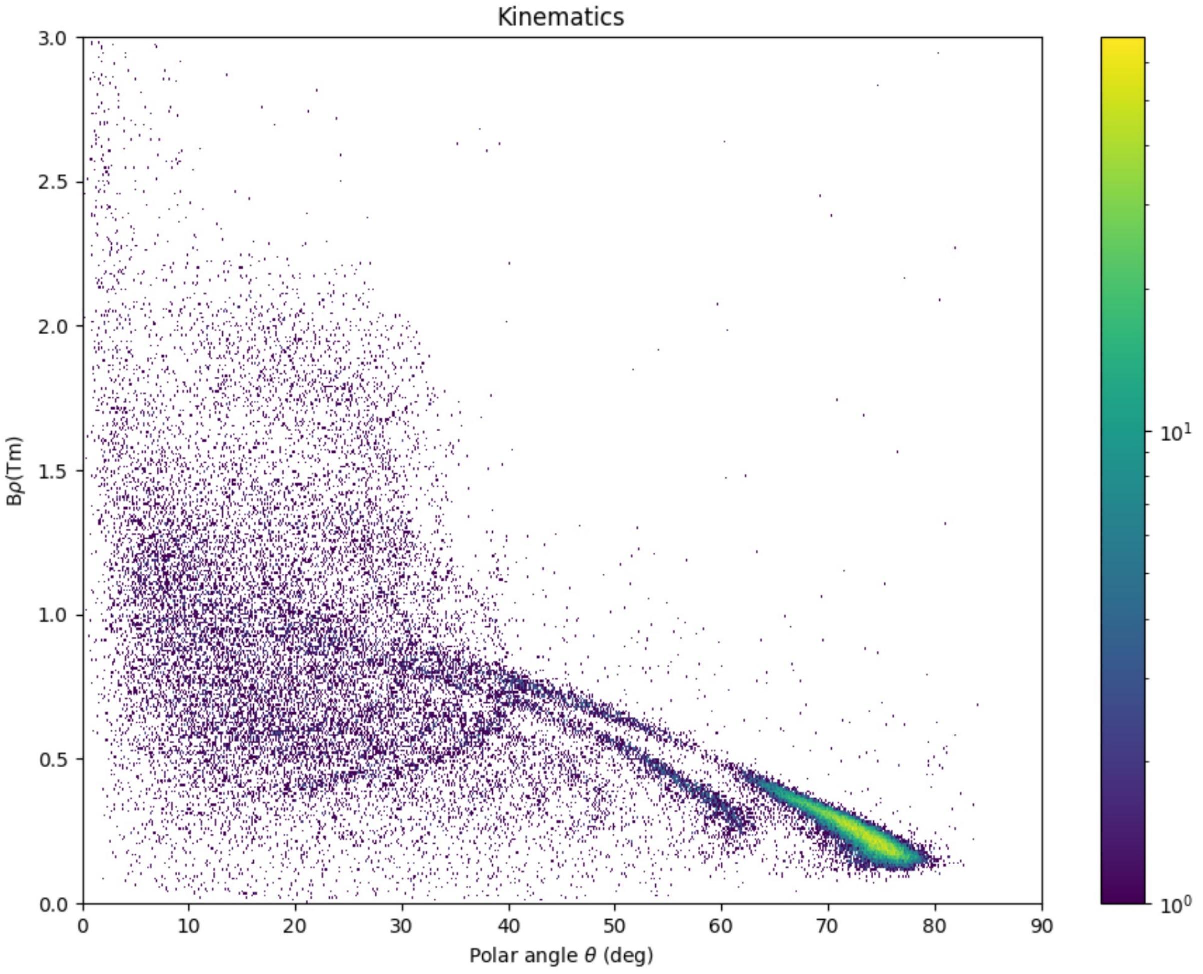
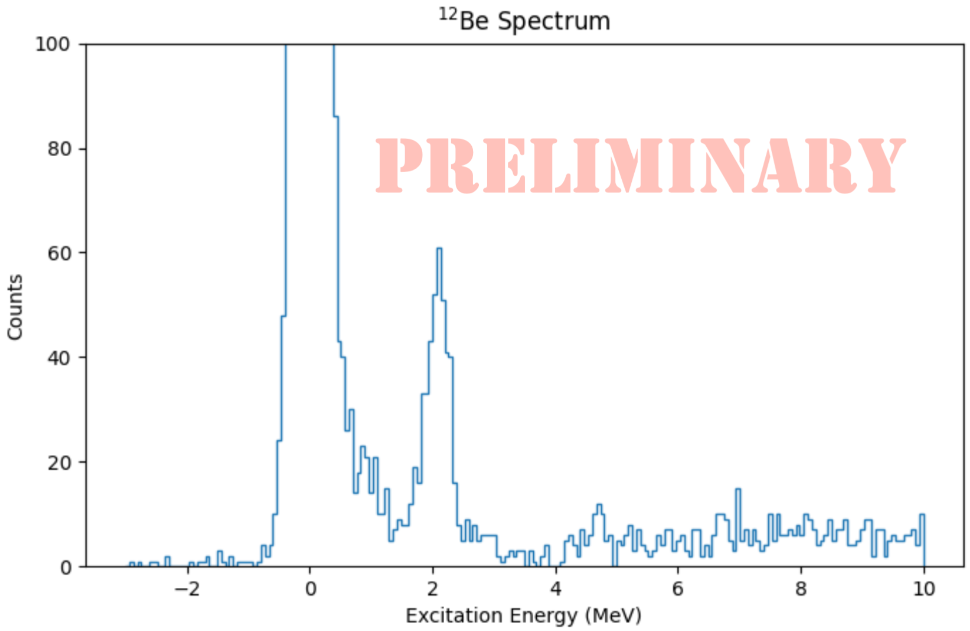


- ^{12}Be+p at 12 MeV/nucleon at ATLAS
- Intensity of 100 pps
- Pure H_2 @ 600 Torr (Eq. 110 mg.cm^{-2} of CH_2)



Courtesy: D. Bazin, FRIB; DREB2024

TRANSFER IN A SOLENOID WITH HELIOS

Measured quantities

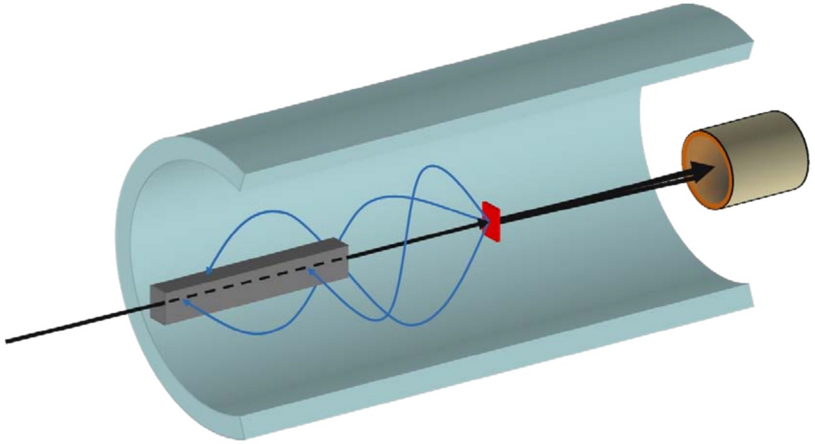
Flight time:	$T_{flight}=T_{cyc}$
Position:	z
Energy:	E_{lab}

Derived quantities

Part. ID:	m/q
Energy:	E_{cm}
Angle:	θ_{cm}

B=2T

Particle	T_{cyc} (ns)
p	34.2
$^3He^{2+}$	51.4
d, α	68.5
t	102.7

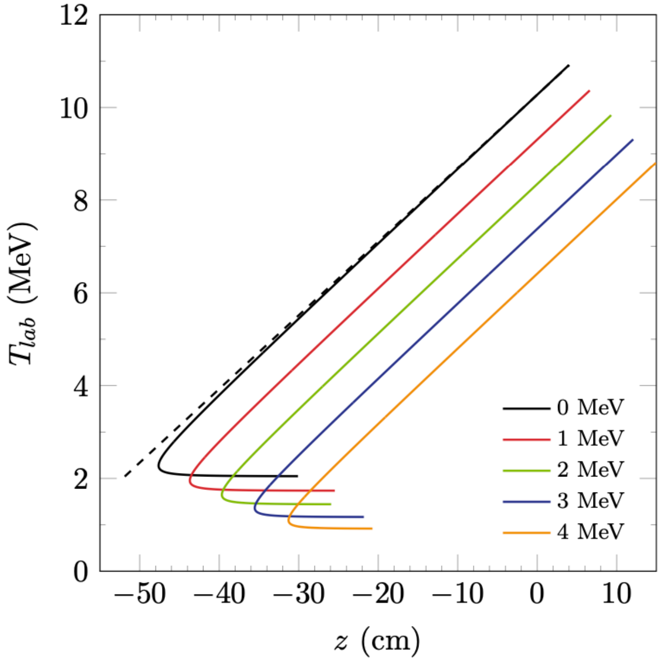


$$\frac{m}{q} = \frac{eB}{2\pi} \times T_{flight}$$

Independent of energy!!

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

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




SOLARIS
HELIOS
ISOLDE Solenoidal
Spectrometer
Greenland
Iceland
Reykjavík
Northwestern
Passages
NUNAVUT
Hudson Bay
Canada
MANITOBA
SASKATCHEWAN
ONTARIO
QUEBEC
Labrador Sea
NEWFOUNDLAND
AND LABRADOR
Winnipeg
Ottawa
Montreal
Toronto
NOVA SCOTIA
MAINE
NEW YORK
Boston
NORTH
DAKOTA
SOUTH
DAKOTA
MINNESOTA
WISCONSIN
IOWA
NEBRASKA
ILLINOIS
WYOMING
COLORADO
KANSAS
MISSOURI
United States
OKLAHOMA
ARKANSAS
MISSISSIPPI
NEW MEXICO
Dallas
TEXAS
LOUISIANA
San Antonio
Houston
Monterrey
Mexico
Guadalajara
Mexico City
Gulf of
Mexico
FLORIDA
Havana
Cuba
Santo
Domingo
Puerto Rico
Guatemala
Nicaragua
Caribbean Sea
North
Atlantic
Ocean
Sweden
Norway
Oslo
Stockholm
Finland
Baltic Sea
Estonia
Latvia
Lithuania
Denmark
North Sea
Ireland
Belgium
Germany
Berlin
Poland
Warsaw
Belarus
Paris
Czechia
Slovakia
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Barcelona
Madrid
Portugal
Spain
Lisbon
Tyrrhenian Sea
Greece
Athens
Αθήνα
Istanbul
Algiers
مدينة الجزائر
Tunis
تونس
Tunisia
Mediterranean Sea
Morocco
Algeria
Libya
Western
Sahara
Mauritania
Mali
Niger
Chad
Dakar
Senegal
The Gambia
Guinea-Bissau
Bamako
Burkina
Faso

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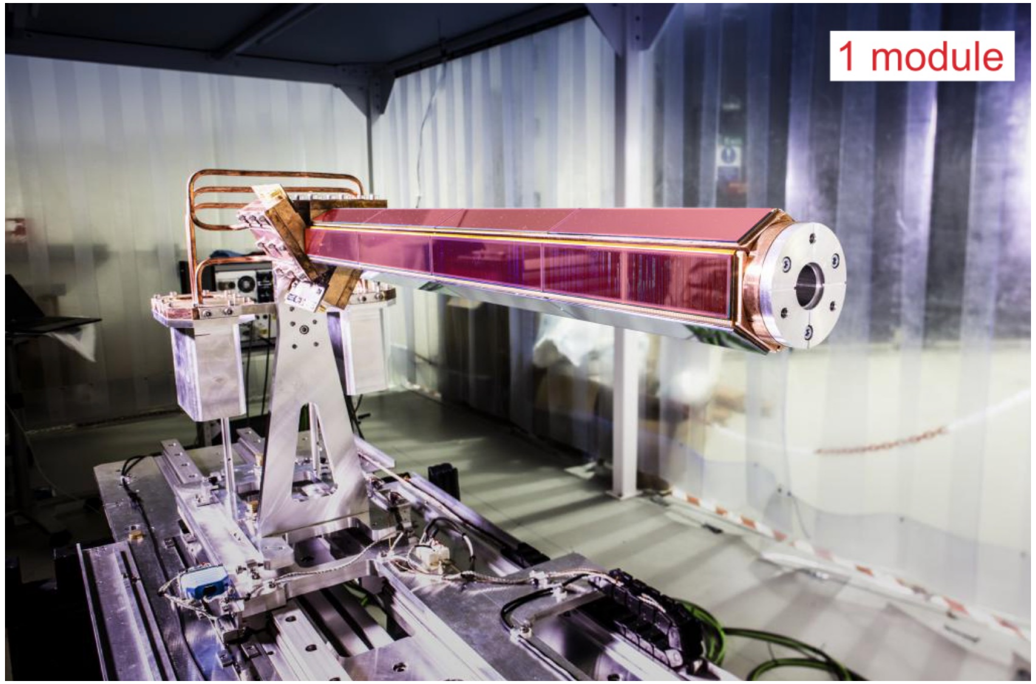
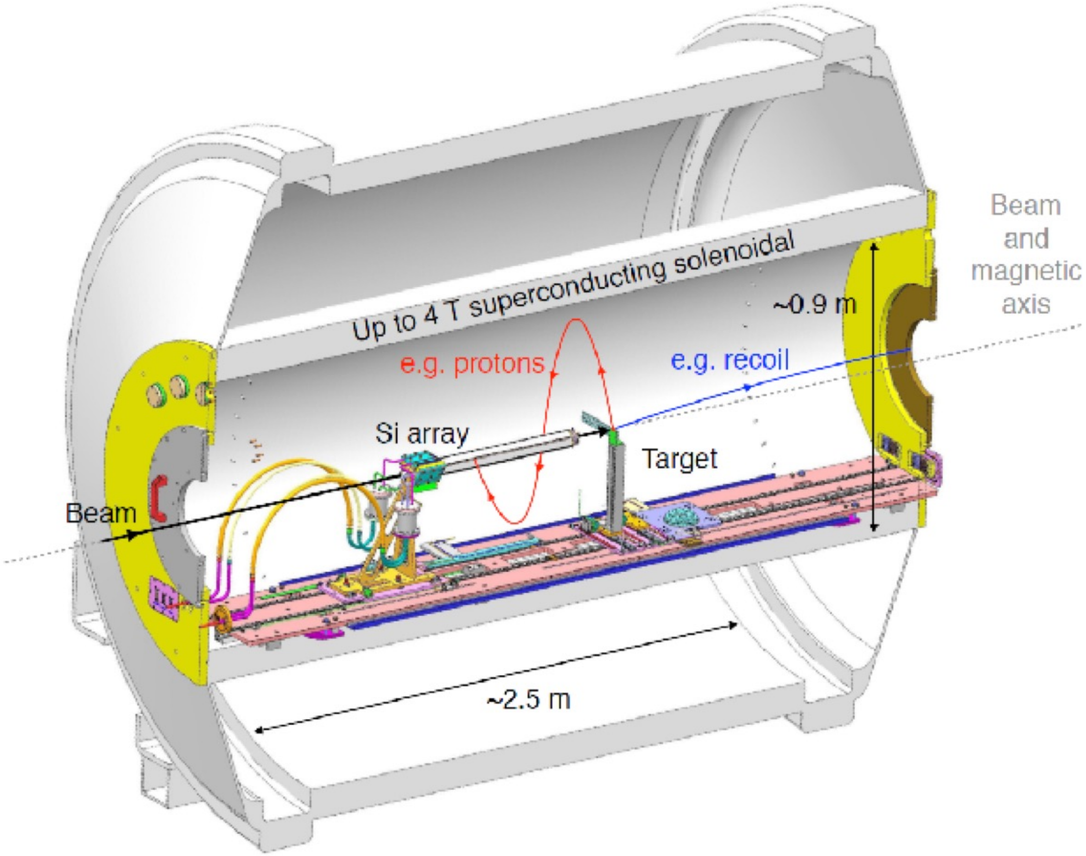
ISS AT CERN





- Hexagonal Si-stripped array
- 1 mm segmentation along symmetry axis
- 500 mm of active silicon length

Courtesy: P. MacGregor, CERN

OUTLINE

- Introduction to direct reactions
- Single-particle energies and spectroscopic factors
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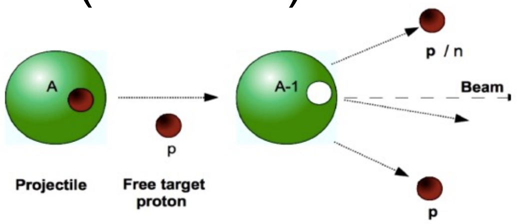
- Quasifree scattering
- Nucleon removal induced from light-ion target
- Instrumentation for quasifree scattering

PROTON QFS

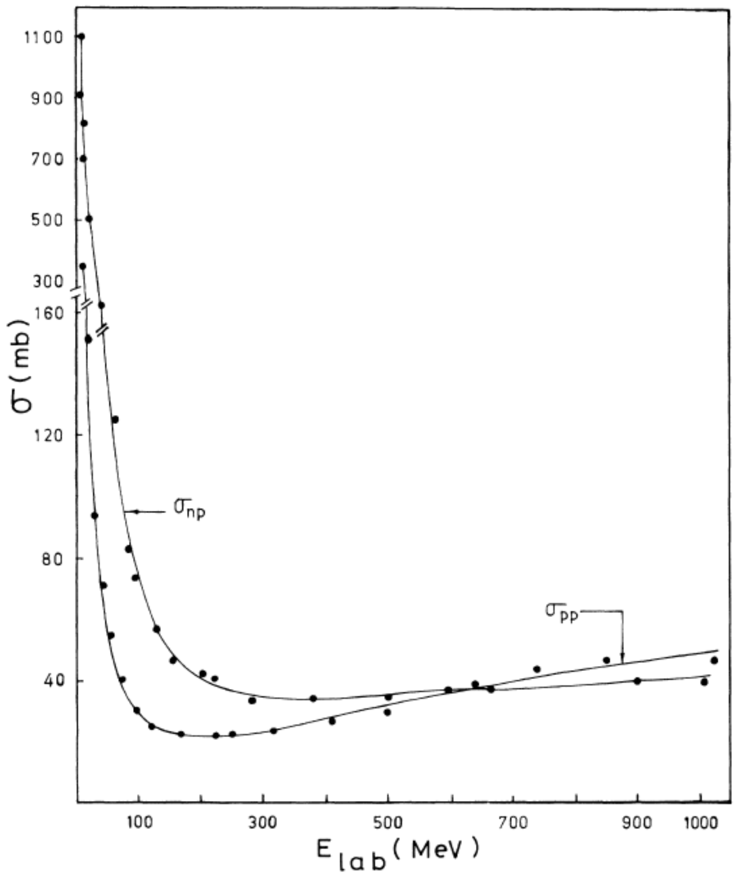
- Quasifree scattering (QFS) to remove a nucleon from a nucleus in one step (**sudden approximation**)

- Incident energy and kinematical region chosen to minimise initial and final state interactions (ISI / FSI): **400 - 700 MeV/nucleon**



- Binding energy of the nucleon inside the nucleus is small compared to the reaction energy: **kinematics follows closely the free NN scattering kinematics** ("quasi-free").

- For stable nuclei, electron-induced quasifree scattering is the most reliable proton-removal mechanism.



KINEMATICS

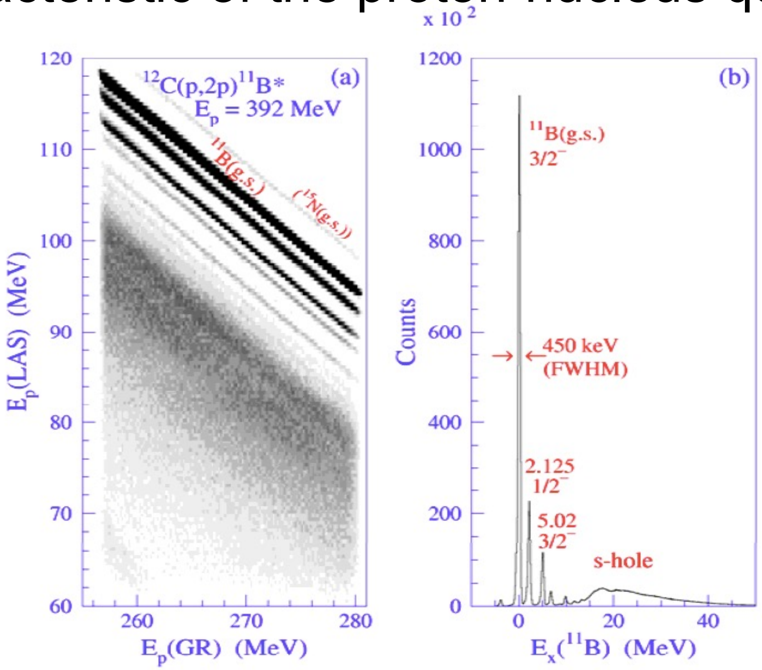
- In a free proton-proton scattering, by momentum and energy conservation, the two scattered protons in the laboratory verify ((1): beam, (2): target, (3,4): scattered particles):

$$T_3 + T_4 = T_1 = \text{constant}$$

$$\phi_3 + \phi_4 = 180^\circ \text{(in plane reaction)}$$

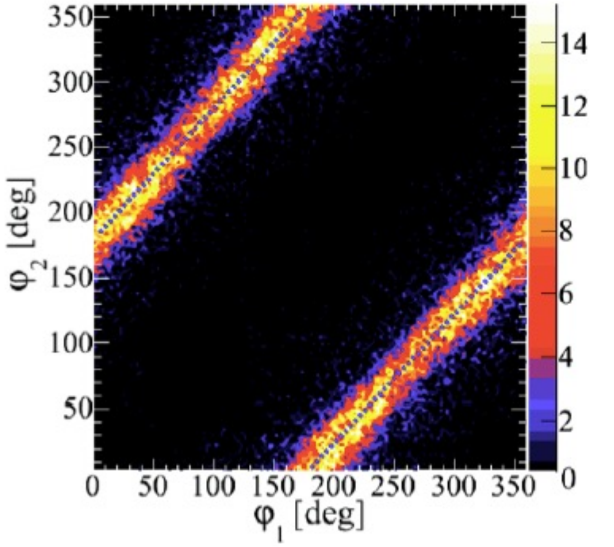
- These features are characteristic of the proton-nucleus quasi-free scattering kinematics

Direct kinematics
$^{12}C(p,2p)^{11}B$ at 392 MeV, RCNP (Japan)



Yosoi et al., NPA 738 (2004)

Inverse kinematics, GSI



Panin et al., PLB 753 (2016)

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MISSING-MASS SPECTROSCOPY

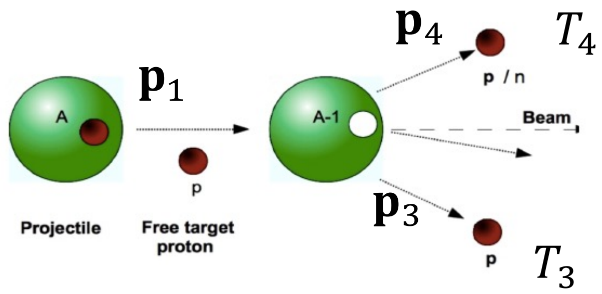
- The excitation energy of the residual nucleus can be determined by **missing mass** from the measurement of **momenta of the two protons**

- Relativistic treatment is necessary.

$$\mathbf{q}_{\perp} = \mathbf{p}_{3\perp} + \mathbf{p}_{4\perp}$$

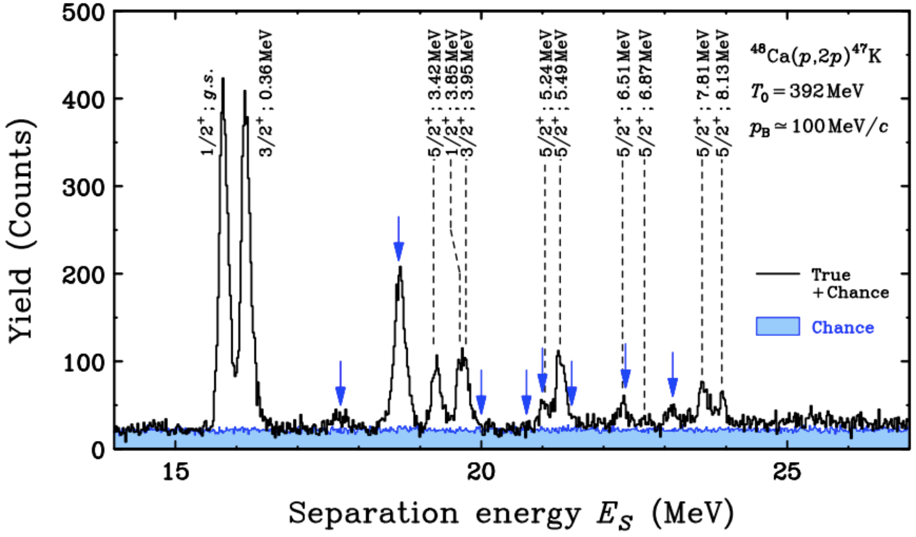
$$q_{\parallel} = \frac{(p_{3\parallel} + p_{4\parallel}) - \gamma\beta(M_A - M_{A-1})}{\gamma}$$

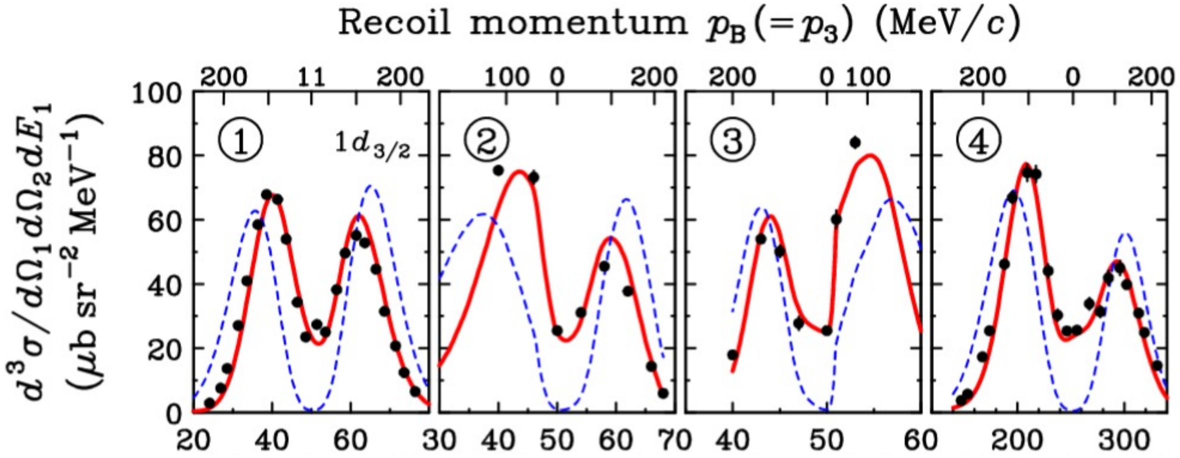
$$E_s = T_1 - \gamma(T_3 + T_4) - 2(\gamma - 1)m_p + \beta\gamma(p_{3\parallel} + p_{4\parallel}) - \frac{q^2}{2M_{A-1}}$$



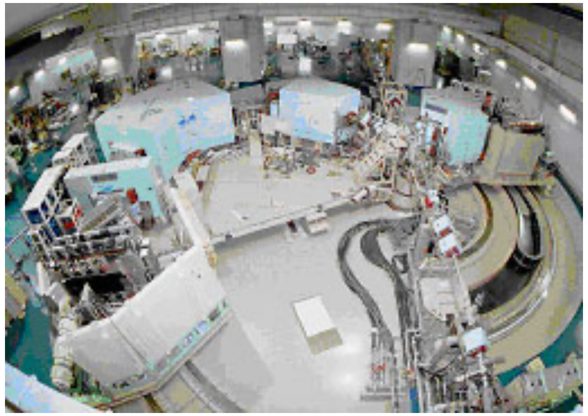
PROTON SPECTROMETERS

- **Ex. Grand Raiden and LAS spectrometers at RCNP (Japan)**

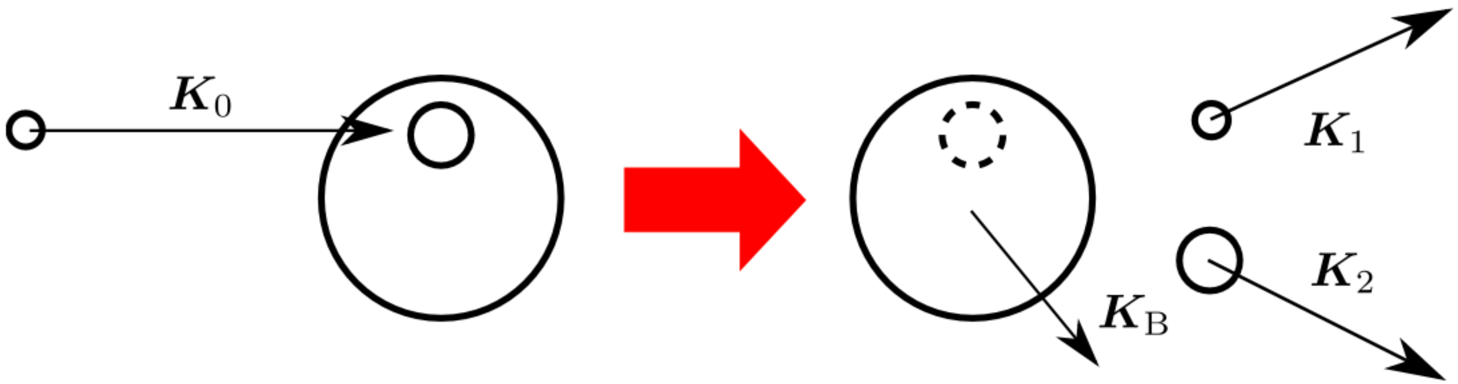




- Separation energy resolution:100 keV FWHM
- Grand Raiden has an intrinsic 1/37000 momentum resolution (16 keV) with a 5% momentum acceptance
- LAS spectrometer reaches 1/5000 momentum resolution with a 30% momentum acceptance



DWIA FORMALISM



- Quasifree scattering cross section (triple differential)

$$\frac{d\sigma_{\alpha\beta}}{dE_1 d\Omega_1 d\Omega_2} = \frac{(2\pi)^4}{\hbar v} \mathrm{F_{kin}} |T_\alpha \beta|^2$$ with F_{kin} kinematical factor

- Transition matrix for single-particle state $\varphi_{n\ell j}$ in Distorted Wave Impulse Approximation

$$T = \langle \chi_1 \chi_2 | t_{pN} | \chi_0 \varphi_{n\ell j} \rangle$$

Impulse Approximation: one step, t_{pN} NN interaction in free space
Distorted Wave: incoming proton and outgoing protons influences by optical potential

DWIA FORMALISM

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journal homepage: www.elsevier.com/locate/cpc

ELSEVIER

Computer Programs in Physics

PIKOE: A computer program for distorted-wave impulse approximation calculation for proton induced nucleon knockout reactions ☆

Kazuyuki Ogata[a,b,*], Kazuki Yoshida[c], Yoshiki Chazono[d]

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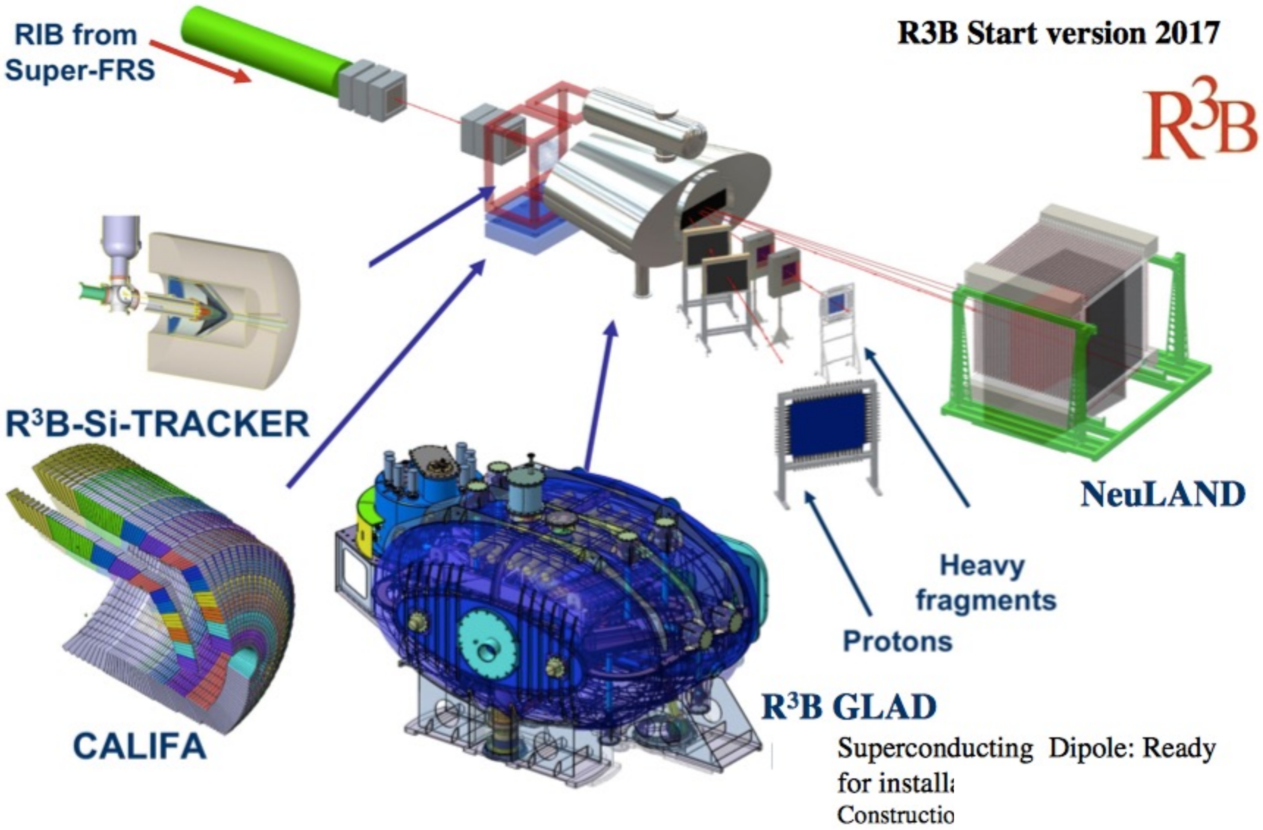
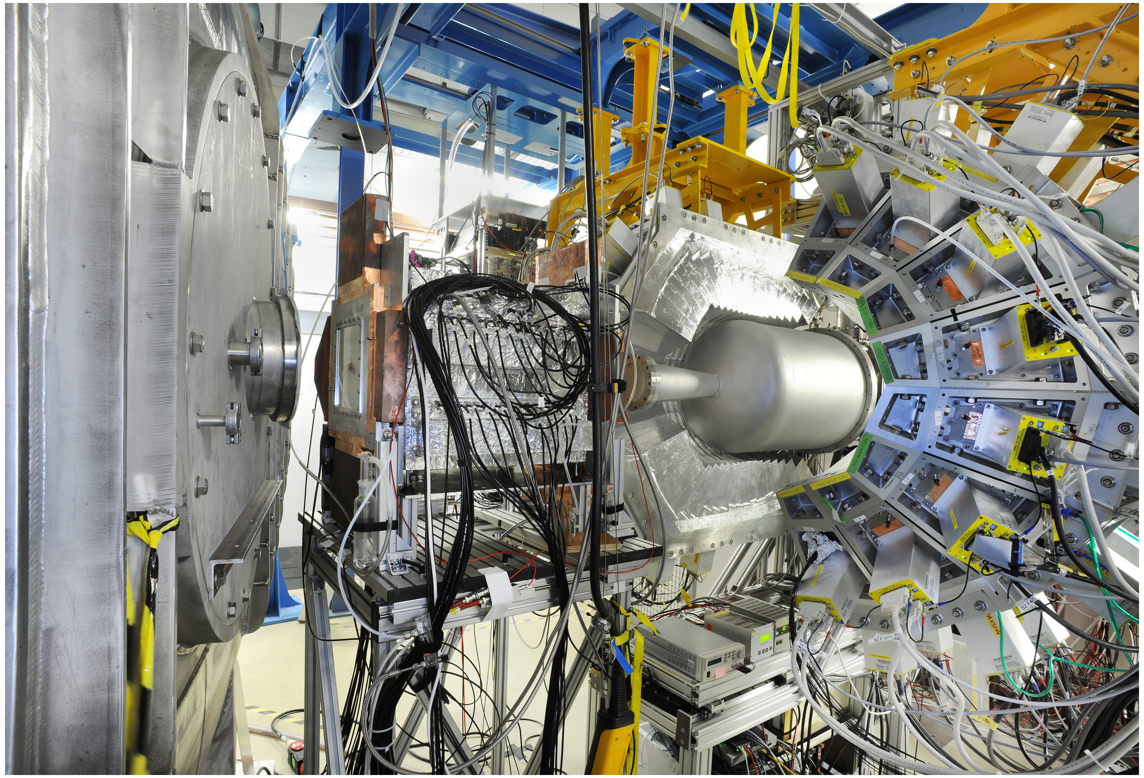
[b] *Research Center for Nuclear Physics, Osaka University, Ibaraki 567-0047, Japan*
[c] *Advanced Science Research Center, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan*
[d] *RIKEN Nishina Center for Accelerator-Based Science, 2-1 Hirosawa, Wako 351-0198, Japan*

- Other similar methods: Quantum Transfer to the Continuum (QTC, Sevilla group), eikonal (Bertulani, Texas A&M), Fadeev: no open code while theorists very collaborative

R3B AT GSI/FAIR





QFS AND GAMMA IN-BEAM

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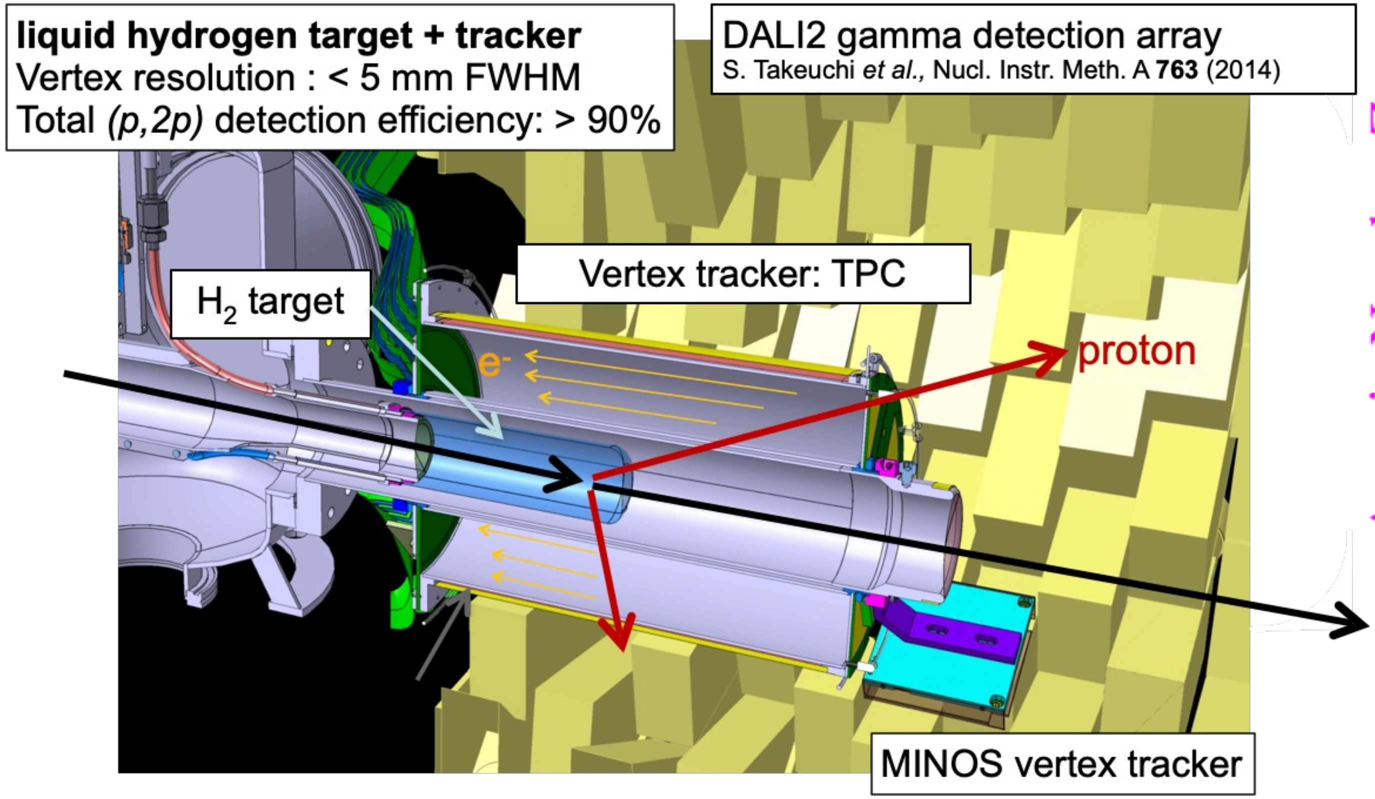

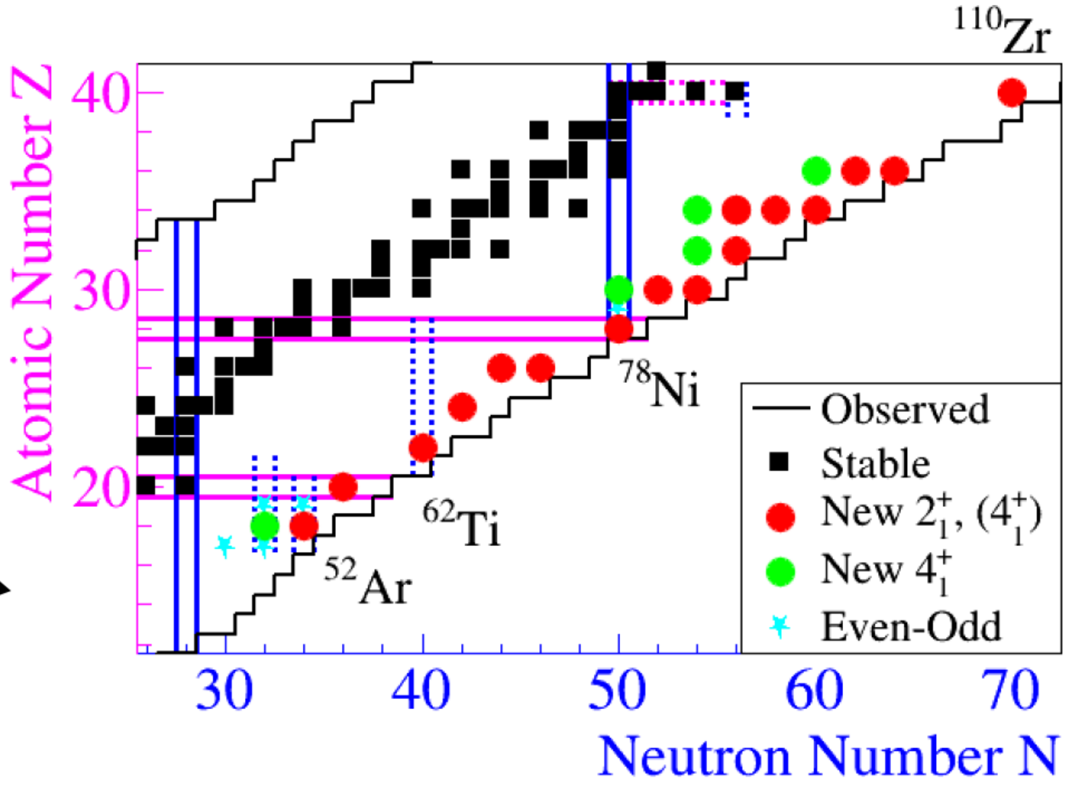

Obertelli et al., EPJA (2014)

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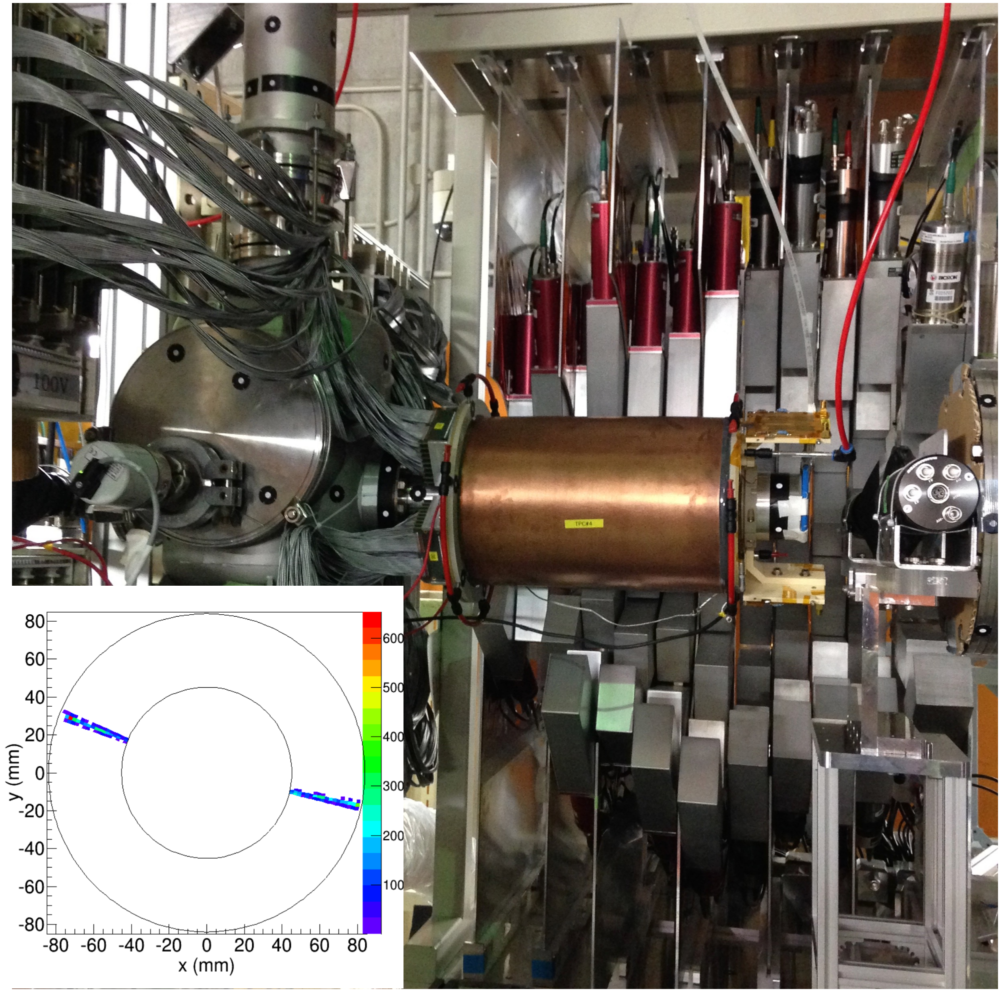
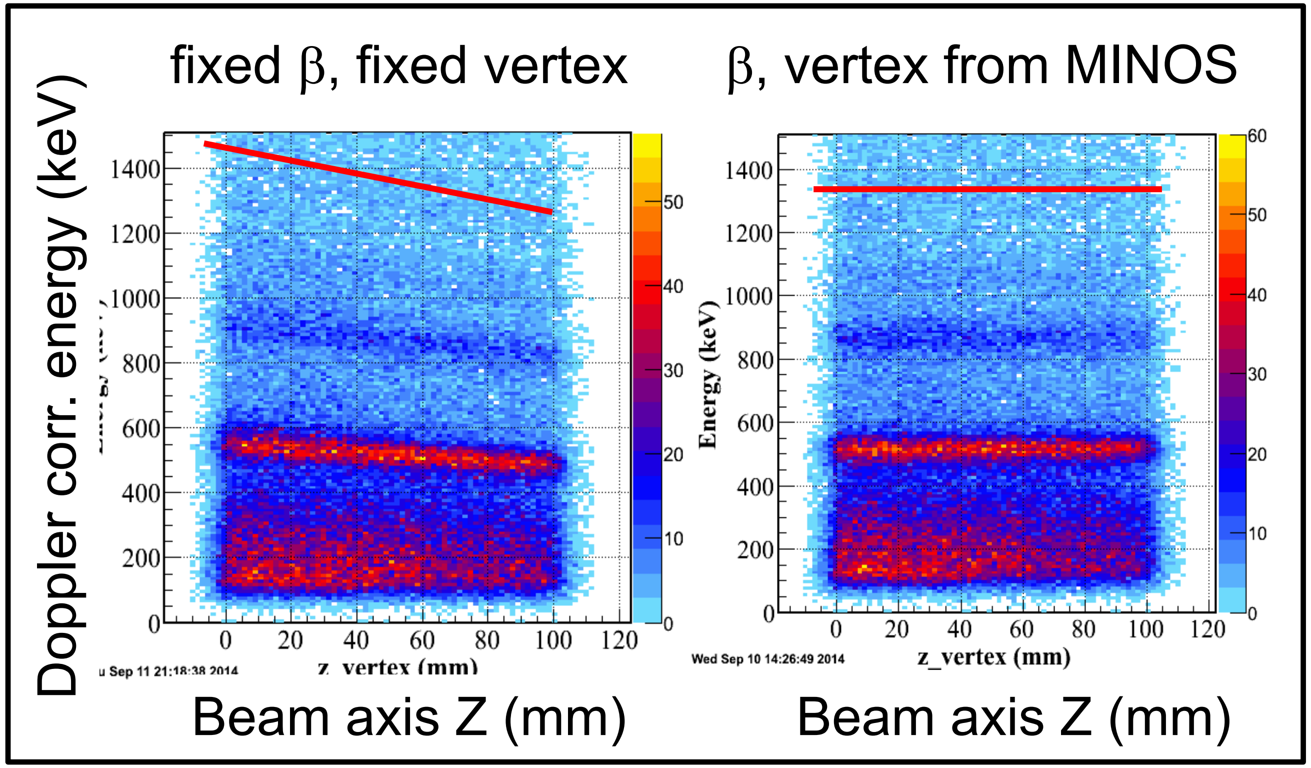
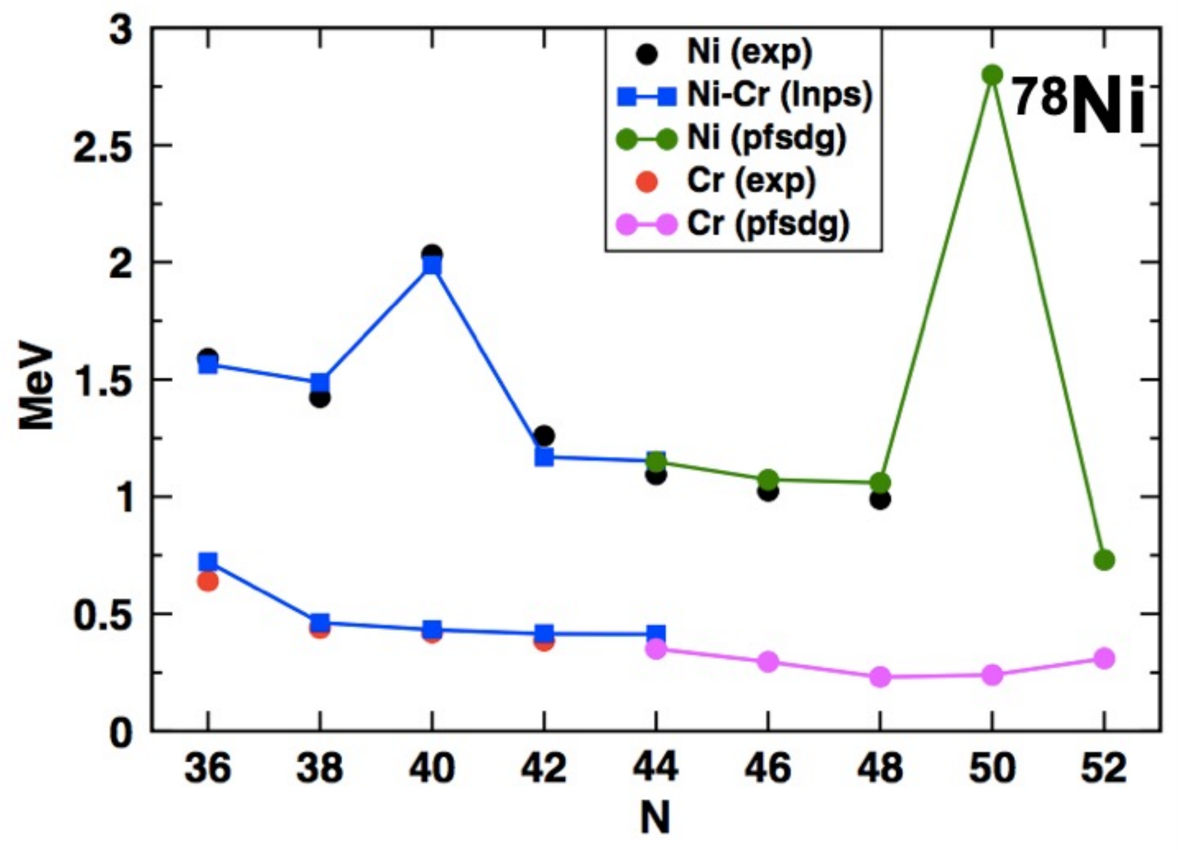
MINOS

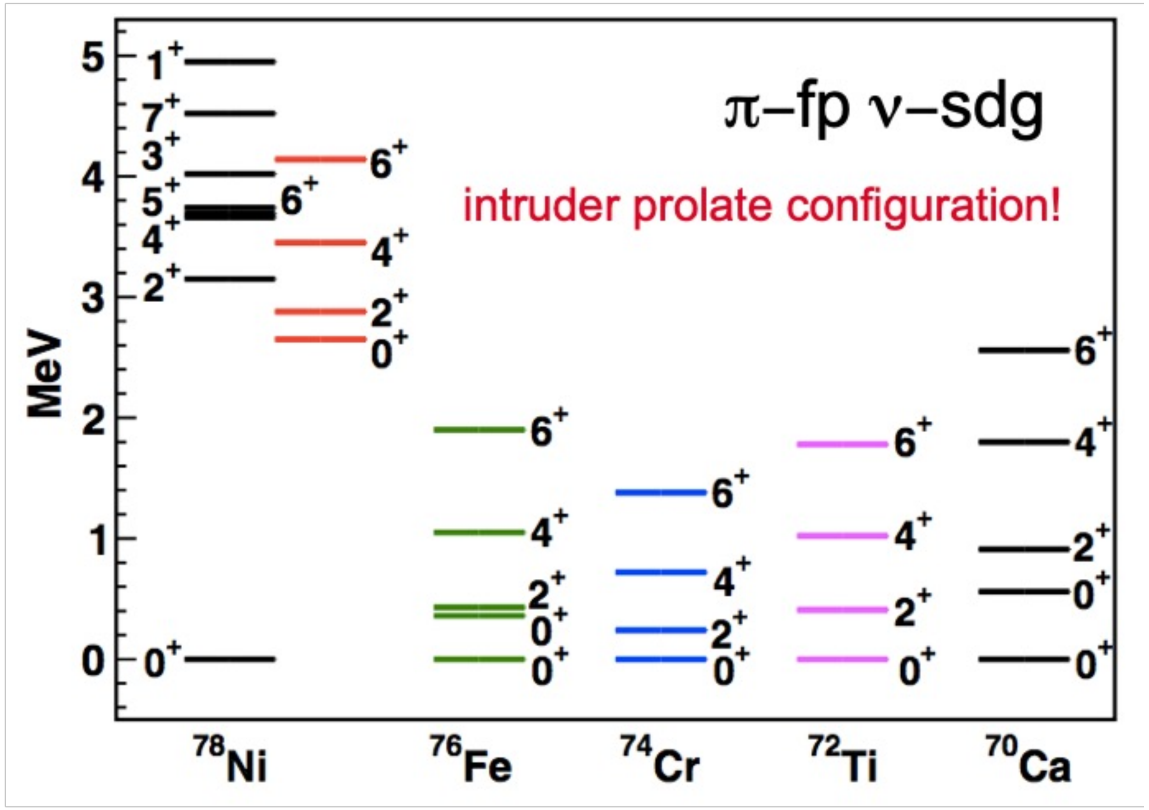




DOUBLY MAGIC ^{78}NI



Shell Model



Nowacki et al., PRL (2016)

See lecture of Dr. Suzuki

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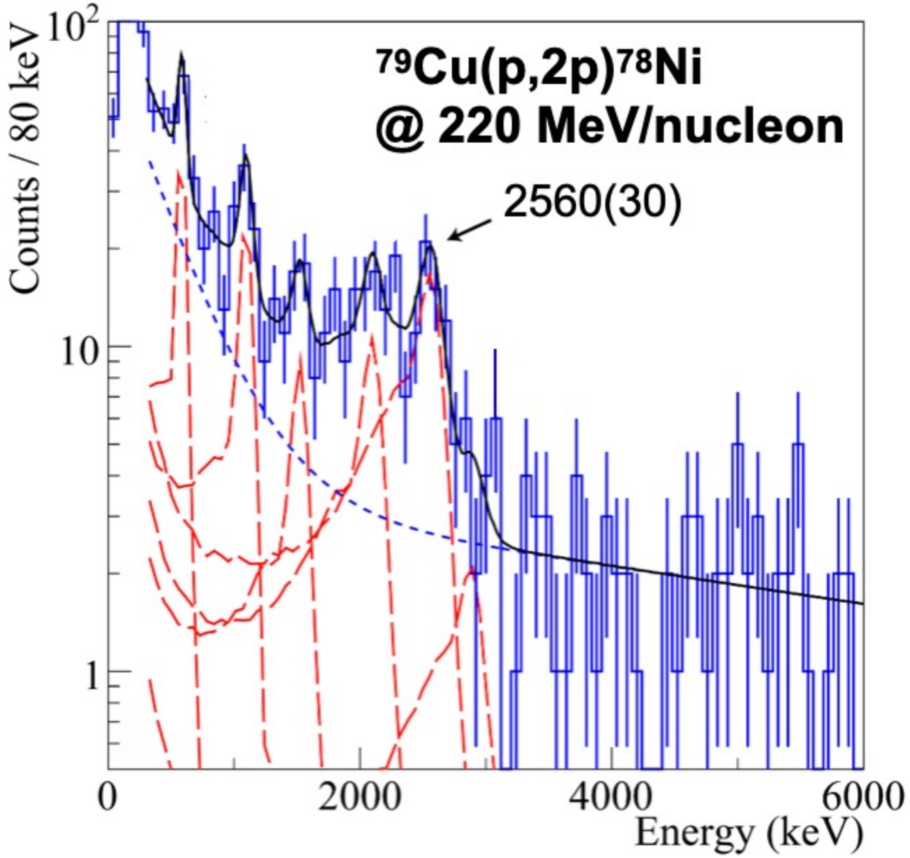
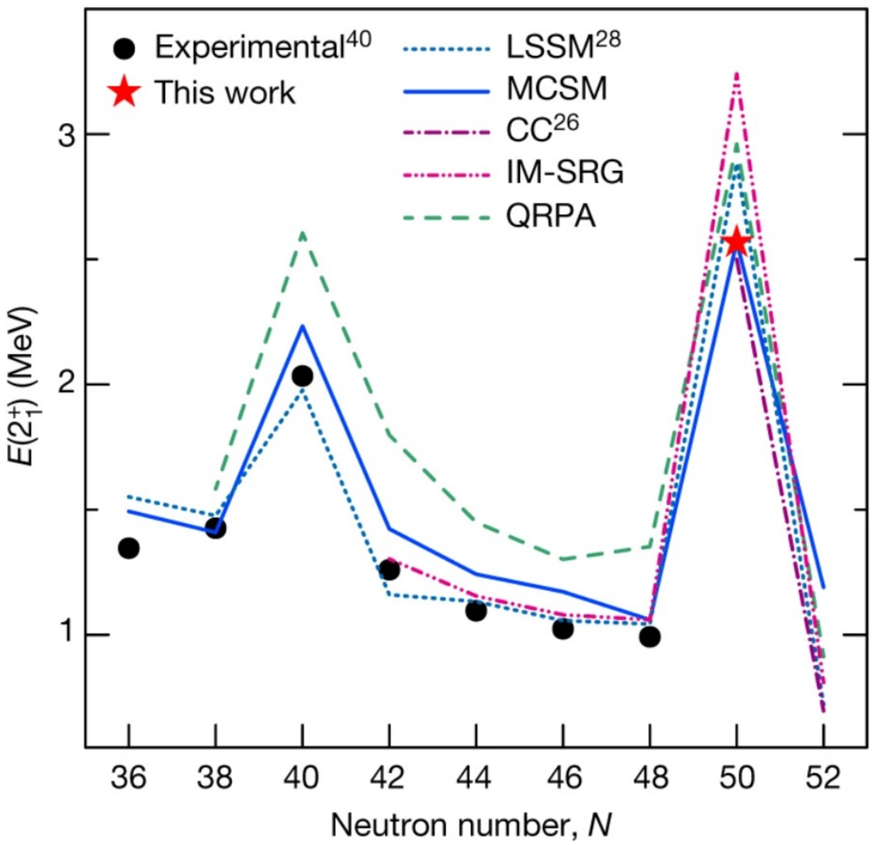
DOUBLY MAGIC ^{78}NI

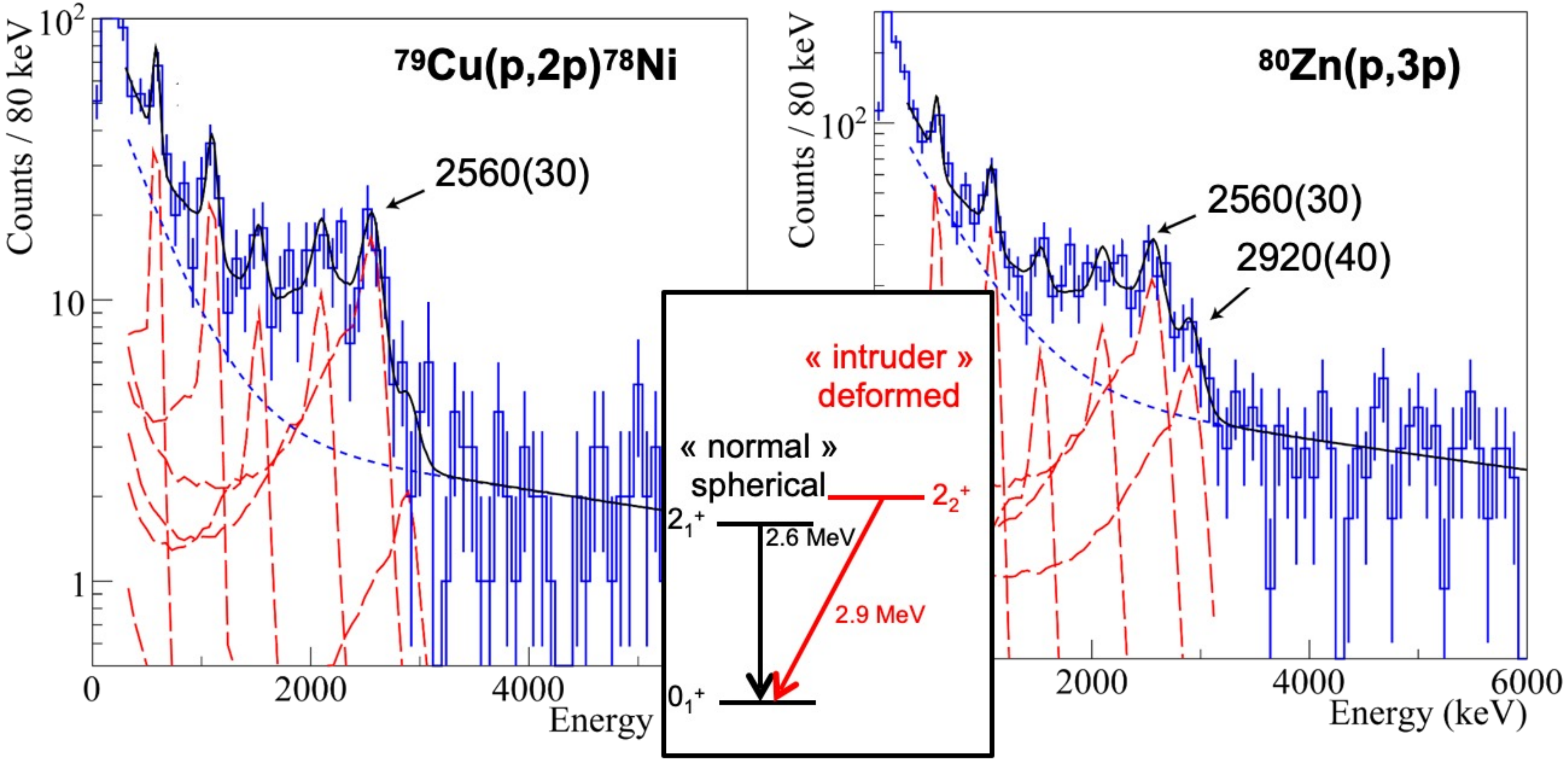
^{238}U primary beam at 20 pnA, ^{79}Cu, 220 MeV/nucleon, intensity: 5 pps





Taniuchi et al., Nature (2019)

DOUBLY MAGIC ^{78}NI



Taniuchi et al., Nature (2019)

EXAMPLE OF ALPHA CLUSTER QFS

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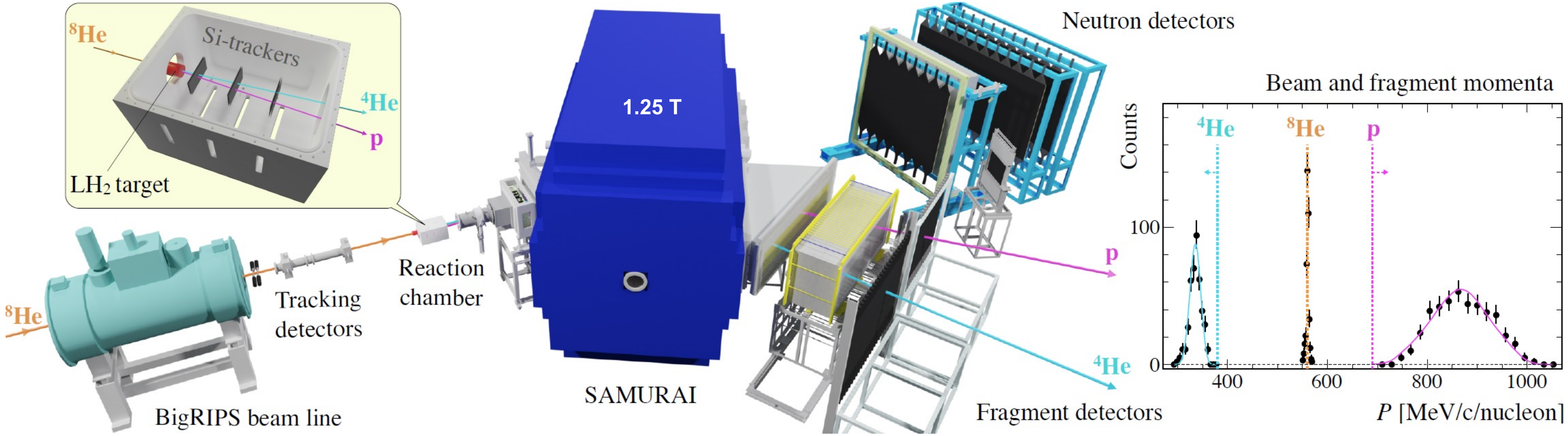
- Quasifree scattering applicable to nuclei, such as alpha particles
- Kinematics is modified accordingly
- Very small cross sections (~100 pb)



- ^{8}He beam at 156 MeV / nucleon
- Evidence of interacting four free neutrons

Duer et al., Nature 606 (2022)

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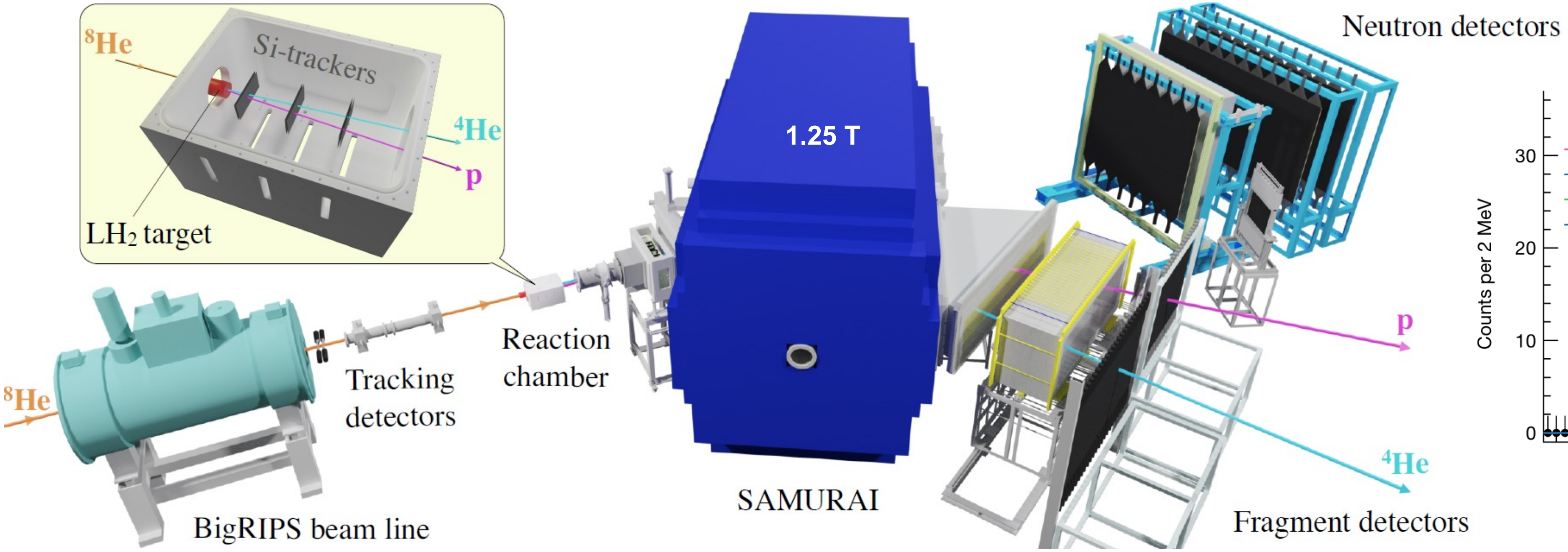

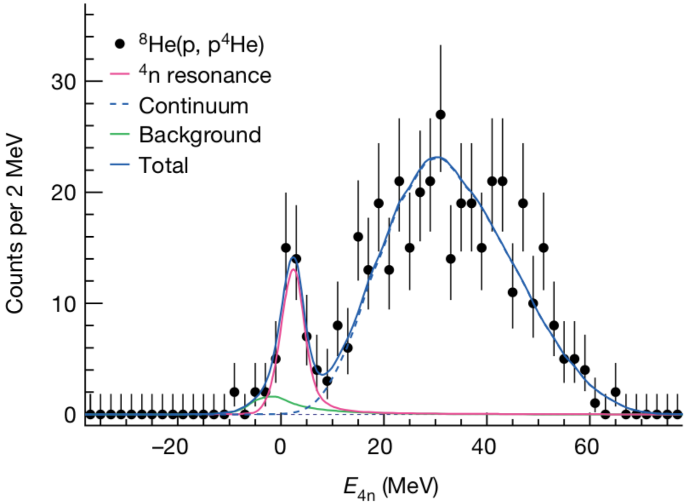

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Duer et al., Nature 606 (2022)

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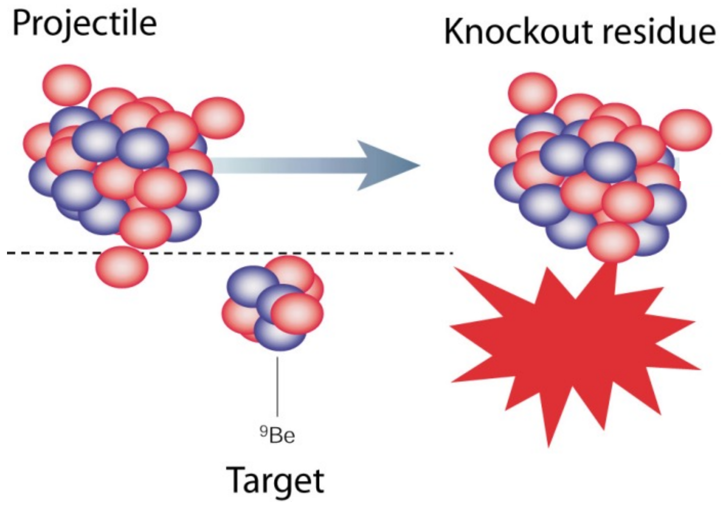
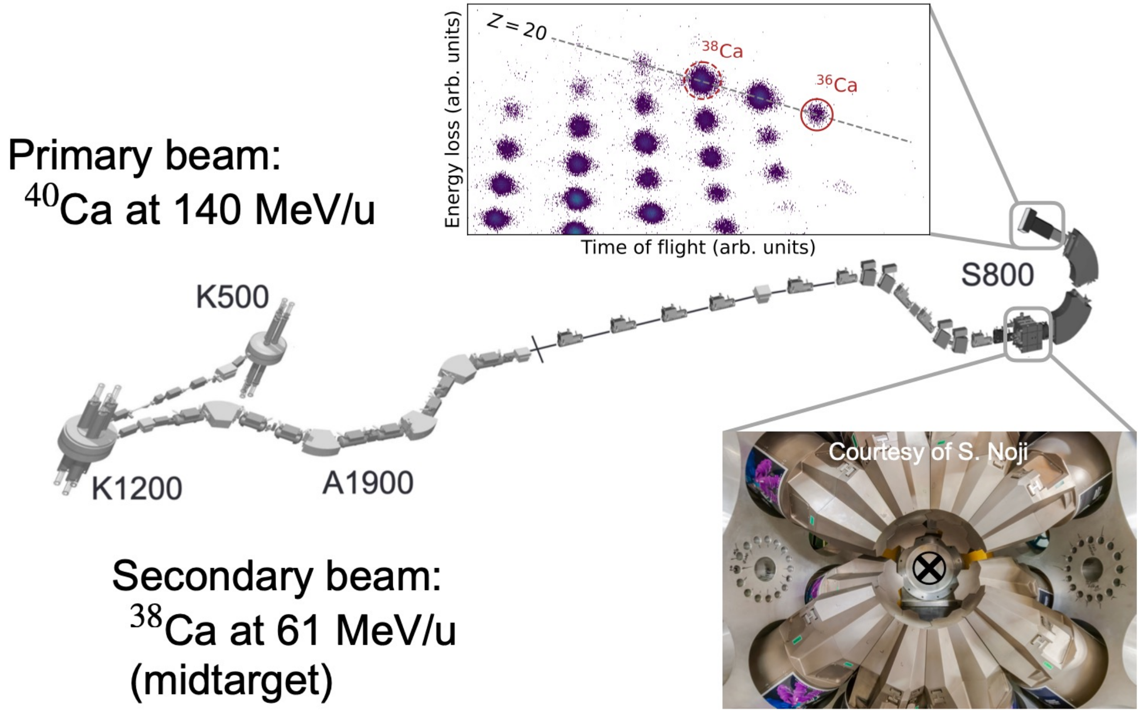
LIGHT-ION INDUCED KNOCKOUT

- One-nucleon removal from light ion target (^{9}Be, ^{12}C) at incident energies above ~50 MeV/nucleon
- Experimentally easier to implement; routinely used at NSCL from 90s
- Eikonal formalism for cross section interpretation (see next slide)





From T. Beck, FRIB
DREB 2024

FRIB

EIKONAL FORMALISM

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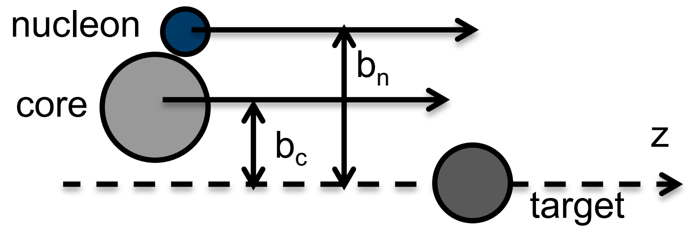
$$\psi(\vec{r}) = s(\vec{r})\, e^{i\vec{k}.\vec{r}}$$

$$\text{and} \quad S(\vec{r}) = e^{-i\frac{\mu}{\hbar^2 k}\int_{-\infty}^{z} U(\sqrt{b^2+z'^2})\,dz'} \quad \text{with } b = r_\perp$$

Eikonal approximation: straight line



- **Single-particle cross section** $\sigma_{sp}(n\ell j) = \sigma_{sp}^{strip}(n\ell j) + \sigma_{sp}^{diff}(n\ell j)$
- **Stripping cross section** (the target is excited) $\sigma^{strip} = 2\pi \int_0^\infty b\,db \int d^3 r \left|\phi_{n\ell j}(\vec{r})\right|^2 \left|S_{core}(\vec{b_c})\right|^2 \left(1 - \left|S_{nucl}(\vec{b_n})\right|^2\right)$

Core « survives » × Nucleon « adsorbed »

- **Diffractive cross section** (the target remains in its ground state)

$$\sigma_{diff} = 2\pi \int b\,db \left\langle \phi_0 \left| \left|S_{core} S_{nucl}\right|^2 \right| \phi_0 \right\rangle - \left| \left\langle \phi_0 \left| S_{core} S_{nucl} \right| \phi_0 \right\rangle \right|^2$$

EXAMPLE

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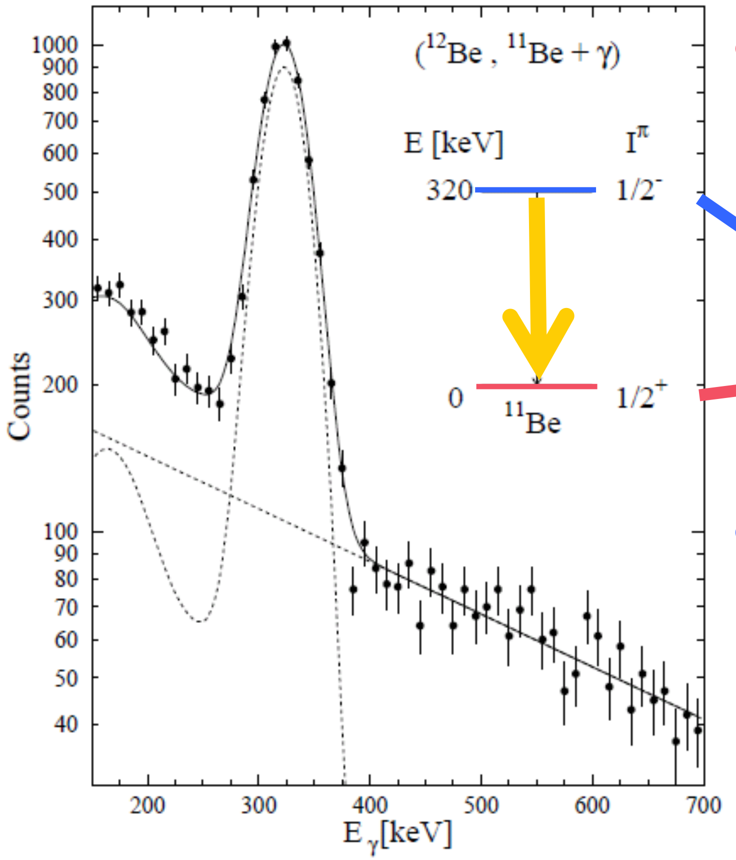
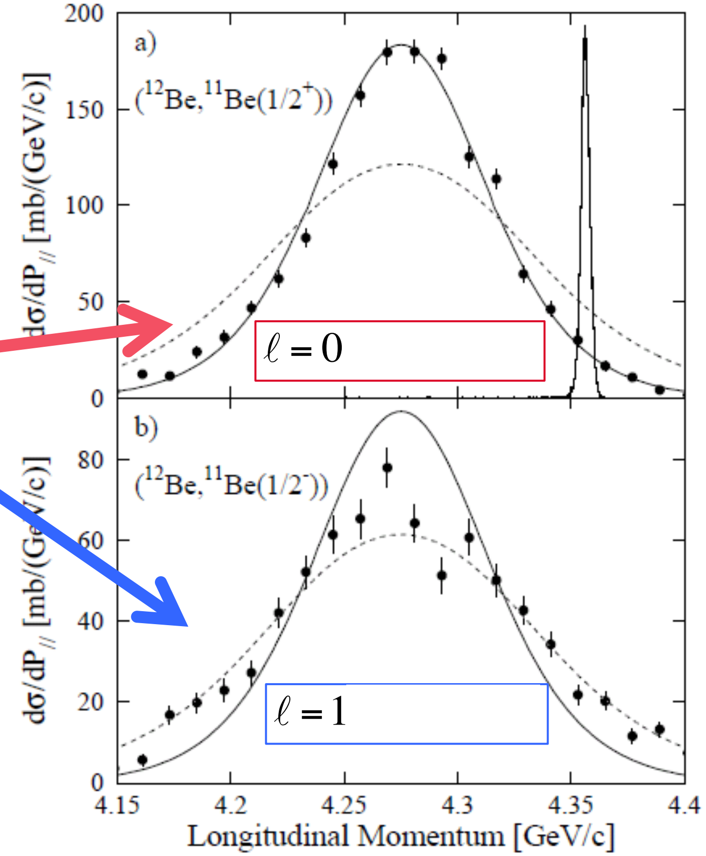
A. Navin et al., PRL 85 (2000)



$\sigma_{1/2+}$ = 32(5) mb

$\sigma_{1/2-}$ = 17(3) mb



EXAMPLE

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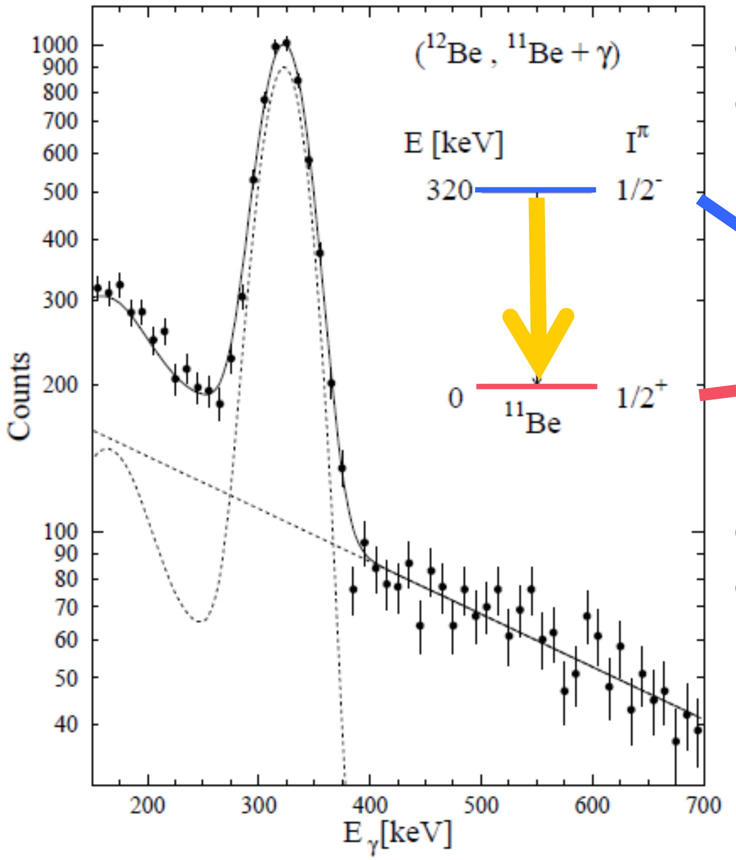
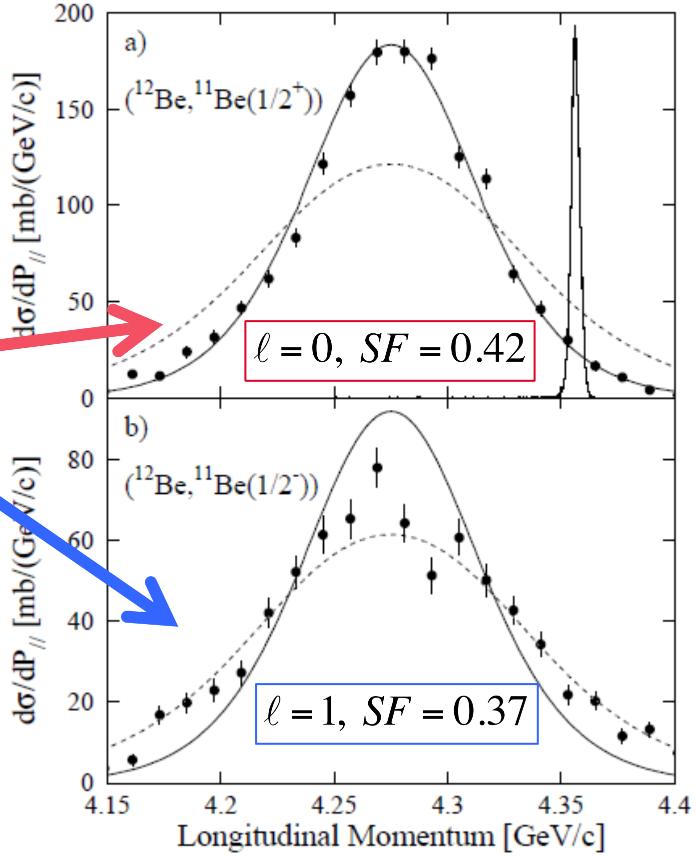


$\sigma_{1/2+}$ = 32(5) mb
σ_{eik}(l=0)= 76 mb
➔ SF=32/75=0.42

$\sigma_{1/2-}$ = 17(3) mb
σ_{eik}(l=1)= 47 mb
➔ SF=17/47=0.37



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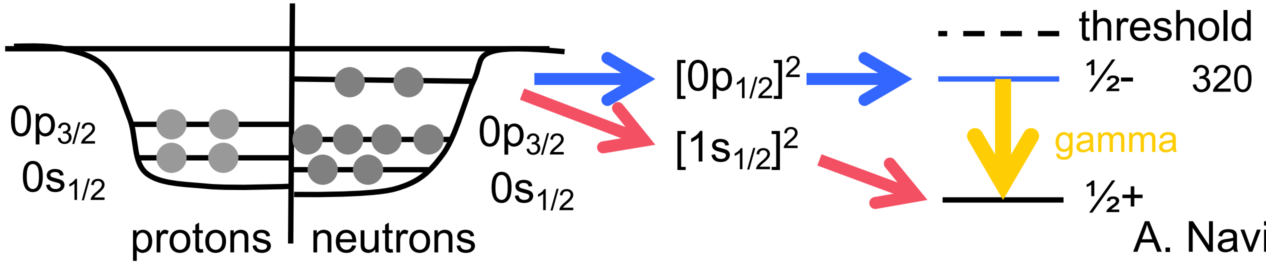
EXAMPLE



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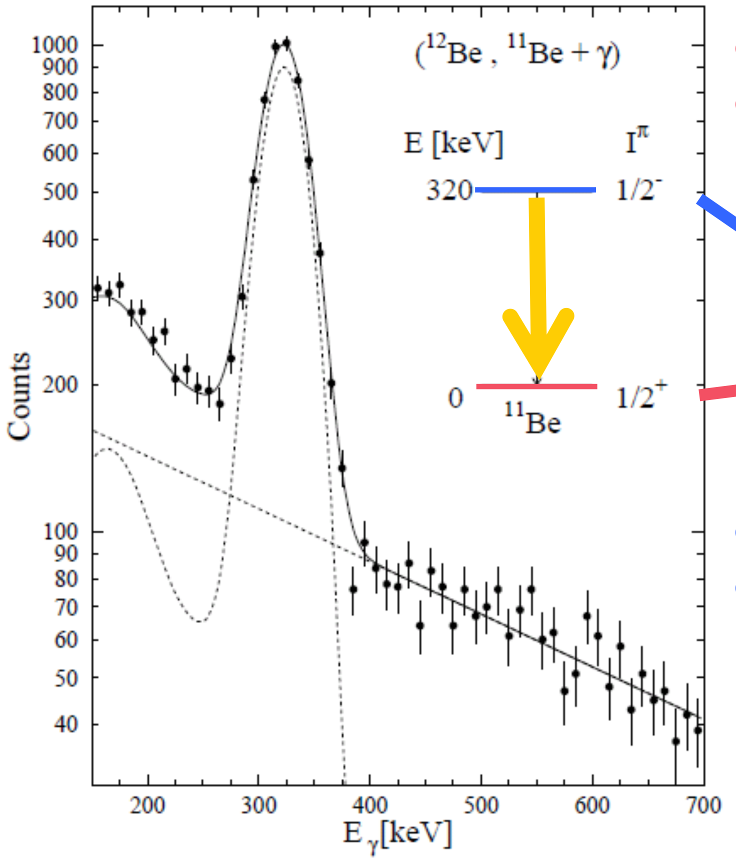

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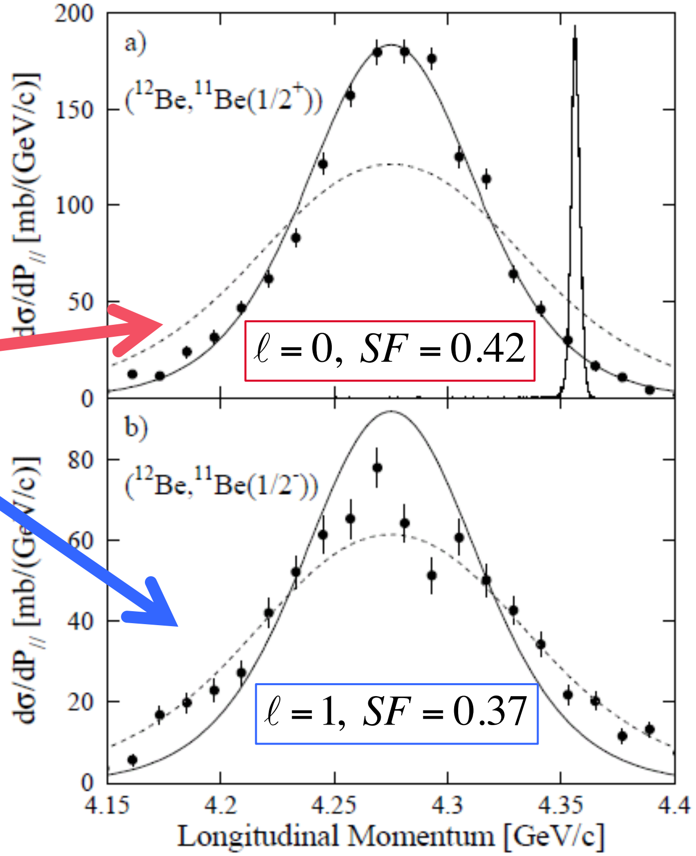
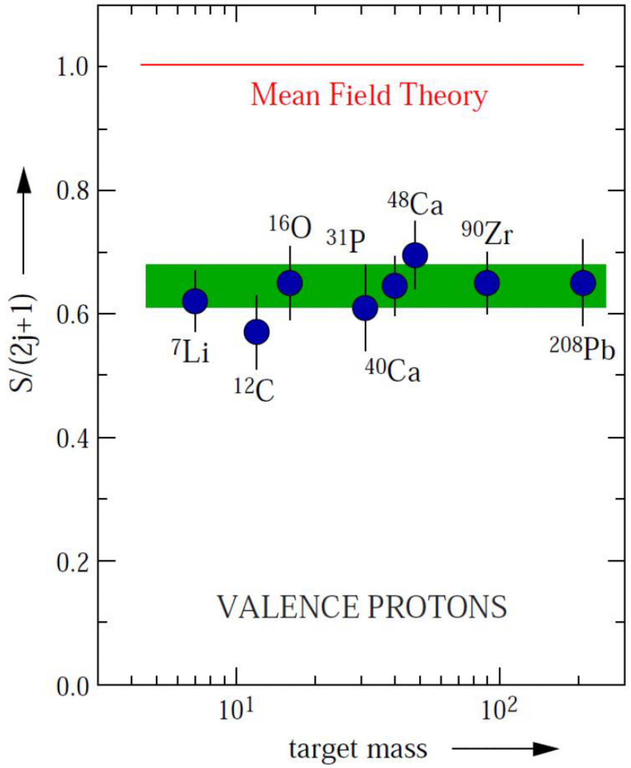
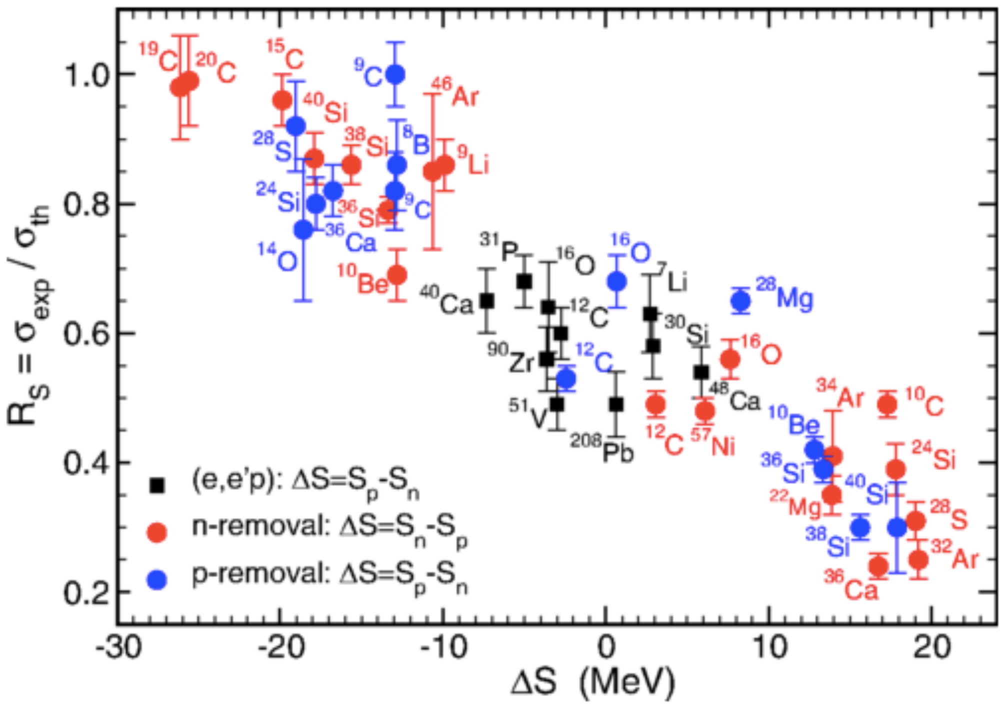


STRENGTH QUENCHING





A. Gade et al., Phys. Rev. C 77 (2008)
J.A. Tostevin and A. Gade, Phys. Rev. C 90 (2014)

STRENGTH QUENCHING

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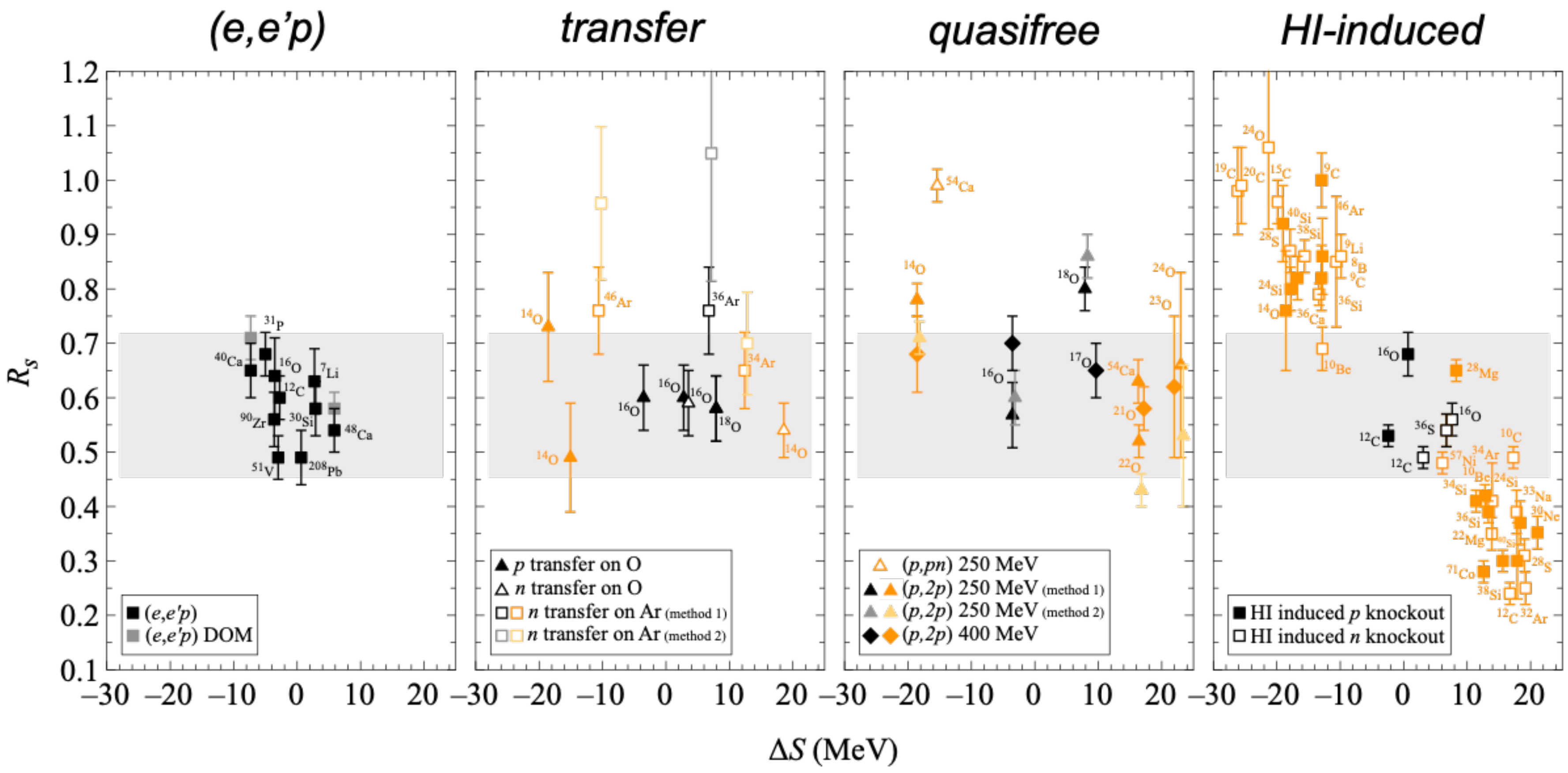

Aumann et al., Prog. Part. Nucl. Phys. (2021)

END OF LECTURE 3