THE CUTTING EDGE OF NUCLEAR DIRECT REACTIONS WITH EXOTIC BEAMS

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CEA Saclay

EURISOL town meeting
October 30th and 31st, 2014

Outline

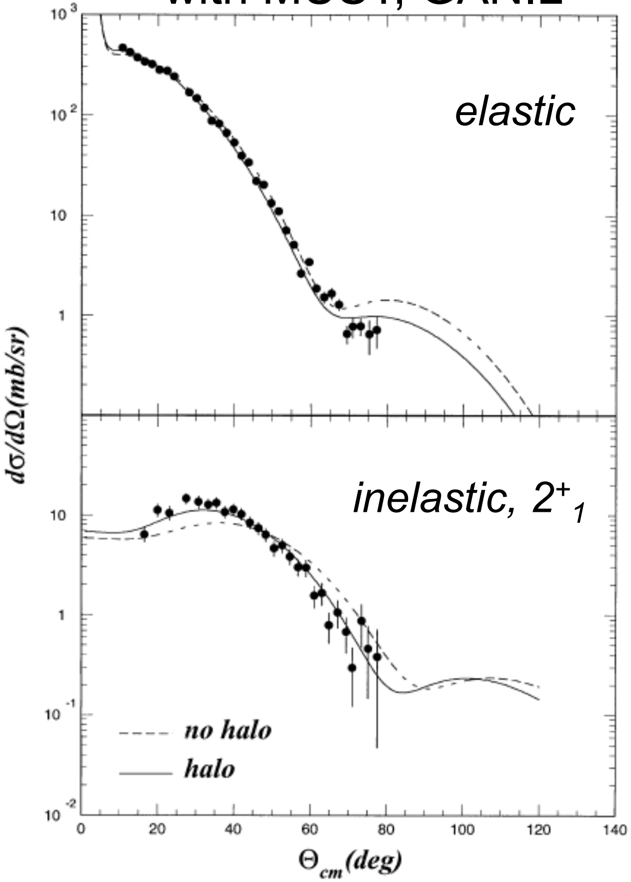
- **elastic and inelastic scattering**
  - nuclear radii
  - low-lying collectivity
  - collective states

- **nucleon transfer / knockout**
  - sensitivity to the shell model
  - limits of reaction mechanism formalisms
  - correlations from transfer / knockout

- **new probes and techniques**

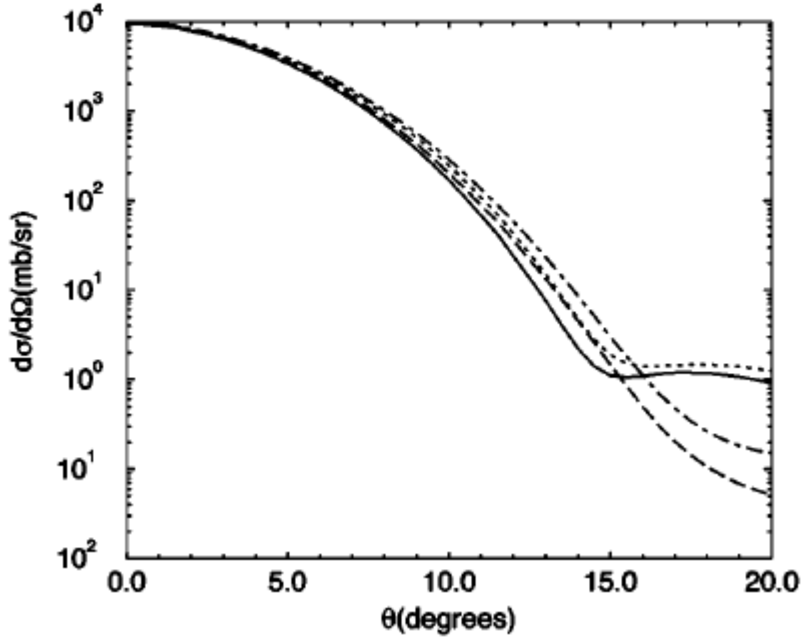
Nuclear radii from elastic and inelastic scattering

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



A. Lagoyannis et al., PLB **518**, 27 (2001).

$^{11}Li(p,p)$ at 800 MeV/nucleon



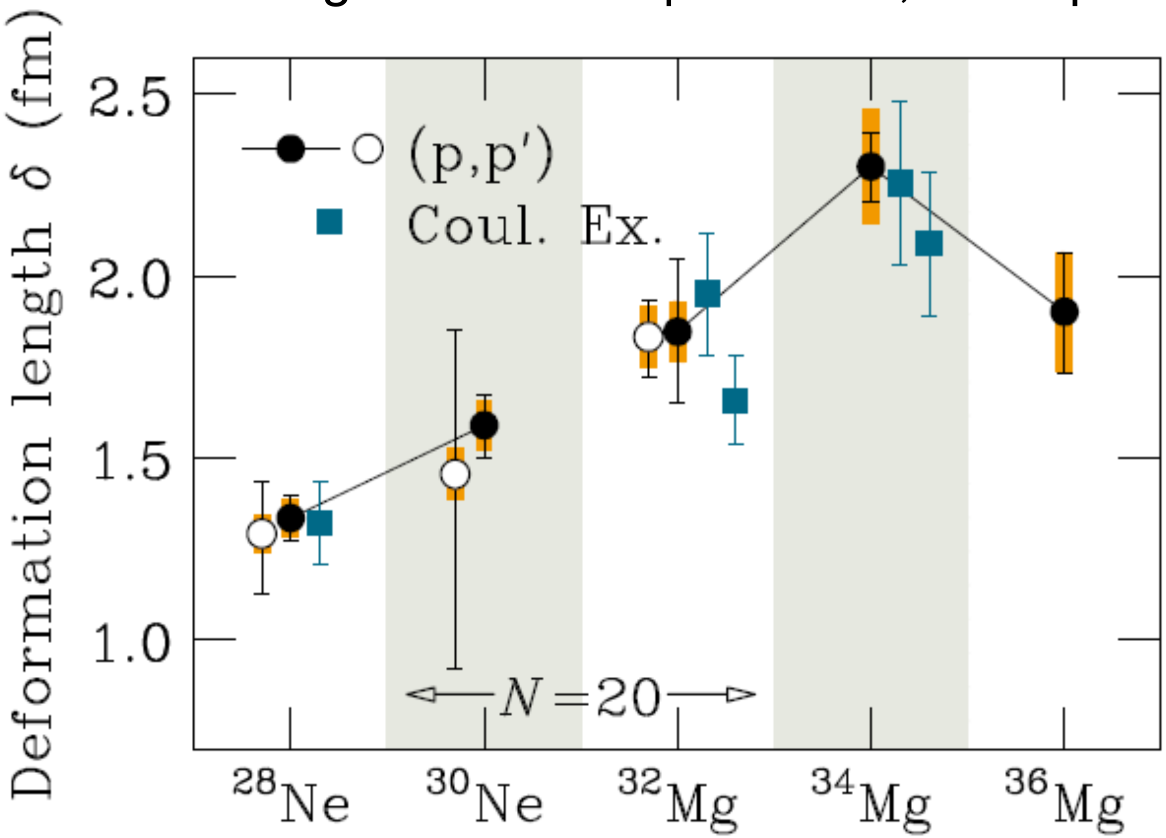
R. Crespo and R. Johnson, PRC **60**, 034007 (1999).

Typical precision: ±0.1 fm FWHM

High statistics exclusive data necessary to access radii and structure information

Inclusive inelastic scattering

Inclusive : higher model dependence, lower precision



S. Michimasa *et al.*, PRC **89**, 054307 (2014).

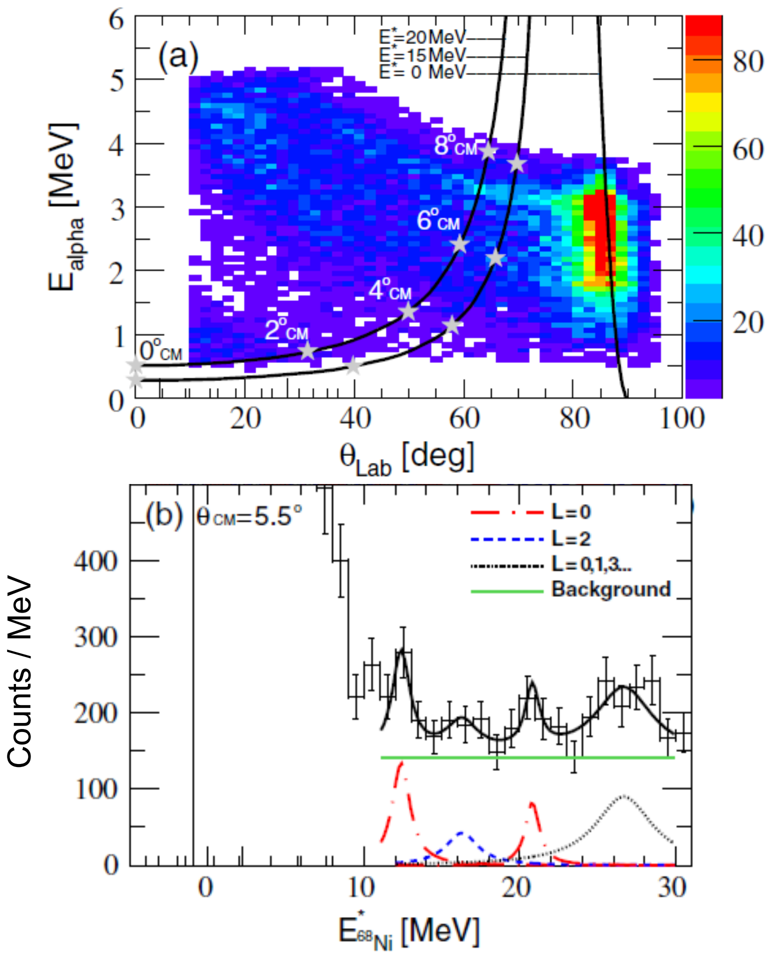
- **Differential cross sections**, **elastic AND inelastic** necessary to be quantitative
- 10-50 MeV/nucleon sensitive to neutron collectivity
- Ideal: measurement at two different energies

High-lying collective states from inelastic scattering

***Ex.* GMR:** nuclear matter compressibility / **unstable nuclei:** asymmetry term

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

^{68}Ni(α,α') at 50 A MeV, GANIL with MAYA



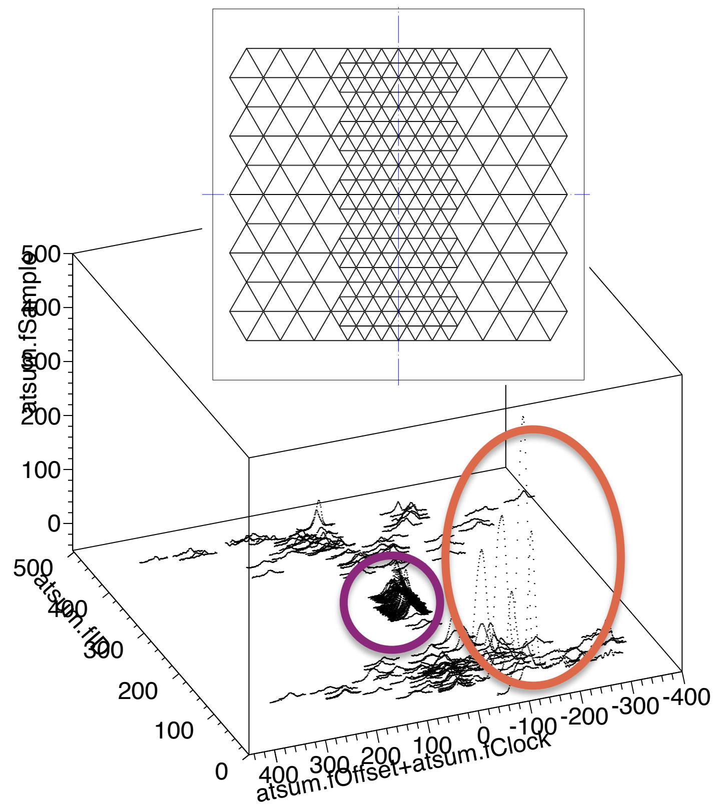
M. Vandebrouck *et al.,* Phys. Rev. Lett. **113**, 032504 (2014).

^{132}Sn GMR, accepted experiment at RIKEN

S. Ota, CNS

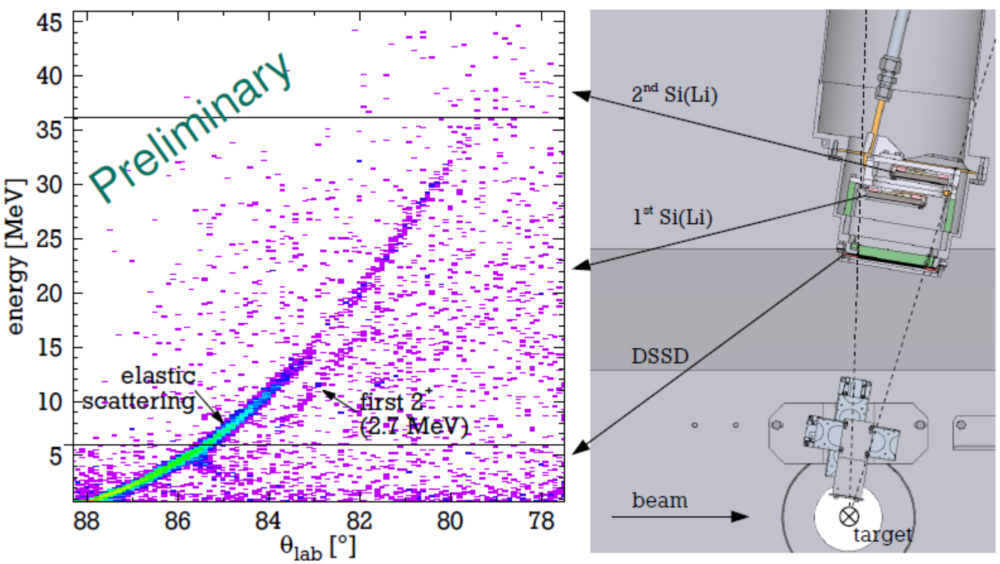
Successful test of the CAT TPC

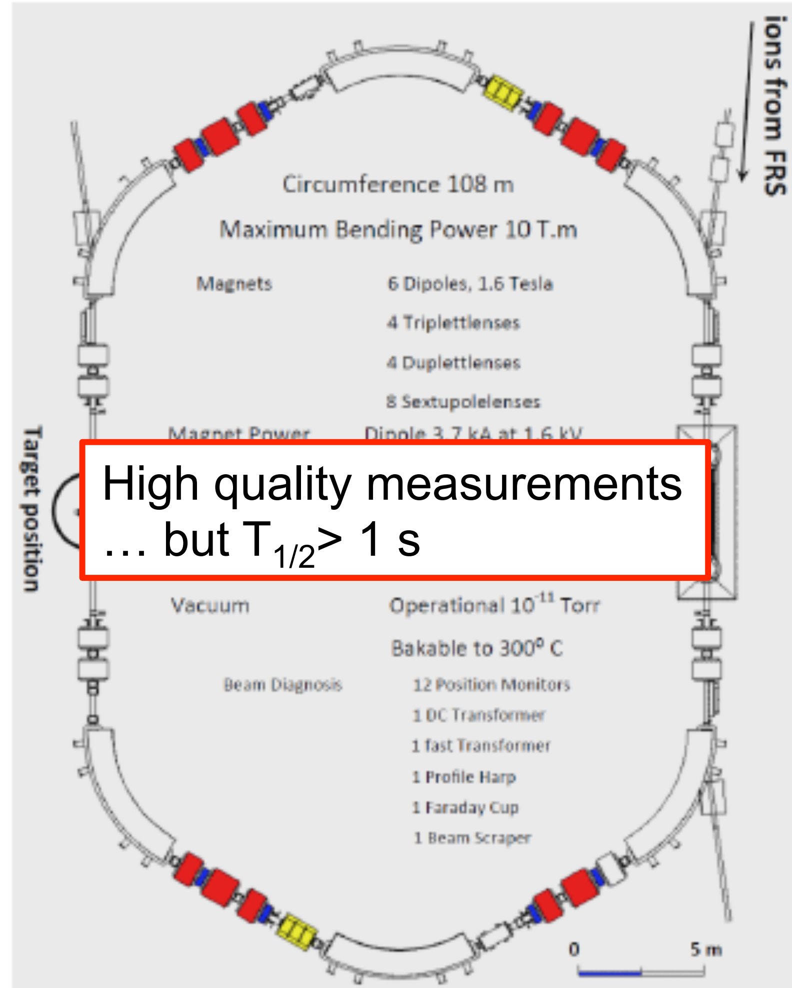
^{124}Xe + d at 100 MeV/u, HIMAC



Proton-induced elastic scattering

^{56}Ni(p,p') at 400 MeV/nucleon, GSI





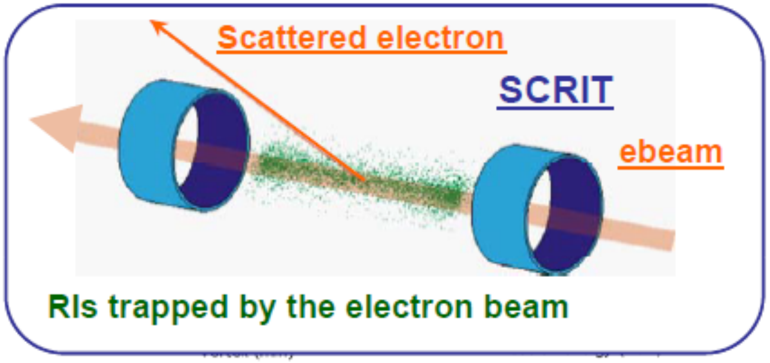
High quality measurements … but $T_{1/2}$> 1 s

Proof of principle for future EXL experiments at FAIR *(Courtesy: P. Egelhof)*

Electron scattering from unstable nuclei

e-RI scattering, SCRIT ring at RIKEN

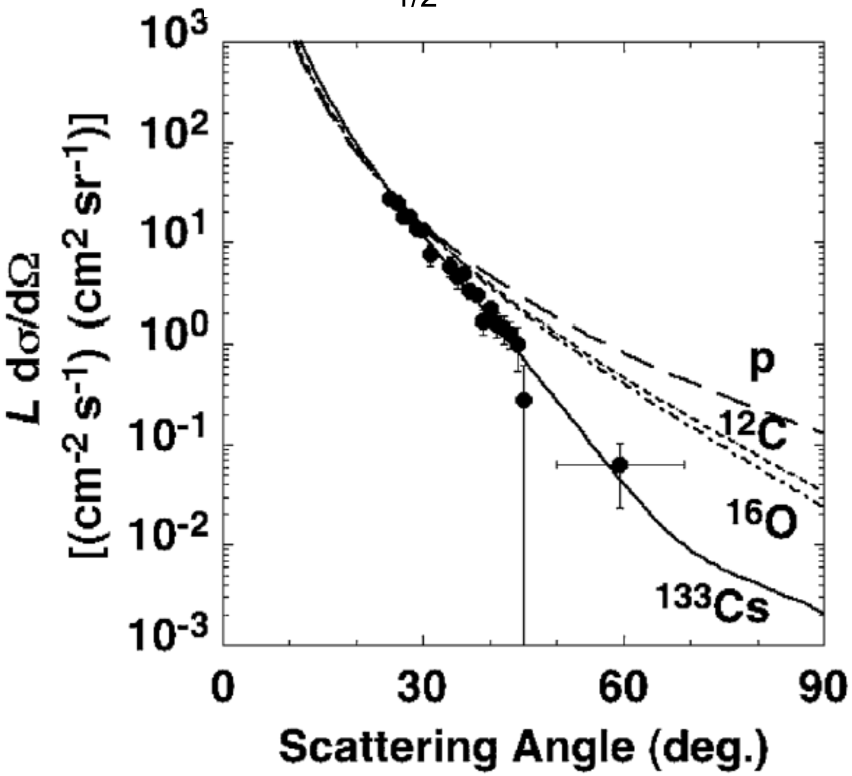
unstable nuclei from 2014



Luminosity >10^{27} cm^{-2} s^{-1}

+ electron – nuclei collider
eLISE @FAIR from > 2030

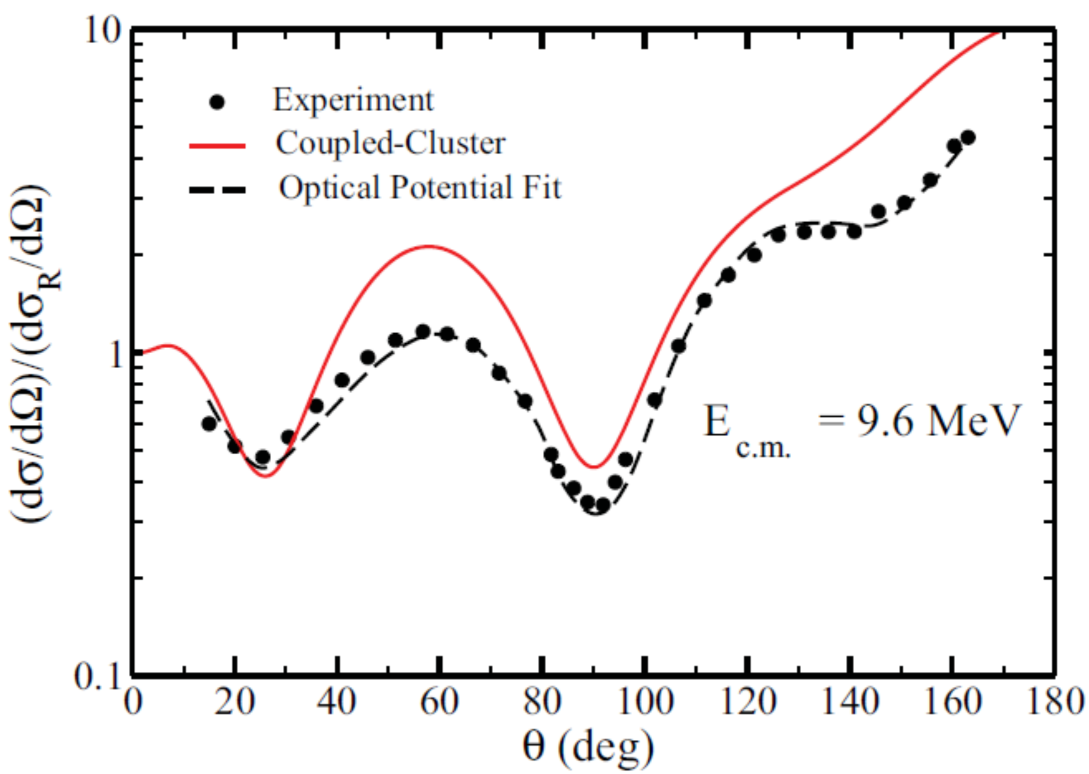
High quality measurements
… but $T_{1/2}$> 1-10 ms



T. Suda *et al.*, Phys. Rev. Lett. **102**, 102501 (2009).

Combining high resolution and high luminosity ***(e,e') and (p,p')*** will lead to proton AND neutron radial densities and form factors
Stable nuclei studies: see Ref. Q. Chen *et al.*, Phys. Rev. C **41**, 2504 (1990).

First ab initio description of elastic scattering



G. Hagen and N. Michel, PRC **86**, 021602(R) (2012)

Ingredients:
Coupled Cluster theory
A *unique* Hamiltonian

2N: N3LO
Effective 3N (NLO)
Λ=500 fm^{-1}

Ab initio overlap functions
Specific Coulomb treatment
Berggen basis

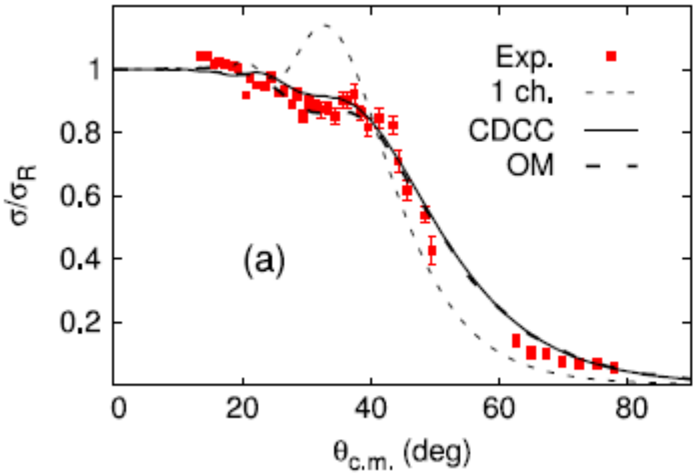
Also :first ab initio description of low energy fusion reactions (No Core SM)
P. Navratil and S. Quaglioni, PRL **108**, 042503 (2012)

Elastic scattering and coupled channels

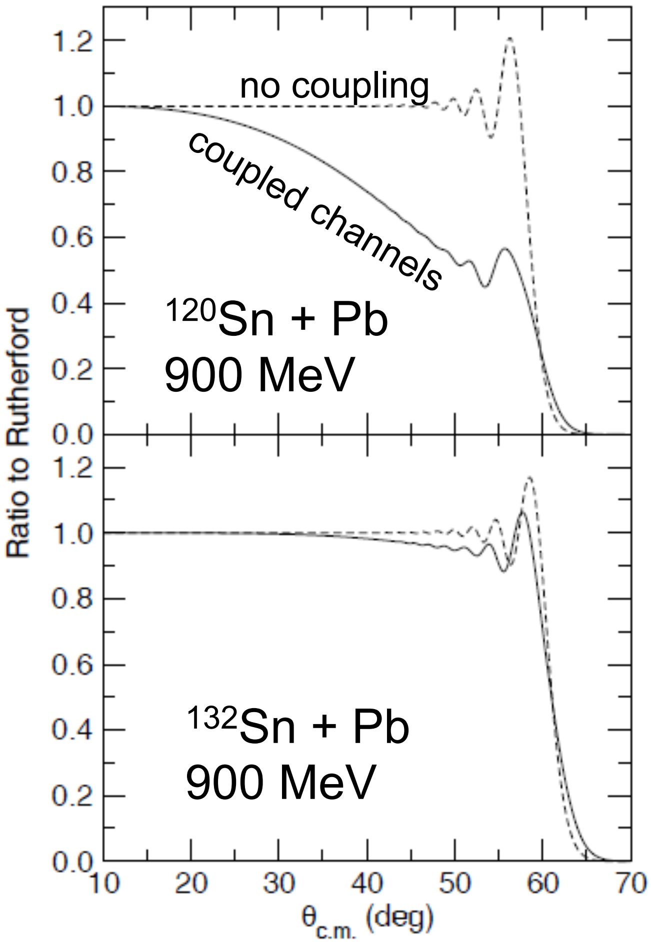
Importance of **channel couplings** in the vicinity of the **Coulomb barrier and beyond**
Exotic nuclei : choice of binding energy, level scheme

Quantum de-coherence
Elastic and continuum breakup channels

$^{11}Be + ^{64}Zn$, E_{cm}=24.5 MeV



A. Diaz-Torres and A.M. Moro, PLB **733**, 89 (2014)

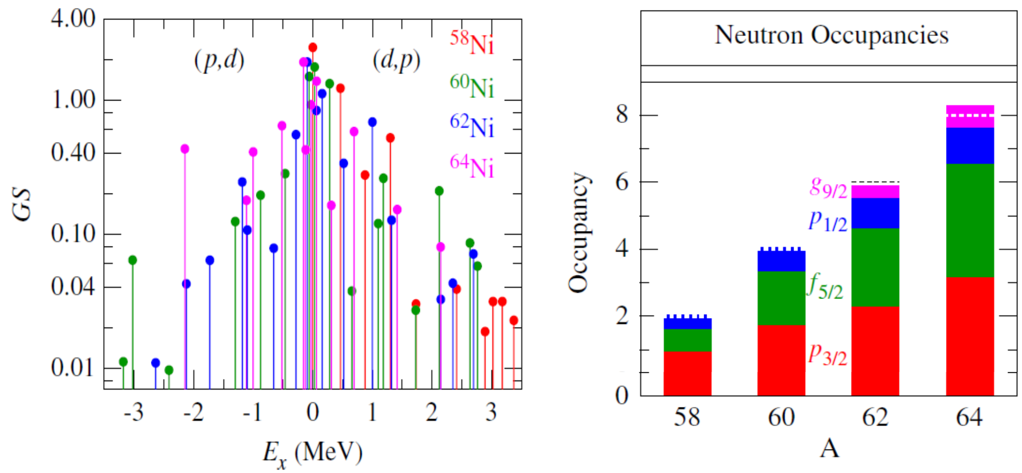


N. Keeley, K.W. Kemper, K. Rusek, EPJ A **50**, 145 (2014)

Direct nucleon stripping and pickup reactions

Interest / belief: sensitive to shell occupancy / overlap from initial to final states

DWBA formalism, finite range



Renormalization by 0.5-0.6 for correlations beyond the shell model

J.P. Schiffer *et al.,* Phys. Rev. Lett. **108**, 022501 (2012).

Major assumption in treatment : separation of reaction mechanism and structure inputs

Cross section to populate a final state μ

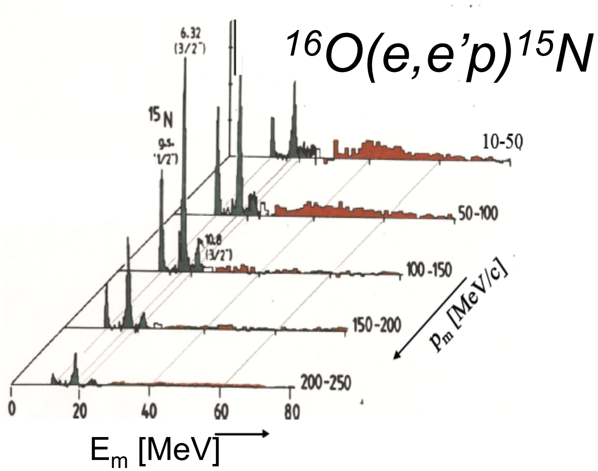
$$\sigma_\mu = \sum_{p\, \in H < H_1} \left| \left\langle \varphi_\mu{}^{A-1} \middle| a_p^- \middle| \varphi_0{}^A \right\rangle \right|^2 \times \sigma_p$$

→ reaction (σ_p)

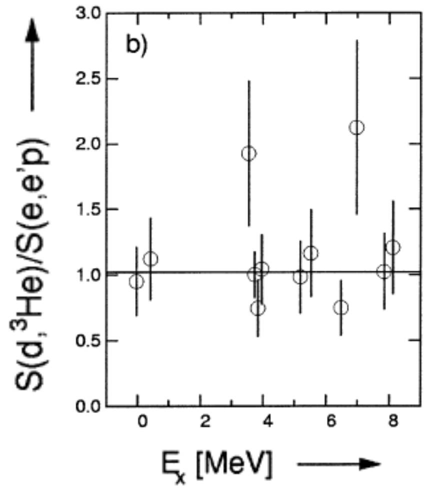
→ Structure (overlap)

Counter-examples: see previous slides, transfer: coupled channels sometimes mandatory

Stripping reactions at intermediate energies

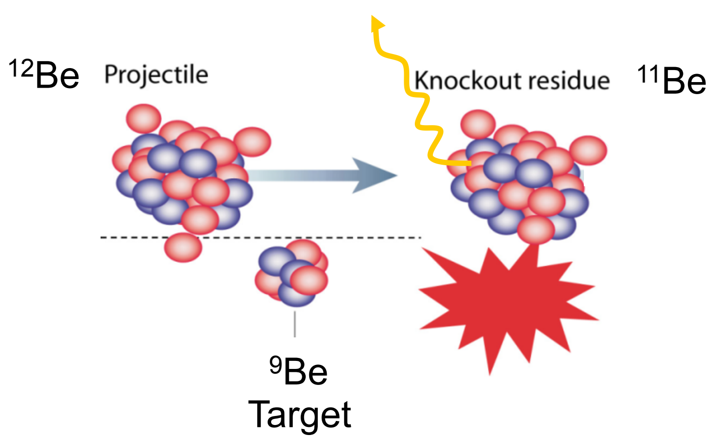


J. Mougey *et al.,* CEA Saclay (1980)

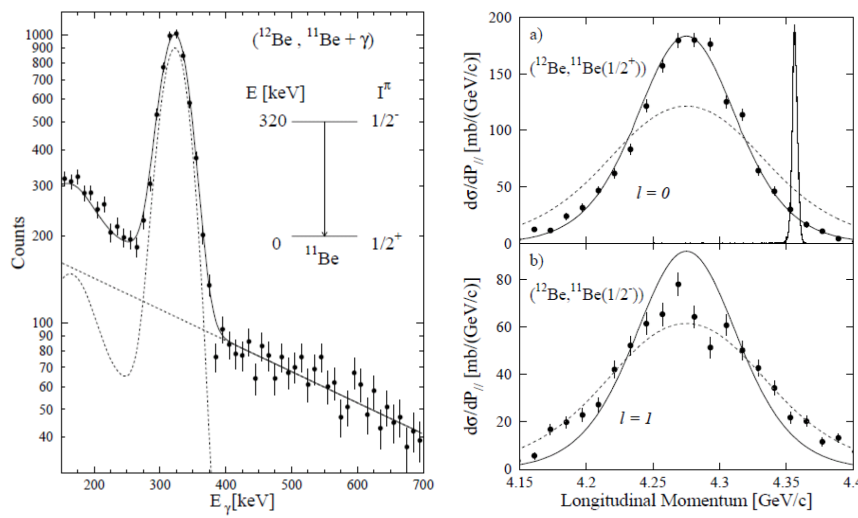


Consistency of *(e,e'p)* and *(d,^{3}He)* analysis

G.J. Kramer *et al.,*
Nucl. Phys. A **679**, 267 (2001).

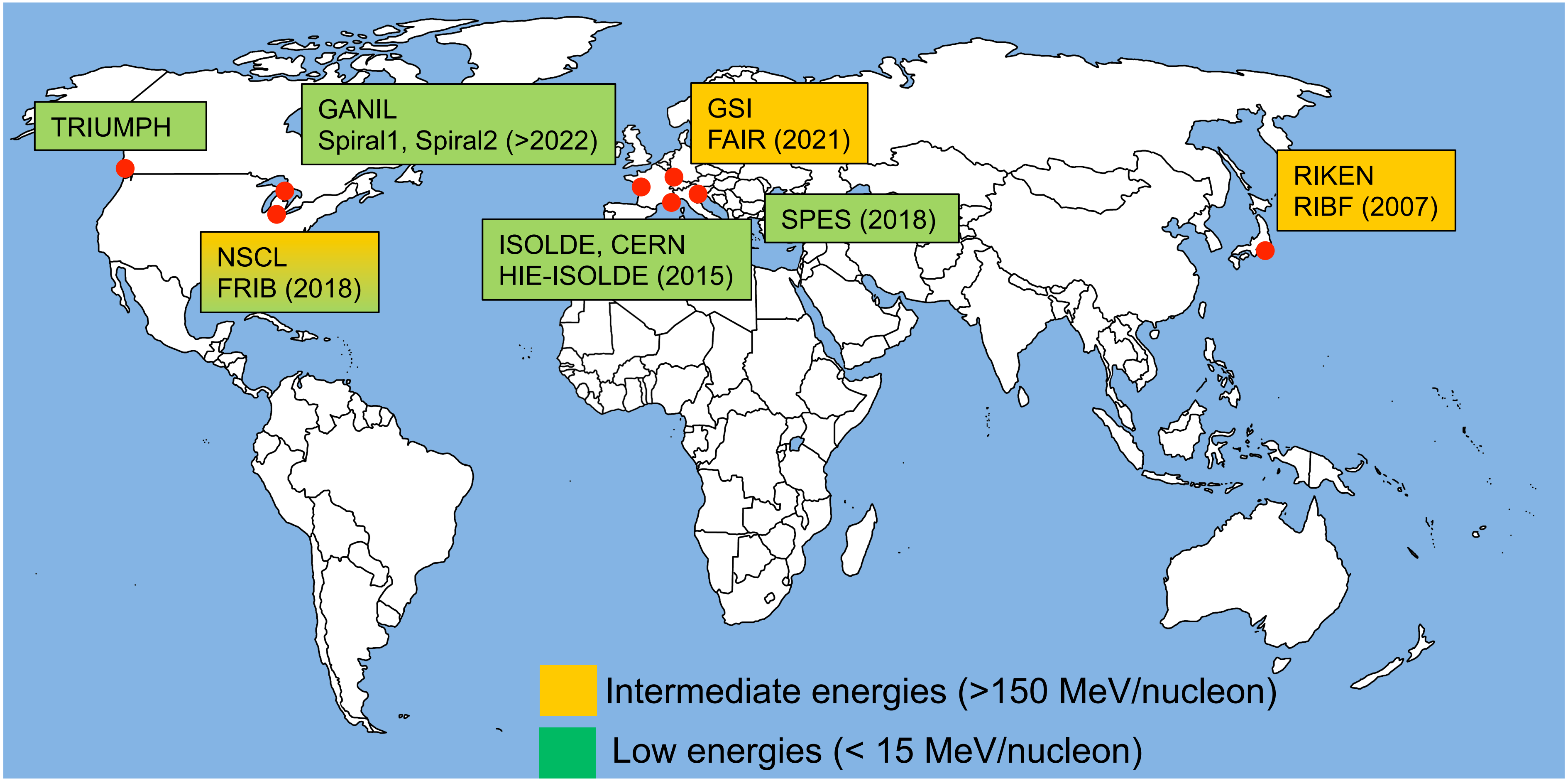


Exotic nuclei = inverse kinematics



A. Navin *et al.,* Phys. Rev. Lett. **85**, 266 (2000)

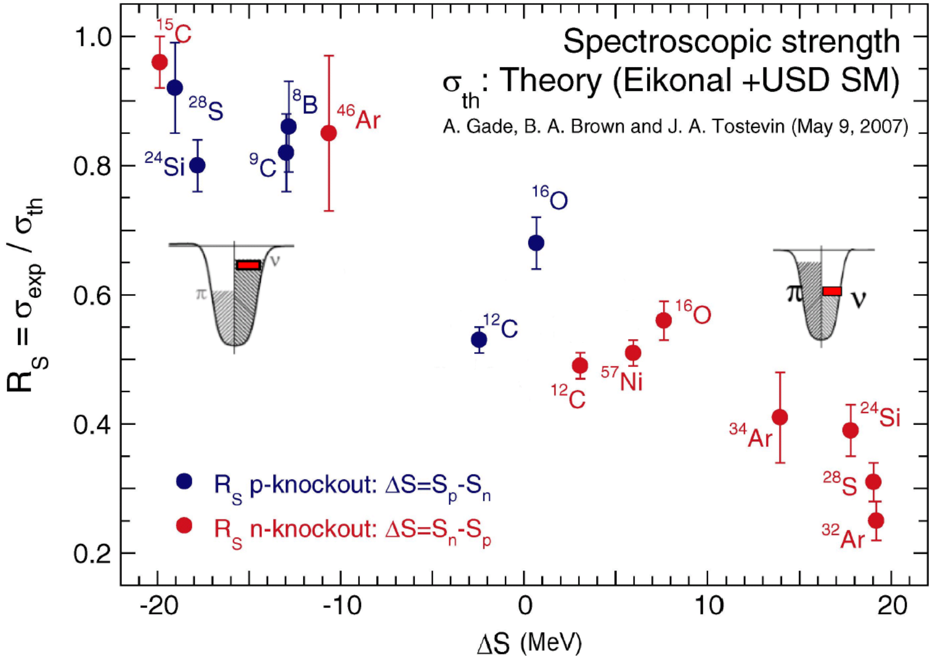
(Accelerated) unstable nuclei in the world

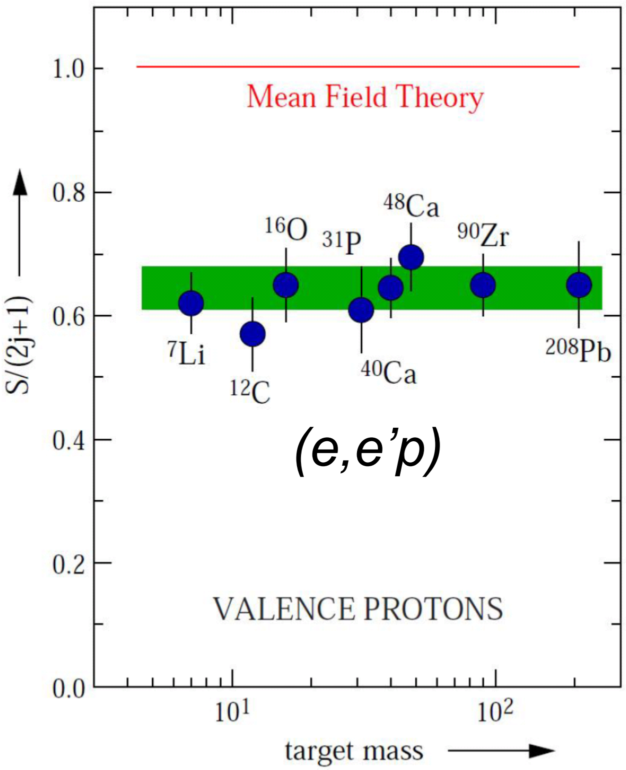


EURISOL (>2030): bridging the gap from low to intermediate energies

Deeply bound nucleon removal

A. Gade *et al*, PRL. **93** 042501 (2004) ; PRC **77**, 044306 (2008)



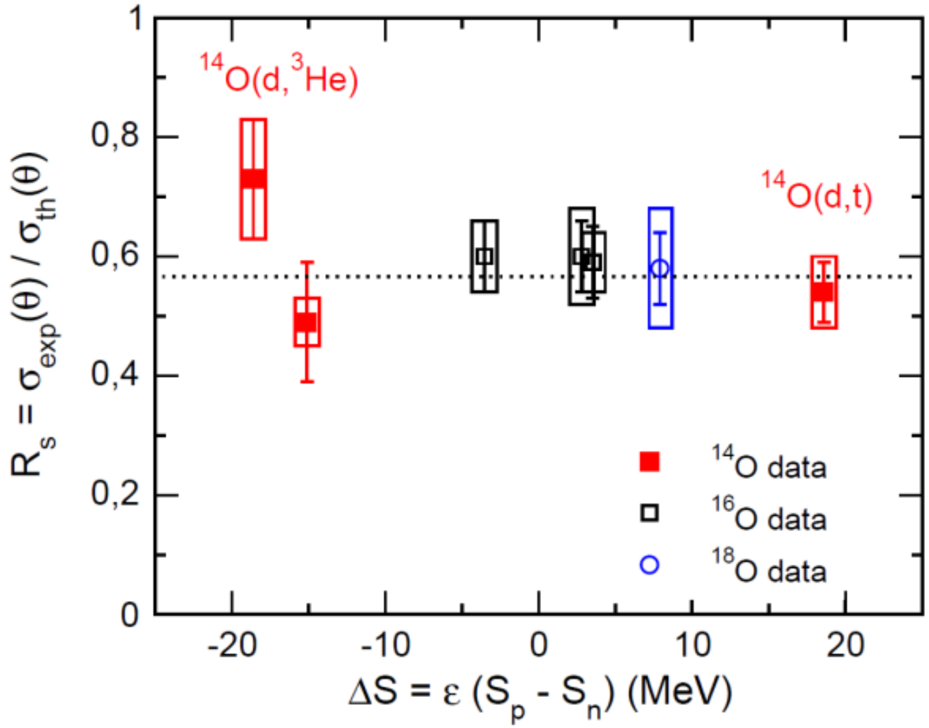


Intermediate-energy knockout

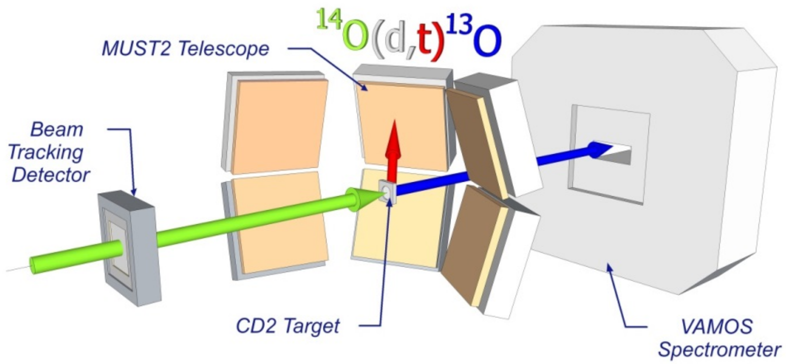
Disagreement between theory and experiment

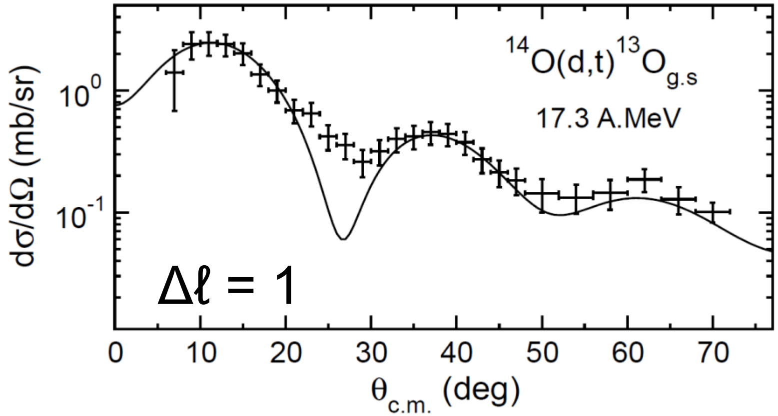
Oxygen isotopes via transfer

^{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**, 122503 (2013)





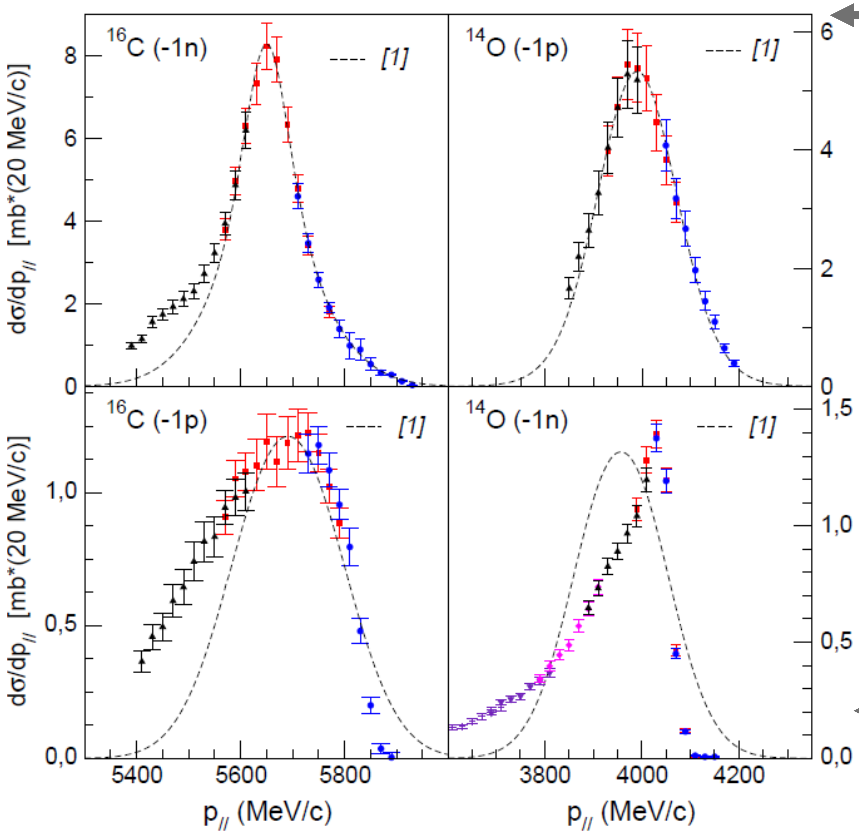
Conclusions

- **weak ΔS dependence**
- **Disagreement** between intermediate-energy nucleon removal and transfer analysis

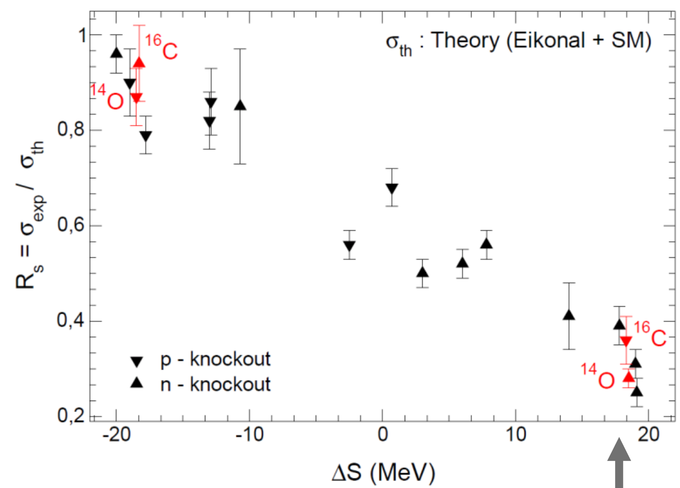
Intermediate-energy nucleon removal from ^{14}O, ^{16}C (ΔS~19 MeV)

F. Flavigny *et al.*, Phys. Rev. Lett. **108,** 252501 (2012)

^{9}Be target, ^{14}O: 53 MeV/u, ^{16}C: 70 MeV/u, NSCL



Loosely-bound valence nucleon



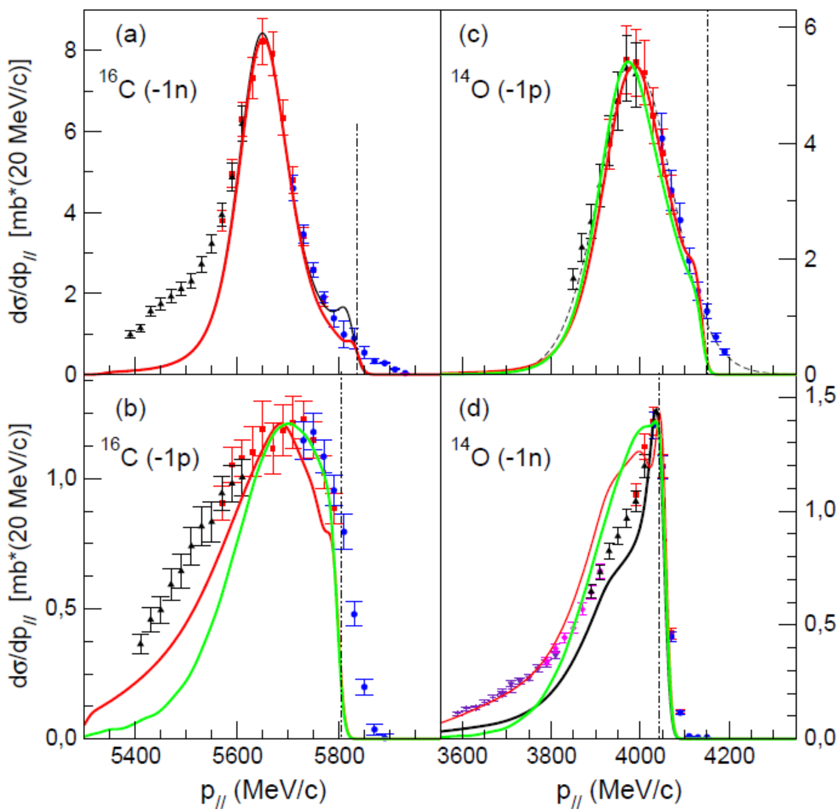
Deeply-bound valence nucleon

Open questions

- Microscopic origin of the observed **dissipative processes ?**
- **Incident-energy** dependence of the reaction process ?

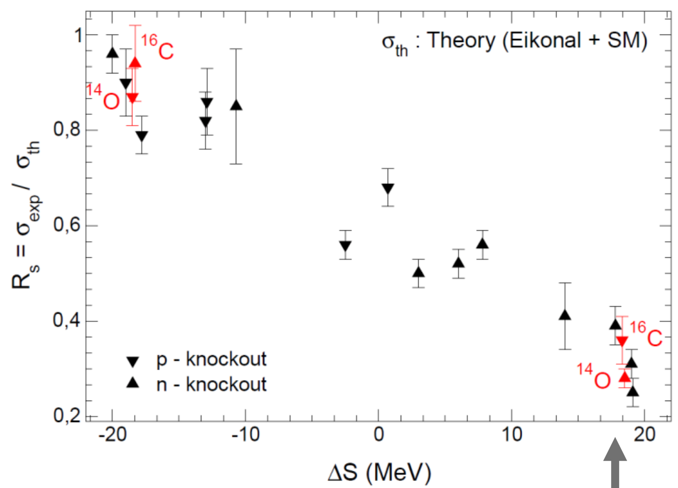
Intermediate-energy nucleon removal from ^{14}O, ^{16}C ($\Delta S \sim 19$ MeV)

Transfer to the Continuum Model



^{9}Be target, ^{14}O: 53 MeV/u, ^{16}C: 70 MeV/u, NSCL

Loosely-bound valence nucleon



Deeply-bound valence nucleon

Intrinsic momentum of the neutron + energy-dependent n-^{9}Be potential taken into account

A. Bonaccorso and D.M. Brink, Phys. Rev. C **43**, 299 (1991); A. Bonaccorso and G.F. Bertsch, Phys. Rev. C **63**, 044604 (2001)

Open questions

- Microscopic origin of the observed **dissipative processes ?**
- **Incident-energy** dependence of the reaction process ?

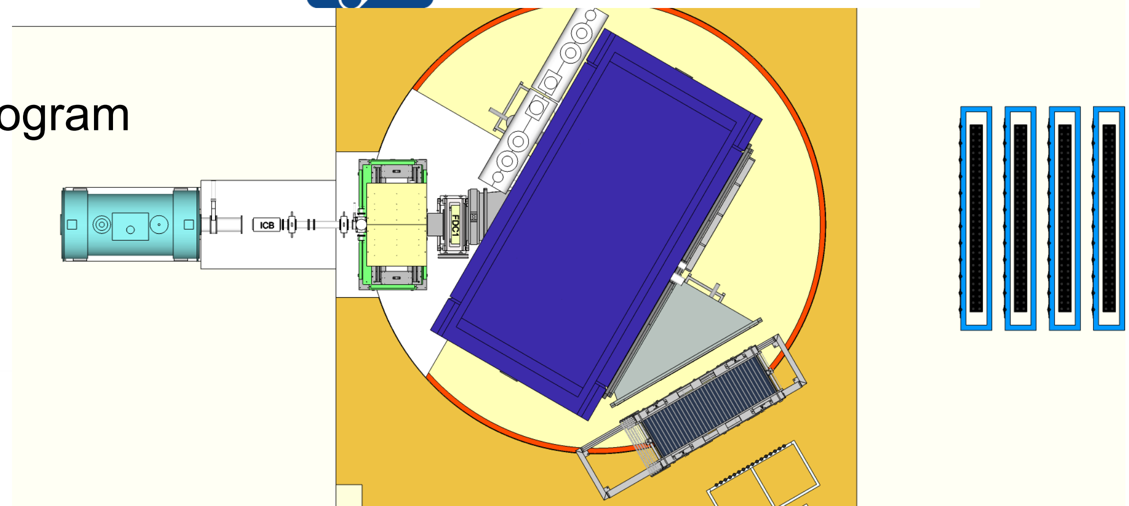
Spectroscopy of the most exotic nuclei at the RIBF

The spectroscopy of several key nuclei is being performed / planed:

- ^{78}Ni, ^{110}Zr, ^{100}Sn
- invariant-mass spectroscopy program beyond the neutron dripline (^{28}O)

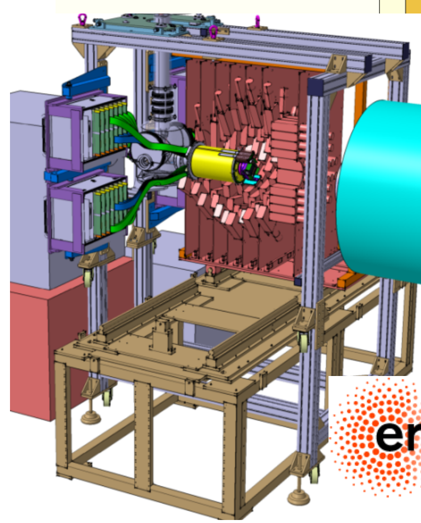
All produced from knockout

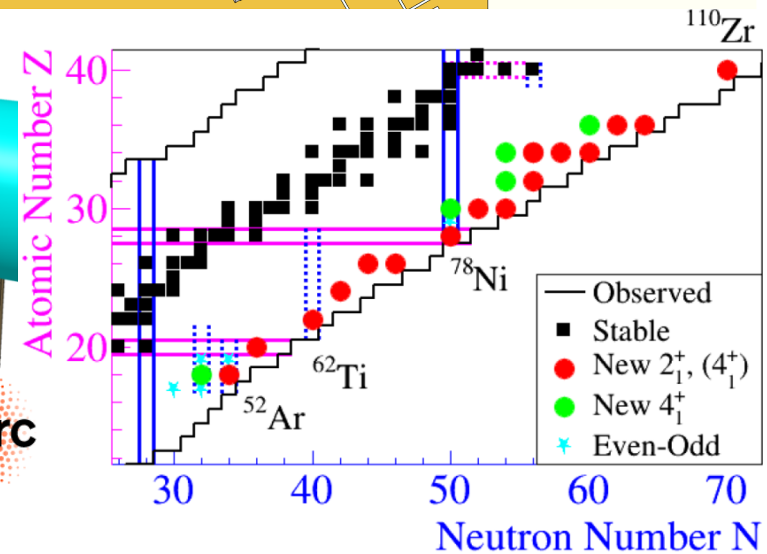
BUT



Other key aspects of nuclear Structure require specific probes:

- quadrupole moments
- radii
- single-particle states
- matter density distribution





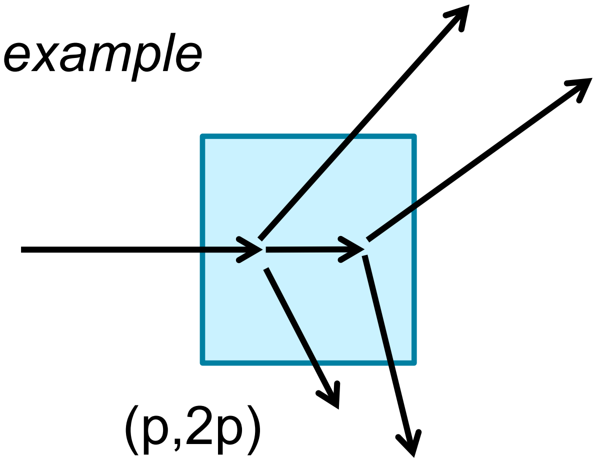
Only reachable with
at lower energy with high (>10^4) intensities

A. Obertelli *et al.*, Eur. Phys. Jour. A **50**, 8 (2014)

Possible future studies

Use of two-step reactions (*tracking*) and missing mass:
a new way to probe **overlap functions from short-lived to short-lived states**

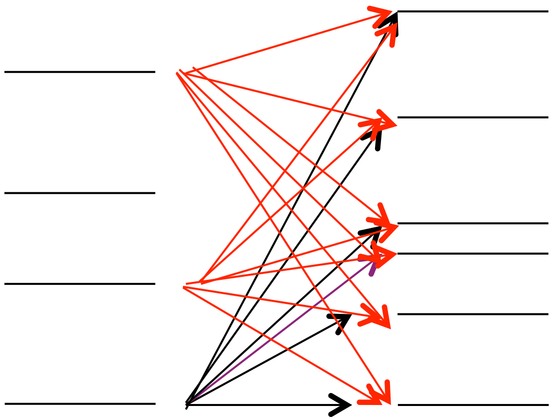
example



(p,2p)

(p,2p)

new



ground state

Proj.

C^2S

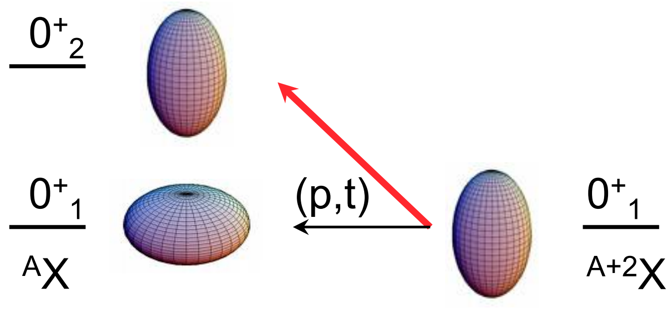
Res.

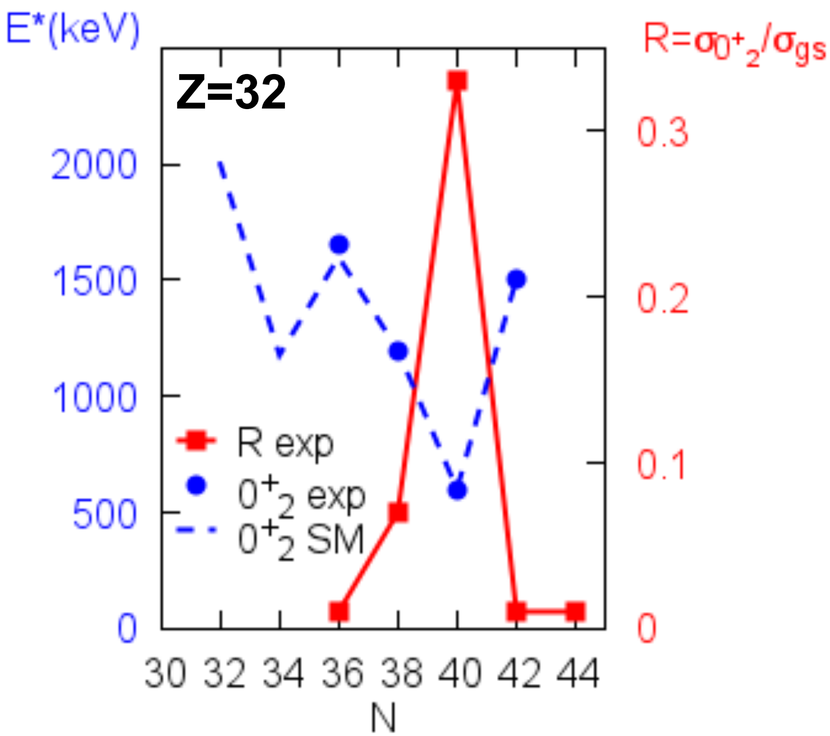
100 MeV/nucleon: 1 mm distance of flight = 100 ps

- Spectroscopic factors from short lived to short-lived states from *(p,pn)* and *(p,2p)*
- cluster component of bound excited states from (p,pα)

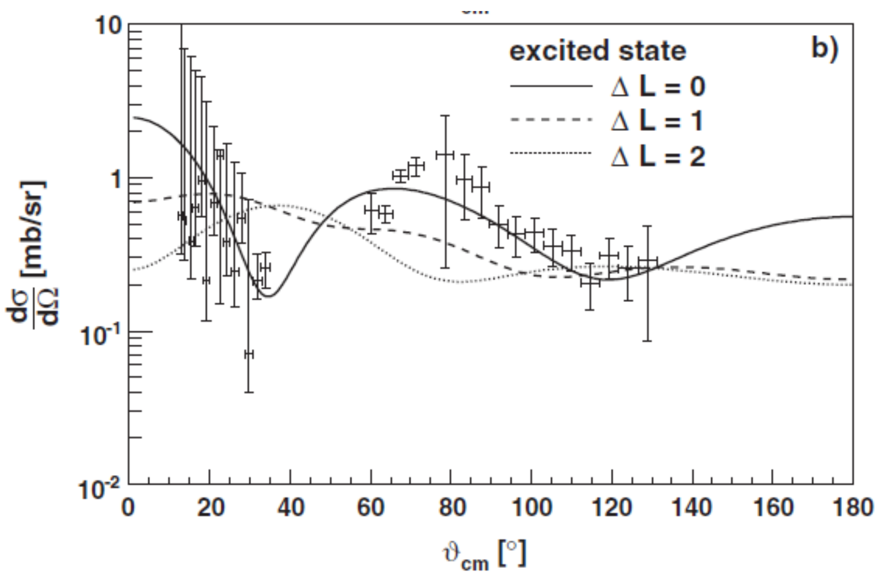
Pair transfer: a probe for correlations

Shape transition in light Ge isotopes





Intruder configurations at N=20



^{30}Mg(t,p)^{32}Mg at 1.8 MeV/u, REX-ISOLDE

K. Wimmer *et al.*, Phys. Rev. Lett. **105**, 252501 (2010).

… Higher energies required!

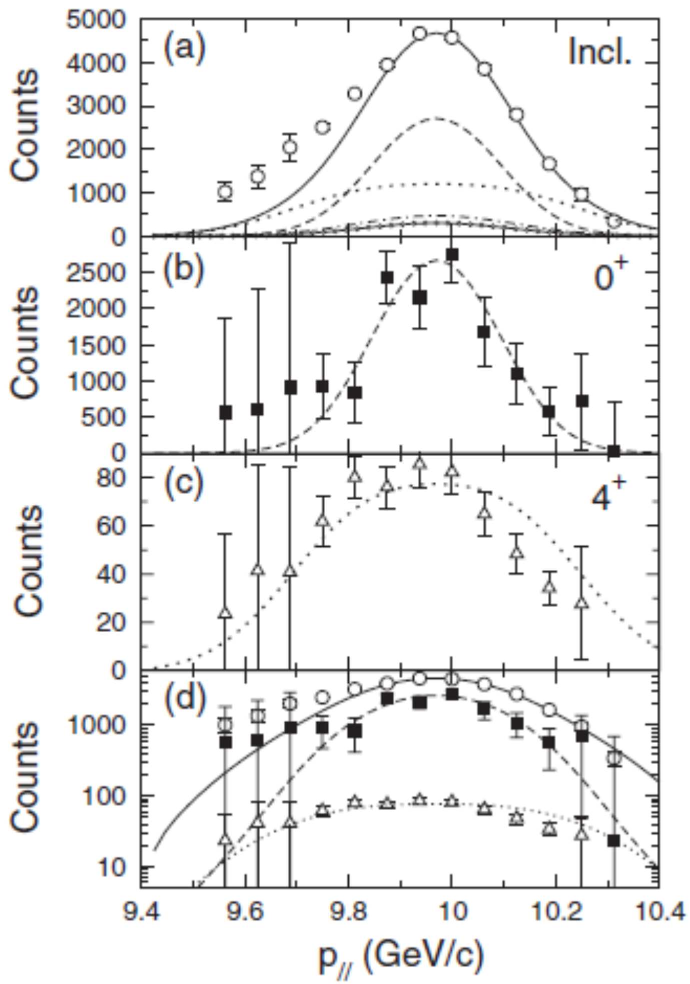
Pairing regimes in Sn isotopes

G. Potel *et al.*, Phys. Rev. Lett. **107**, 092501 (2011).

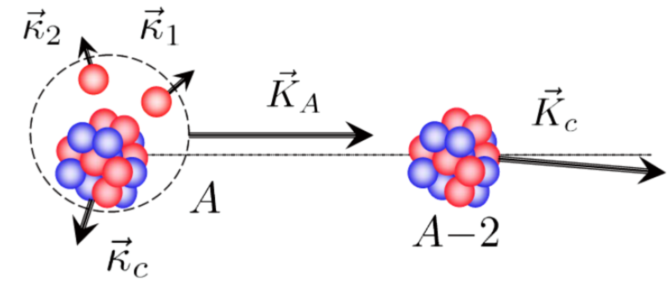
Energies from 10 to 50 MeV/nucleon / low cross sections (100 μb)

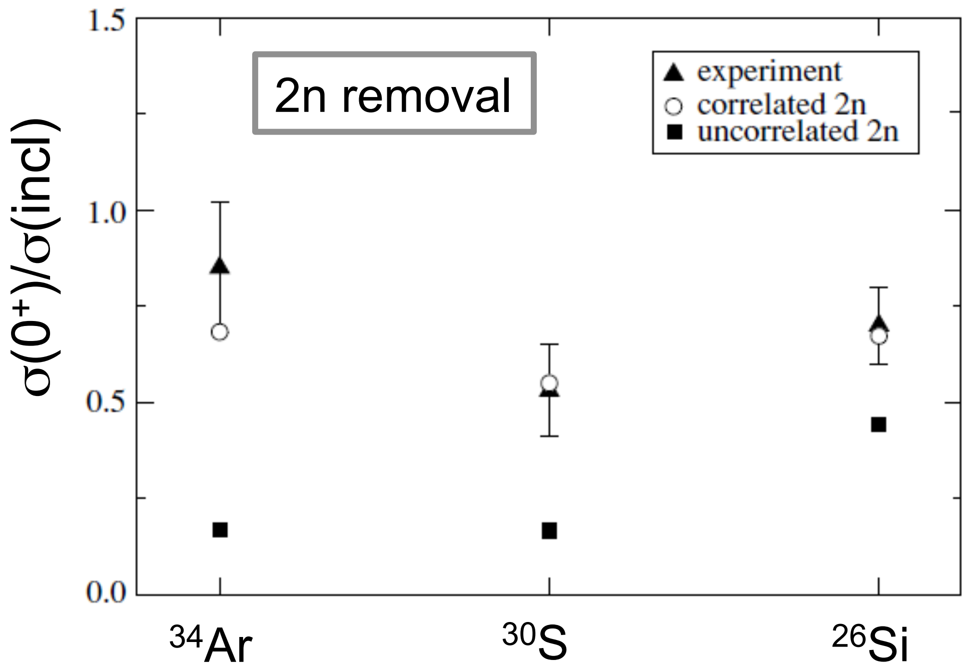
Two nucleon removal: sensitivity to correlations

Eikonal formalism by J. Tostevin, E.C. Simpson
Mostly used at NSCL energies (50-100 MeV/nucleon)



E.C. Simpson *et al.,* Phys. Rev. Lett. **102**, 132505 (2009)





K. Yoneda *et al.,* Phys. Rev. C **74**, 021303(R) (2006)

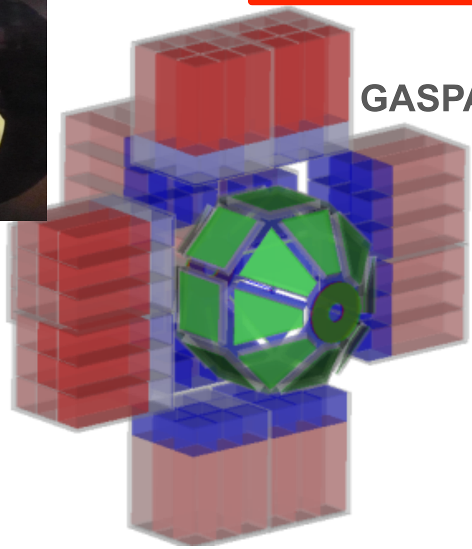
Associated detector developments

See presentation by R. Raabe

Transfer and (in)elastic scattering

CHyMENE (IRFU)

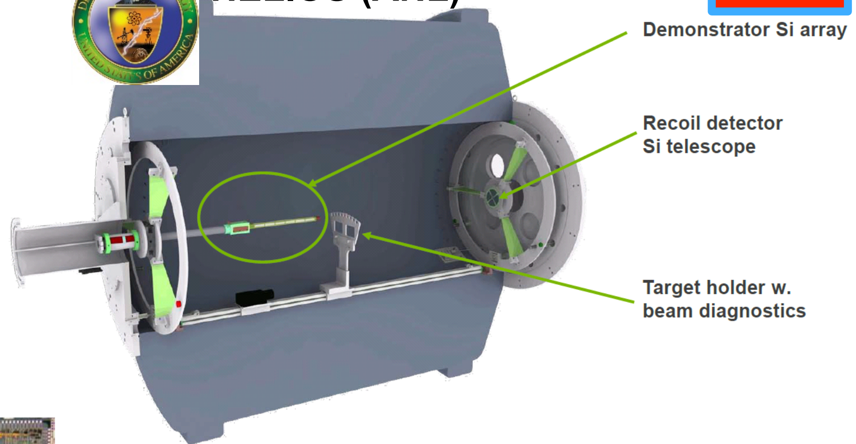
GASPARD (IPN)



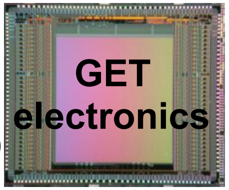
EU

US

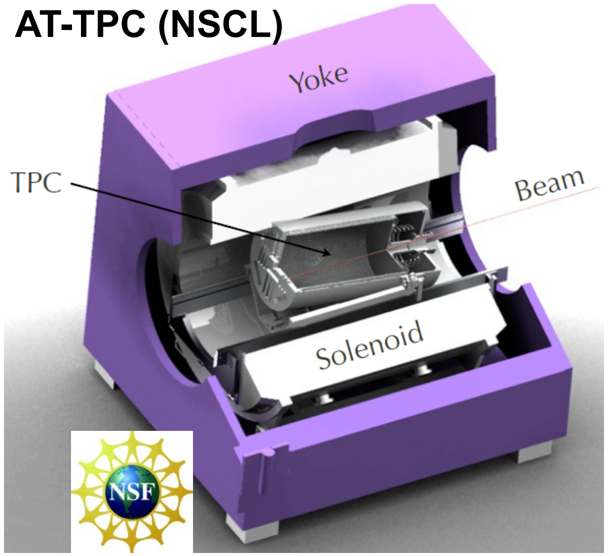
HELIOS (ANL)



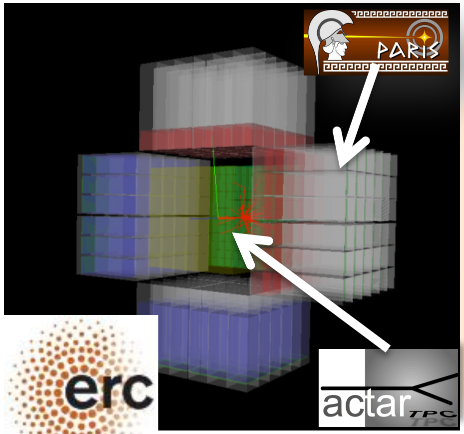
GET electronics

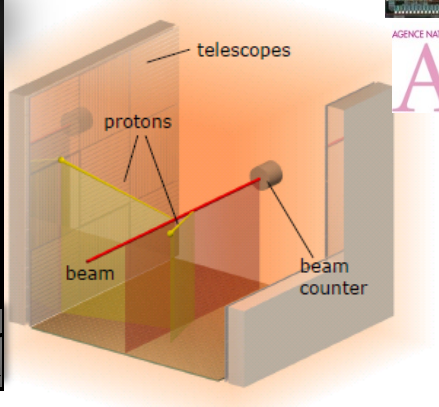


AT-TPC (NSCL)



ACTAR TPC (GANIL)





Ion ring project (Isolde)

+ ongoing similar EU projects

Summary

- **Elastic scattering** and **direct reactions** provide unique tools for nuclear structure
- ❑ nuclear radii, neutron-skin thickness
- ❑ collective modes
- ❑ spectroscopy and single particle shell structure
- ❑ correlations

⇒ **Mono-energetic beams (re-acceleration)**
⇒ **Regime from 10 to few hundred of MeV/nucleon**
⇒ **high intensities (> 10^4 pps) for quantitative results**

- **Nuclear reaction theory is far from being accurate**
  Necessary theoretical improvements & dedicated experiments
- ❑ core excitations and channel coupling
- ❑ consistent treatment of reaction and structure
- ❑ comprehensive understand of incident AND binding energy dependence
- ❑ structure inputs beyond the shell model

⇒ **(not so) exotic nuclei + variable energy from few to 200 MeV/nucleon**

- **Fundamental nuclear dynamical processes** to be studied
  ⇒ nuclear direct reactions are by themselves a **motivation for EURISOL**
- ❑ dynamics of few-body systems
- ❑ quantum de-coherence

- **New tools and techniques** to be invented