PROBING NUCLEAR STRUCTURE WITH DIRECT REACTIONS

OBSERVABLES, METHODS AND HIGHLIGHTS WITH RARE ISOTOPES

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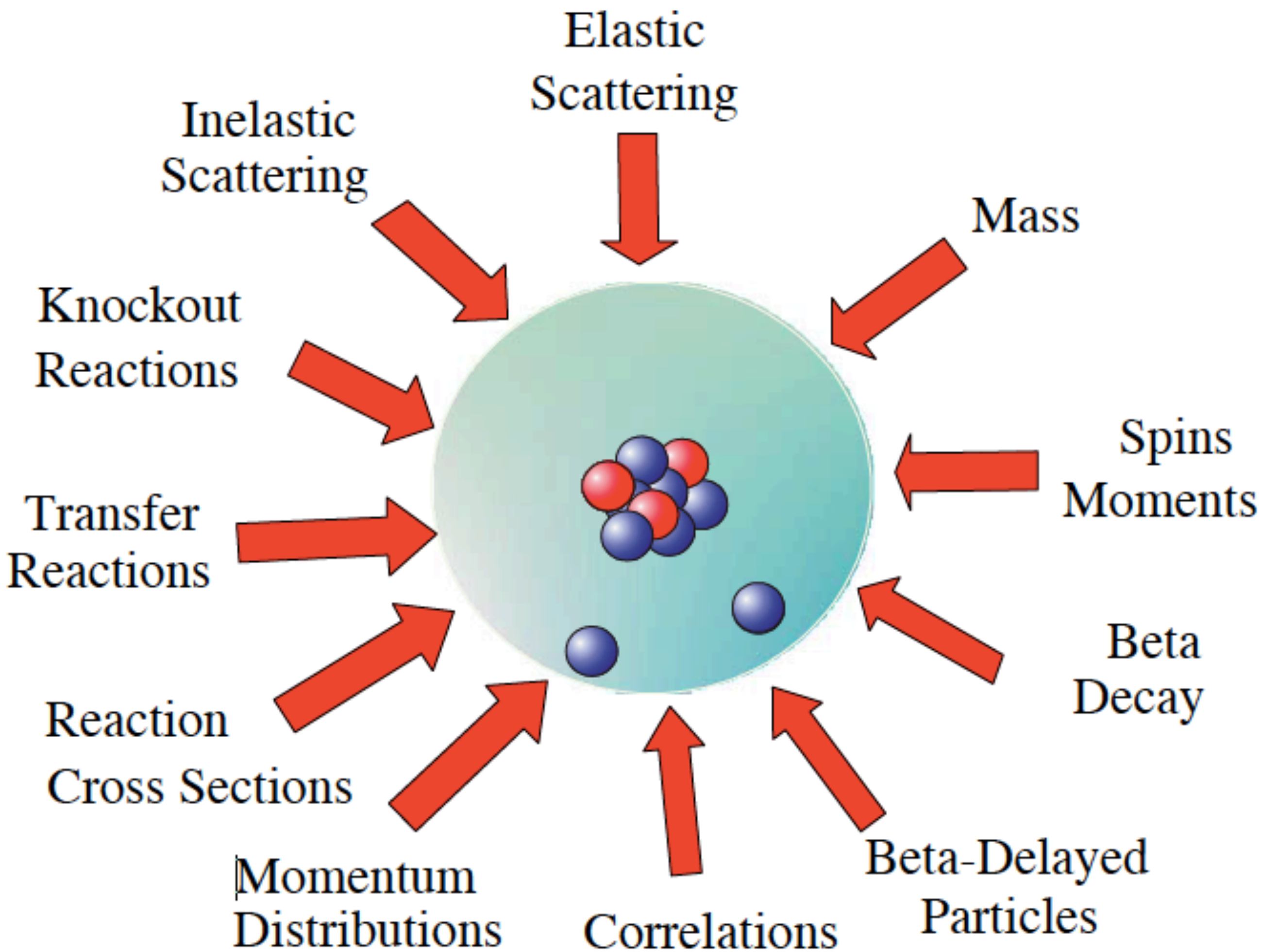
Rewriting Nuclear Physics textbooks:
30 years of exotic nuclei studies
July 2015



Björn Jonson, Physics Report **389** (2004)

Nuclear reactions

In fundamental physics, Nuclear Reactions *are used for :*

- Probing **nuclear structure** (topic of this lecture)
- Production of Radioactive Ions beams
- Studying nuclear dynamics and nuclear matter equation of state

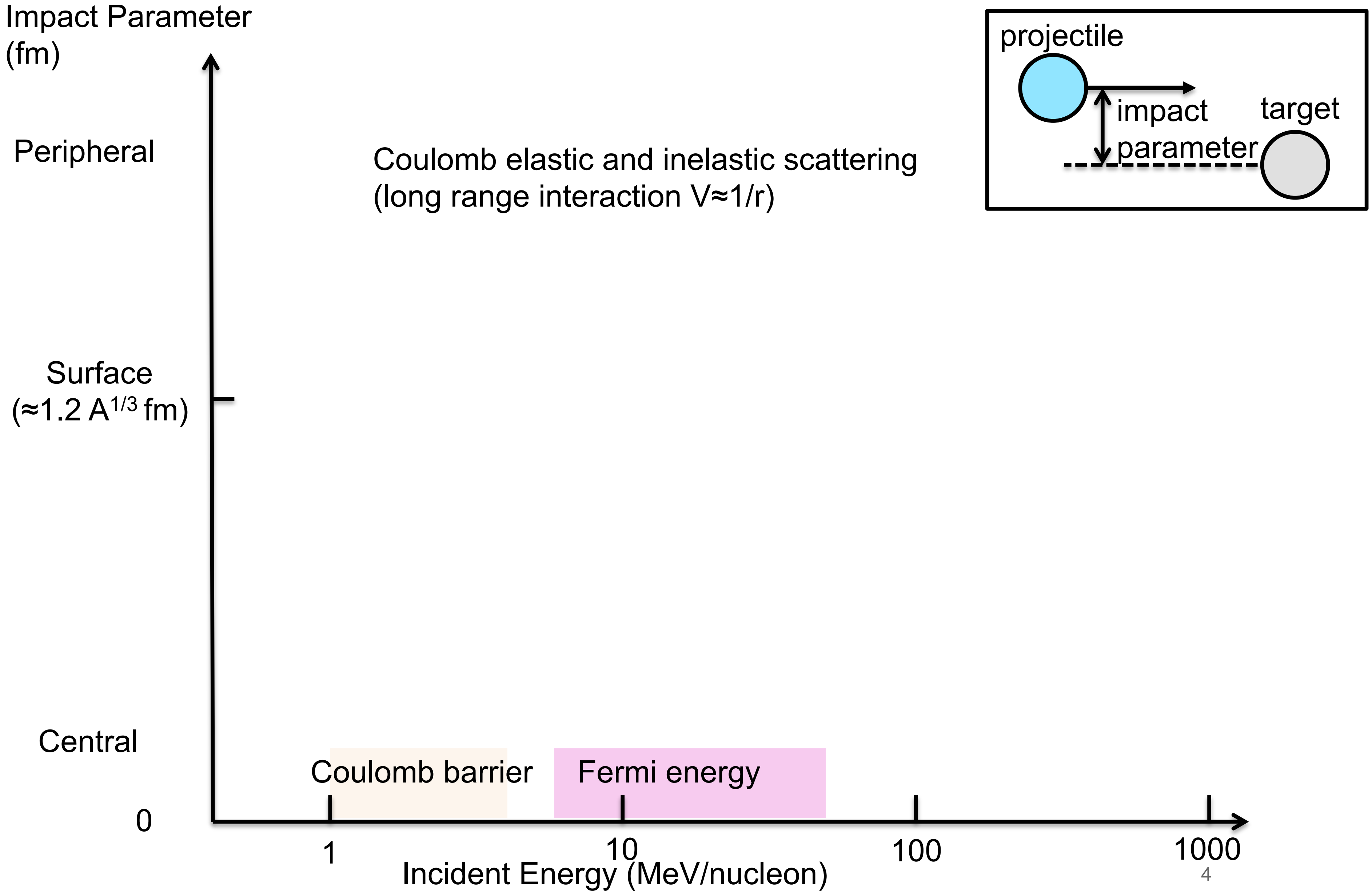
✓ **The quantum many-body problem can not be solved exactly**

➔ true for static systems, even more true for dynamical systems

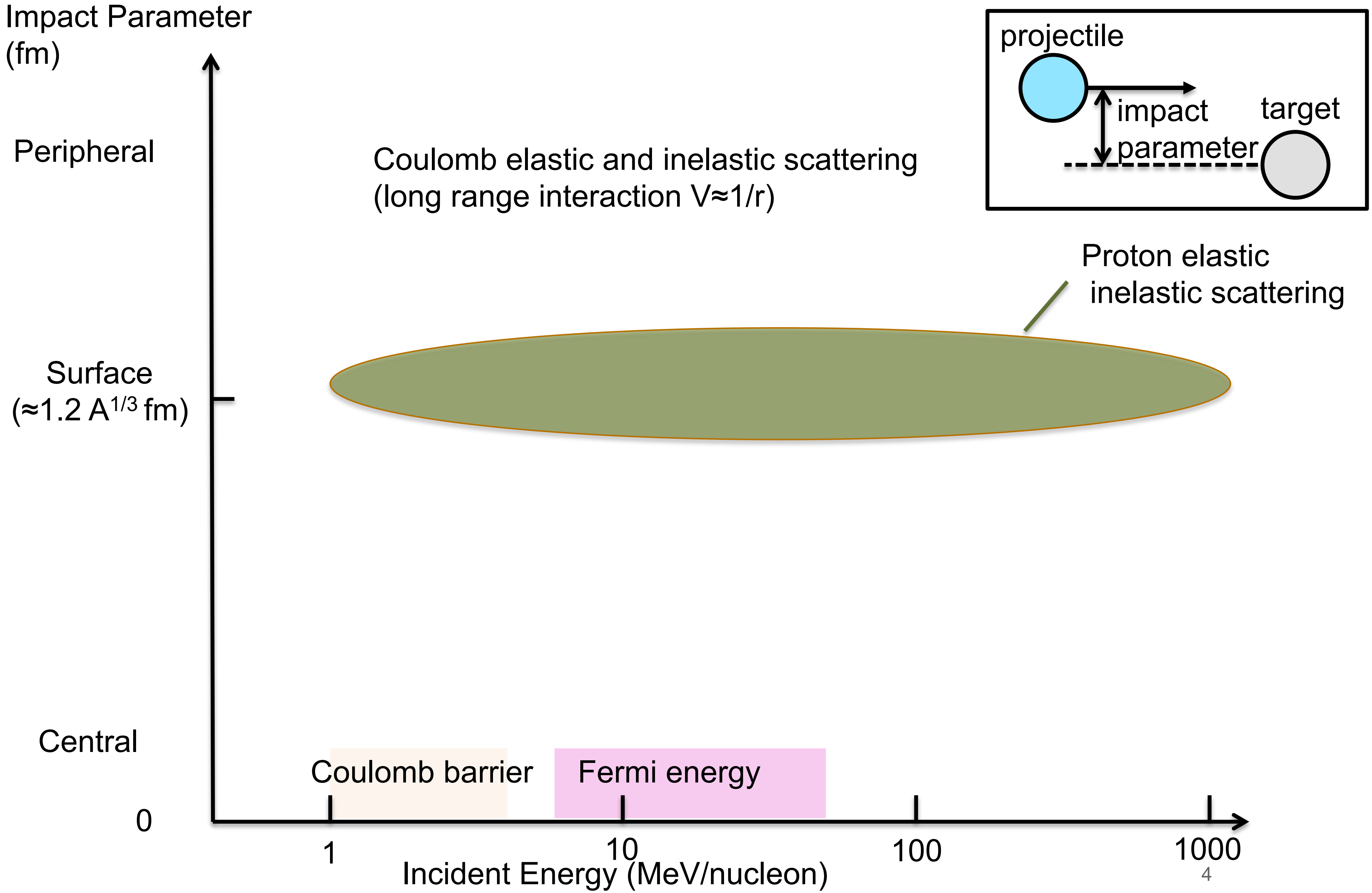
✓ **Strong approximations are made**

➔ natural cycle (feedback) between experiment and theory

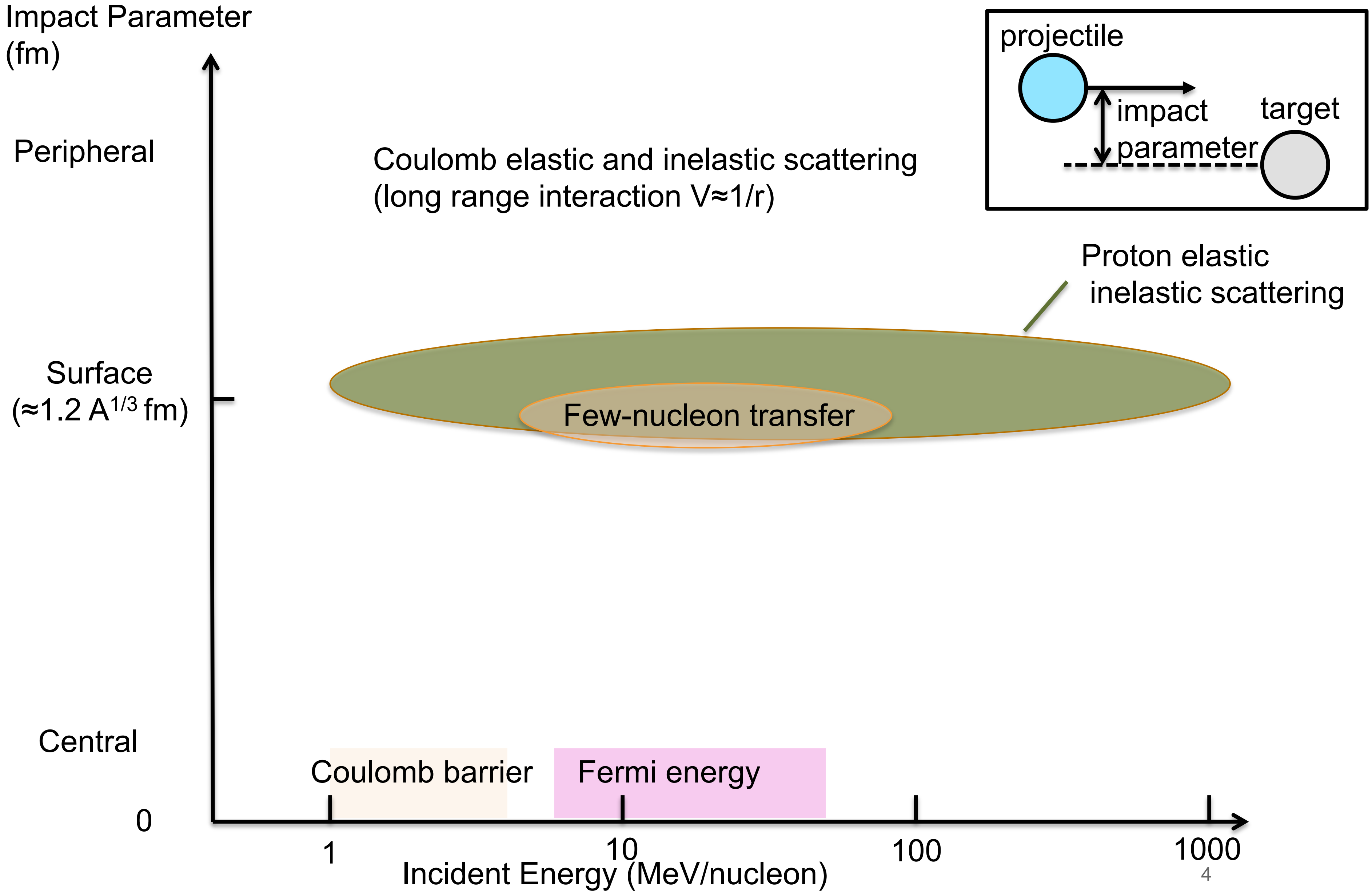
Nuclear reactions



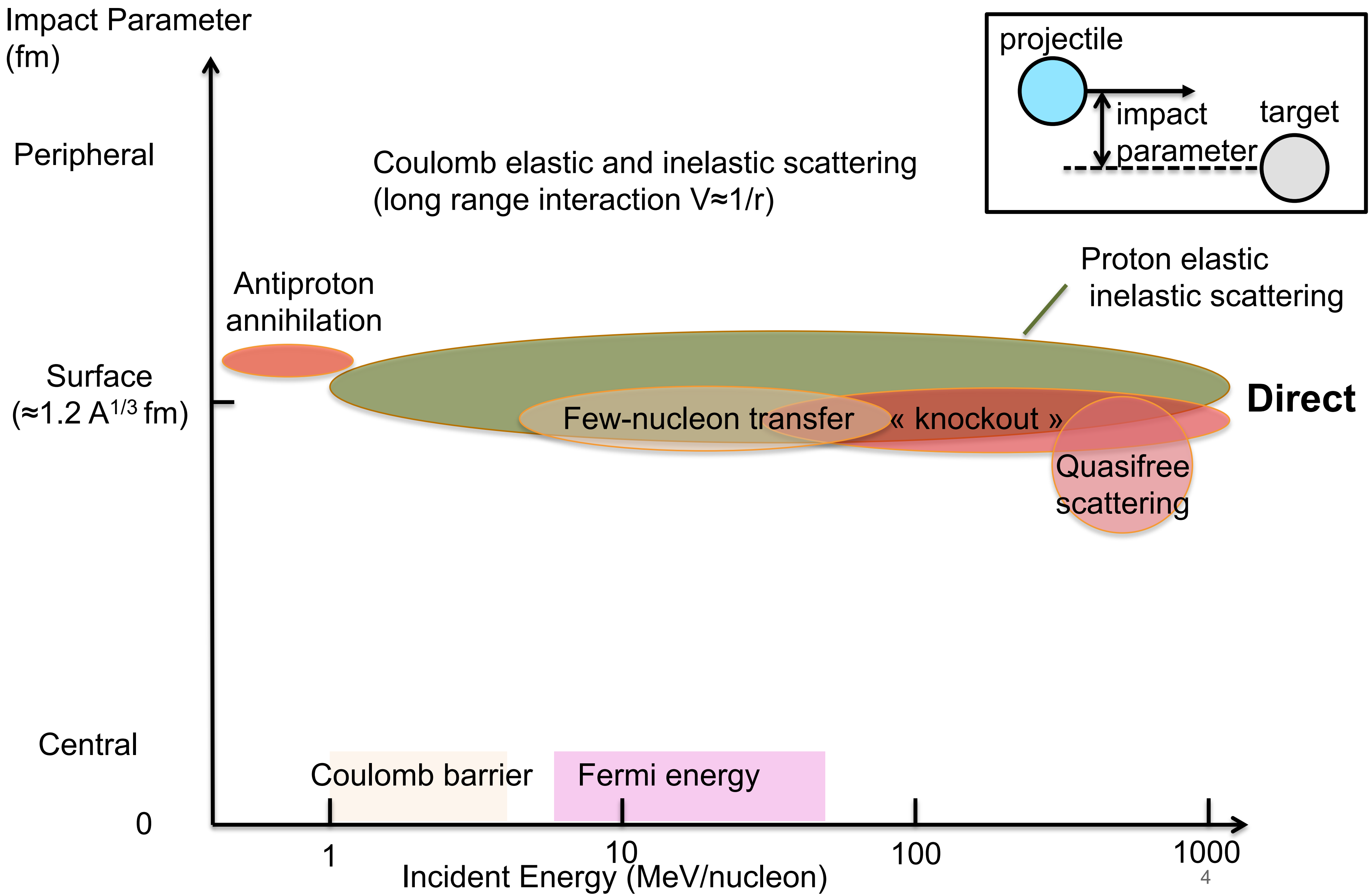
Nuclear reactions



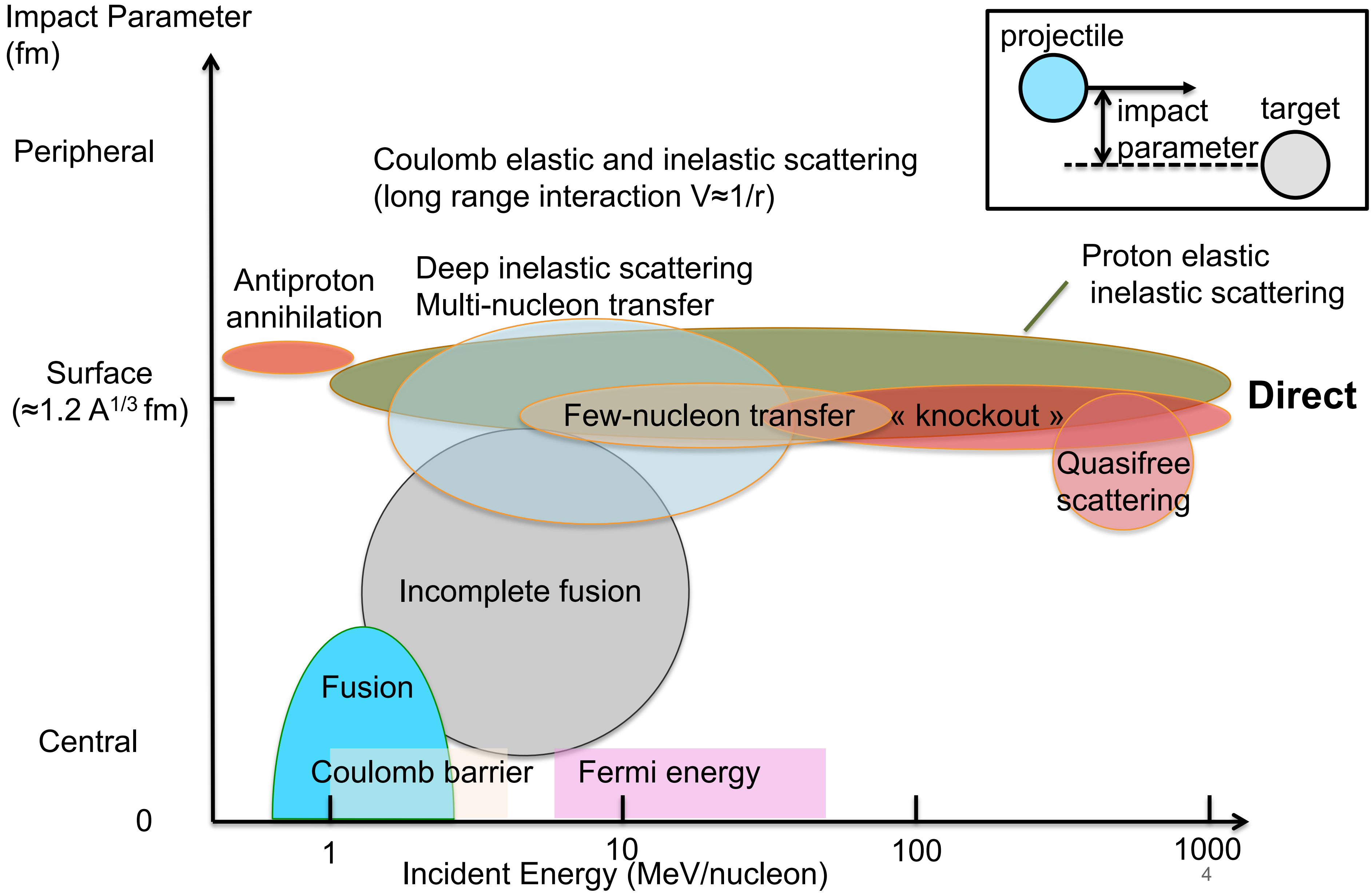
Nuclear reactions



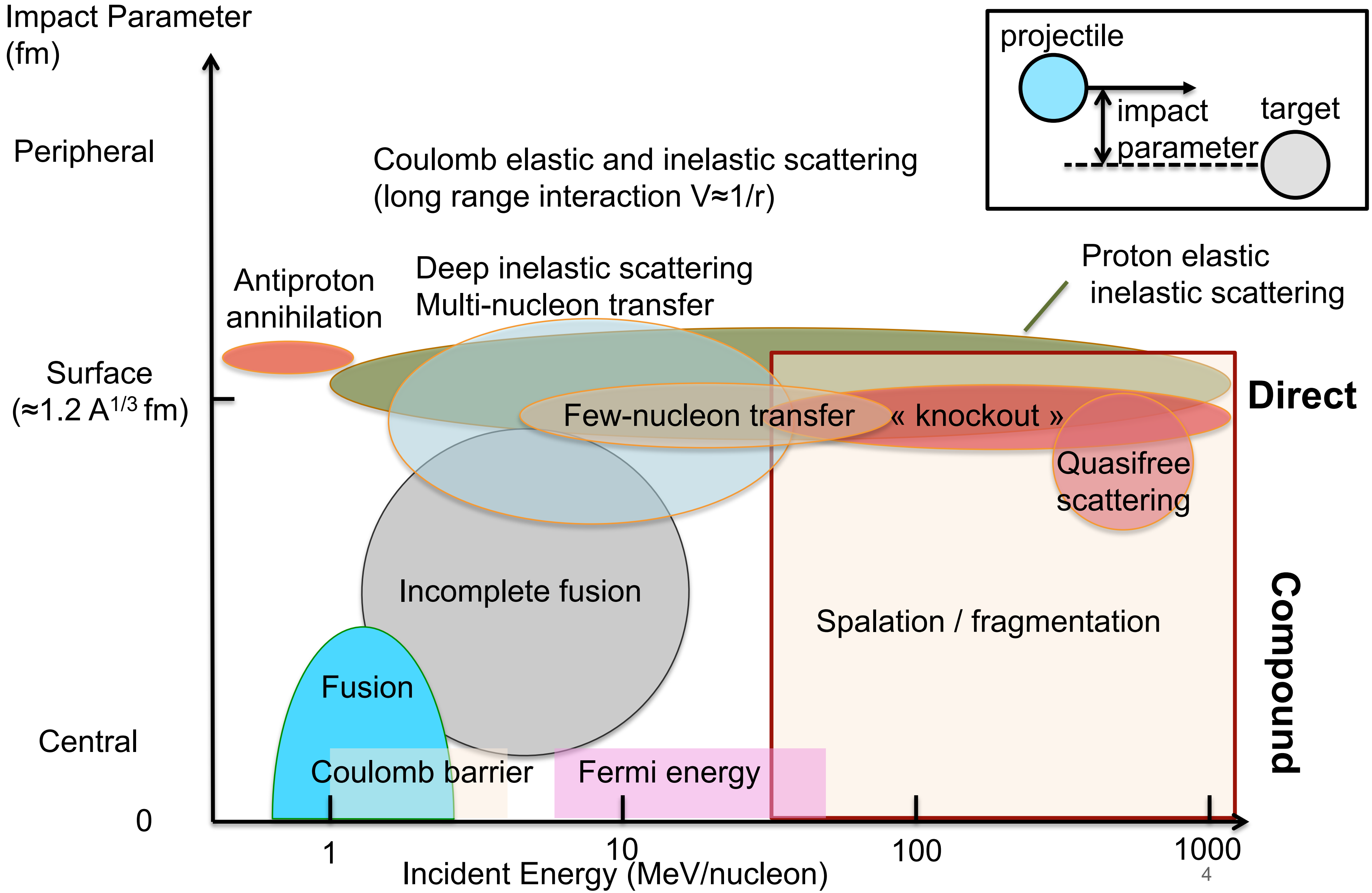
Nuclear reactions



Nuclear reactions

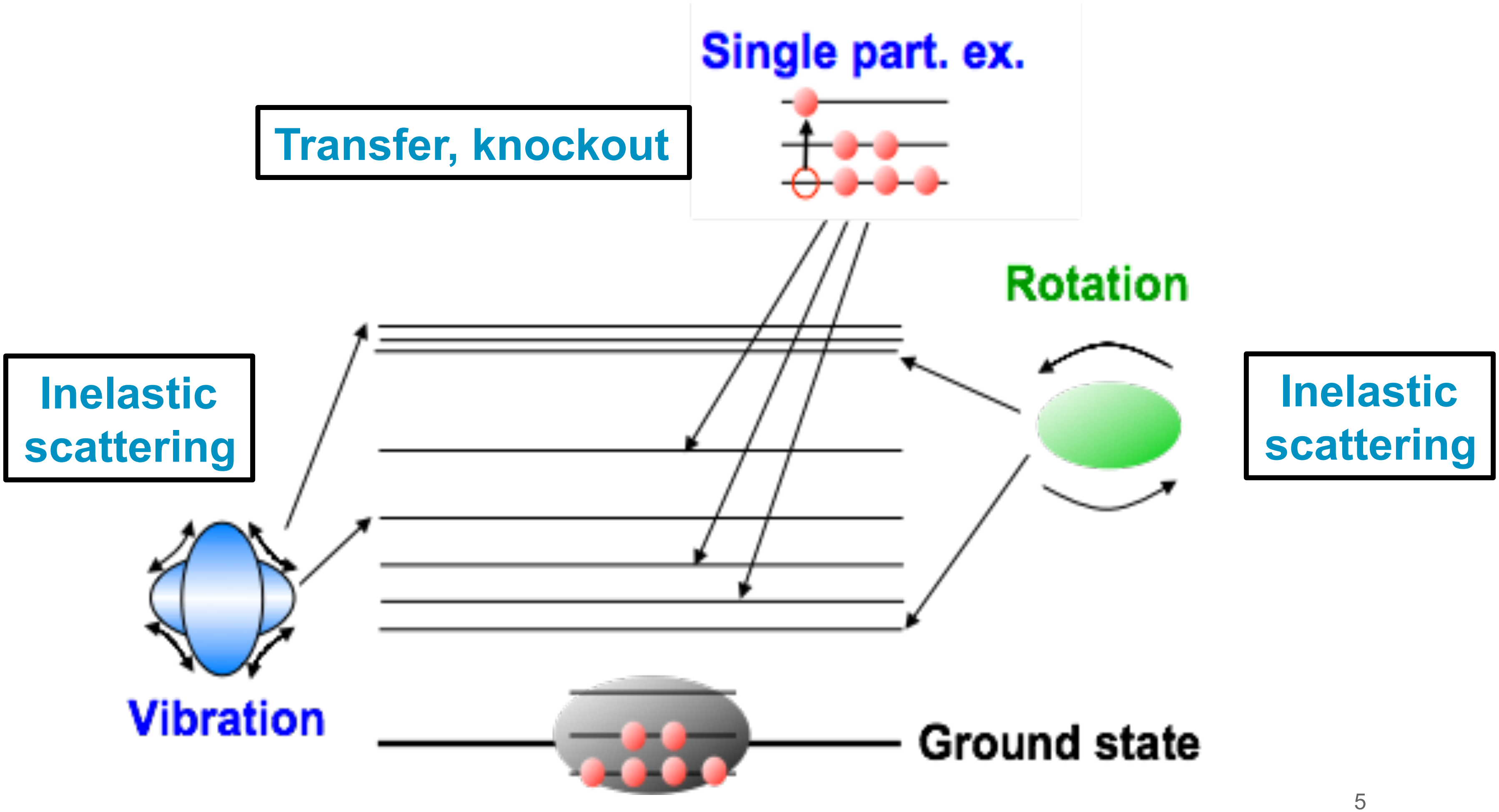


Nuclear reactions

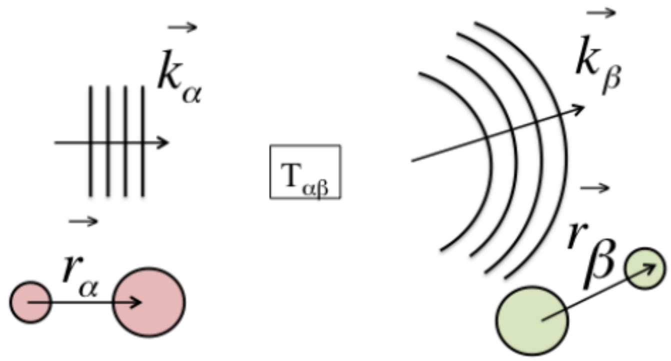


Why do we need direct reactions?

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



Direct reaction cross sections (operator formalism)



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

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

Common assumptions

- Separation of internal and relative degrees of freedom (**optical potential**)
- One-step reaction mechanism (**Born Approximation**)
- Simplification of the wave functions (clusters description / **plane or distorted waves**)

Outline

- **Elastic and inelastic scattering**

- **Nucleon transfer**
  - sensitivity to the shell model / spectroscopic factors
  - the Distorted-Wave Born Approximation (DWBA)
  - achievements with exotic nuclei
  - correlations from two nucleon transfer

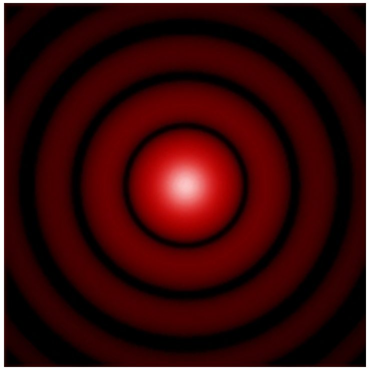
- **Knockout reactions**
  - S-matrix theory and eikonal approximation
  - Nuclear structure from knockout & in-beam γ spectroscopy
  - Absolute SF: transfer versus knockout
  - Quasifree scattering

- **Future developments and probes**

Diffractive pattern / electron elastic scattering

Light diffraction off an aperture:
- Far source
- Far detection

} Fraunhofer diffraction

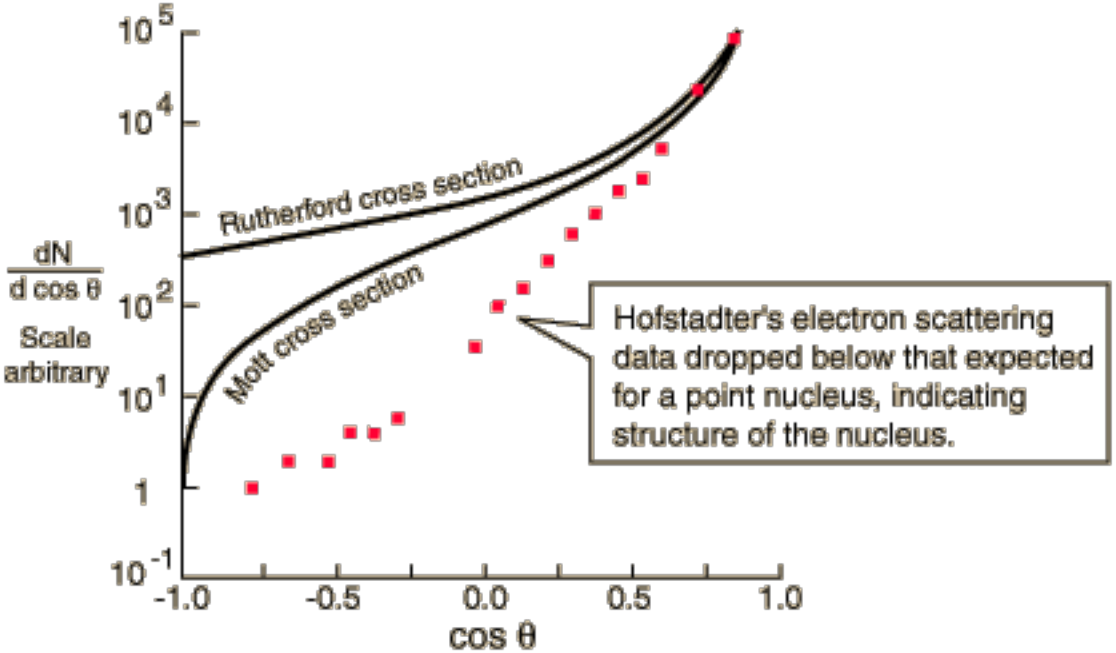


Pattern oscillations (Airy) : $\Delta\theta = \lambda / (2R)$

➔ Depends on the **size of the aperture**

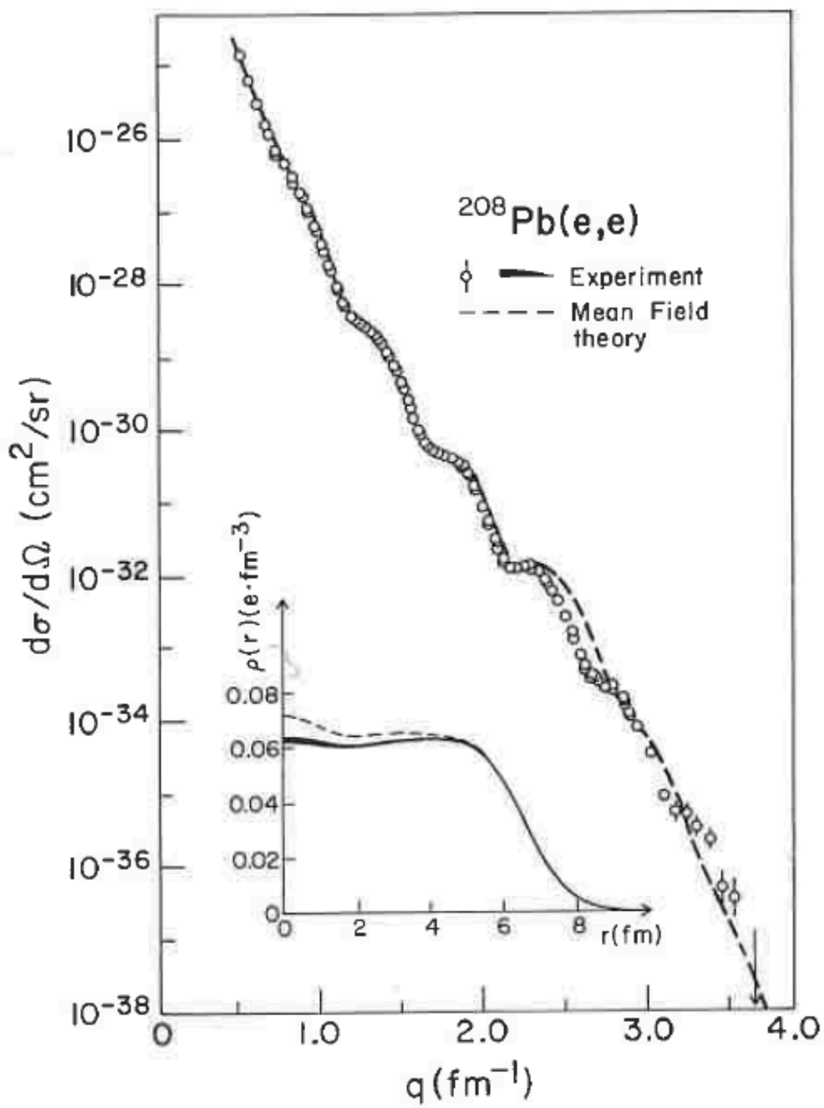
Electron scattering off a nucleus:

$$\lambda = \frac{\hbar}{p}$$



Mott cross section and charge form factor

B. Frois and C.N. Papanicolas,
Ann. Rev. Nucl. Part. Sci. **37**, 133 (1987)



- **Elastic scattering cross section:**
  (assuming ONE exchanged direct photon)

$$\frac{d^2\sigma}{dEd\Omega} = \sigma_{Mott} \left|F(q)\right|^2$$

q: transfered momentum

$$q^2 = 4EE'\sin^2(\frac{\theta}{2})$$

- **Form factor:**

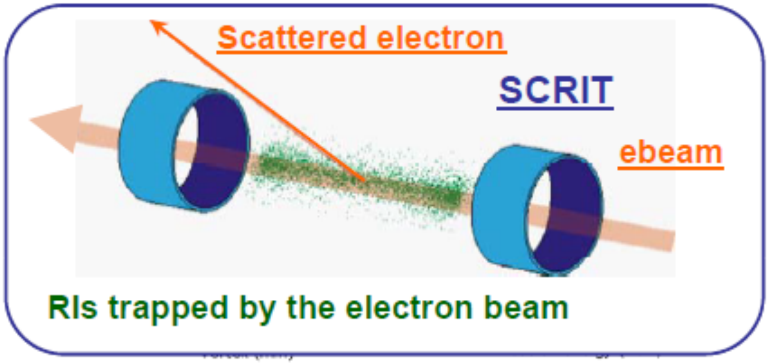
$$F(q) = \left\langle \phi_{k_f} \left| V \right| \phi_{k_i} \right\rangle$$

$$= \int e^{\frac{i\vec{q}.\vec{r}}{\hbar}} \rho(\vec{r}\,')d^3\vec{r}\,'$$

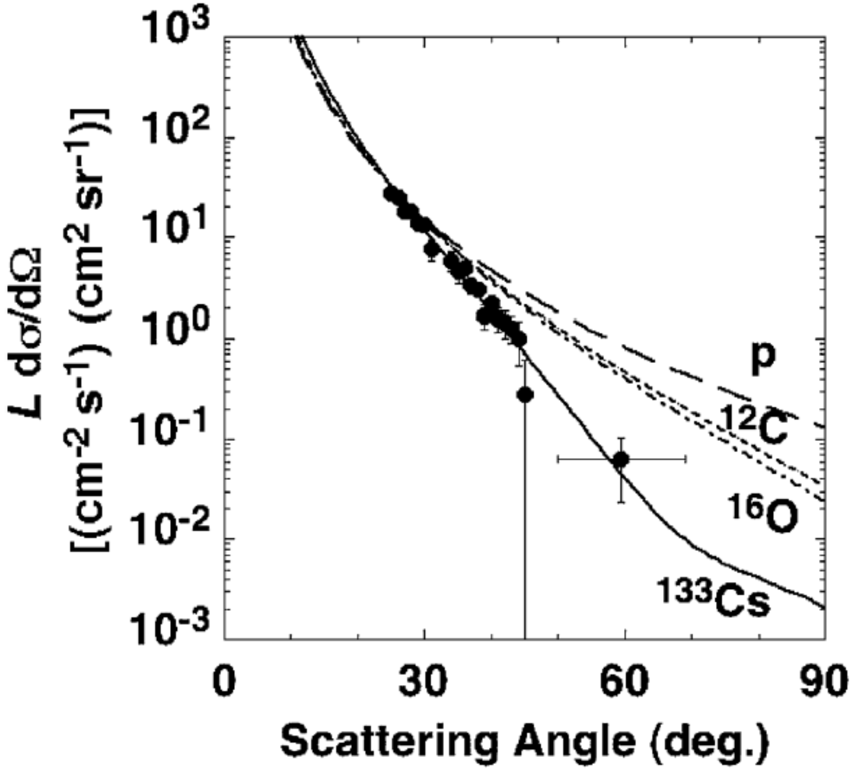
Electron scattering from unstable nuclei

e-RI scattering, SCRIT ring at RIKEN

unstable nuclei from 2015 !



Luminosity up to 10^{27} cm^{-2} s^{-1}

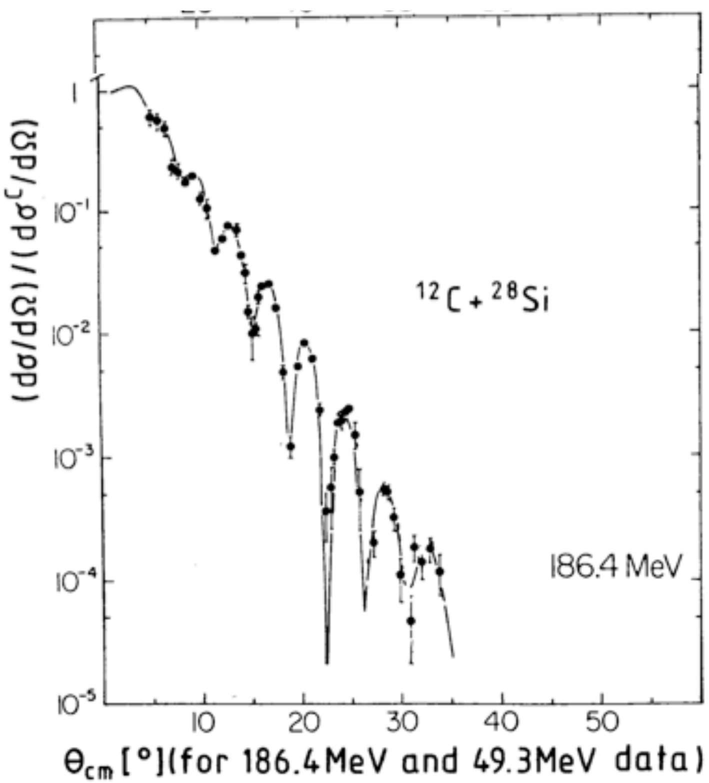


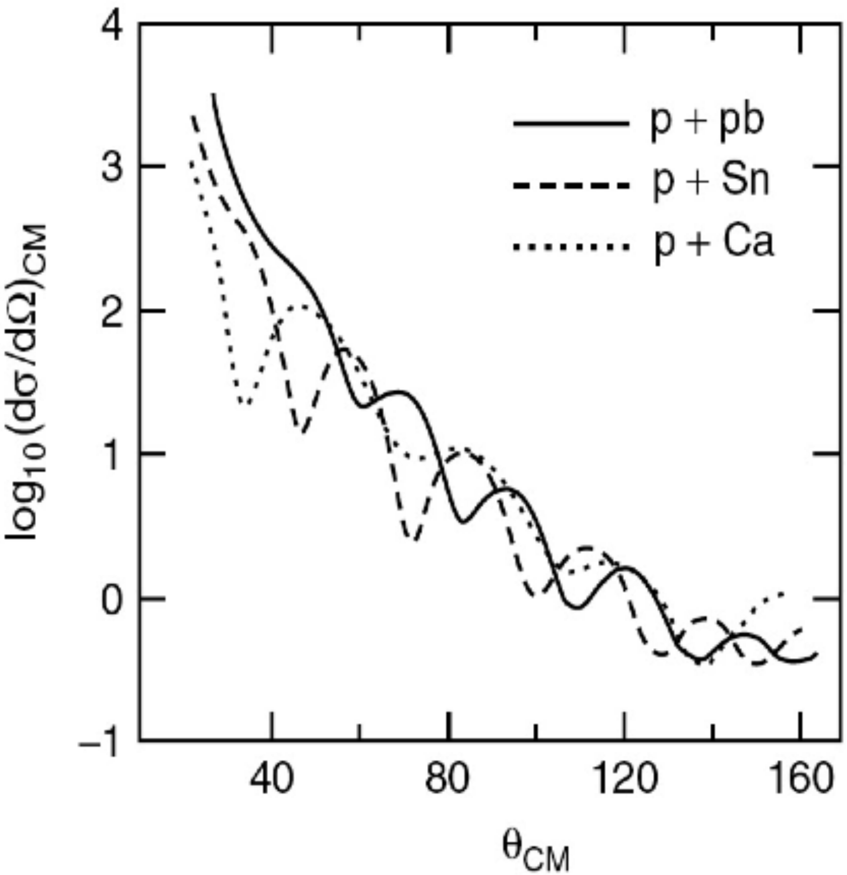
T. Suda *et al.,* Phys. Rev. Lett. **102** (2009).

Heavy-ion & proton elastic scattering

- Nuclear absorption
- Fraunhofer-type interferences

$$\Delta\theta = 1/(Rp)$$





C. Bertulani, Wiley Encyclopedia of Physics

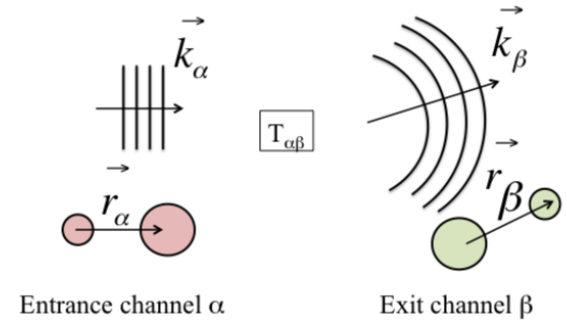
Solving the Schrodinger equation for elastic scattering

$$(H-E)\psi=0$$

$V_\alpha = V_\alpha(\vec{r}_\alpha)$ optical potential approximation

$H = h_\alpha + T_\alpha + V_\alpha$ with h_α is the intrinsic hamitonian

$\psi = \Phi_A \chi$ intrinsic wave **X** relative motion



Homogenous equation (no interaction potential)

$$(h_\alpha + T_\alpha - E)\phi_\alpha = 0 \Rightarrow \phi_\alpha = e^{i\vec{k}_\alpha.\vec{r}_\alpha}\Phi_\alpha$$

Inhomogenous equation: $(T_\alpha - E)\chi = -V_\alpha \chi$

$$\Rightarrow \chi = \phi_\alpha - \frac{V_\alpha}{T_\alpha - E}\chi$$ distorted wave

$T_{\alpha\beta} = \langle \phi_\beta | V_\alpha | \chi_\alpha \rangle$ transition matrix element (prior form)

Remark if one assumes $\psi_\alpha = \phi_\alpha$ (**First Born approximation**)

$T_{\alpha\beta} = \langle \phi_\beta | V | \phi_\alpha \rangle = \int e^{i(\vec{k}_\alpha - \vec{k}_\beta).\vec{r}} V(\vec{r})\, d^3\vec{r}$ for elastic scattering

Optical potentials

1) **Empirical** Optical Potentials (Parameterized on data)

$V(R) = V_0(R) + i\,W(R) + \ldots$ (surface, spin-orbite, Coulomb)

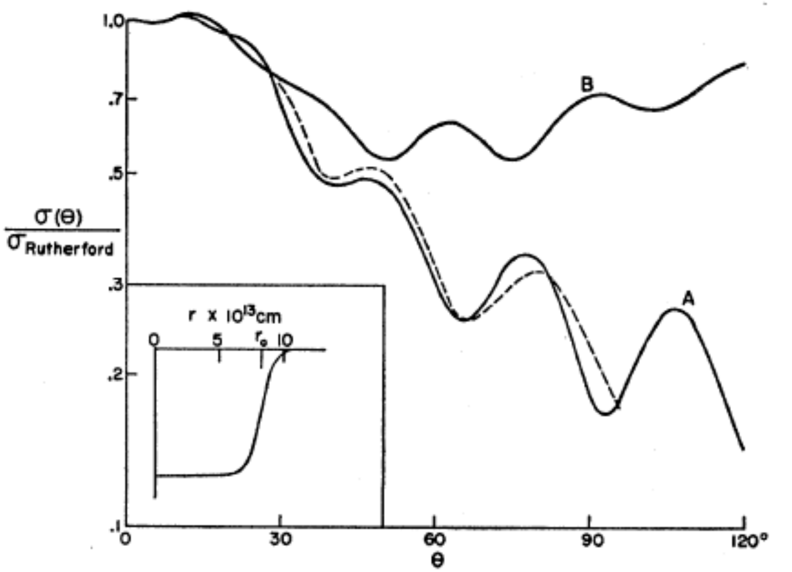


FIG. 1. Elastic scattering of 22-Mev protons by Pt relative to Rutherford scattering. The dashed curve is the experimental result of Cohen and Neidigh (see reference 3), the normalization of which is somewhat uncertain. Curve A is calculated for a diffuse surface model with $V=38$ Mev, $W=9$ Mev, $r_0=8.24\times10^{-13}$ cm, and $a=0.49\times10^{-13}$ cm. The shape of the well is shown in the small drawing at the lower left. Curve B is calculated for a square well of comparable size and depth.

Optical potentials

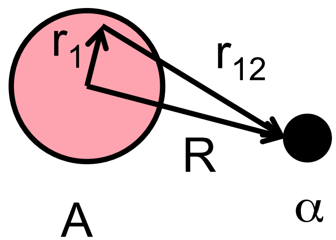
1) **Empirical** Optical Potentials (Parameterized on data)

V(R) = V_0(R) + i W(R) + … (surface, spin-orbite, Coulomb)

2) **Microscopic** Optical Potential

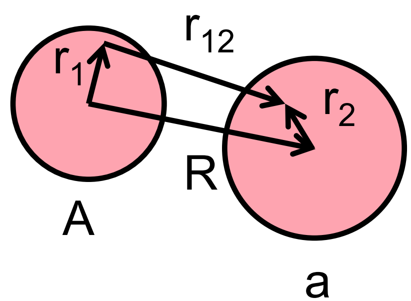
Simple folding

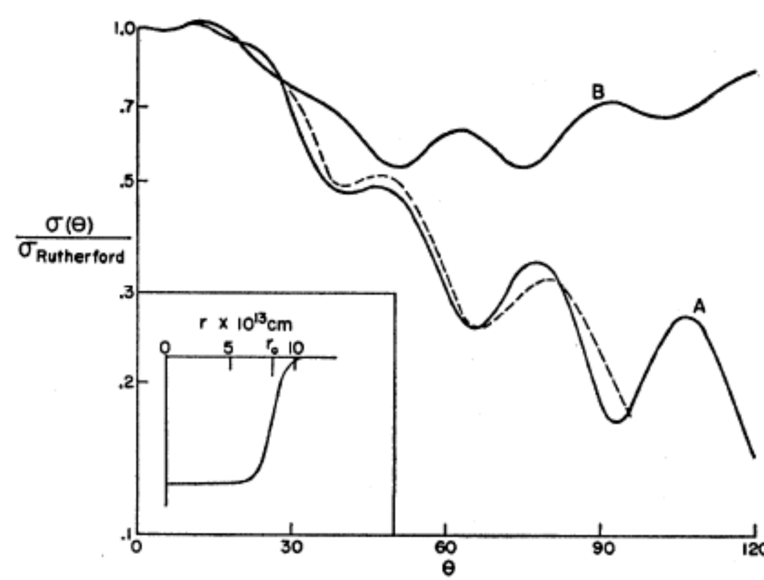
$$V(\vec{R}) = \int \rho_A v(\vec{r_{12}})$$



Double folding

$$V(\vec{R}) = \int\int \rho_\alpha \rho_A v(\vec{r_{12}})$$





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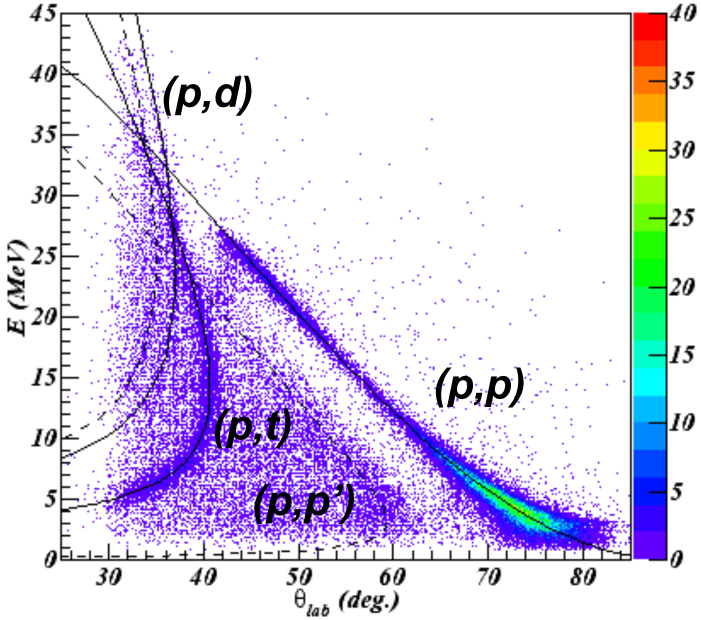
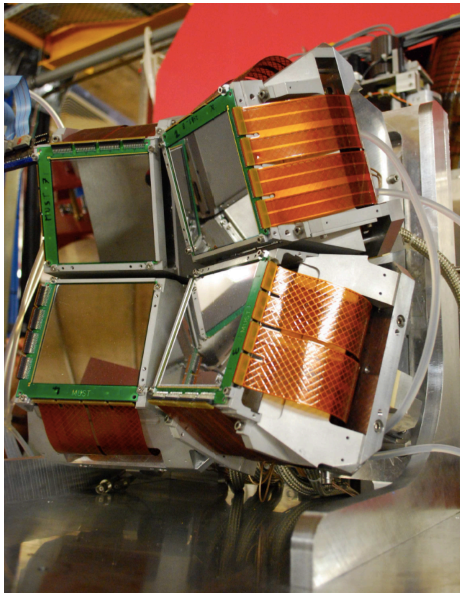
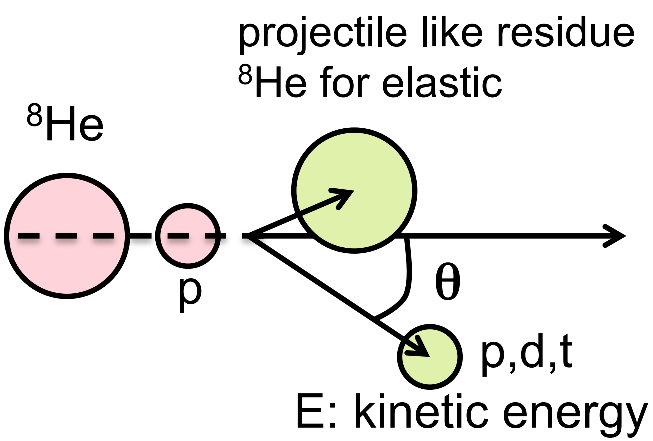
Example of proton elastic scattering from ^{8}He

^{8}He+p at 16 MeV/nucleon, with MUST2 @ GANIL







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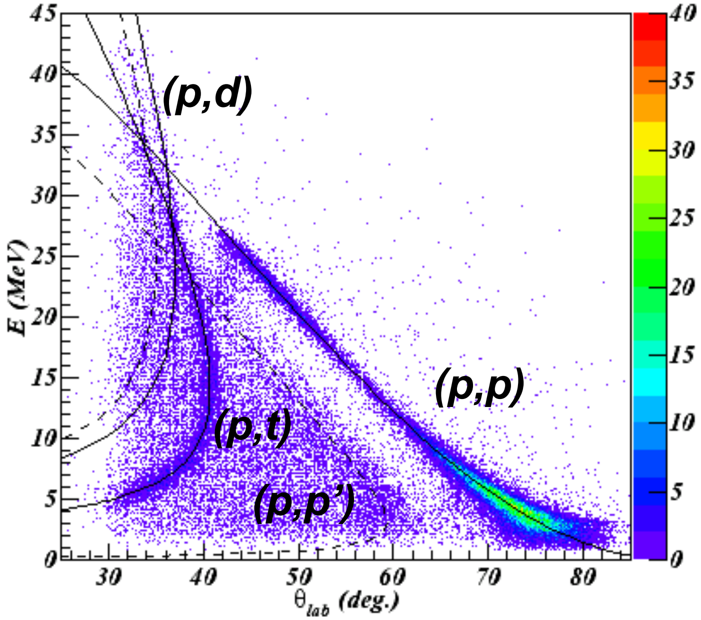
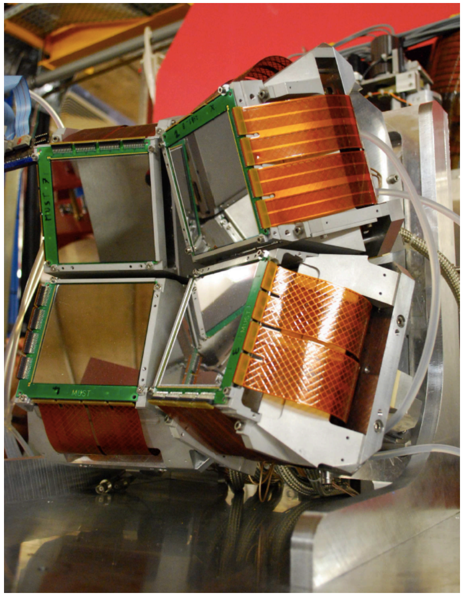
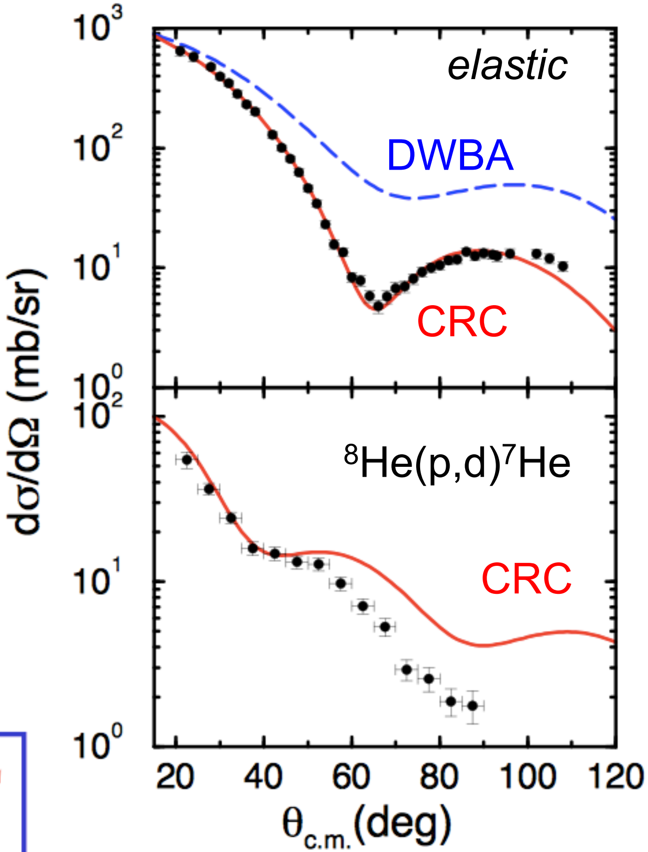


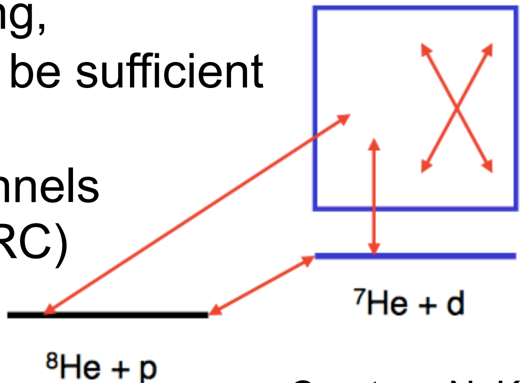




N. Keeley et al., PLB **619** (2005).

Nota Bene:
When reaction channels are strong, treating the elastic alone may not be sufficient

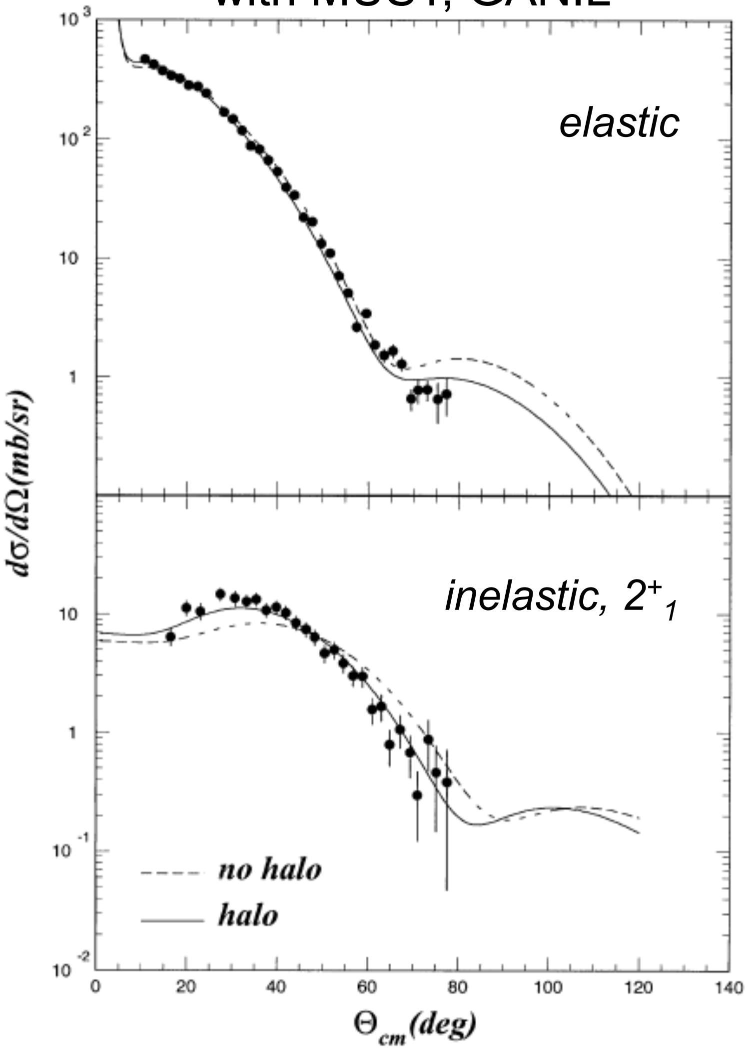
➔ Explicit treatment of other channels
➔ Coupled reaction channels (CRC)



Courtesy N. Keeley (Warsaw) and V. Lapoux (CEA)

Proton inelastic scattering

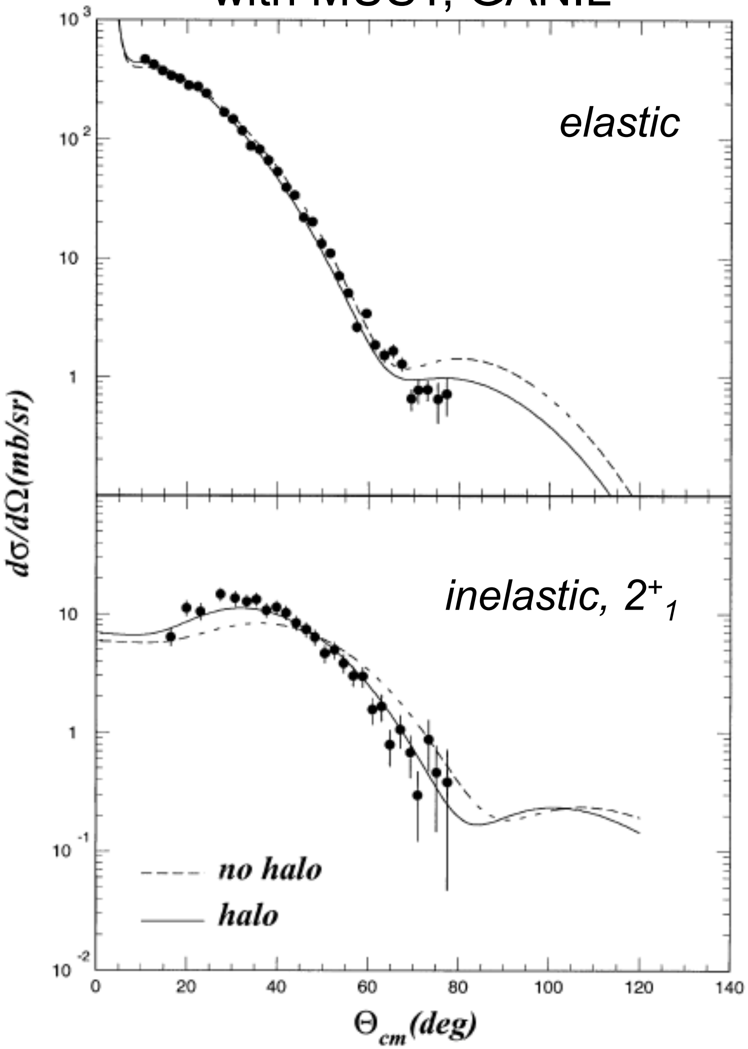
^{6}He(p,p') at 40.9 MeV/nucleon,
with MUST, GANIL



A. Lagoyannis et al., PLB **518** (2001).

Proton inelastic scattering

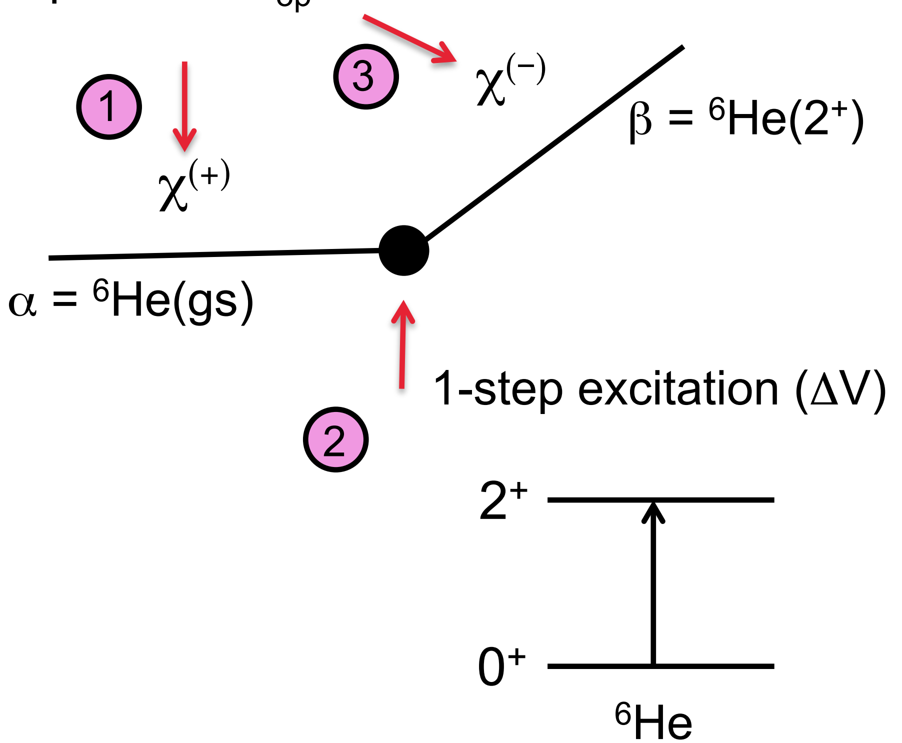
$^6He(p,p')$ at 40.9 MeV/nucleon, with MUST, GANIL



A. Lagoyannis et al., PLB **518** (2001).

The **Distorted Wave Born approximation**

Distorsion of the incoming & outgoing waves
Optical potential V_{op}



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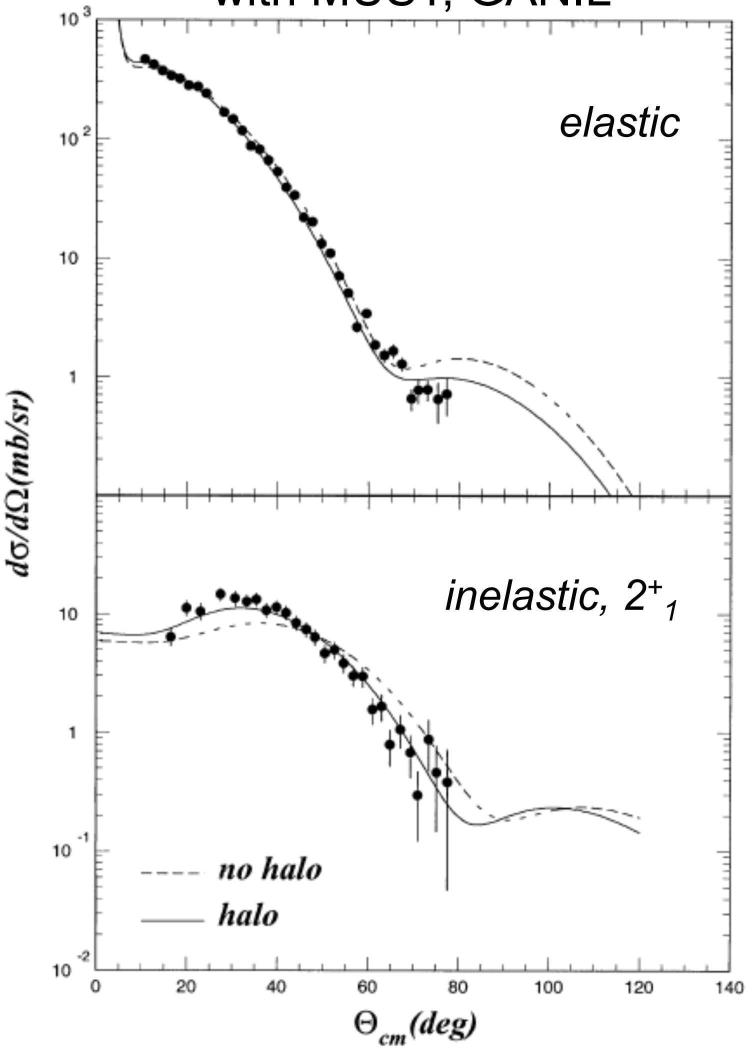


A. Lagoyannis et al., PLB **518** (2001).

Two potential equation

$$(H - E)\psi = 0$$

$$H = h_\alpha + T_\alpha + V_{OP} + \Delta V$$

Distorted wave χ:

$$(h_\alpha + T_\alpha + V_{OP} - E)\chi_\alpha^{(+)} = 0$$

Transition matrix element (**DWBA** approximation)

$$T_{\alpha\beta} = \left\langle \chi_\beta^{(-)}\Phi_\beta \middle| \Delta V \middle| \chi_\alpha^{(+)}\Phi_\alpha \right\rangle$$

$$= \int\int \chi_\beta^{(-)}(\vec{k}_\beta, \vec{r}_\beta)\left\langle \Phi_\beta \middle| \Delta V \middle| \Phi_\alpha \right\rangle \chi_\alpha^{(+)}(\vec{k}_\alpha, \vec{r}_\alpha) d^3r_\alpha d^3r_\beta$$

Nota Bene: ΔV depends on the structure model

1) **Microscopic** description of $<\Phi_\beta|\Delta V|\Phi_\alpha>$

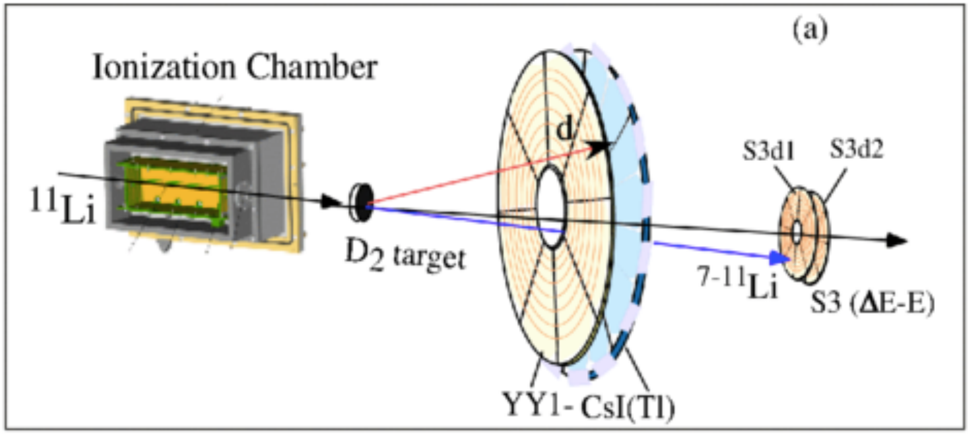
2) **Collective model** (*ex.* rotational)

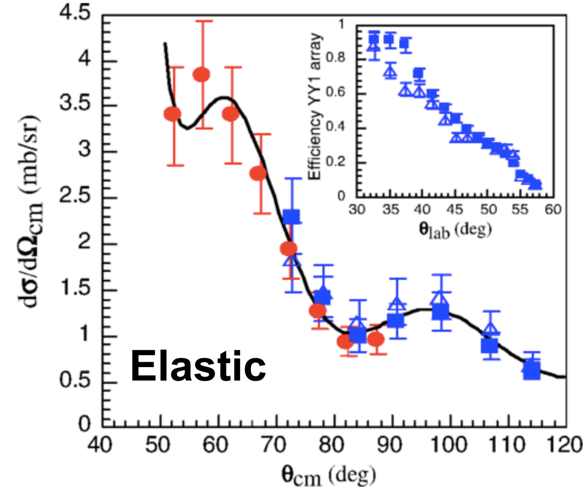
Amplitude of ΔV governed by a parameter

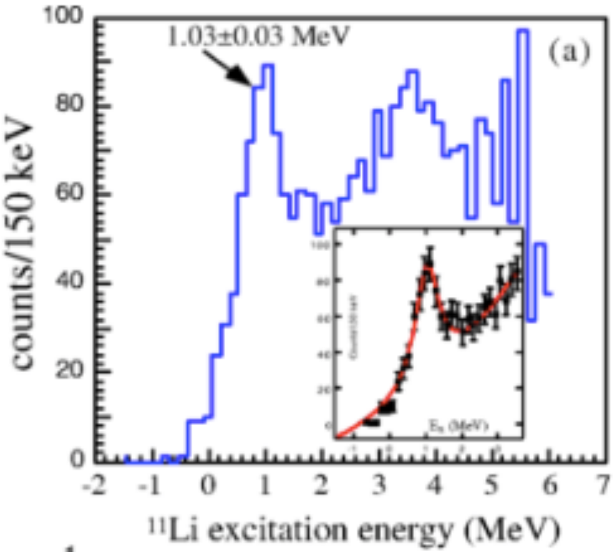
$$\delta_{LM} = deformation\ length$$

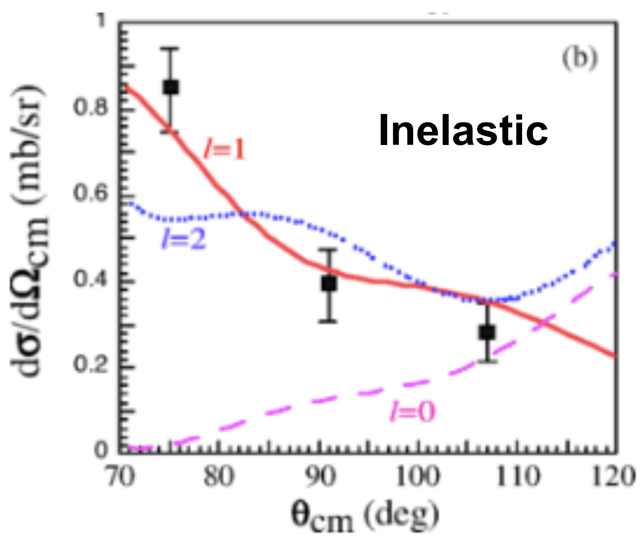
Inelastic scattering from ^{11}Li: soft dipole resonance

R. Kanungo *et al.*, PRL **114** (2015)









- ^{11}Li at 5.5 MeV/u
- **3000 pps**
- D_2 solide target (100μm)
- TRIUMF

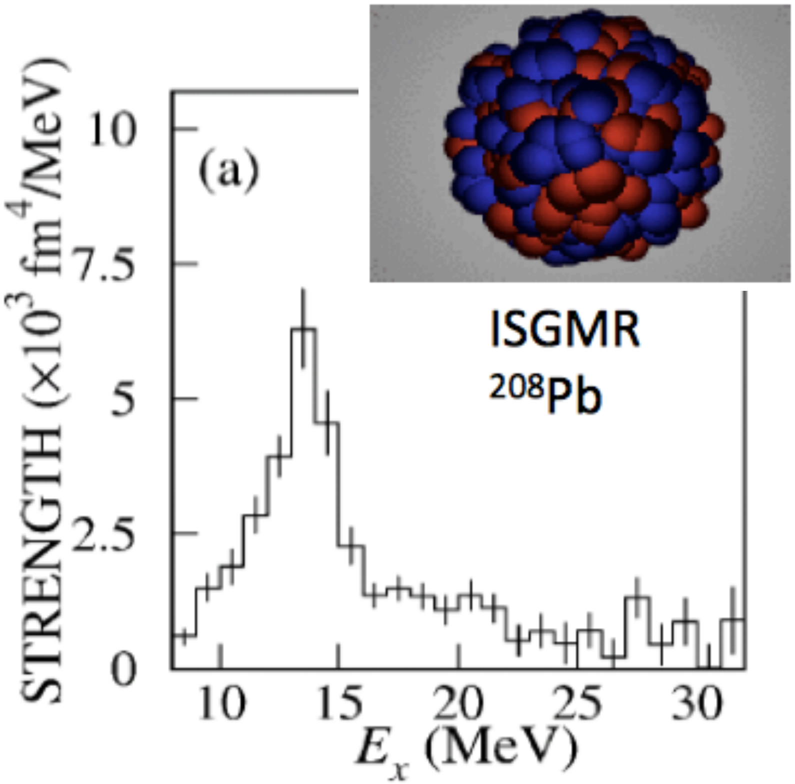
- **DWBA analysis**
- collective (δ) model
- L =1 assignement

➔ Dipole resonnance

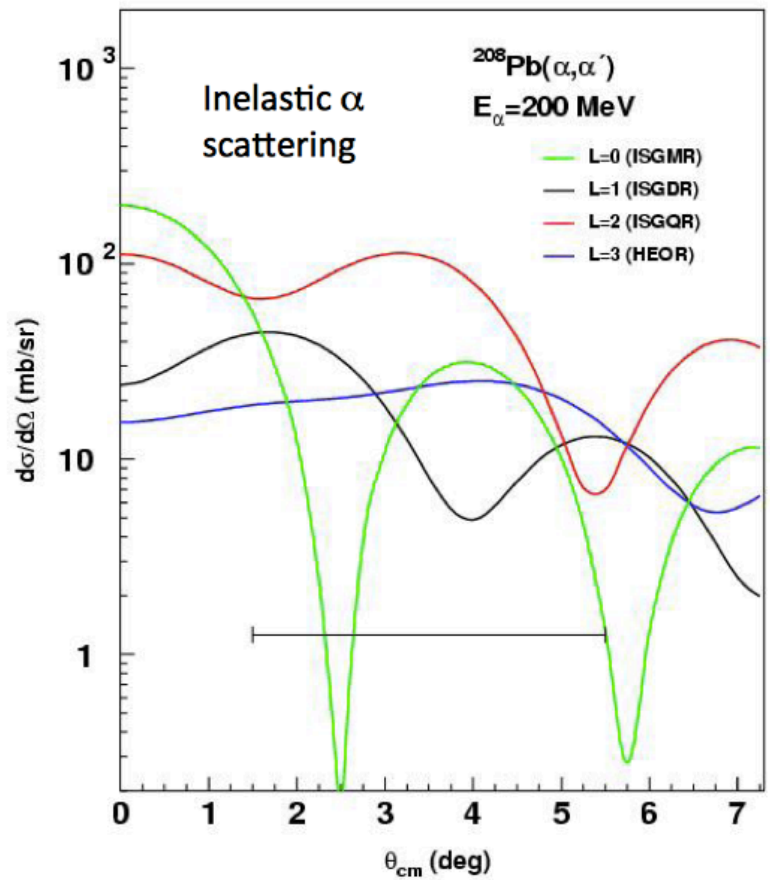
Giant Monopole Resonance (GMR)

Isoscalar Giant Monopole Resonance: **compression mode** of the nucleus

Measure around 0°$_{cm}$ is needed to maximize and extract the Monopole (L=0 transfer)

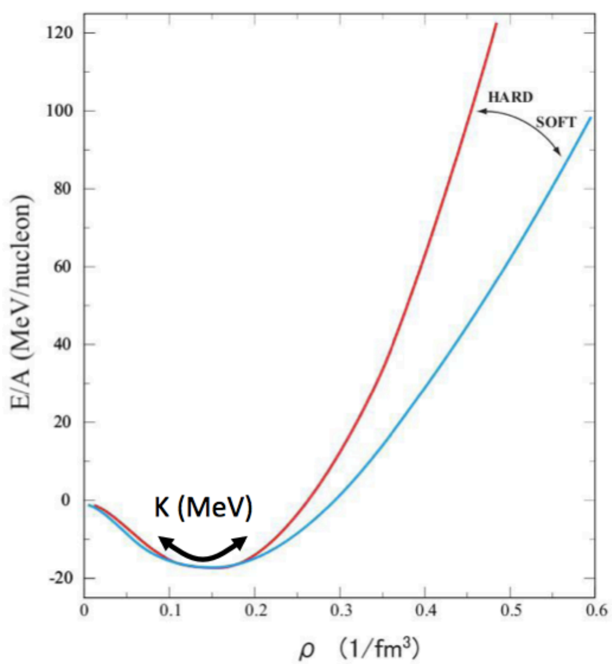


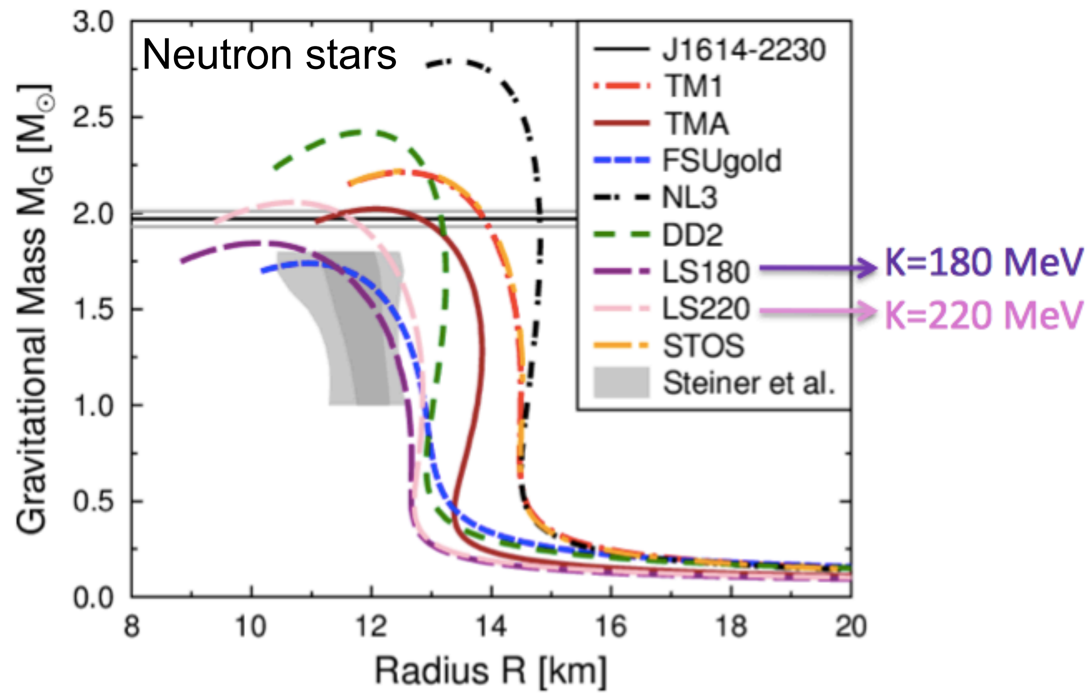
M. Uchida *et al.*, Phys. Lett. B **557** (2003)



Nuclear incompressibility

Energy needed to change the density of nuclear matter around equilibrium





Incompressibility from a nucleus to the infinite matter:

$$K_A = K_\infty + K_{surf} A^{-1/3} + K_\tau \delta^2 + K_{Coul} \frac{Z^2}{A^{4/3}}$$

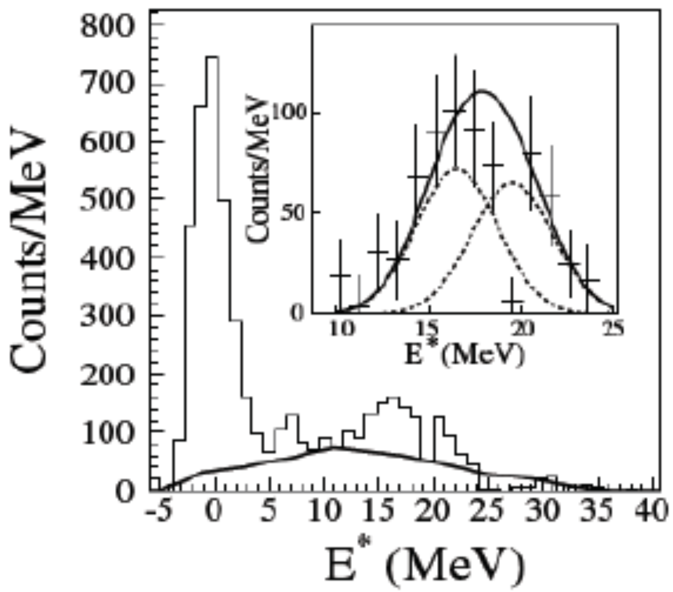
From GMR energy

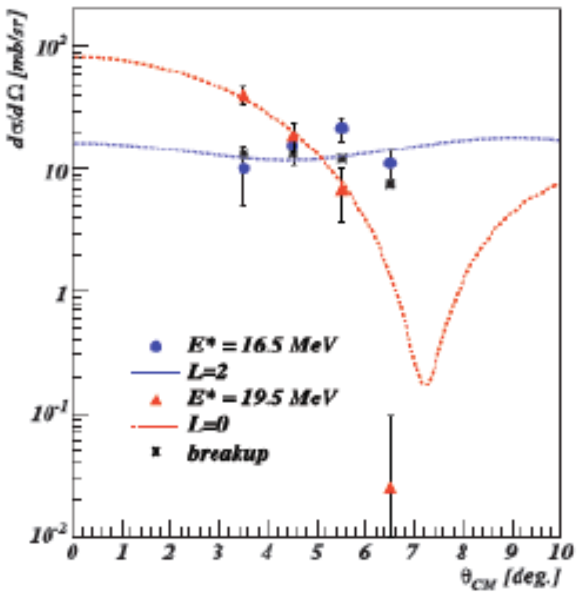
asymmetry term δ = (N-Z)/A => **exotic nuclei only!**

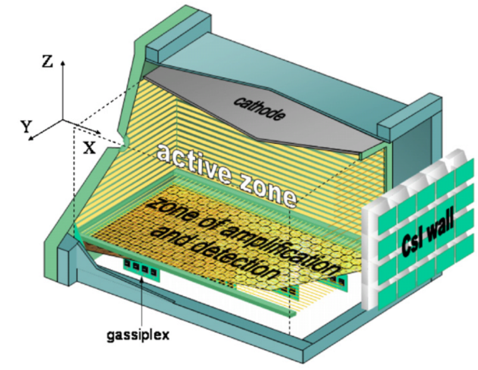
GMR in unstable nuclei

Low-energy recoil (specific detection), incident energies from 50 to 100 MeV/nucleon

^{56}**Ni(α,α')** at 50 A MeV, GANIL with MAYA : **first GMR from unstable nucleus**





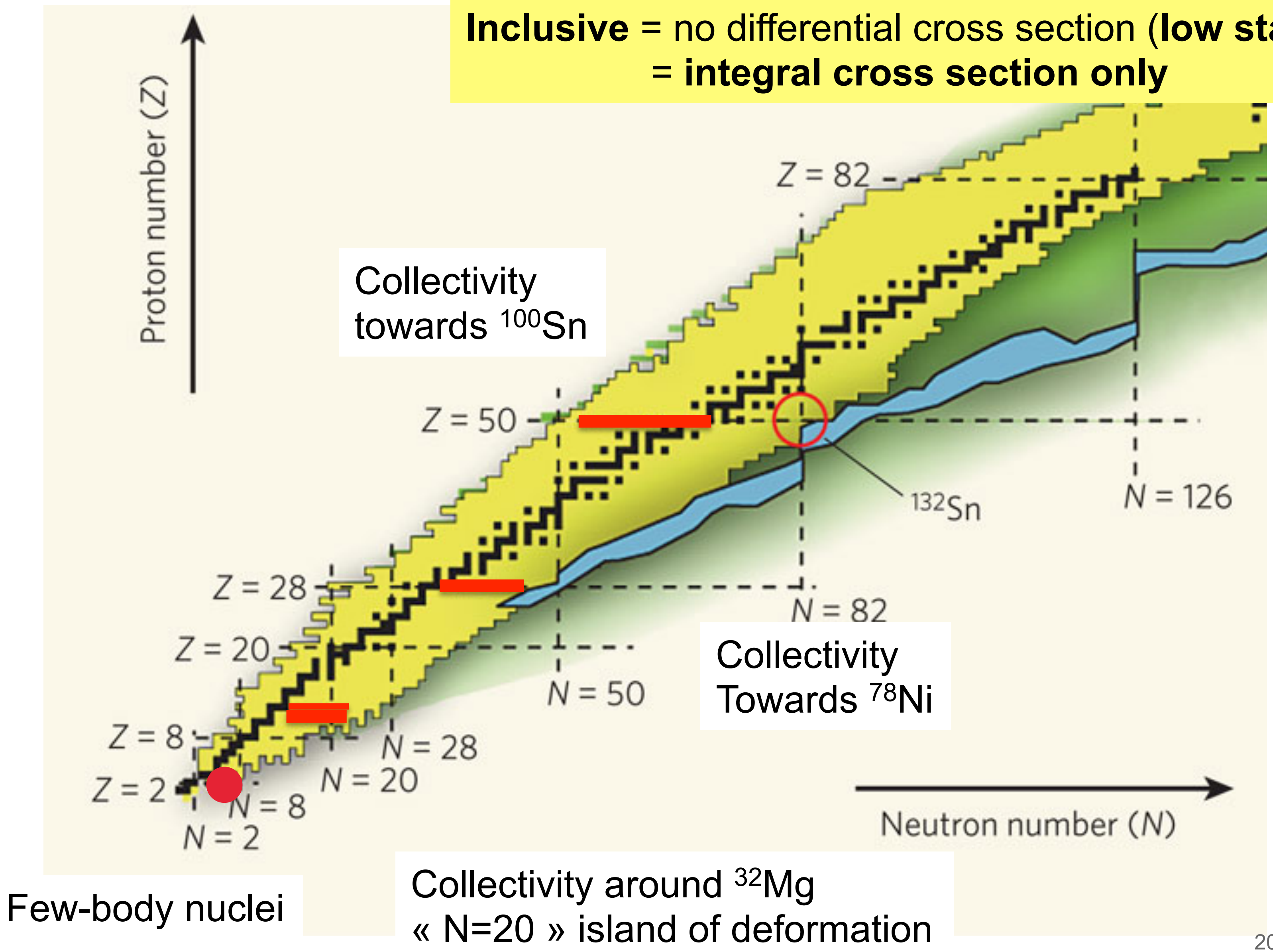


C. Monrozeau *et al.*, Phys. Rev. Lett. **100** (2008).

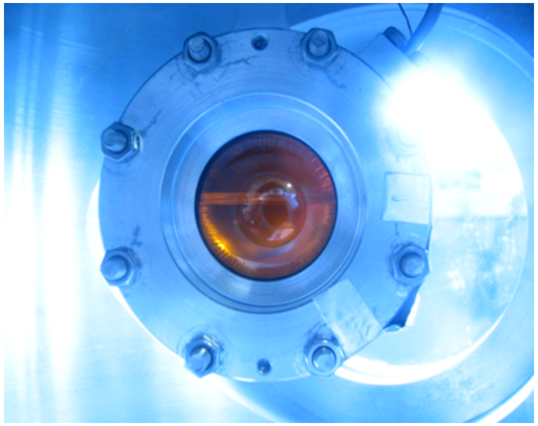
Recently ^{68}**Ni(α,α')**, GANIL, M. Vandebrouck et al., Phys. Rev. Lett. **113** (2014).
Near future, ^{132}**Sn(α,α')**, RIKEN, S. Ota (CNS) *et al.*

Collectivity in unstable nuclei from inclusive (p,p')

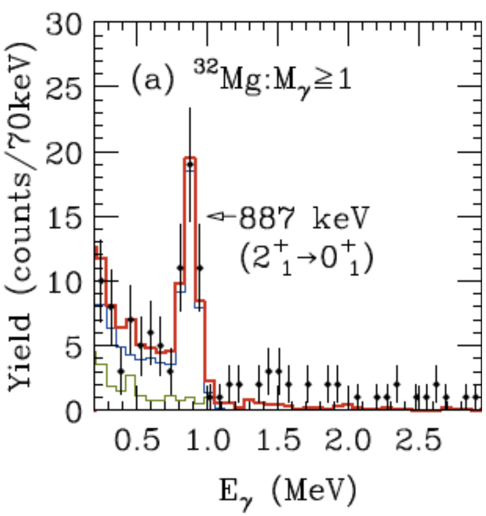
Inclusive = no differential cross section (**low statistics**)
= **integral cross section only**



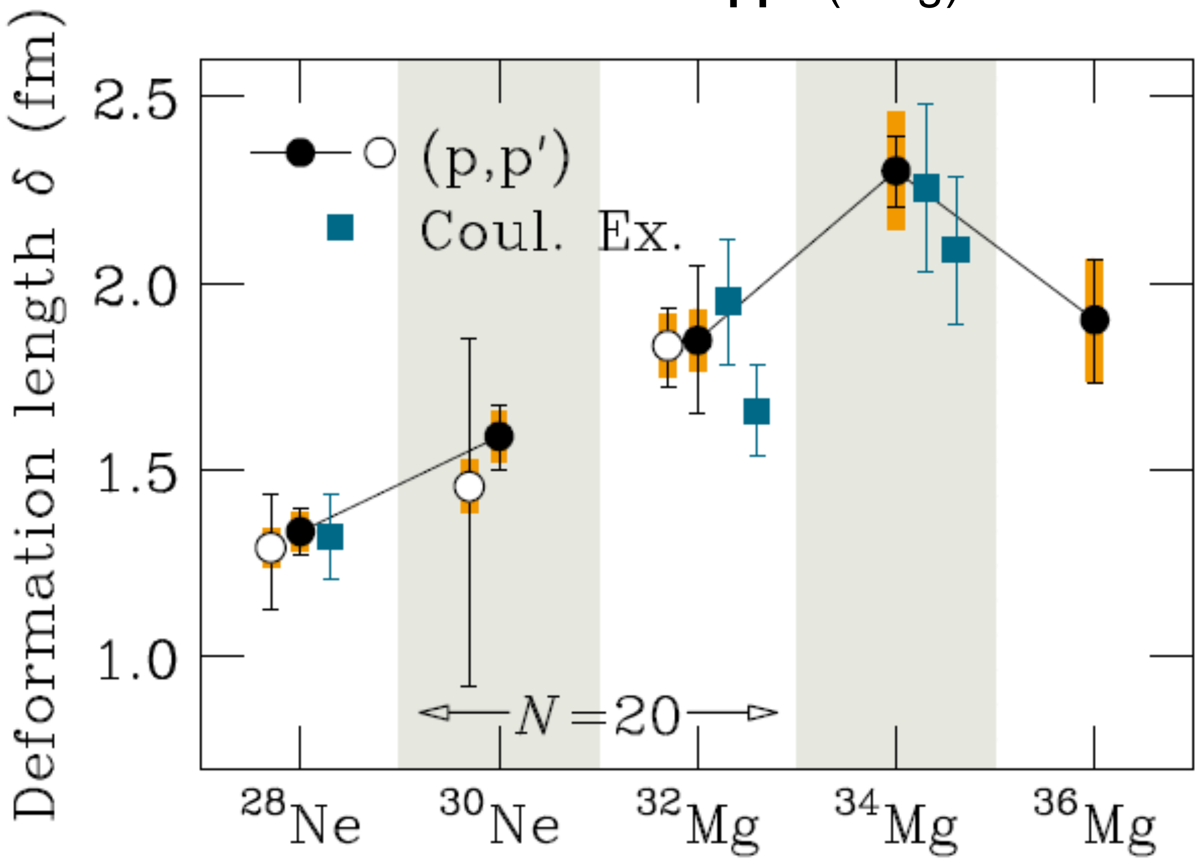
Onset of deformation in the region of ^{32}Mg (N=20)



RIKEN experiment:
liquid H_2 target
+ DALI2 NaI scintillator array



^{28,30}Ne, $^{32\text{-}36}$Mg beams at about 50 MeV/nucleon
Intensities: **Down to 0.3 pps** (^{36}Mg)



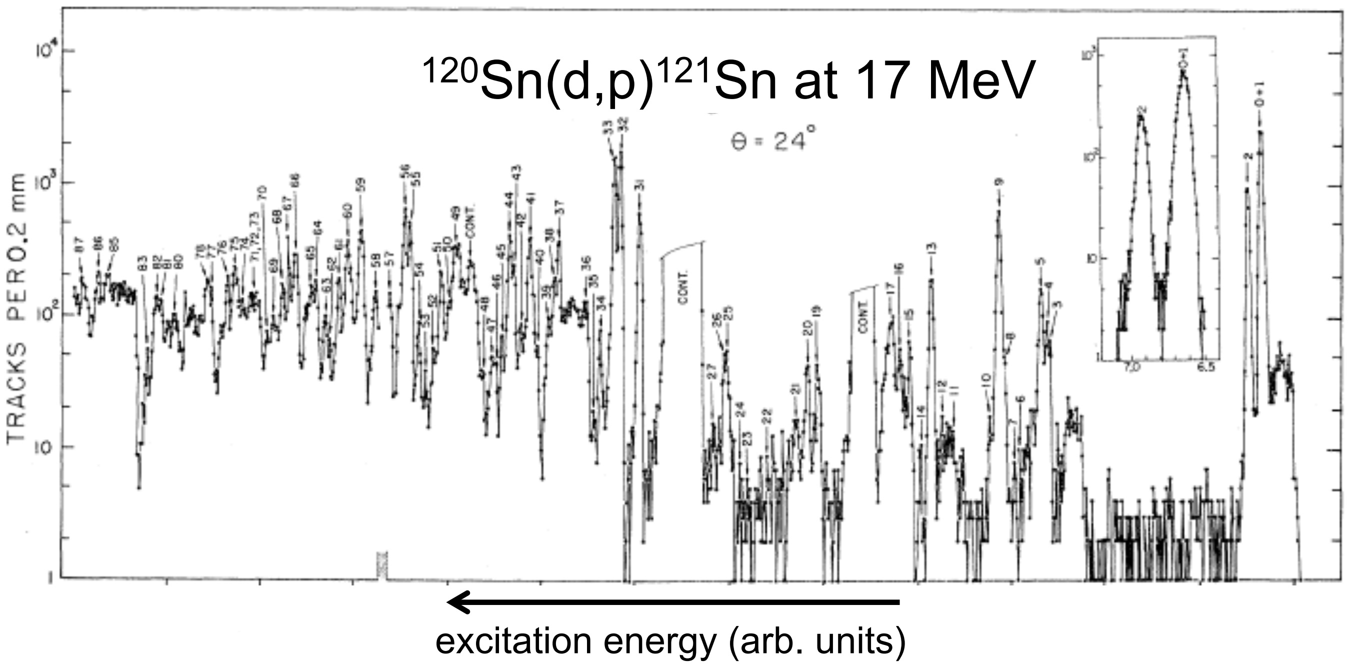
S. Michimasa *et al.*, Phys. Rev. C **89** (2014).

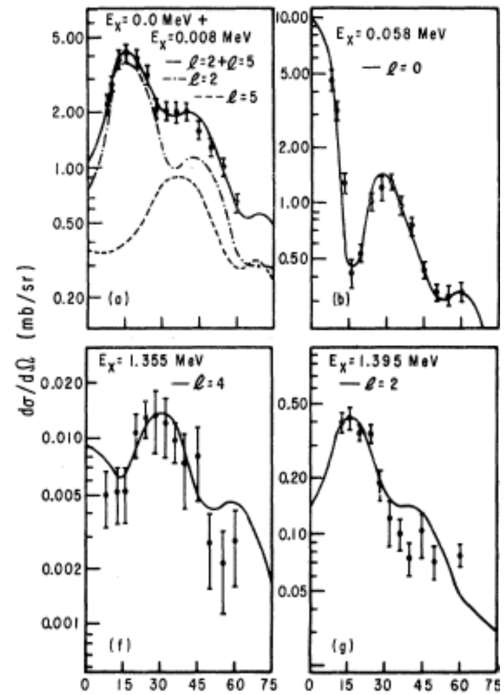
Inclusive cross section: low beam intensity… and high uncertainties

Outline

- Elastic and inelastic scattering
- Nucleon transfer
  - sensitivity to the shell model / spectroscopic factors
  - the Distorted-Wave Born Approximation (DWBA)
  - achievements with exotic nuclei
  - correlations from two nucleon transfer
- Knockout reactions
  - S-matrix theory and eikonal approximation
  - Nuclear structure from knockout & in-beam γ spectroscopy
  - Absolute SF: transfer versus knockout
  - Quasifree scattering
- Future developments and probes

Transfer reactions : selectivity / direct





M.J.Bechara and O.Dietzsch, Phys. Rev. C **12** (1975).

- Direct: **surface process**
- Transfer: **momentum matching** (Fermi velocities, 5 to 50 MeV/nucleon)
- **Conservation** of: spin, parity, angular momentum

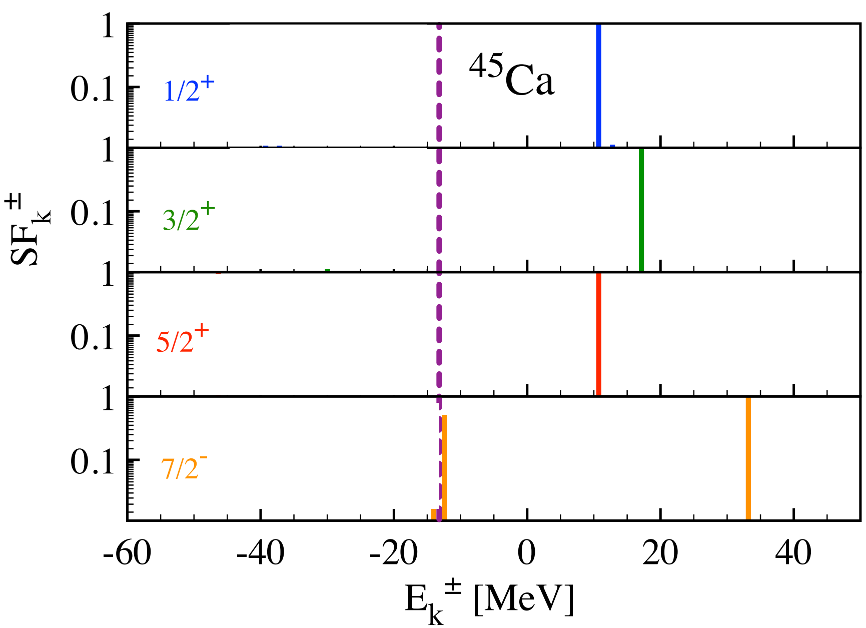
Intuitive view of Spectroscopic Factors (SFs)

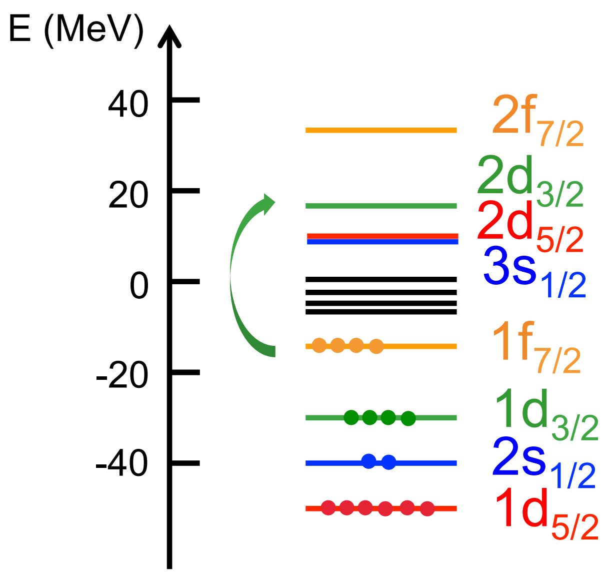
Spectroscopic factor: the square overlap of a final state with a single particle state

$$S_k^{n\ell j\ +} = \left| \left\langle \psi_k^{A+1} \middle| a_{n\ell j}^{+} \middle| \psi_0^{A} \right\rangle \right|^2$$

Pickup, ex: $^{44}Ca(d,p)^{45}Ca$

Pure single-particle ^{44}Ca nucleus





Ab Initio calculations (Gorgov Green's function): courtesy V. Somà, CEA

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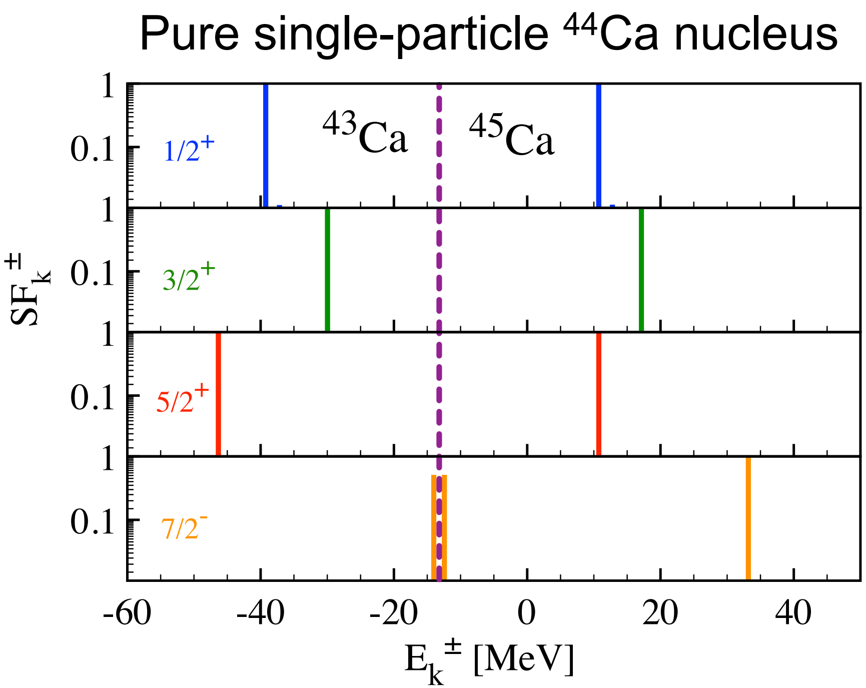
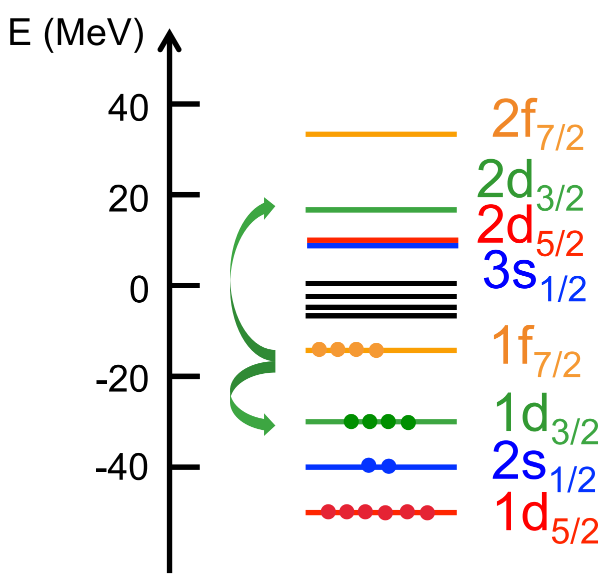
Pickup, ex: ^{44}Ca(d,p)^{45}Ca

$$S_k^{n\ell j\ -} = \left| \left\langle \psi_k^{A-1} \middle| a_{n\ell j} \middle| \psi_0^{A} \right\rangle \right|^2$$

Stripping, ex: ^{44}Ca(p,d)^{43}Ca





Ab Initio calculations (Gorgov Green's function): courtesy V. Somà, CEA

Intuitive view of Spectroscopic Factors (SFs)

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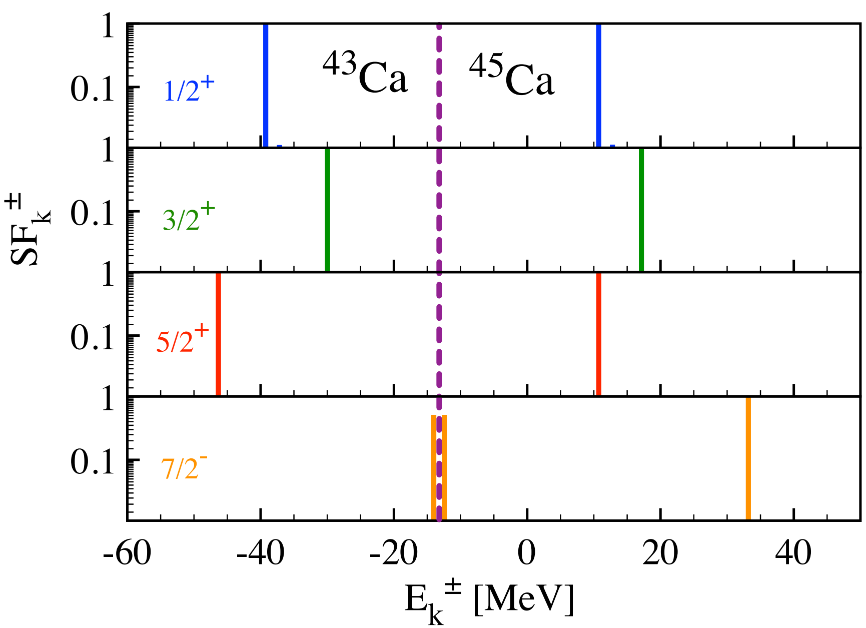
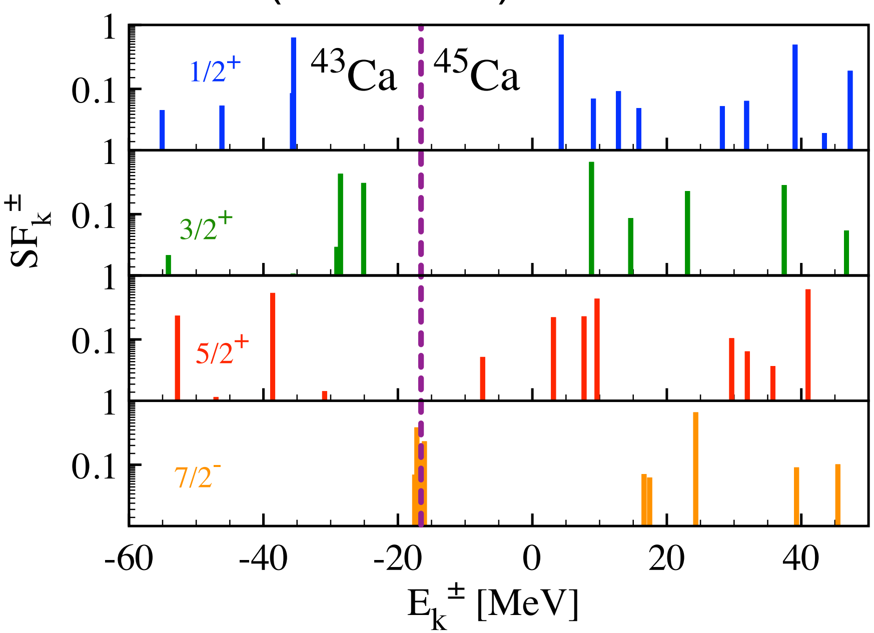
Pure single-particle ^{44}Ca nucleus



Real (correlated) ^{44}Ca nucleus



In reality: $0 < SF < 1$

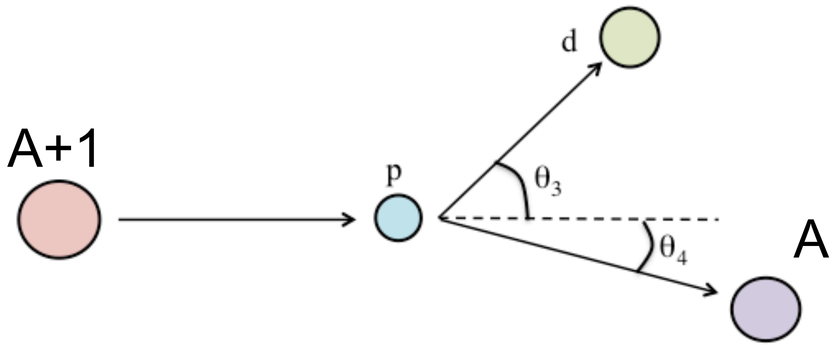
Ab Initio calculations (Gorgov Green's function): courtesy V. Somà, CEA

Transfer reaction in the Born Approximation

Plane wave approx.: p+(A+1) ➔ d + A

$$|\psi_\alpha\rangle = e^{i\vec{k}_p.\vec{r}_p}\Phi_{A+1,\alpha}$$

$$|\psi_\beta\rangle = e^{i\vec{k}_d.\vec{r}_d}\Phi_{A,\beta}\Phi_d(\vec{r}_n - \vec{r}_p)$$



Transition matrix element

$$T \propto \langle\psi_\beta|V|\psi_\alpha\rangle = \int e^{-i\vec{k}_d.\vec{r}_d}\Phi_d^*(\vec{r})\Phi_A^* V(\vec{r}) e^{i\vec{k}_p.\vec{r}_p}\Phi_{A+1} d^3r_{A+1} d^3r_p$$

Transfer reaction in the Born Approximation

Plane wave approx.: **p+(A+1) ➔ d + A**

$$|\psi_\alpha\rangle = e^{i\vec{k}_p.\vec{r}_p}\Phi_{A+1,\alpha}$$

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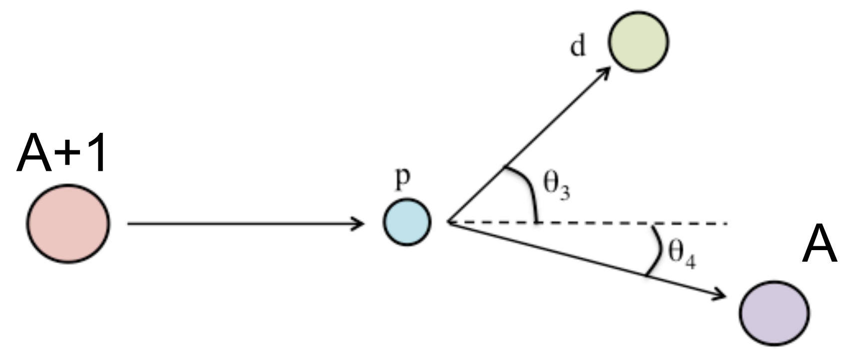

Transition matrix element

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In the case of a **pure single-particle neutron state** $\Phi_{A+1,\alpha} = \Phi_{A,\beta}\phi_{n\ell j}(\vec{r}_n)$

$$T = \int e^{-i\vec{k}_d.\vec{r}_d}\Phi_d^*(\vec{r})\Phi_A^* V_{np}(\vec{r}) e^{i\vec{k}_p.\vec{r}_p}\phi_{n\ell j}\Phi_A d^3 r_A d^3 r_n d^3 r_p$$

Fourier transform of The picked-up neutron

which leads to $T = \int e^{-i\vec{K}.\vec{r}}\Phi_d^*(\vec{r})V_{np}(\vec{r})d^3 r \times \int_R^\infty e^{-i\vec{q}.\vec{r}_n}\phi_{n\ell j}(\vec{r}_n)d^3 r_n$

$\vec{q} = \vec{k}_d - \vec{k}_p$ momentum carried by the picked-up neutron

$K = k_p - k_n/2$

Transfer reactions: DWBA

$$T_{\alpha\beta} = \left\langle \chi_\beta^{(-)} \Phi_\beta \middle| V \middle| \chi_\alpha^{(+)} \Phi_\alpha \right\rangle \quad with \left| \Phi_{A+1,\beta} \right\rangle = \sum_{n\ell j} \sqrt{S_\beta^{n\ell j+}} \left| \phi_{n\ell j} \Phi_A \right\rangle$$

$$= \sum_{n\ell j} \sqrt{S_\beta^{n\ell j+}} \int \chi_d^{(-)*}(\vec{k}_d, \vec{r}_d) \Phi_d^*(\vec{r}) \left\langle \Phi_A^* \phi_{n\ell j}^* \middle| V_{np}(\vec{r}) \middle| \Phi_{A+1,\beta} \right\rangle \chi_p^{(+)}(\vec{k}_p, \vec{r}_p) d^3 r_p d^3 r_d$$

nuclear structure — deuteron wf & reaction process

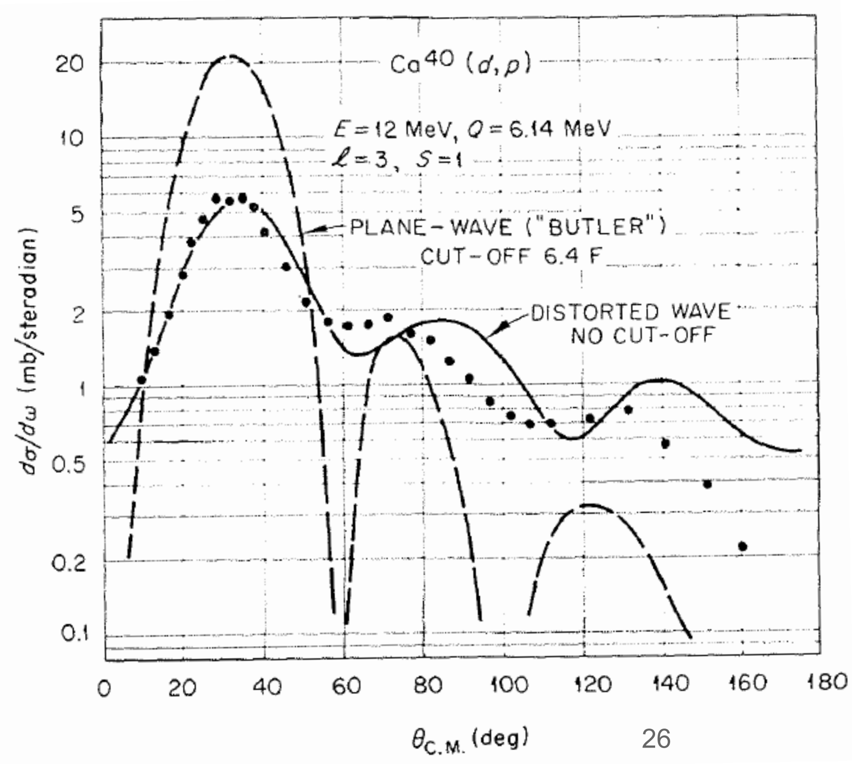
Nota Bene: **in the DWBA, reaction mechanism and structure are separated**

Transfer cross section in DWBA

$$\frac{d\sigma_{\alpha\beta}}{d\Omega} = \sum_{n\ell j} S_{n\ell j} \left. \frac{d\sigma_{\alpha\beta}}{d\Omega} \right|_{n\ell j}$$

Analysis of experiments

1) Measure dσ/dΩ
2) Calculate dσ/dΩ single particle
3) Extract S_{nlj} by comparison
4) Compare to S_{nlj} from theoretical model



Why spectroscopic factors are so important?

Single particle energies e_{nlj} can be accessed from:

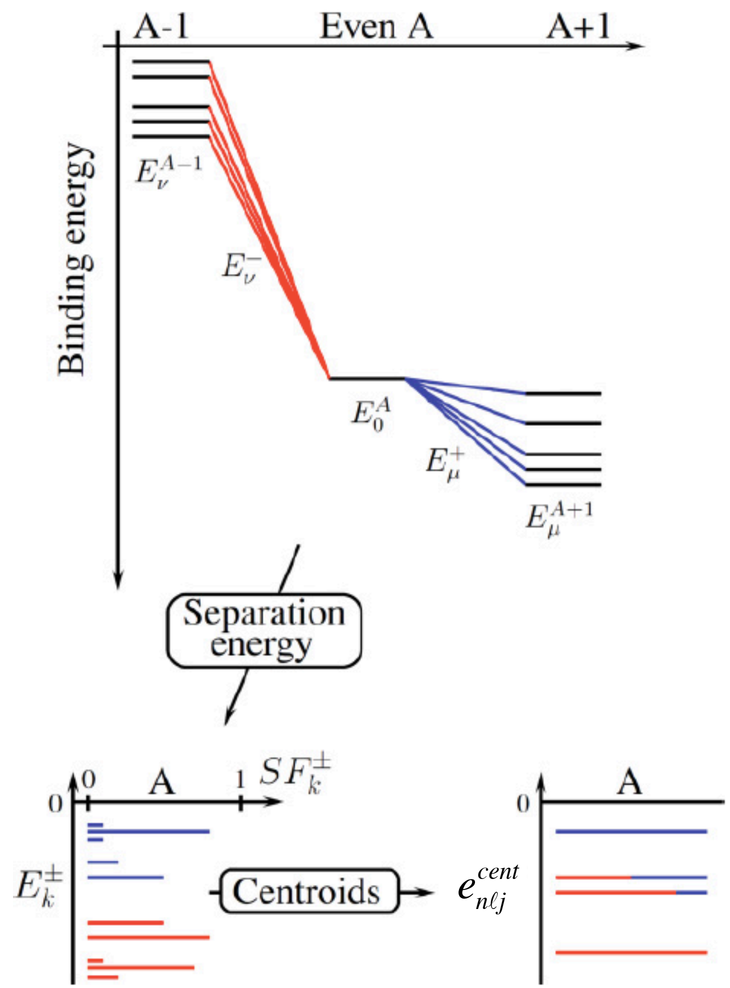
- **physical state energies E_k** (observables) from pickup AND stripping
- **spectroscopic factors S_k^{nlj}** (not observables)

Baranger equation:

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

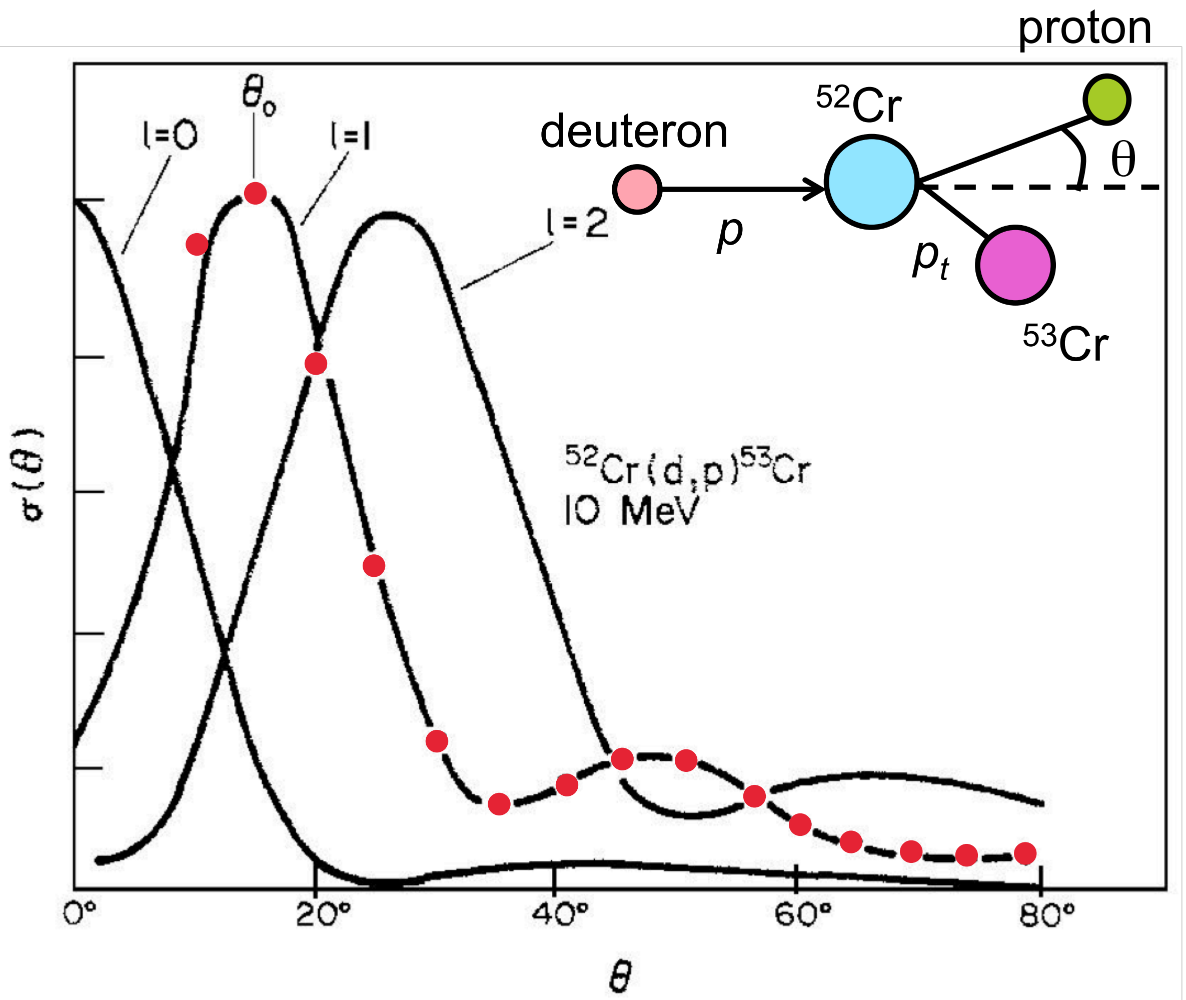
In principle, in a given theoretical framework, **SFs** can be obtained from **cross sections.**

In reality, uncertainties are today too large to extract single-particle energies directly from the Baranger equation.



T. Duguet and G. Hagen, PRC **85** (2012)

Transfer reactions: angular distributions



L.D. Knutson and W. Haeberli, Prog. Part. Nucl. Phys. **3** (1980).

- Classical derivation:

$$\hat{L}^2 \left|\phi_{n\ell j}\right\rangle = (\ell+1)\ell\hbar^2 \left|\phi_{n\ell j}\right\rangle$$

$$p_t \approx p \times \sin(\theta)$$

$$L = R \times p_t \Rightarrow Rp\sin(\theta) = \sqrt{(\ell+1)\ell}\hbar$$

$$\Rightarrow \theta_0 = \sin^{-1}\left(\frac{\sqrt{(\ell+1)\ell}\hbar}{Rp}\right)$$

- Numerical application:

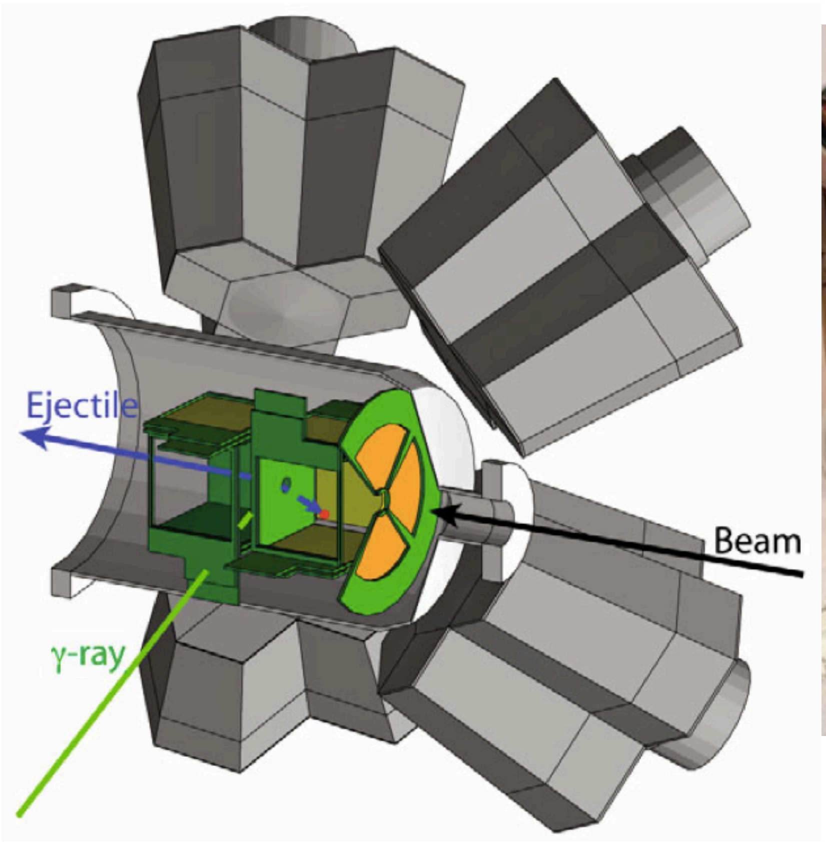
$$\ell = 0 \Rightarrow \theta_0 = 0^\circ$$

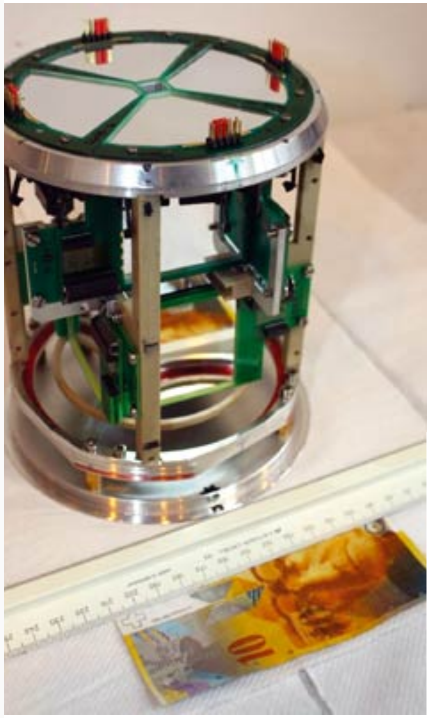
$$\ell = 1 \Rightarrow \theta_0 = 19^\circ$$

$$\ell = 2 \Rightarrow \theta_0 = 34^\circ$$

Example of setup for low-energy reaction studies

T-REX+MINIBALL setup at **ISOLDE, CERN**: particle-γ detection for direct reactions
ISOLDE: energies up to 5.5 MeV/nucleon (from 2015), up to 8 MeV/nucleon from 2018





Particle resolution

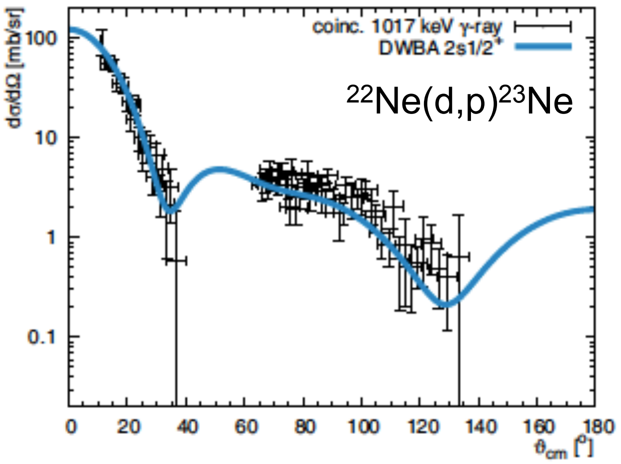
- 150 keV FWHM

For a 100 μg.cm^{-2} target

- 600 keV FWHM

For a 1 mg.cm^{-2} target

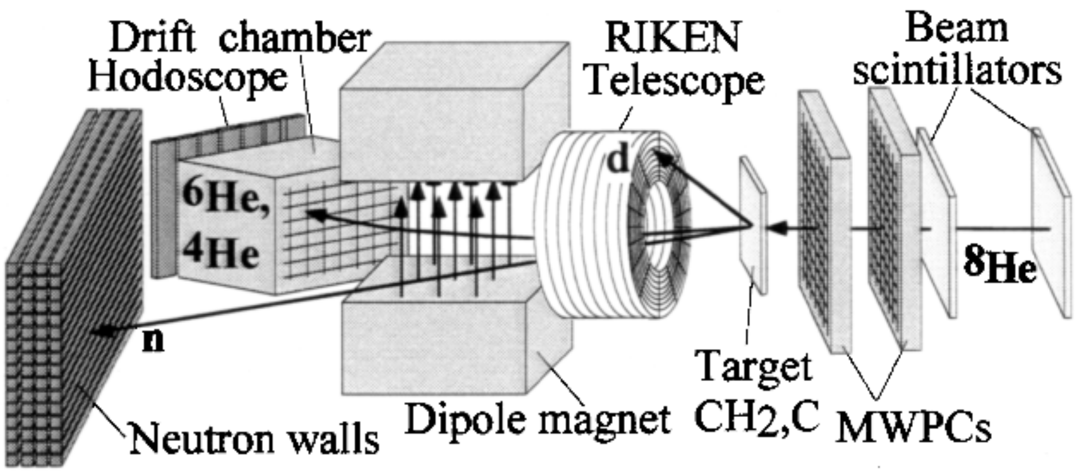
Photopeak gamma efficiency
5% at 1.3 MeV

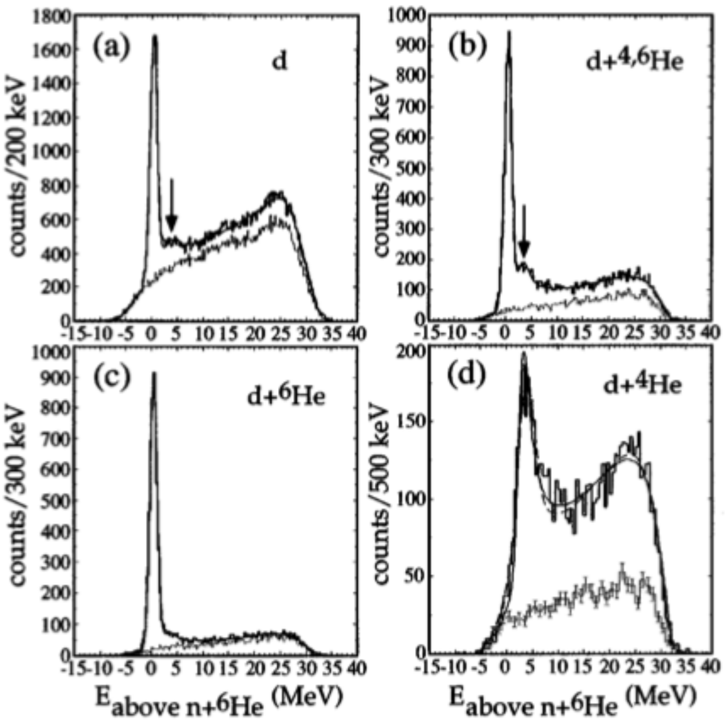


Other « similar » setups worldwide:
SHARC+Tigress at TRIUMF,TIARA+MUST2+EXOGAM at GANIL
… other ongoing developments (TRACE - GASPARD for SPES/GANIL in Europe)

Few-body systems and nuclear resonances

- spectroscopy of **few-body systems** (bound and **unbound states**) is key to understand nuclear structure
- transfer reactions are unique **to populate selectively and identify states**
- a huge work in many laboratories (Dubna, RIKEN, GANIL, TRIUMF,…)

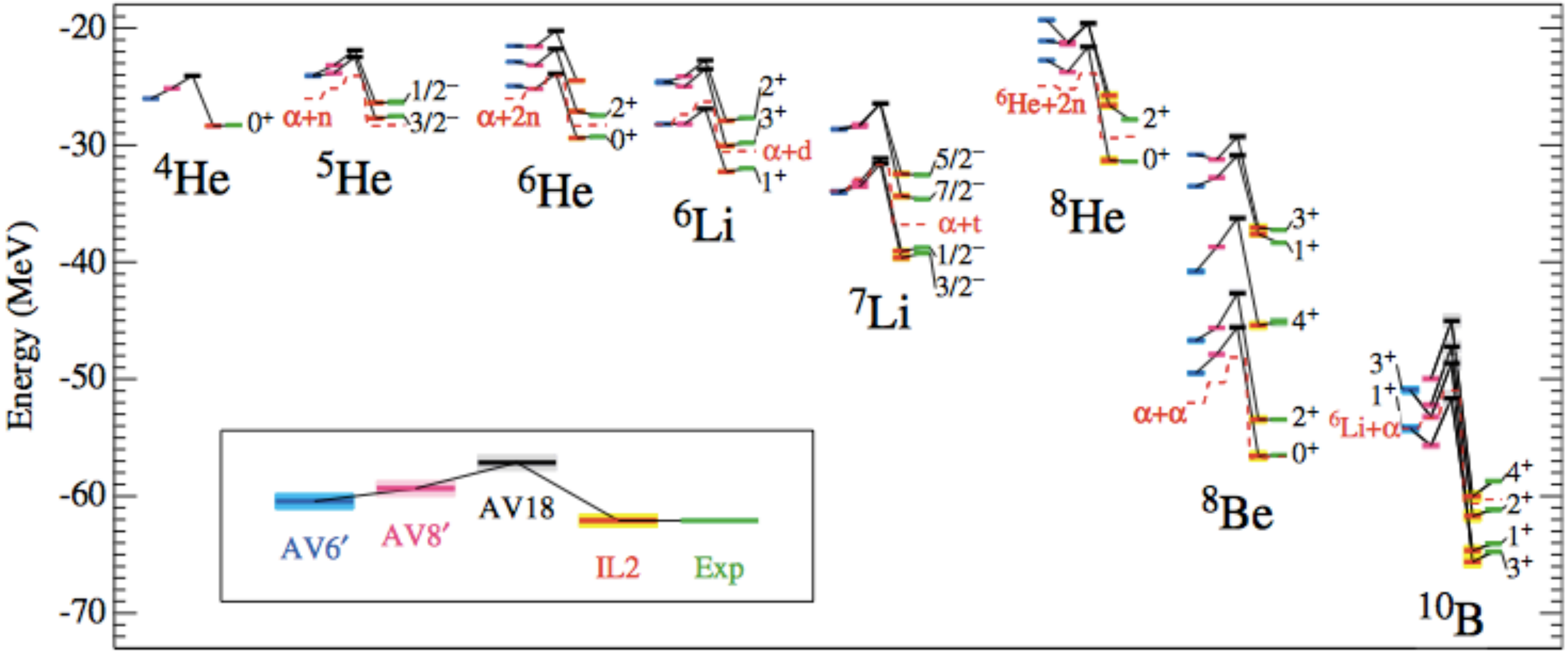




^{8}He(p,d)^{7}He at 50 MeV/nucleon, RIPS, RIKEN
A.A. Korshenninikov *et al.*, PRL **82** (1999)

Few-body systems and nuclear resonances

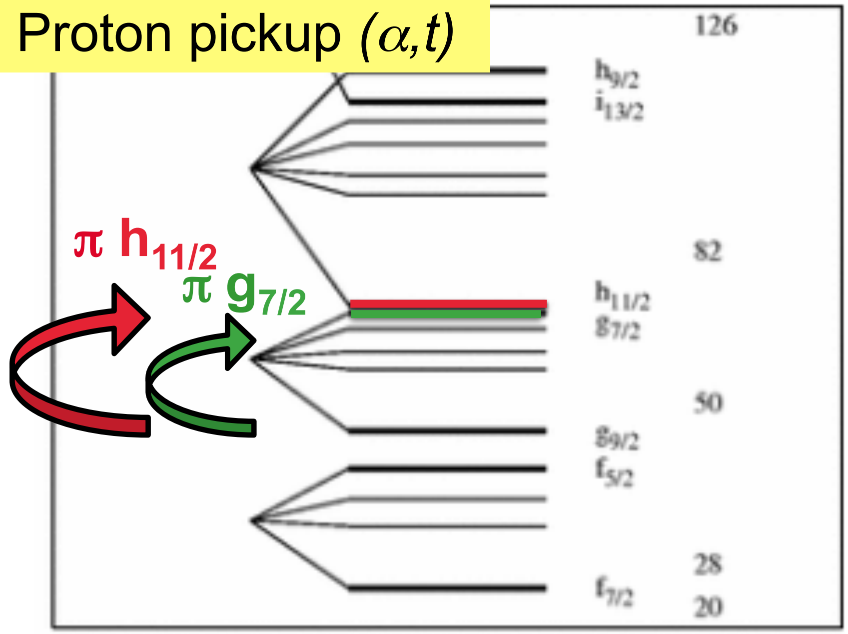
R.B. Wiringa *et al.*, PRL **89** (2002)

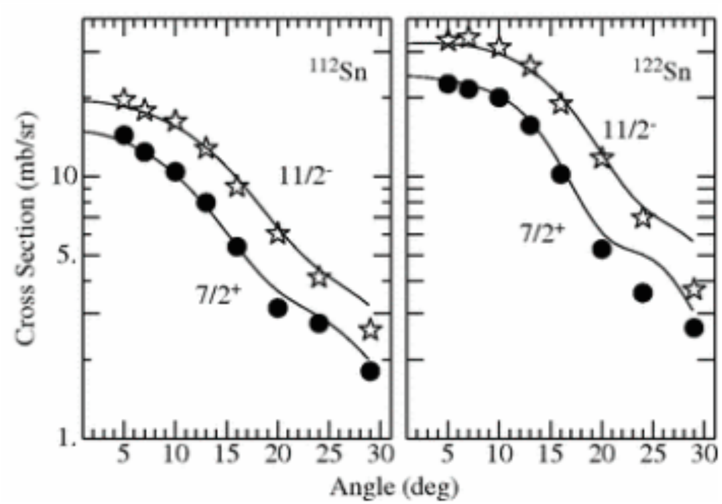


- Few-body resonances are still searched experimentally
- Transfer to the continuum active domain
  - *Ex.* MAGNEX collaboration in Catania, MUST2 collaboration

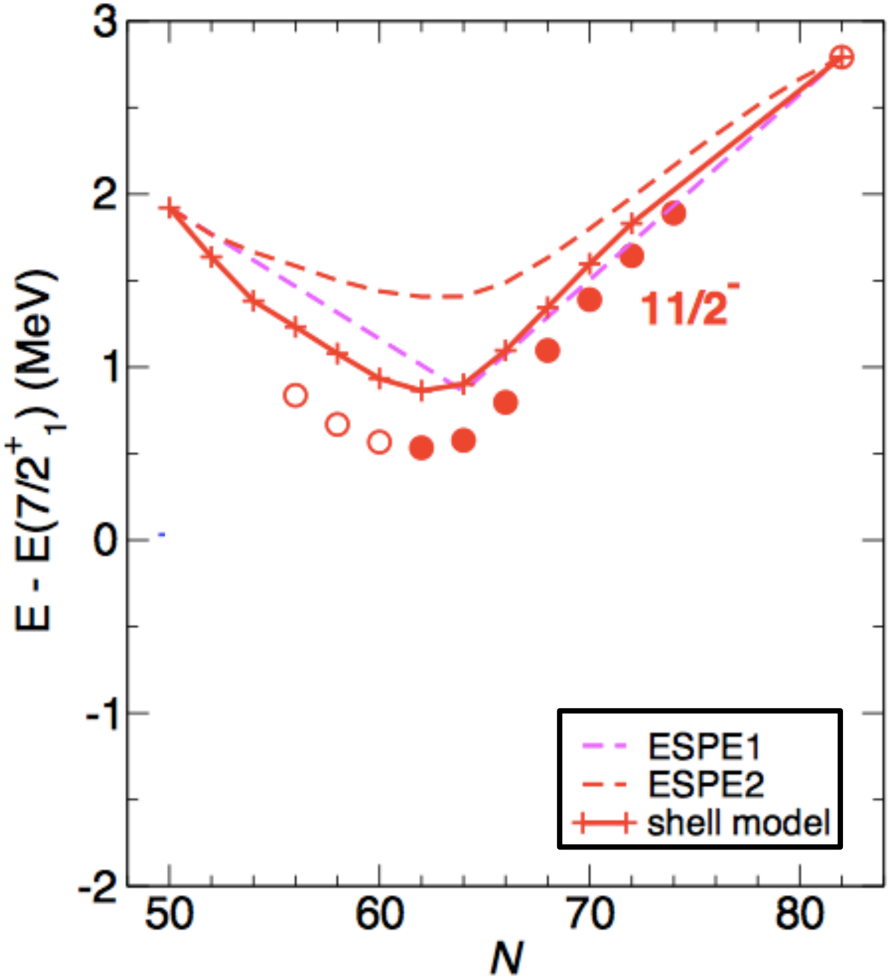
Shell evolution: spin-orbit reduction

Proton pickup *(α,t)*



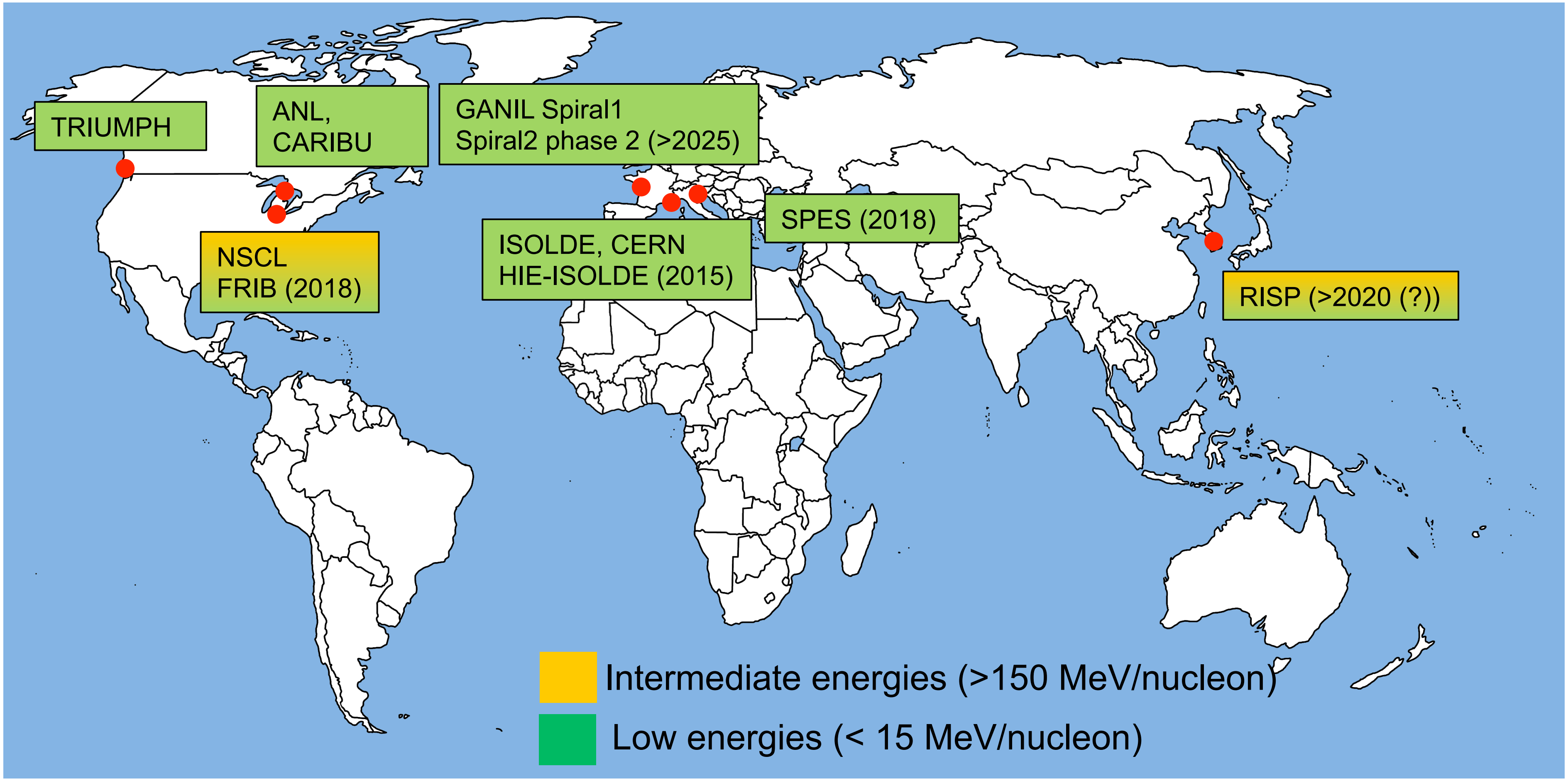


Shell model calculations



J.P. Schiffer et al., PRL **92** (2004)

New ISOL / re-accelerated beam facilities worldwide

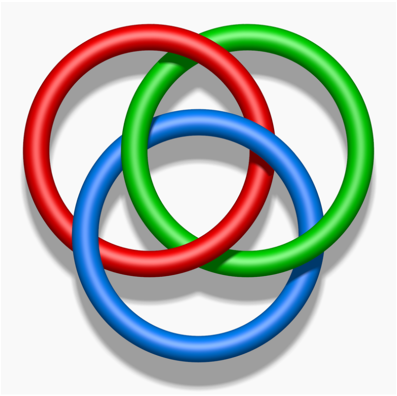


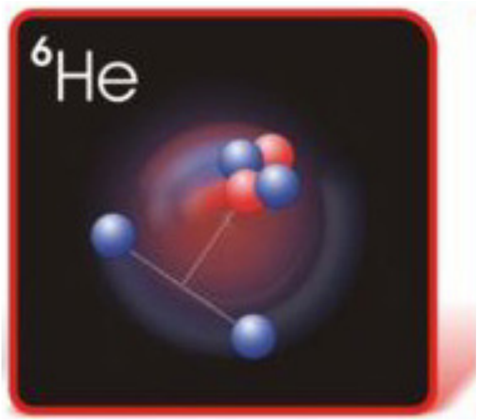
…and many associated new detector developments

See lecture by R. Raabe

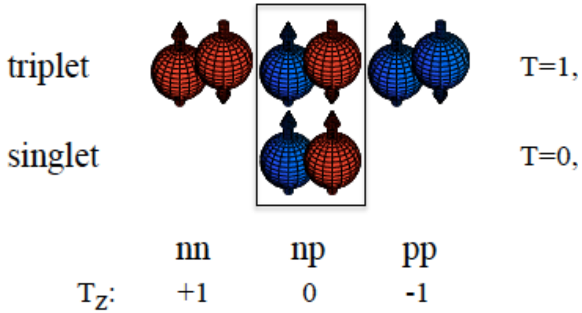
Beyond single particles : few body correlations

T=1 pairing, dineutron

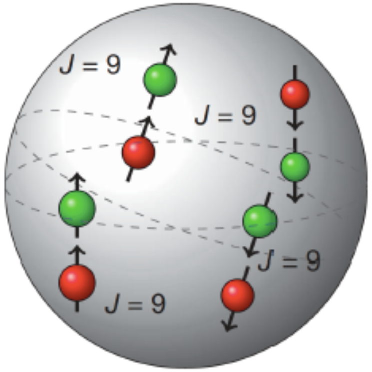




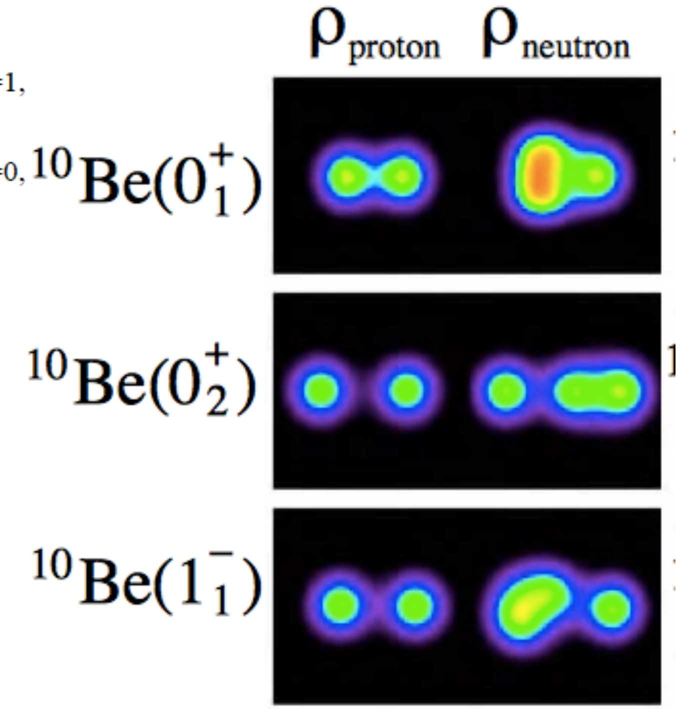
T=0 pairing



Does this T=0 phase exist ?



α cluster states



➔ two-neutron transfer

➔ deuteron transfer

➔ α cluster transfer

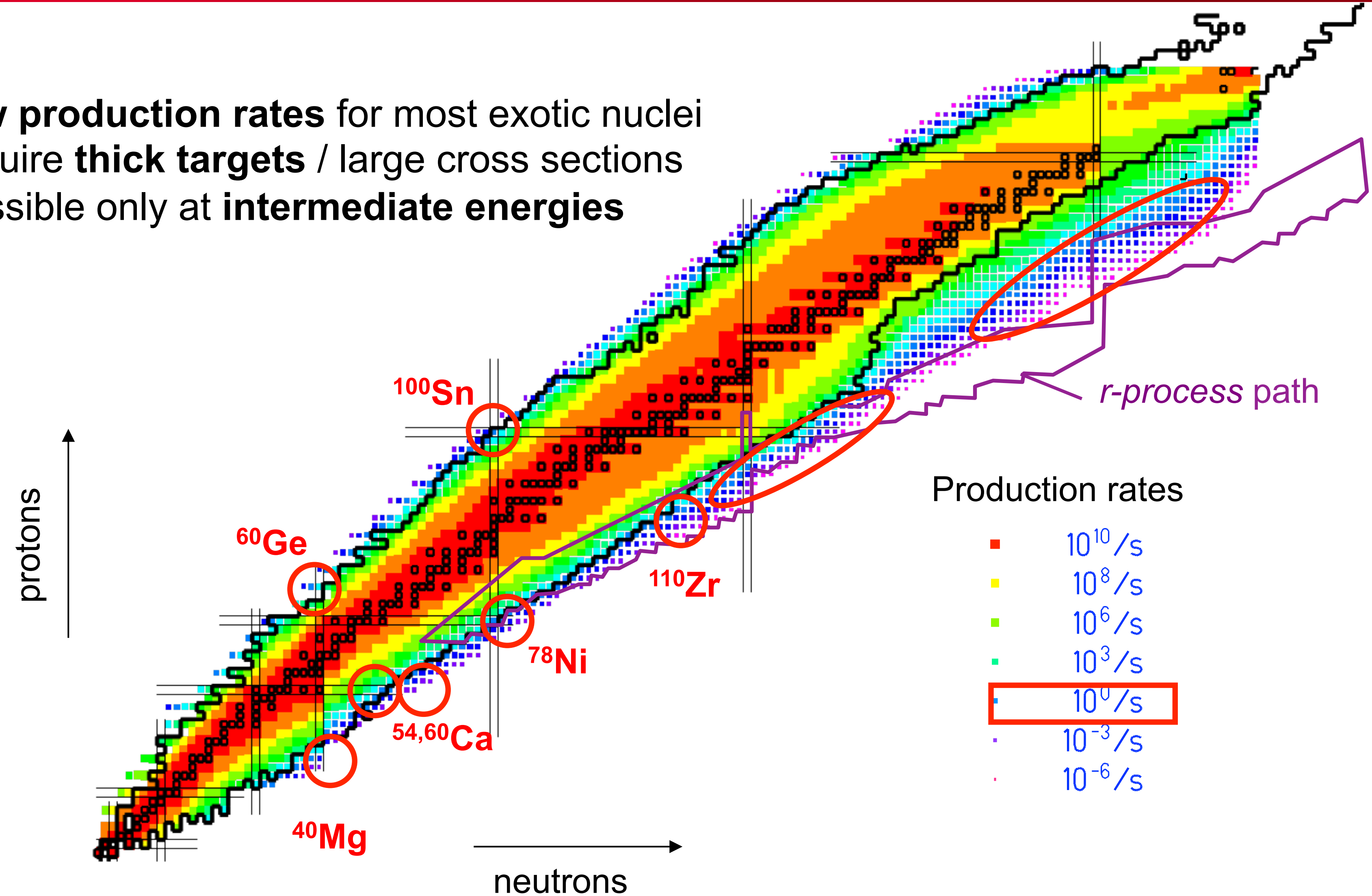
… small cross sections and complex analysis compared to one-nucleon transfer

Outline

- Elastic and inelastic scattering
- Nucleon transfer
  - sensitivity to the shell model / spectroscopic factors
  - the Distorted-Wave Born Approximation (DWBA)
  - achievements with exotic nuclei
  - correlations from two nucleon transfer
- **Knockout reactions**
  - S-matrix theory and eikonal approximation
  - Nuclear structure from knockout & in-beam γ spectroscopy
  - Absolute SF: transfer versus knockout
  - Quasifree scattering
- Future developments and probes

Shell evolution: far away from stability

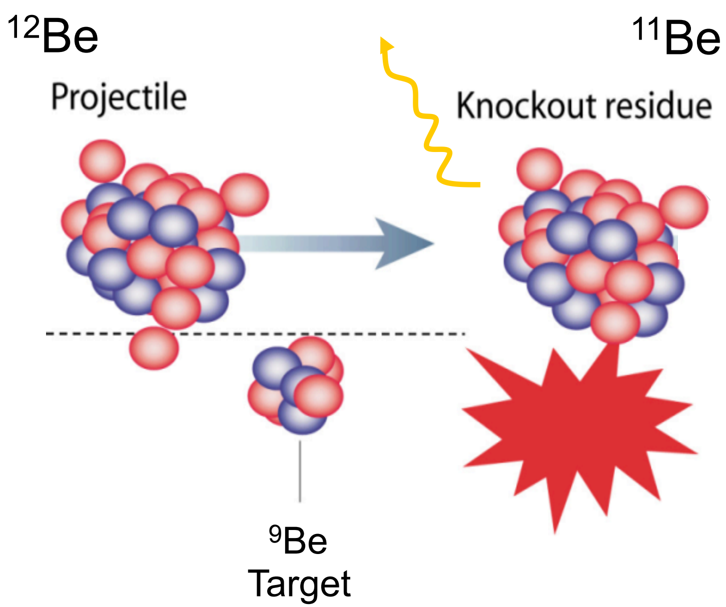
- **low production rates** for most exotic nuclei
- require **thick targets** / large cross sections
- possible only at **intermediate energies**

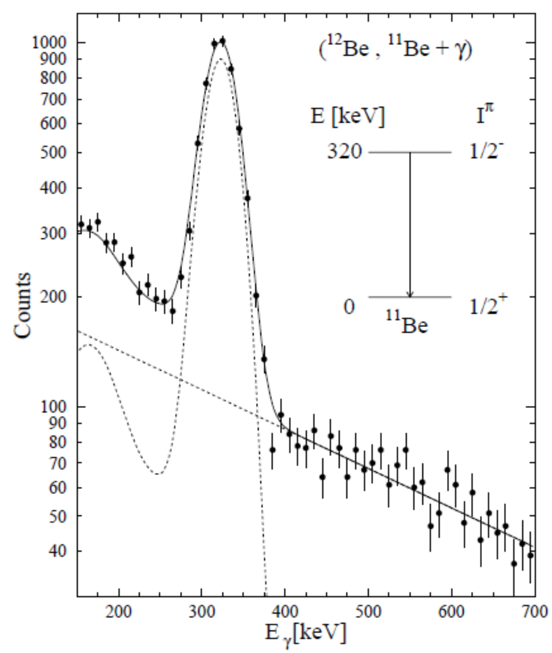


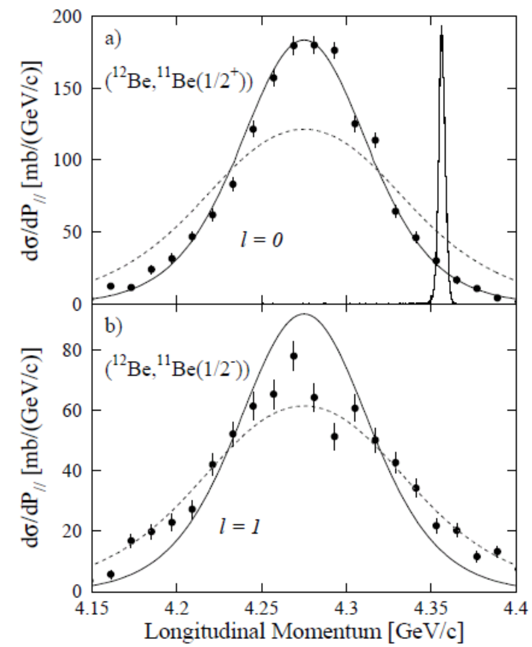
Inclusive knockout reactions

Inclusive = detection of the projectile-like residue
[what happens to the removed nucleon or target is unknown]

In-beam gamma spectroscopy to tag final states (« *exclusive* » cross sections)



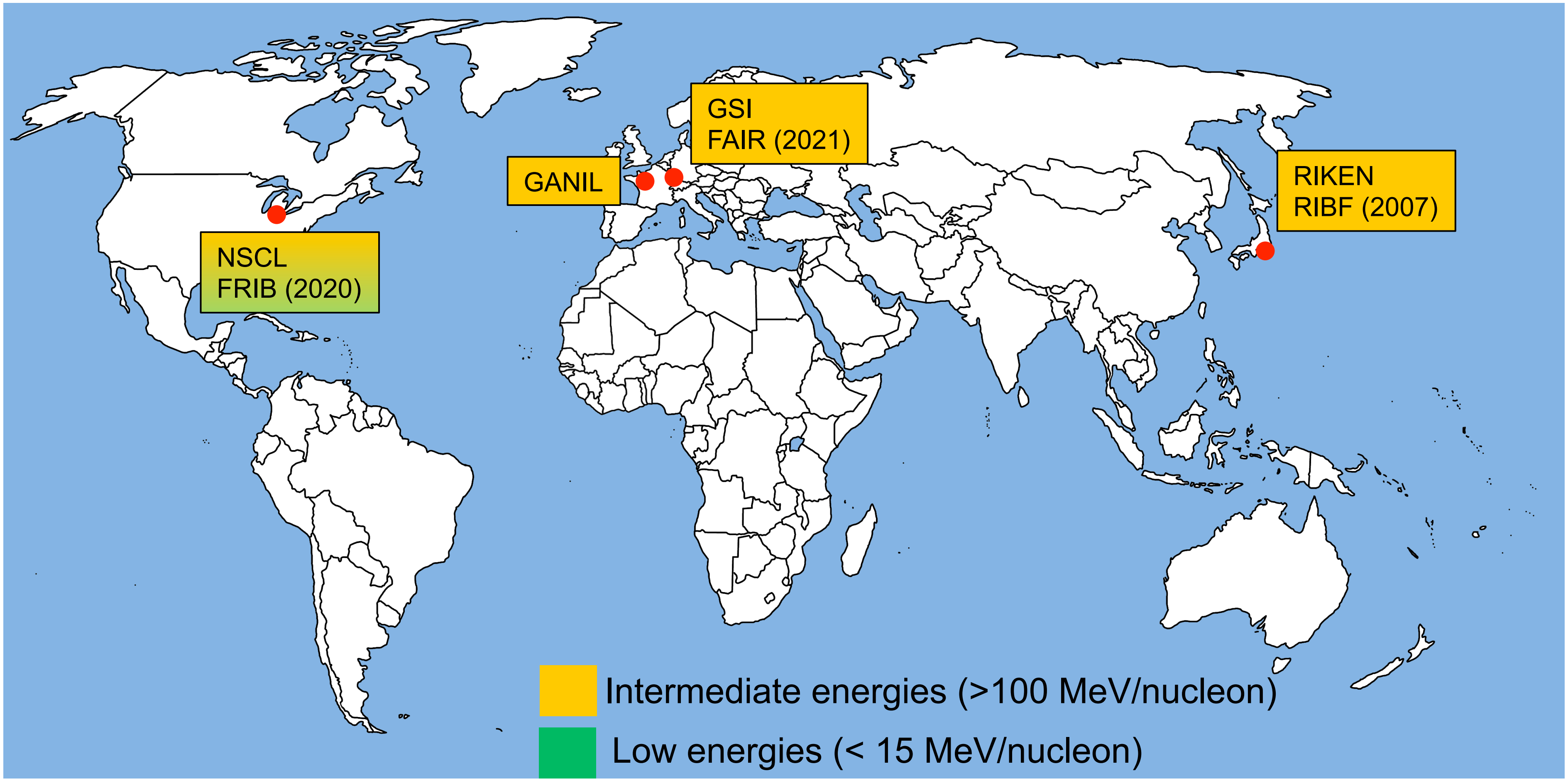




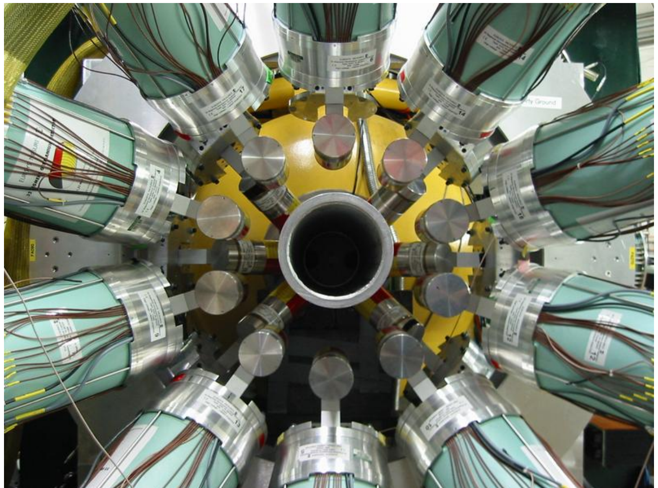
2000 pps
80 MeV/nucleon, NSCL

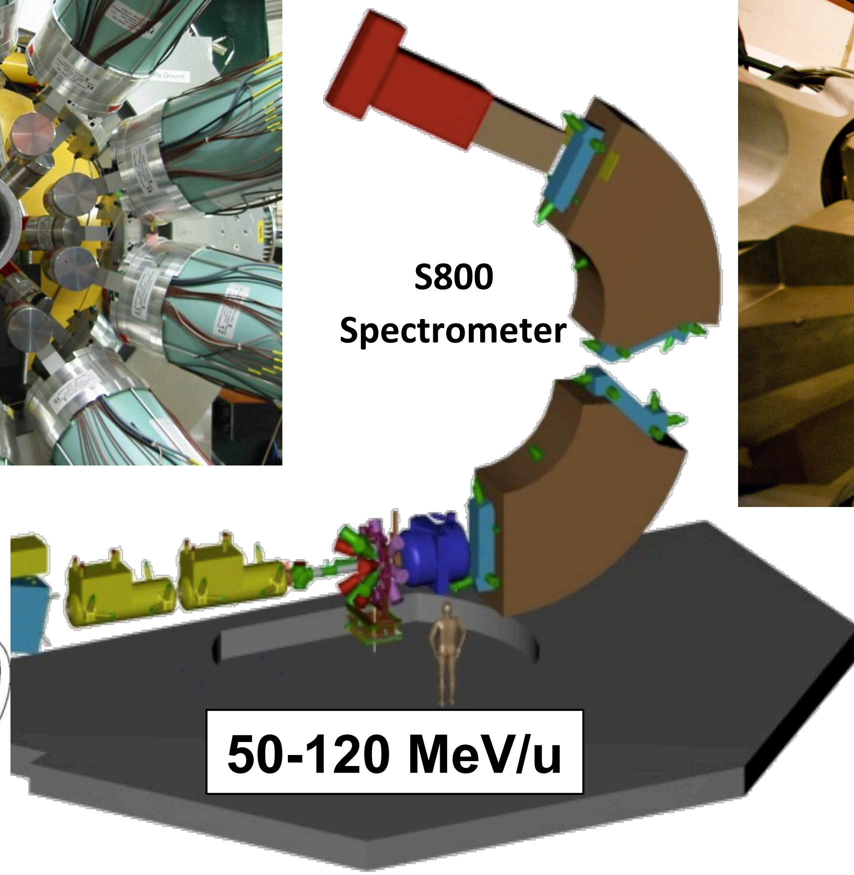
A. Navin *et al.*, PRL **85** (2000)

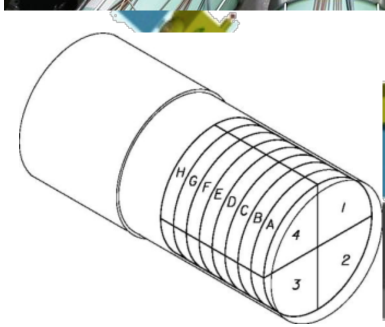
Leading fragmentation RIB facilities in the world



Example of setup: SeGA/GRETINA + S800 @ NSCL







GRETINA= US Ge array new generation / tracking (like AGATA in Europe)

SeGa=18 HPGe detectors

- Resolution=2-4% @ 1 MeV β=0.4
- ε=2.5% @ 1 MeV and β=0.4

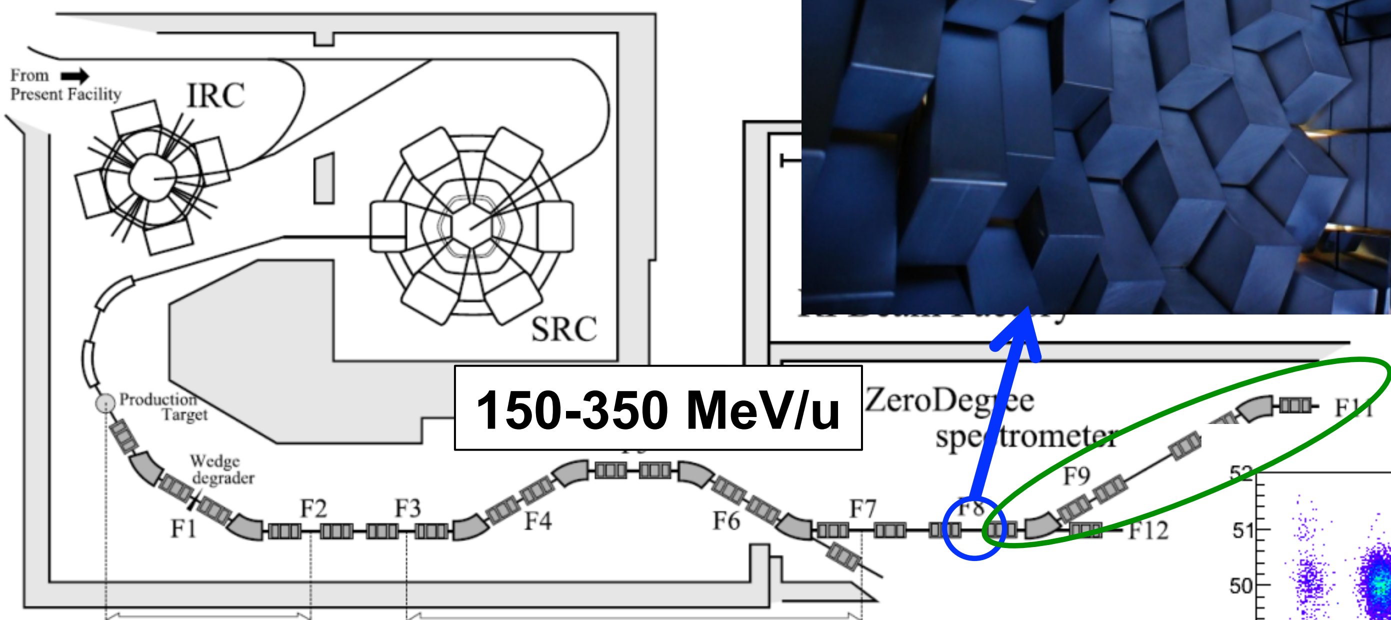
GRETINA=GRETA/4@MSU (2013-2014):
7 qadruplets x 4 HPGe crystals

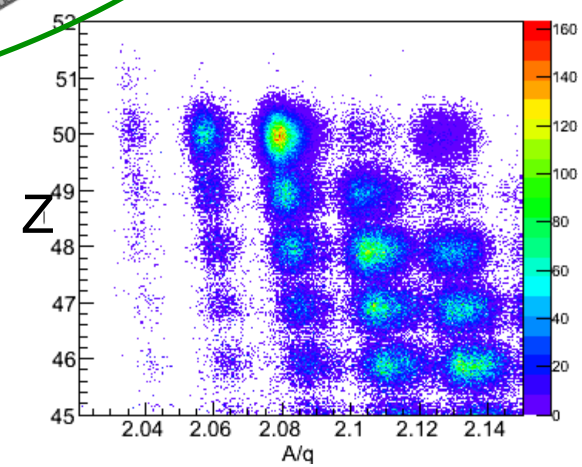
- Resolution 1% FWHM @ 1 MeV and β=0.4
- ε=9% @ 1 MeV and β=0.4

Another experimental setup: DALI2 @ RIBF

DALI2=186 NaI(Tl) crystals
- Resolution=10% @ 1 MeV β=0.6
- ε=20% @ 1 MeV and β=0.6

T. Takeuchi *et al.*, Nucl. Instr. Meth. A **763** (2014)





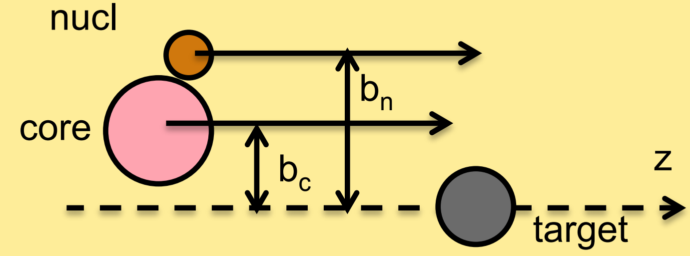
ZeroDegree Spectrometer
- Momentum acceptance: ±3%
- High resolution: P/DP≈6000

Eikonal approximation, S matrix and knockout

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

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

Eikonal approximation: straight line



Single-particle cross section

$$\sigma_{sp}(n\ell j) = \sigma_{sp}^{strip}(n\ell j)$$

Stripping cross section (the target is excited)

$$\sigma^{strip} = 2\pi\int_0^\infty b\,db \int d^3r \left|\phi_{n\ell j}(\vec{r})\right|^2 \left|S_{core}(\vec{b}_c)\right|^2 \left(1 - \left|S_{nucl}(\vec{b}_n)\right|^2\right)$$

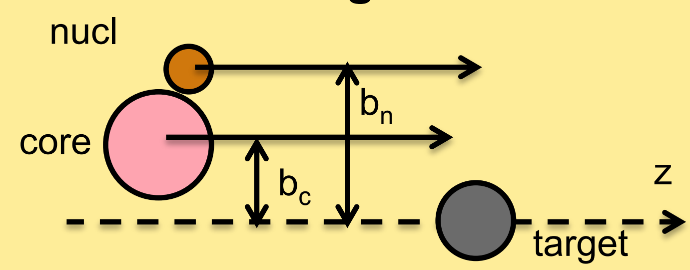
Core « survives » × Nucleon « adsorbed »

Eikonal approximation, S matrix and knockout

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

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

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)

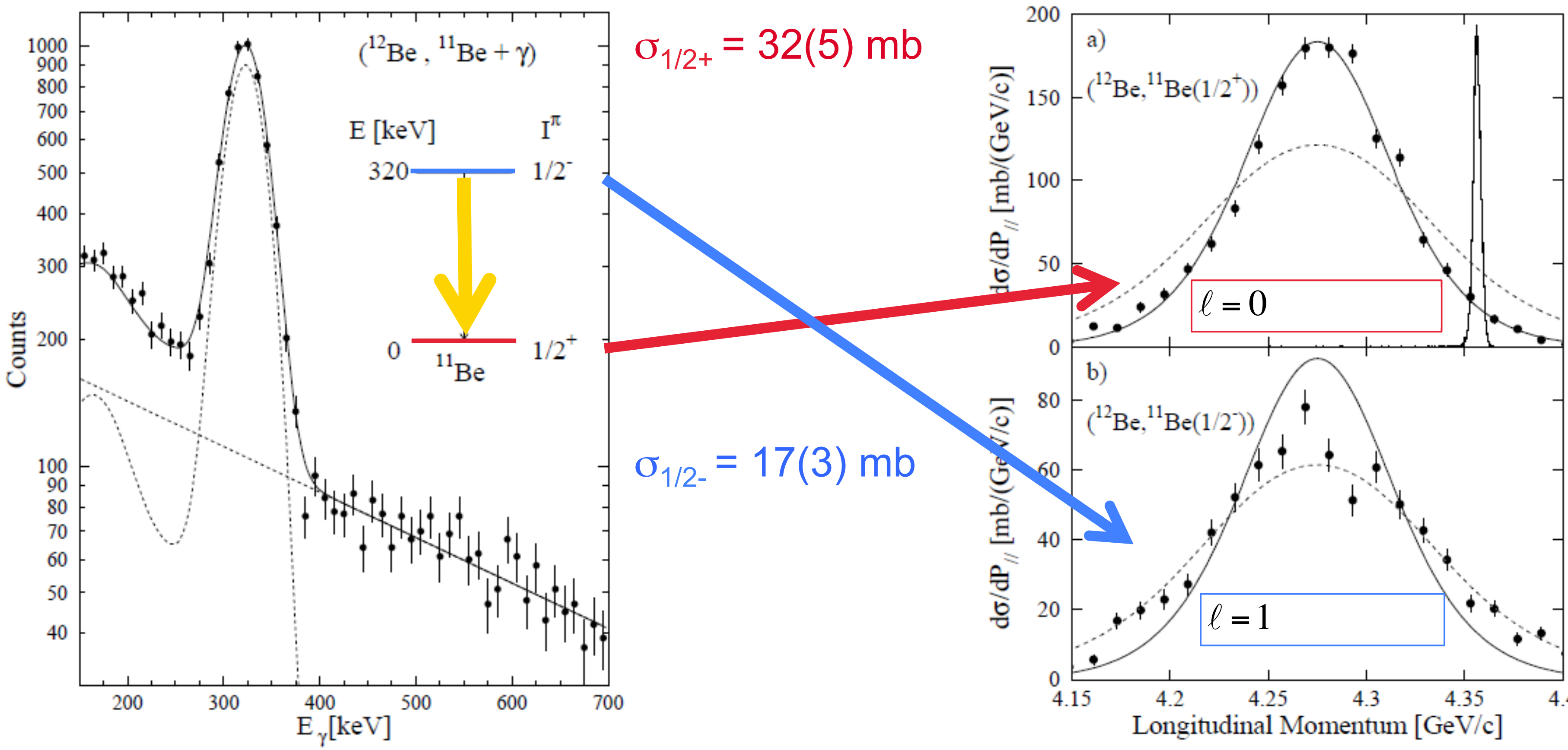
$$\sigma^{strip} = 2\pi\int_0^\infty b\,db\int d^3r\left|\phi_{n\ell j}(\vec{r})\right|^2 \left|S_{core}(\vec{b_c})\right|^2 (1-\left|S_{nucl}(\vec{b_n})\right|^2)$$

Core « survives » × Nucleon « adsorbed »

DIffractive cross section (the target remains in its ground state)

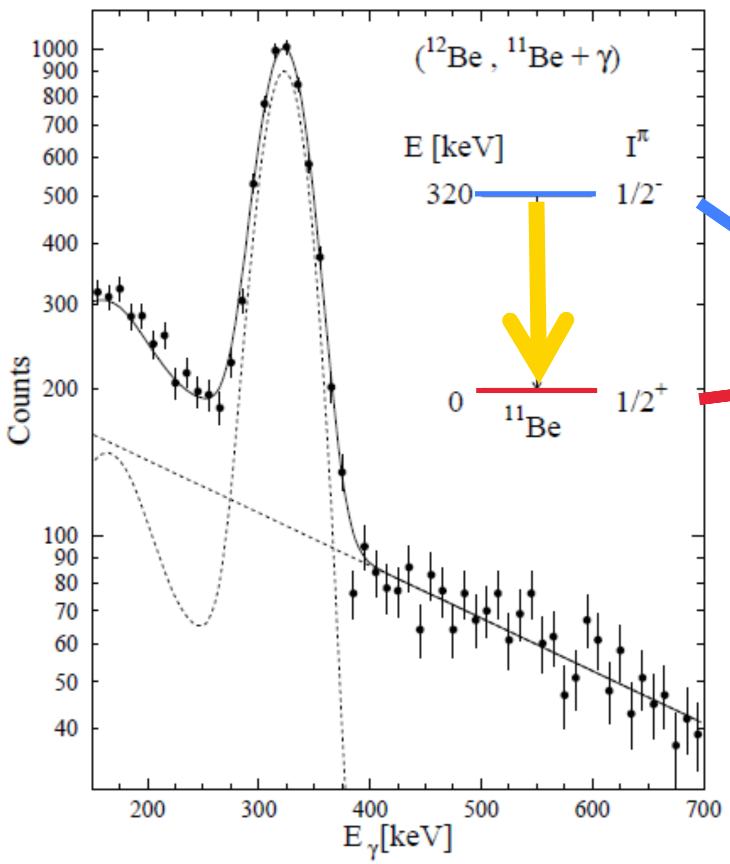
$$\sigma_{diff} = 2\pi\int b\,db\left\langle\phi_0\left|\left|S_{core}S_{nucl}\right|^2\right|\phi_0\right\rangle - \left|\left\langle\phi_0\left|S_{core}S_{nucl}\right|\phi_0\right\rangle\right|^2$$

Breakdown of the N=8 shell closure



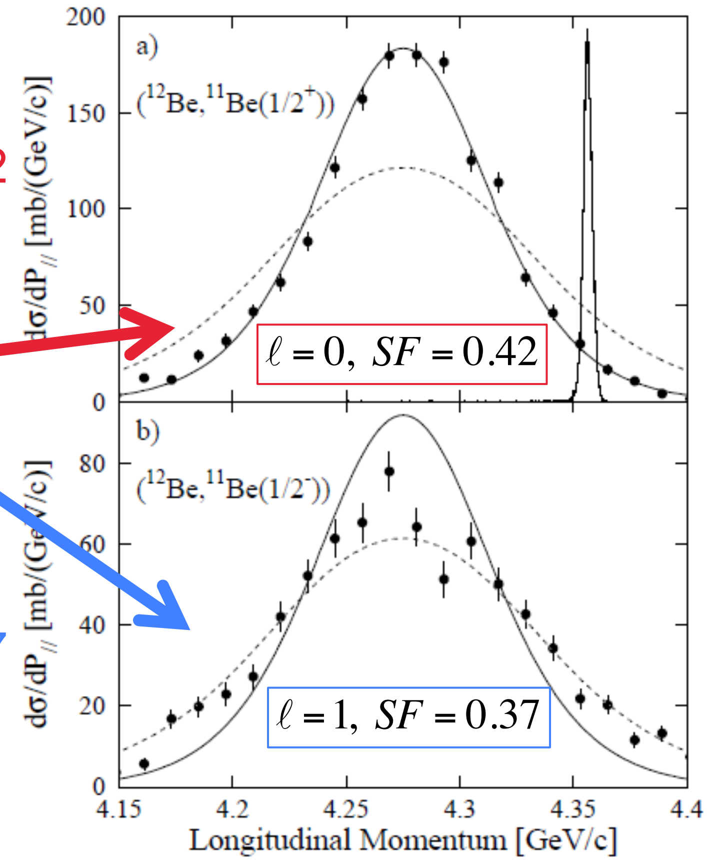
A. Navin *et al.*, PRL **85** (2000)

Breakdown of the N=8 shell closure



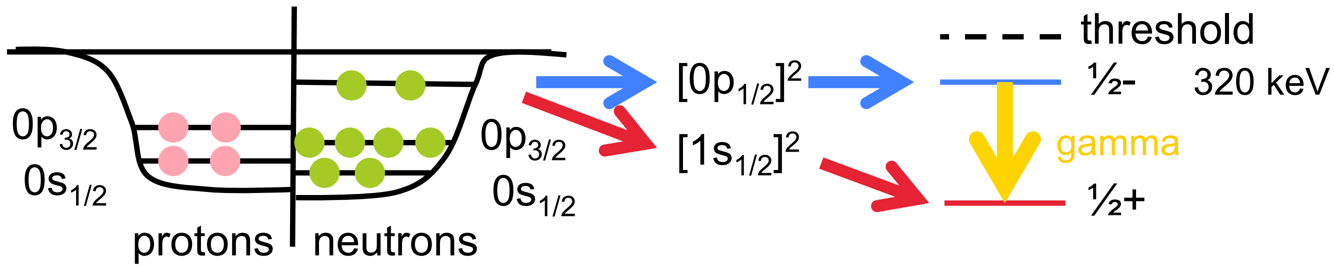
$\sigma_{1/2+}$ = 32(5) mb
σ_{eik}(l=0)= 76 mb
➔ SF=32/75=0.42

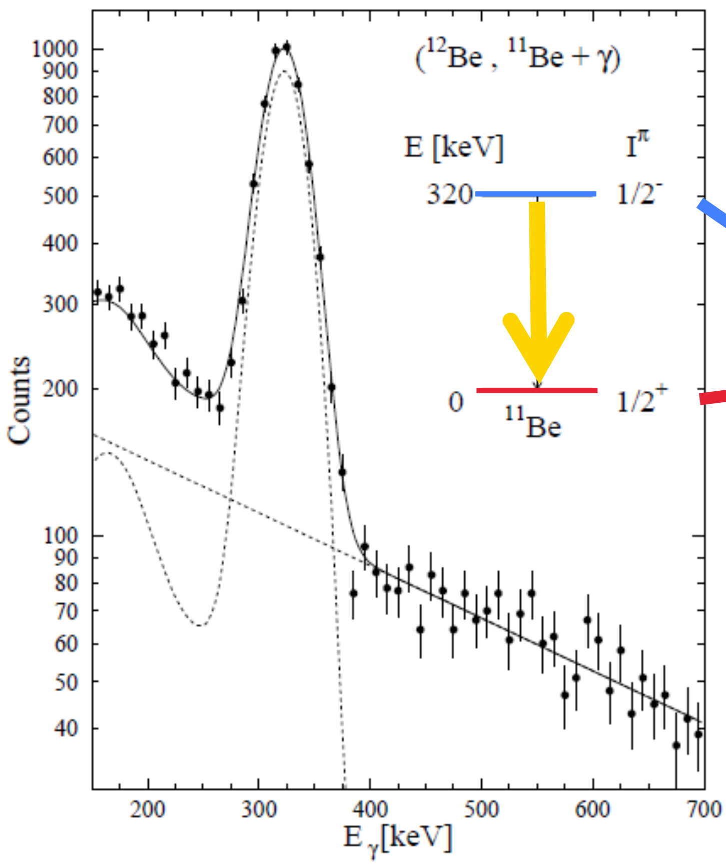
$\sigma_{1/2-}$ = 17(3) mb
σ_{eik}(l=1)= 47 mb
➔ SF=17/47=0.37



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

Breakdown of the N=8 shell closure





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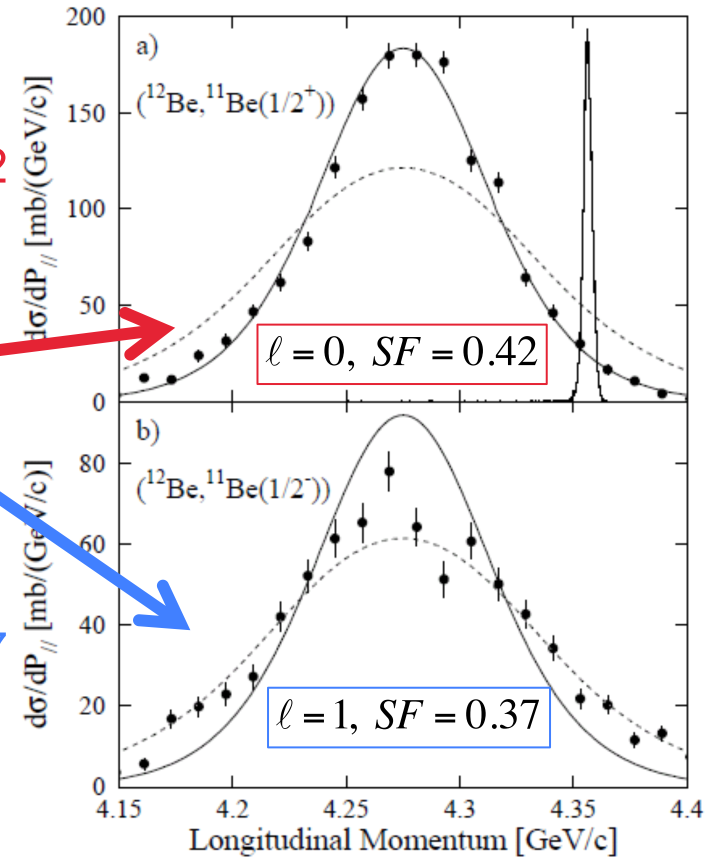


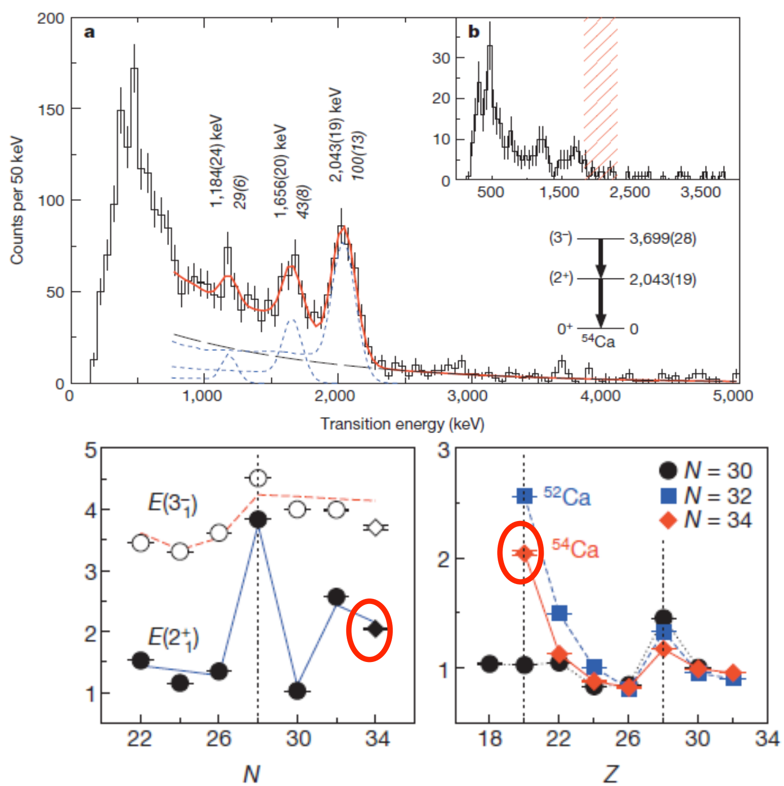
A. Navin *et al.*, PRL **85** (2000)

The N=34 new magic number

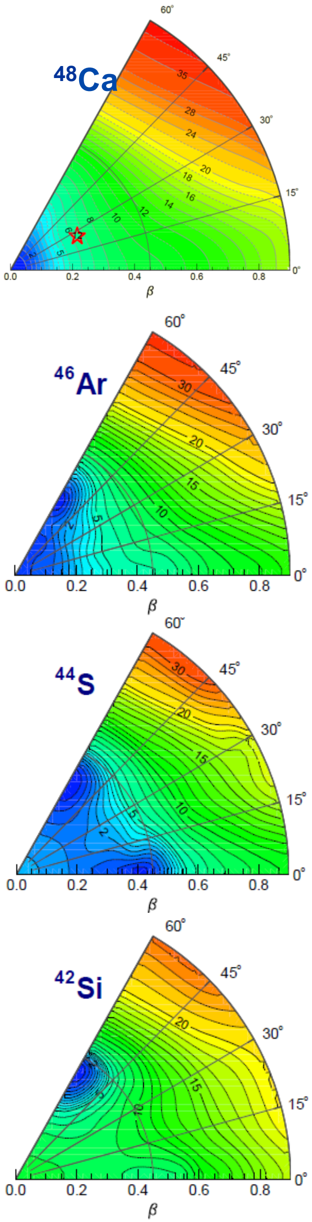
D. Steppenbeck *et al.*, Nature **502** (2013)

^{70}Zn primary beam (100 pnA max)
^{56}Ti 120 pps/pnA, ^{55}Sc 12 pps/pnA

^{54}Ca produced by one, two proton knockout:
^{56}Ti, 55Sc + Be -> ^{54}Ca + X

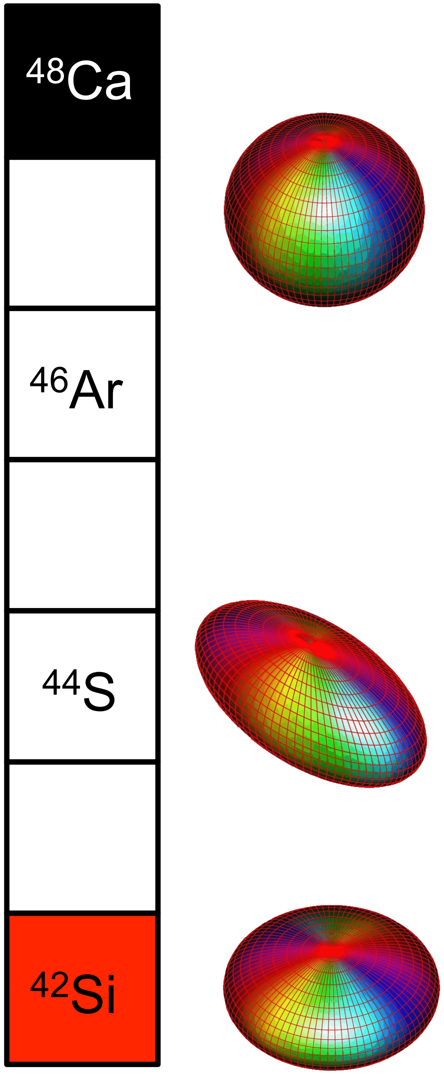


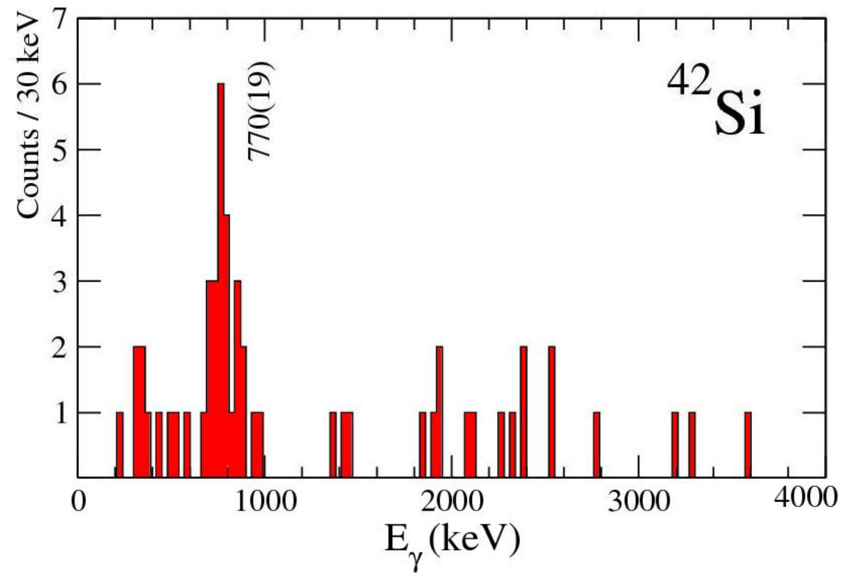
Collapse of the N=28 shell closure in ^{42}Si

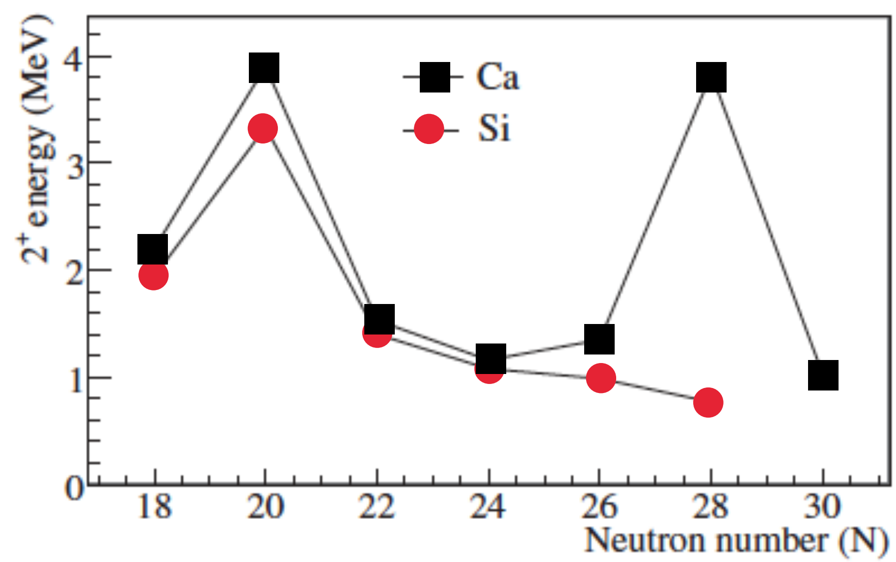


HFB - D1S calculations from CEA-DAM

^{44}S beam, GANIL





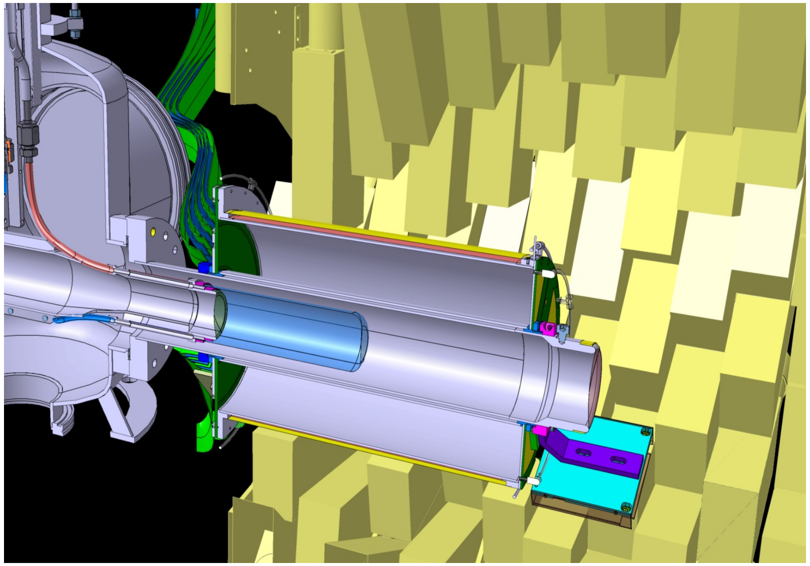


B. Bastin et al., PRL **99** (2007)

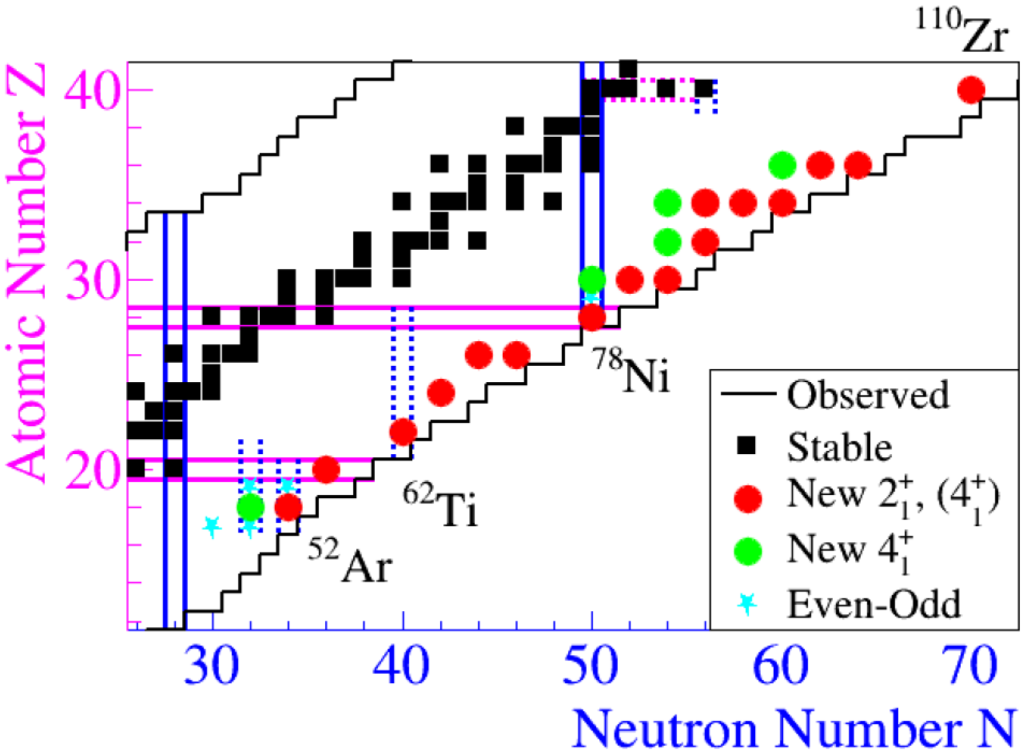
The SEASTAR program at the RIBF

Seastar: Shell Evolution and Search for Two-plus energies At the RIBF

Setup composed of DALI2 scintillator array + MINOS (thick H_2 target and Vertex tracker)
First experiments in **2014** and **2015**



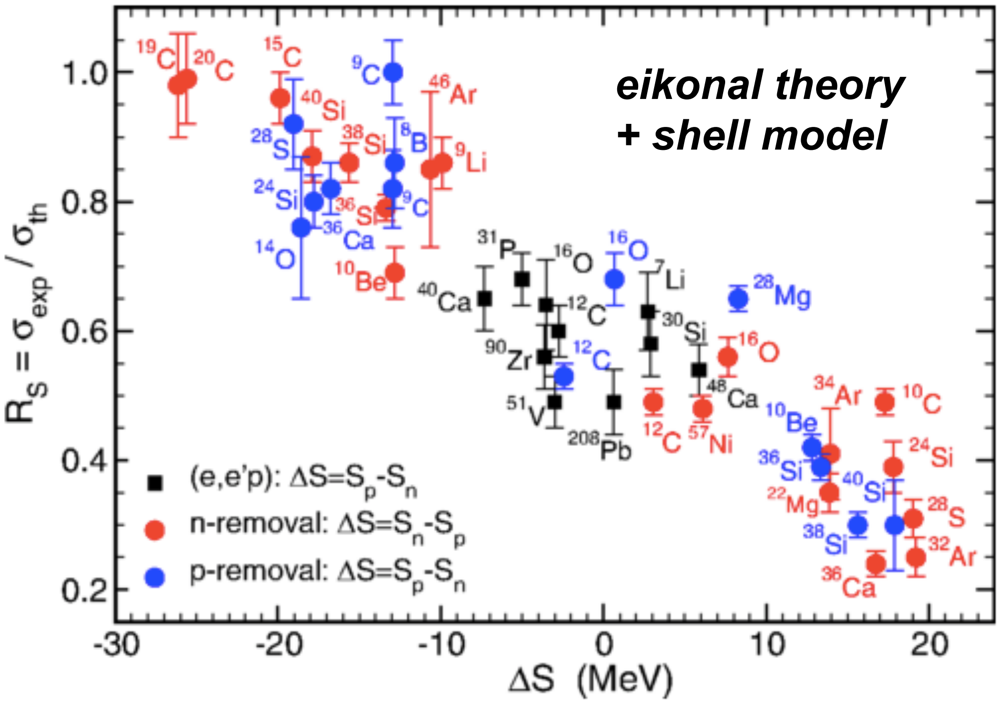
MINOS: AO *et al.*, EPJA **50** (2014)

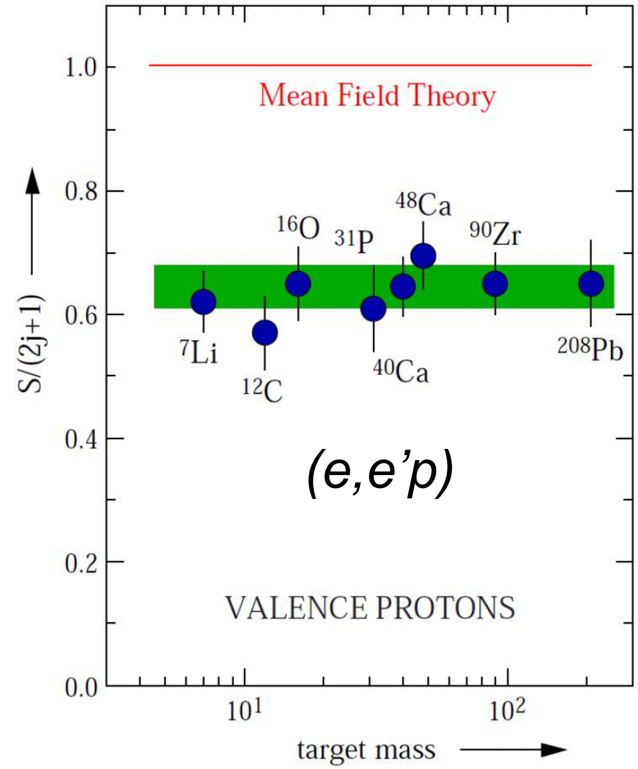


http://www.nishina.riken.jp/collaboration/SUNFLOWER/experiment/seastar/index.html

Stripping cross sections: eikonal versus data

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

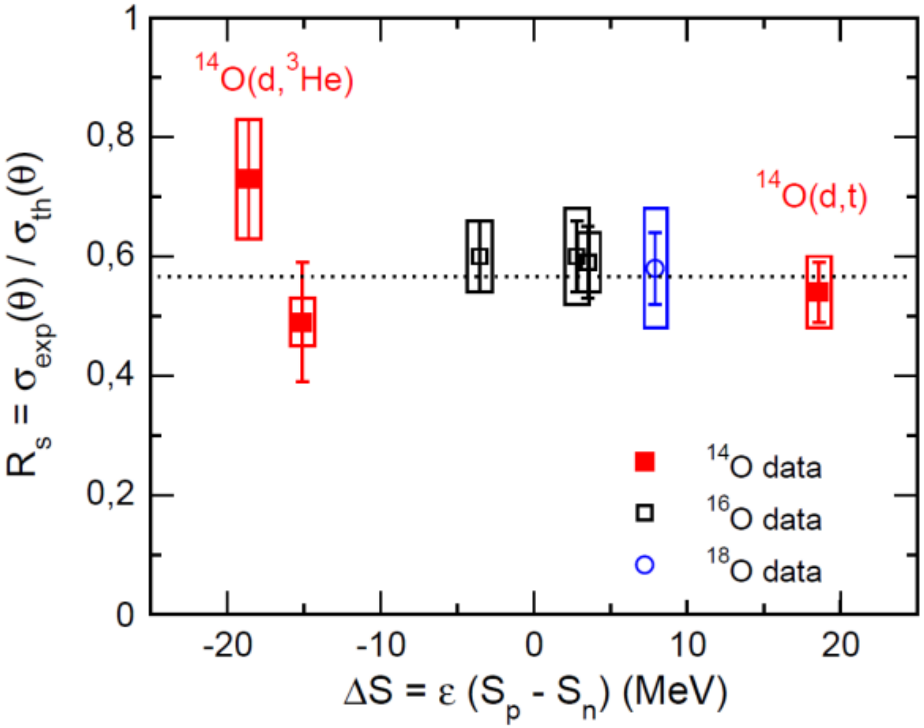




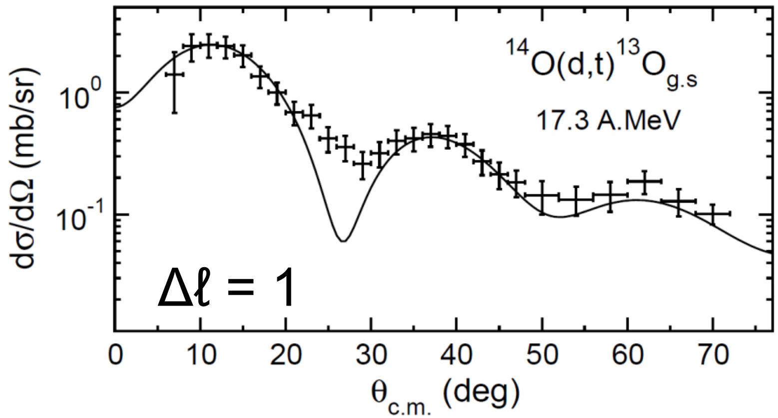
Intermediate-energy knockout
Disagreement between theory and experiment

Comparing heavy-ion induced knockout and transfer

$^{14}O(d,t)$, $(d,^{3}He)$ and elastic scattering, 19 MeV/nucleon, SPIRAL (GANIL) **ΔS~19 MeV**



F. Flavigny *et al.,* Phys. Rev. Lett. **110** (2013).

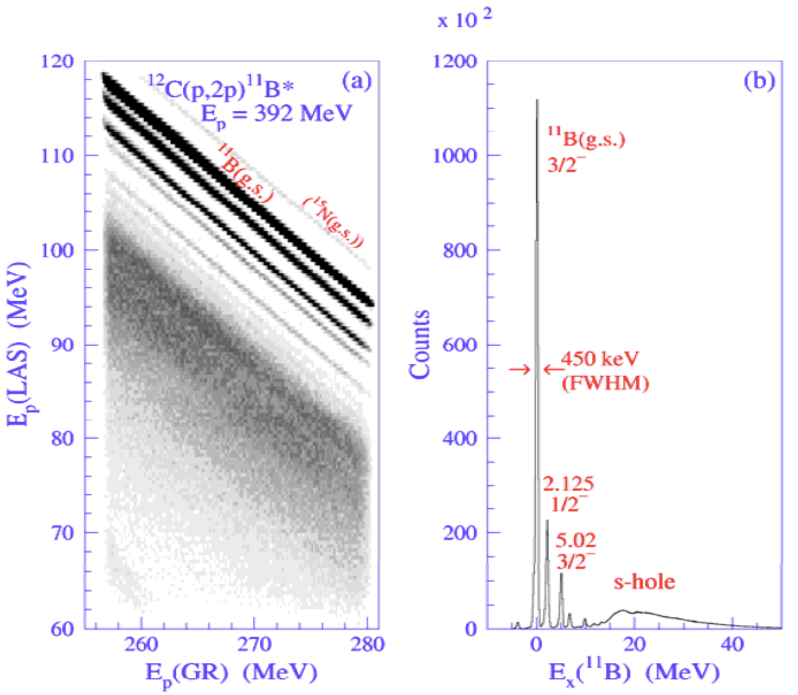


Coupled channel analysis

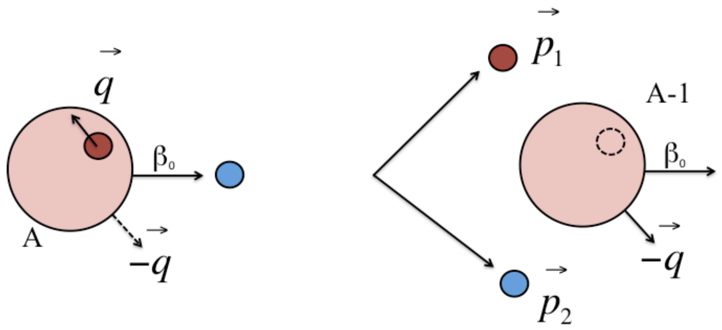
Conclusions

- **weak ΔS dependence**
- **Disagreement** between intermediate-energy nucleon removal and transfer analysis
- *Ab initio* calculations in agreement with transfer

Proton-induced quasifree scattering



Direct kinematics $^{12}C(p,2p)^{12}C$, RCNP (Japan)



Distorted Wave Impulse Approximation

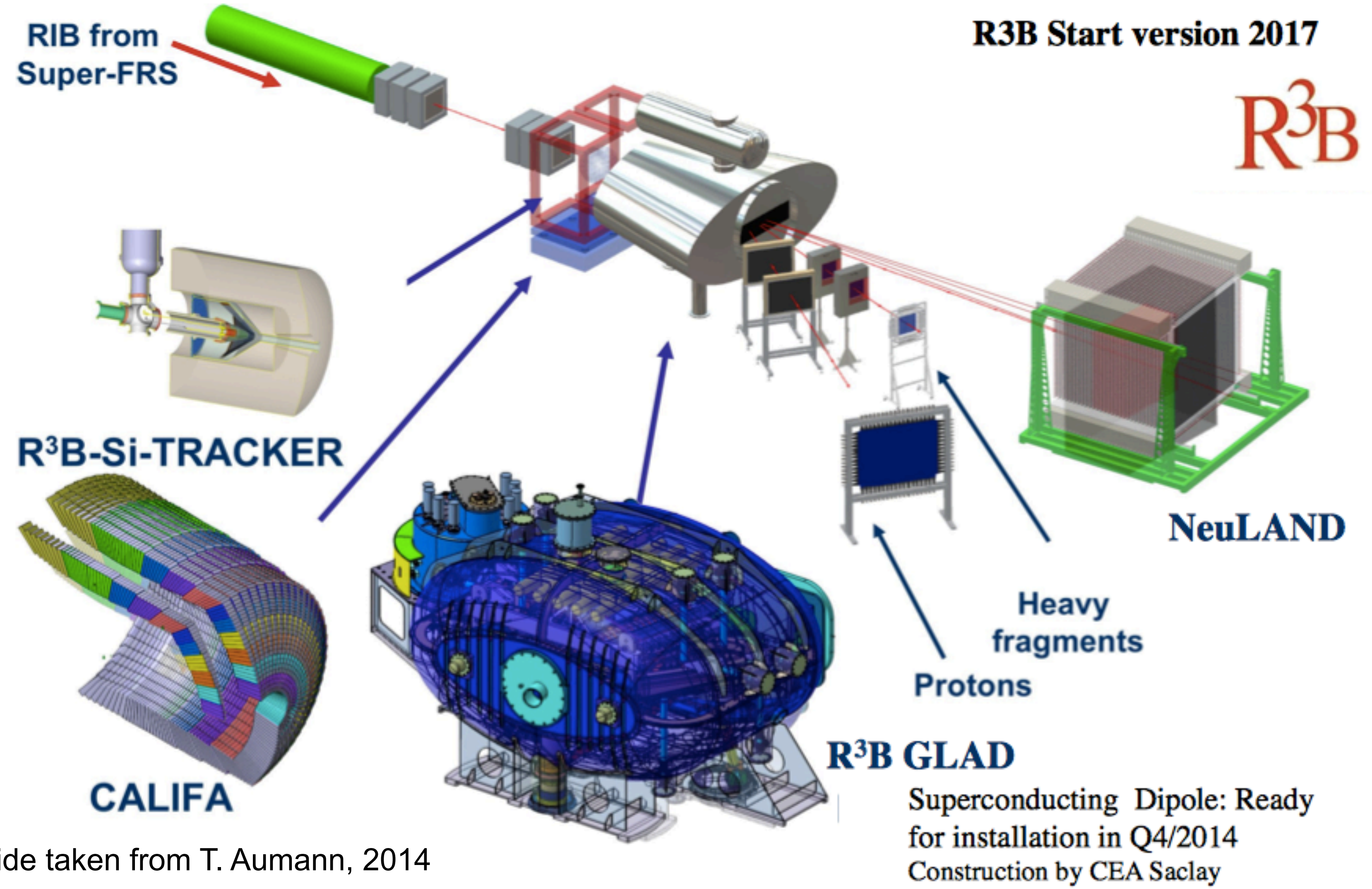
$$T_{p,pN} = \sqrt{S_{n\ell j}} \left\langle \chi^{(-)}_{k'_p} \chi^{(-)}_{k_N} \middle| \tau_{pN} \middle| \chi^{(+)}_{k_p} \phi_{n\ell j} \right\rangle$$

Recent work:
T. Aumann, C. Bertulani, J. Ryckebusch, PRC **88** (2013)

- **(e,e'p) best spectroscopic tool** proton stripping (electromagnetic interaction)
- large momentum transfer: minimize final state interactions
- **(e,e'p)** = not sensitive to neutron, not possible with short-lived nuclei

- **(p,2p) exclusive quasifree scattering** expected to be a clean high energy probe
  In inverse kinematics: best energies from 300/nucleon to 1 GeV/nucleon

The R3B project at GSI/FAIR



Slide taken from T. Aumann, 2014

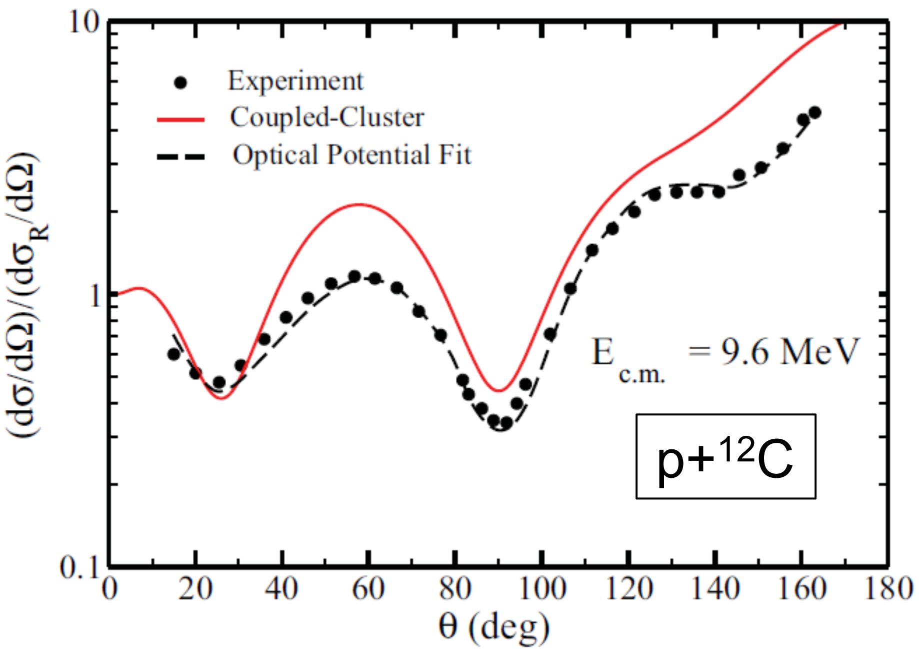
Similar setup / program at **RIBF** with the **SAMURAI** spectrometer and collaboration

Outline

- **Elastic and inelastic scattering**
- **Nucleon transfer**
  - sensitivity to the shell model / spectroscopic factors
  - the Distorted-Wave Born Approximation (DWBA)
  - achievements with exotic nuclei
  - correlations from two nucleon transfer
- **Knockout reactions**
  - S-matrix theory and eikonal approximation
  - Nuclear structure from knockout & in-beam γ spectroscopy
  - Absolute SF: transfer versus knockout
  - Quasifree scattering
- **Future developments and probes**

Ab initio description of reactions

Long term objective: **a fully consistent treatment of reaction and structure**
i.e. same initial Hamiltonian, parameter free and theoretical uncertainties



G. Hagen and N. Michel, PRC **86** (2012)

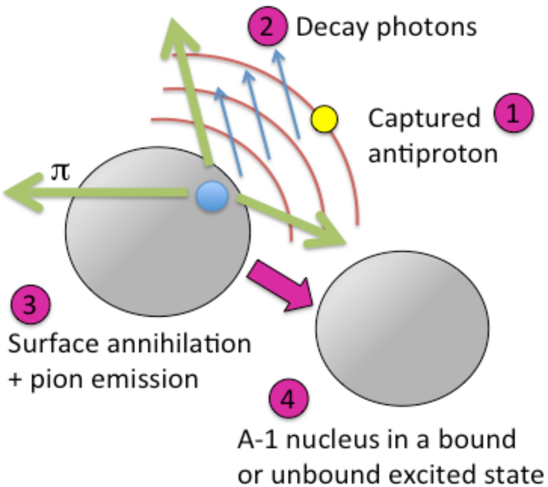
Ingredients:
Coupled Cluster theory

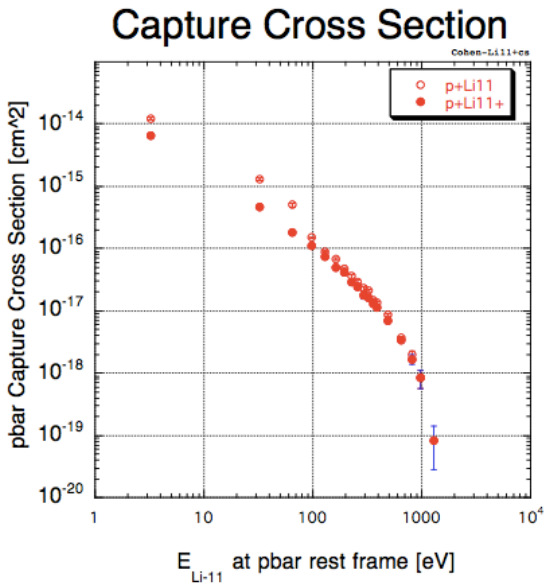
Two- and three body interactions from chiral theory

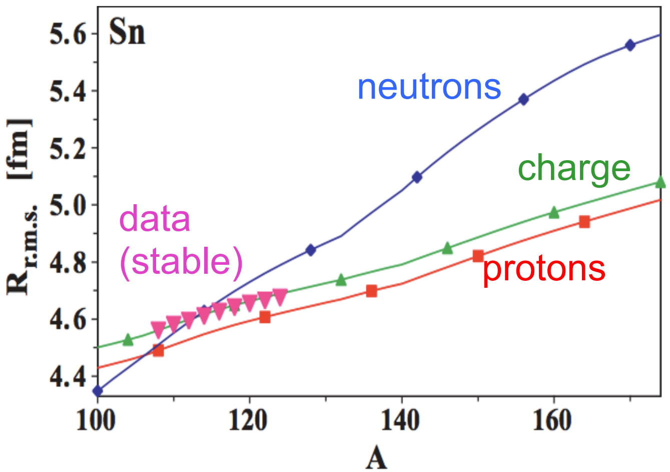
Also :first ab initio description of low energy fusion reactions (No Core SM)
P. Navratil and S. Quaglioni, PRL **108** (2012)

Antiprotons annihilation from RI: neutron skins

- **antiproton annihilation** with neutrons and protons
- very high cross section at low energy (**up to Giga-barns!!!**)
- very clean probe (pure stripping) with no Coulomb barrier effect







M. Wada and Y. Yamazaki, Nucl. Instr. Meth. B **214** (2004)

Direct measurement of surface neutron *vs* proton densities!

How to collide antiprotons and exotic nuclei?

1) Bringing antiprotons to RI facilities ➔ portable trap
2) Low energy collider ➔ FLAIR@FAIR (>2030)

ELISe at FAIR: electron – Radioactive Ion collider

Electron – RIB collider

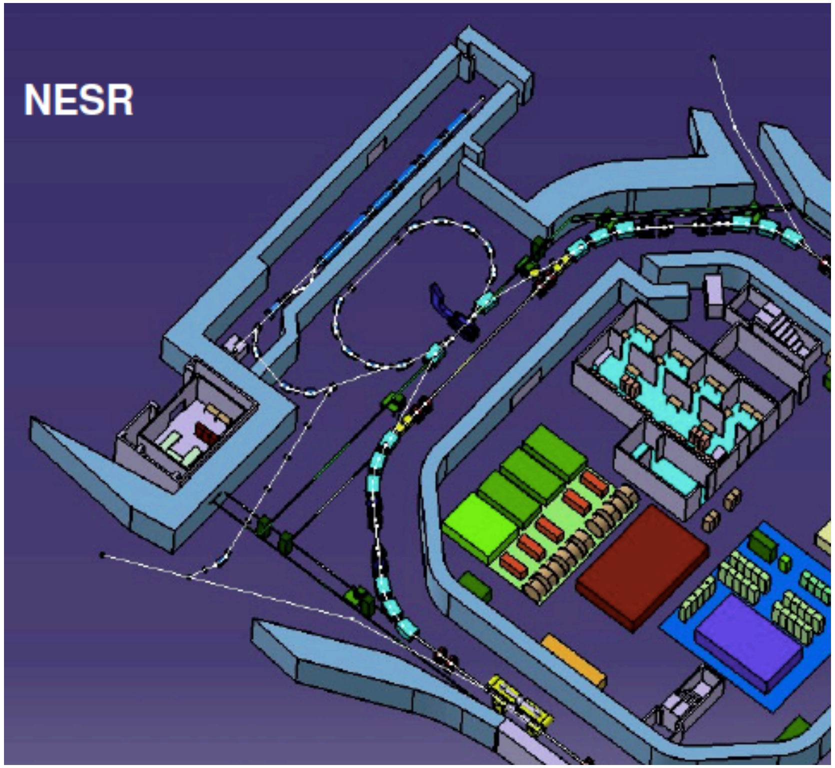
- 125-500 MeV electrons
- 200-700 MeV/u RIBs

Part of the FAIR facility (expected >2030)

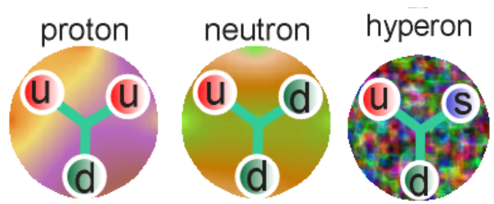
Pure electromagnetic studies with RIBs

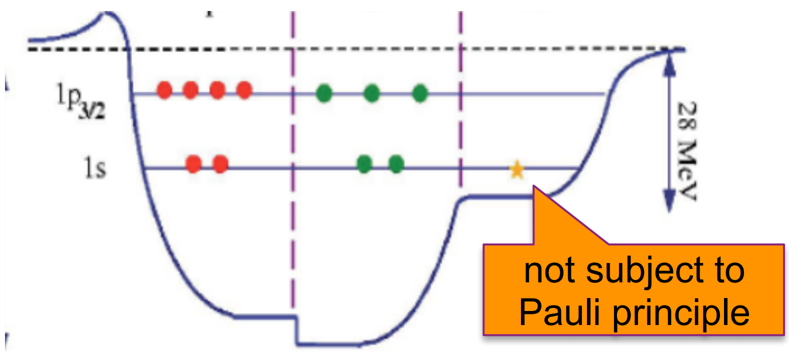
(luminosity <10^{28} cm^2s^{-1} / Lorentz focusing)
High resolution spectrometer

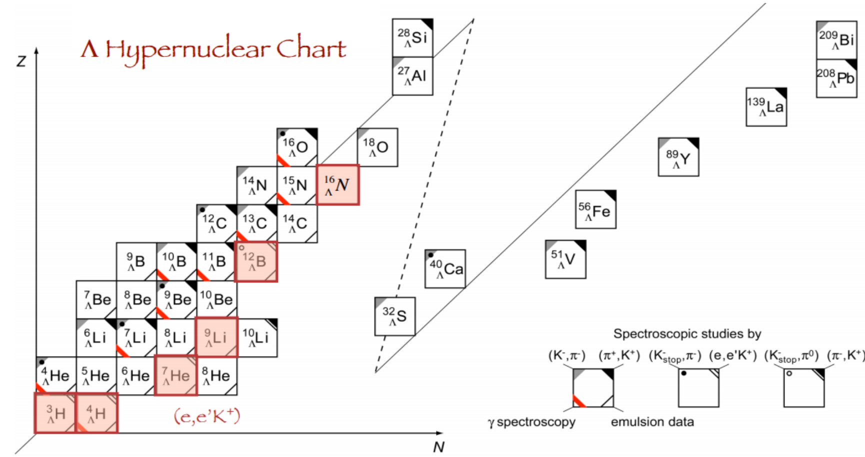
- charge distributions
- access to nuclear interior
- high-precision spectroscopic factors



Neutron rich hypernuclei







Unique probe of ΛN interaction

Today: direct kinematics from **stable nuclei**
Hypernuclei experiments at COSY (Germany), Berkeley (USA), DAPHNE (Italy), J-PARC (Japan), JLAB (USA), GSI (Germany)….

Tomorrow: Neutron-rich hypernuclei
Existing program at GSI/FAIR (HyPHI, T. Saito, GSI)
New opportunity of production from direct reaction: $^{A}X + p \rightarrow {}^{A}_{\Lambda}X$

Summary

- Elastic, inelastic, transfer, knockout and quasi-free scattering

- Unique probes for **quantum nuclear effects in Exotic Nuclei**:
  - ✓ Nuclear size and density distributions (elastic/inelastic scattering)
  - ✓ Nuclear collectivity (neutron *vs* protons, compression modes (GMR), …)
  - ✓ Shell evolution with isospin
  - ✓ Short range correlations
  - ✓ Pairing correlations (T=1, T=0)
  - ✓ Shape / configuration coexistence

- Importance of **hydrogen**-induced and exclusive reactions
  (simplest and cleanest hadronic probe among all)

- Large prospects and **detection developments** in view of new/recent RIB machines
  Ex. RIBF (Japan), FAIR, HIE-ISOLDE, SPES, SPIRAL2 (Europe) and FRIB (US)

- **Many new prospects**:
  ex. Fully consistent theory, p-bar annihilation, electron-RI collider, neutron-rich hypernuclei,…

So more to say about direct reactions…

- Charge exchange reactions
- proton-neutron pairing and cluster states from transfer reactions
- two-nucleon correlations via knockout
- cluster components from alpha quasifree scattering
- Quantum decoherence from elastic scattering and coupling to the continuum
- Proton versus neutron colllectivity from inelastic scattering
- Short range correlations by high energy transfer (momentum matching)
- Many experimental recent highlights with exotic nuclei
- Progresses of theory beyond DWBA (coupled channels)
- …

References to go further

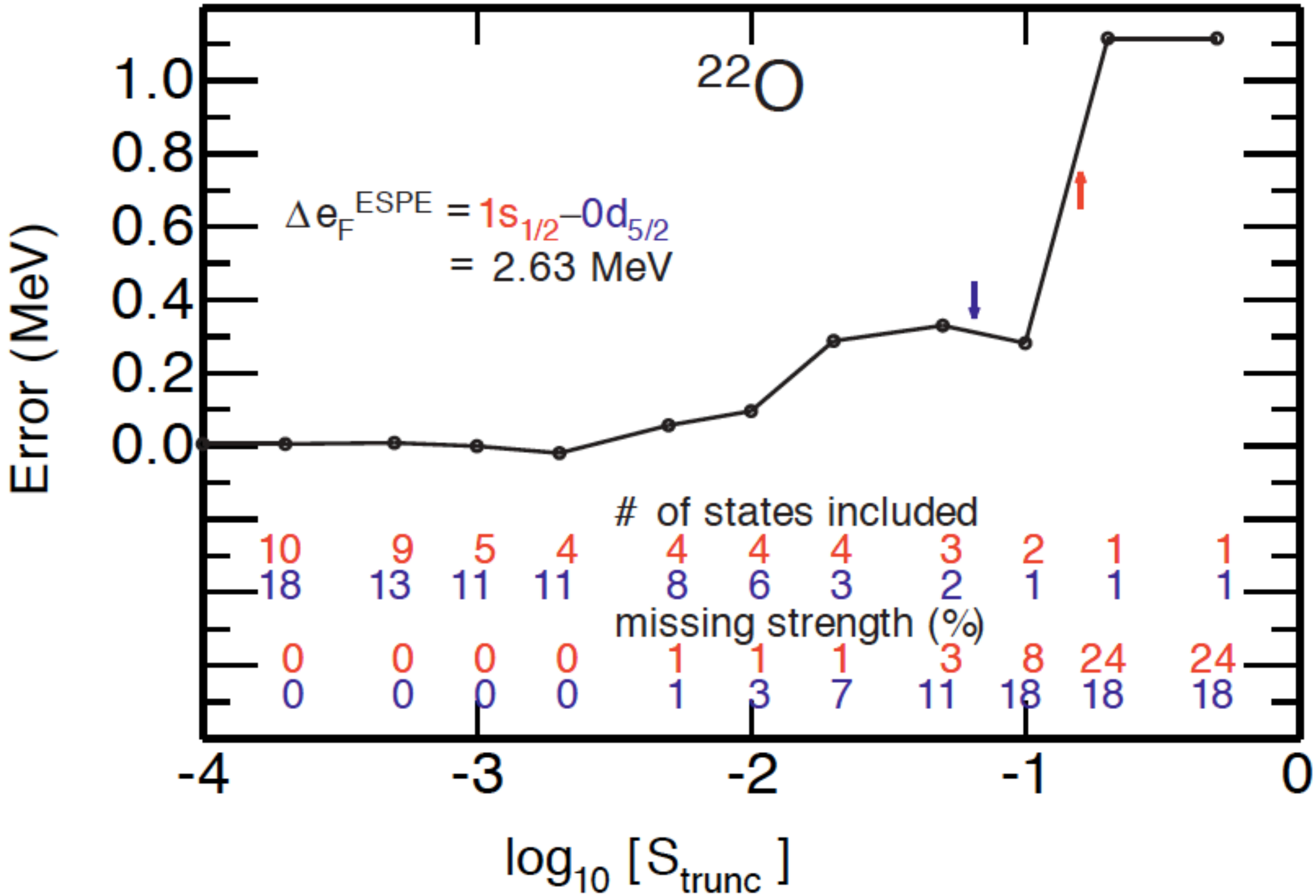
- **NR**, D. F. Jackson, Methuen edition (1970)
- **Introduction to NR**, G.R. Satchler, Mc Millan press (1980)
- **Direct NR**, N. K. Glendenning, World Scientific (1983)
- **Introduction to NR**, C. A. Bertulani and P. Danielewicz, IoP (2004)
- **NR for Astrophysics**, I. J. Thompson and F. M. Nunes, Cambridge (2009)

NR = Nuclear Reactions

Few backup slides

Importance of most "all" states to extract shell gaps

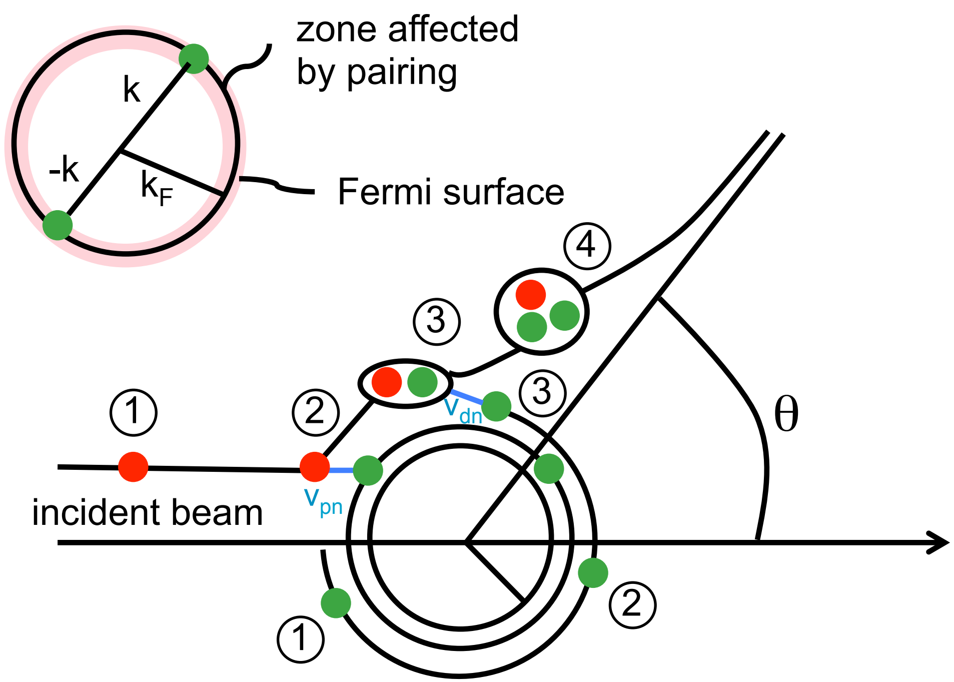
$^{22}O(d,p)^{23}O$: a theoretical study by A. Signoracci, T. Duguet



Two-nucleon transfer: a probe for pairing correlations

Ex. (p,t), (t,p), (^{12}C,^{14}C), …

two-nucleon transfer probes
spatial, momentum, spin correlations



From G. Potel *et al.*, Rep. Prog. Phys. **76** (2013)

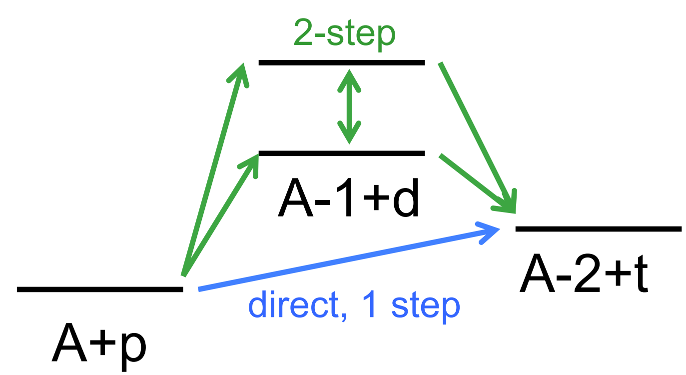
- depends on **correlations functions**

$$\left\langle \Phi_{A-2,\beta} \middle| a_{n\ell j} a_{n'\ell' j'} \middle| \Phi_{A,\alpha} \right\rangle$$

- **transfered angular momentum** obtained from angular distribution

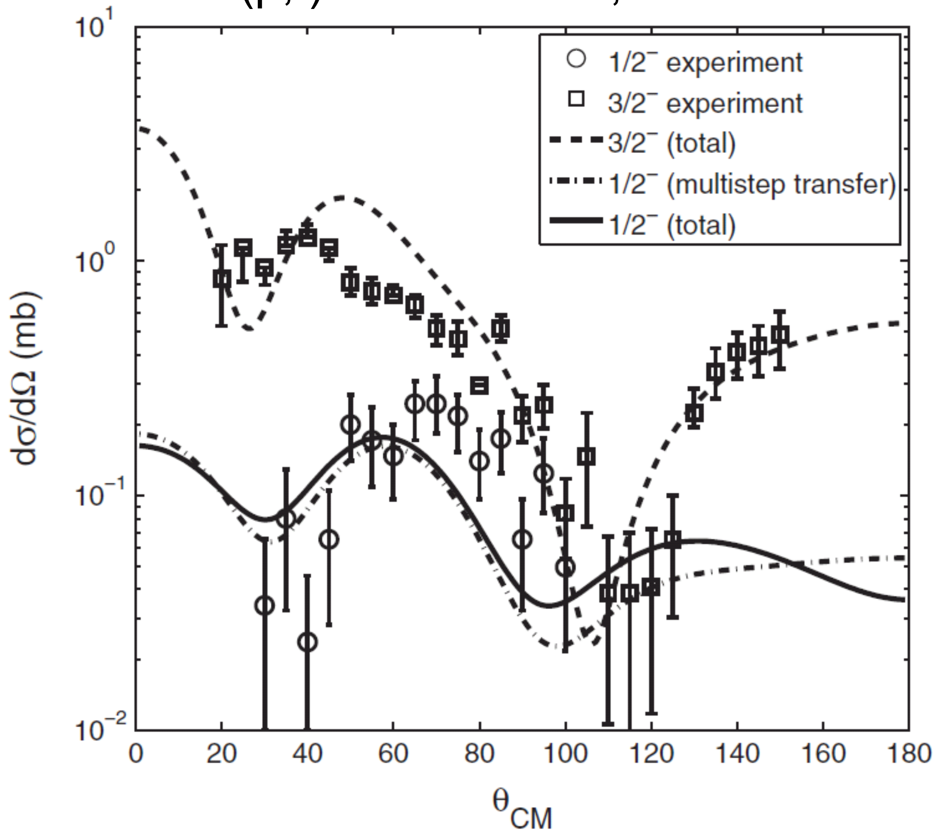
- More complex mechanism:
  > **1-step and 2-step components**

- **low cross section** (typically 0.1-1 mb)



Two-nucleon transfer: a probe for pairing correlations

$^{11}Li(p,t)^{9}Li$ at 3 AMeV, TRIUMF



I. Tanihata *et al.*, Phys. Rev. Lett. **100** (2008).
G. Potel *et al.*, Phys. Rev. Lett. **105** (2010).

Energies from few to 50 MeV/nucleon / low cross sections (100 μb)

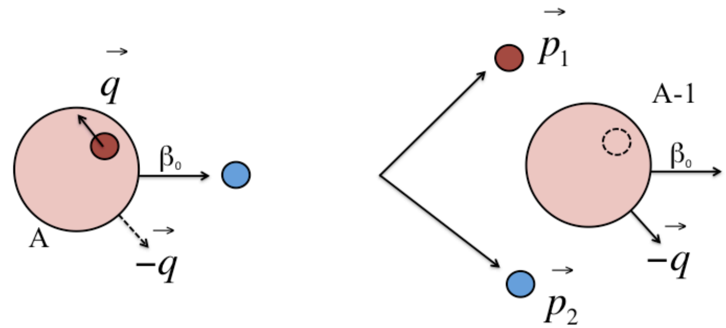
(p,2p) quasifree scattering

Kinematics

$$\overrightarrow{q_\perp} = +\overrightarrow{p_{1\perp}} + \overrightarrow{p_{2\perp}}$$

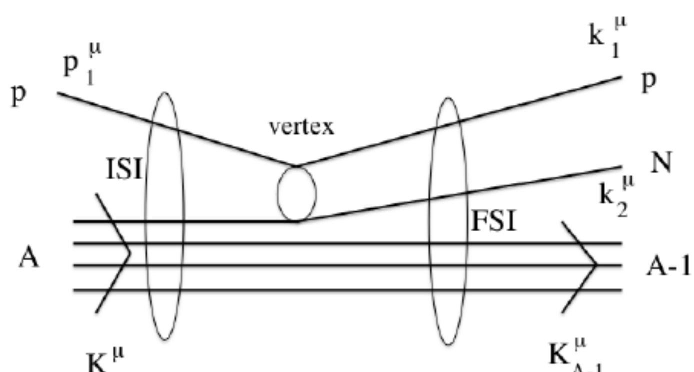
$$\overrightarrow{q_{//}} = \frac{(\overrightarrow{p_{1//}} + \overrightarrow{p_{2//}}) - \gamma(M_A - M_{A-1})}{\gamma}$$

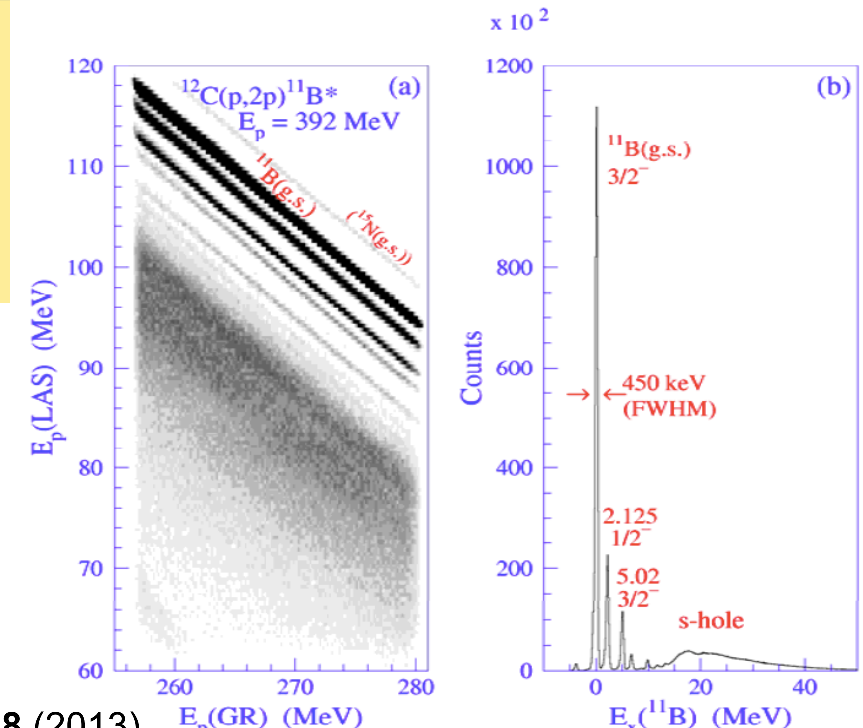
$$E_s = T_0 - \gamma(T_1 + T_2) - 2(\gamma - 1)m_p + \beta\gamma(\overrightarrow{p_{1//}} + \overrightarrow{p_{2//}}) - \frac{q^2}{2M_{A-1}}$$



Distorted Wave Impulse Approximation

$$T_{p,pN} = \sqrt{S_{n\ell j}} \left\langle \chi^{(-)}_{k'_p} \chi^{(-)}_{k_N} \middle| \tau_{pN} \middle| \chi^{(+)}_{k_p} \phi_{n\ell j} \right\rangle$$





Recent work: T. Aumann, C. Bertulani, J. Ryckebusch, PRC **88** (2013)