LECTURE 4: DIRECT TRANSFER AND KNOCKOUT REACTIONS

NUCLEAR STRUCTURE STUDIED WITH SPECTROSCOPY AND REACTIONS

A. Obertelli

CEA Paris-Saclay

TU Darmstadt, IKP, February 2017

Reactions: tools to excite and probe nuclear states

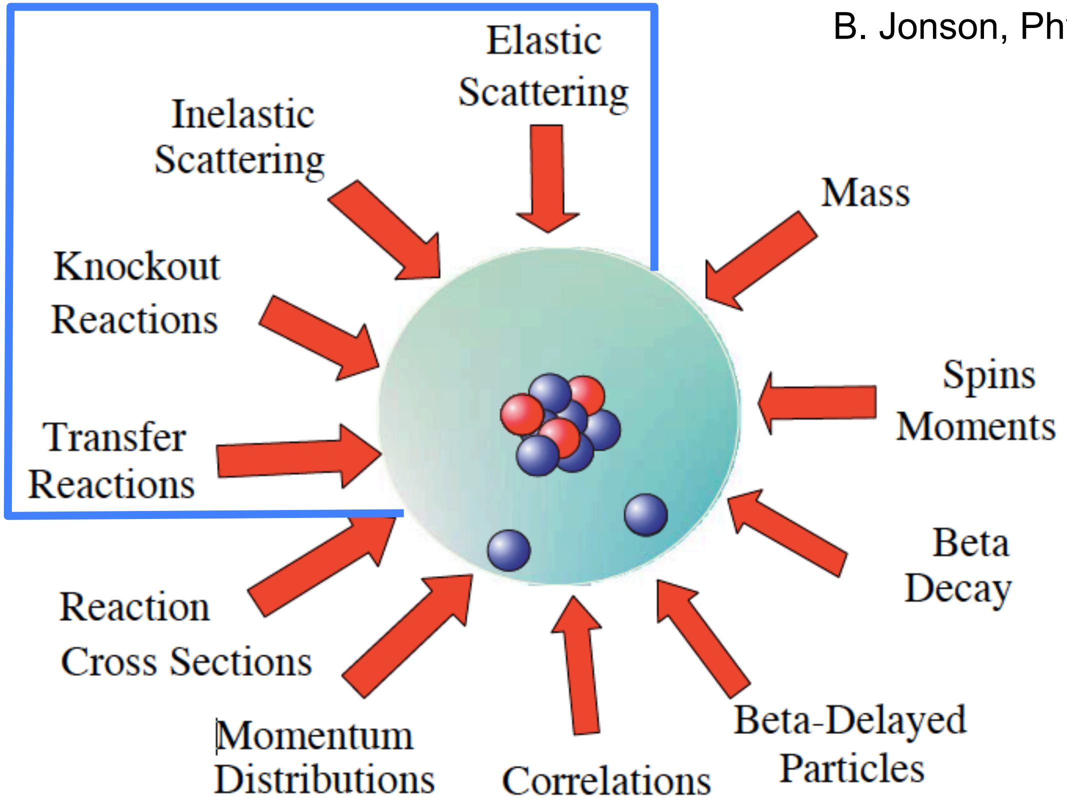
Direct reactions

= cross section informs on structure

= final state keeps memory of initial state

= few degrees of freedom modified

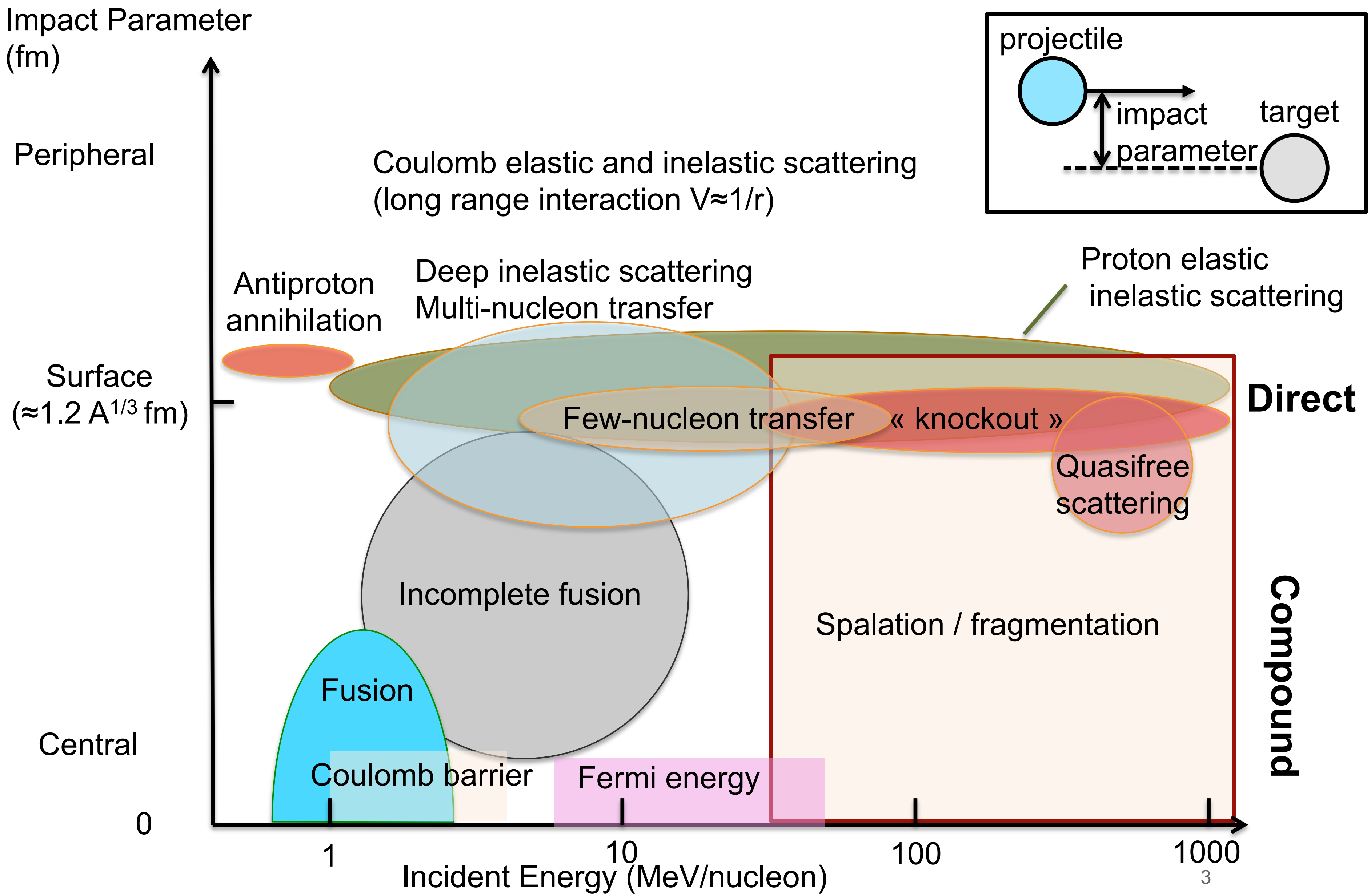
B. Jonson, Physics Report **389** (2004)



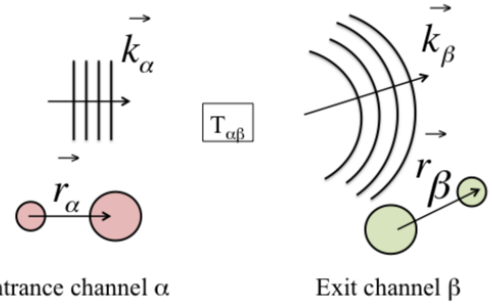
- **Reactions** are used for several reasons to
  - **excite specific states** and probe **nuclear structure,**
  - produce Radioactive Ions beams,
  - study nuclear dynamics and nuclear matter equation of state

- **The dynamical quantum many-body problem can not be solved exactly**
- **Approximations are made**: multiple feedback between experiment and theory

Nuclear reactions



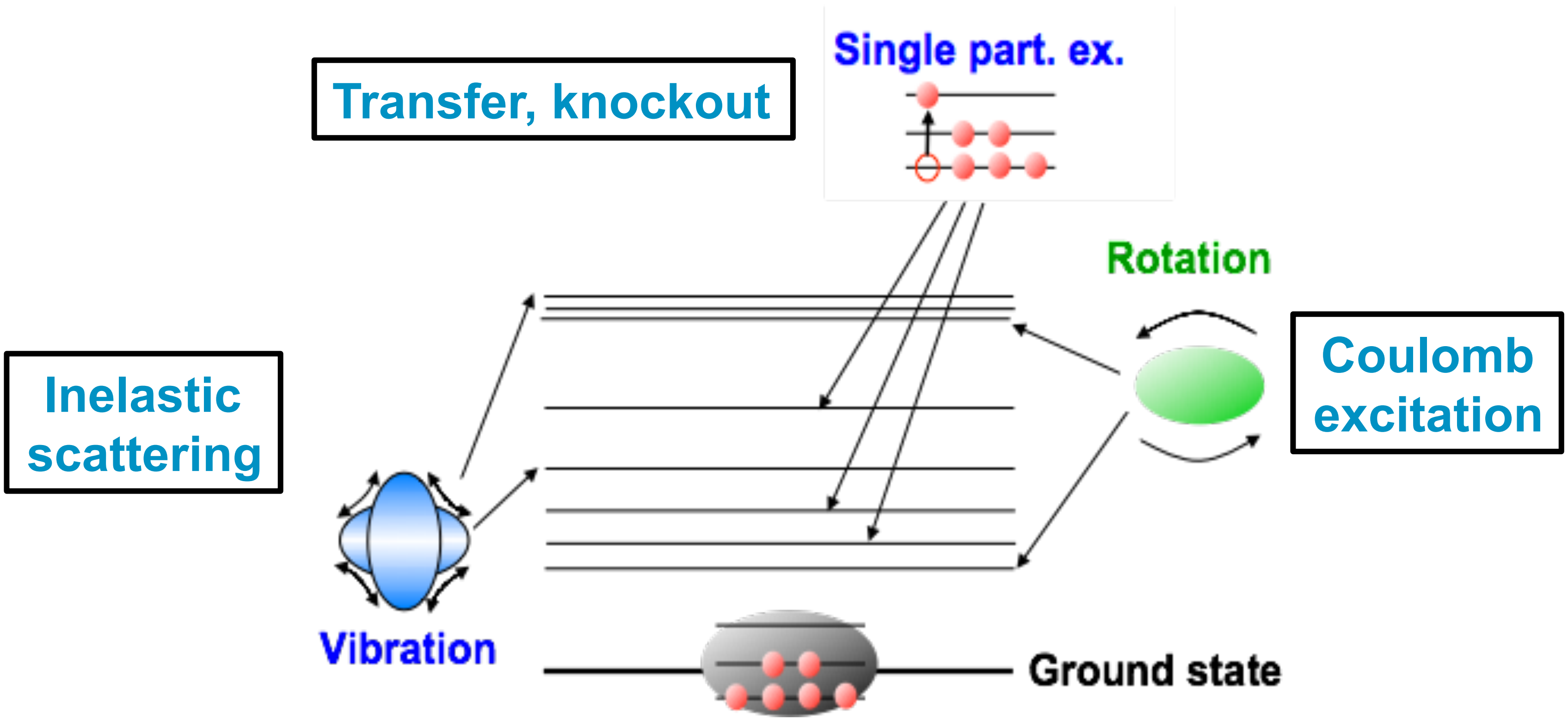
Selectivity of direct reactions



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

General form
Operator formalism

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



Outline

- **Single-particle description**
  - Spectroscopic factors
  - The Baranger sum rule

- **Nucleon transfer at low energy**
  - the Distorted-Wave Born Approximation (DWBA)
  - experimental methods with exotic nuclei
  - detection systems for transfer

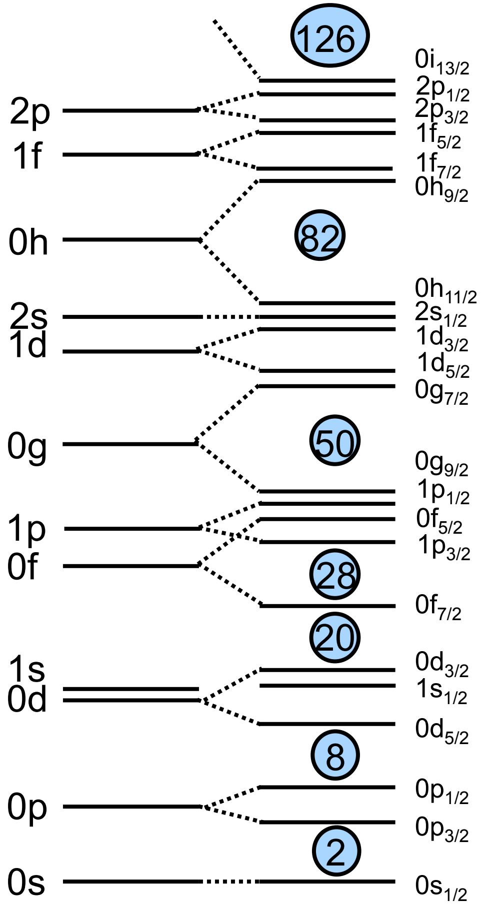
- **Intermediate-energy nucleon removal**
  - S-matrix theory and eikonal approximation
  - Physics case: breakdown of the N=8 shell closure in ^{12}Be
  - Quasifree scattering
  - Invariant-mass technique
  - Physics case: oxygen binding energy systematics

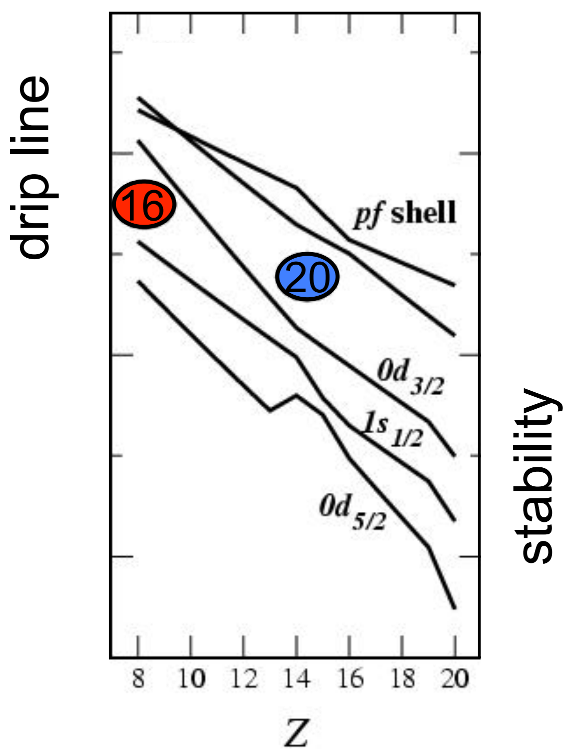
- **Short range correlations and stripping reactions**
  - Short Range Correlations (SRC) and spectroscopic strength reduction
  - Deeply-bound nucleon removal

Main motivation: probing the nuclear shells

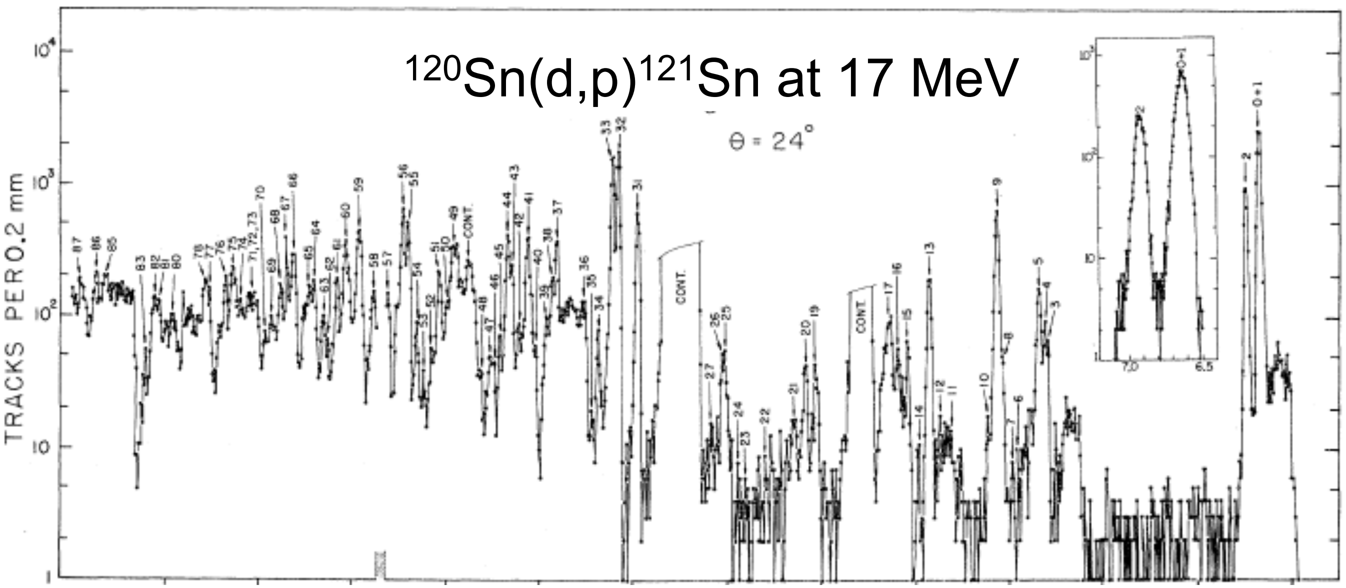
Direct reations

- ❑ absolute excitation energy from invariant mass
- ❑ transfered angular momentum from angular distributions
- ❑ can resolve the nature of states (proton or neutron excitations / single-particle character)

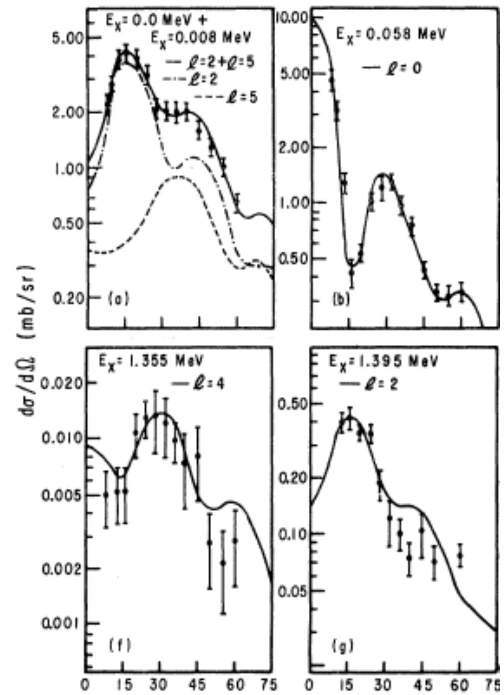




Transfer reactions



excitation energy (arb. units)



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

- Direct: **surface process** and **selectivity**
- Transfer: **momentum matching:** Fermi velocities, 5 to 50 MeV/nucleon
- **Conservation** of spin, parity, angular momentum
- Typical cross section of 1 mb (for one final state): > 10^4 pps for $d\sigma/d\Omega$

Intuitive view of Spectroscopic Factors (SFs)

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

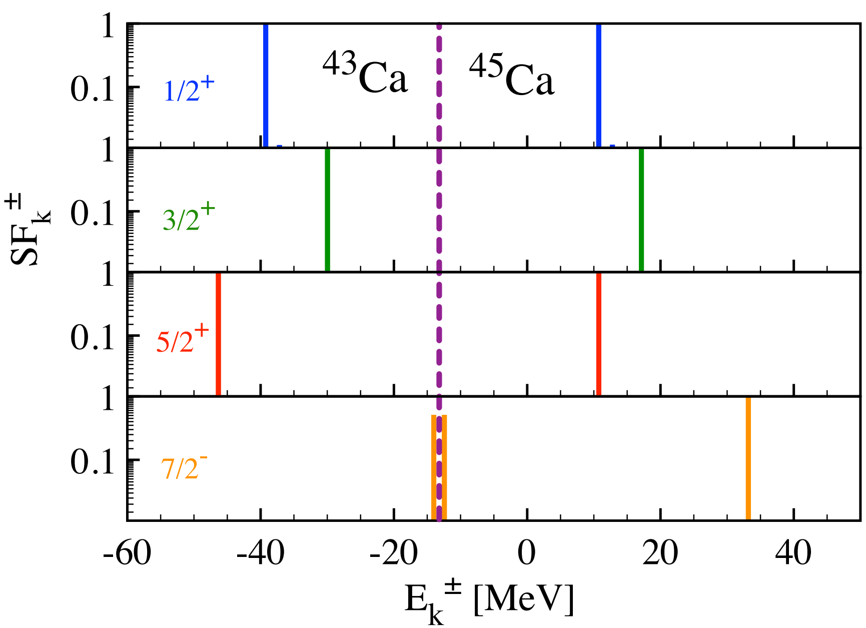
$$S_k^{n\ell j\,+} = \left|\left\langle \psi_k^{A+1} \middle| a_{n\ell j}^{+} \middle| \psi_0^{A} \right\rangle\right|^2$$

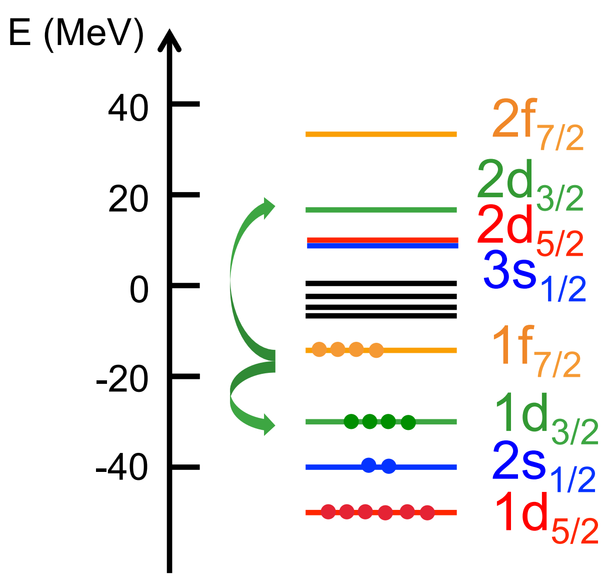
Pickup, ex: ^{44}Ca(d,p)^{45}Ca

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

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

Pure single-particle ^{44}Ca nucleus





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

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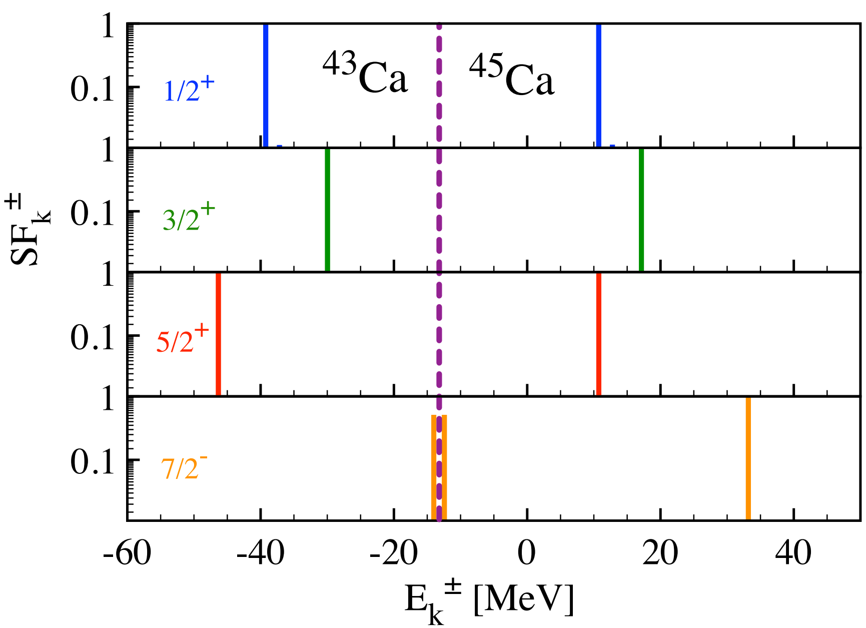
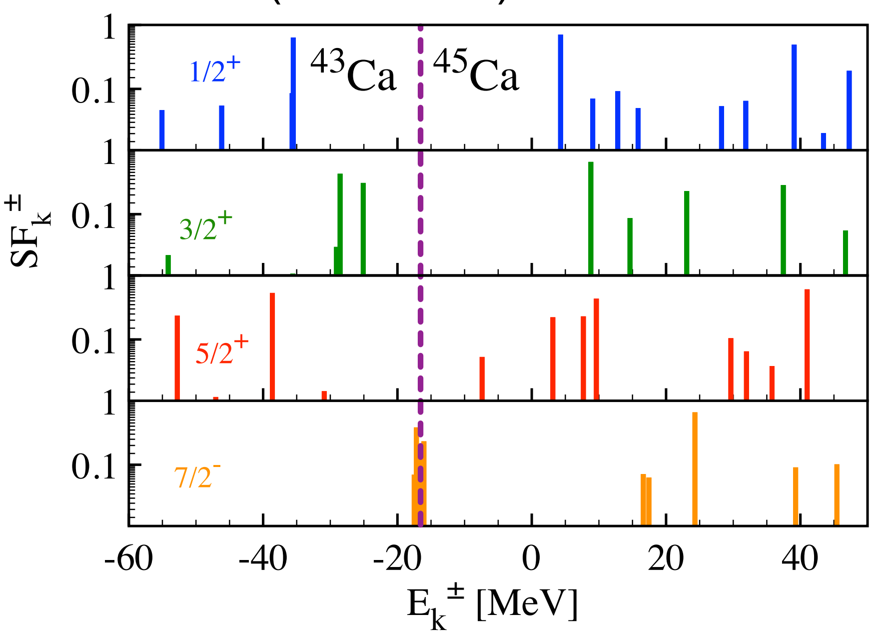


Real (correlated) ^{44}Ca nucleus



In reality: 0 < SF < 1

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

Why spectroscopic factors are so important?

- Single particle energies e_{nlj} can be reconstructed from:
  - ➢ **physical state energies E_k** (observables) from pickup AND stripping
  - ➢ **spectroscopic factors S_k^{nlj}** (not observables)

- Remark (!): SPE not observables (i.e. modified under unitary transform of the Hamiltonian)

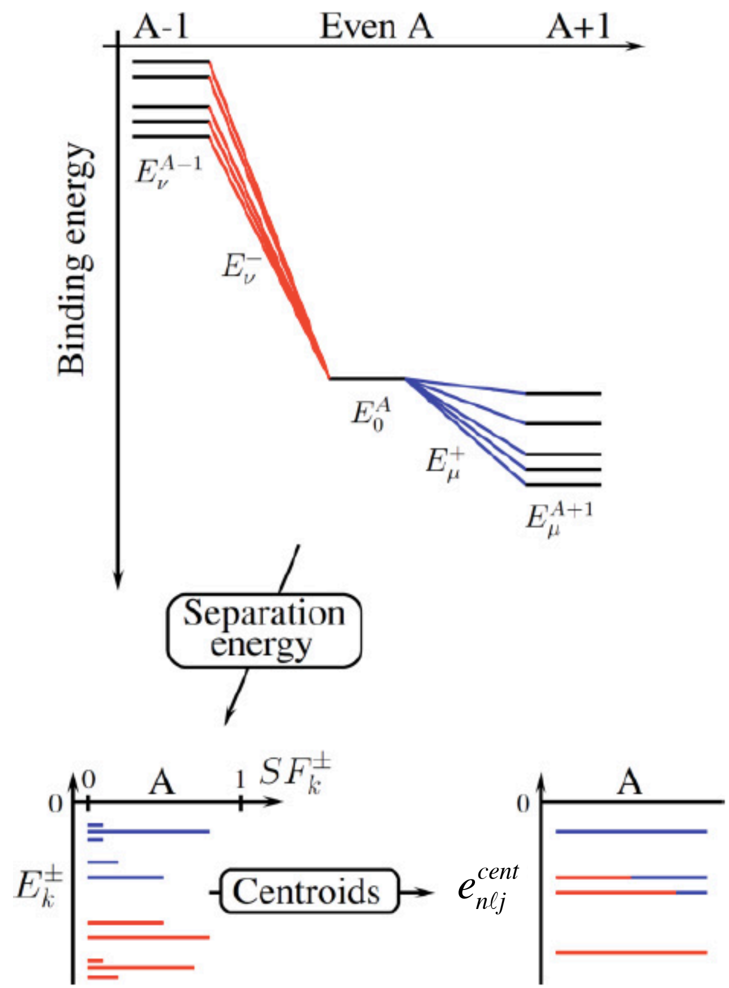
Baranger sum rule:

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

M. Baranger, NPA **149**, 225 (1970)

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

- **Experimental and theoretical uncertainties are often considered too large** to extract single-particle energies directly from the Baranger equation.



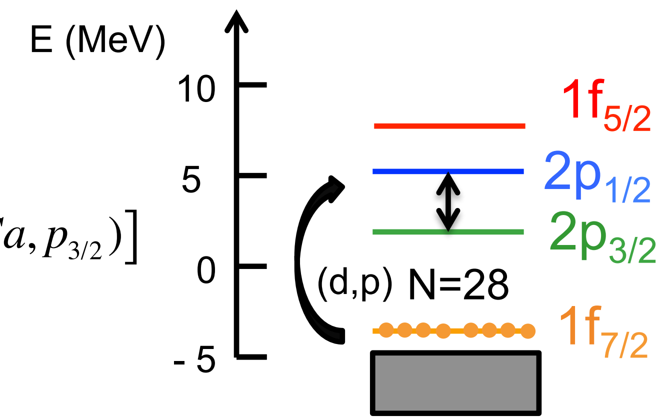
T. Duguet and G. Hagen, PRC **85** (2012)

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

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

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

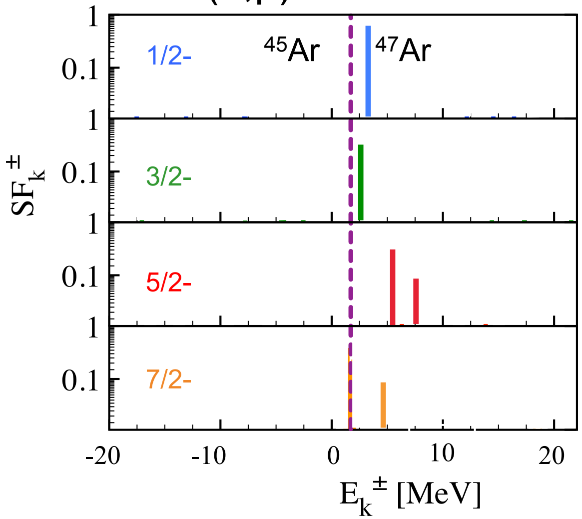
$$\delta\varepsilon_{SO} = \left[\varepsilon(Ar, p_{1/2}) - \varepsilon(Ar, p_{3/2})\right] - \left[\varepsilon(Ca, p_{1/2}) - \varepsilon(Ca, p_{3/2})\right]$$



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 10 A.MeV



$$\delta\varepsilon_{SO} = \left[\varepsilon(Ar, p_{1/2}) - \varepsilon(Ar, p_{3/2})\right] - \left[\varepsilon(Ca, p_{1/2}) - \varepsilon(Ca, p_{3/2})\right]$$

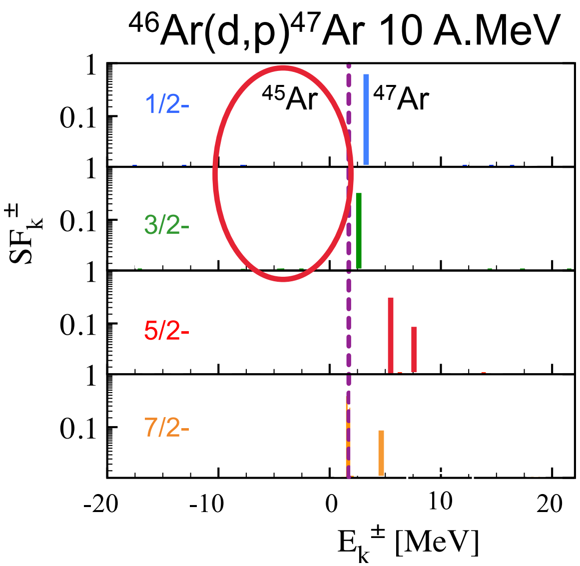
$$\varepsilon(Ar, p_{1/2}) - \varepsilon(Ar, p_{3/2}) = \frac{\sum_{f=1/2-} S^{+}_{1/2-}(E_{1/2-} - E_0)}{\sum_{f=1/2-} S^{+}_{1/2-}} - \frac{\sum_{f=3/2-} S^{+}_{3/2-}(E_{3/2-} - E_0)}{\sum_{f=3/2-} S^{+}_{3/2-}}$$

From experiment: $\boxed{\delta\varepsilon_{SO} = -330(90)\,keV \;\Rightarrow\; \text{spin-orbit reduction}}$

What is missing in this analysis?

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

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



$$\delta\varepsilon_{SO} = \left[\varepsilon(Ar,p_{1/2}) - \varepsilon(Ar,p_{3/2})\right] - \left[\varepsilon(Ca,p_{1/2}) - \varepsilon(Ca,p_{3/2})\right]$$

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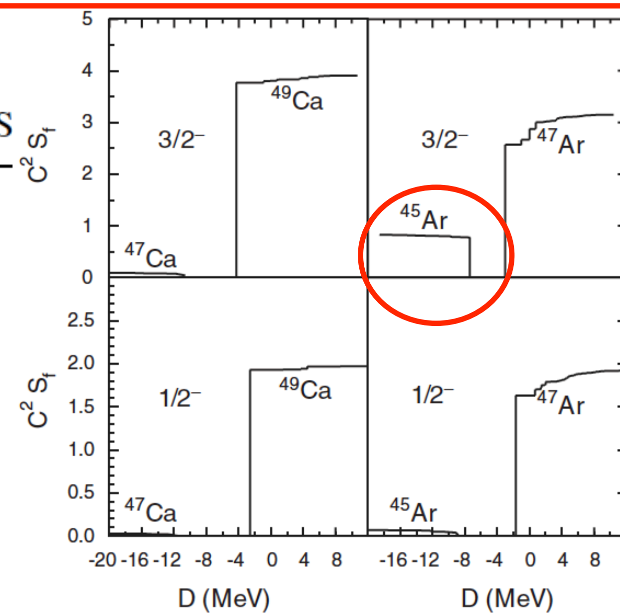
From experiment: $\boxed{\delta\varepsilon_{SO} = -330(90)\,keV}$ ➔ spin-orbit reduction

PRL **99,** 099201 (2007) PHYSICAL REVIEW LETTERS

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

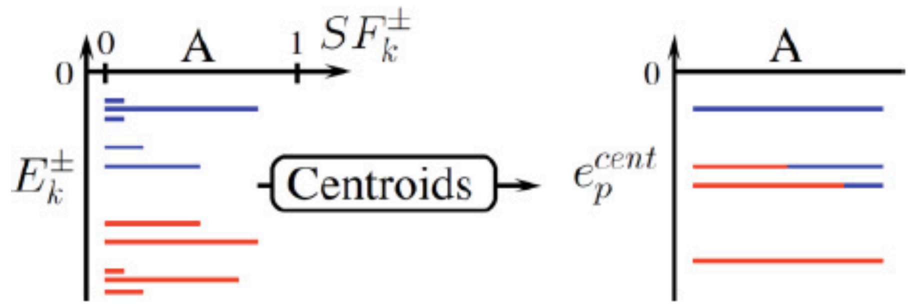


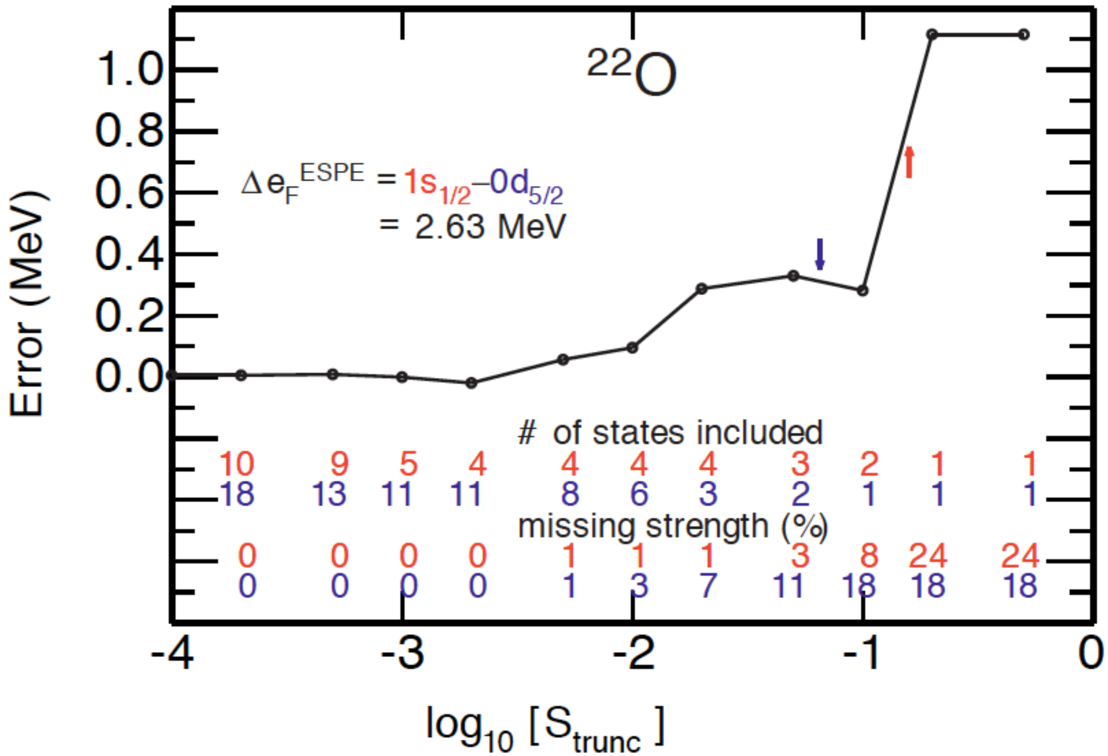
With correction from full strength, including « (d,t)^{45}Ar »:

$\boxed{\delta\varepsilon_{SO} = +0.09(13)\,keV}$ ➔ No spin-orbit reduction!

Sensitivity study to shell gaps

$^{22}O(d,p)^{23}O$, $^{22}O(d,t)^{21}O$: a theoretical study by A. Signoracci, T. Duguet



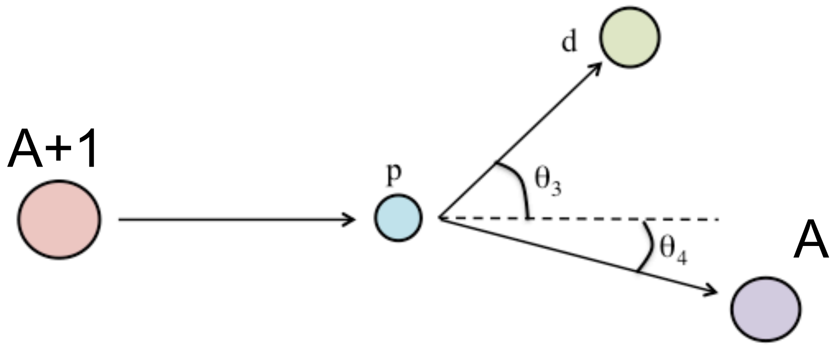


Transfer reaction in the Born Approximation

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

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

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

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

Fourier transform of
The picked-up neutron

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

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

$K=k_p-k_n/2$

Transfer reactions: DWBA

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

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

deuteron wf & reaction process **nuclear structure**

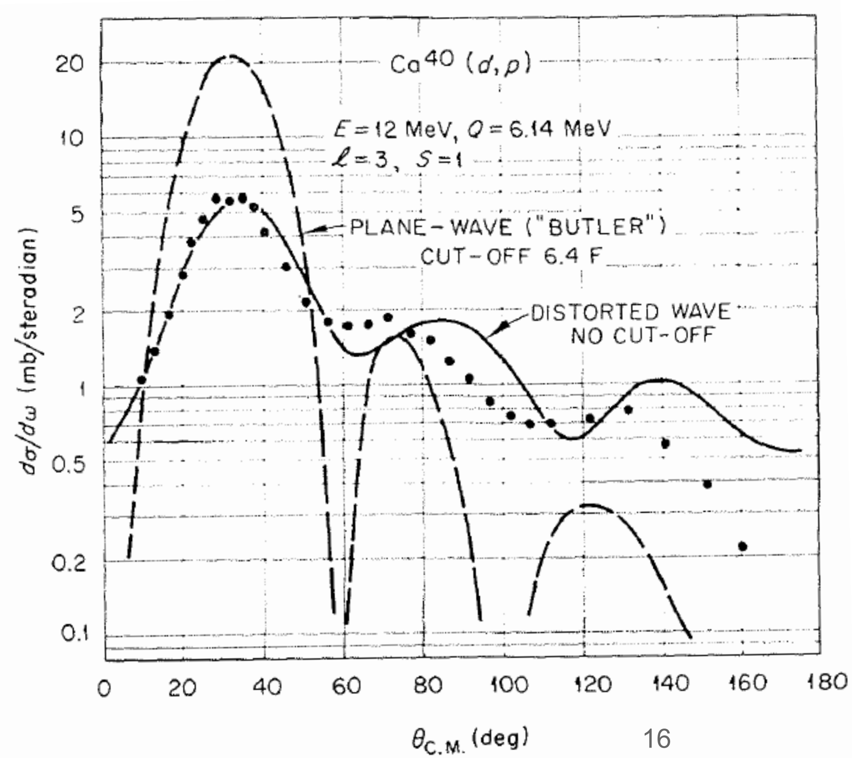
Nota Bene: **in the DWBA, reaction mechanism and structure are separated**

Transfer cross section in DWBA

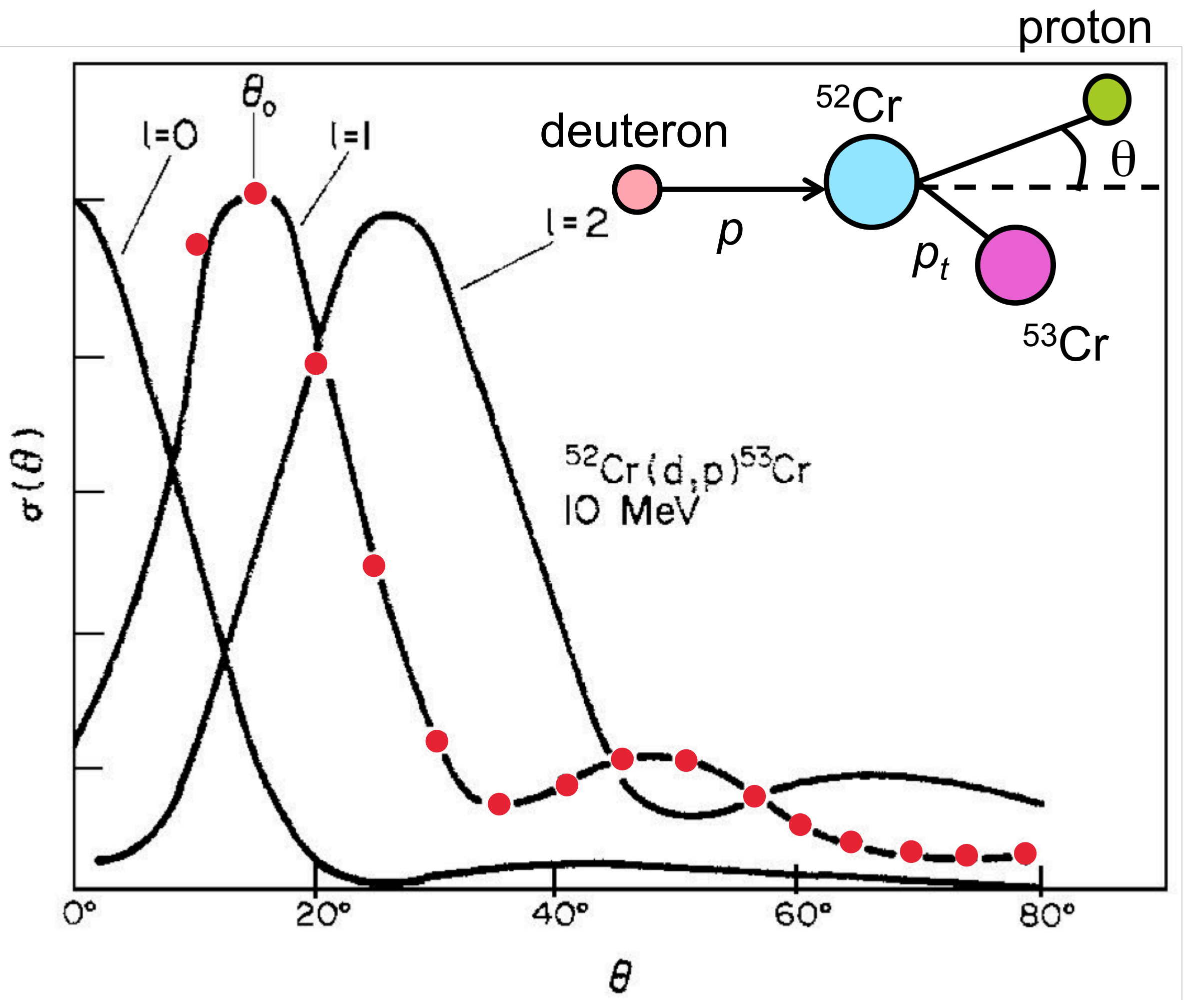
$$\frac{d\sigma_{\alpha\beta}}{d\Omega} = \sum_{n\ell j} S_{n\ell j} \left. \frac{d\sigma_{\alpha\beta}}{d\Omega} \right|_{n\ell j}$$

Analysis of experiments

1) Measure dσ/dΩ
2) Calculate dσ/dΩ single particle
3) Extract S_{nlj} by normalization of theo. vs exp.
4) Compare to S_{nlj} from theoretical structure model or use in the Baranger sum rule for ESPEs



Transfer reactions: angular distributions



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

- Classical derivation:

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

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

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

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

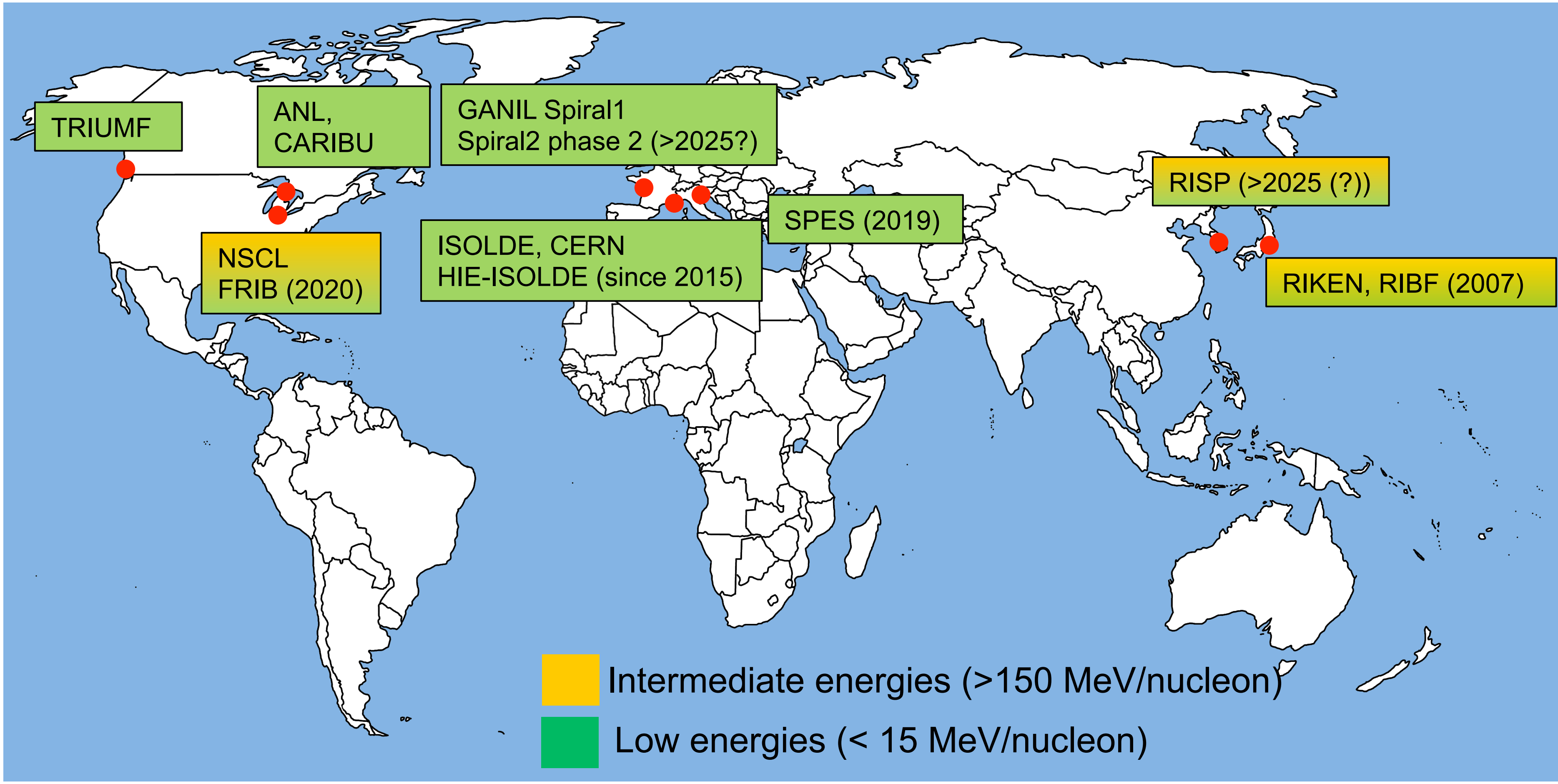
- Numerical application:

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

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

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

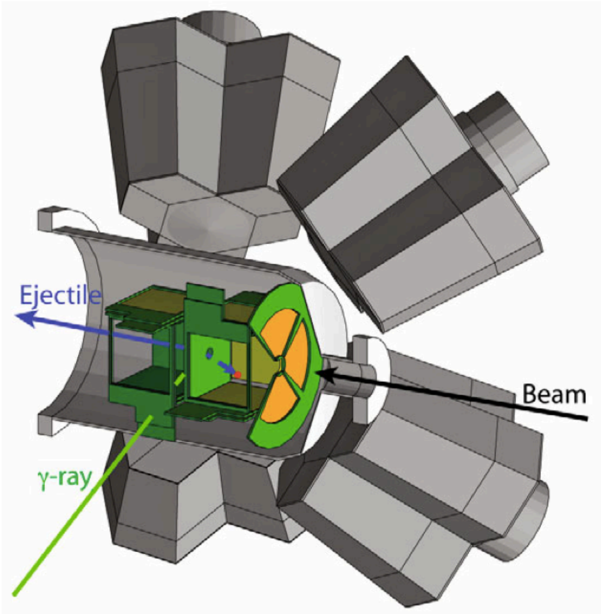
ISOL RI beam facilities worldwide

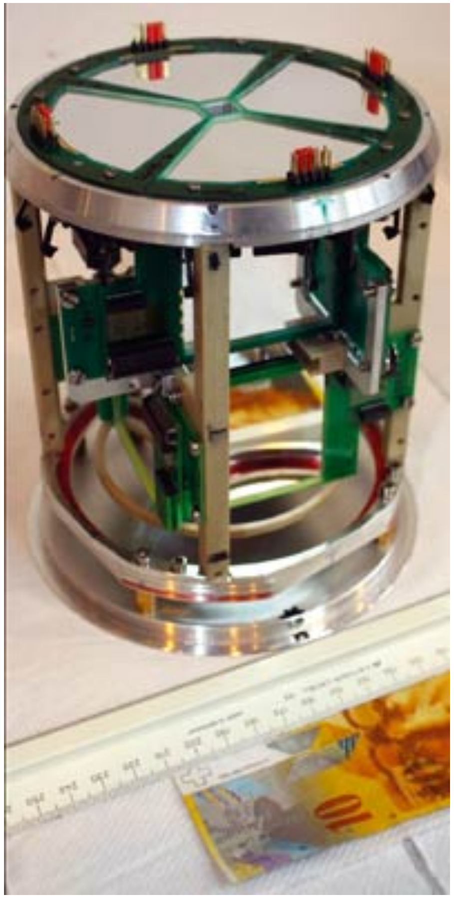


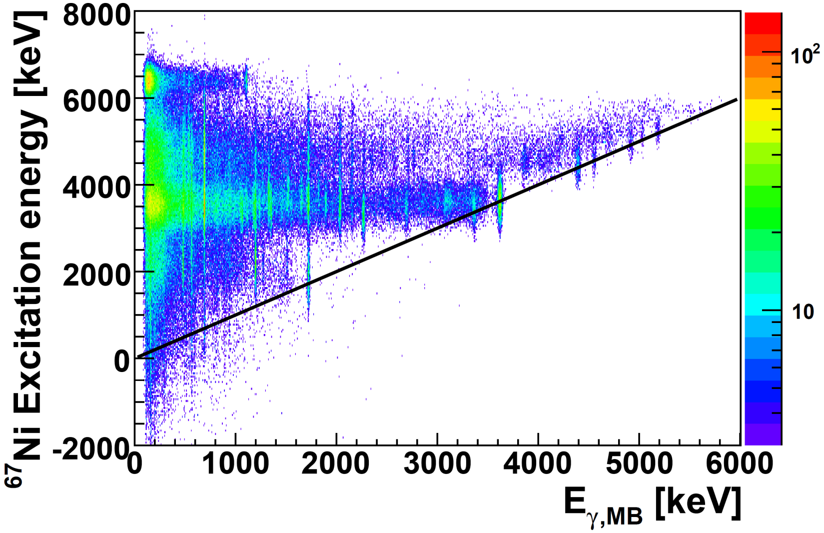
- ❑ Several low energy beam facilities suited for transfer reactions worldwide
- ❑ Many detector developments to adapt to low-beam intensities and/or resolution requirements

Example of setup: TREX-Miniball at ISOLDE

- **T-REX+MINIBALL** setup at **ISOLDE, CERN**: particle-γ coincidences for direct reactions
- Position sensitive compact Si « box » for angular distributions
- **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

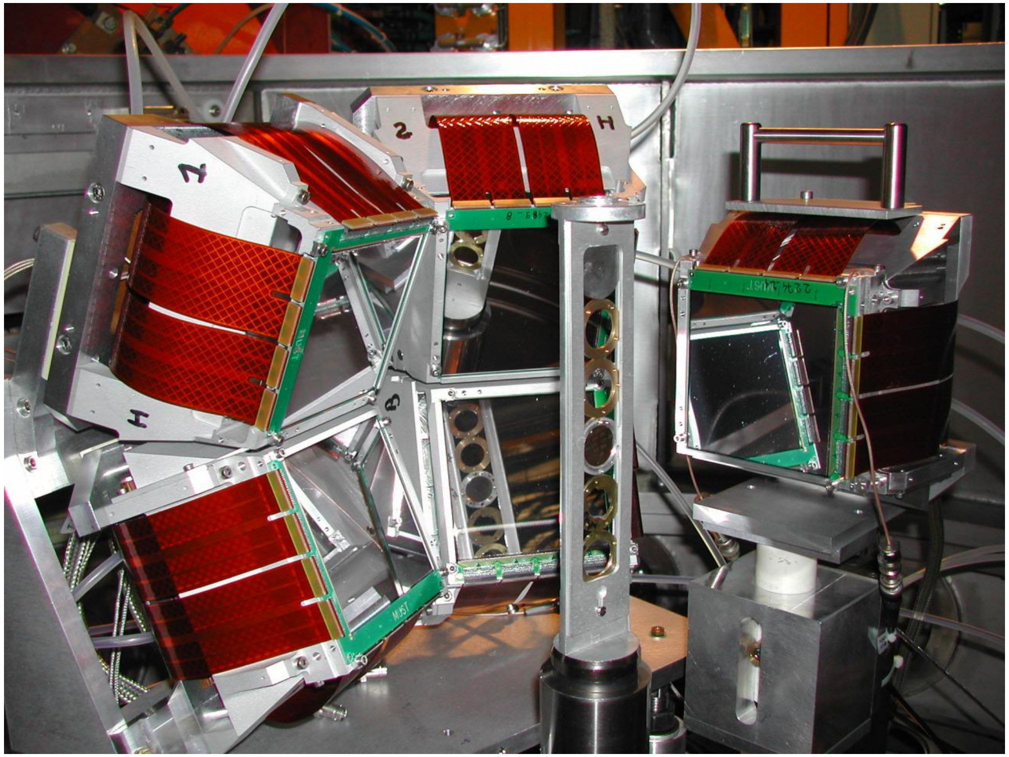


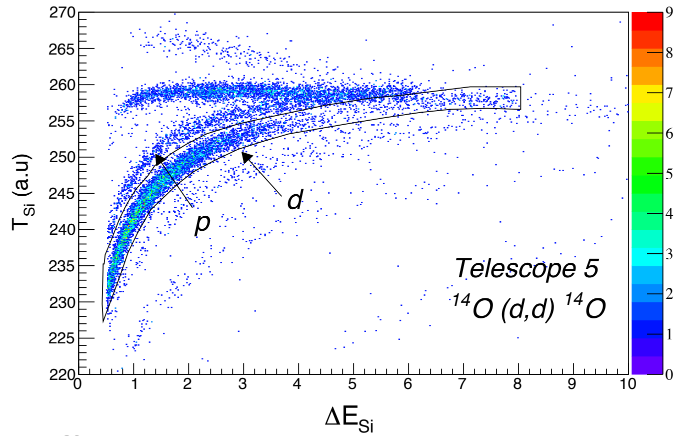


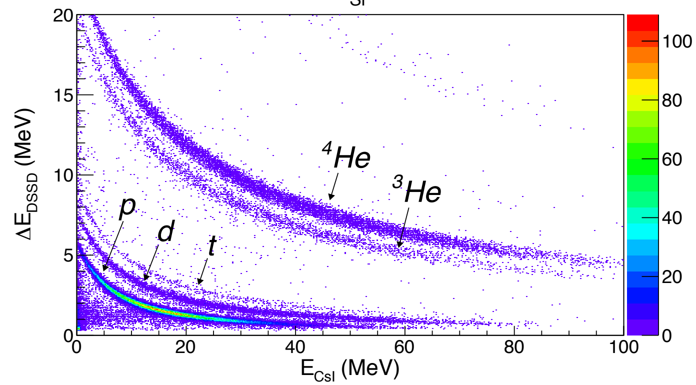


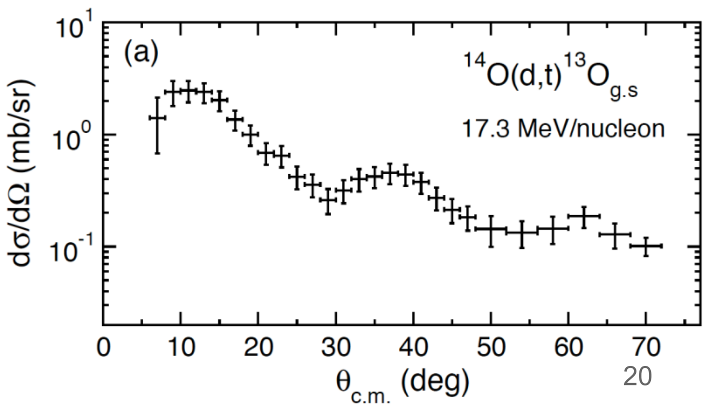
J. Diriken et al. PRC 91 054321 (2015)

MUST2







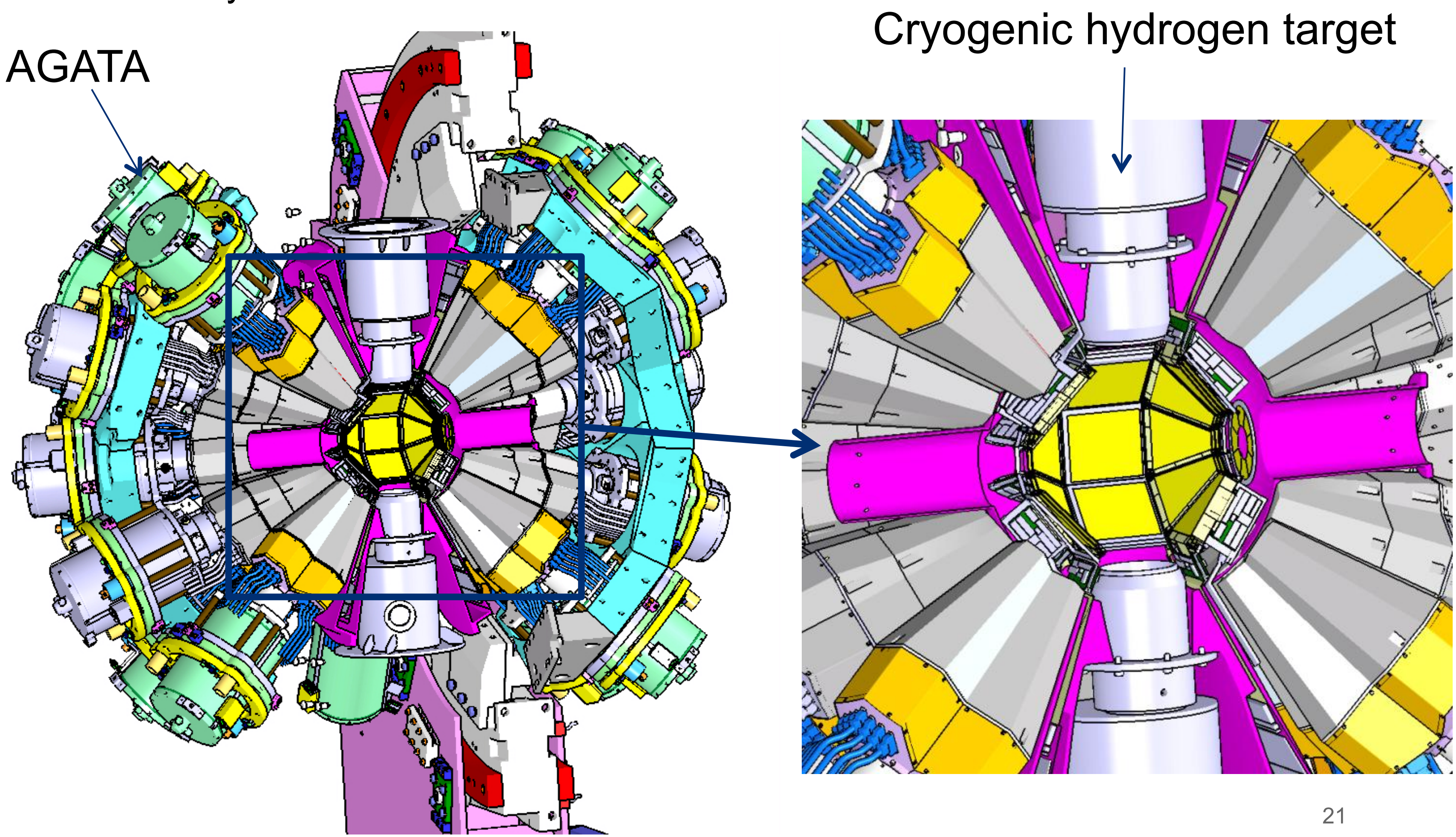


- 6 MUST2 Telescopes, modular array
- 10x10 cm^2 300μm DSSSD (700 μm strips)
- SiLi (3 mm) or CsI

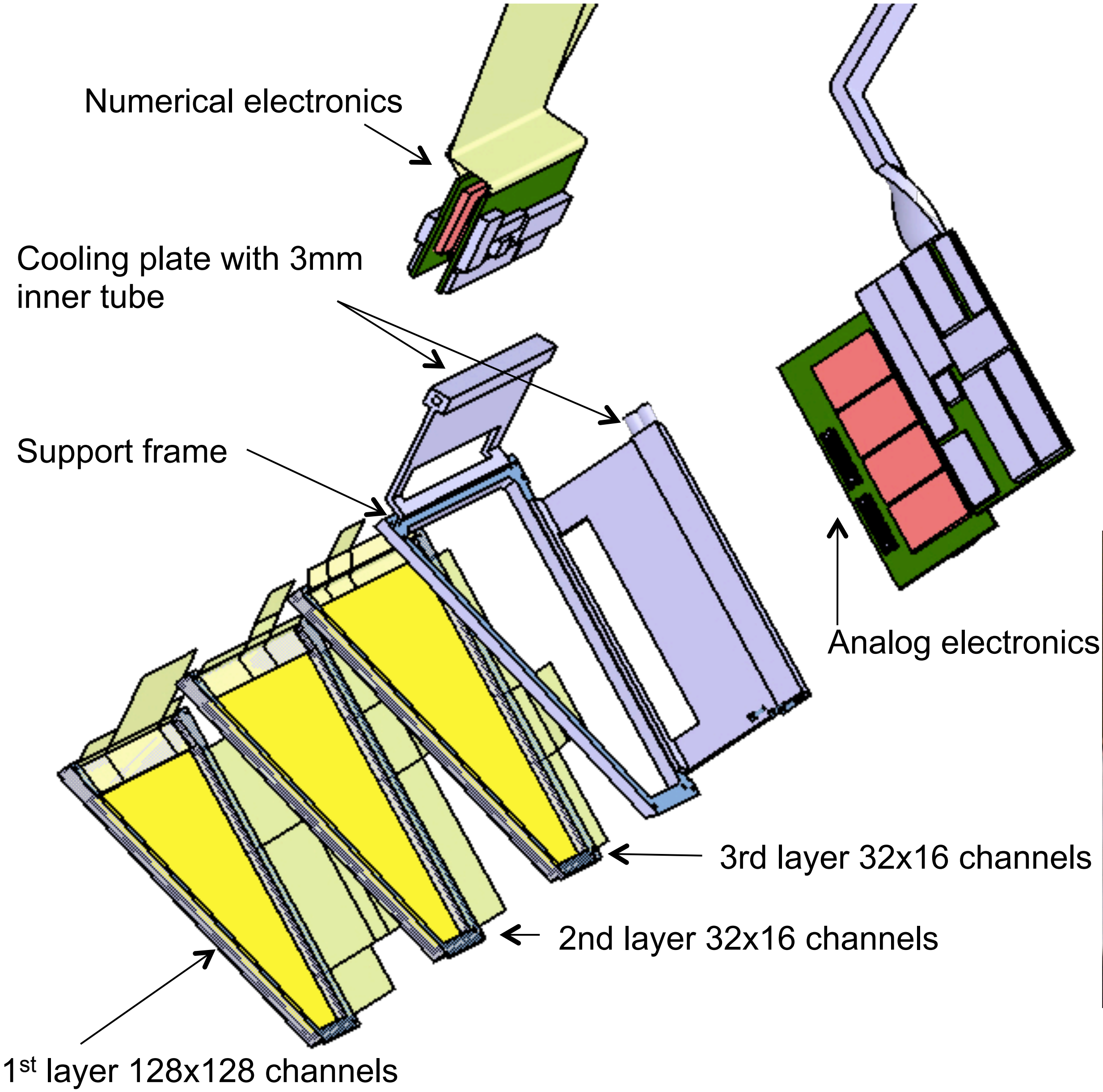
- Mostly used in GANIL, campaign at RIKEN in 2010
- Inspired from the previous MUST array
- E.C. Pollacco *et al.*, EPJA **25**, 287 (2005)

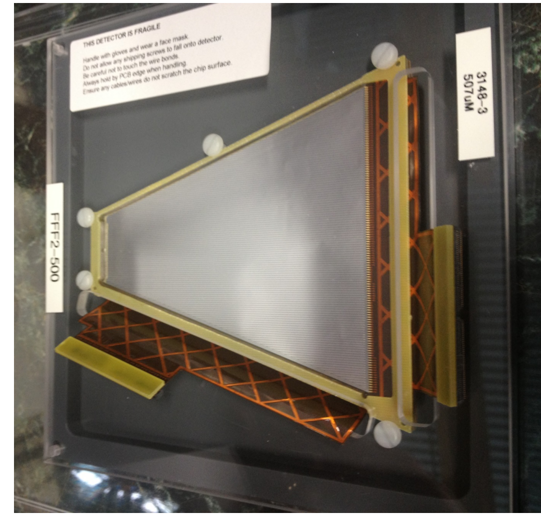
GASPARD-TRACE

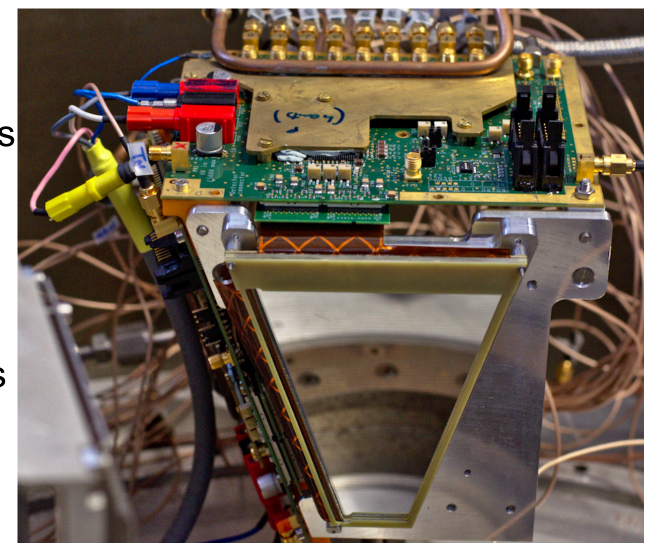
- next-generation of compact Si array
- compatible with AGATA
- driven by IPN Orsay and LNL (Italy)
- 4π Si array with new PID



GASPARD-TRACE

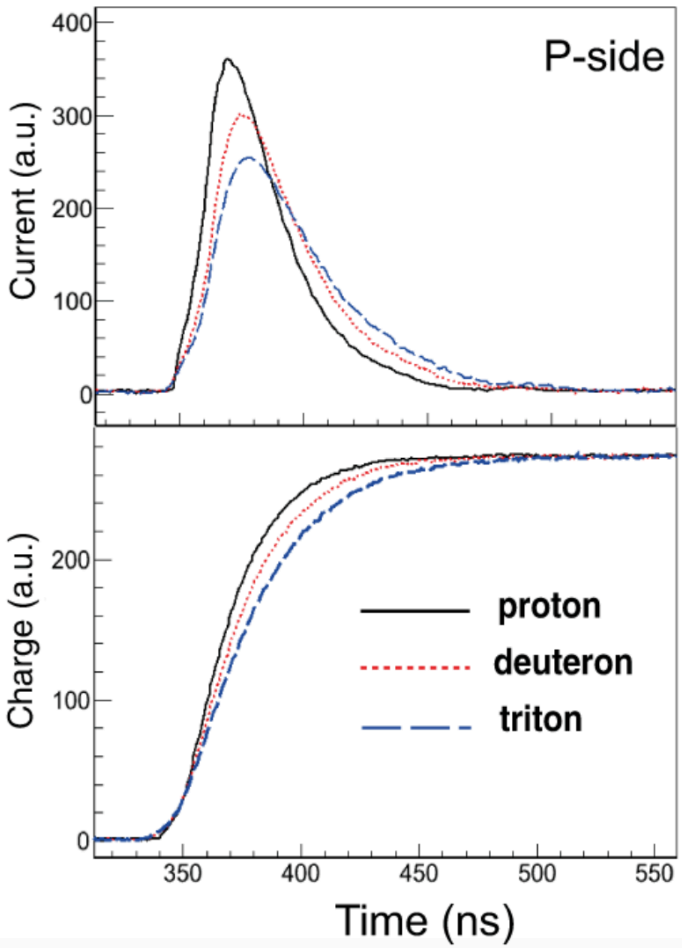




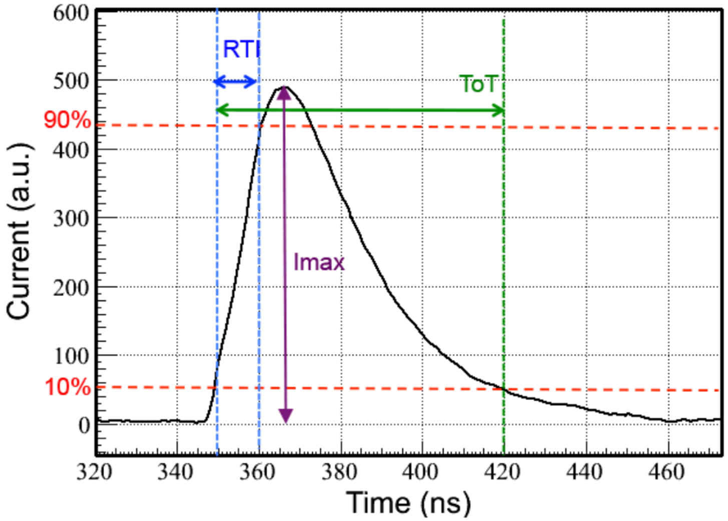


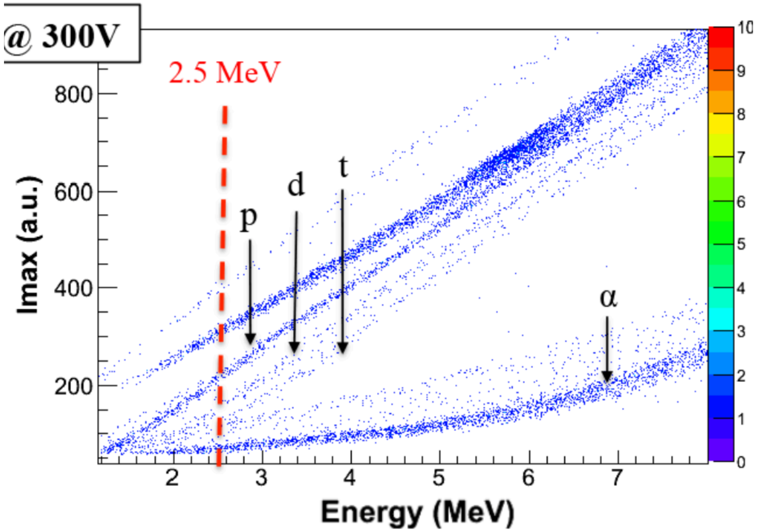
GASPARD-TRACE

- digital electronics
- pulse-shape based PID
- demonstrated for individual strips of DSSDs



M. Assié et al., EPJA 51 11 (2015)





CHyMENE: a pure and thin solid hydrogen target

Objective

Solid H_2 or D_2 target 50 µm
50 µm H2 = 350 μg.cm^{-2}
Windowless

CHyMENE specifications

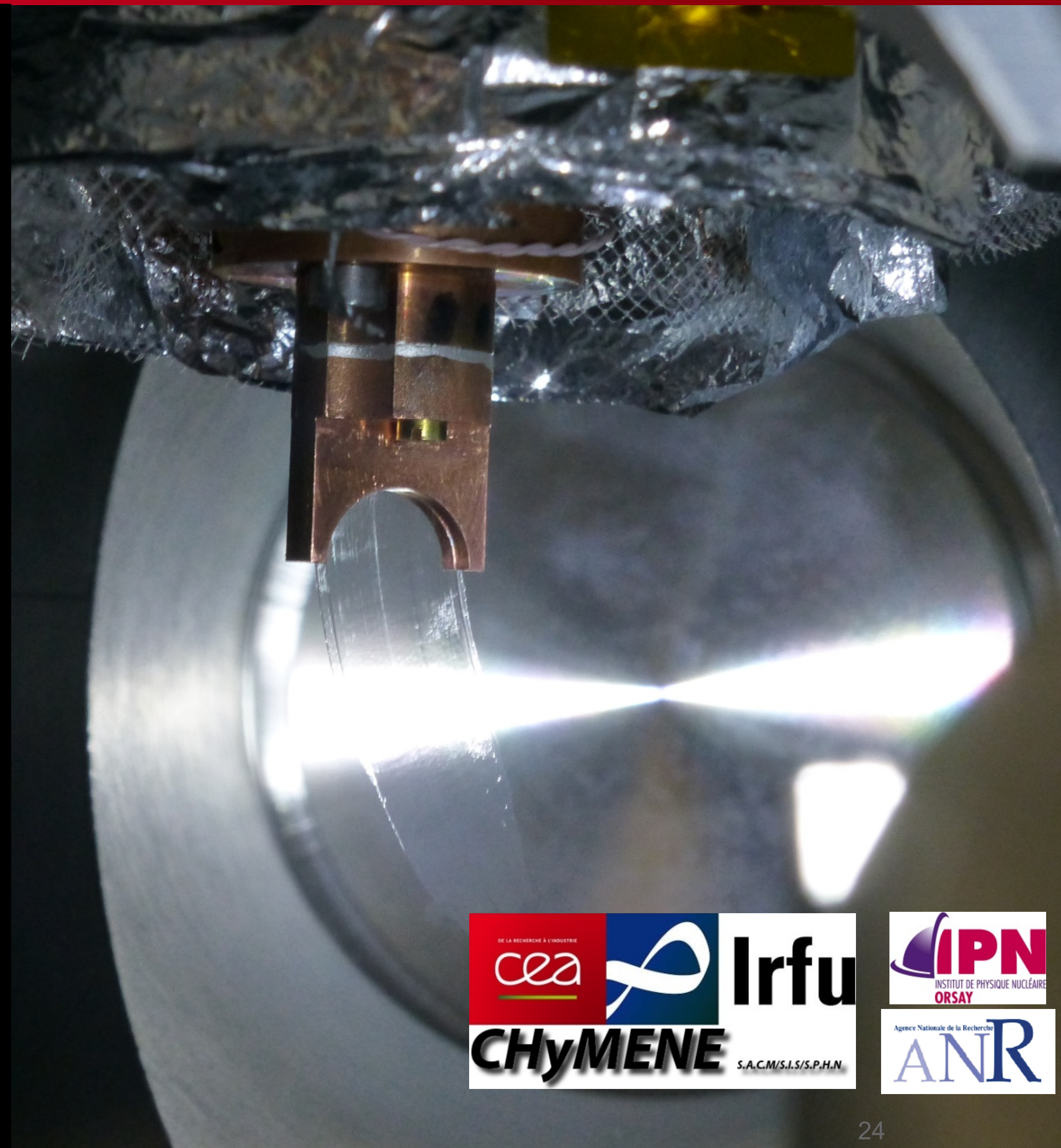
Cryogenic Power: 15 W at 12 K
Extrusion speed: 2 to 10 mm/s
Correct positioning of the ribbon
Vacuum reaction chamber: 5.10^{-5} mbar
Autonomy: At least 2 weeks
Target vertical translation: 100 mm
Target rotation: +/- 45 °

Homogeneity

Estimated in-beam to about 10%
To be improved with current system

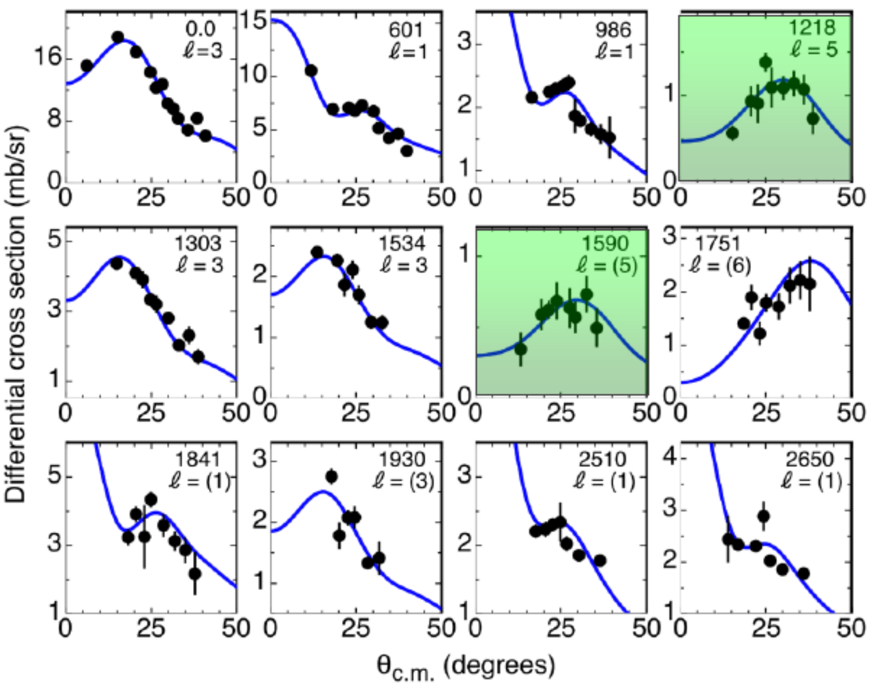
A. Gillibert *et al.*, EPJA **49** (2013).

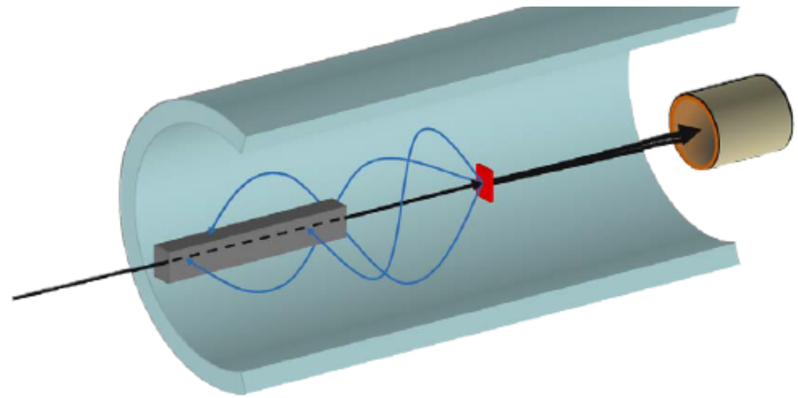
Operational from 2017



HELIOS

- HELIOS at ANL
- large efficiency, simple, excellent energy resolution for thin targets
- New concept based on E, ToF and magnetic field
- A. H. Wuosmaa *et al.,* NIM A 580, 1290 (2007)





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

Independent of energy!!

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

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

HELIOS

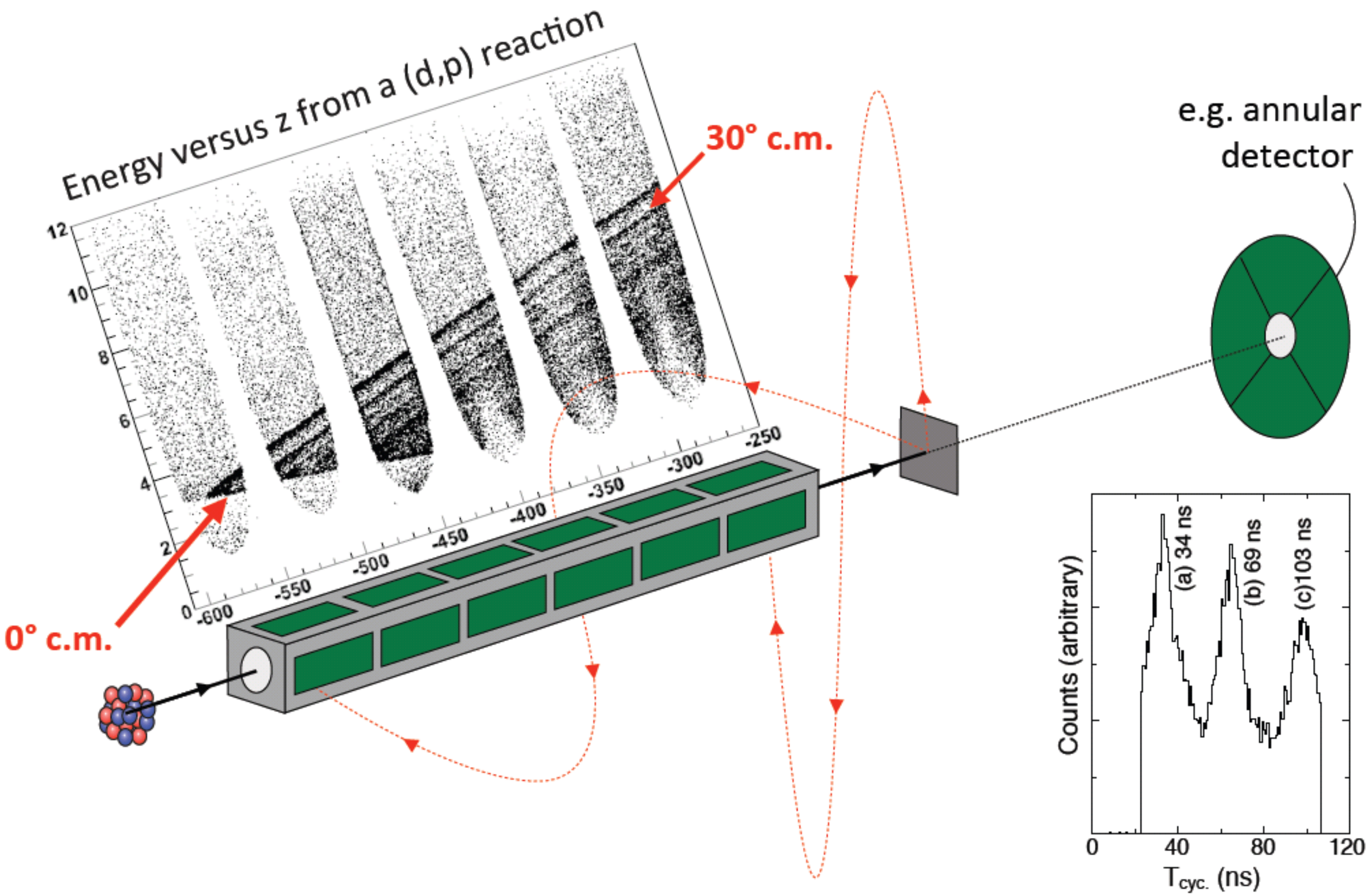


Image from B. Kay, ANL

HELIOS

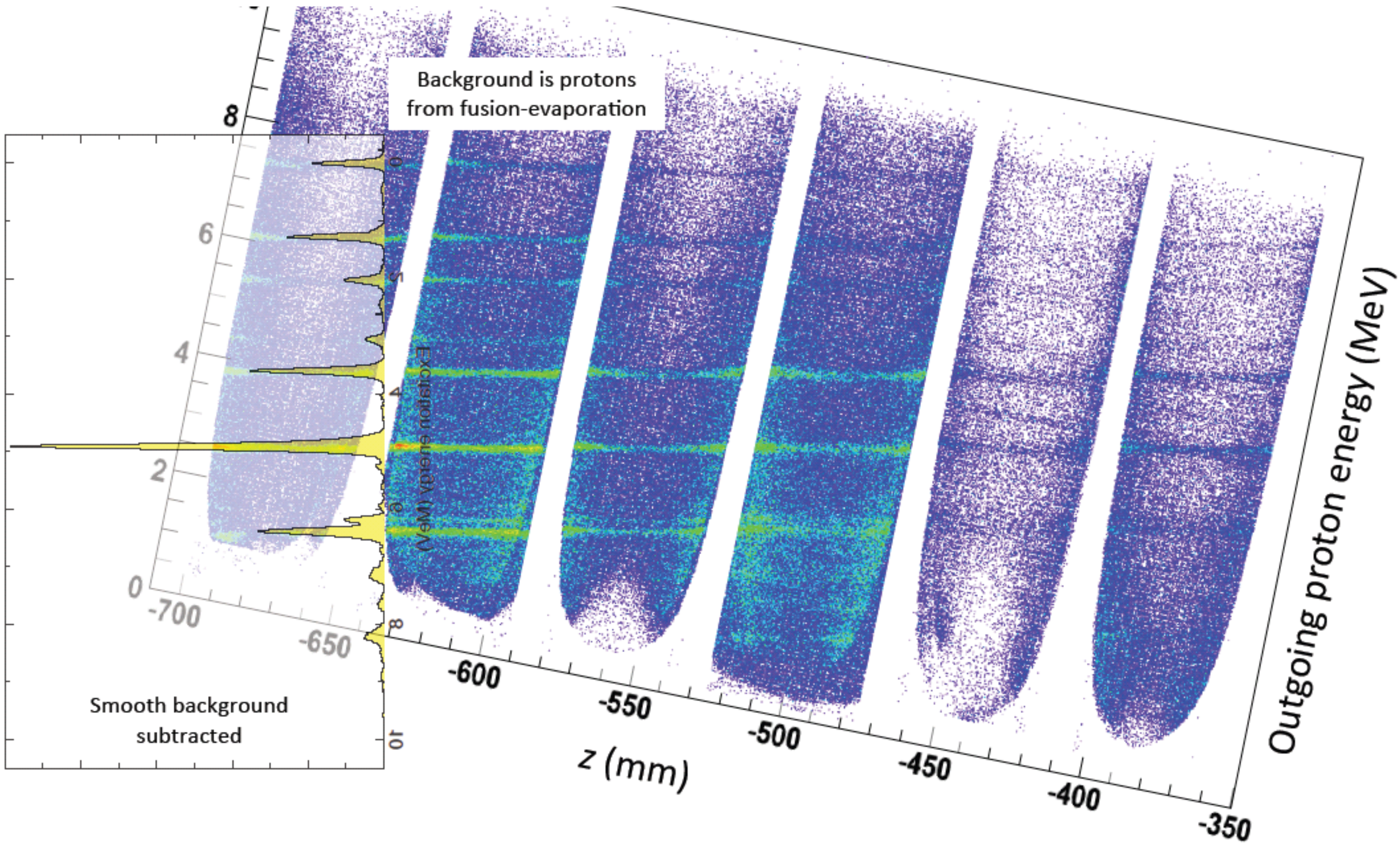
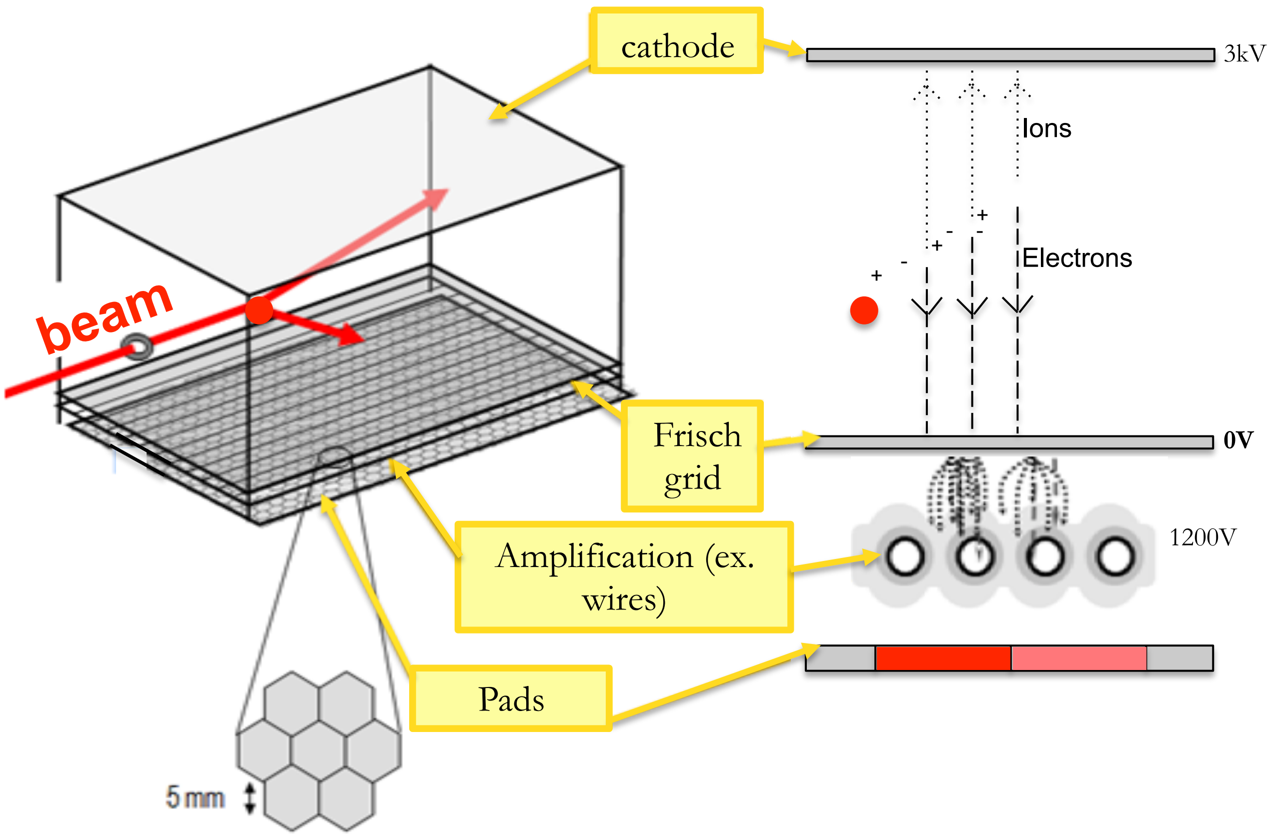


Image from B. Kay, ANL

Principle of Time Projection Chambers (TPC)



C. E. Demonchy *et al., Nucl. Instrum. Meth.* **573,** 145 (2007)

Time Projection Chamber (TPC) :

1. The scattered deuteron or α ionizes the gas

2. The electrons drift towards the Frisch grid

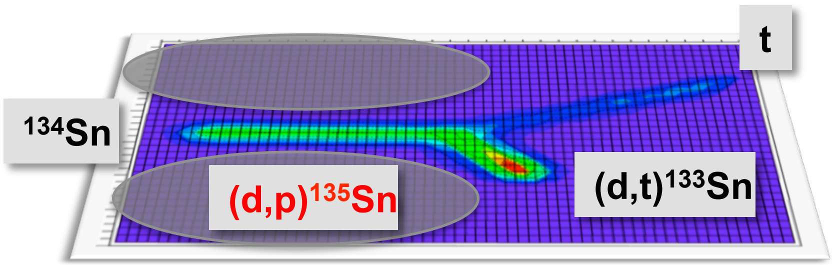
3. Amplification

4. Signal on each pad proportionnal to the amount of electrons

Slide from M. Vandebrouck, CEA

TPCs: features and ongoing developments

- Several main advantages
  - Efficiency (factor 2-3 of gain)
  - Low thresholds
  - Thick targets (factor 5-10 of gain)
  - Angular and spatial resolution

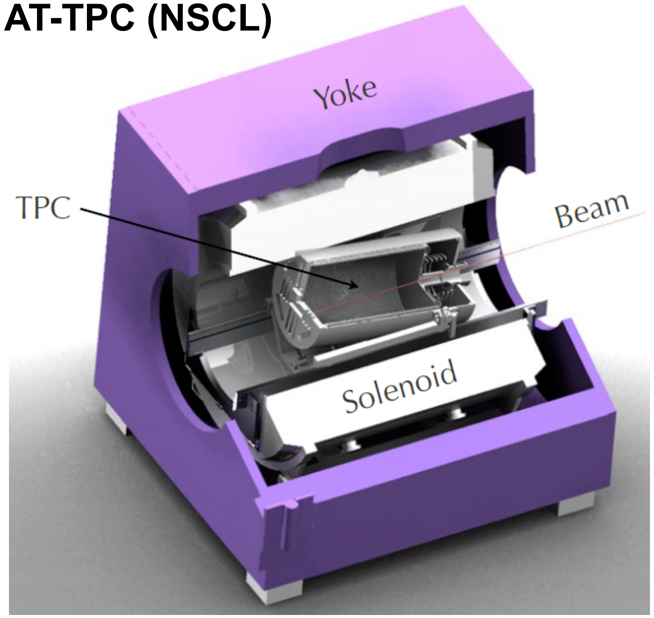


- Wide physics cases

	(MeV/u)
Nucleon transfer	5-10
Resonant scattering	8-10
Nuclear astrophysics	10
Giant resonances	50
Decay (2p, β3p, …)	>100

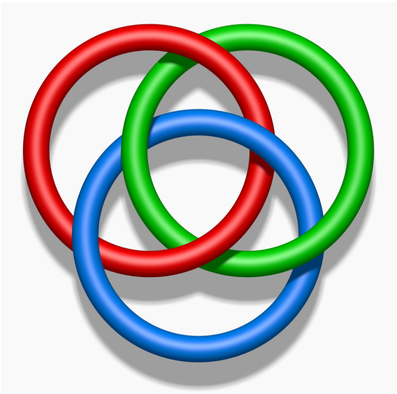
- Several TPCs for nuclear physics developed worldwide:
- ACTAR (France): GANIL and Isolde
- AT-TPC (USA): NSCL/FRIB
- ACTAF (Russia): FAIR
- Spirit TPC (Japan/USA): RIKEN
- CAT (Japan): RIKEN

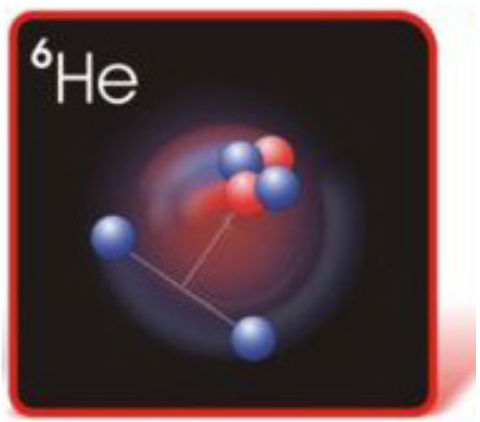
AT-TPC (NSCL)



Beyond single particles : few body correlations

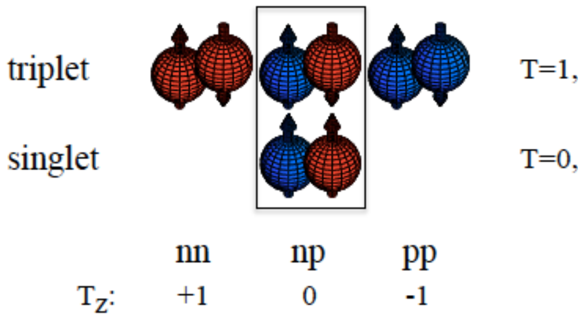
T=1 pairing, dineutron



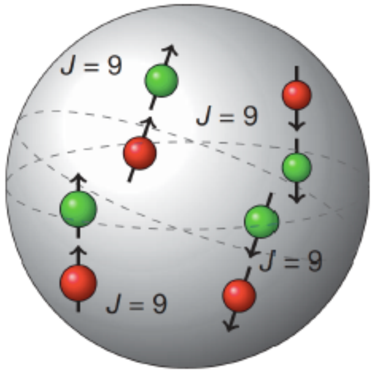


➔ two-neutron transfer

T=0 pairing

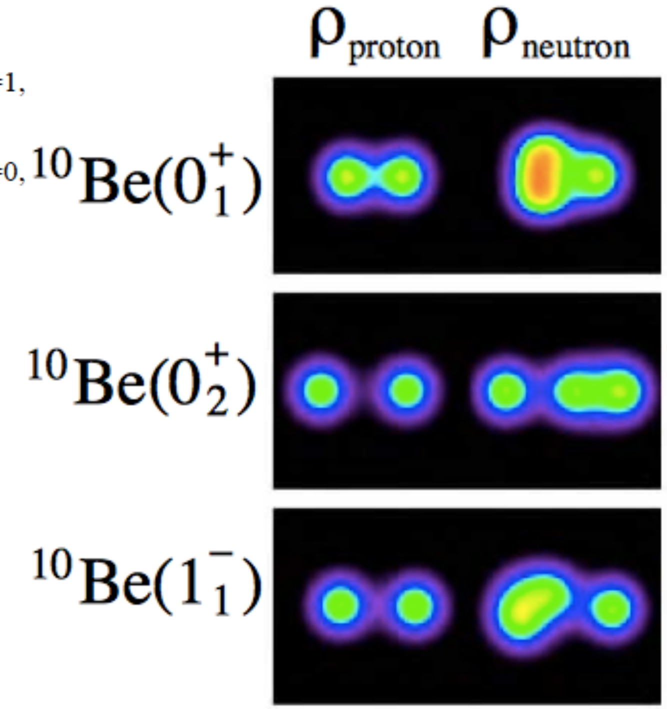


Does this T=0 phase exist ?



➔ deuteron transfer

α cluster states



➔ α cluster transfer

… small cross sections and more complex analysis than for one-nucleon transfer

Interplay of structure and reaction: a challenge

- **Unitary transform and scale dependence of operators**:
  Unitary transform U(*s*) ($U^+(s)U(s)=1$) define equivalent Hamiltonians:

$$H(s) = U(s) H U^+(s) \Rightarrow \begin{cases} H(s)\left|\psi_k^A(s)\right\rangle = E_k^A \left|\psi_k^A(s)\right\rangle \\ \left|\psi_k^A(s)\right\rangle = U(s)\left|\psi_k^A\right\rangle \end{cases}$$

  Observables $\hat{O}(s) = U(s)\hat{O}U^+(s)$ lead to $\left\langle \psi_k^A(s)\right|\hat{O}(s)\left|\psi_k^A(s)\right\rangle = \left\langle \psi_k^A\right|\hat{O}_k^A\left|\psi_k^A\right\rangle = O_k^A$

- **Not transforming an operator leads to a non observable quantity**
  i.e. spectroscopic amplitudes vary under U(s) and or not observables
  i.e. impulse approximation is *s* dependent

- **What would be the proper (ideal) way then?**

1) Define resolution scale *s* and specify *H(s)*
2) Resolve the many-body (target+projectile) using H(s)
3) Validate theoretical cross sections against measured values
4) Extract scale dependent SFs *S(s)* or SPEs *e(s)* from many-body structure calculation

- **The deuteron D-wave** (possible puzzling) example: D-wave component **not an observable**
  Unitary transform dependence of the wave function and operators
  R.D. Amado, PRC **19**, 473 (1979), J.L. Friar, PRC **20**, 325 (1979)
  S.N. More et al., Phys. Rec. C **92**, 064002 (2015)

See lecture by Kai Hebeler

- **Single-particle description**
  - Spectroscopic factors
  - The Baranger sum rule

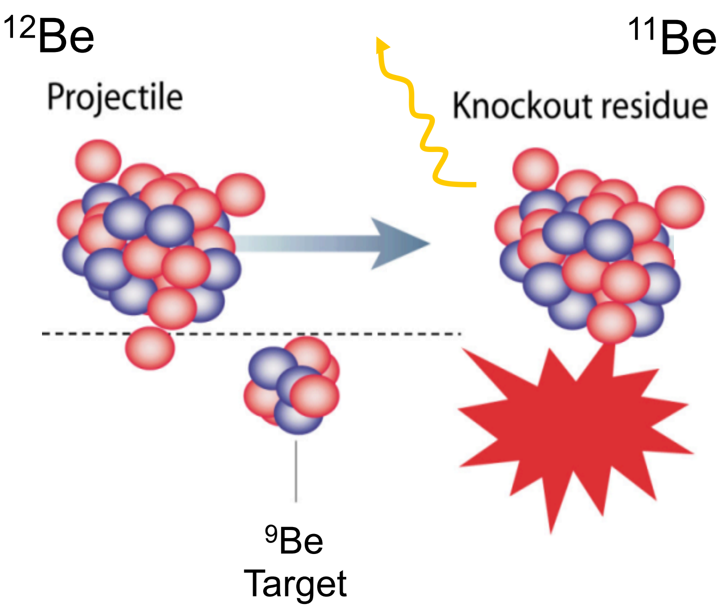
- **Nucleon transfer at low energy**
  - the Distorted-Wave Born Approximation (DWBA)
  - experimental methods with exotic nuclei
  - detection systems for transfer

- **Intermediate-energy nucleon removal**
  - S-matrix theory and eikonal approximation
  - Physics case: breakdown of the N=8 shell closure in ^{12}Be
  - Quasifree scattering
  - Invariant-mass technique
  - Physics case: oxygen binding energy systematics

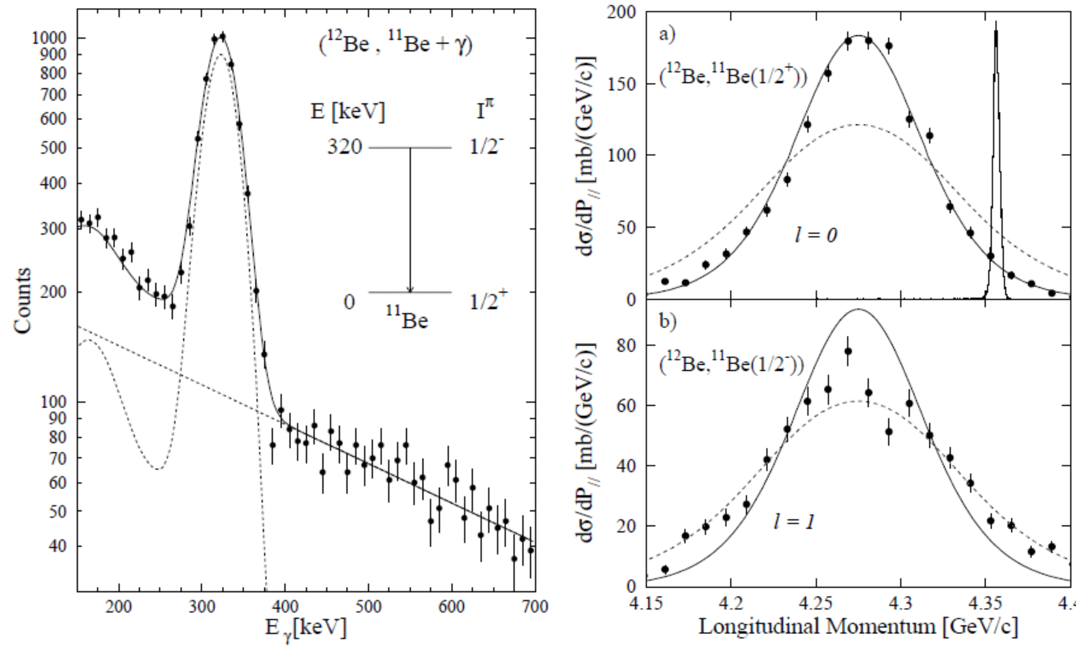
- **Short range correlations and stripping reactions**
  - Short Range Correlations (SRC) and spectroscopic strength reduction
  - Deeply-bound nucleon removal

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)
- Strong advantages for RIB: (i) **large cross sections** (1-100 mb), (ii) **thick targets** can be used

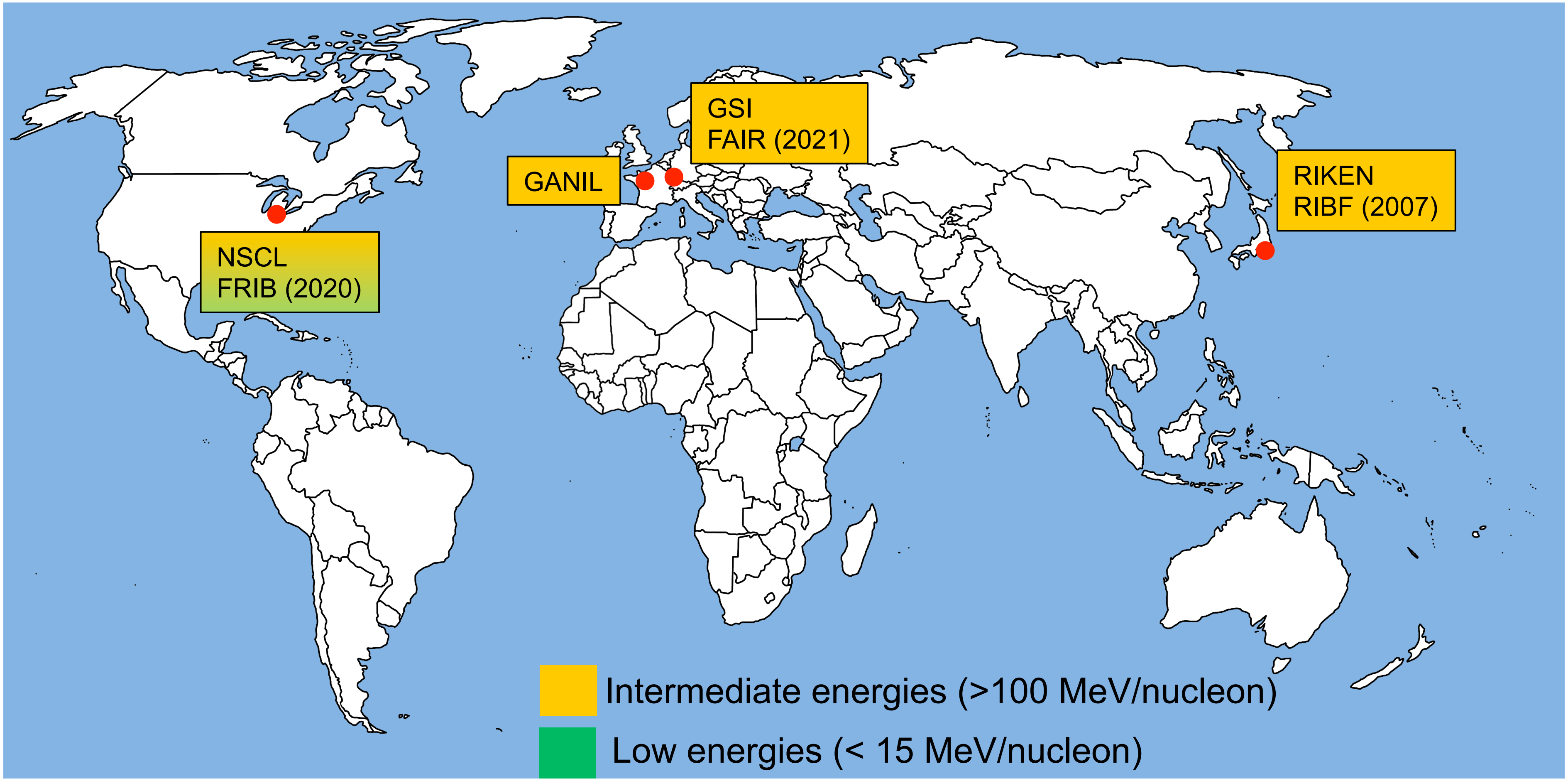


2000 pps
80 MeV/nucleon, NSCL

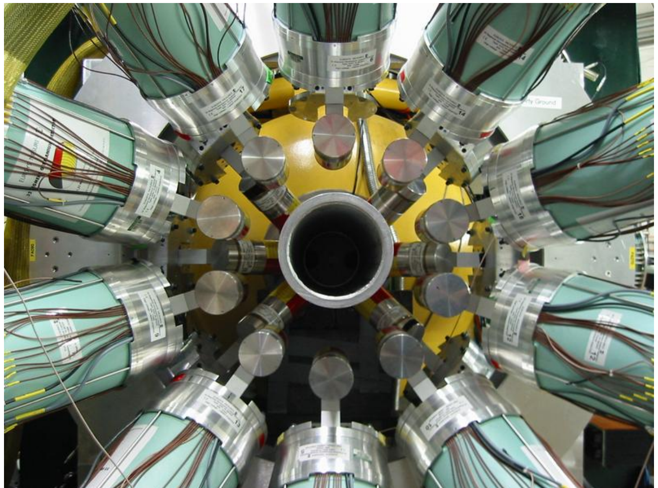


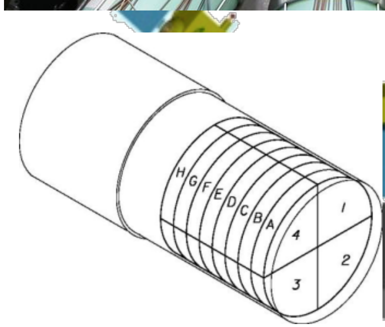
A. Navin *et al.*, PRL **85** (2000)

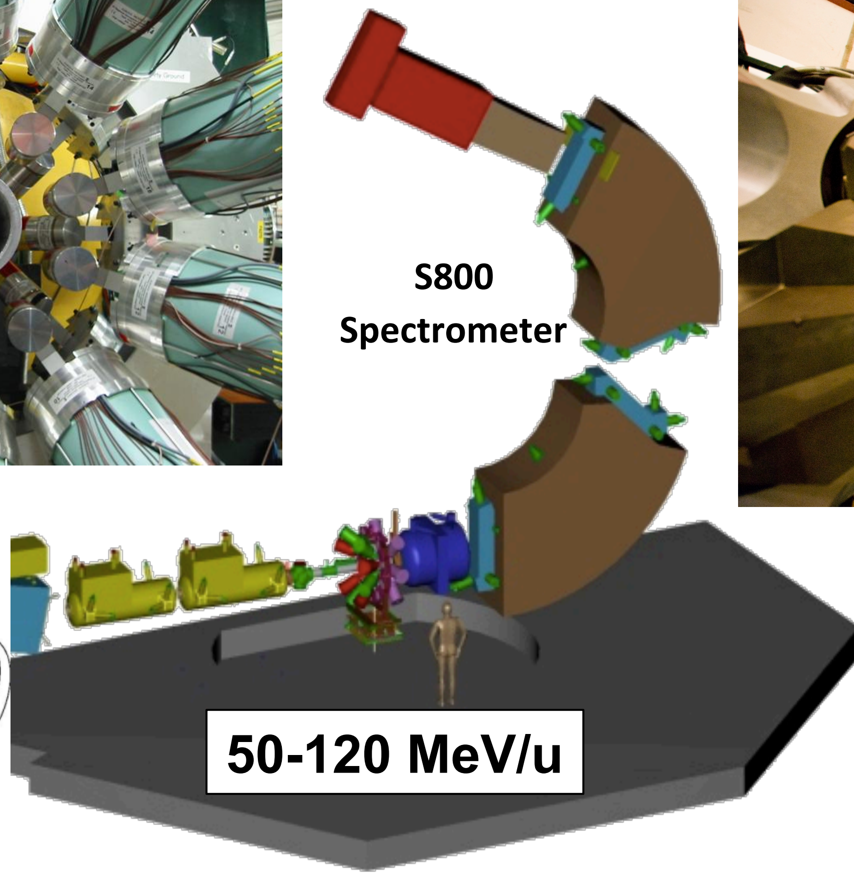
Leading fragmentation RIB facilities in the world



Example of setup: SeGA/GRETINA + S800 @ NSCL







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

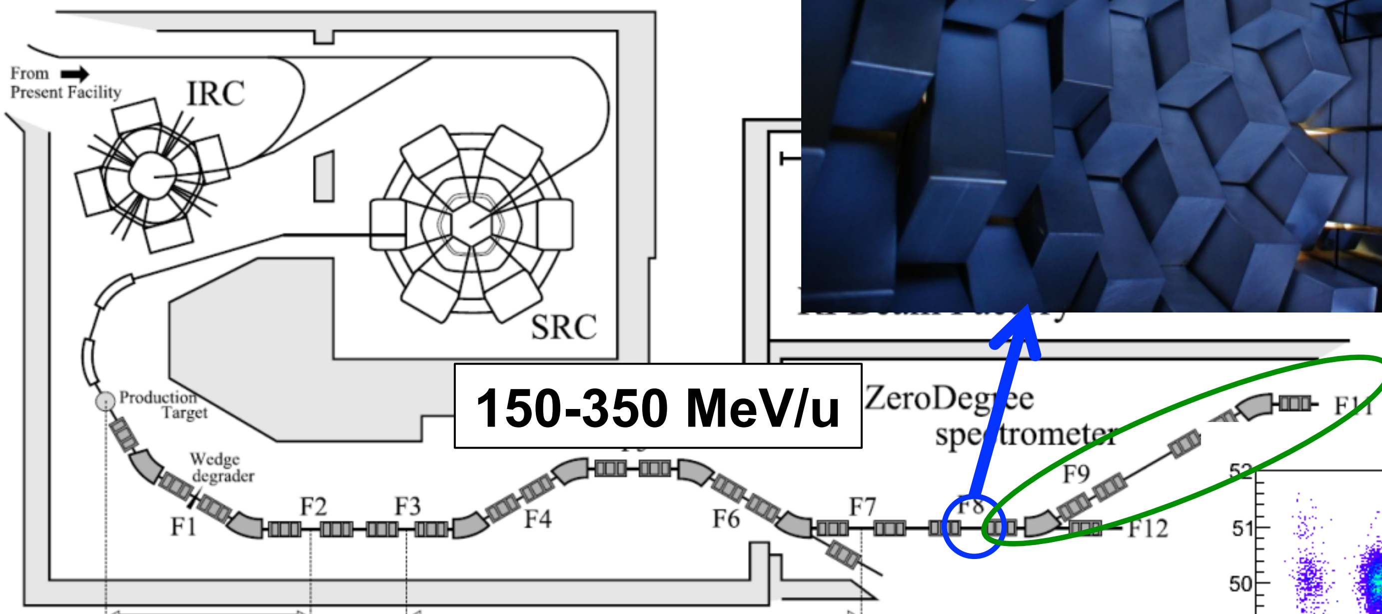
SeGa=18 HPGe detectors
- Resolution=2-4% @ 1 MeV β=0.4
- ε=2.5% @ 1 MeV and β=0.4

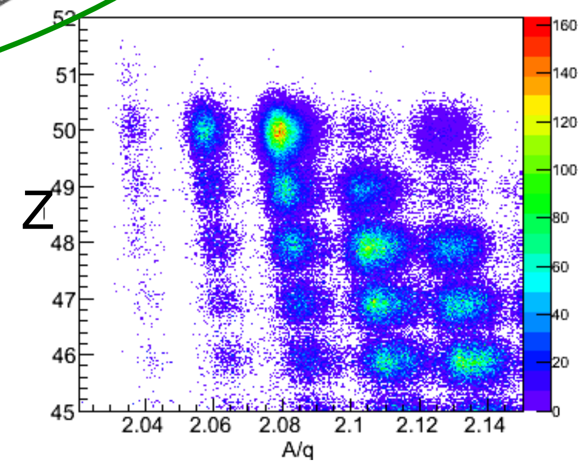
GRETINA=GRETA@MSU (2013-2014):
7 qadruplets x 4 HPGe crystals
- Resolution 1% FWHM @ 1 MeV and β=0.4
- ε=9% @ 1 MeV and β=0.4

Another experimental setup: DALI2 @ RIBF

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

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





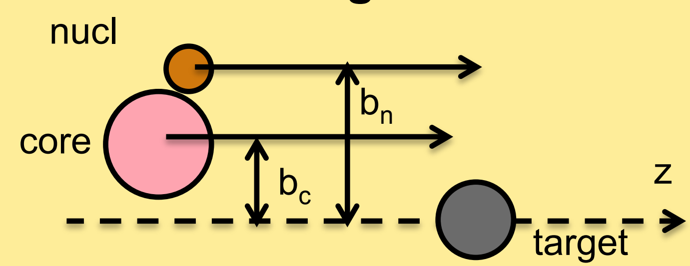
ZeroDegree Spectrometer
- Momentum acceptance: ±3%
- High resolution: P/DP≈6000

Eikonal approximation, S matrix and knockout

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

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

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)

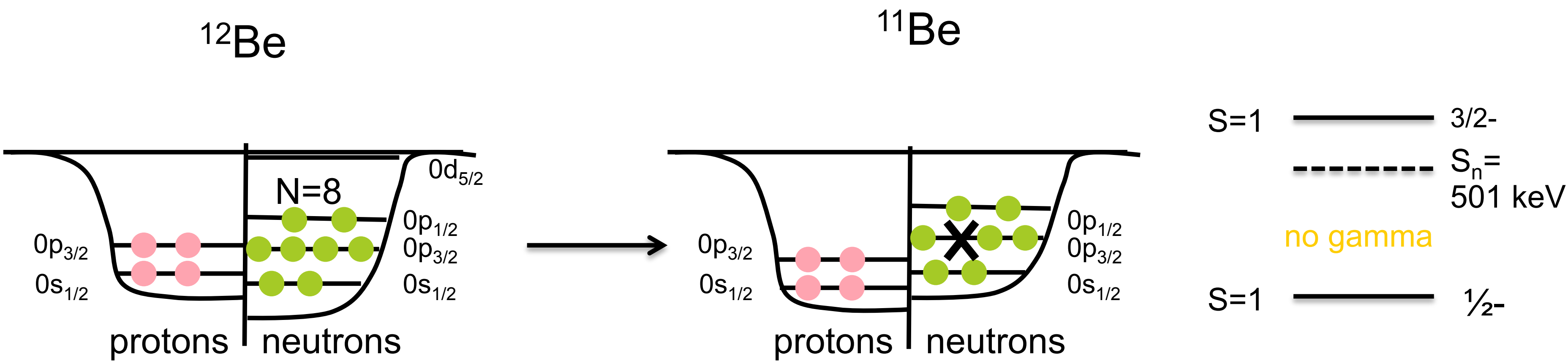
$$\sigma^{strip} = 2\pi\int_0^\infty b\,db\int d^3r\left|\phi_{n\ell j}(\vec{r})\right|^2 \left|S_{core}(\vec{b_c})\right|^2 (1 - \left|S_{nucl}(\vec{b_n})\right|^2)$$

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

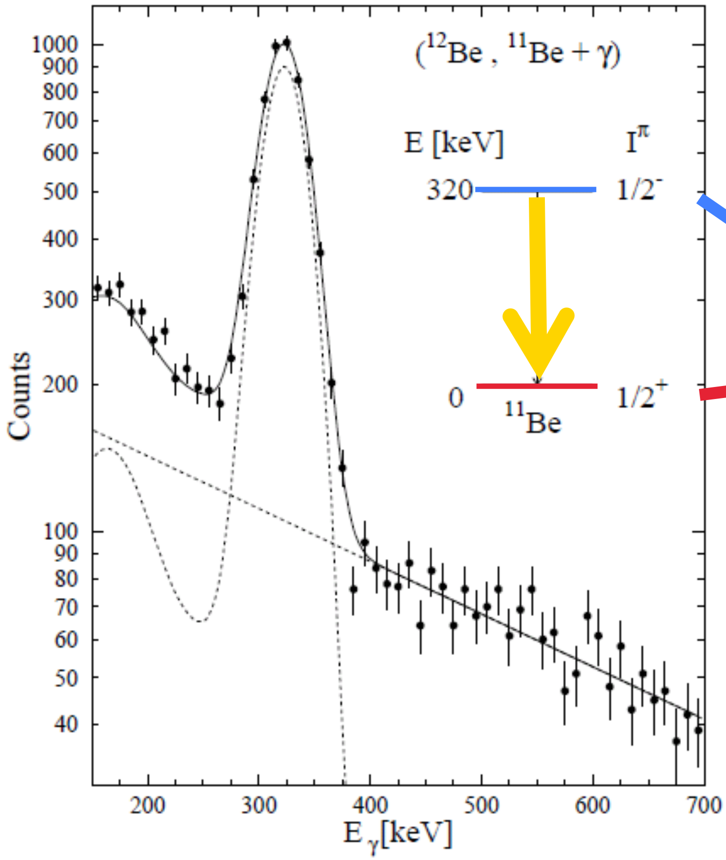


First guess assuming N=8 shell closure

… but ^{11}Be has a low excited state at 320 keV

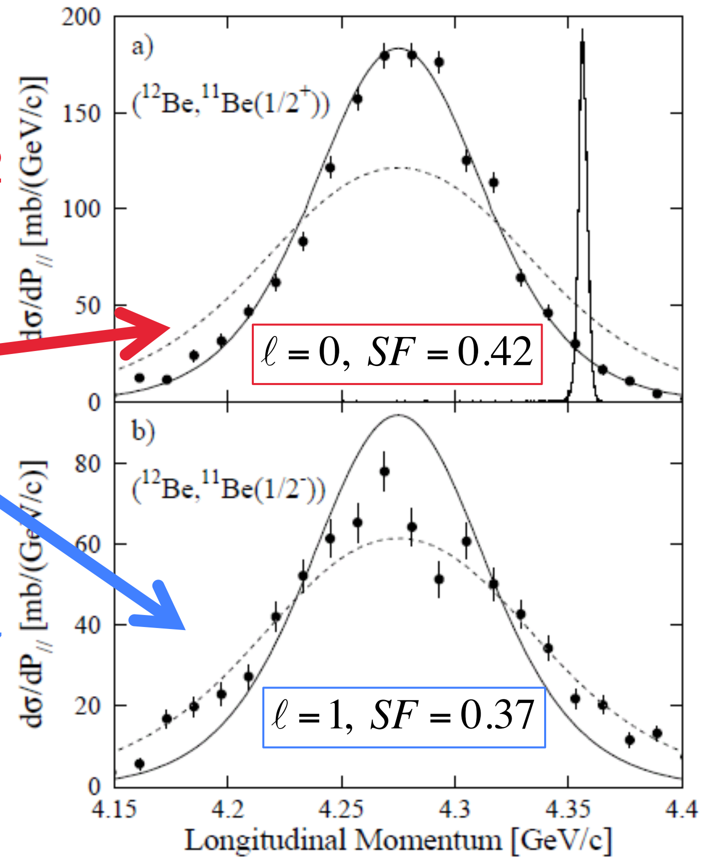
^{12}Be(^{9}Be,X)^{11}Be at 80 MeV/nucleon

Breakdown of the N=8 shell closure



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

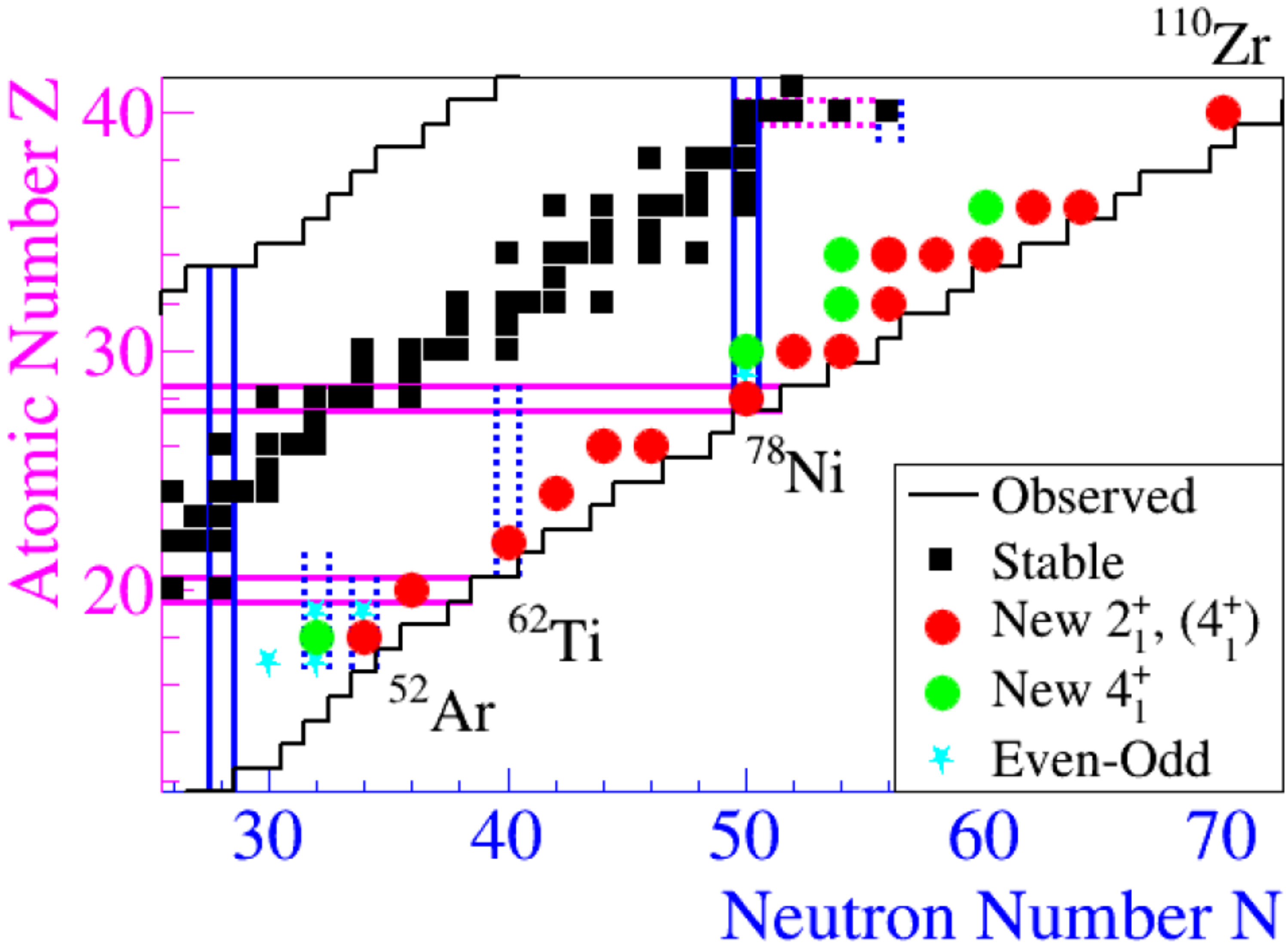
$\sigma_{1/2-}$ = 17(3) mb
σ_{eik}(l=1)= 47 mb
➔ SF=17/47=0.37



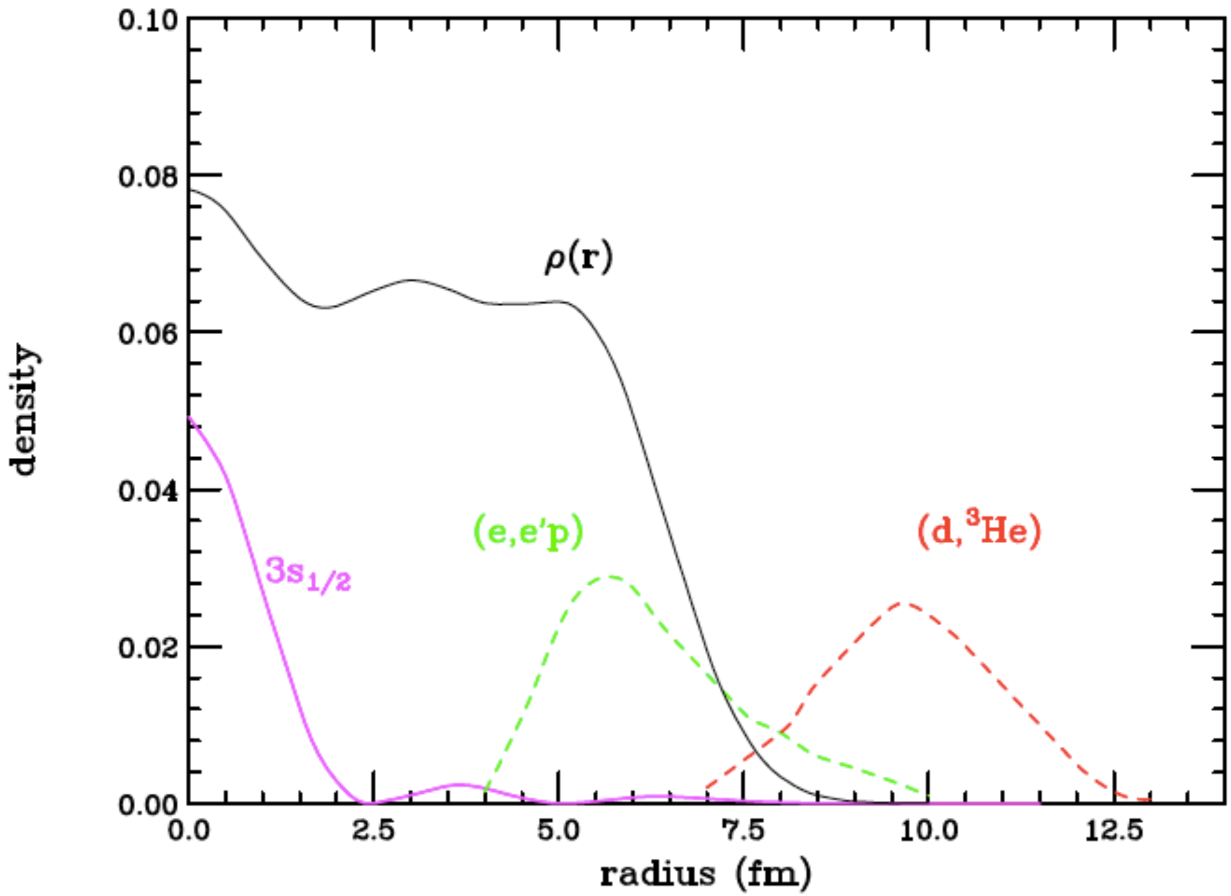
A. Navin *et al.*, PRL **85** (2000)

In-beam γ spectroscopy of exotic nuclei today

- RIBF best facility to explore very neutron rich nuclei
- Ongoing dedicated program (see Lecture 3)

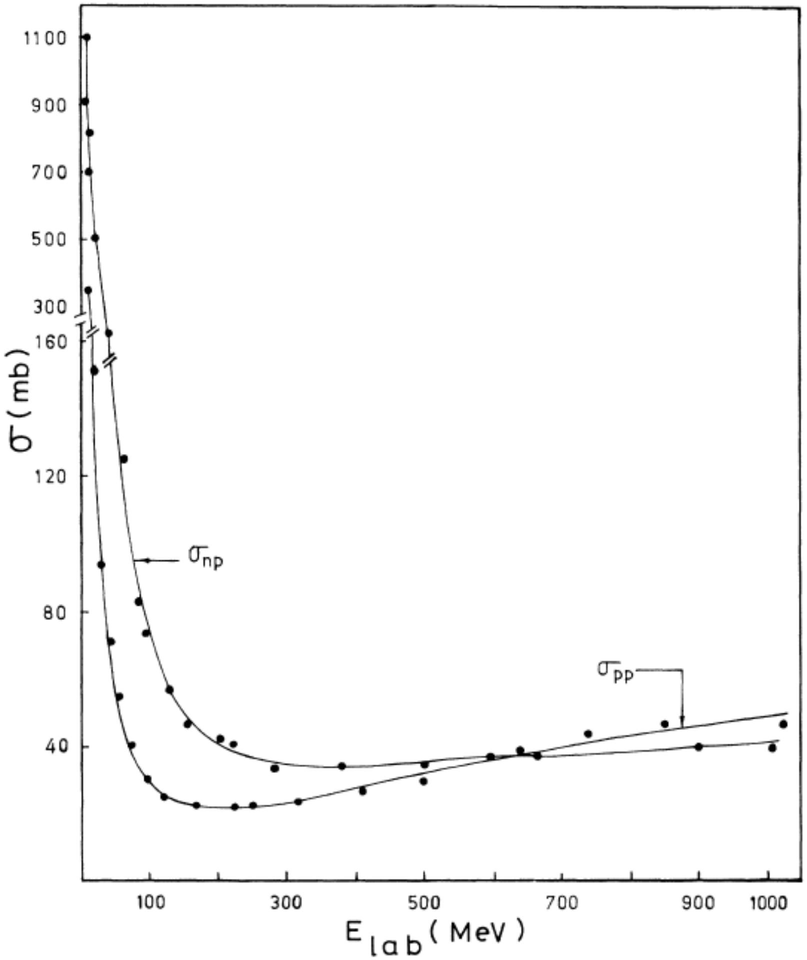


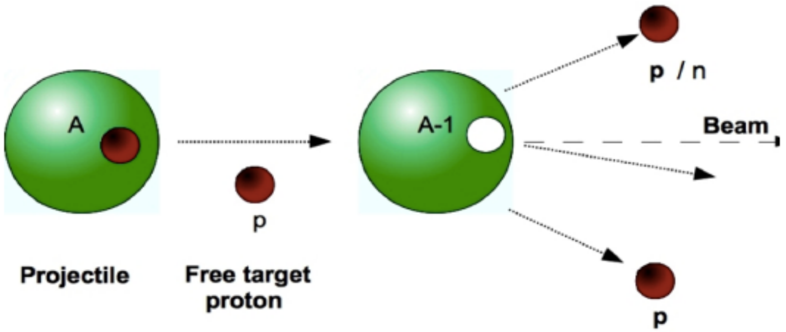
Particle spectroscopy at intermediate energies



- **Missing mass**: absolute excitation energy, differential cross section
- **(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
- **Exclusive (p,2p)**: best (almost ideal) tool!

Proton-induced quasifree scattering





Distorded-wave Impulse Approximation:

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

- **(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 to minimize FSI**
- Only one RIB facility in the world: GSI and FAIR in the near future

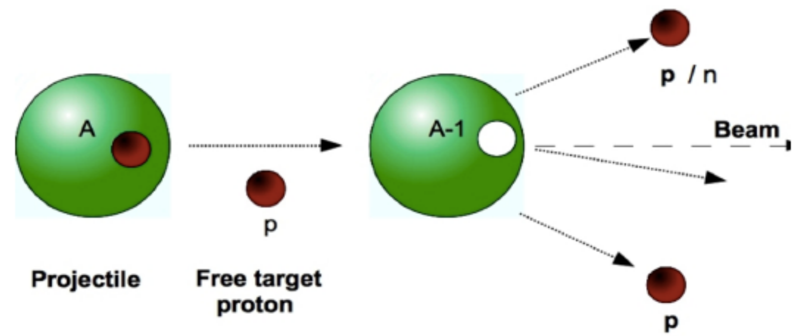
(p,2p) quasifree scattering

Kinematics (missing mass technique)

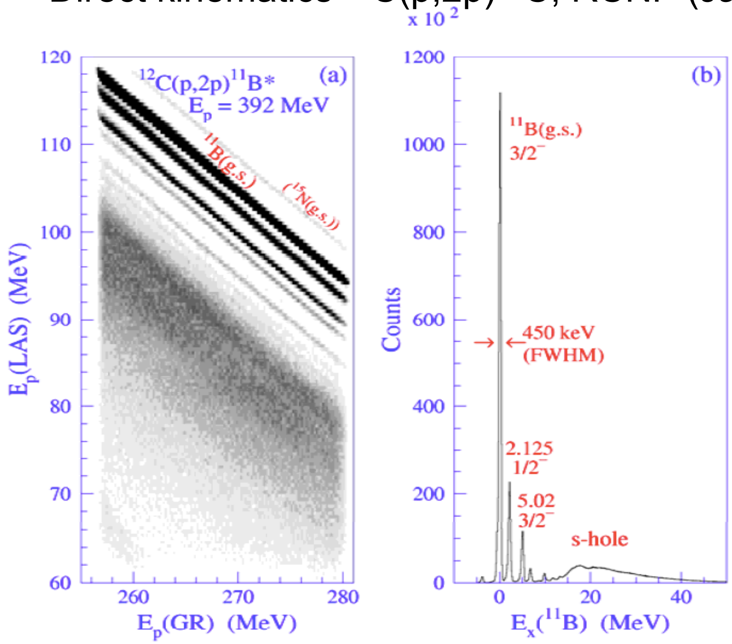
$$\overrightarrow{q_{\perp}} = +\overrightarrow{p_{1\perp}} + \overrightarrow{p_{2\perp}}$$

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

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

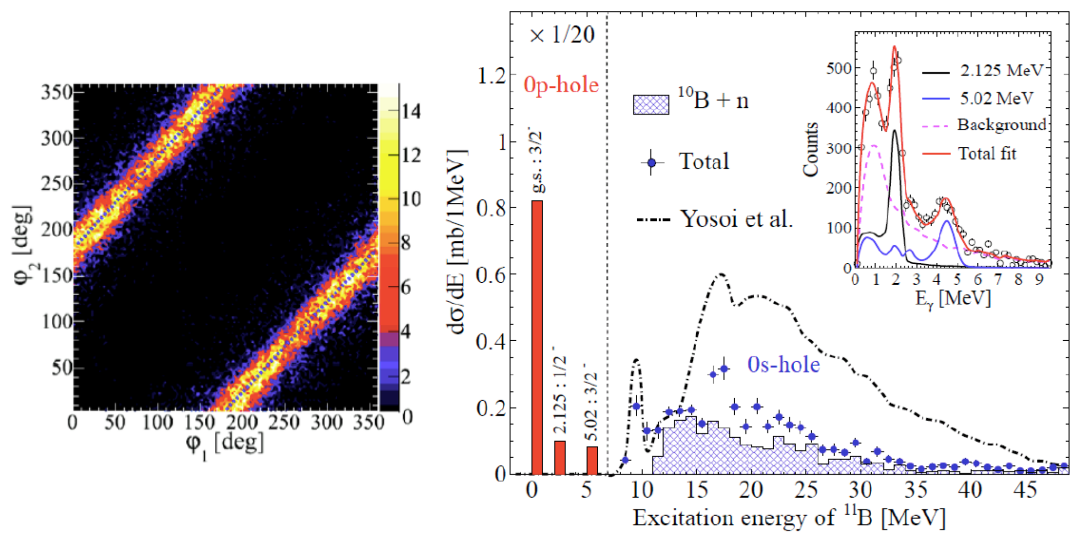


Direct kinematics $^{12}C(p,2p)^{12}C$, RCNP (Japan)



M. Yosoi et al., NPA **738**, 451 (2004)

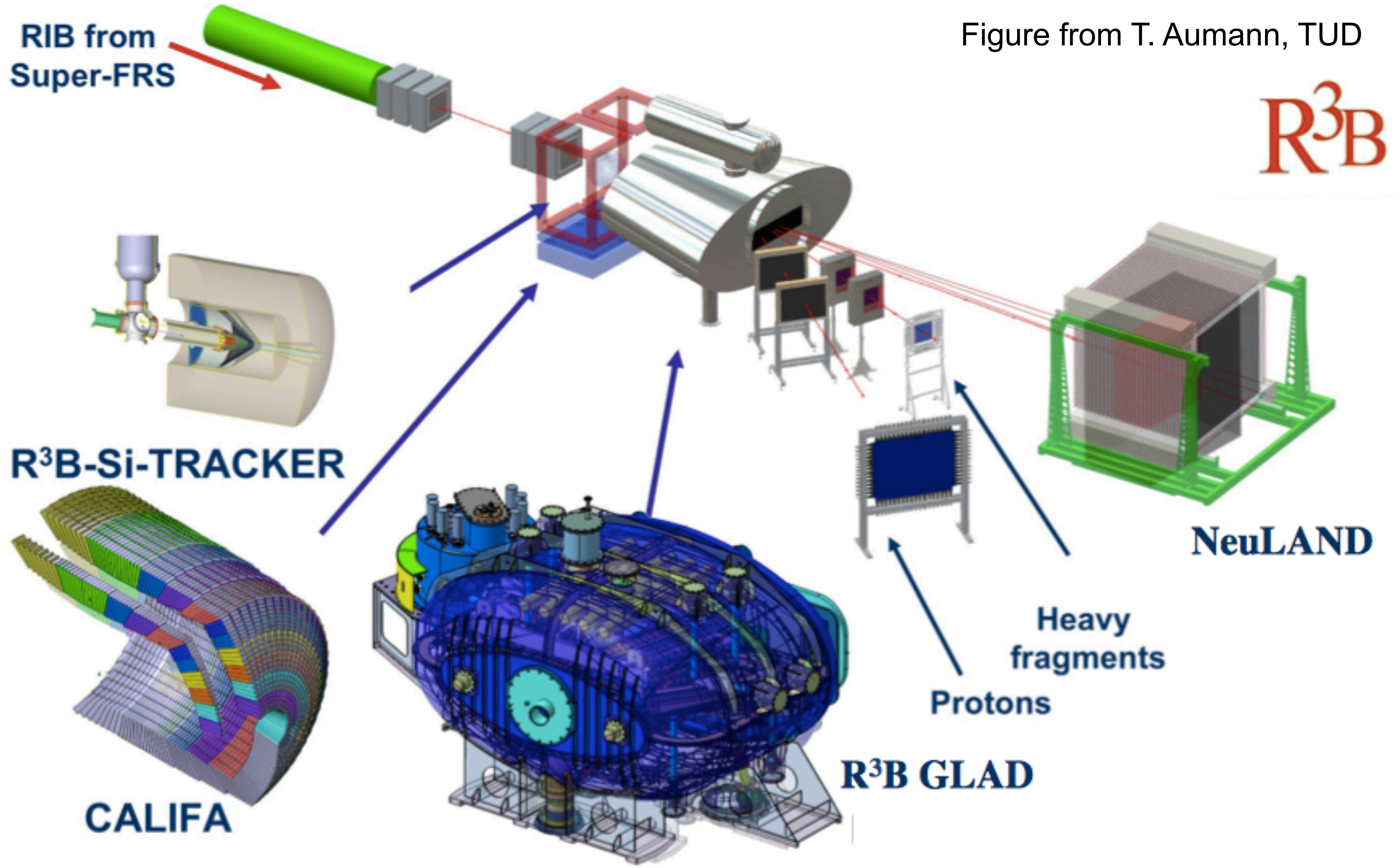
Inverse kinematics, $^{12}C(p,2p)$, GSI
.. towards R3B@FAIR



V. Panin *et al.*, PLB **753**, 204 (**2016**)

The R3B project at GSI/FAIR

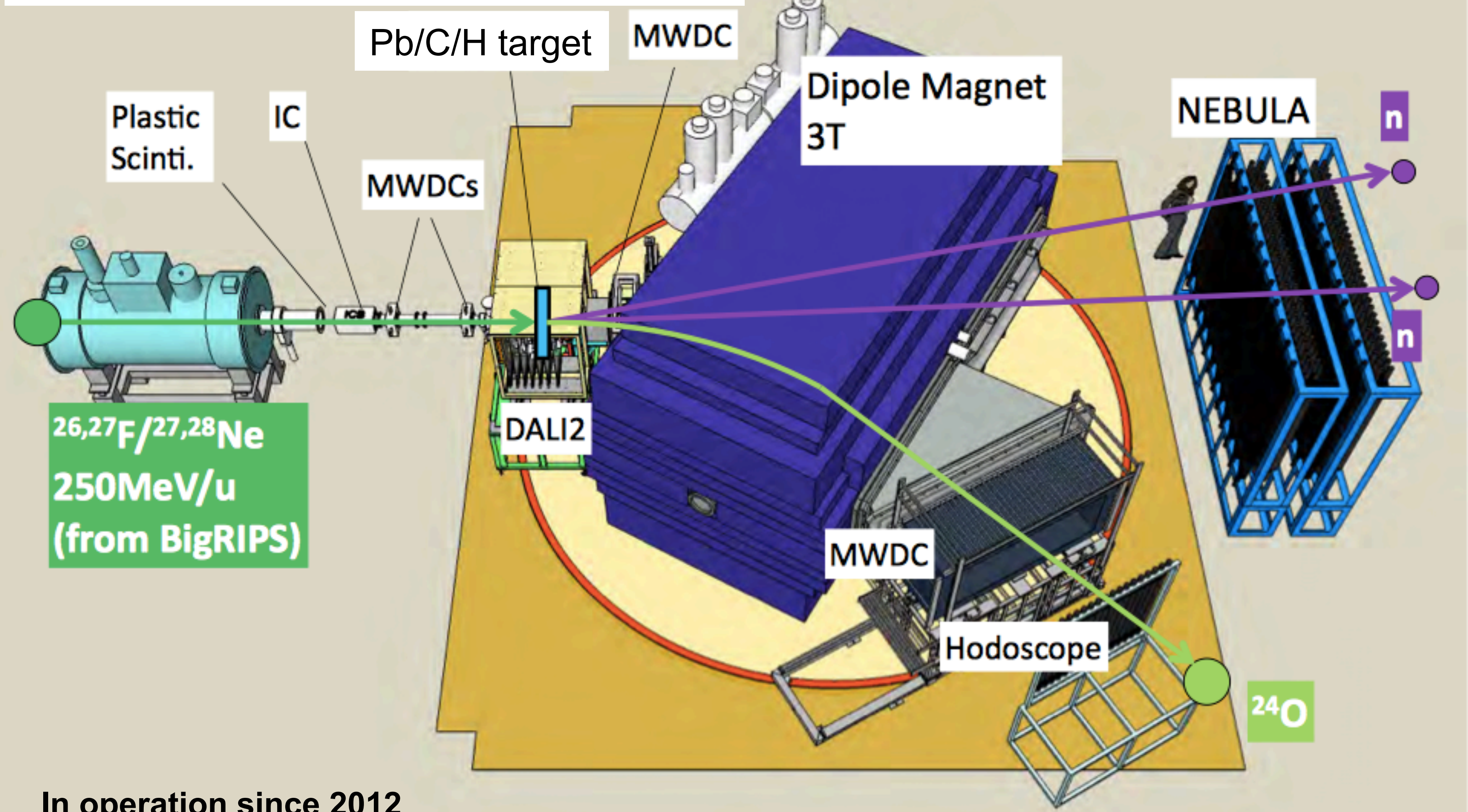
Figure from T. Aumann, TUD



- GLAD magnet installed, detection (partly) exists
- First experiments foreseen in 2018

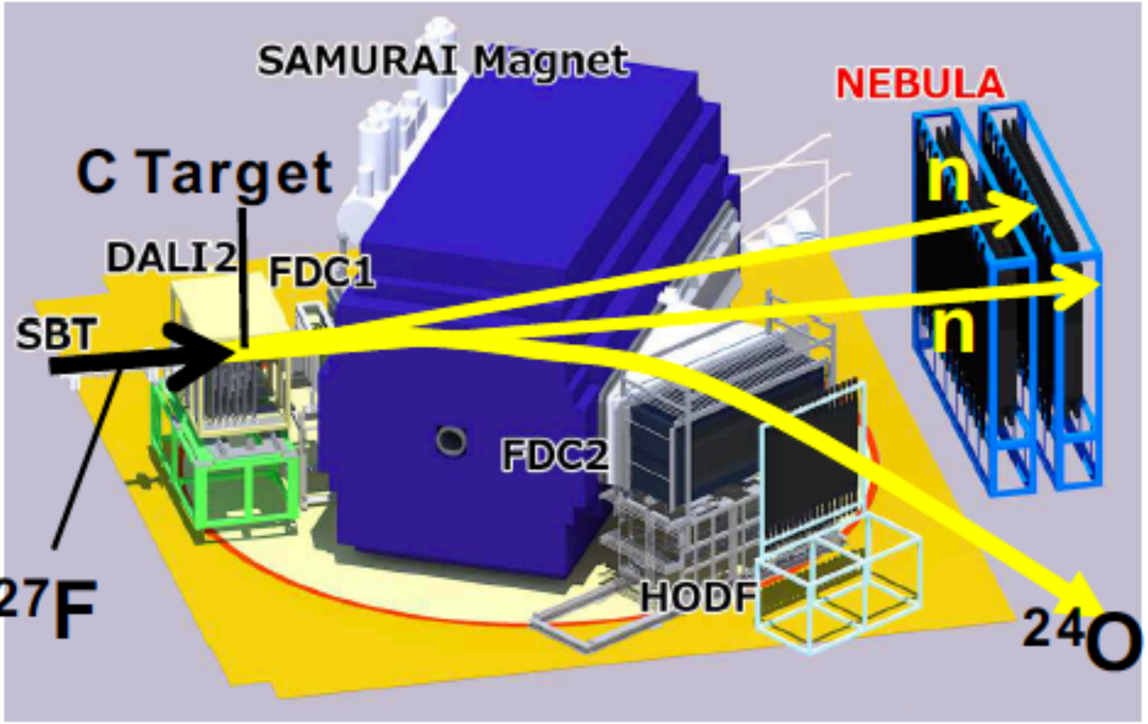
Similar-concept setup at the RIBF: SAMURAI

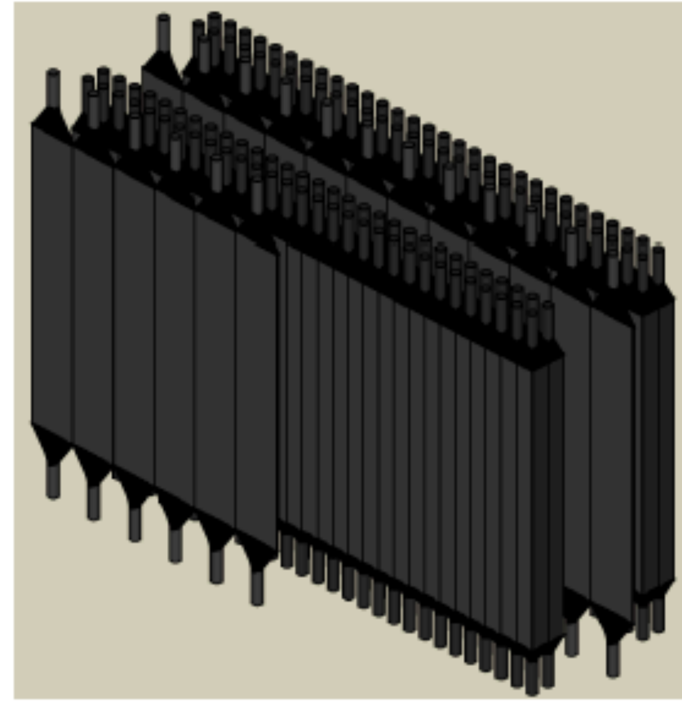
Ex. $^{27}F + C \rightarrow {}^{26}O + X \rightarrow {}^{24}O + 2n$ (published in 2016)



In operation since 2012

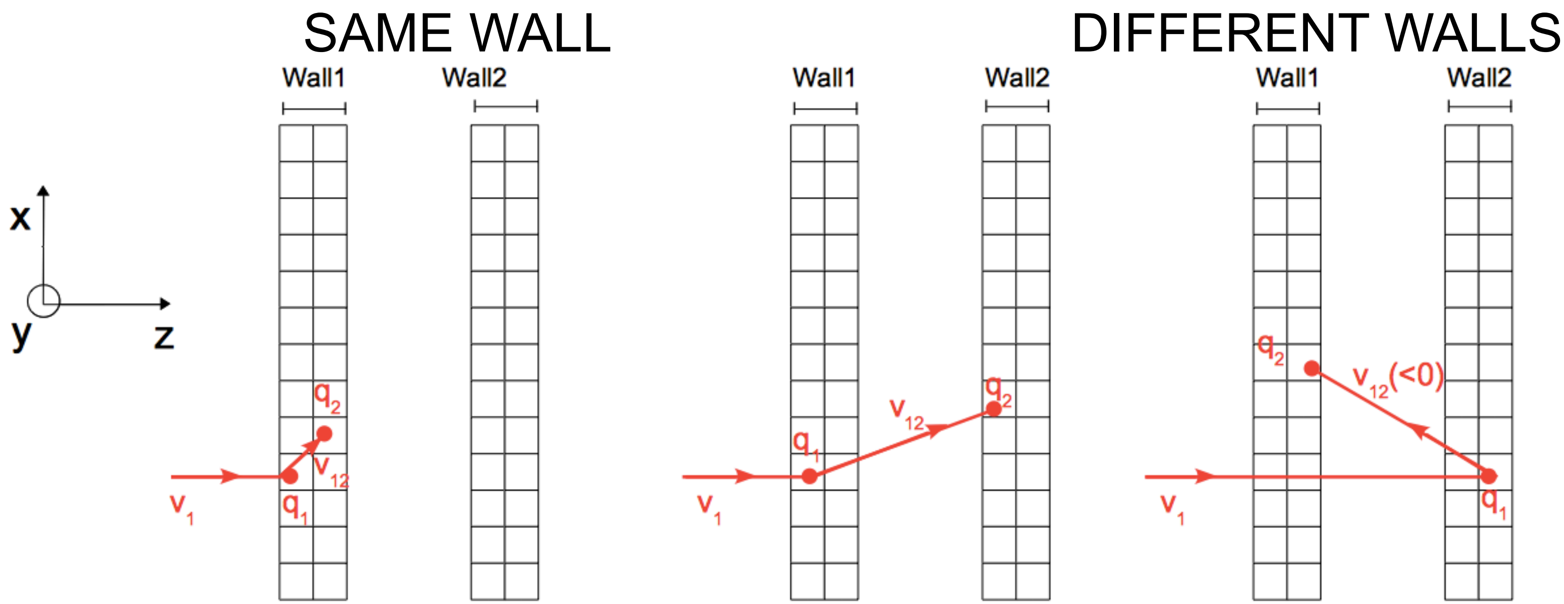
Neutron detection





- Plastic scintillator, detection based on neutron scattering on Hydrogen atoms
- 1 wall: 60 detectors (12x12x180cm3) + 12 veto counters (to reject charge particles)
- Neutron energy determined via ToF, ~100 ps time resolution
- With 2 walls: 40% efficiency for 1 n
- Multi –neutron detection capability

Neutron detection

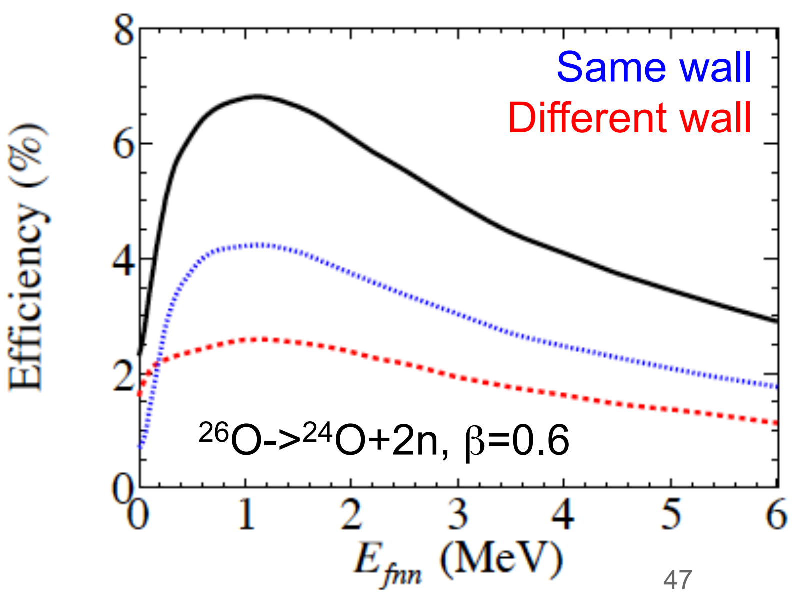


Same wall event → position information

- 2 hits are regarded as 1hit if positions are close
- lose efficiency for small E_{rel}

Different wall event → velocity information

- the event is true if $\beta_{12} > \beta_1$
  - because crosstalk neutron must be slow
- can measure up to $E_{rel} \sim 0$



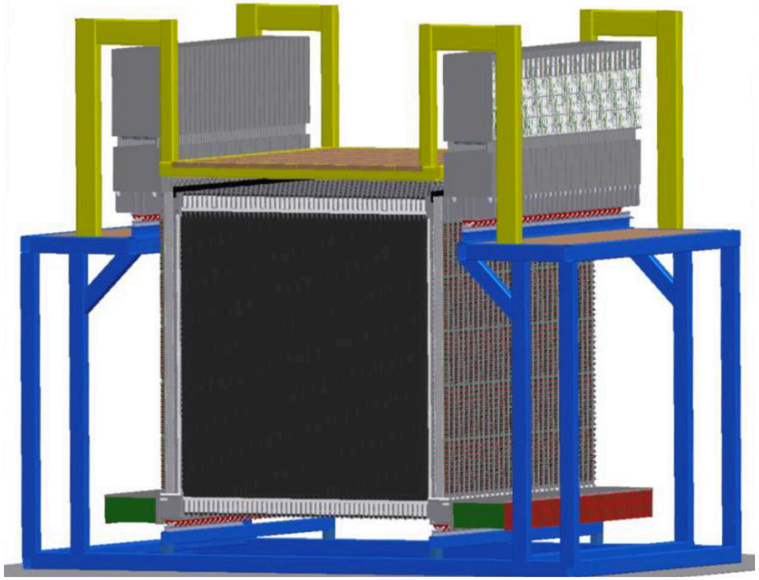
NeuLAND

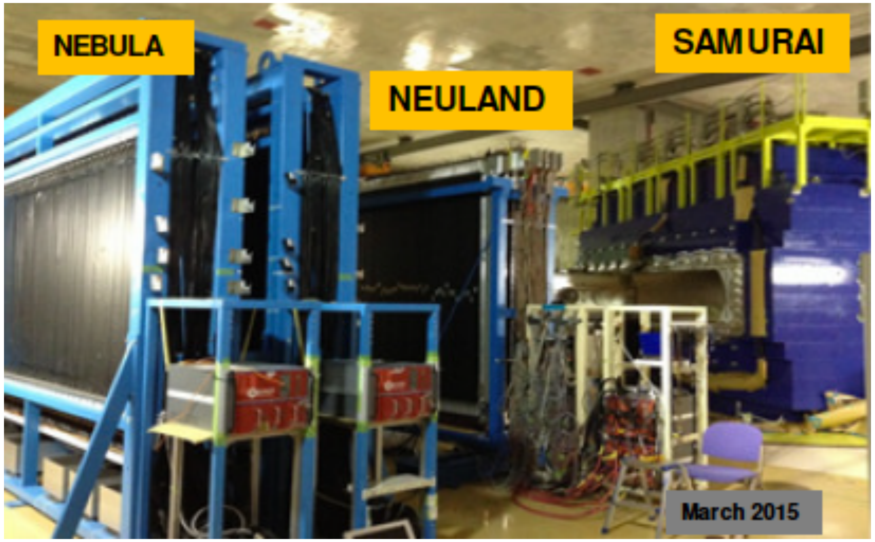
- **NeuLAND** = High resolution fast neutron ToF spectrometer for R3B

- **Characteristics**
  - Efficiency 1n: 90% @ ~200MeV
    95% @ 1.0GeV
  - 60% efficiency for 4n
  - Separation up to 5 neutrons

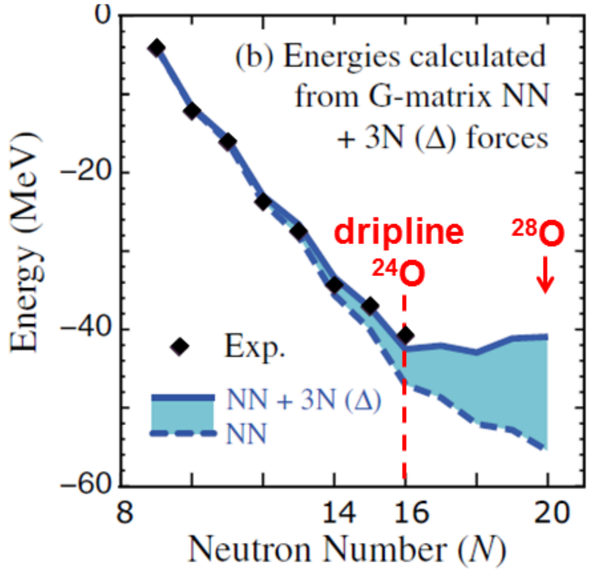
- **Technical specifications**
  - Fully active plastic detector
  - 3000 scintillator bars, 2.5m x 5cm x 5cm
  - 6000 PMTs
  - Each plane = 50 bars, two crossed planes form a double plane → 30 double planes
  - Double planes act as modules, dedicated readout electronics and HV separable
  - Full WxHxD = 2.5m x 2.5m x 3m

- Successfully used at RIKEN (2015-2017)
- RIBF: 4 double planes used



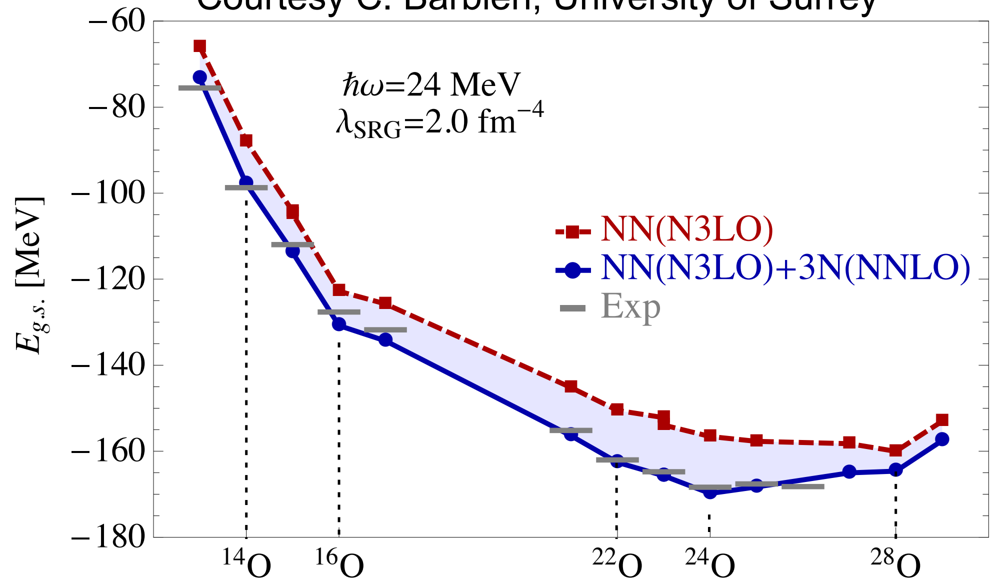


Invariant mass spectroscopy beyond the dripline



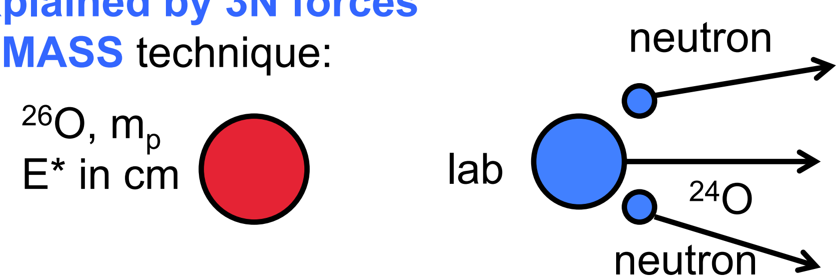
T. Otsuka *et al.*, PRL **105**, 032501 (2010)

Self-Consistent Green's Function theory
Courtesy C. Barbieri, University of Surrey



- ❑ Dripline location along the oxygen isotopes **explained by 3N forces**
- ❑ Separation energy accessible by **INVARIANT MASS** technique:

$$M^2c^2 = \left(\sum_i \left|\vec{P}_i\right|^2\right) = (mc^2 + E^*)^2 / c^2$$



- ❑ Neutron unbound heavy oxygen isotopes: **^{25,26}O measured at SAMURAI**

  Y. Kondo *et al.*, Phys. Rev. Lett. **116**, 102503 (2016)

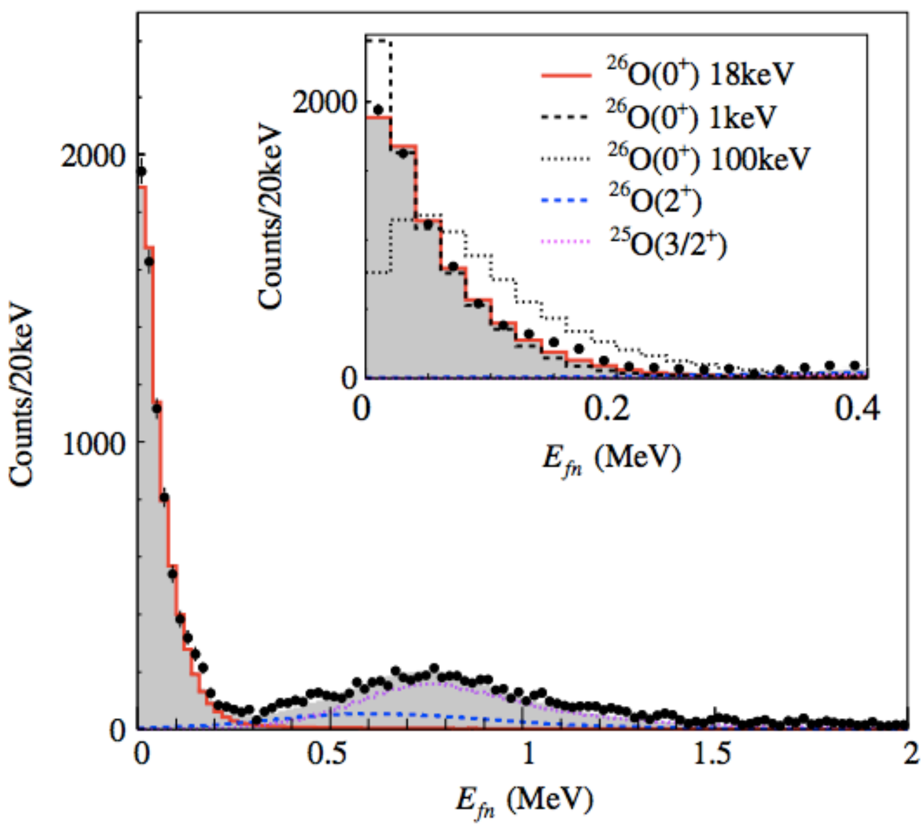
- ❑ **Spectroscopy of ^{28}O** measured in December 2015 via ^{29}F(p,2p)^{28}O➔^{24}O+4n

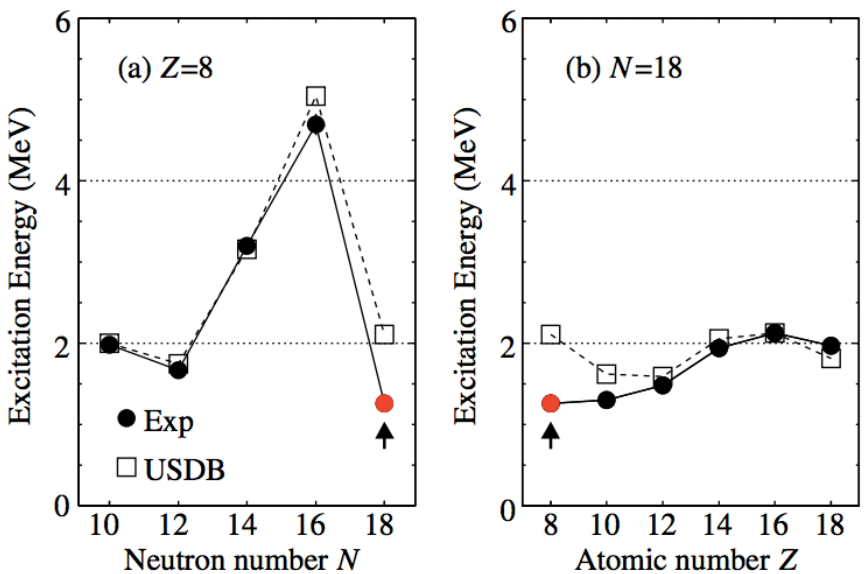
Binding energy and spectroscopy of ^{26}O

PRL **116,** 102503 (2016) PHYSICAL REVIEW LETTERS week ending 11 MARCH 2016

Nucleus ^{26}O: A Barely Unbound System beyond the Drip Line

Y. Kondo,[1] T. Nakamura,[1] R. Tanaka,[1] R. Minakata,[1] S. Ogoshi,[1] N. A. Orr,[2] N. L. Achouri,[2] T. Aumann,[3,4] H. Baba,[5] *et al.*





- **Single-particle description**
  - Spectroscopic factors
  - The Baranger sum rule

- **Nucleon transfer at low energy**
  - the Distorted-Wave Born Approximation (DWBA)
  - experimental methods with exotic nuclei
  - detection systems for transfer

- **Intermediate-energy nucleon removal**
  - S-matrix theory and eikonal approximation
  - Physics case: breakdown of the N=8 shell closure in ^{12}Be
  - Quasifree scattering
  - Invariant-mass technique
  - Physics case: oxygen binding energy systematics

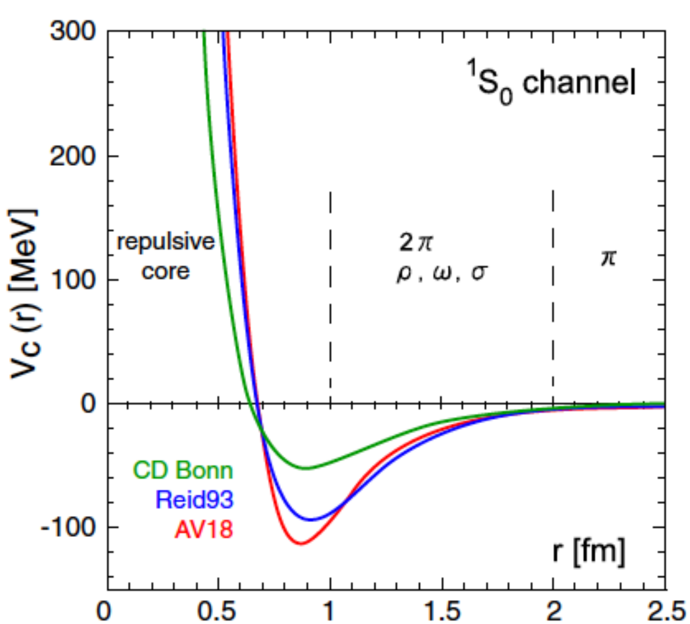
- **Short range correlations and stripping reactions**
  - Short Range Correlations (SRC) and spectroscopic strength reduction
  - Deeply-bound nucleon removal

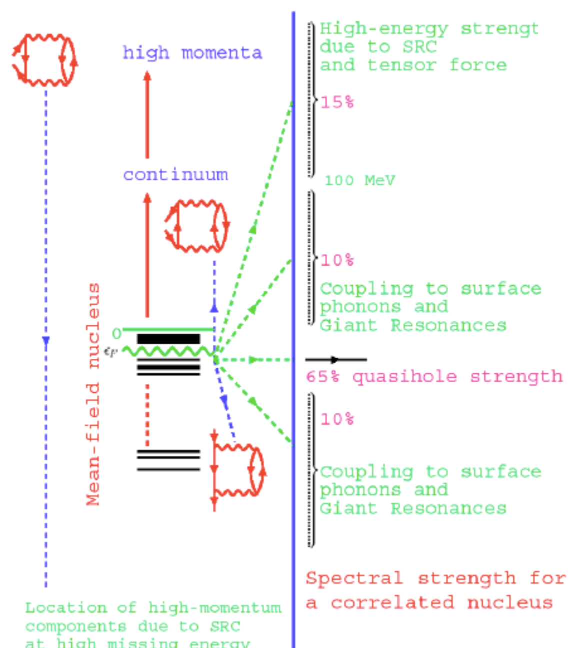
Beyond shell model: short and long range correlations

- The repulsive core of NN interaction implies **high momentum** in the nuclear wavefunction
- Modern theories generate **renormalized interactions without hard core** (Observables unchanged by these transformations)
- Actively debated today

- **Model space is often / always reduced**

$$|\psi\rangle_{full} = |\psi\rangle_{space} + |\phi\rangle \otimes GR + high\,momentum$$

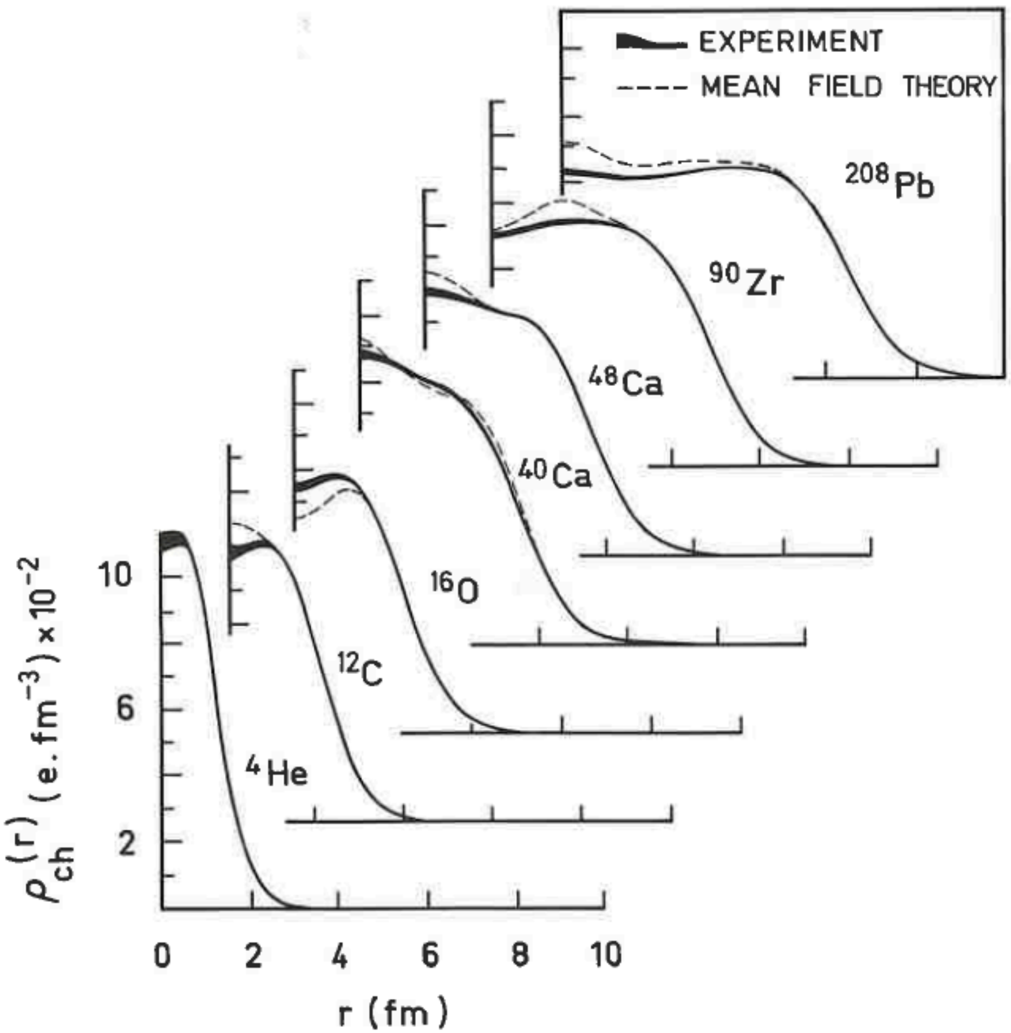




From W. Dickhoff

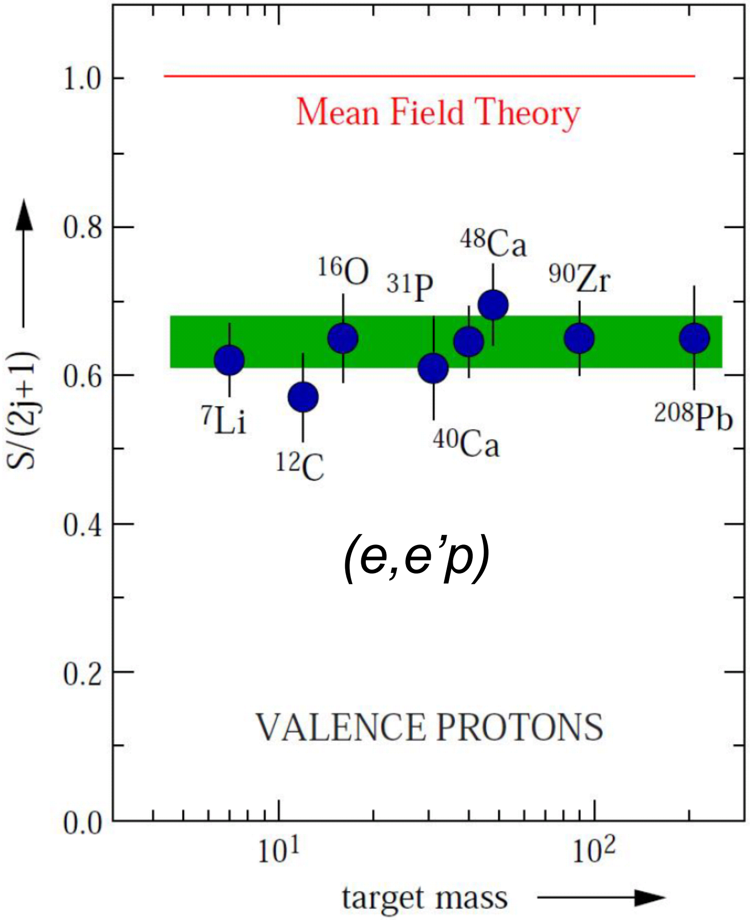
Correlations beyond the mean field

- charge density distribution from electron elastic scattering
- depletion in inner region originating from **short-range correlations**

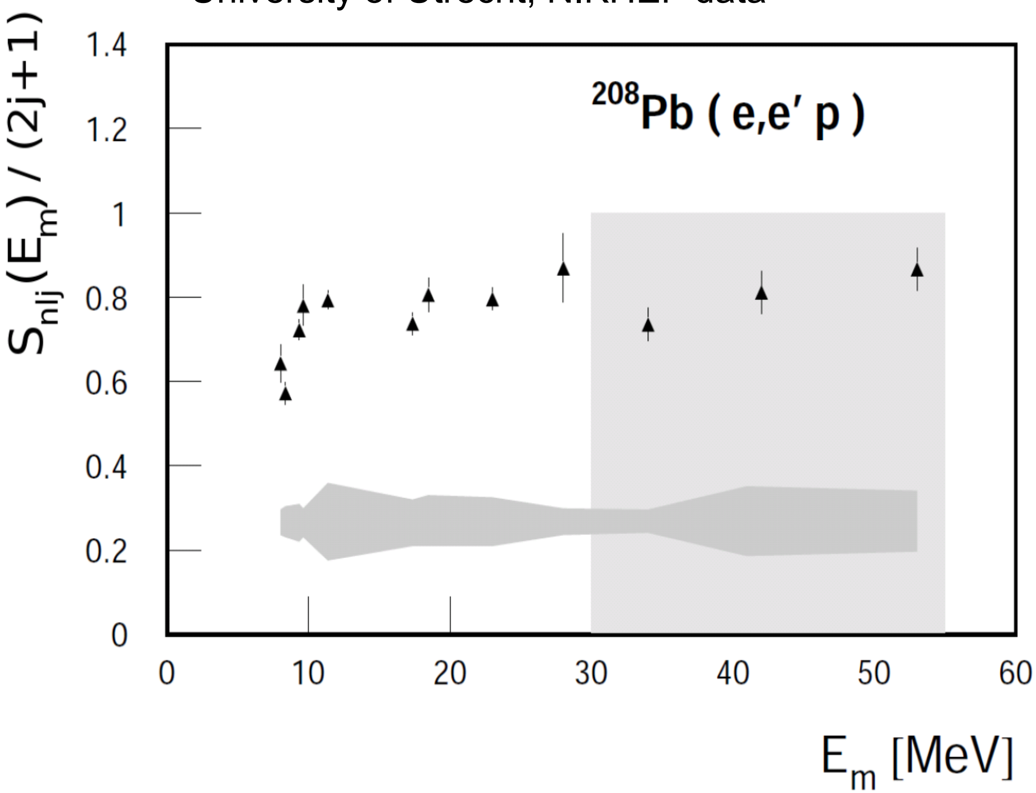


B. Frois, C. N. Papanicolas, Ann. Rev. Nucl. Part. Sci. 37, 133 (1987)

Correlations beyond the shell model



M.F. Van Batenburg, PhD thesis (2001)
University of Utrecht, NIKHEF data

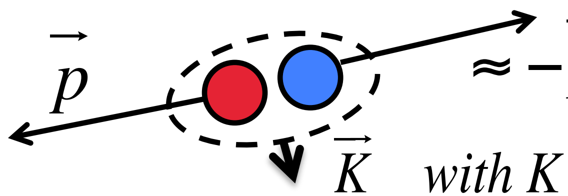


Beyond the mean-field:

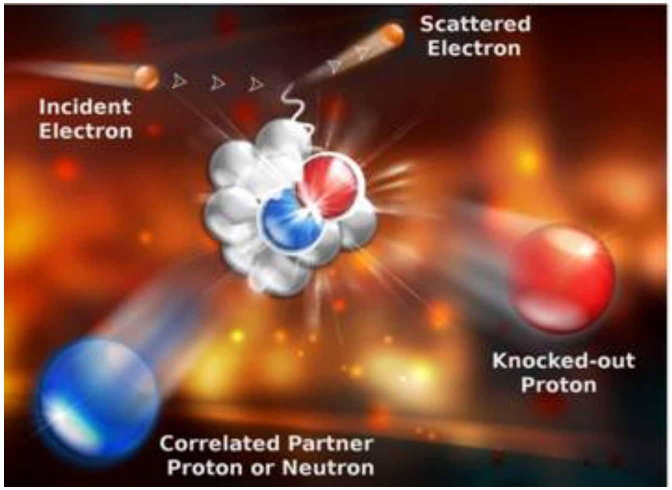
- Long range correlations coupling to high energy collective states (GR): **15-20%**
- Short range correlations (hard core): **10-15%**

Further evidence for SRC/high-momentum correlations

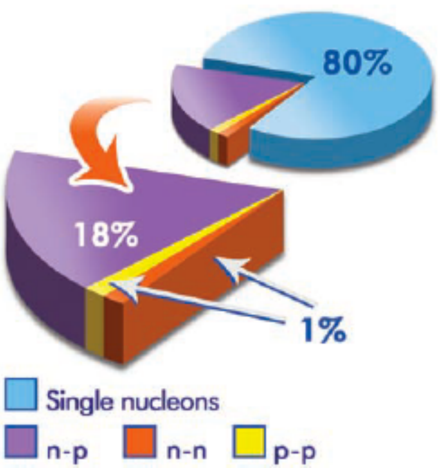
- **High-momentum nucleons** contained in **low-momentum pairs**

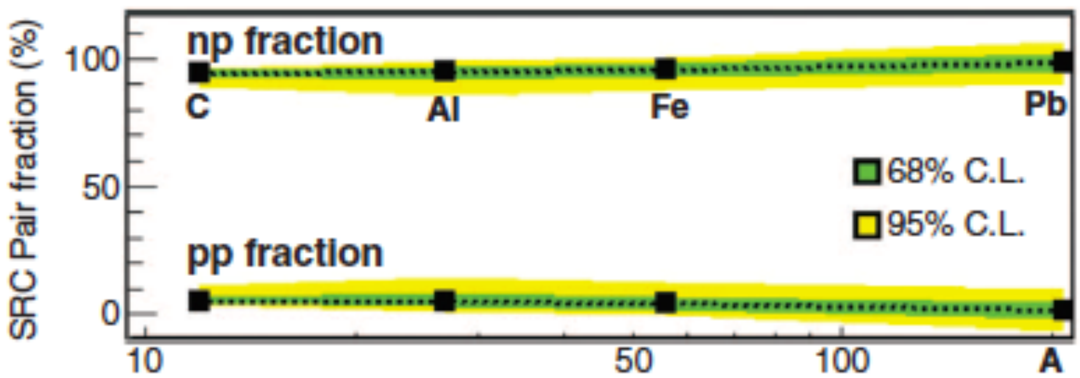


$\vec{p}$ $\approx -\vec{p}$ $\vec{K}$ *with* $K << p$



- Experiment: Jlab, Subedi *et al.*, Science **320** (2008)
  - **^{12}C(e,e'pn) @ 4.6 GeV**
  - proton quasifree scattering
  - recoil correlated partner (back to back in center of mass)

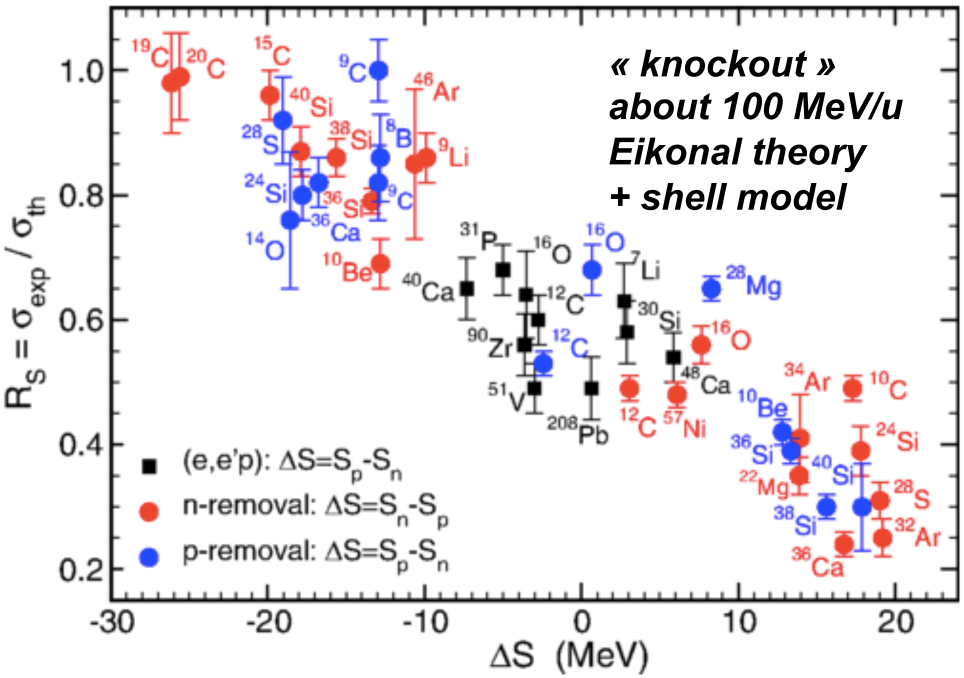


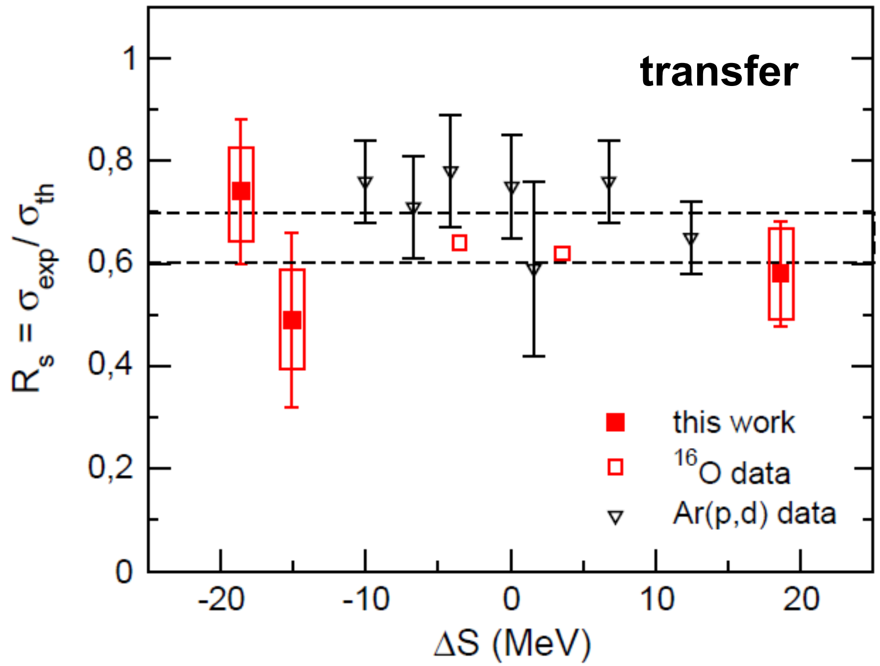


Stripping cross sections from unstable nuclei

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

J. Lee *et al.*, Phys. Rev. C **83** (2011).
F. Flavigny *et al.*, Phys. Rev. Lett. **110** (2013).





- ❑ ***Intermediate-energy knockout***
  - **disagreement** between theory (eikonal+shell-model) and experiment

- ❑ ***Low-energy transfer***
  - **weak ΔS dependence**
  - ***ab initio* calculations predict weak dependence**, in agreement with transfer analysis

- ❑ ***Quasifree scattering*** at ≈500 MeV/nucleon to be submitted soon

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)

- ❑ Coupling particle and gamma spectroscopy (compact arrays) is an asset
- ❑ Time projection chambers appear to be very promising tools for future

- ❑ **Reaction theory** “still in its infancy” compared to current nuclear-structure developments

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