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DIRECT NUCLEAR REACTIONS EXPERIMENT

Alexandre Obertelli, TU Darmstadt

OUTLINE

- Introduction to direct reactions
- Formalism
- Single-particle energies and spectroscopic factors

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

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

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NUCLEAR FORCES & NUCLEI

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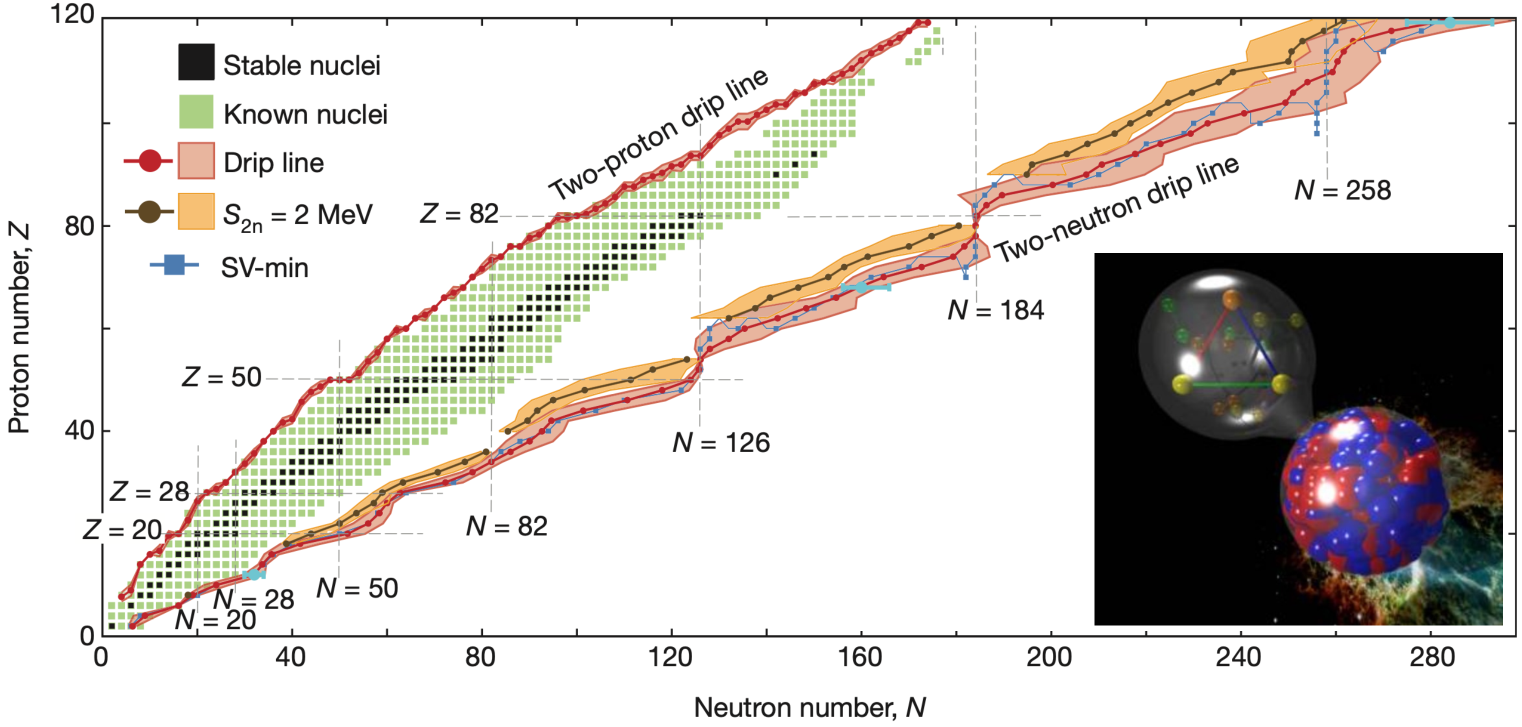
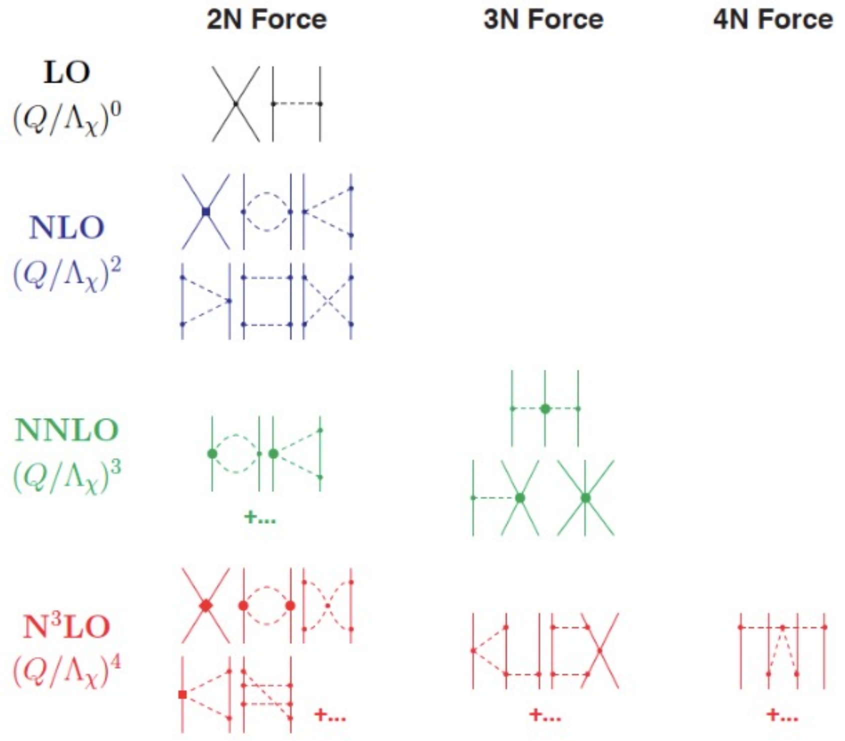
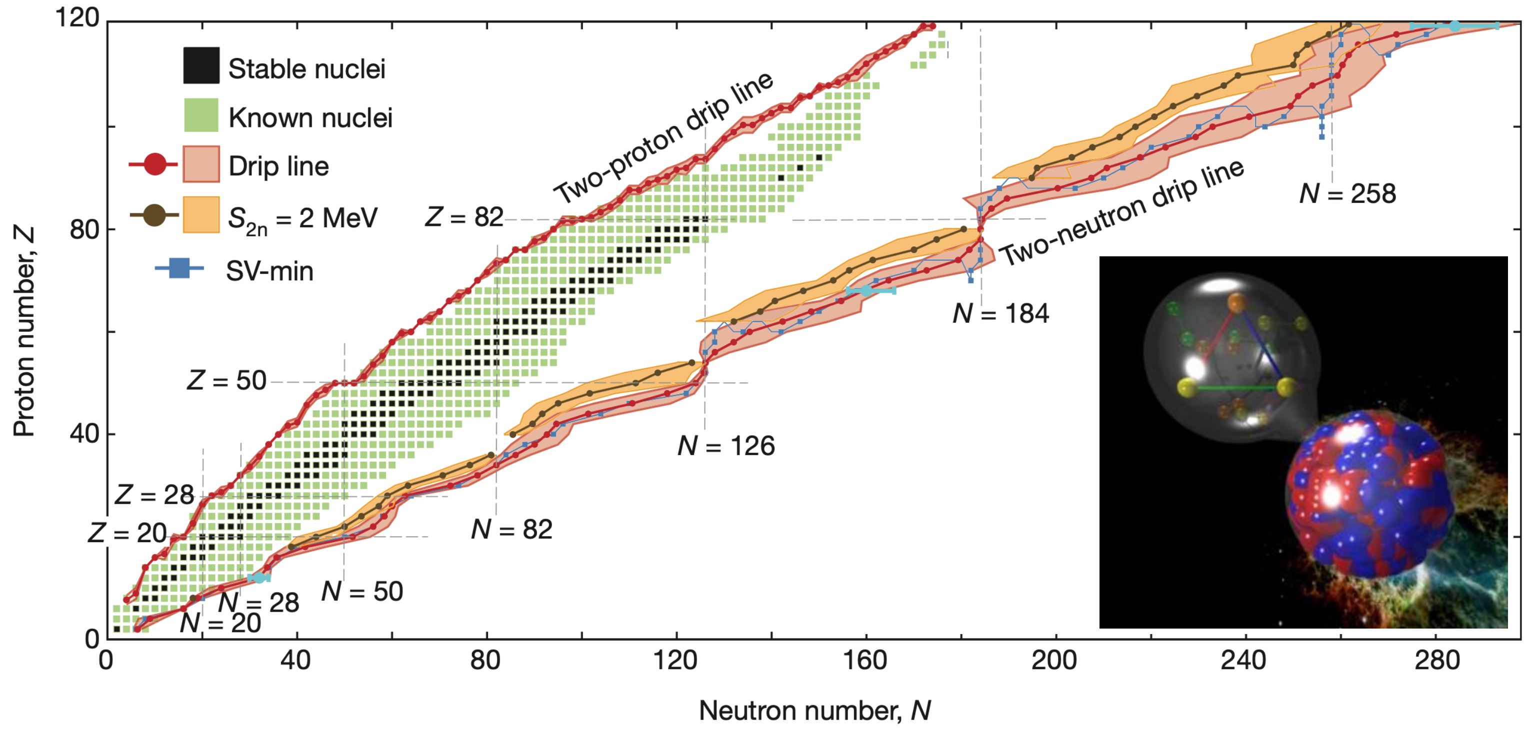


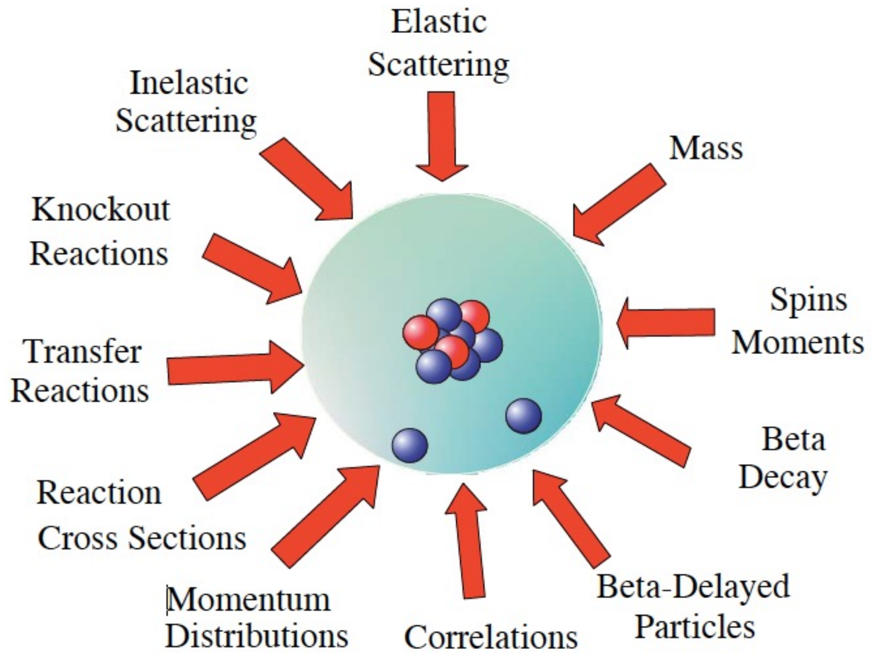
Erler et al., Nature (2020)



NUCLEAR FORCES & NUCLEI



Erler et al., Nature (2020)



Jonson, Physics Report 389 (2004)

WHY DO WE NEED REACTIONS?

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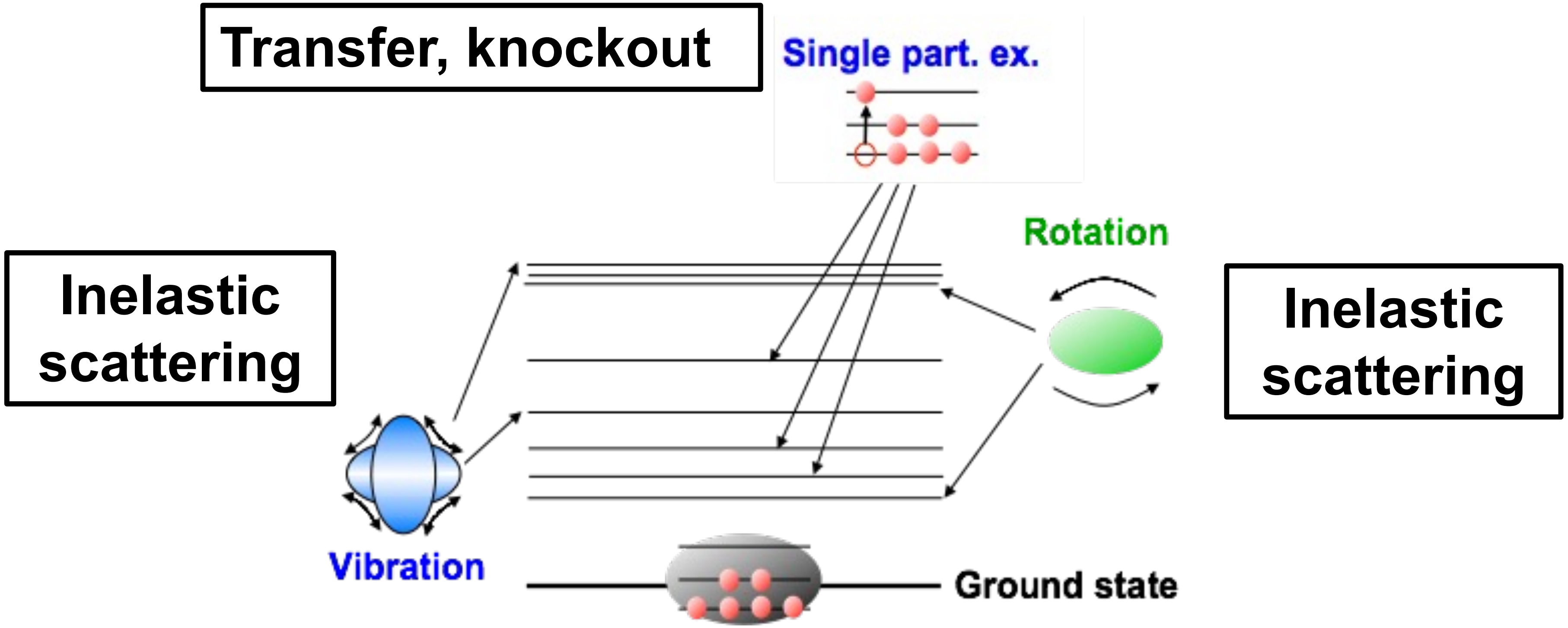
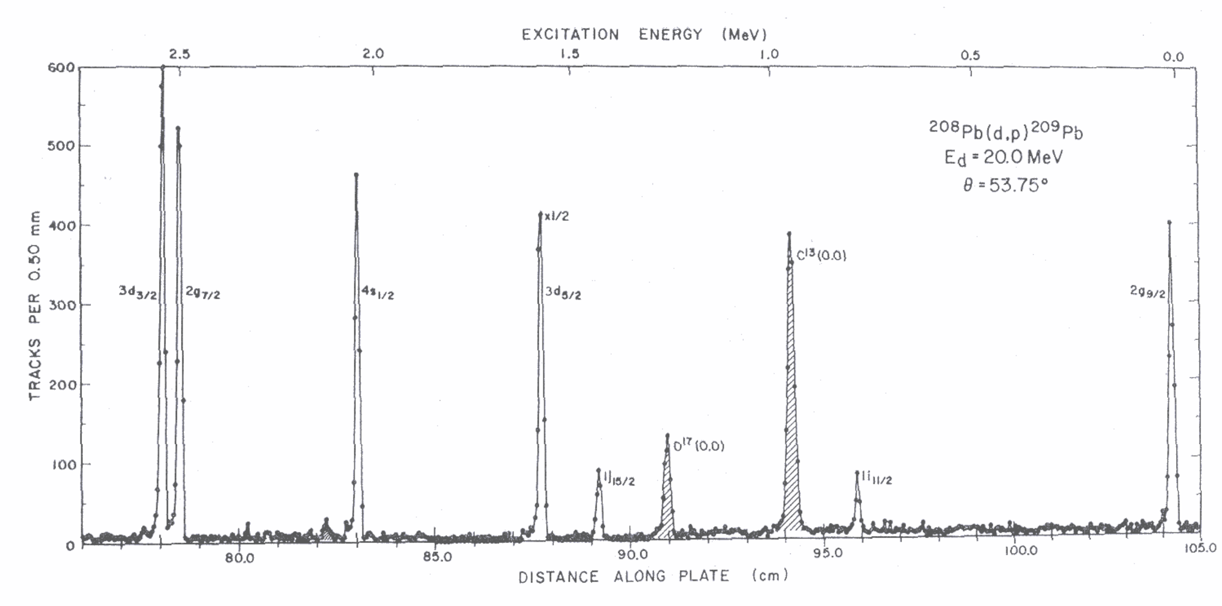
- to produce nuclei and to go beyond ground-state properties (to **excite** nuclei)
- to measure and identify populated states (**spectroscopy**)
- to understand the nature of nuclear states (**cross sections**)



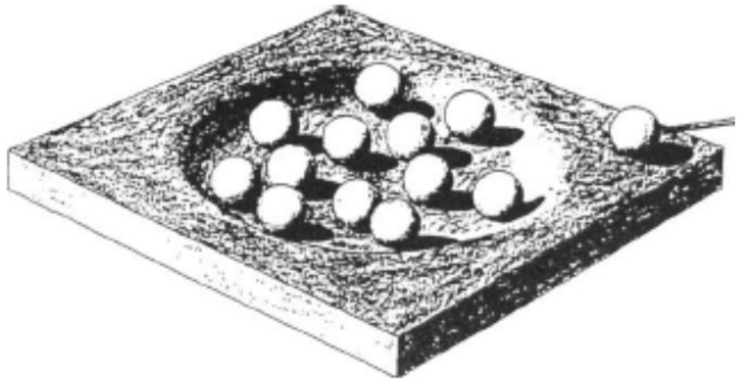
DIRECT REACTIONS

Nuclear reactions range between two limit scenarios:
- direct reactions
- compound-nucleus reactions



D.G. Kovar et al., NPA 231 (1974)

Direct reactions:
- **short time** reactions (**about 10^{-22} second**)
- occur dominantly at the **surface** of the target nucleus
- **keep memory of the initial state** through the overlap with the final state



Niels Bohr's classical representation of a compound-nucleus reaction

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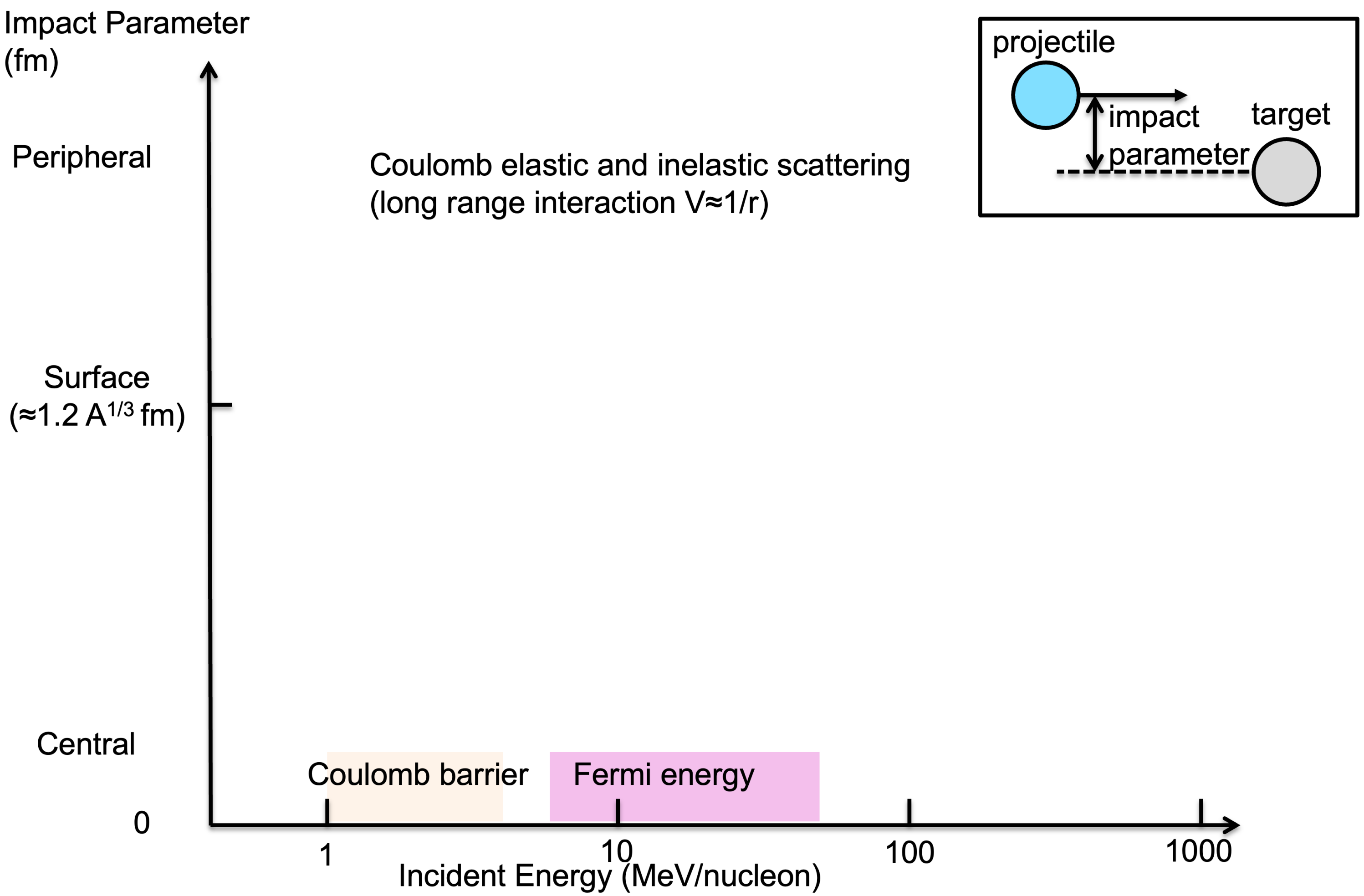
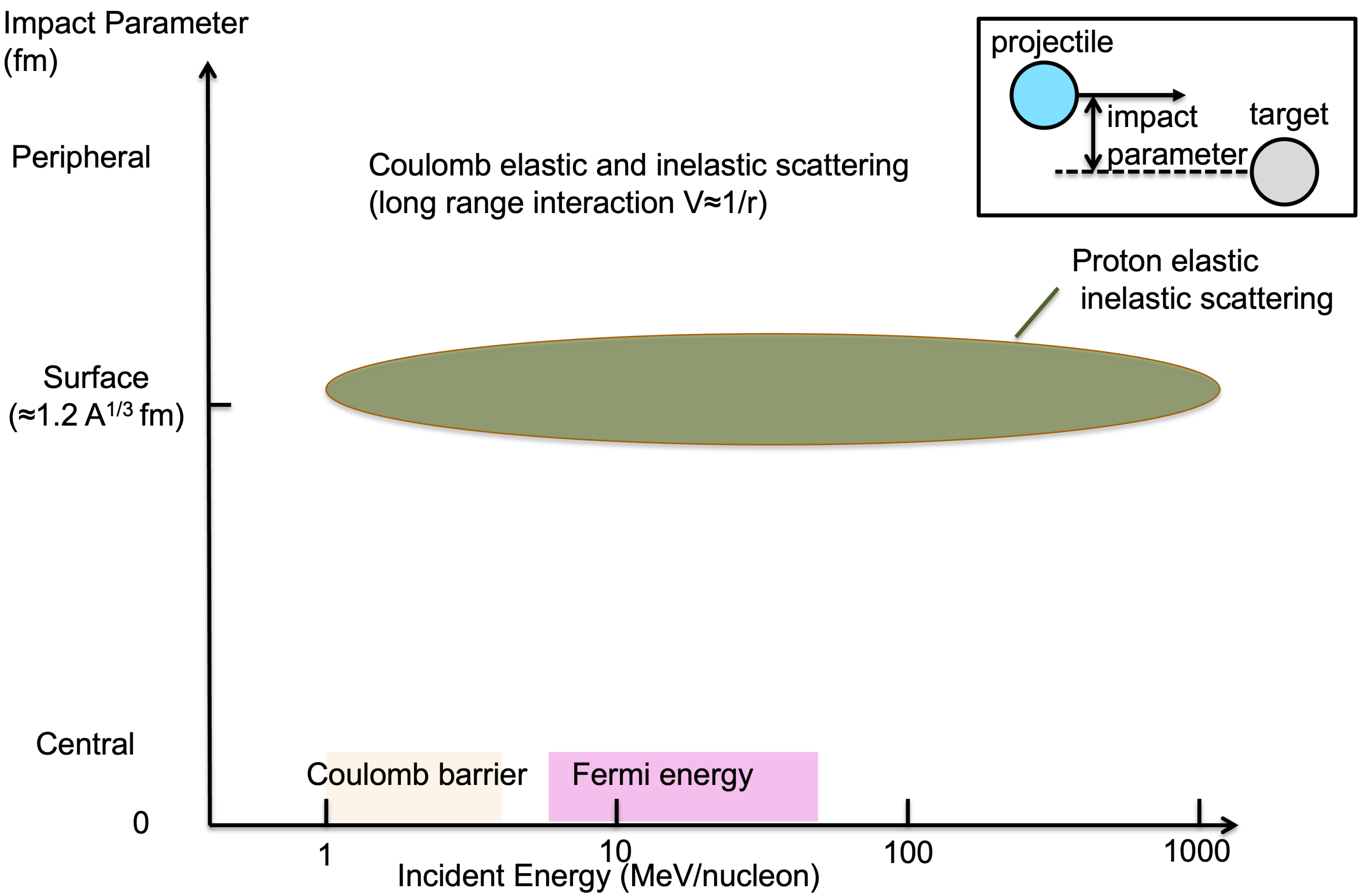
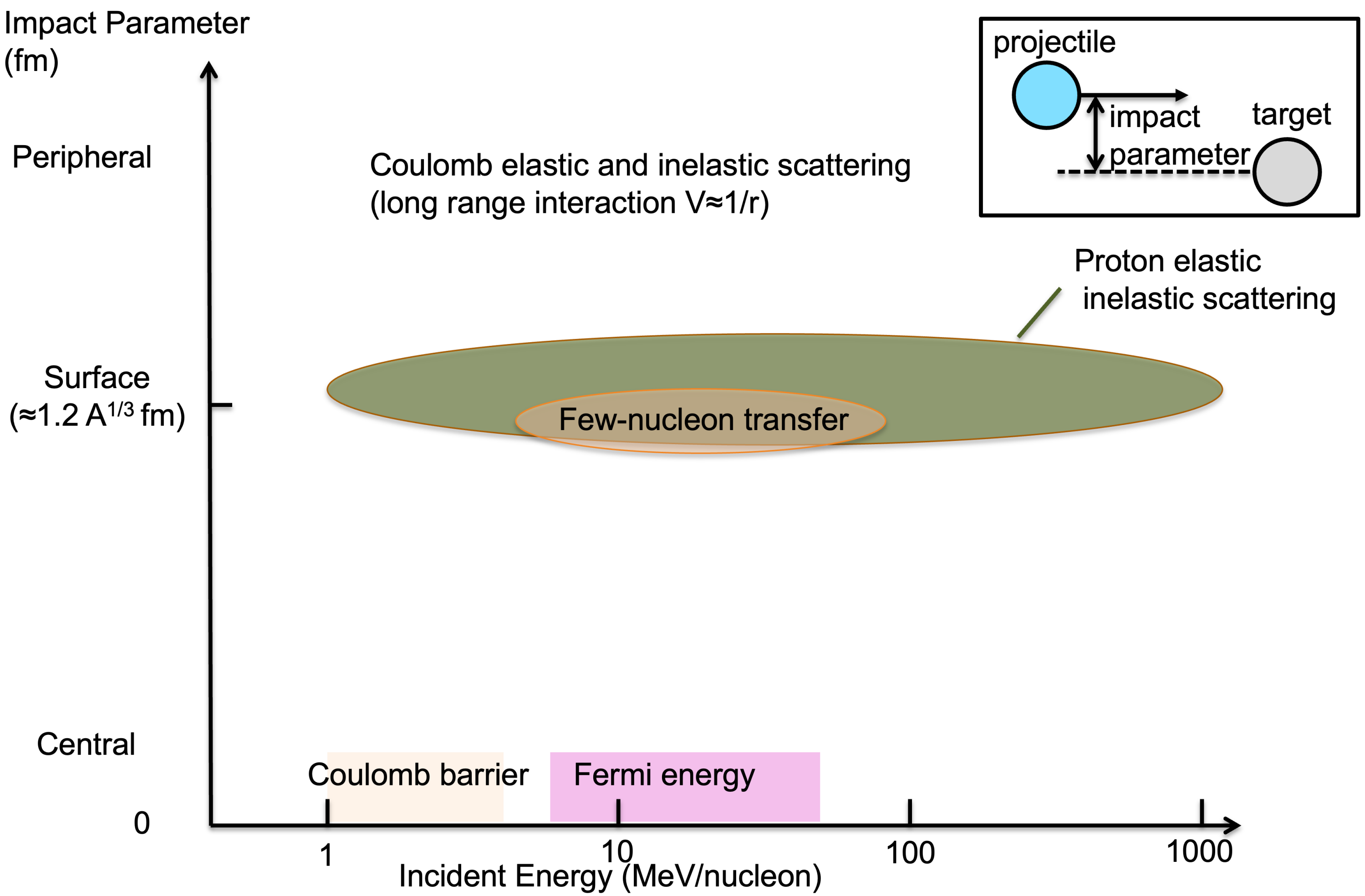
DIRECT REACTIONS



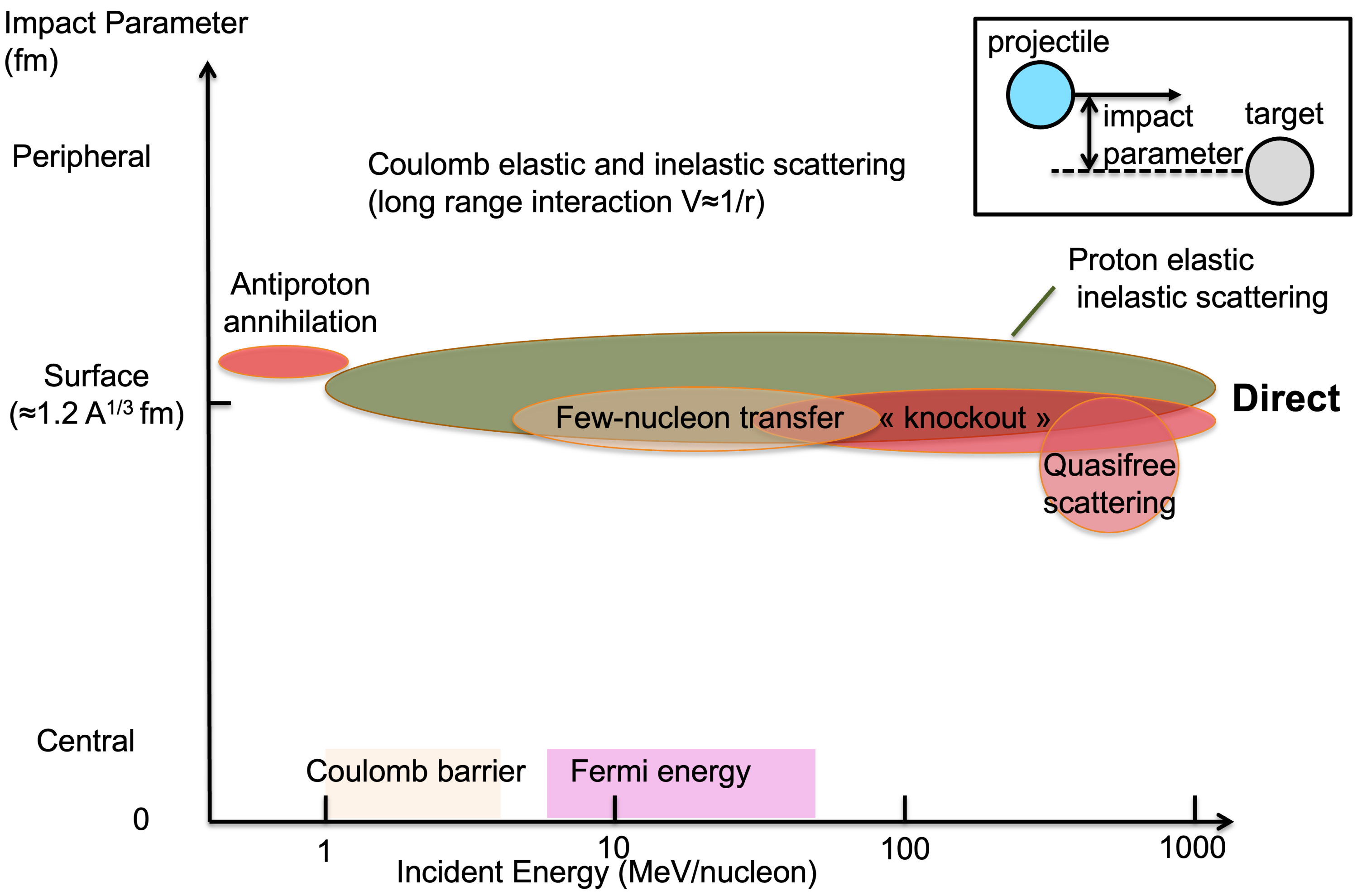
DIRECT REACTIONS



DIRECT REACTIONS



DIRECT REACTIONS



DIRECT REACTIONS

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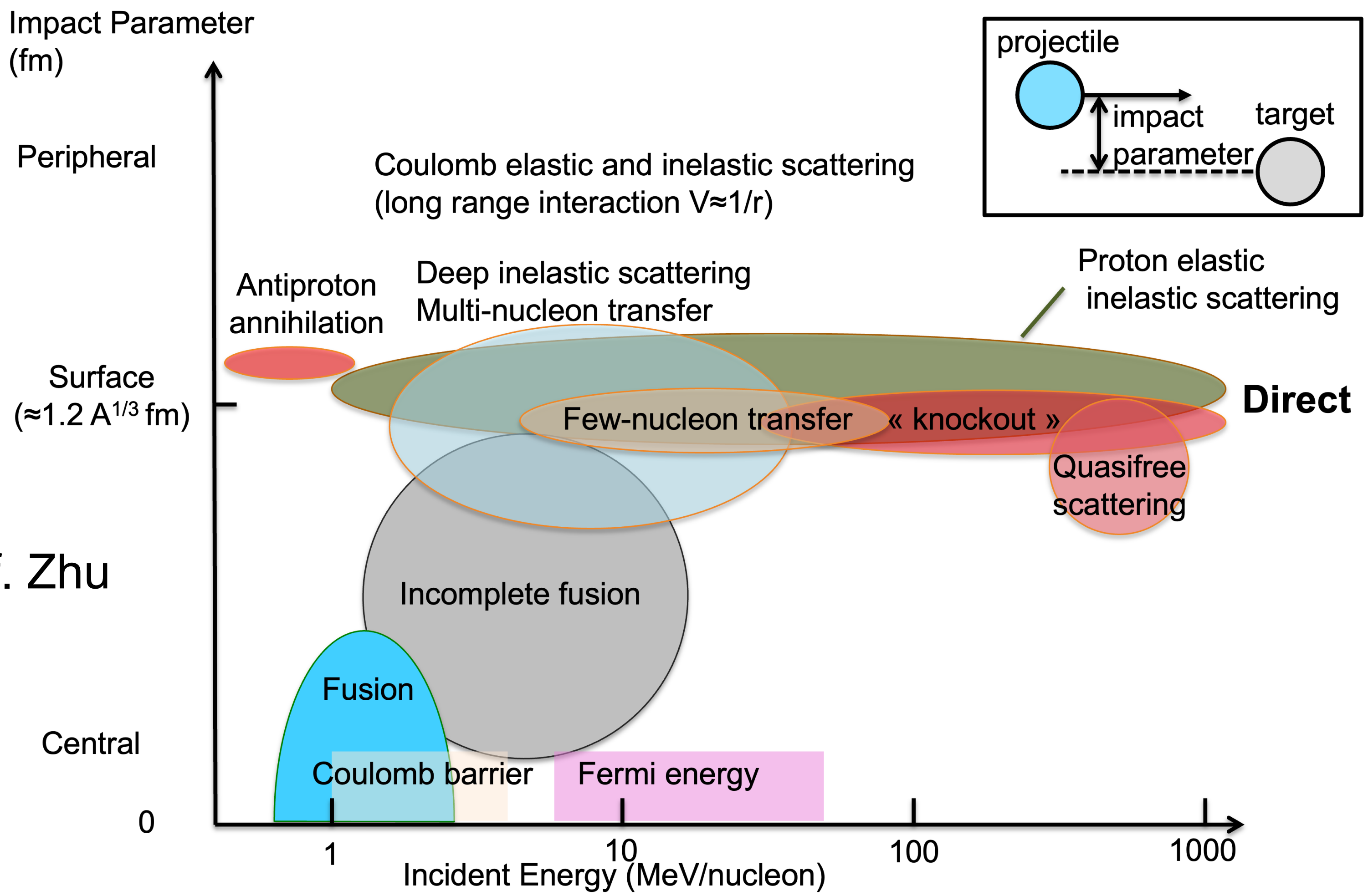
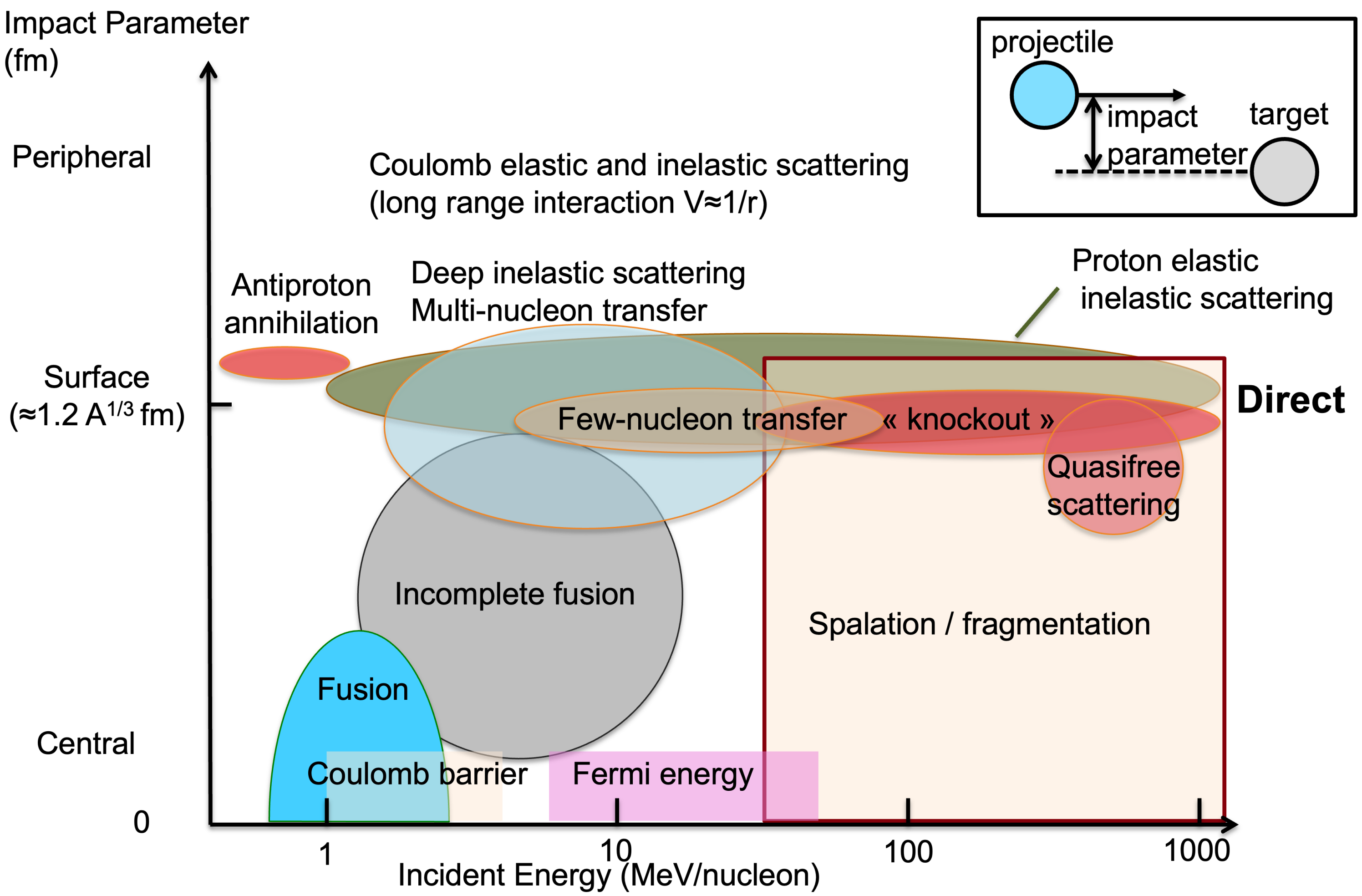
See lecture of Prof. Zhu



DIRECT REACTIONS

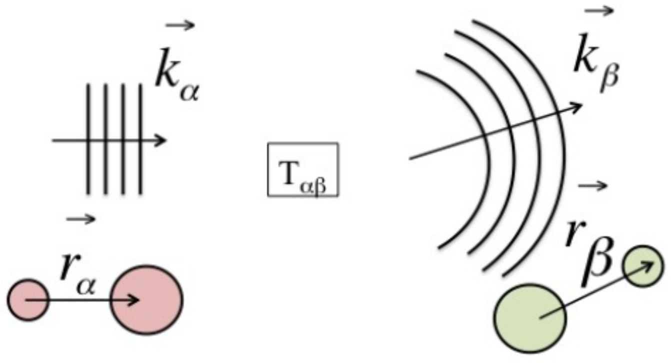


DIRECT REACTIONS

General form

$$\frac{d\sigma_{\alpha\beta}}{d\Omega} = \frac{\mu_\alpha \mu_\beta}{(2\pi\hbar^2)^2} \left(\frac{k_\beta}{k_\alpha}\right) |T_{\beta\alpha}(\overrightarrow{k_\beta}, \overrightarrow{k_\alpha})|^2$$

$T_{\alpha\beta} = \langle \beta | V | \alpha \rangle$ contains all the **structure and interaction** information



Unfortunately, T cannot be computed exactly in most of the cases

⇒ **Common approximations**

- Simplification of the wave functions (**clusters description**, **plane or distorted waves**)
- Separation of internal and relative degrees of freedom (**optical model**)
- One-step reaction mechanism (**Born approximation**) or deviations to it (**coupled channels**)

DEGREES OF FREEDOM

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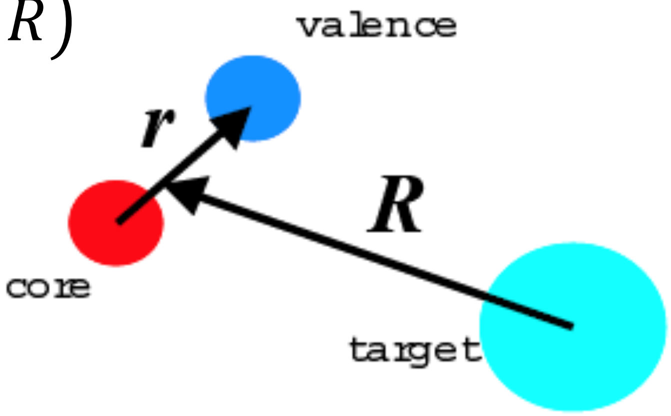
- Separation of internal and relative degrees of freedom

$$\psi\left(\{\vec{r}\},\vec{R}\right) = \Phi_P(\{\vec{r}_i\})\Phi_T(\{\vec{r}_j\})\chi(\vec{R})$$

- Schrodinger equation

$$H\left(\{\vec{r}\},\vec{R}\right)\psi\left(\{\vec{r}\},\vec{R}\right) = \mathrm{E}\,\psi\left(\{\vec{r}\},\vec{R}\right)$$
$$H\left(\{\vec{r}\},\vec{R}\right) = H_P(\{\vec{r}\}_P) + H_T(\{\vec{r}\}_T) + T\left(\vec{R}\right) + V\left(\vec{r},\vec{R}\right)$$

- **Approximations** Often the wave functions are (very) simplified
  - projectile is an inert core + a cluster (nucleon)
  - target is a one body with no internal structure



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OPTICAL MODEL

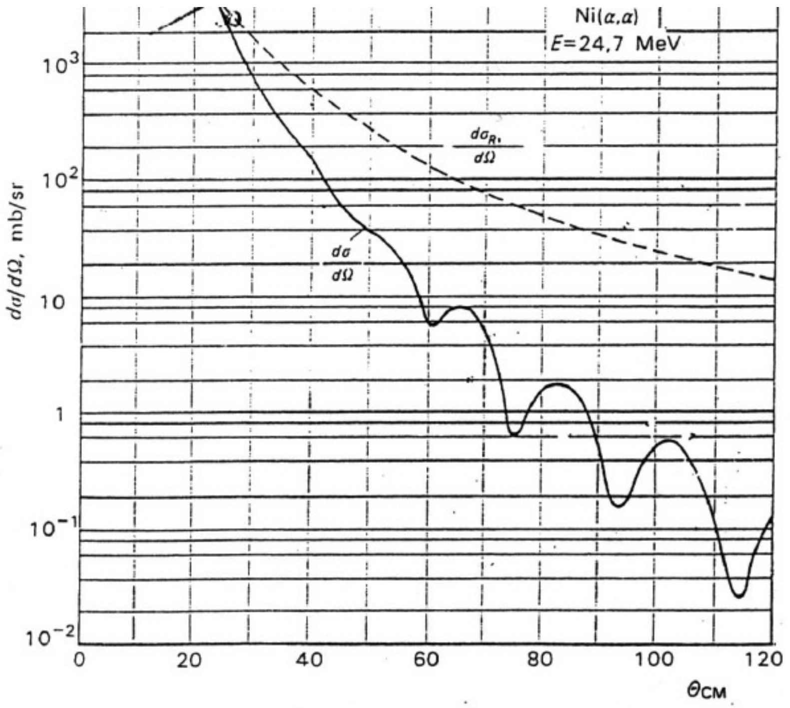
- **Approximation** The interaction potential between the projectile and the target responsible of the elastic scattering does not depend on internal degrees of freedom $\{\vec{r}\}$

$$V(\vec{r},\vec{R}) \equiv V(\vec{R})$$

- $V(\vec{R})$ is the optical (model) potential for the projectile – target **elastic scattering**

$$H(\vec{R})\,\chi(\vec{R}) = E\chi(\vec{R})$$
$$H(\vec{R}) = T(\vec{R}) + V(\vec{R})$$
$$V(\vec{R}) = V_0(\vec{R}) + i\,W(\vec{R})$$

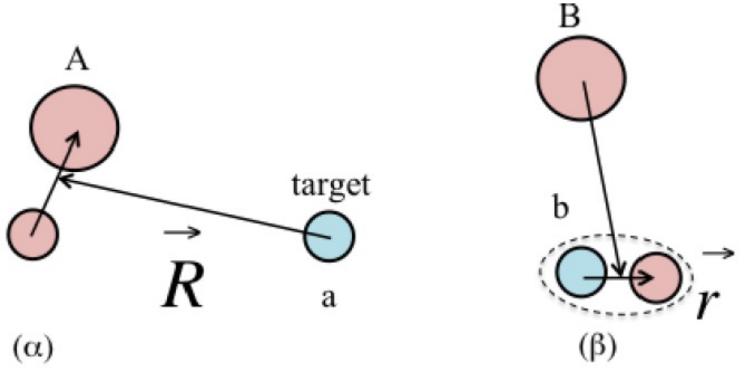
- $V(\vec{R})$ has a real and imaginary part which represents the effect of all inelastic channels not treated explicitely



BORN APPROXIMATION

- For a one nuclen transfer / knockout, we write the interaction potential U between the projectile and the target in two parts: the scattering potential that can be approximated by an optical potential V(R) and the transition potential ΔV(R,r) that will be responsible for the inelastic part (transfer, knockout) itself and considered as a **perturbation**.

$$U = V(\mathbf{R}) + \Delta V(\mathbf{R}, \mathbf{r})$$



- The homogeneous and inhomogeneous equations for the scattering problem are:

$$(T + V - E)|\chi\rangle = 0 \qquad (T + V - E)|\phi\rangle = \Delta V|\phi\rangle$$

$|\chi\rangle$: distorted wave $|\phi\rangle$: relative motion wave function

- **Approximation** First order **Distorted Wave Born Approximation (DWBA)**

$$T_{\beta\alpha} = \langle \chi_\beta \Phi_\beta | \Delta V | \chi_\alpha \Phi_\alpha \rangle$$

$|\Phi_{\alpha,\beta}\rangle$: intrinsic wave functions

PLANE WAVE BORN APPROXIMATION

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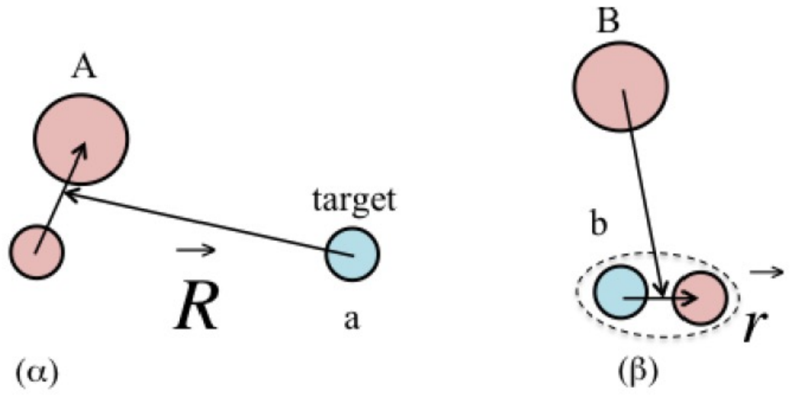
- Ex. **one neutron pickup reaction from a nucleus (*A*) by a proton (a) through the reaction (p,d)** to populate a given state in the residual nucleus *B*.



- In the **plane wave Born approximation**, the incoming and outgoing waves are treated as unperturbed by the potential (i.e. assuming **V = 0**)

$$\phi_\alpha \Phi_\alpha = e^{i\mathbf{k_p}\cdot\mathbf{r_{pA}}}\Phi_A \qquad \phi_\beta \Phi_\beta = e^{i\mathbf{k_d}\cdot\mathbf{r_d}}\Phi_B \Phi_d$$

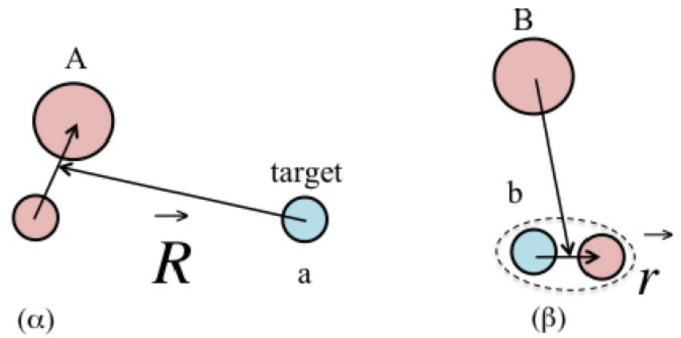
- In the case of a **pure single-particle neutron state with quantum numbers $n\ell j$, the wave function of the initial state can be written as $\Phi_A = \Phi_B \varphi_{n\ell j}(\vec{r}_n)$** and the transition matrix element is then given by

$$T_{\beta\alpha}^{n\ell j} = \int\int\int e^{-i\mathbf{k_d}\cdot\mathbf{r_d}}\Phi_d^\dagger(\mathbf{r})\Phi_B^\dagger \Delta V(\mathbf{r}) e^{i\mathbf{k_p}\cdot\mathbf{r_{pA}}}\Phi_B \phi_{n\ell j} d\mathbf{r_B} d\mathbf{r_n} d\mathbf{r_p}$$

With all vectors given in the target frame, and with $\mathbf{r} = \mathbf{r_n} - \mathbf{r_p}$

Considering that

$$\mathbf{r_d} = \frac{1}{2}(\mathbf{r_n} + \mathbf{r_p}) \qquad \boldsymbol{r}_p = \frac{A}{A+1}\mathbf{r}_n - \mathbf{r}$$



One gets

$$\mathbf{k_p} \cdot \mathbf{r_{pA}} - \mathbf{k_d} \cdot \mathbf{r_d} = -(\mathbf{k_d} - \frac{A}{A+1}\mathbf{k_p}) \cdot \mathbf{r_n} - (\mathbf{k_p} - \mathbf{k_d}) \cdot \mathbf{r}$$

By introducing $\mathbf{q} = \mathbf{k_d} - \frac{A}{A+1}\mathbf{k_p} \qquad \mathbf{K} = \mathbf{k_p} - \mathbf{k}_d$

q: momentum carried by the picked-up neutron.

One gets the following factorisation for the transition matrix element

PWBA approximation

$$T_{\beta\alpha}^{n\ell j} = \int e^{-i\mathbf{K}\cdot\mathbf{r}}\Phi_d^\dagger(\mathbf{r})\Delta U(\mathbf{r})d\mathbf{r} \times \int_{R_{cut}}^{\infty} e^{i\mathbf{q}\cdot\mathbf{r_n}}\phi_{n\ell j}(\mathbf{r_n})d\mathbf{r_n}$$

Reaction mechanism — Nuclear structure

R_{cut}: effective radius to take into account adsorption (transfer takes place at surface only)

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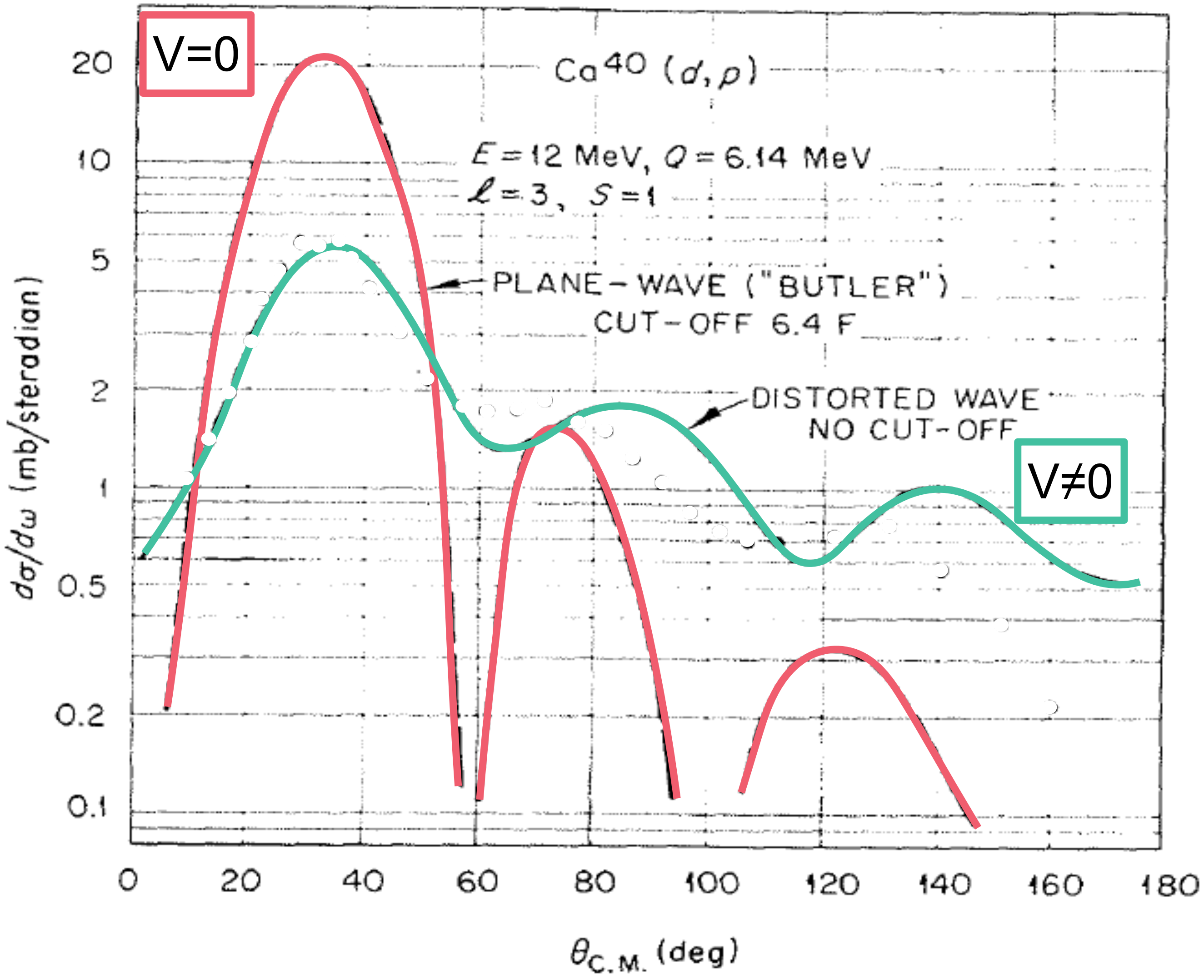
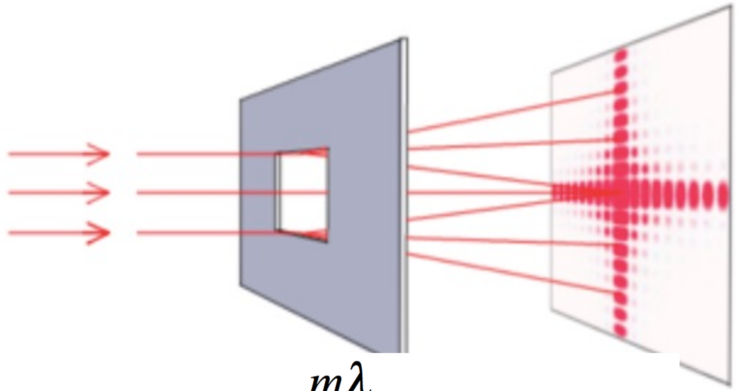
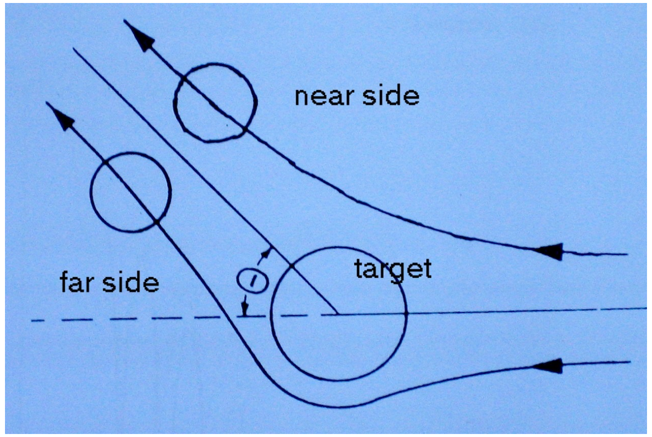


Analogy to classical diffraction
[far-field: Fraunhofer diffraction]



$$\sin\theta = \frac{m\lambda}{d}, \quad m = 1, 2, 3, -$$



TRANSFERED ANGULAR MOMENTUM

- The shape of the angular distribution pattern for a one-nucleon transfer reaction is driven by the **transferred angular momentum**.

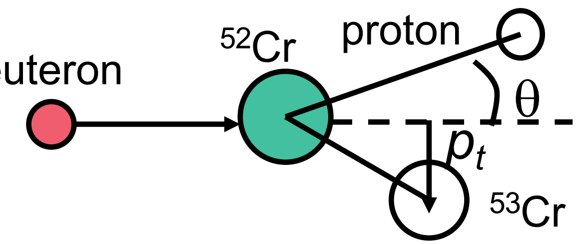
- *Example:* in a transfer from spin-zero nucleus, the transferred angular momentum is the angular momentum of the final state orbital, as in $^{52}Cr(d,p)^{53}Cr$ at 10 MeV.

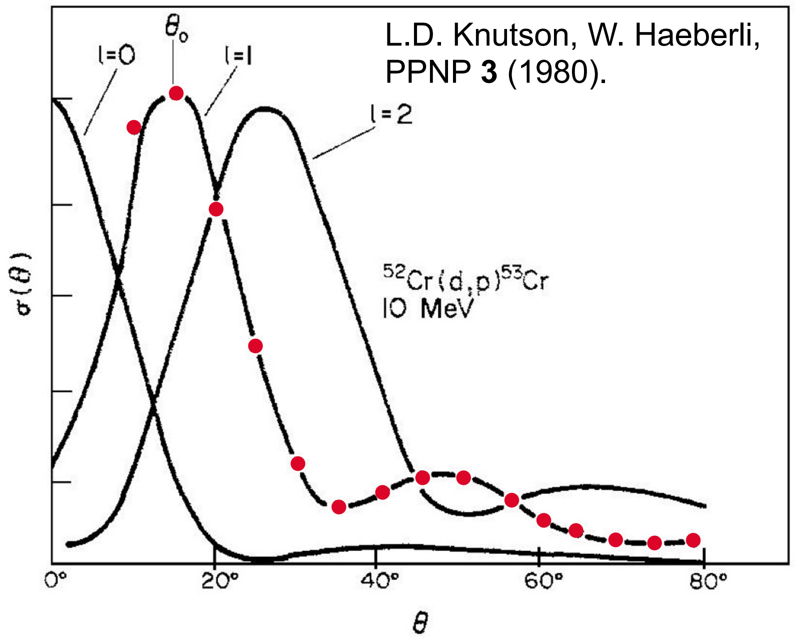
- Semi-classical approximation:

$$L = R \times p\sin(\theta) \Rightarrow \theta_{max} = \sin^{-1}(\hbar \frac{\sqrt{\ell(\ell+1)}}{Rp})$$

- Numerical application for $^{52}Cr(d,p)$ with $R=r_0A^{1/3}$:
$\ell = 0: \theta = 0, \ell = 1: \theta = 19°, \ell = 2: \theta = 34°$

Direct kinematics





L.D. Knutson, W. Haeberli, PPNP **3** (1980).

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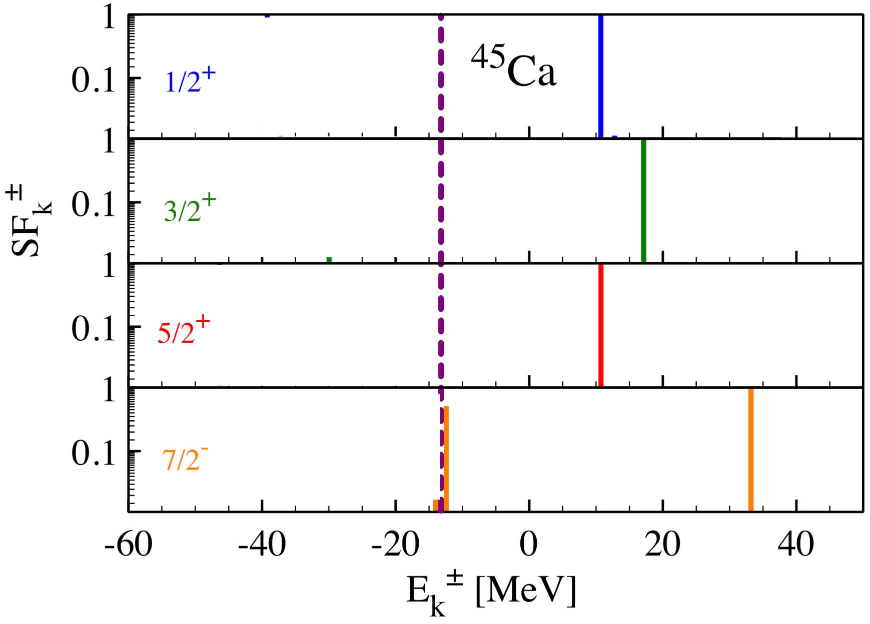
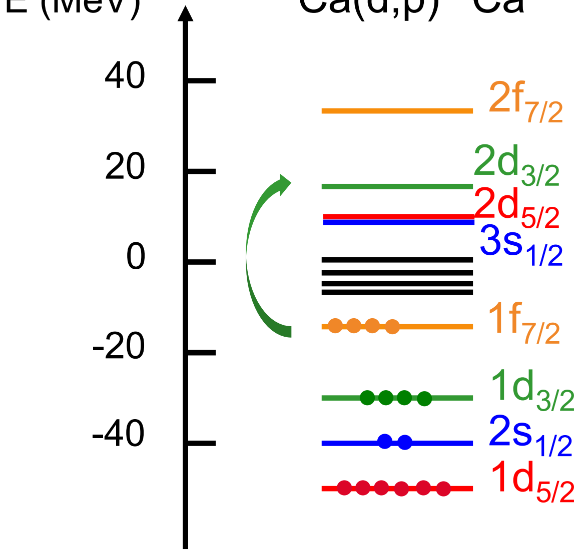
SPECTROSCOPIC FACTORS

$$S_k^{n\ell j,+} = |\langle \Psi_k^{A+1} | a_{n\ell j}^{\dagger} | \Psi_0^A \rangle|^2$$



On-neutron pickup
$^{44}Ca(d,p)^{45}Ca$



Gorkov Green's function theory calculations: V. Soma, CEA Saclay

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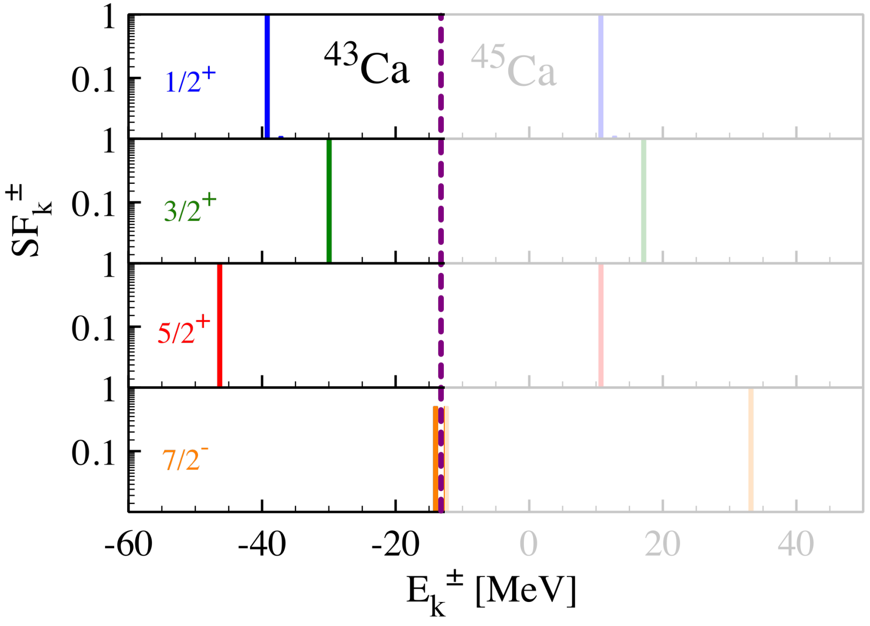
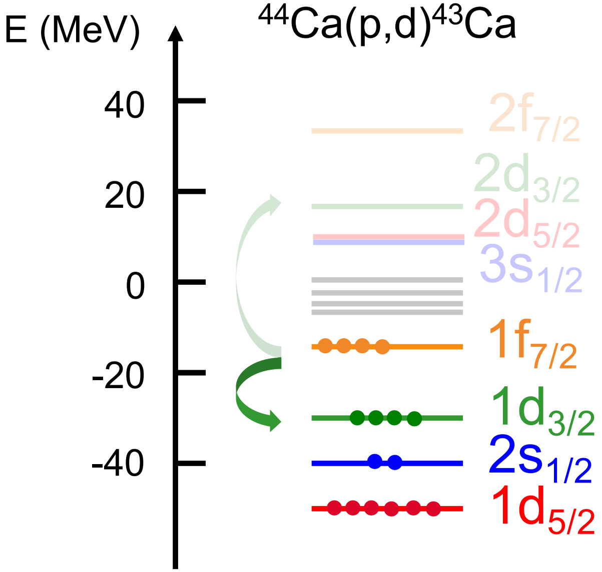
SPECTROSCOPIC FACTORS

$$S_k^{n\ell j,-} = |\langle \Psi_k^{A-1} | a_{n\ell j} | \Psi_0^A \rangle|^2$$

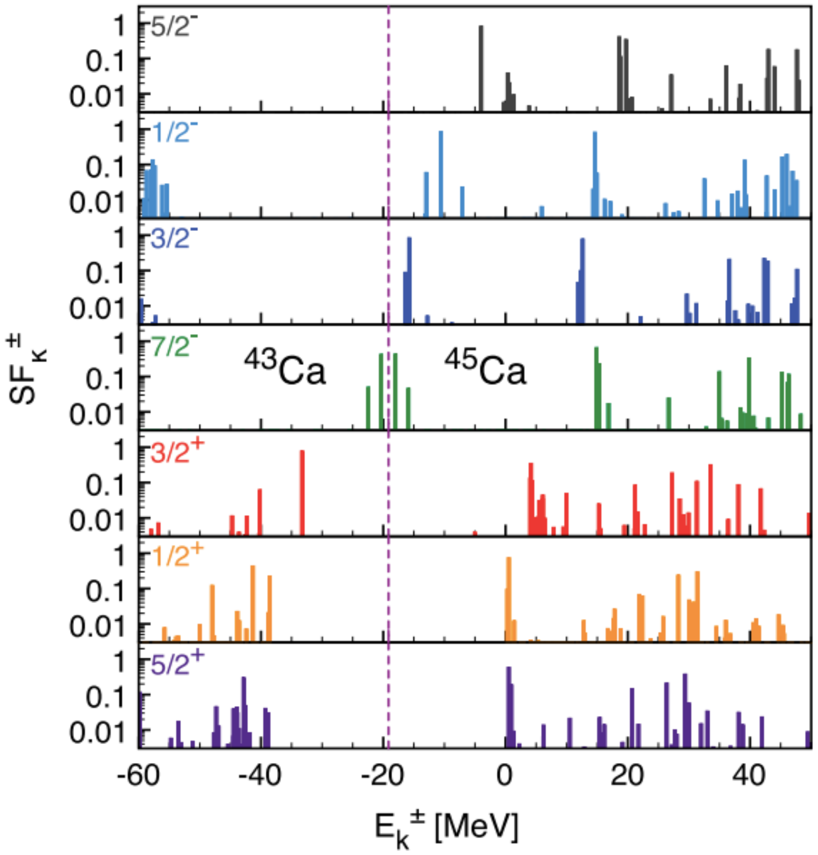


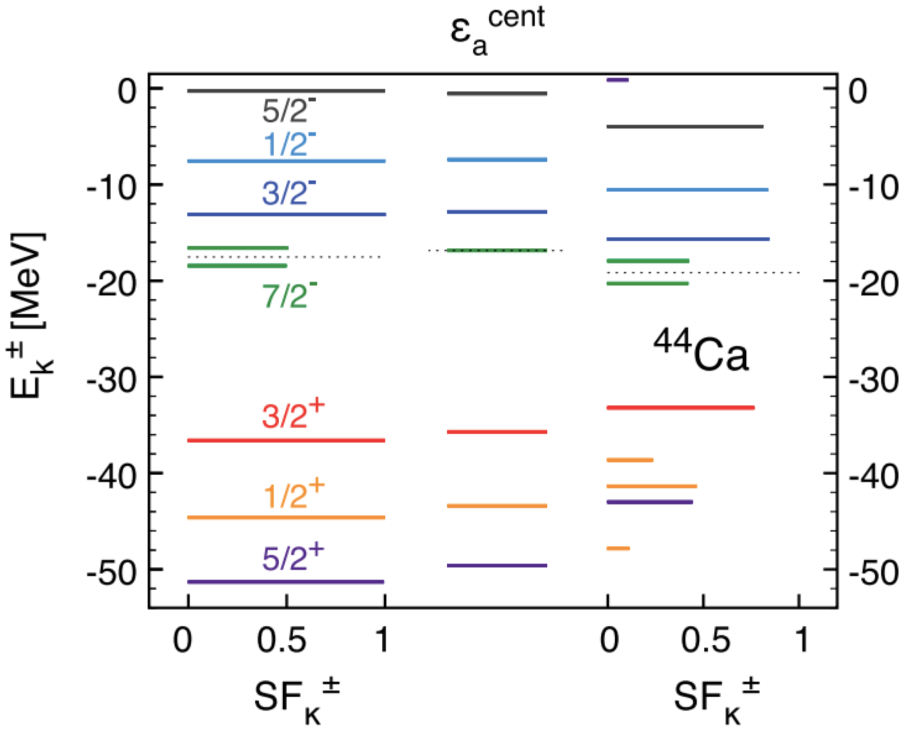
One-neutron stripping

^{44}Ca(p,d)^{43}Ca



SPECTROSCOPIC FACTORS





Soma, Barbieri, Duguet, PRC 87 (2013)

SUMMARY OF APPROXIMATIONS

$$\frac{d\sigma_{\alpha\beta}}{d\Omega} = \sum_{n\ell j} S^{n\ell j} \left(\frac{d\sigma}{d\Omega}\right)_{DWBA,n\ell j}$$

- **Wave functions** Ex. target / projectile is a structureless core + 1 nucleon
- **Optical model** The elastic scattering is driven by an optical potential which does not depend on the internal degrees of freedom of the projectile and target
- **Transition matrix** Ex. Born approx. where reaction is a perturbation to elastic scattering

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SINGLE-PARTICLE ENERGIES

(see lecture by Dr. Suzuki)

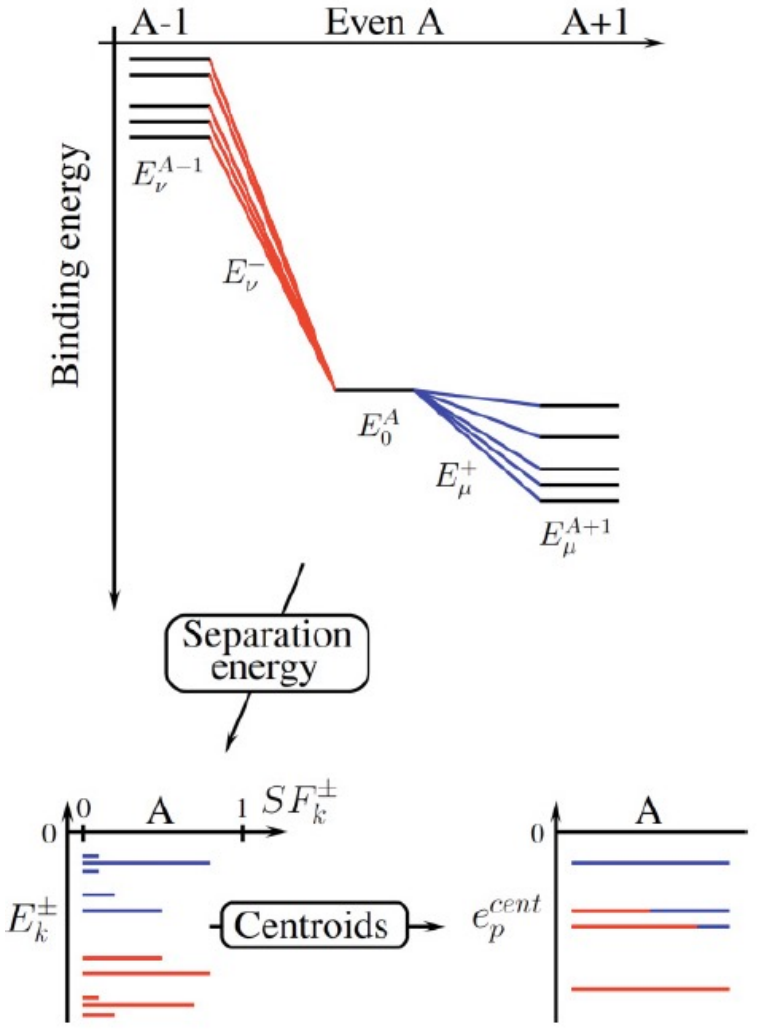
- **Spectroscopic factors** for one nucleon addition / removal:

$$S_k^{n\ell j,+} = |\langle \Psi_k^{A+1} | a_{n\ell j}^{\dagger} | \Psi_0^A \rangle|^2 \qquad S_k^{n\ell j,-} = |\langle \Psi_k^{A-1} | a_{n\ell j} | \Psi_0^A \rangle|^2$$

- Cross sections (and extraction of **spectroscopic factors**) and spectroscopy allow to access the **effective single particle energies** (ESPEs) via the Baranger relation:

$$e_{n\ell j} = \frac{\sum_k S_k^{n\ell j,+}(E_k - E_0) + S_k^{n\ell j,-}(E_0 - E_k)}{\sum_k S_k^{n\ell j} + S_k^{n\ell j}}$$

- Spectroscopic factors and ESPEs are NOT observables



AN EXAMPLE

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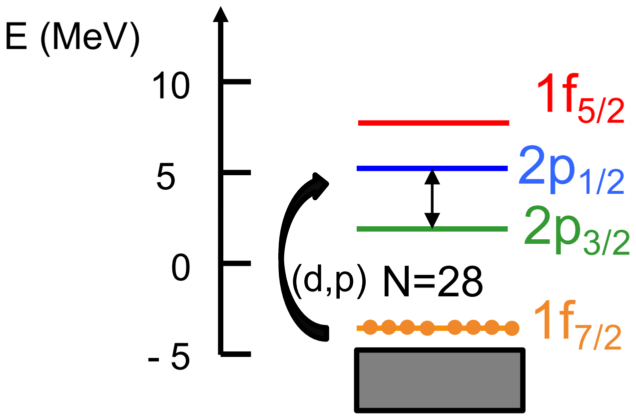
PRL 97, 092501 (2006) PHYSICAL REVIEW LETTERS week ending 1 SEPTEMBER 2006

How does the $p_{3/2}$-$p_{1/2}$ spin-orbit splitting changes from ^{48}Ca to ^{46}Ar?

$$\delta\Delta E_{p_{3/2}-p_{1/2}} = [e^{p_{1/2}}(^{46}Ar) - e^{p_{3/2}}(^{46}Ar)] - [e^{p_{1/2}}(^{48}Ca) - e^{p_{3/2}}(^{48}Ca)]$$



AN EXAMPLE

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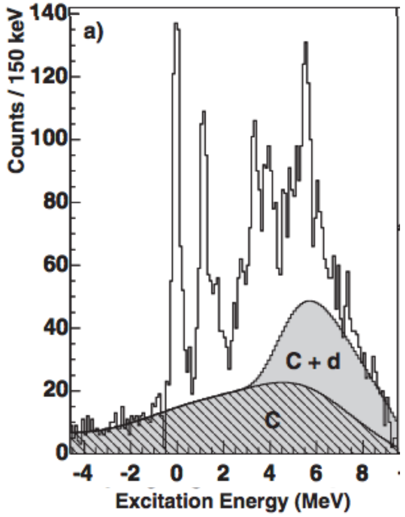
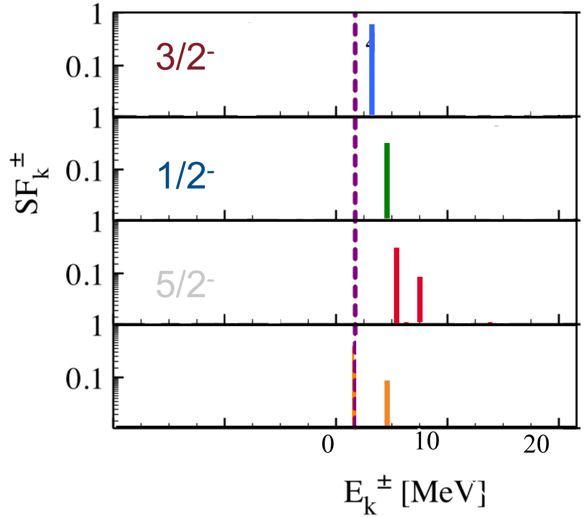
PRL 97, 092501 (2006) PHYSICAL REVIEW LETTERS week ending 1 SEPTEMBER 2006

Reduction of the Spin-Orbit Splittings at the $N = 28$ Shell Closure

- **^{46}Ar(d,p)^{47}Ar at 10 MeV/nucleon**
- ^{46}Ar: two proton less than ^{48}Ca
- Objective: spin-orbit splitting between the two neutron orbitals $2p_{1/2}$ and $2p_{3/2}$



Experiment			Shell model		
E^*	ℓ	$(2J+1)C^2S$	E^*	J^π	$(2J+1)C^2S$
0	1	2.44(20)	0	$3/2^-$	2.56
1130(75)	1	1.62(12)	1251	$1/2^-$	1.62
1740(95)	3	1.36(16)	1365	$7/2^-$	0.8
2655(80)	3,(4)	1.32(18)	2684	$5/2^-$	0.78
3335(80)	3,(4)	2.58(18)	3266	$5/2^-$	2.76
3985(85)	4,(3)	3.40(40)	...	...	...
4790(95)	...	...	...	...	...
5500(85)	4	2.10(10)	...	...	...
6200(100)	...	...	...	...	...



$$\delta\Delta E_{p_{3/2}-p_{1/2}} = \Delta E_{p_{3/2}-p_{1/2}}(^{47}\mathrm{Ar}) - \Delta E_{p_{3/2}-p_{1/2}}(^{49}\mathrm{Ca}) = 1130(75) - 2023 = -893(75)\ \mathrm{keV}$$

PRL 99, 099201 (2007) PHYSICAL REVIEW LETTERS week ending 31 AUGUST 2007

Comment on "Reduction of the Spin-Orbit Splittings at the $N = 28$ Shell Closure"

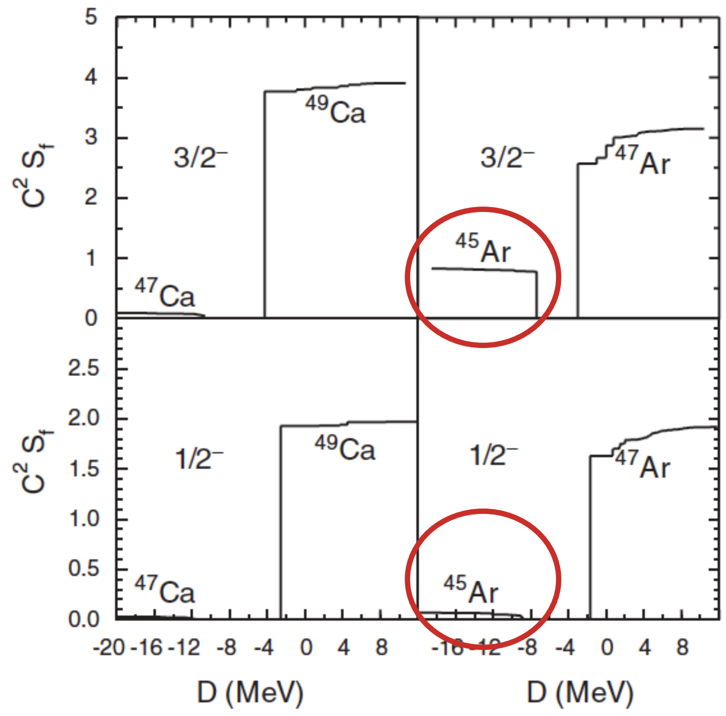
- The initial analysis did not take into account the 3/2- strength from neutron removal, and led to an under-estimate of the $p_{1/2}$ - $p_{3/2}$ spin-orbit splitting

was missing

$$e_{n\ell j} = \frac{\sum_k S_k^{n\ell j,+}(E_k - E_0) + S_k^{n\ell j,-}(E_0 - E_k)}{\sum_k S_k^{n\ell j} + S_k^{n\ell j}}$$

- With correction from full strength from the shell model (could be measured via «(d,t)^{45}Ar »):

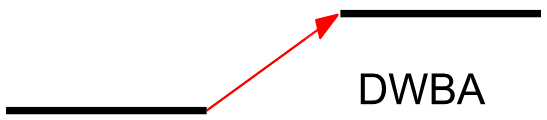
$$\delta\Delta E_{p_{3/2}-p_{1/2}} = +0.09(13)\ \mathrm{keV}$$ No spin-orbit reduction!



MODELS

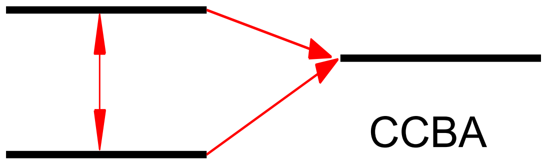
There are four main reaction models :

- The Distorted Wave Born Approximation (DWBA): simplest useful model, assumes a weak one-step process that is treated by perturbation theory.

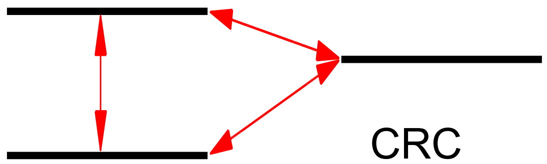


- The adiabatic model: a modification of DWBA for (d,p), (p,d) reactions that takes deuteron breakup effects into account in an approximate way.

- The Coupled Channels Born Approximation (CCBA): used when the DWBA breaks down; strong inelastic excitations modelled with coupled channels theory, transfers still with DWBA.
  Ex. Continuum Discretized Coupled Channel (CDCC) for deuteron breakup



- Coupled Reaction Channels (CRC): does not assume one-step transfer process. All processes on equal footing; rearrangements of flux possible.



COMPUTER CODES

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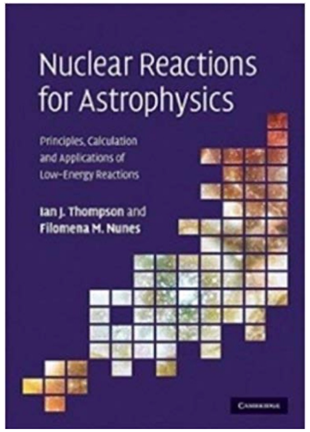
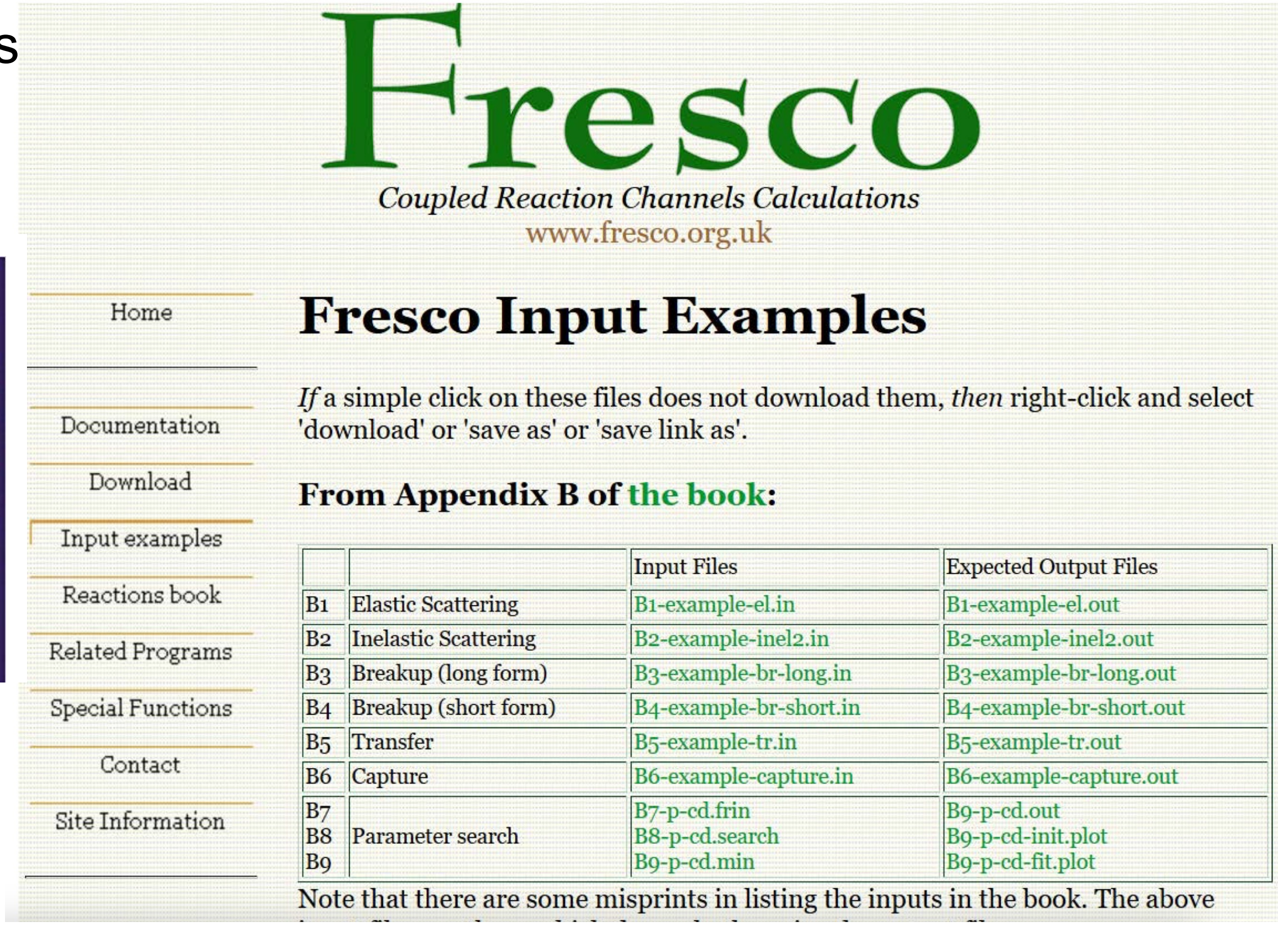
FRESCO developped by I. Thompson, Surrey, is an open source software for transfer and (in)elastic reactions

- DWBA, CCBA, CRC
- Non relativistic
- Widely used in the community
- Details in book:
- www.fresco.org.uk



Other codes exist and are accessible: DWUCK (old), ECIS (Dirac equations, relativistic) for DWBA.



Fresco

Coupled Reaction Channels Calculations

www.fresco.org.uk

Home

Documentation

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Input examples

Reactions book

Related Programs

Special Functions

Contact

Site Information

Fresco Input Examples

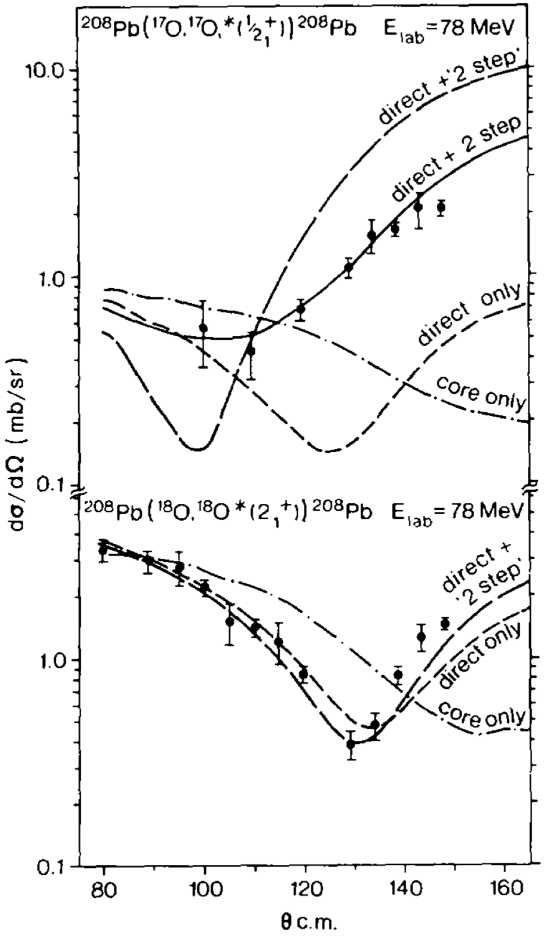
If a simple click on these files does not download them, *then* right-click and select 'download' or 'save as' or 'save link as'.

From Appendix B of the book:

		Input Files	Expected Output Files
B1	Elastic Scattering	B1-example-el.in	B1-example-el.out
B2	Inelastic Scattering	B2-example-inel2.in	B2-example-inel2.out
B3	Breakup (long form)	B3-example-br-long.in	B3-example-br-long.out
B4	Breakup (short form)	B4-example-br-short.in	B4-example-br-short.out
B5	Transfer	B5-example-tr.in	B5-example-tr.out
B6	Capture	B6-example-capture.in	B6-example-capture.out
B7 B8 B9	Parameter search	B7-p-cd.frin B8-p-cd.search B9-p-cd.min	B9-p-cd.out B9-p-cd-init.plot B9-p-cd-fit.plot

Note that there are some misprints in listing the inputs in the book. The above

CRC: HISTORICAL EXAMPLE



- Two step contribution to the ^{17}O inelastic excitation
- $^{17}O+^{208}Pb$ at 4.6 MeV/nucleon
- CRC analysis compared to DWBA

- Lilley et al., PLB 128 (1983)
- Lilley et al., NPA 463 (1987)

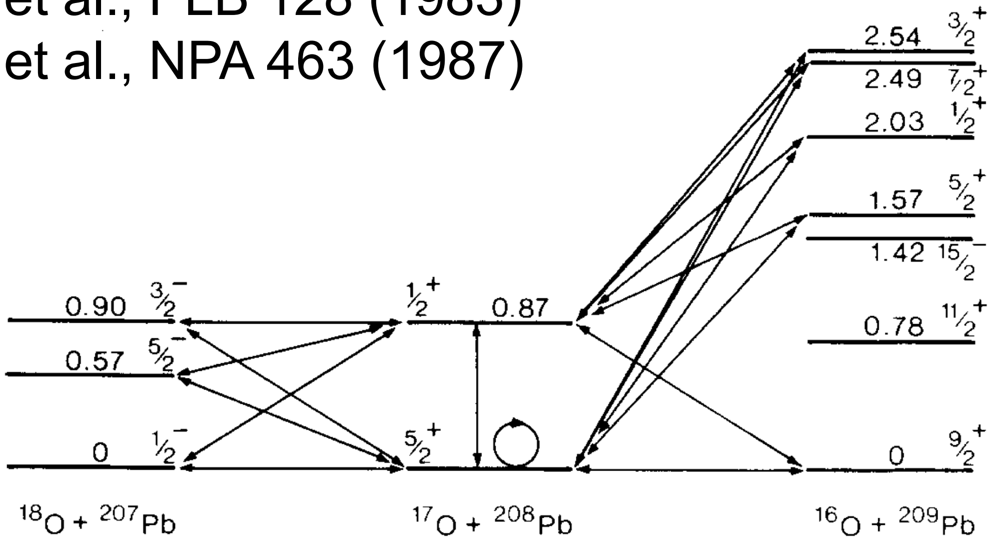
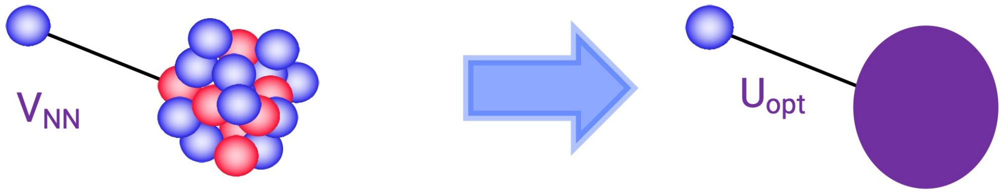


Fig. 6. Channel couplings used in the multistep CRC calculations of the ^{17}O–^{208}Pb interaction at 78 MeV.

OPTICAL POTENTIAL

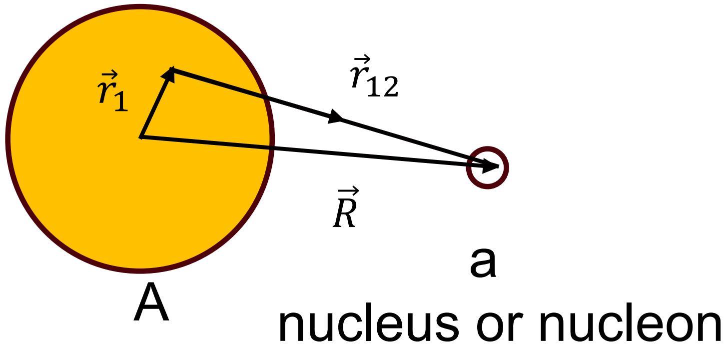


- The optical potential is the projection of the many-body scattering problem onto the ground state

$$P\,\psi\left(\vec{R};\vec{r}_1,\ldots,\vec{r}_A\right)=\chi(\vec{R})\Phi(\vec{r}_1,\ldots,\vec{r}_A)$$

- $V\left(\vec{R}\right)=V_0\left(\vec{R}\right)+i\,W(\vec{R})$

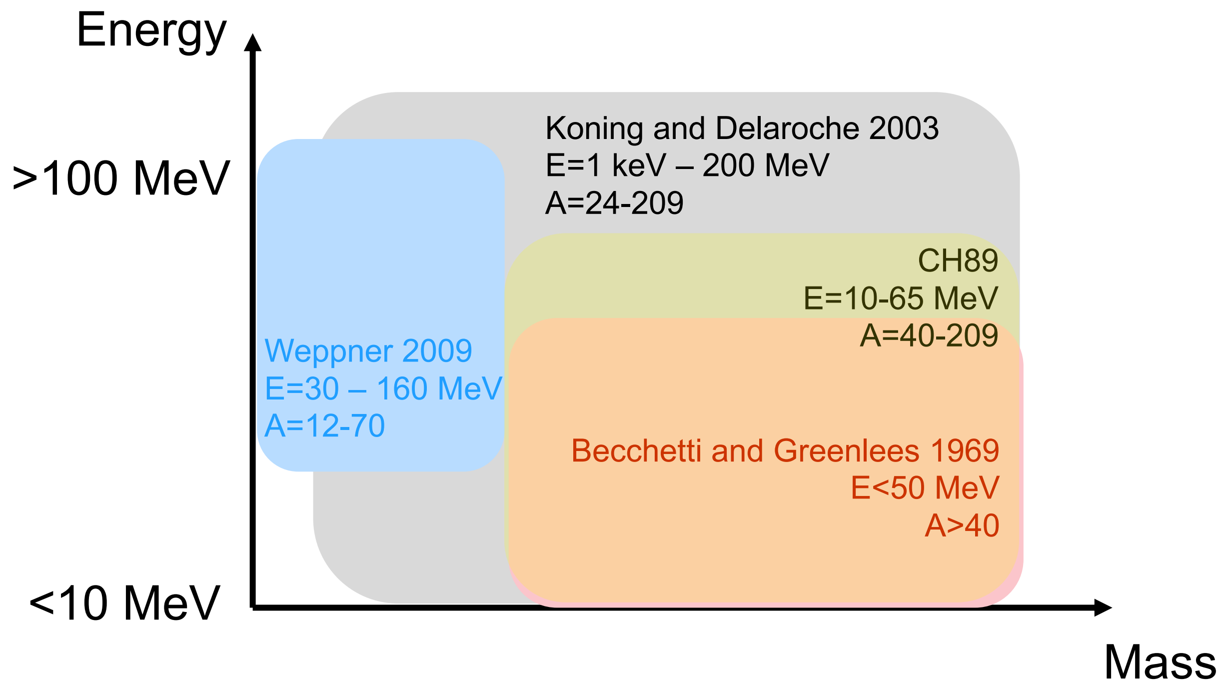
- Optical potentials can be obtained
  - from data (phenomenological),
  - semi-microscopic (folding),
  - ab initio

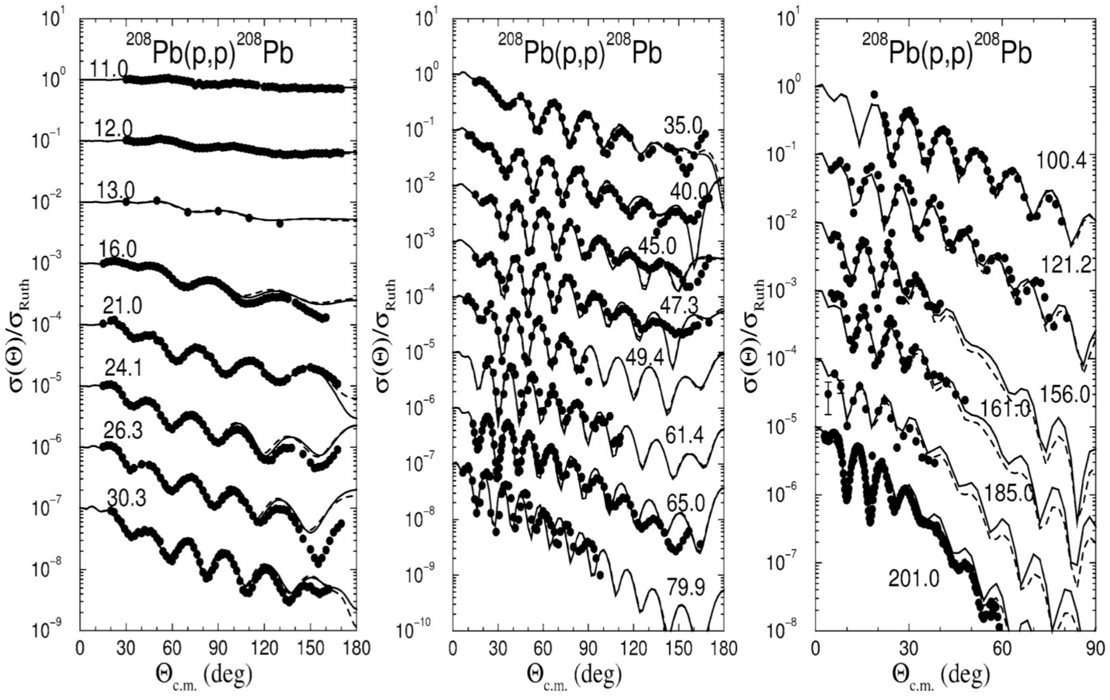


Single folding: $V\left(\vec{R}\right)=\int\rho_A(\vec{r}_1)v(\vec{r}_{12})d^3r_{12}$

OPTICAL POTENTIALS FROM DATA

- Fit on a large set of elastic scattering data
- Extract global nucleon-nucleus optical potential (inputs are A,Z,E), also d,^{3}He,…-nucleus OP exist
- Usually local, L-independent, E-dependent

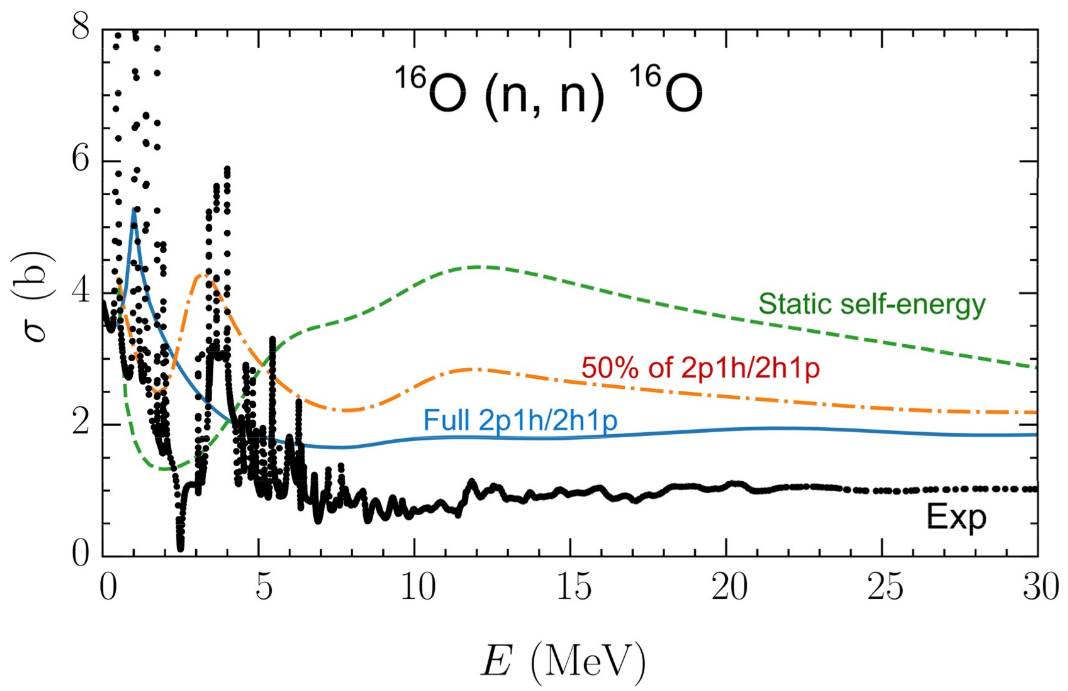




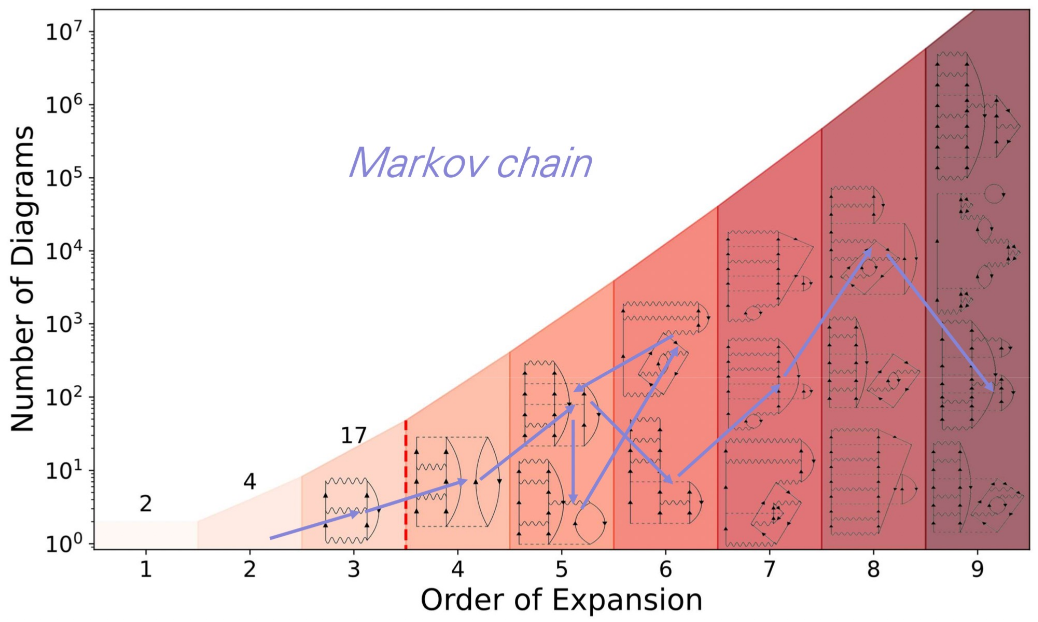
Koning and Delaroche, NPA 713 (2003)

EXAMPLE OF AB INITIO EFFORTS

- A consistent treatment of reaction and theory remains the goal, but not yet reached
- Ab initio derived optical potentials miss so far absorption (imaginary part W too weak)
- Green’s function promising method
- Ongoing efforts to improve description from Diagrammatic Markov Chain



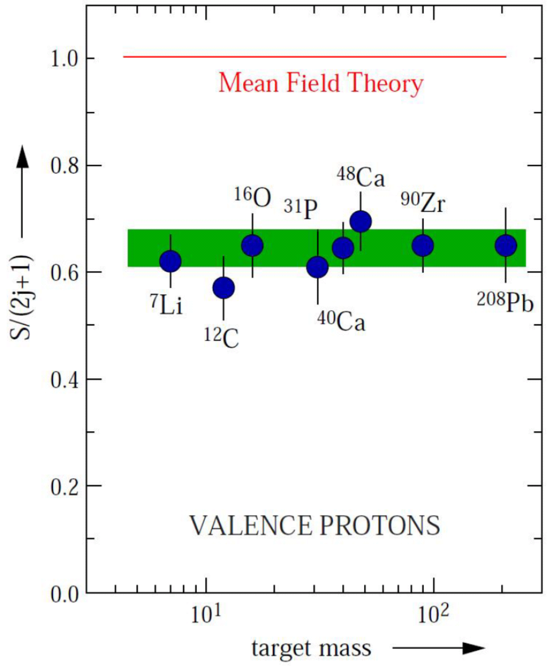
Idini et al., PRL 123 (2019)



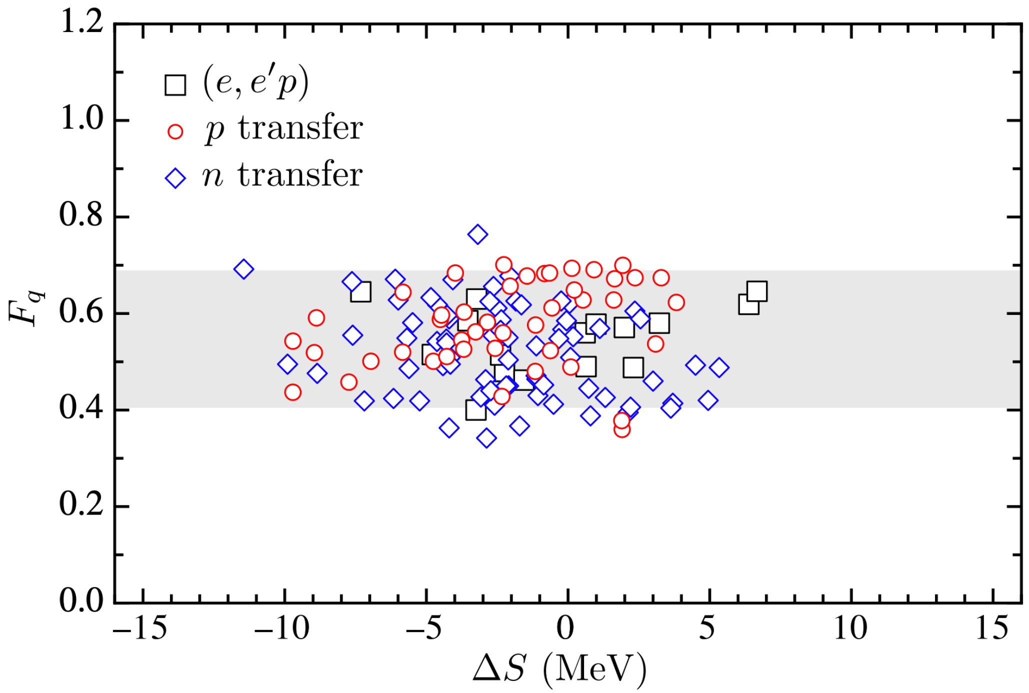
From S. Brolli, Milano University

SINGLE-PARTICLE STRENGTH

- Shell model misses correlations: SRCs (15%), coupling to high-lying excitations (10%)
- Consistent results among several transfer reactions can be reached
- The main uncertainties comes from the optical potential U(R)
- A reaction model uncertainty of 20 % is typically considered for single particle cross sections



L. Lapikas, NPA 553 (1993)



B. P. Kay et al., PRL 111 (2013)

MISSING MASS METHOD

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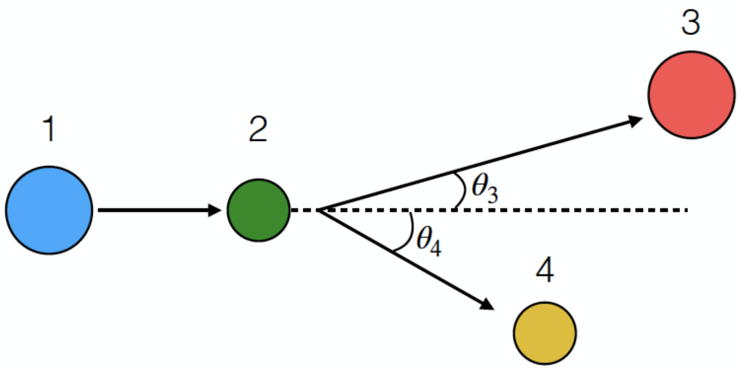

- **Two-body kinematics:** all information about the residue (4) can be obtained by measuring the momentum p3 and using the known mass m_3 of the second outgoing particle (3).
- The **excitation energy E^*_4** of particle (4) is given by:

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

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

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

$$E_4 = T_1 + m_1 + m_2 - (T_3 + m_3) \quad \text{(EC)}$$

$$p_4^2 = p_1^2 + p_3^2 - 2p_1p_3\cos(\theta_3) \quad \text{(MC)}$$

T_1,m_1,m_2,m_3 are known, T3 and θ_3 are measured.

E_4 and p_4 and E^*_4 can be calculated. The method can be extended to more than 2 particles.

TRANSFER IN INVERSE KINEMATICS

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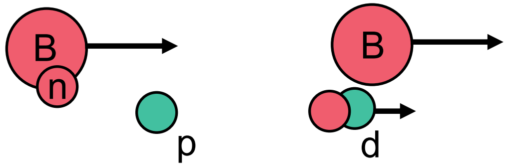
- Momentum conservation implies a **strong constrain on the kinematics of transfer reactions.**

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

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 :

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

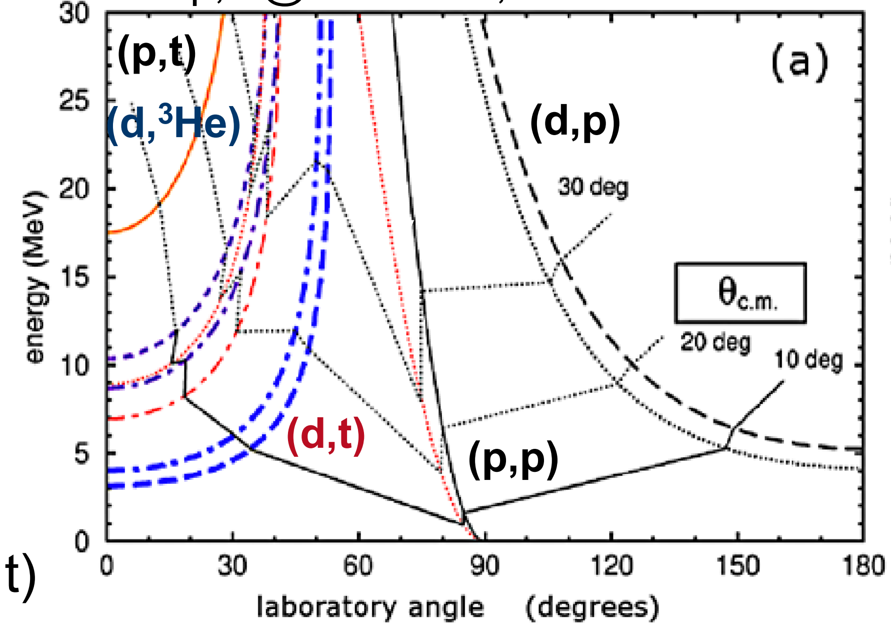
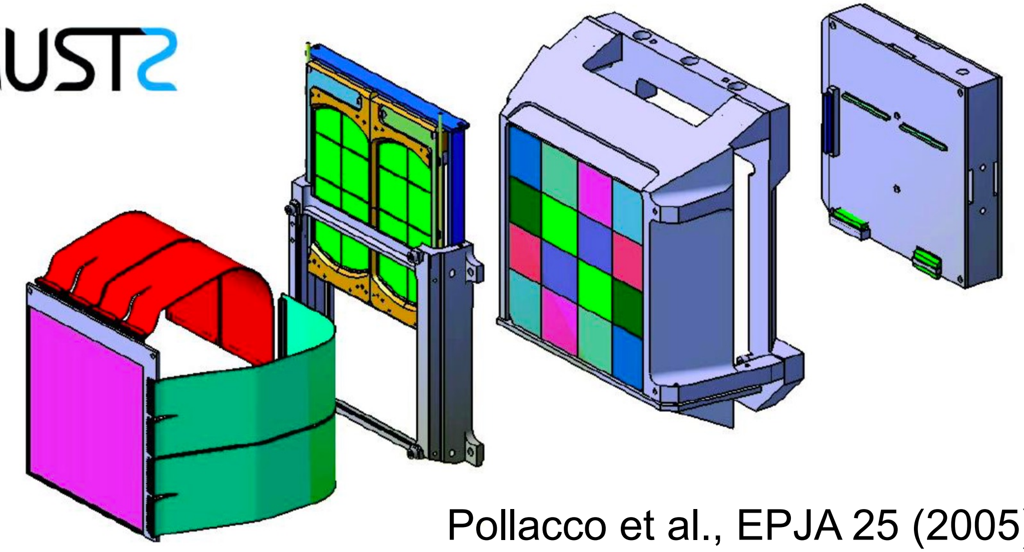


Figure adapted from W. Catford, Lecture

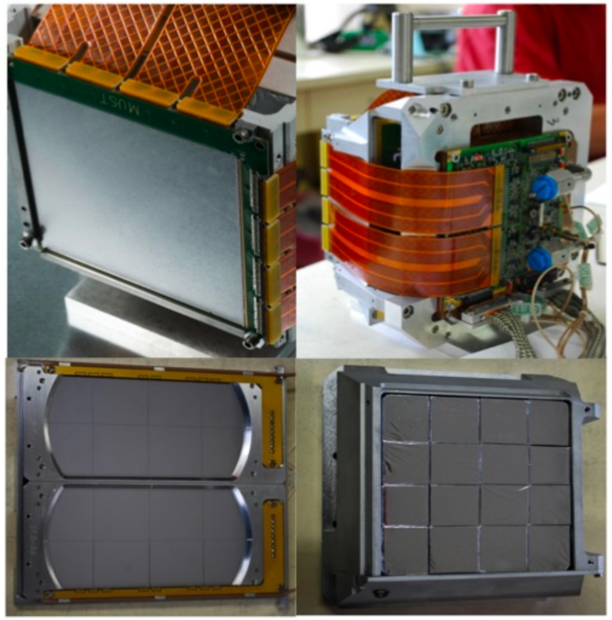
- one nucleon **stripping at forward angles**: (p,d), (d,^{3}He), (d,t), (p,t)
- nucleon **pickup at backward angles**: (d,p), (t,p)
- **Elastic scattering around 90 degrees**: (p,p), (d,d)

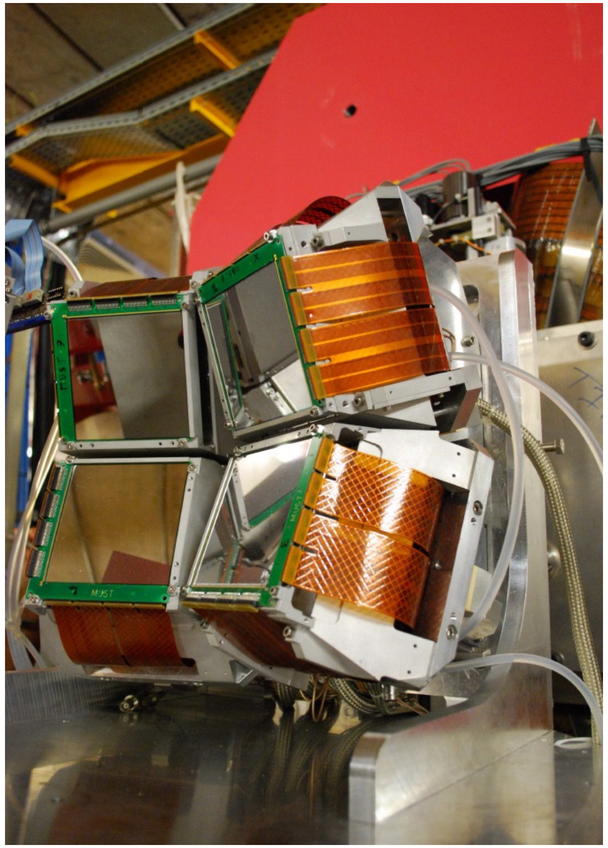
MUST2 CHARGED-PARTICLE DETECTOR

- 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



Pollacco et al., EPJA 25 (2005)



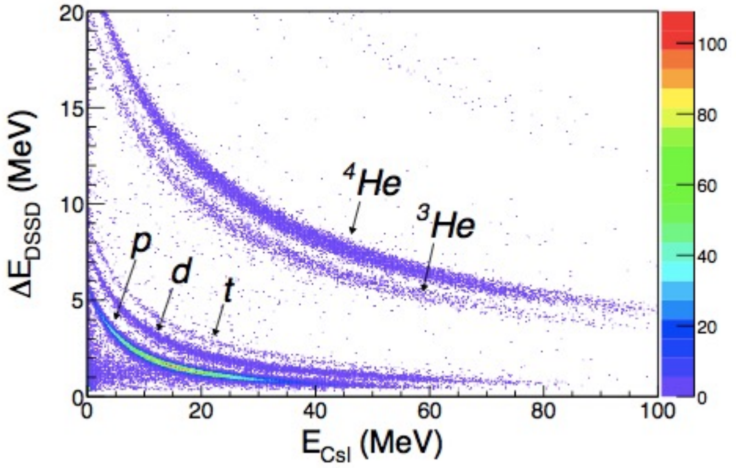


PARTICLE IDENTIFICATION (PID)

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

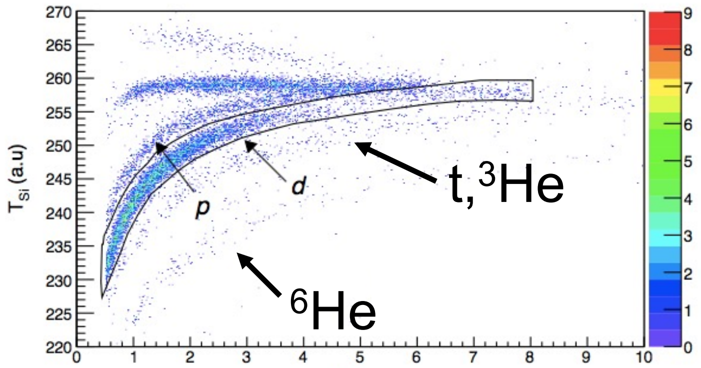
$$-\left\langle\frac{dE}{dx}\right\rangle \propto \frac{\rho Z q^2}{M\beta^2}\left[\ln\left(\frac{2m_e c^2\gamma^2\beta^2}{I}\right)-\beta^2-\text{corrections}\right]$$

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



- 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

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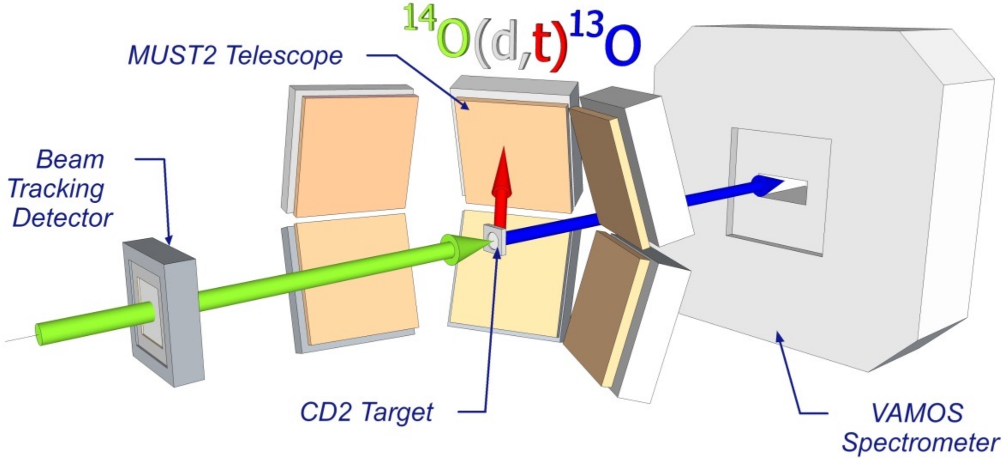
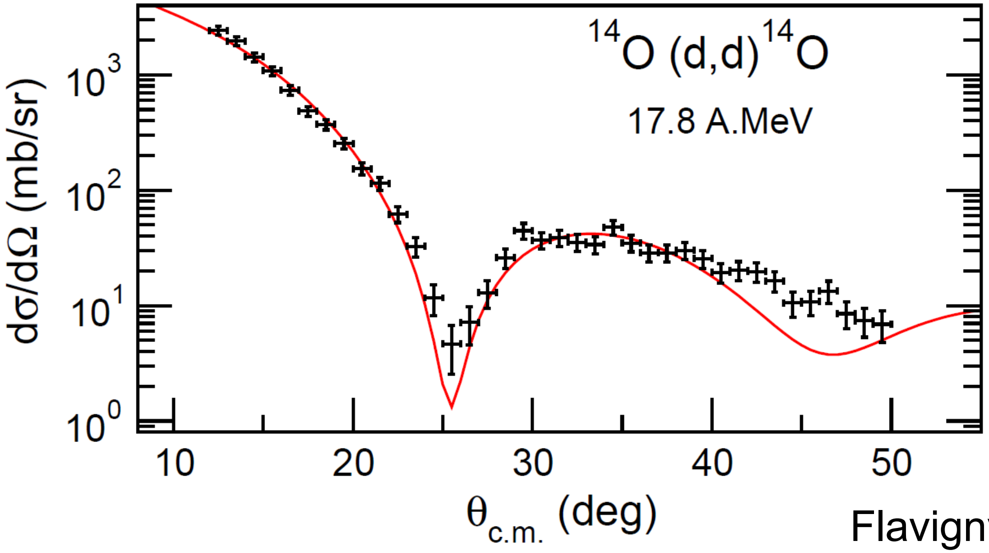
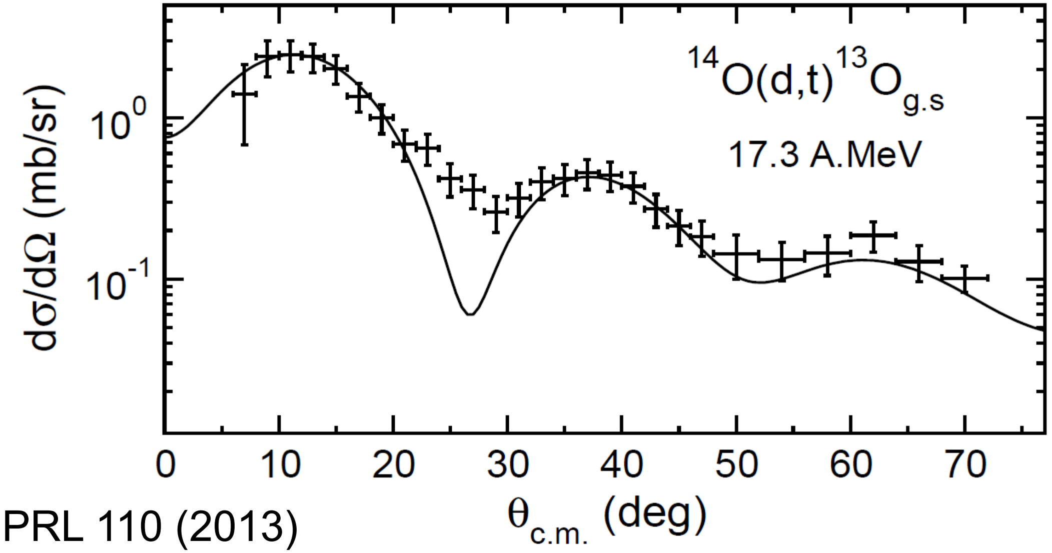
- ^{14}O pure beam, 18 MeV/n, 5. 10^4 pps, SPIRAL (GANIL)
- Target: CD_2
- Reactions: (d,d), (d,^{3}H) and (d,^{3}He) MUST2 array
- VAMOS spectrometer for recoil identification

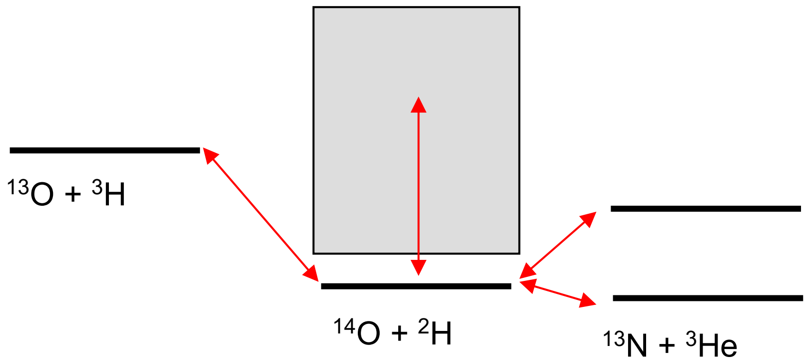


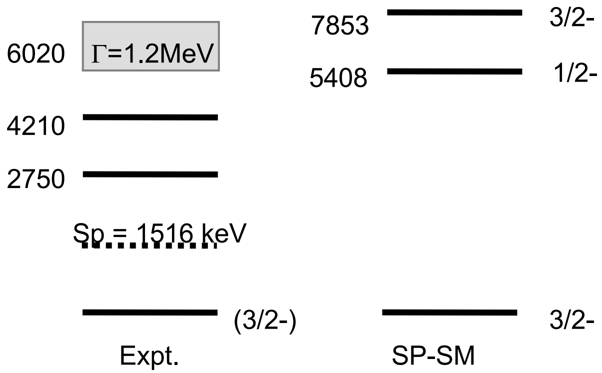




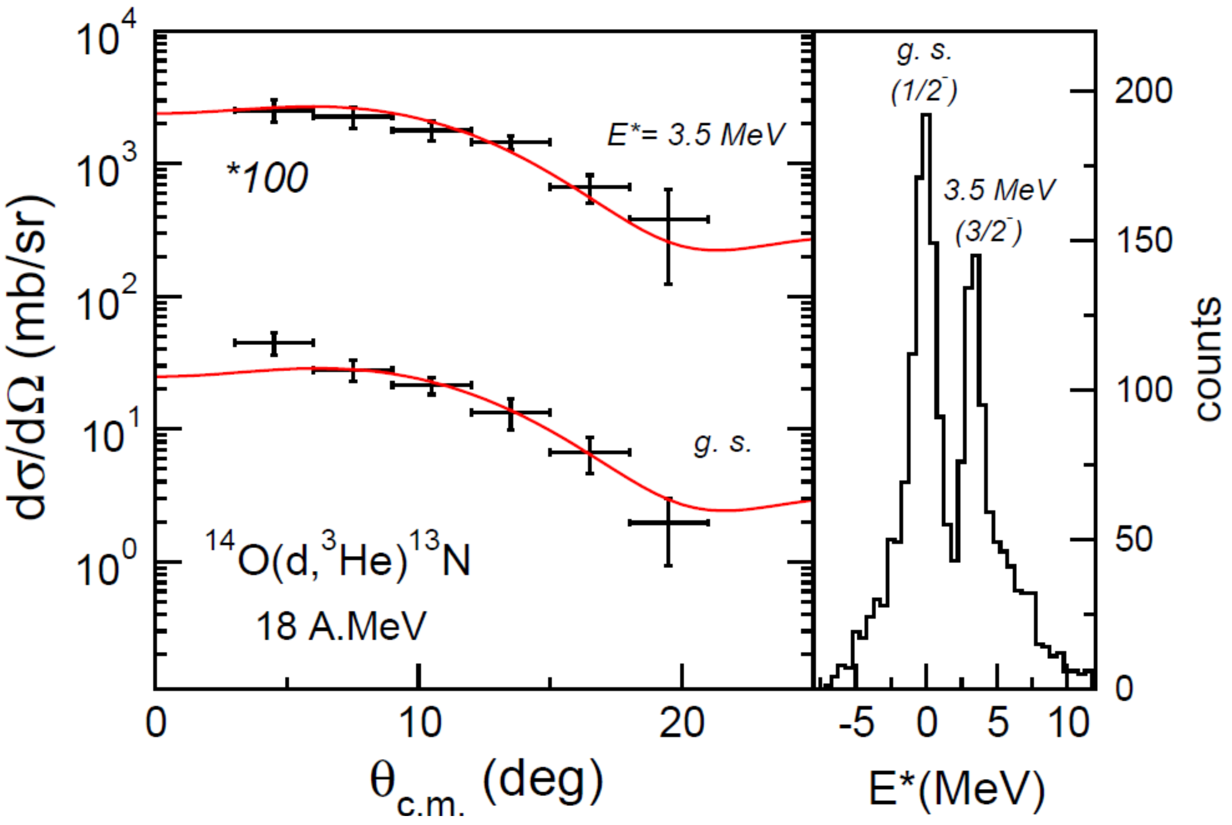
Flavigny et al., PRL 110 (2013)

AN EXAMPLE





^{13}O



MODEL UNCERTAINTIES

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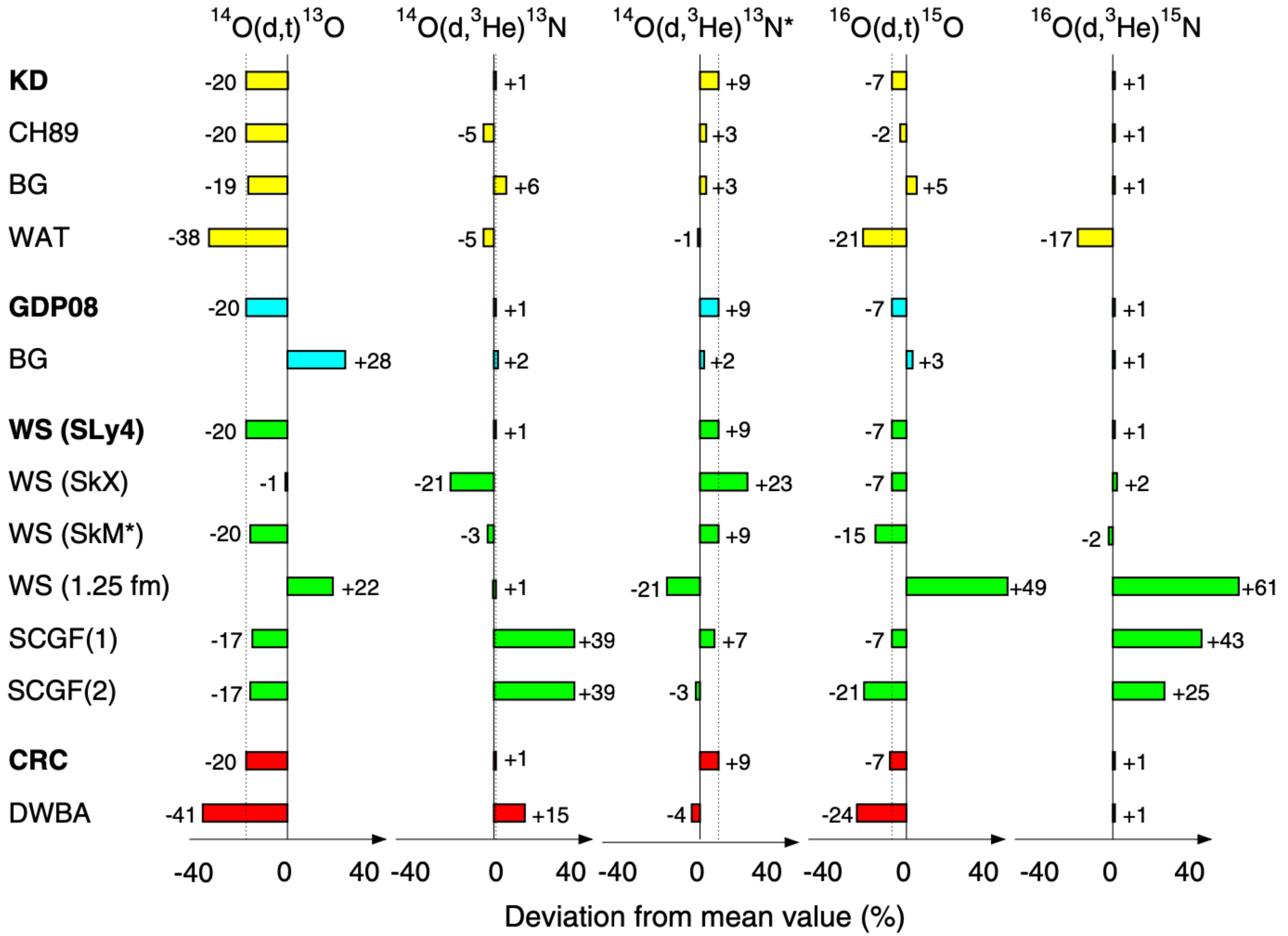
Entrance channel optical potential

Exit channel optical potential

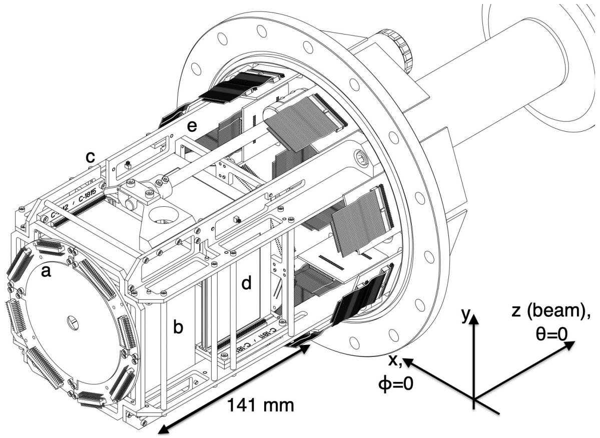
Wave function

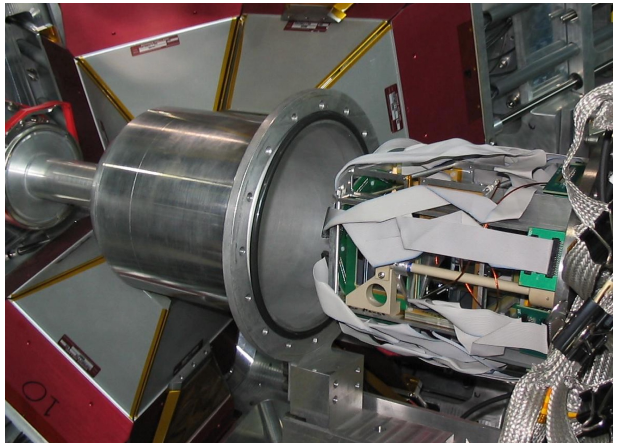
Reaction model



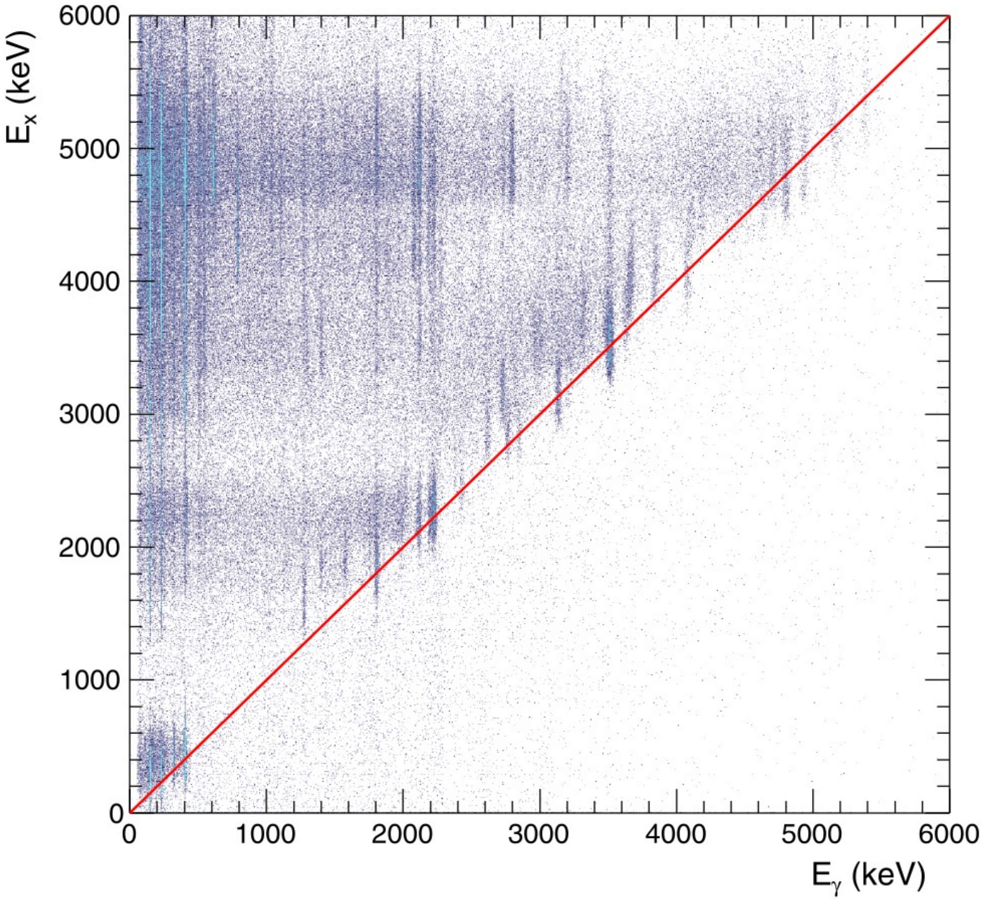
Flavigny et al., PRC 97 (2018)

γ-PARTICLE SPECTROSCOPY





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

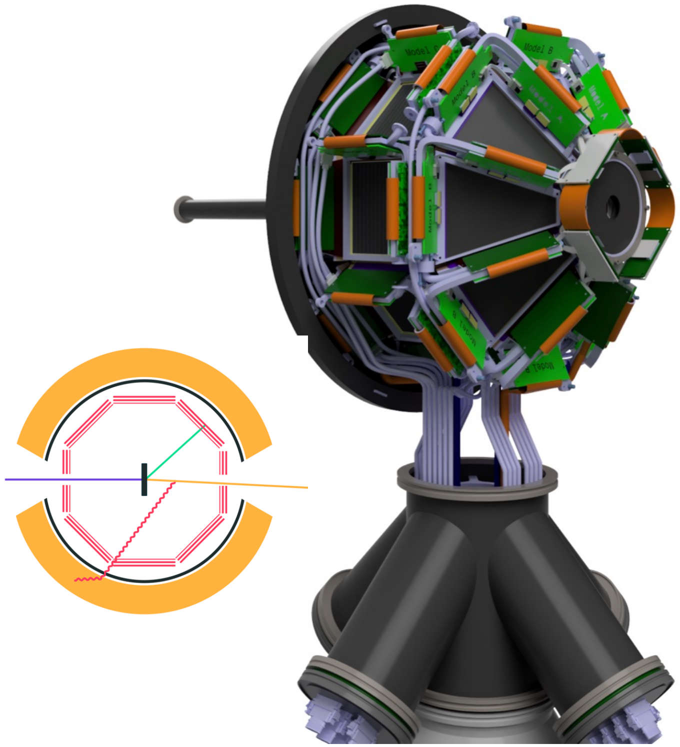


G. L. Wilson et al., PLB 759 (2016)

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

GRIT PROJECT

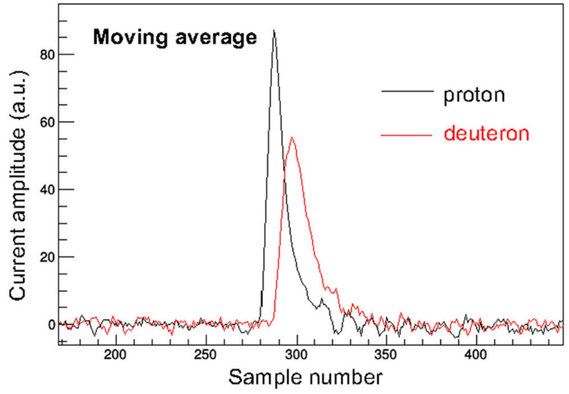
- European project for GANIL, SPES
- To be combined with the γ tracking array AGATA
- Identification from pulse shape analysis

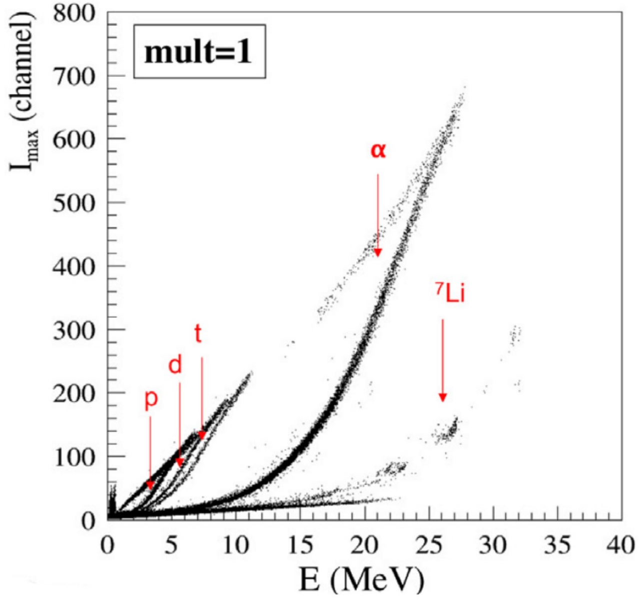


Main features:

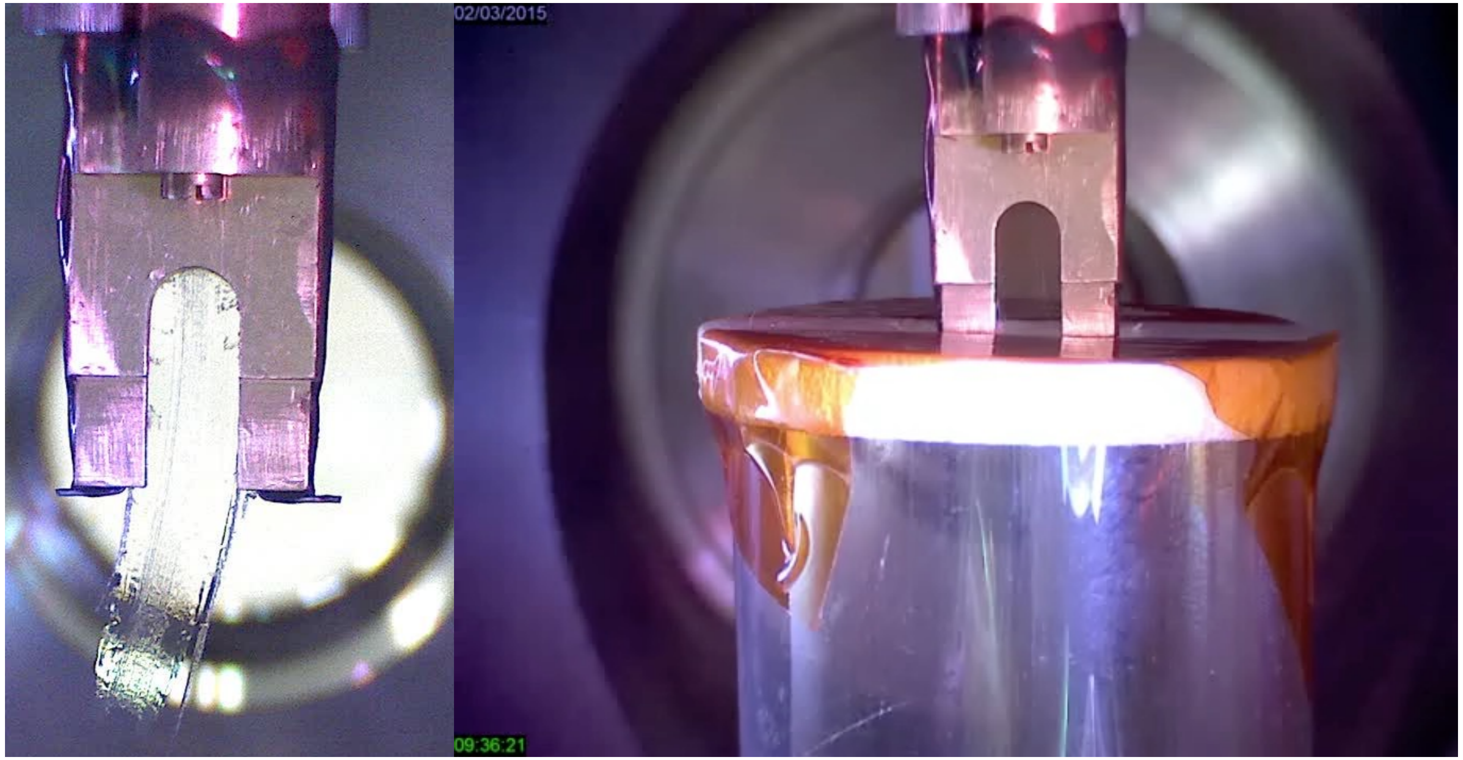
- DSSD (35 keV)
- Identification from:
  - E-ΔE
  - ToF
  - pulse shape analysis
- Transparency
- Compatible with H_2 targets

M. Assié et al., EPJA 51 (2015)
J. Dormard et al., NIMA 1013 (2021)





CHYMENE PURE HYDROGEN TARGET



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

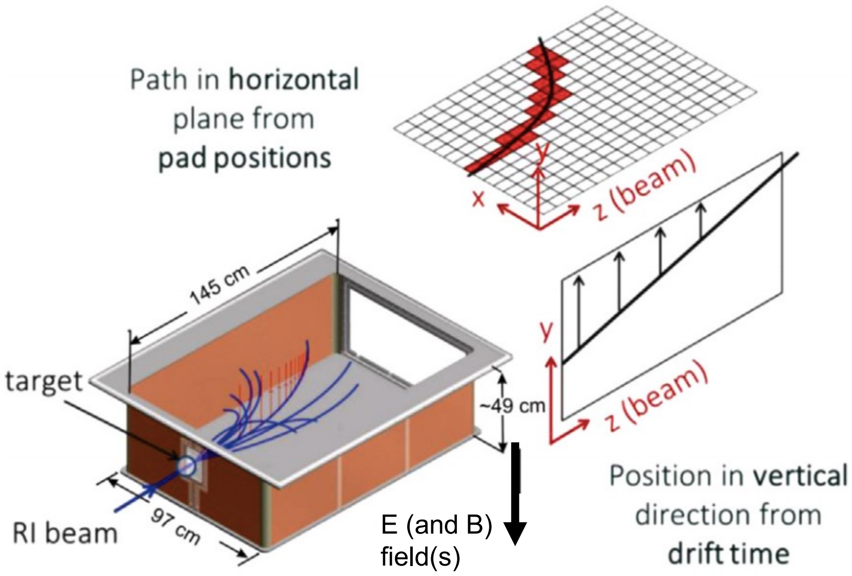
- From fusion technology
- About 100 bars, 16 K
- Thickness down to 30 microns
- 5 – 10 mm radius
- R&D and prototype at CEA Saclay
- Challenge:
  - vacuum
  - thickness homogeneity

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)

- 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)

SOME ACTIVE TARGETS WORLDWIDE

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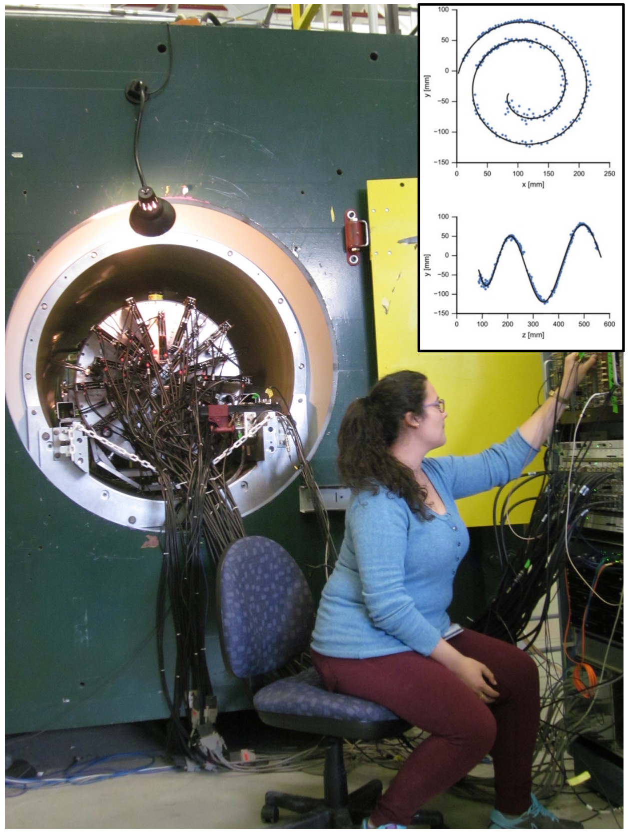
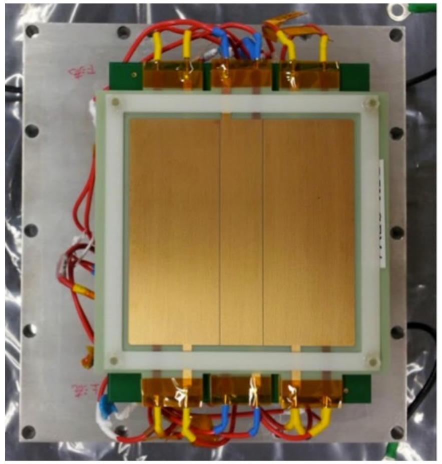
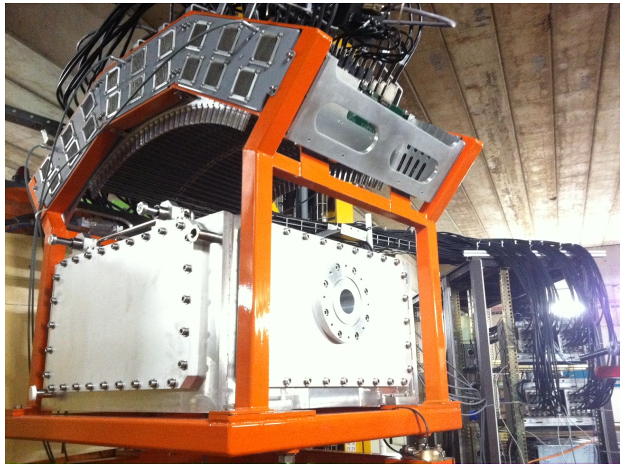


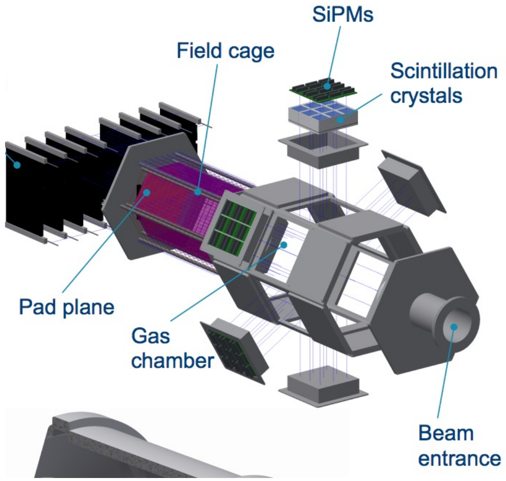
AT-TPC
J. Bradt et al., NIMA (2017)



CAT
S. Ota et al., JRNC (2015)



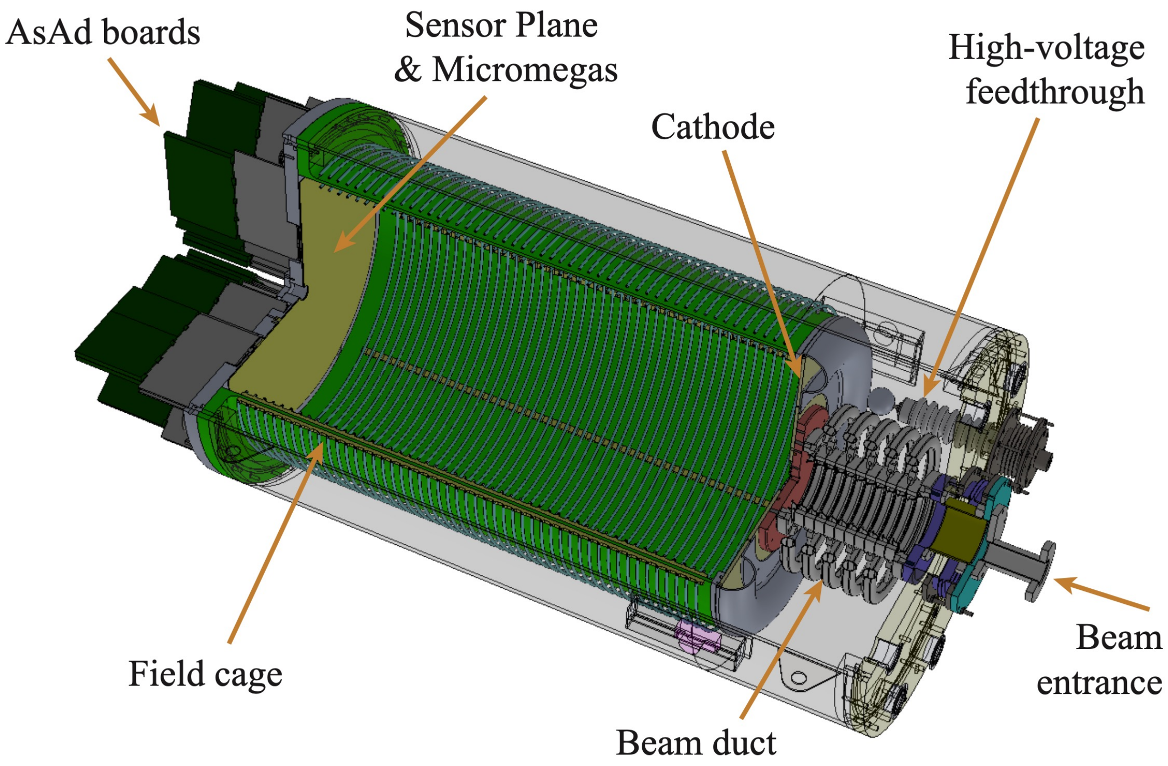
ACTAR
GANIL, Courtesy T. Roger



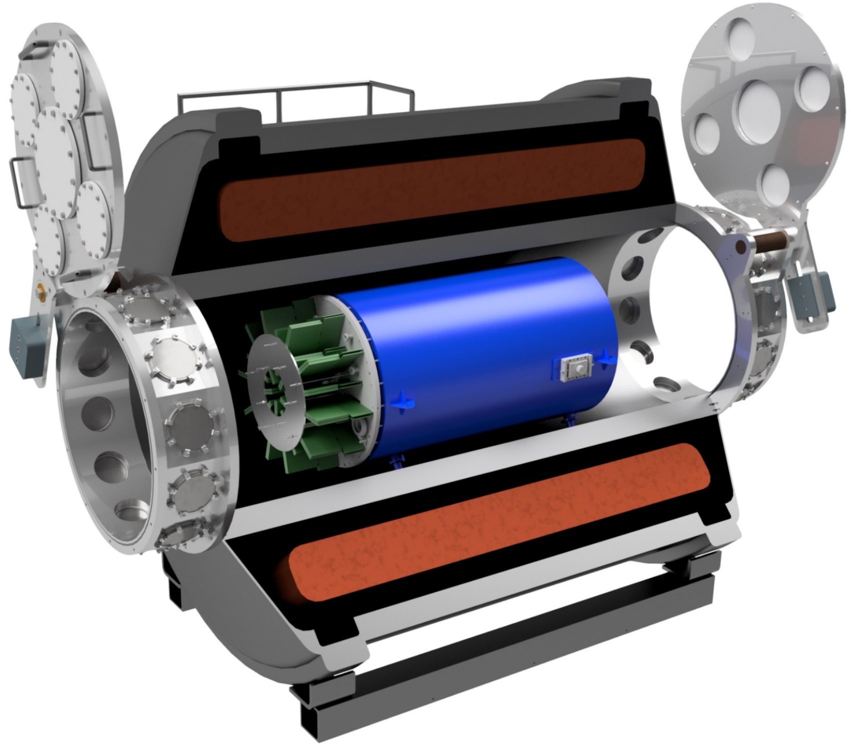
SpecMAT
R. Raabe, KU Leuven

AT-TPC

Active Target Time Projection Chamber



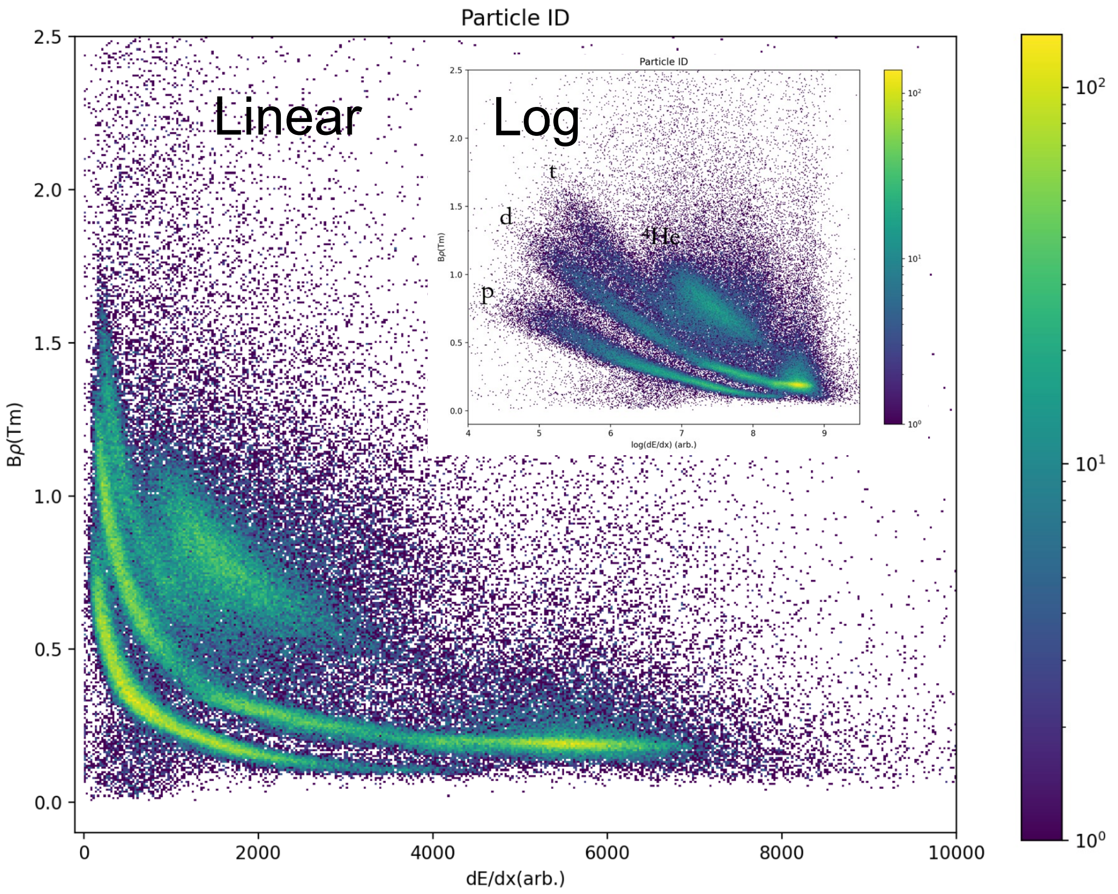
Solenoidal Spectrometer Apparatus for Reaction Studies



Courtesy: D. Bazin, FRIB

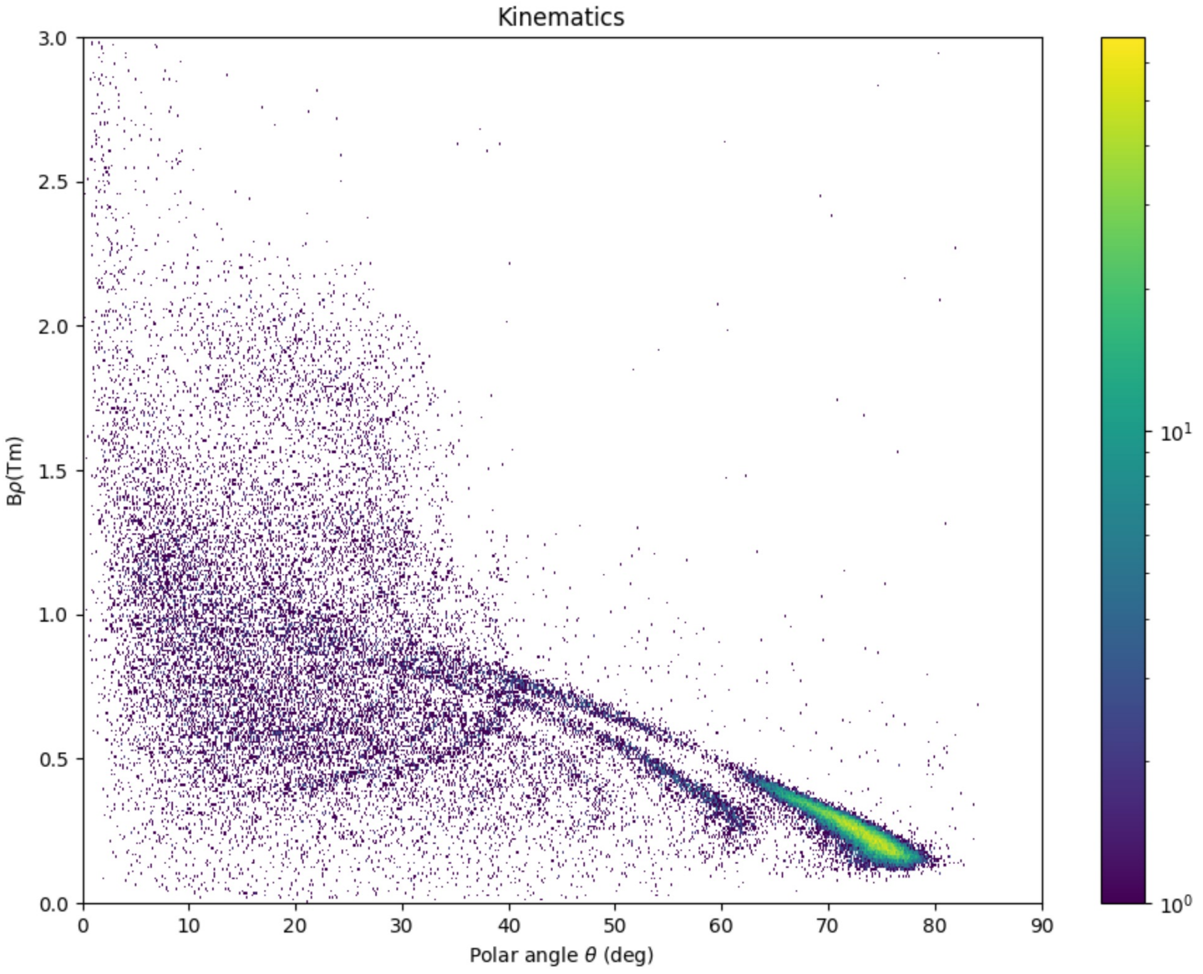
PARTICLE IDENTIFICATION

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

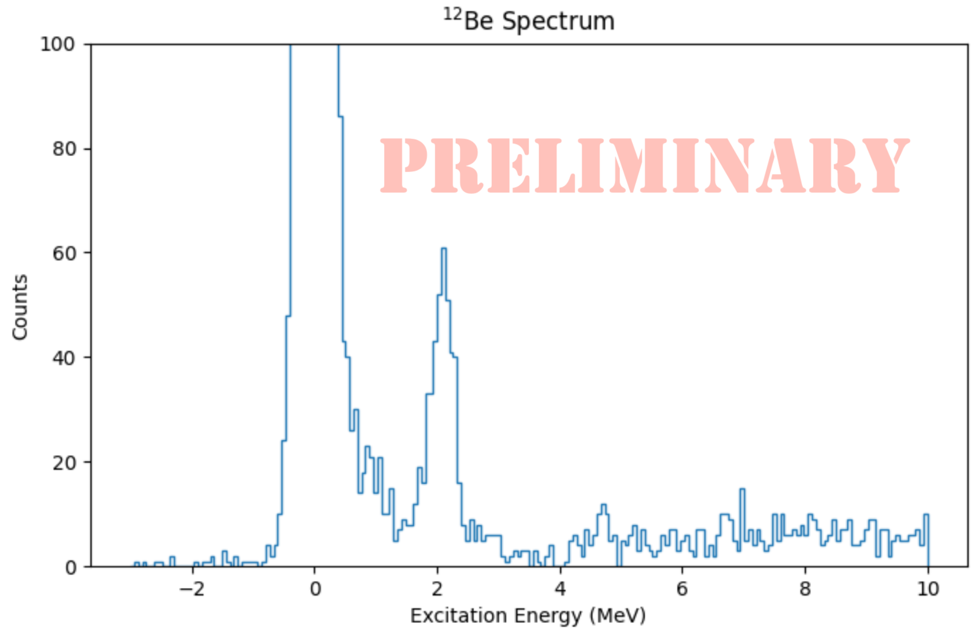


Courtesy: D. Bazin, FRIB; DREB2024

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



- ^{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

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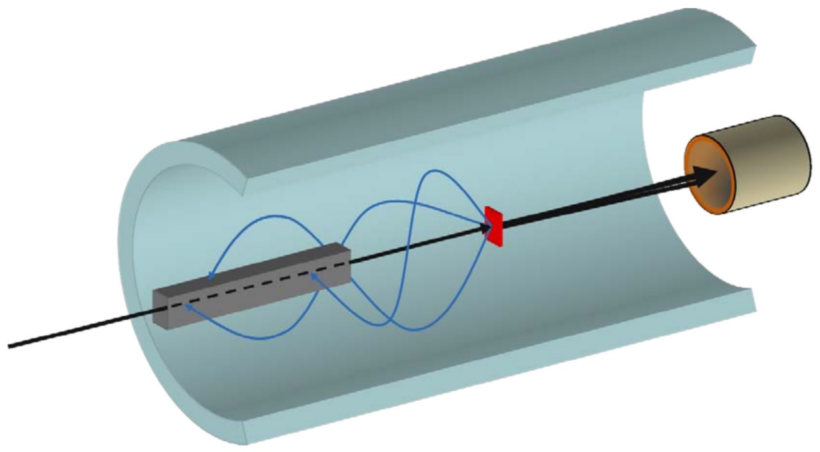
Measured quantities
Flight time: $T_{flight}=T_{cyc}$
Position: z
Energy: E_{lab}

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



B=2T

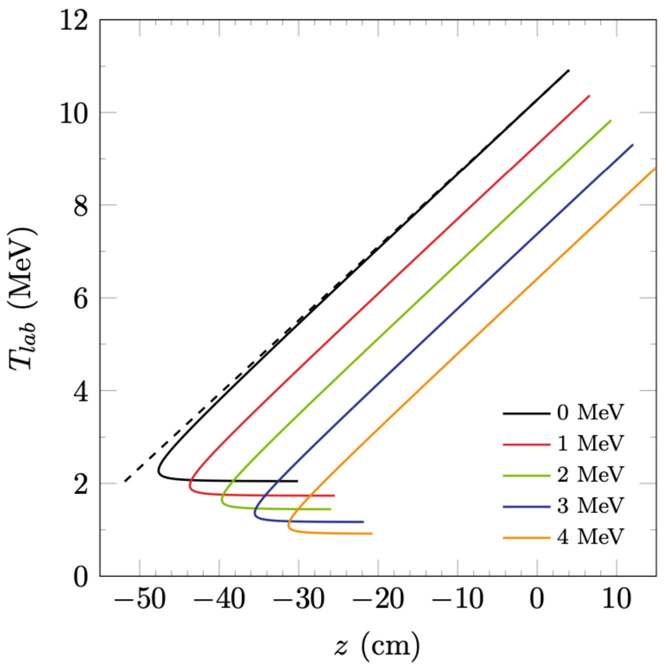
Particle	T_{cyc} (ns)
p	34.2
$^3He^{2+}$	51.4
d, α	68.5
t	102.7

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

Independent of energy!!

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

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



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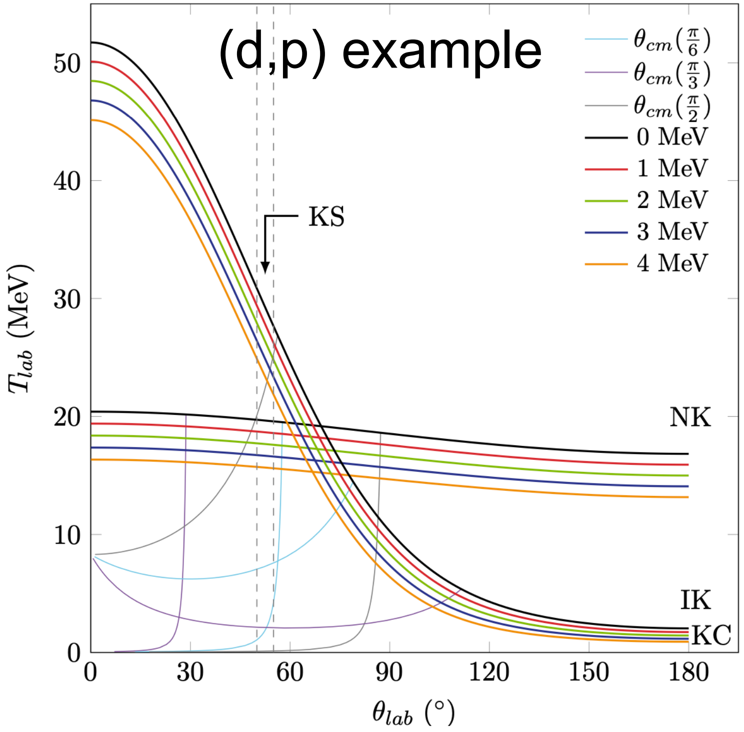
INVERSE KINEMATICS AND ENERGY RESOLUTION



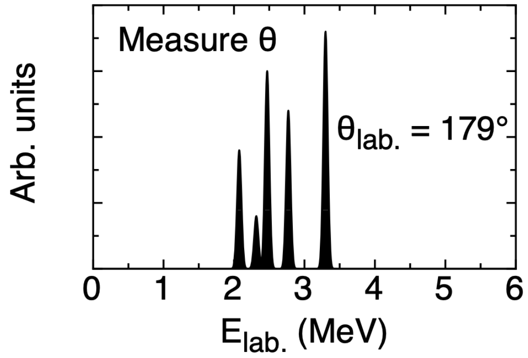
Normal kinematics (NK): beam:d, targ.: ^{A}X

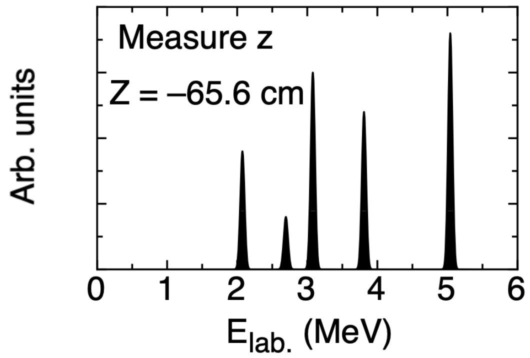
Inverse kinematics (IK): beam:^{A}X, targ.=d

Kinematic shift (KS)
broadens peaks in missing-mass spectrum

Kinematic compression (KC)
reduces spacing between peaks

⇒ inverse kinematics reduces the state separation

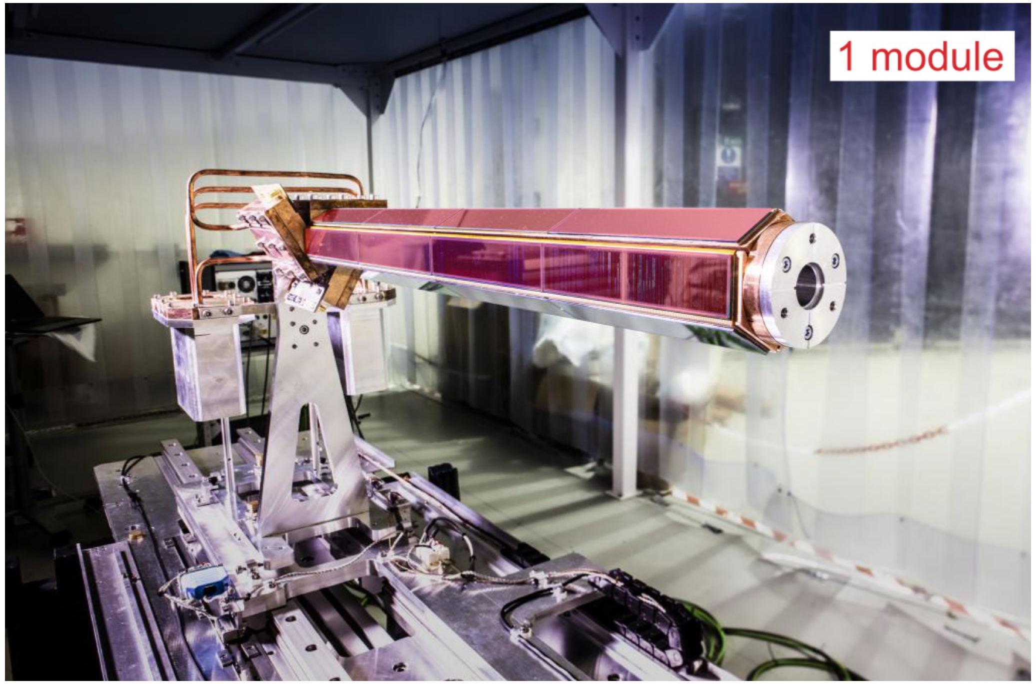




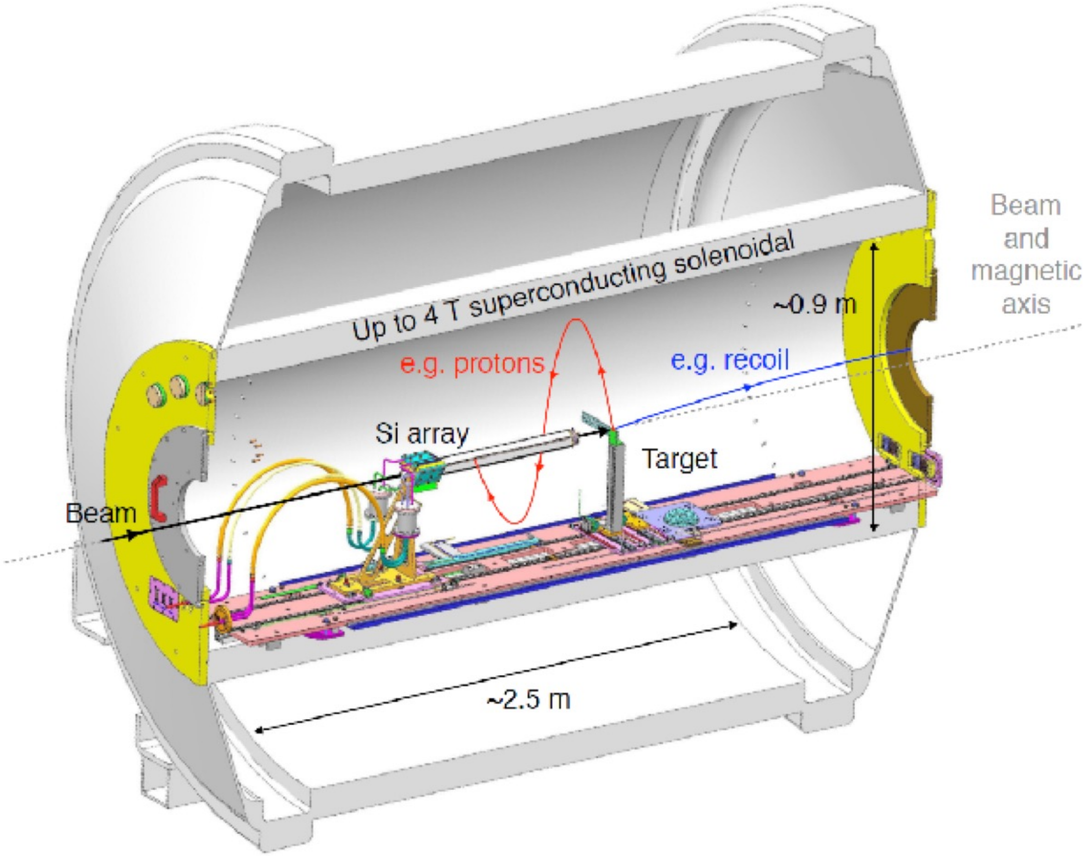
Courtesy: P. MacGregor, CERN


SOLARIS
HELIOS
ISS
ISOLDE Solenoidal Spectrometer
Greenland
Iceland
Reykjavík
Northwestern Passages
NUNAVUT
Hudson Bay
Labrador Sea
Canada
MANITOBA
SASKATCHEWAN
ONTARIO
QUEBEC
NEWFOUNDLAND AND LABRADOR
Winnipeg
Ottawa
Montreal
Toronto
NOVA SCOTIA
MAINE
NEW YORK
Boston
United States
North Atlantic Ocean
Gulf of Mexico
Mexico
Monterrey
Guadalajara
Mexico City
Houston
San Antonio
Dallas
Havana
Cuba
Santo Domingo
Puerto Rico
Guatemala
Nicaragua
Caribbean Sea
Sweden
Norway
Finland
Oslo
Stockholm
Baltic Sea
Estonia
Latvia
Lithuania
Denmark
North Sea
Ireland
Germany
Berlin
Poland
Warsaw
Belarus
Belgium
Paris
France
Czechia
Slovakia
Austria
Hungary
Moldova
Romania
Croatia
Serbia
Italy
Rome
Bulgaria
Greece
Athens
Marseille
Barcelona
Portugal
Lisbon
Madrid
Spain
Tyrrhenian Sea
Algiers
Tunis
Tunisia
Mediterranean Sea
Morocco
Algeria
Libya
Western Sahara
Mauritania
Mali
Niger
Chad
Senegal
Dakar
The Gambia
Guinea-Bissau
Bamako
Burkina Faso

ISS AT CERN

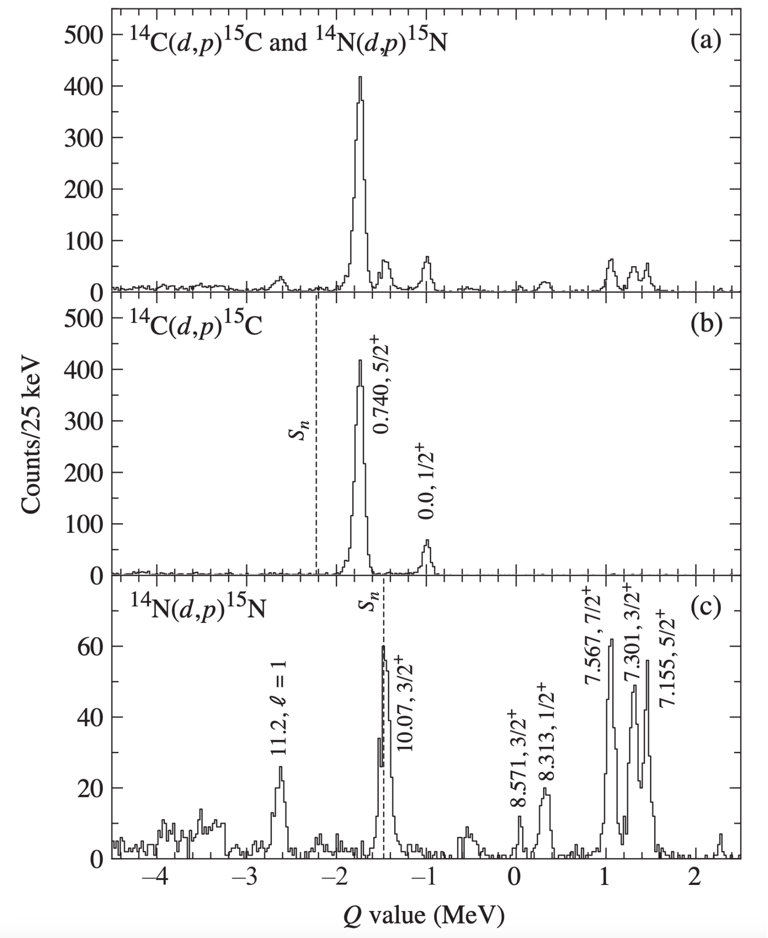


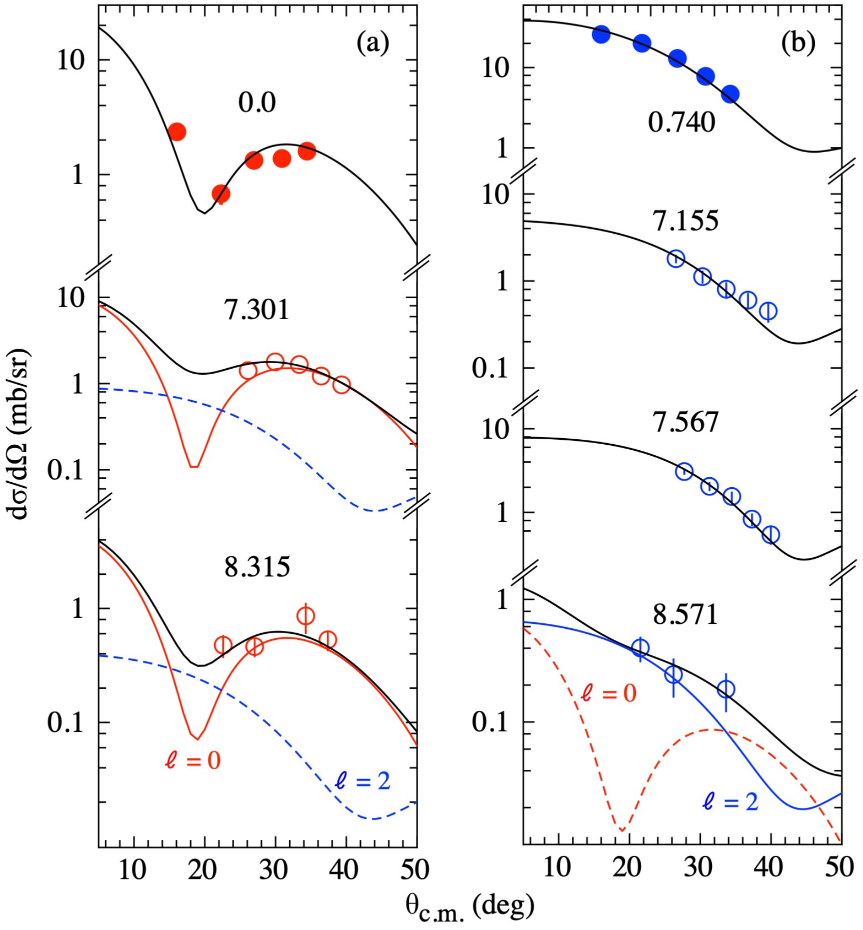
- Hexagonal Si-stripped array
- 1 mm segmentation along symmetry axis
- 500 mm of active silicon length



Courtesy: P. MacGregor, CERN

HELIOS





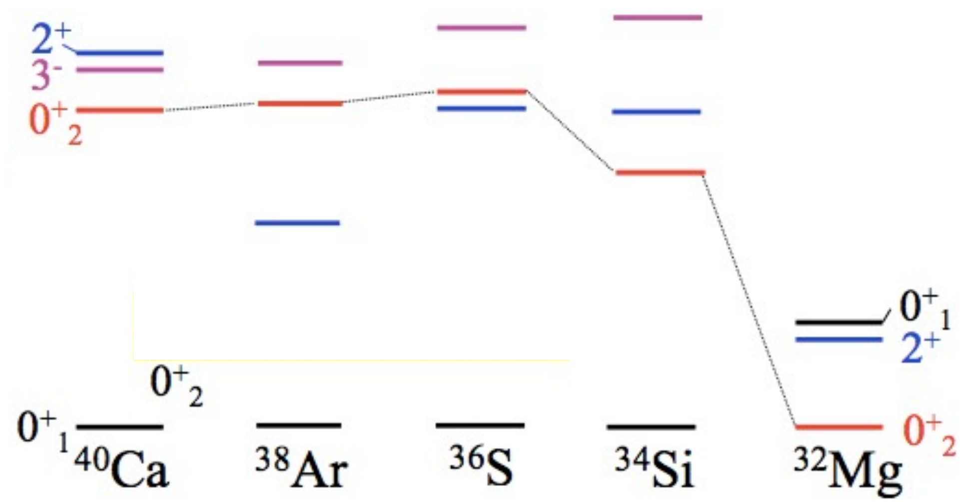
- ^{14}C,^{14}N(d,p) at 10 MeV/n

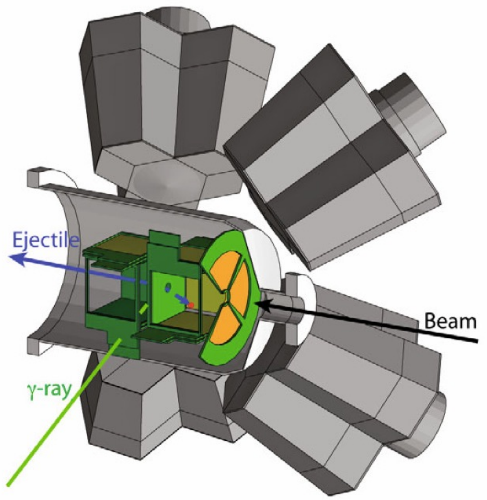
- Beam: 3. 10^5 pps
- HELIOS at ANL
- CD2 target, 127 μg.cm^{-2}
- 125 keV FWHM resolution

B. Kay et al., PRL 129 (2022)

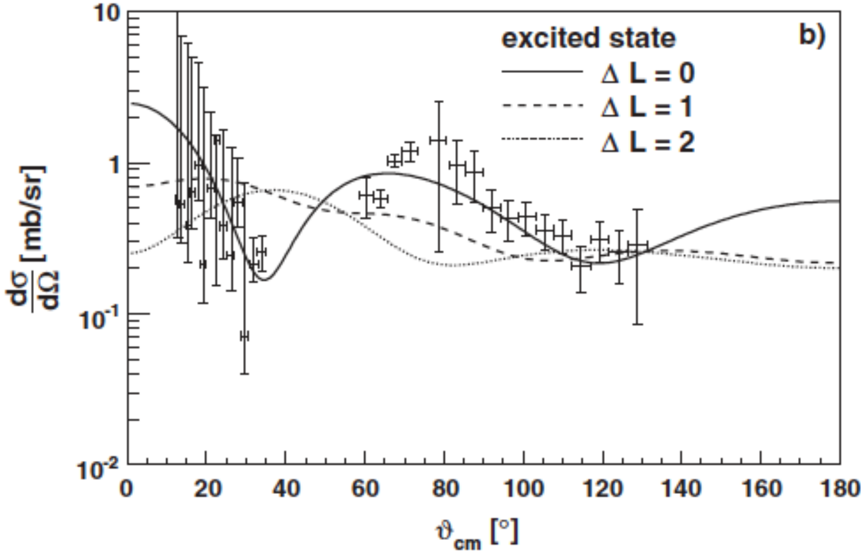
TWO-NUCLEON TRANSFER

- Two neutron transfer (p,t) or (t,p) is a tool to populate 2p or 2h neutron states in nuclei
- Investigation of intruder states, shape coexistence or pairing effects have been performed
- Typical cross sections of 100 μb, i.e. 10-100 times less than for one-neutron transfer
- Ex. ^{30}Mg(t,p)^{32}Mg at 3 MeV/n, ISOLDE





Wimmer et al., PRL 105 (2010)



See lecture of Dr. Suzuki

END OF LECTURE 2

OUTLINE

TECHNISCHE UNIVERSITÄT DARMSTADT

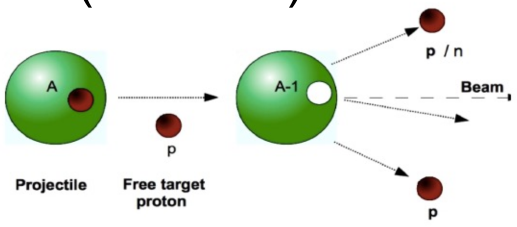
- Introduction to direct reactions
- Single-particle energies and spectroscopic factors
- Observables and non observables

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

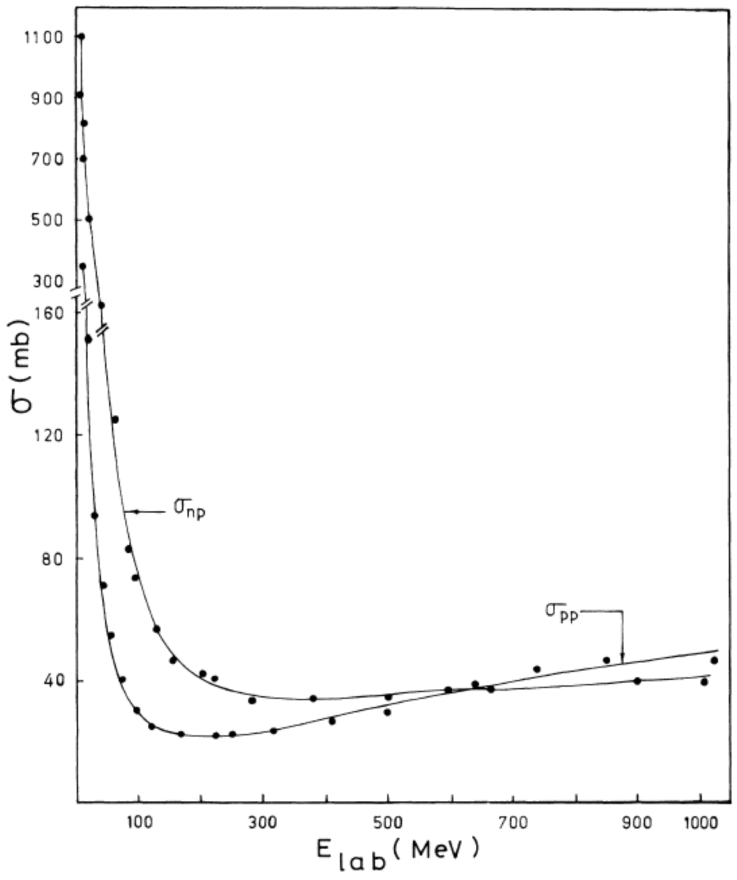
- Quasifree scattering
- Nucleon removal induced from light-ion target
- Instrumentation for quasifree scattering

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

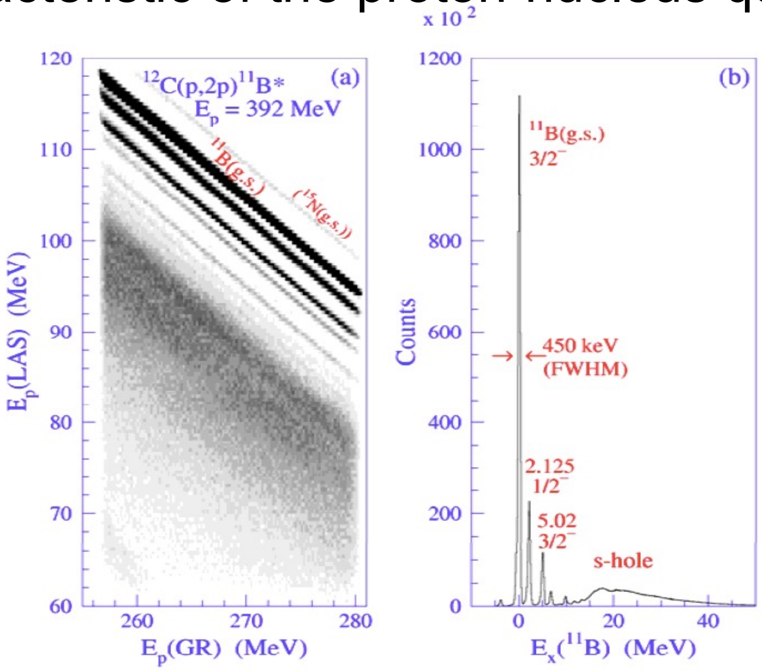
- In a free proton-proton scattering, by momentum and energy conservation, the two scattered protons in the laboratory verify ((1): beam, (2): target, (3,4): scattered particles):

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

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

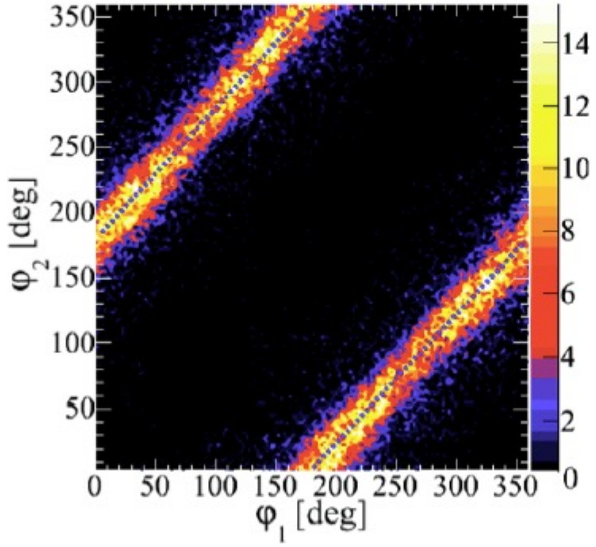
- These features are characteristic of the proton-nucleus quasi-free scattering kinematics

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)

MISSING-MASS SPECTROSCOPY

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- 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.

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

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

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