Physics cases around shell closures with cryogenic targets

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Shell structure: a quantitative description ?

On Closed Shells in Nuclei. II

MARIA GOEPPERT MAYER
Argonne National Laboratory and Department of Physics, University of Chicago, Chicago, Illinois
February 4, 1949

Thanks are due to Enrico Fermi for the remark, "Is there any indication of spin-orbit coupling?" which was the origin of this paper.

PHYSICAL REVIEW VOLUME 78, NUMBER 1 APRIL 1, 1950

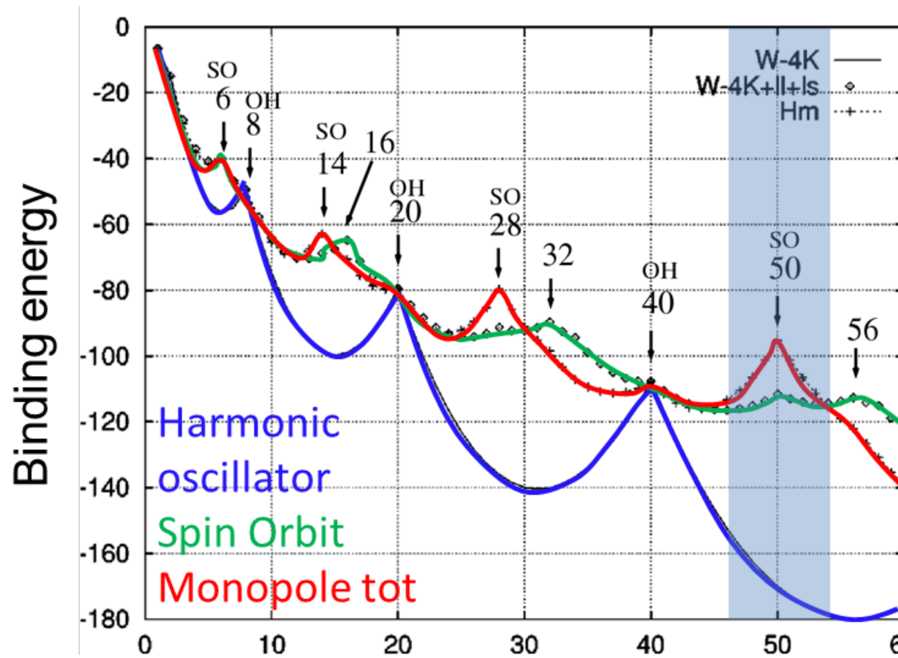
Nuclear Configurations in the Spin-Orbit Coupling Model. I. Empirical Evidence

MARIA GOEPPERT MAYER

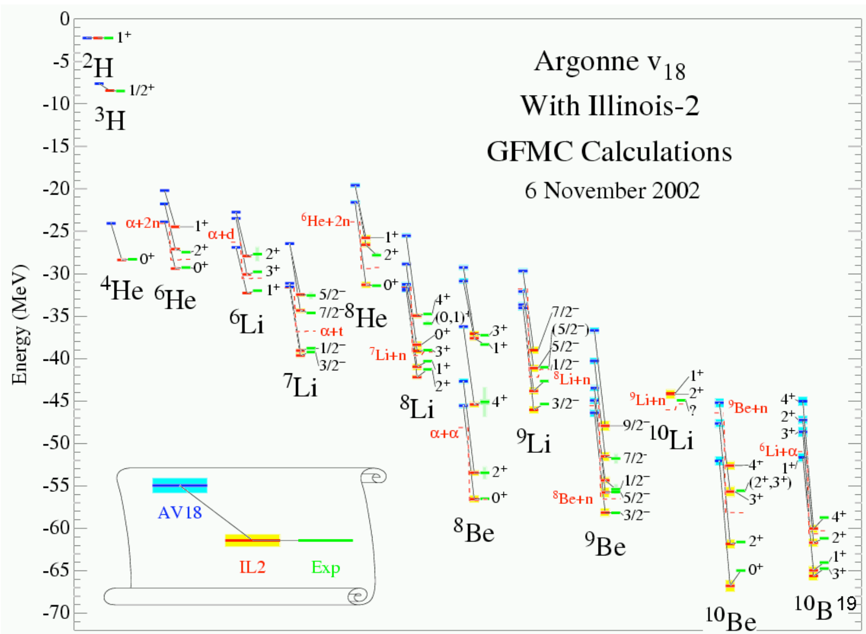
There is no adequate theoretical reason for the large observed value of the spin orbit coupling. The Thomas

J. Duflo et A. P. Zuker, Phys. Rev. C 59, R2347 (1999)

Extruder-Intruder shell gaps



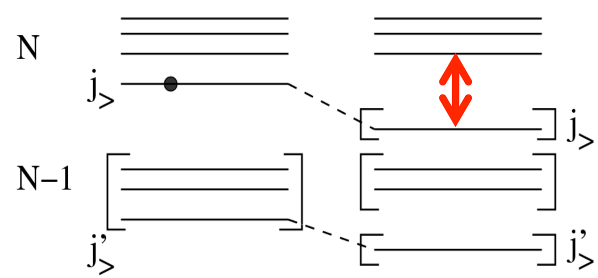
Maybe three-body forces ?
Maybe unbinding of upper shells ?



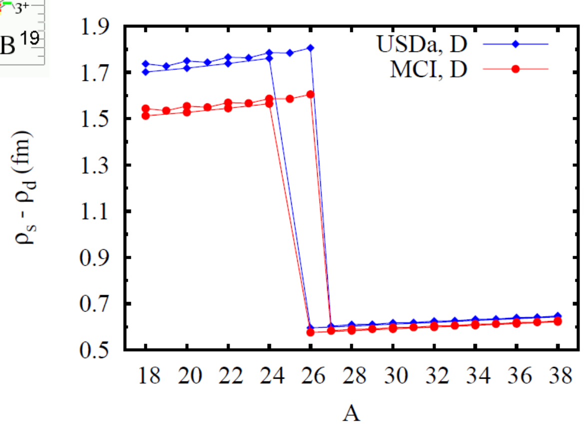
Phys. Rev. Lett. **89**, 182501 (2002)

3-body interactions produce “naturally” overbinding of large j shell

Phys. Rev. Lett. 90, 042502 (2003)



Journal of Physics: Conf. Series 1023 (2018) 012016



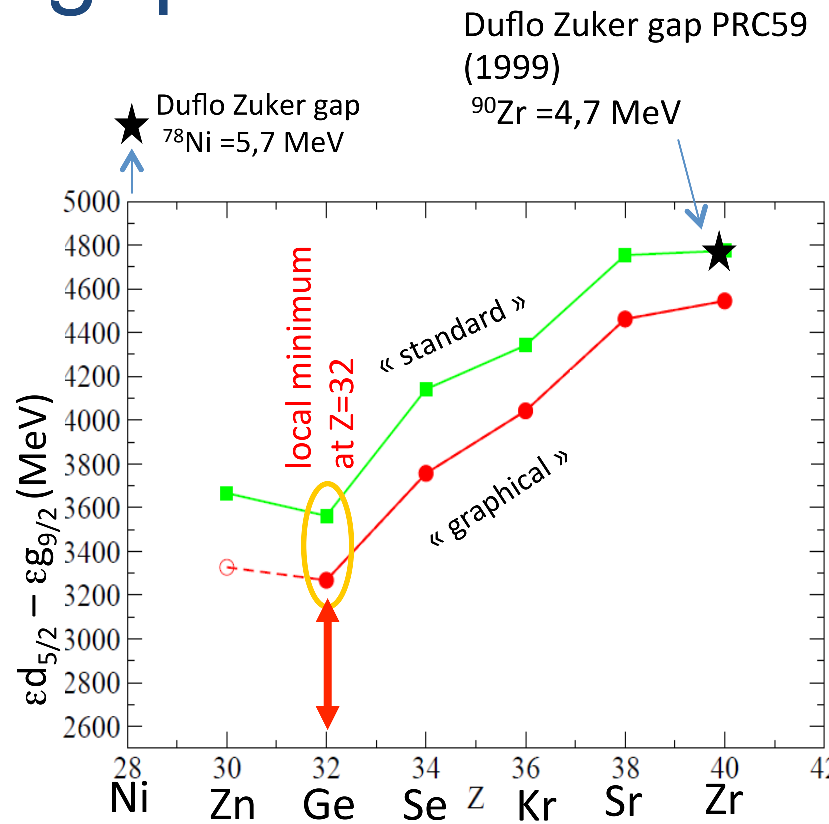
3-body generating SO gaps:

- N=14 in oxygen
- N=28 in calcium

T. Otsuka et al., Phys. Rev. Lett. 104, 012501 (2010),
J. D. Holt et al. arXiv :1009.5984v3 [nucl-th] (2012)

Or maybe is the unbinding of the higher-lying shells creating the gap ?

Can we measure shell gaps ? N=50 case



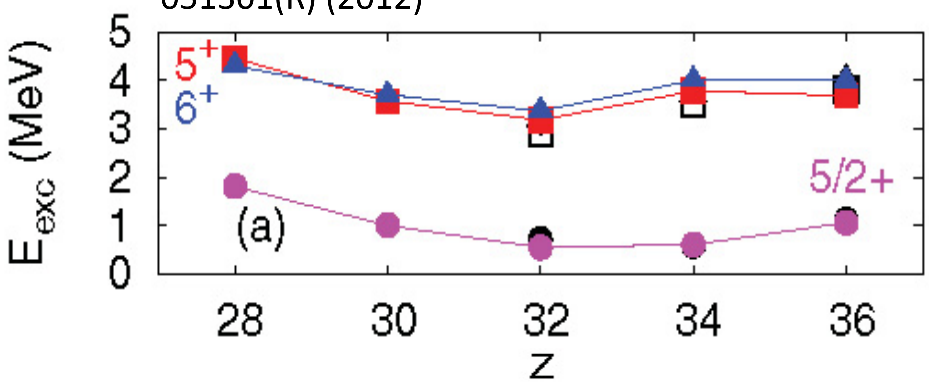
Shell-gap from masses

Reduction of the N=50 spherical gap from N=51 isotones mass ?

M.-G. Porquet and O. Sorlin, Phys. Rev. C 85, 014307 (2012)

Shell-gap from spectroscopy

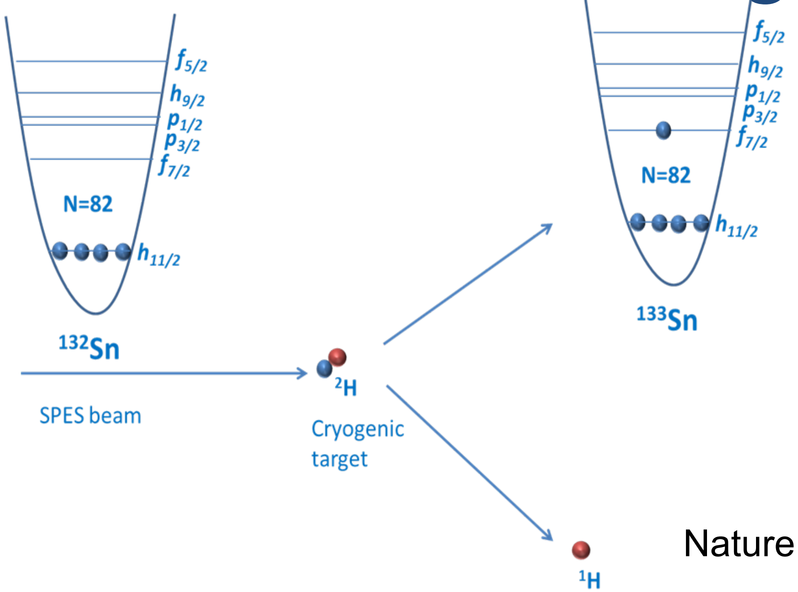
K. Sieja et F. Nowacki, Phys. Rev. C 85, 051301(R) (2012)

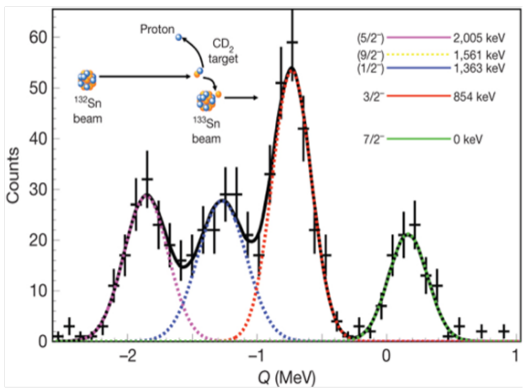


p-h states across N=50 in N=49 and N=50 isotones: minimum at Z=32

CONSTANT GAP

Single-nucleon transfer as a probe of shell structure





Nature 465, 454–457 (2010)

One-nucleon transfer populates mainly single-particle states

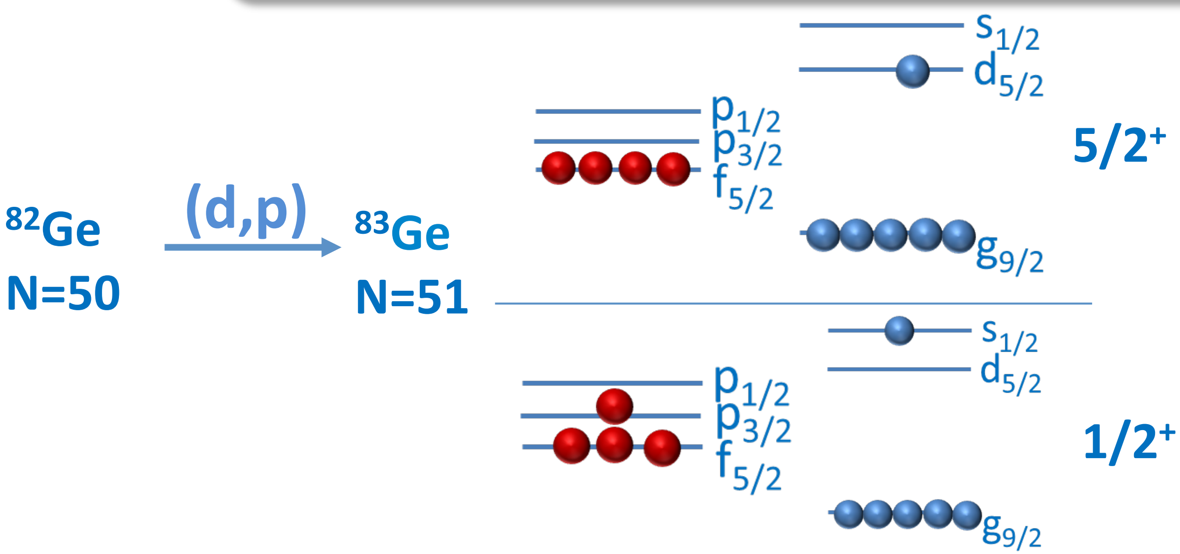
Caveat: SF NOT an observable, many fragments

- SF are defined within a model: different models may yield different SF for same wave functions (Phys. Rev. C 92, 034313 (2015))
- Need of measuring small fragments of the force (what if unbound ?)
- Need of probing both particles and holes to get an idea of ESPE

Single vs. collective states after transfer

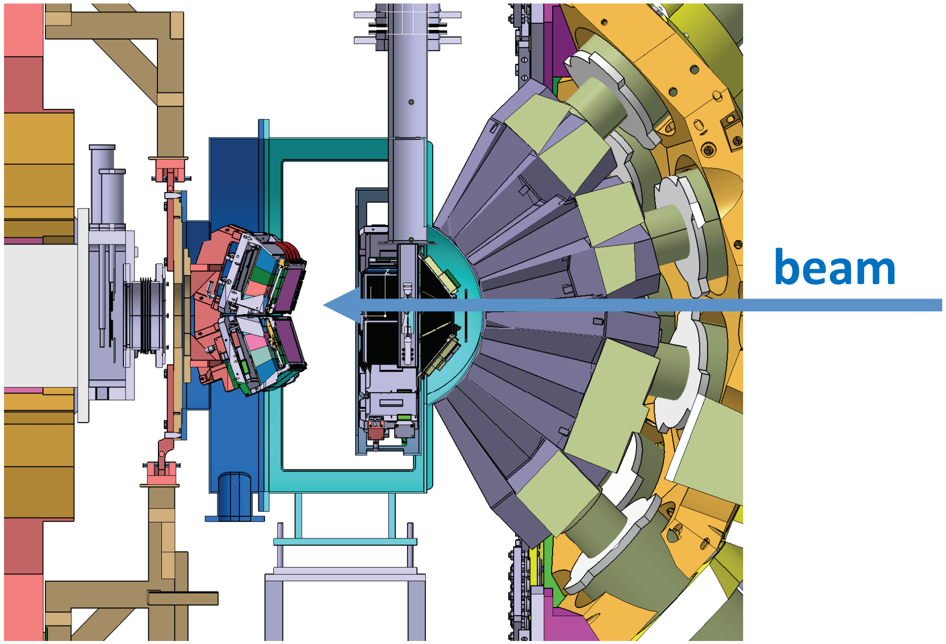
Always single-particle states?

- When adding/stripping one/two nucleons, the other fluid may also change due to isovector polarizability
- Ex: changing proton wave function in a (d,p) reaction
- Consequences on cross section estimation, hence SF extraction



One-neutron transfer causes a shift in proton occupation numbers

Targets for radioactive beams



Cryogeinc targets

- Compact targets (thickness few mm, cold finger penetrating in the chamber)
- Thick targets (~ mg/cm^2)

At the same time: - **high-resolution γ-ray spectroscopy** with high efficiency (10-20%): energy, angular distribution, polarity, lifetimes (?)
- **light ejectile spectroscopy** (p,d,t, ^{3}He,α): ℓ transferred
- **heavy ion spectroscopy**: contamination, thickness control, ℓ transferred, invariant mass for unbound states

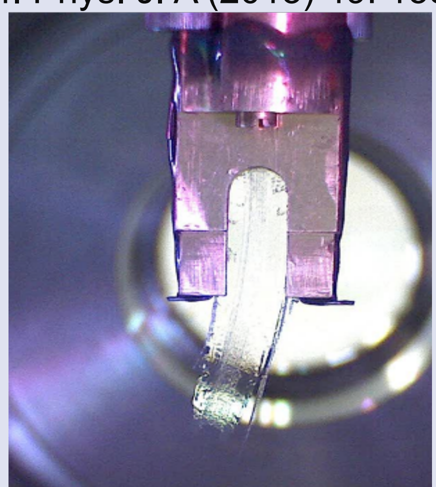
Cryogenic targets

Gel-like targets: CHyMENE

Cryogenic target that extrudes a solid state paste for ^{1}H and ^{2}H

- Thickness: several 10^{20} atoms/cm^2
- No windows needed
- Impossible for ^{3}H (radioprotection)

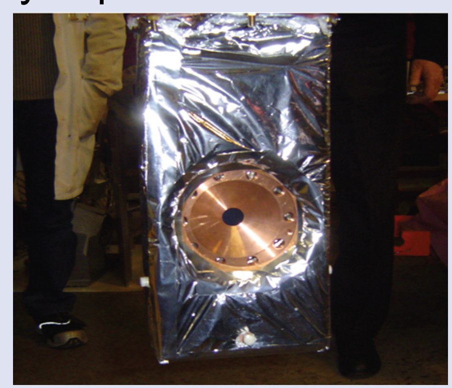
Eur. Phys. J. A (2013) 49: 155



Cryogenic gas: $^{3,4}He$

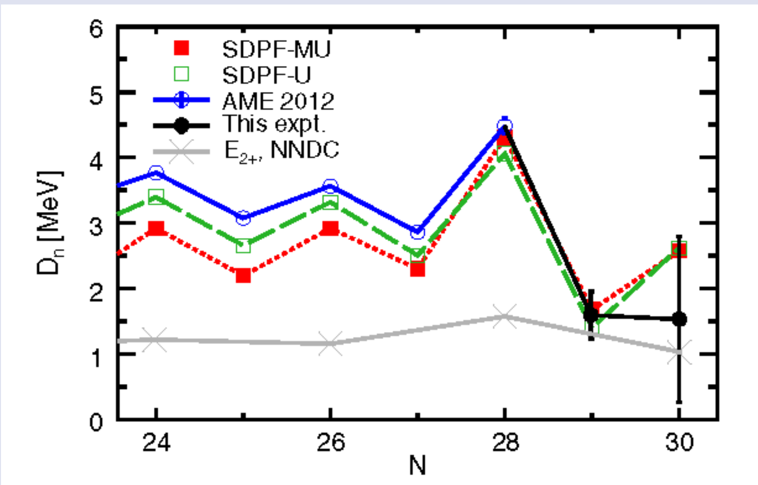
Cryogenic target in the gas phase but at low temperature: high density gas for ^{3}He and ^{4}He

- Thickness: 1-2 mg/cm^2, several 10^{20} atoms/cm^2
- windows needed: secondary reactions, energy straggling
- ^{3}He very expensive



Physics case along N=28 (I)

Neutron observables understood

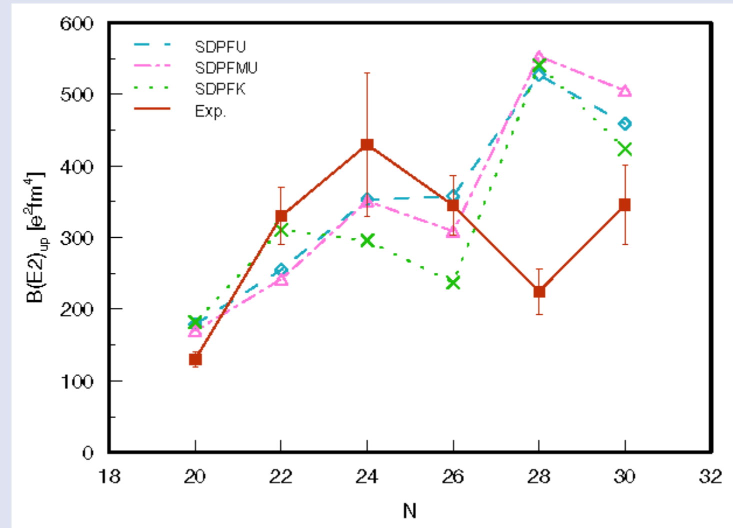


Excellent theory for neutron-space related quantities:

- confirming N=28 shell closure in ^{46}Ar
- SDPF interaction describes valance-core neutrons interaction very well

Z. Meisel et al. PRL 114, 022501 (2015)

Large discrepancy in B(E2)



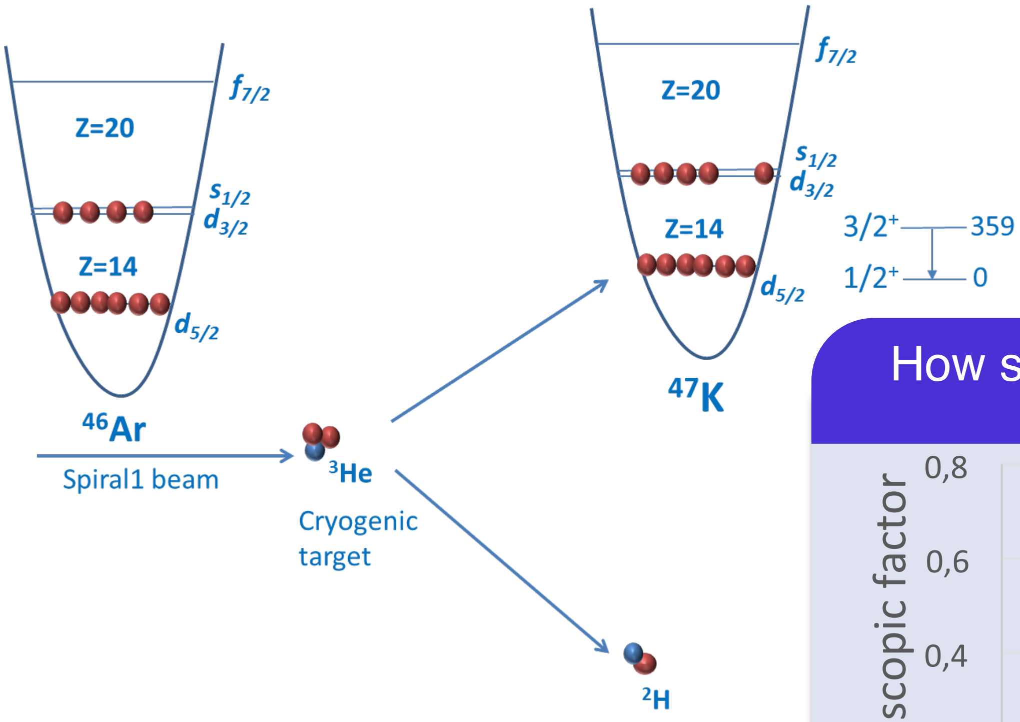
Large discrepancy with the measured B(E2) value at N=28:

problem with the proton E2 contribution ?

A. Gade et al., PRC 68, 014302 (2003)

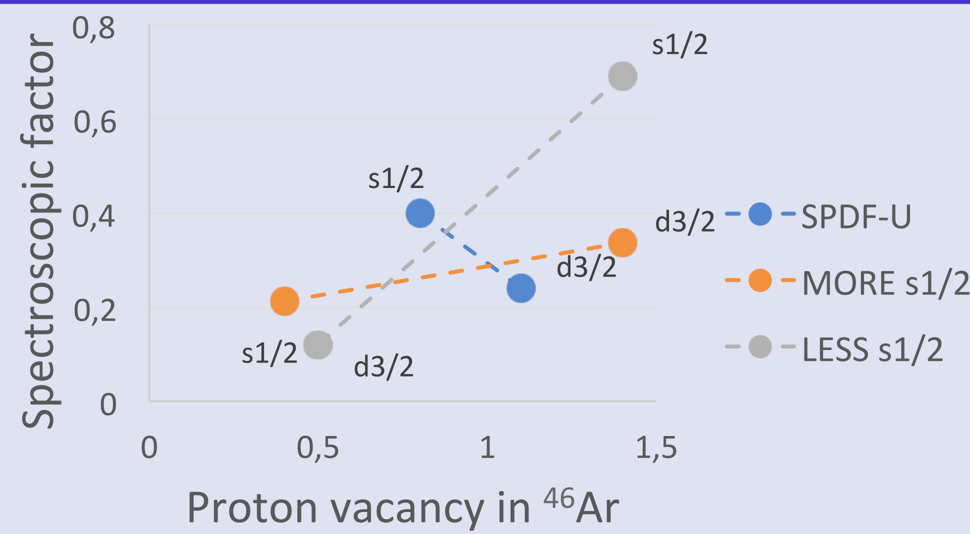
S. Calinescu et al., PRC 93, 044333 (2016)

$^{46}Ar(^{3}He,d)^{47}K$ proton pick-up reaction



Significant dependence of spectroscopic factors from occupation numbers !

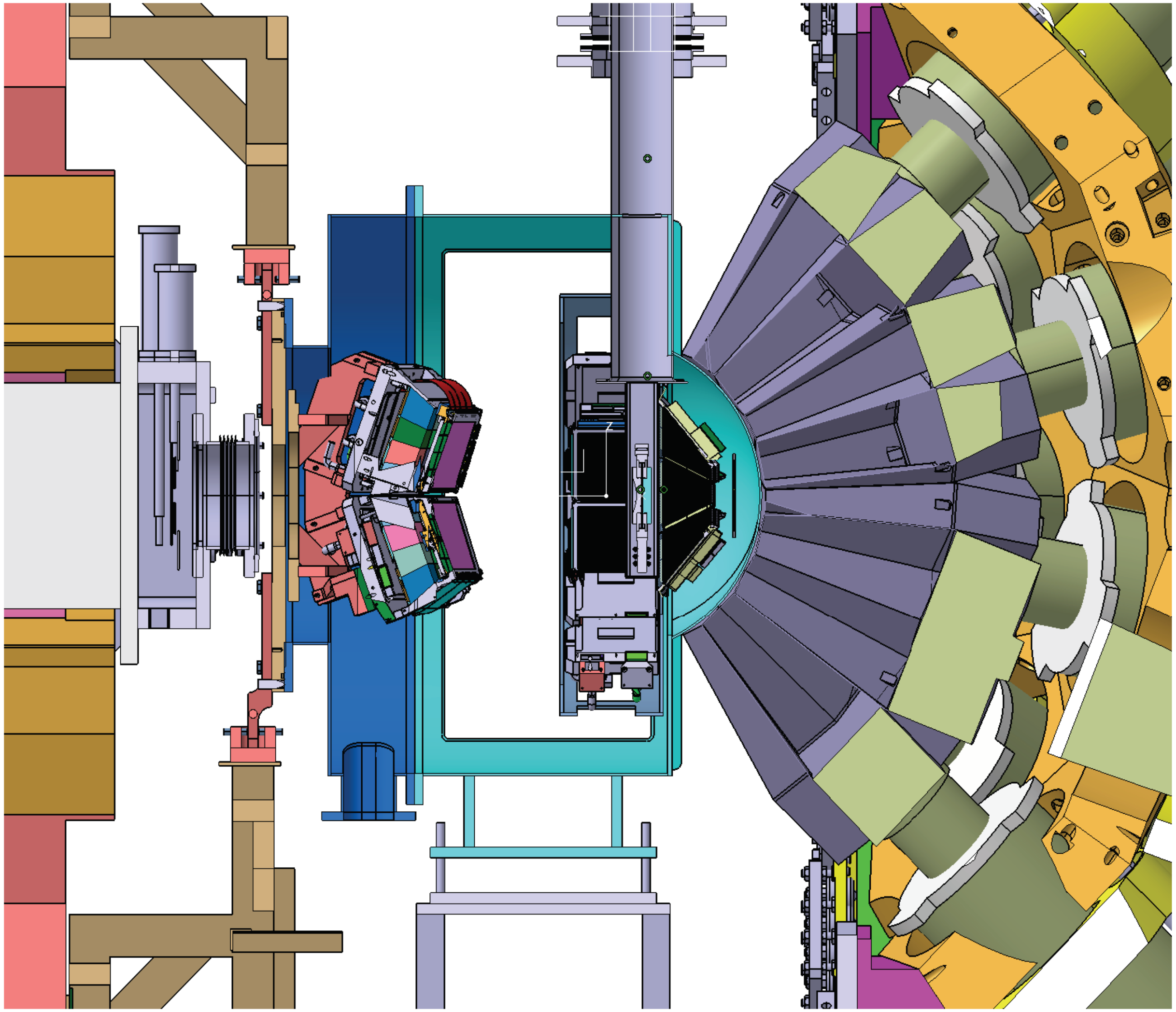
How sensitive are calculated SF to proton wave function in ^{46}Ar ?



Experimental setup

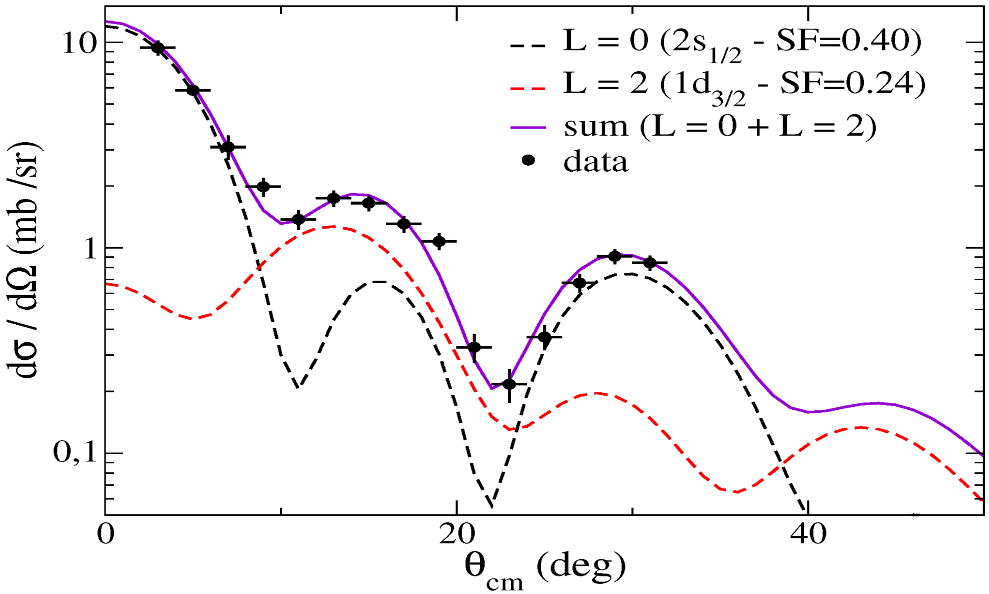
Setup

- ^{46}Ar beam: $2 \cdot 10^4$ pps @10 MeV/u (SPIRAL 1)
- Cryogenic ^{3}He target: 3 mm-thick, T=8 K, P=1 atm MUGAST for deuterons detection
- AGATA for γ-ray spectroscopy
- VAMOS for helping in identification and spectra cleaning



Calculations of cross section with DWBA theory

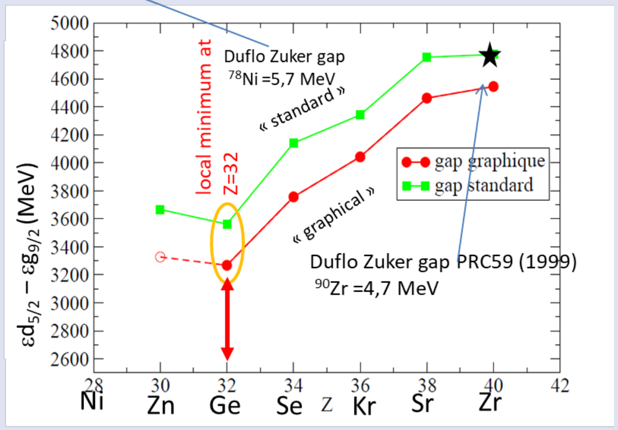
State in ^{46}Ar	Cross sections (mb)	Normalized SF	Deuterons/ week	Deuterons-γ/ week
$1/2^+$	2.5	0.4	1100	-
$3/2^+$	2.7	0.2	640	70

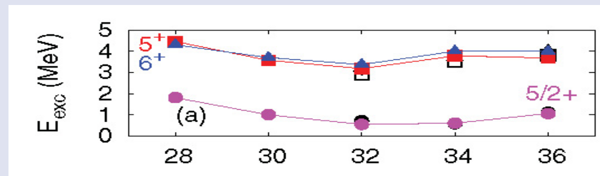


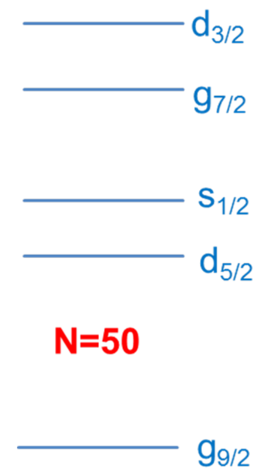
Fit on simulated curves: statistical errors < 10% on measured cross sections

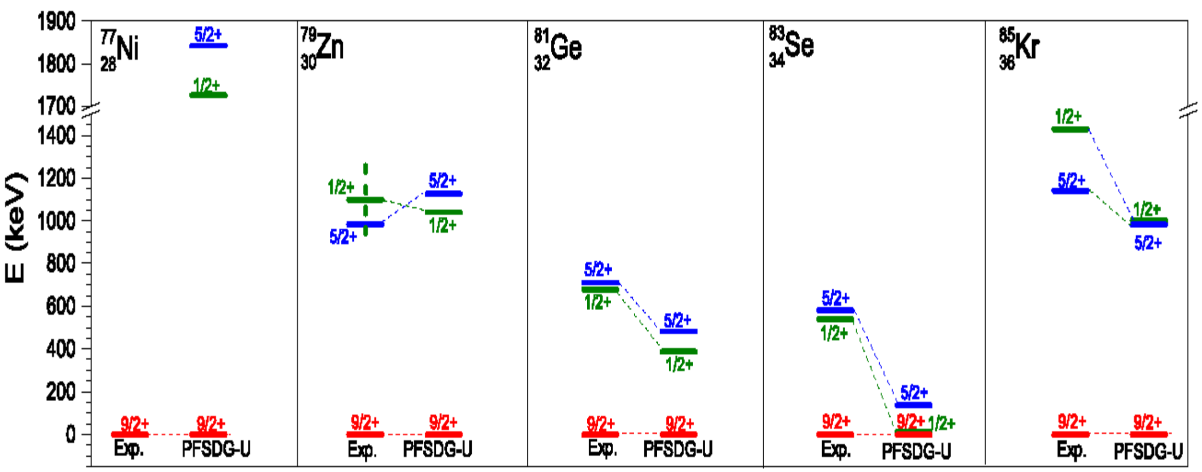
Physics around N=50 (I)

N=50 gap has a parabolic behaviour

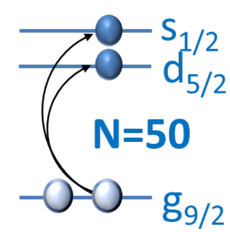








C. Wraith et al., Physics Letters B 771 (2017) 385–391



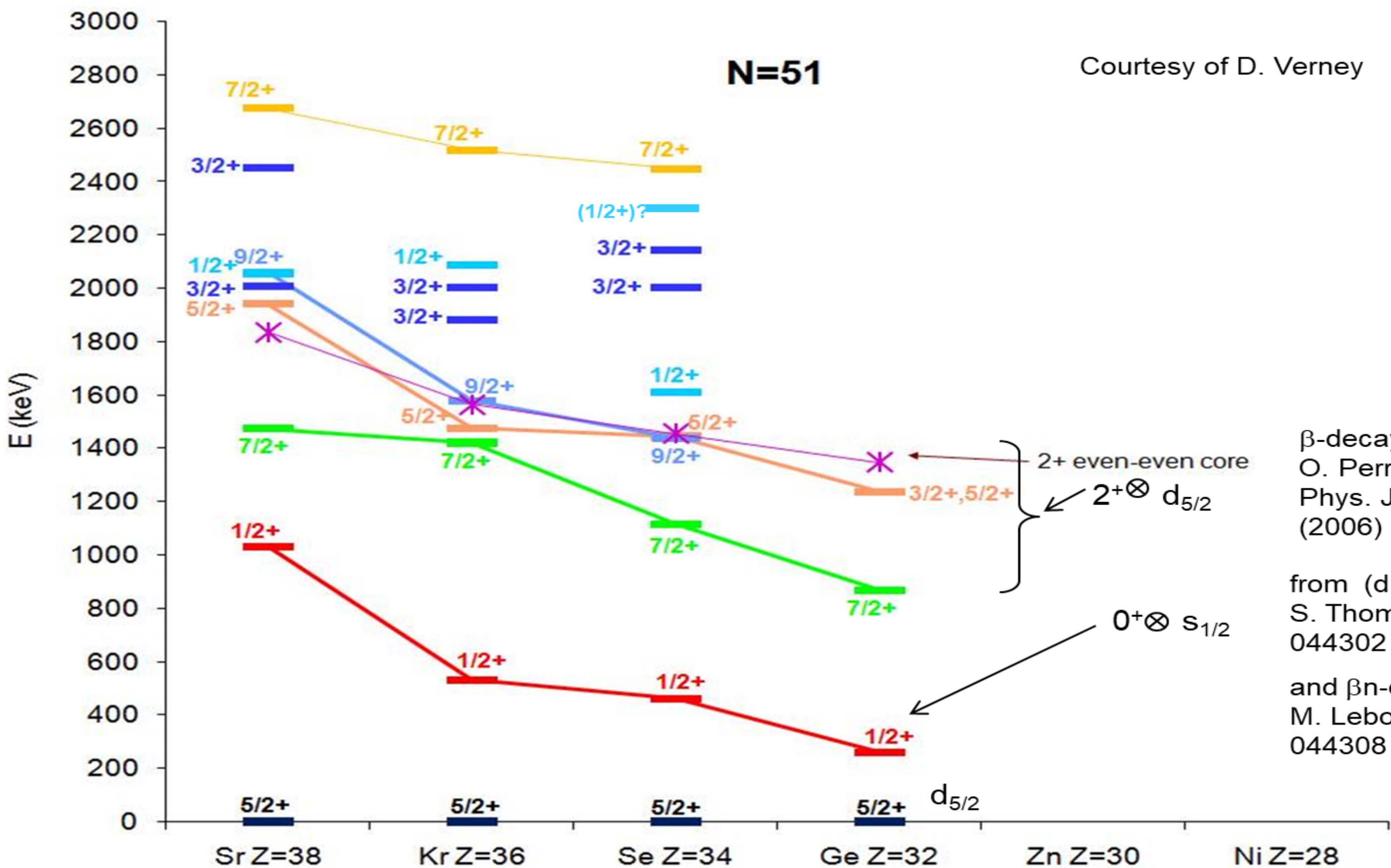
Intruder states (1p-2h) in N=49 states:

- Minimum at Z=34
- Inversion $1/2^+$ - $5/2^+$
- Pure $s_{1/2}$ wave function ?

Physics around N=50 (II)

Rapid decreasing of $s_{1/2}$ ESPE: continuum coupling ?

$g_{7/2}$ behaviour: tensor force effects ?

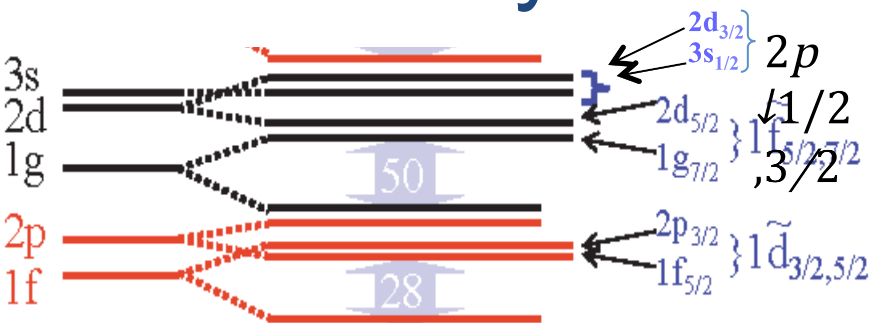


β-decay at Orsay O. Perru et al. Eur. Phys. J. A 28, 307 (2006)

from (d,p) Oak Ridge : J. S. Thomas et al. PRC **76**, 044302 (2007)

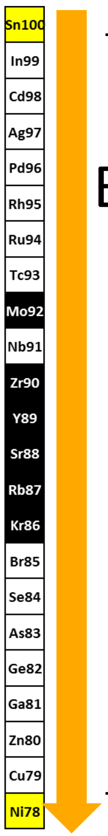
and βn-decay at Orsay : M. Lebois PRC **80**, 044308 (2009)

Physics around N=50 (III)



C. Delafosse et al., PRL 121,192502 (2018)

$\Delta_{PSO} = (\varepsilon_{j<} - \varepsilon_{j>})/[\hbar\omega(2l+1)]$



Binding Σ_n ↘

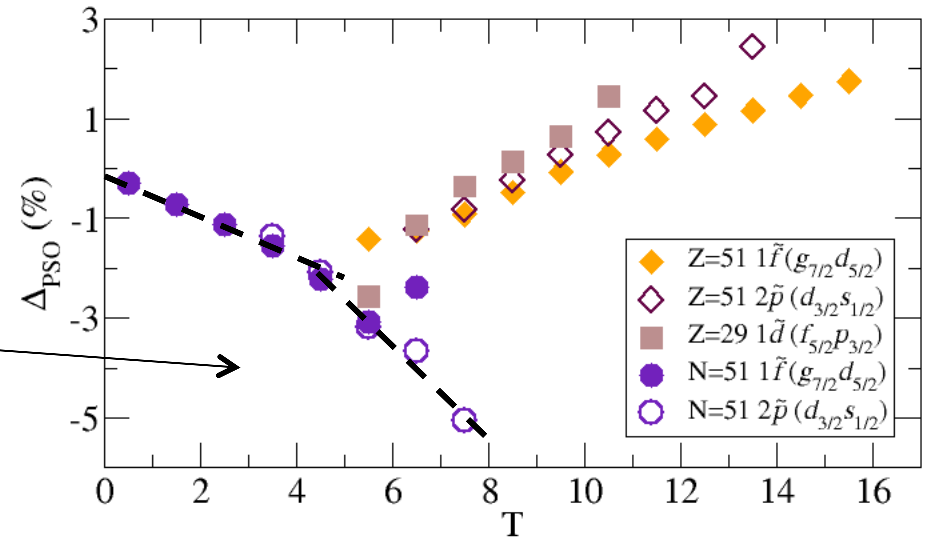
R ↘

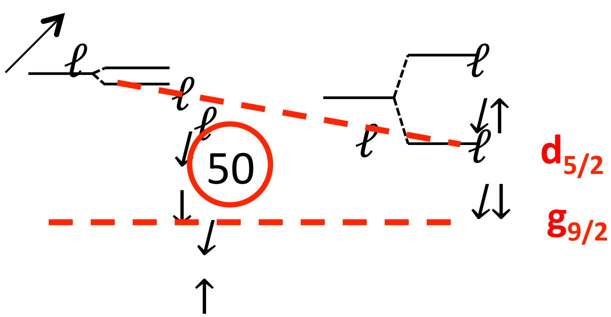
neutron diffusivity ↗

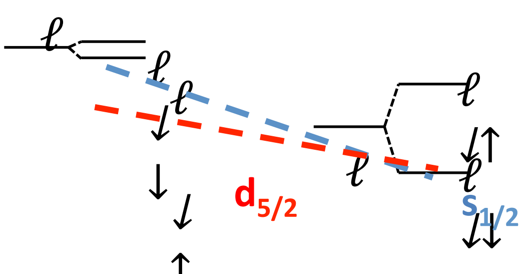
ρ meson interaction, in neutron rich nuclei :
- repulsive for the neutrons
- attractive for the protons

$$V = V_\omega + V_\rho = V_\omega \pm \frac{g_\rho}{2}\rho_0$$

neutron skin formation ?





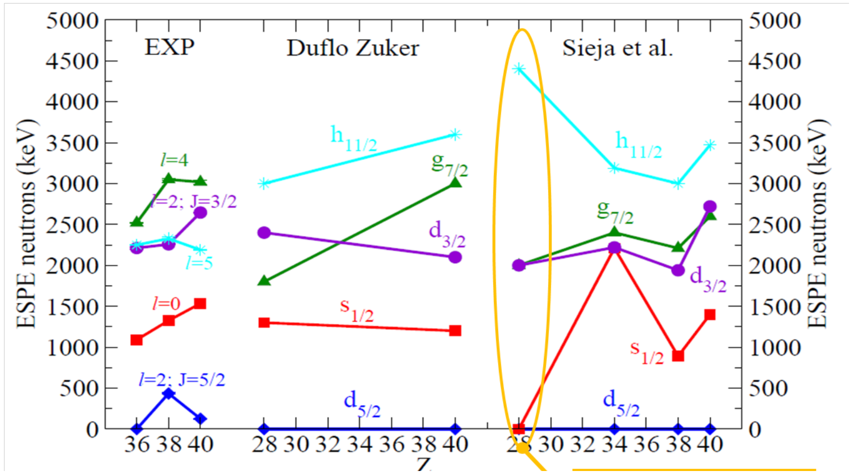


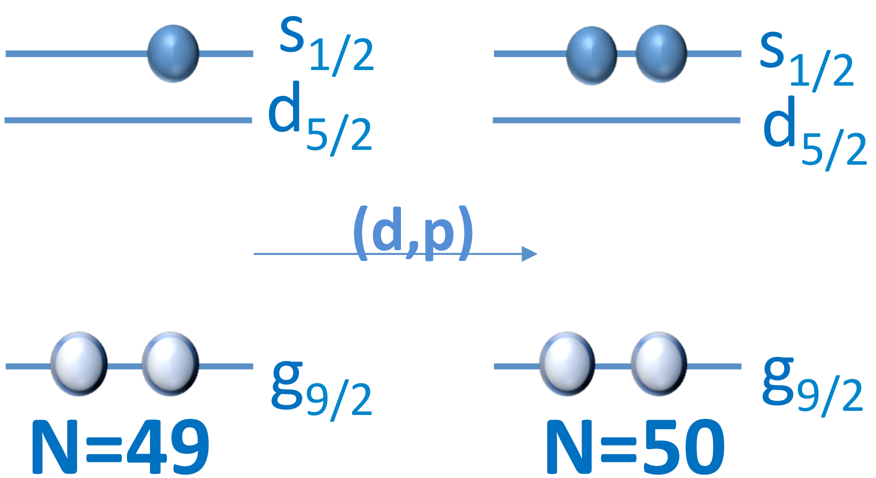
Possible measurements around N=50

(d,p), (α,^{3}He) for N=51

Transfer to N=51,49 isotones

- (d,p), (p,d) for $d_{5/2}$, $s_{1/2}$, $d_{3/2}$, $g_{7/2}$
- (α,^{3}He) for $g_{7/2}$, $h_{11/2}$
- ^{86}Kr, ^{84}Se, ^{82}Ge feasible for example at SPES
- ^{80}Zn at the limit (10^3 pps): no γ-ray spectroscopy ?

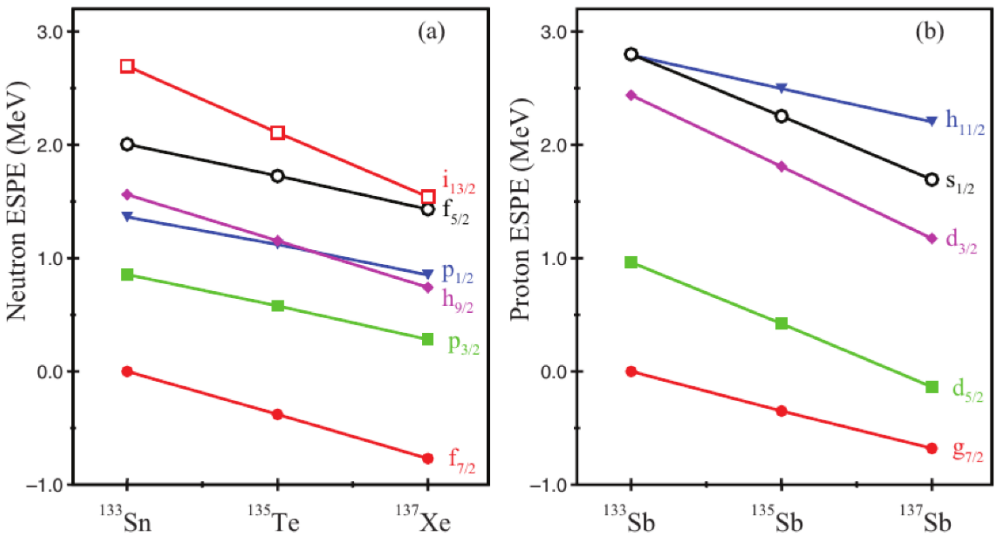




Shape coexistence

- (d,p) transfer on the isomeric 1/2$^+$ state in ^{81}Ge, ^{79}Zn beams for $s_{1/2}$ state
- (t,p) 2n transfer on ^{80}Ge, ^{78}Zn beams
- Population of intruder 0$^+$ states in N=50 ^{82}Ge, ^{80}Zn
- SF can provide information on intruder states structure

Physics around N=82



Phys.Rev.C 87 (2013) 034309

(d,p), (α,^{3}He) for N=82 shell

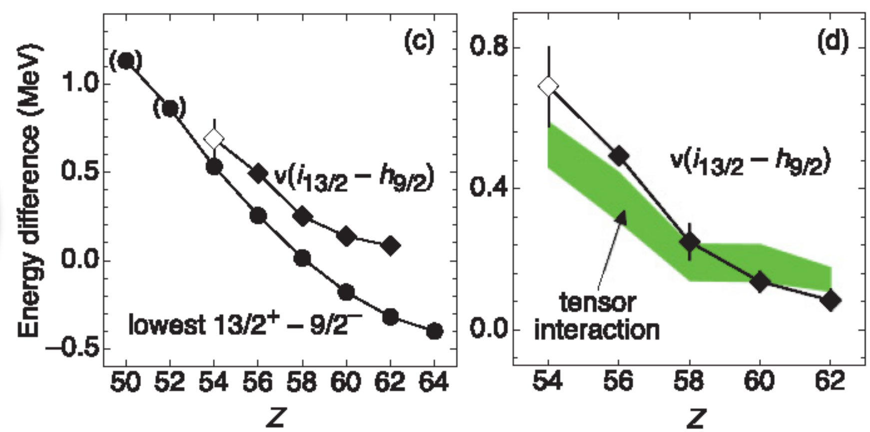
Transfer to N=83 isotones

- (d,p) : ^{133}Sn, ^{134}Sn, ^{133}Sb, ^{131}In
- (d,t) : ^{131}Sn, ^{134}Sn, ^{131}In
- (d,^{3}He) : ^{131}Sn, ^{133}Sn, ^{131}In
- (t,p) : ^{136}Sn (di-neutron cluster)

Mengoni, Goasduff, LoI for SPES

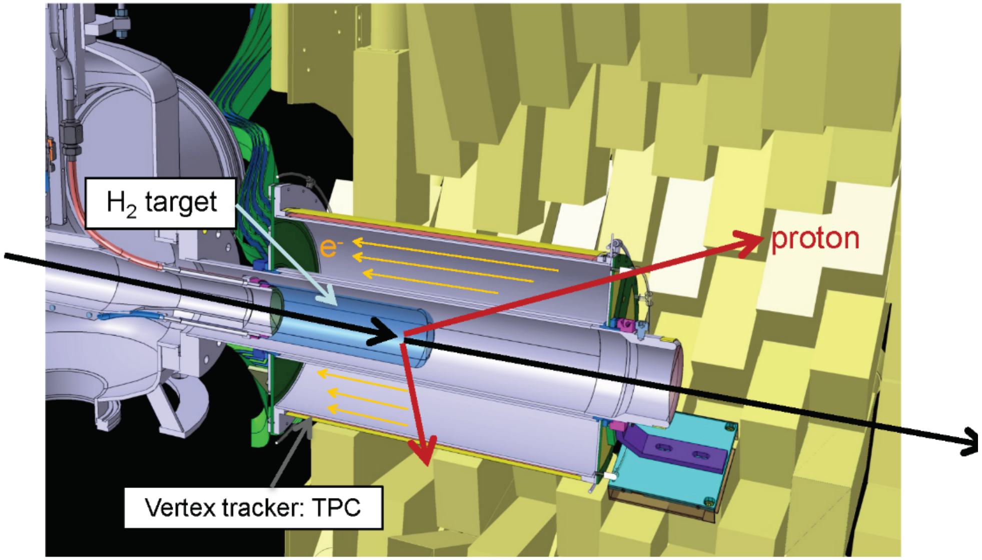
-Evolution of ESPE above N=82 closure

-Pairing interaction in very exotic isotopes (^{134}Sn has the lowest pairing)

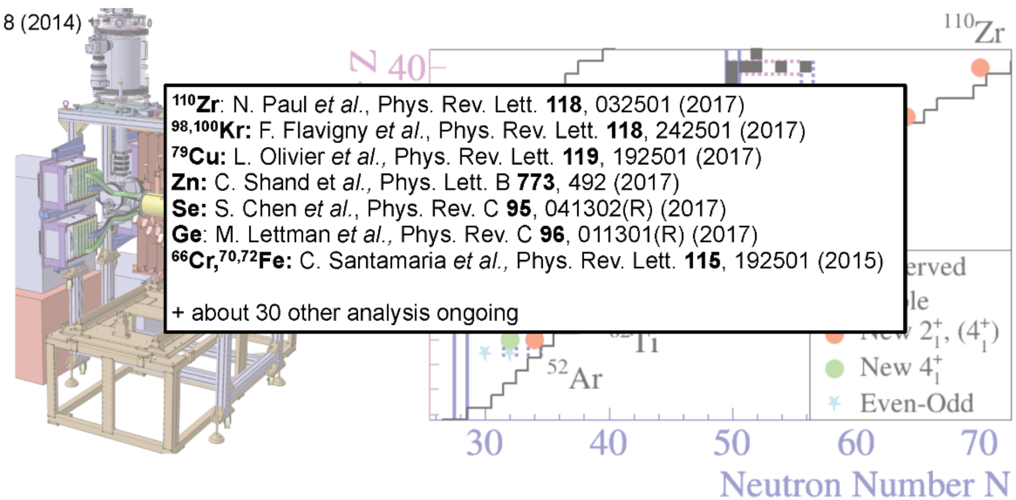


Phys.Rev.C 84 024325 (2011)

MINOS target @ RIKEN



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

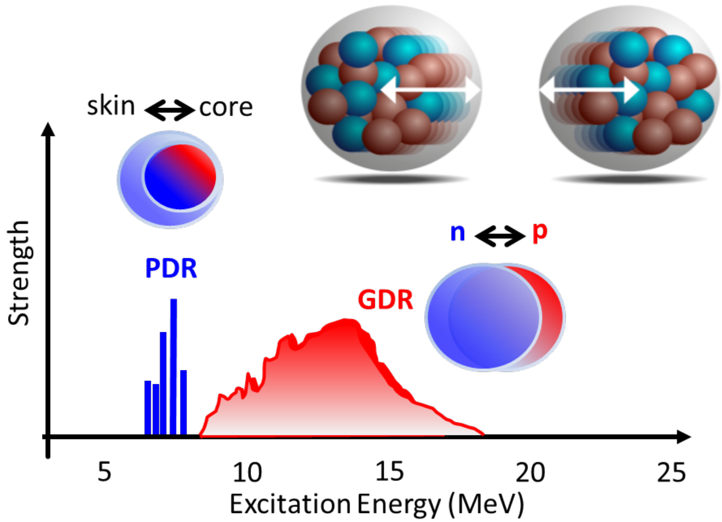


^{110}**Zr**: N. Paul *et al.*, Phys. Rev. Lett. **118**, 032501 (2017)
^{98,100}**Kr:** F. Flavigny *et al.*, Phys. Rev. Lett. **118**, 242501 (2017)
^{79}**Cu:** L. Olivier *et al.*, Phys. Rev. Lett. **119**, 192501 (2017)
Zn: C. Shand et *al.*, Phys. Lett. B **773**, 492 (2017)
Se: S. Chen *et al.*, Phys. Rev. C **95**, 041302(R) (2017)
Ge: M. Lettman *et al.*, Phys. Rev. C **96**, 011301(R) (2017)
^{66}**Cr,**^{70,72}**Fe:** C. Santamaria *et al.*, Phys. Rev. Lett. **115**, 192501 (2015)

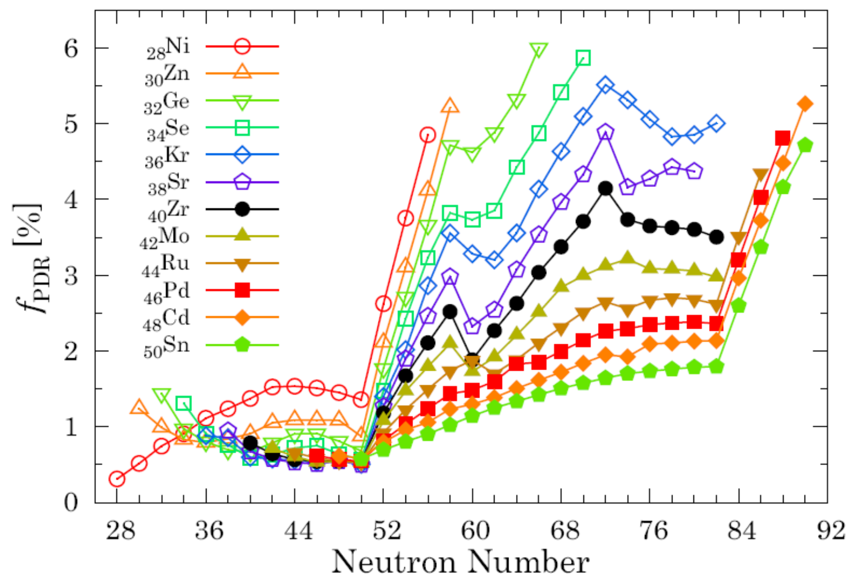
+ about 30 other analysis ongoing

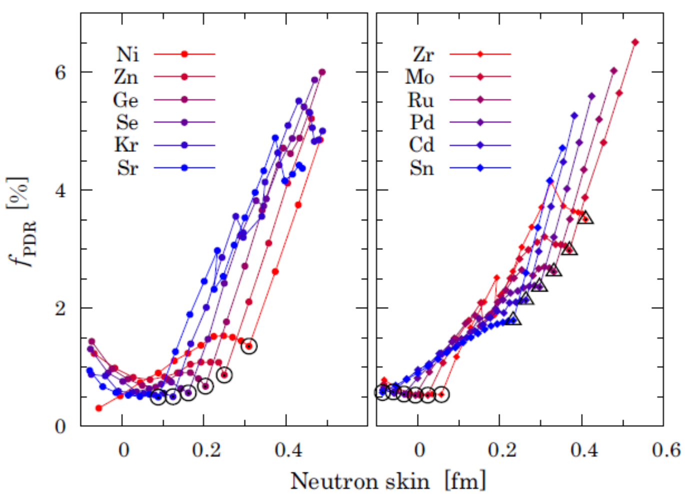
SEASTAR spokespersons: P. Doornenbal (RIKEN), A. Obertelli

Pygmy Dipole Resonance in the N=50, 82 region



Strong increase of PDR after N=50 in Ge, Zn, Ni linked to an increased skin thickness





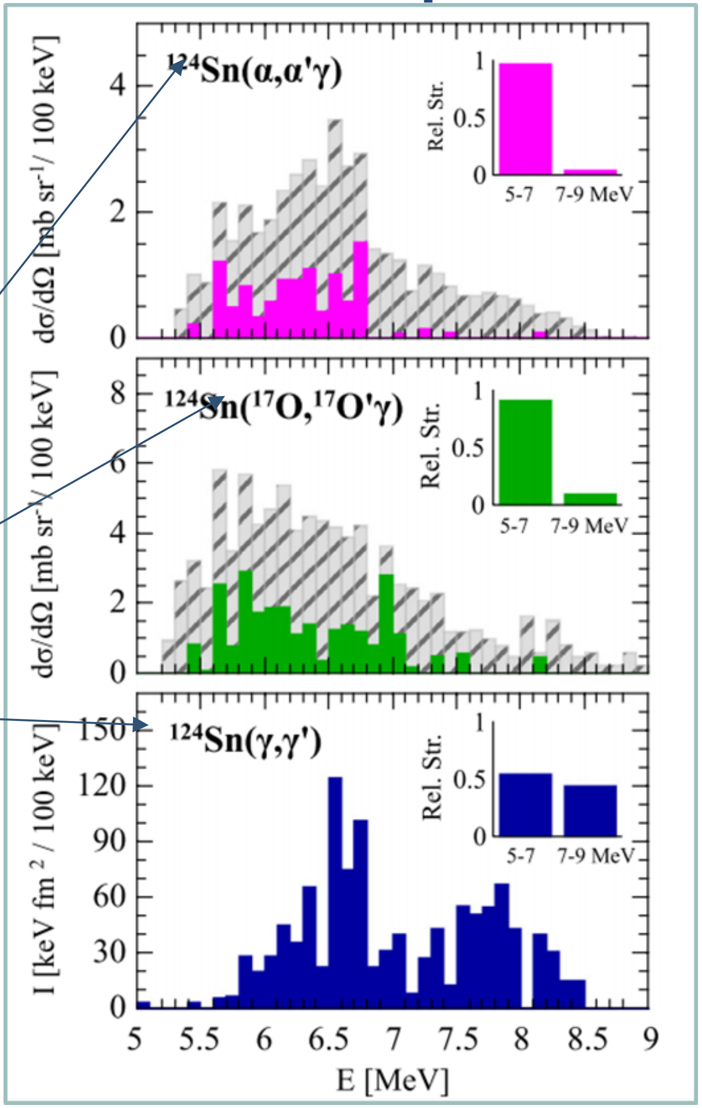
S. Ebata, T. Nakatsukasa, T. Inakura, Phys. Rev. C 90 (2013) 024303.

Pygmy Dipole Resonance : different probes

Different energy ranges

- low energy part: isoscalar character (neutron-skin oscillationsγ spectroscopy for angular distribution: firm multipole assigmenent
- high-energy states: isovector nature (transition towards the GDR)

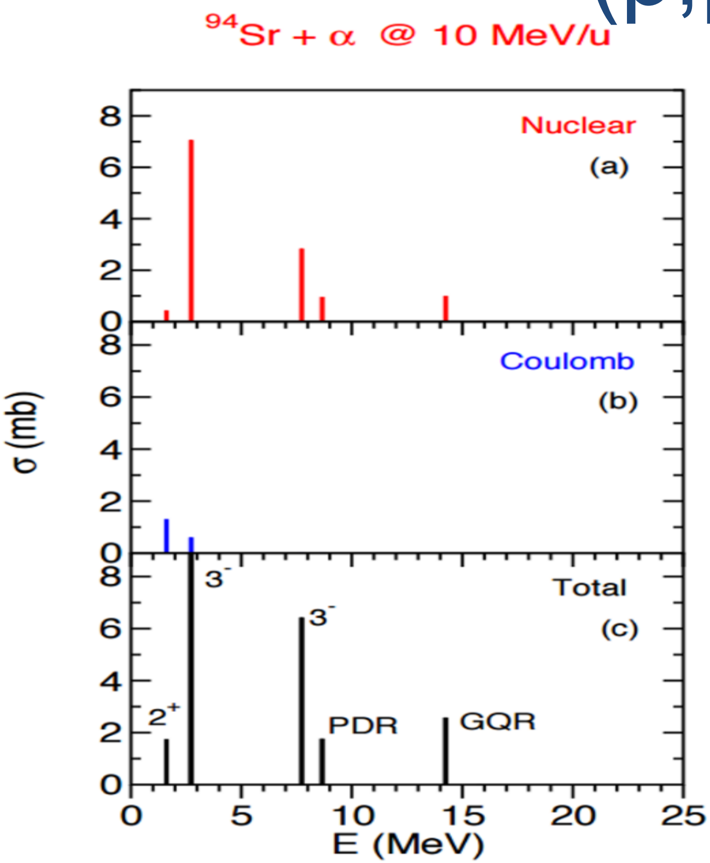
IMPORTANCE of experimental investigation with different (complementary) probes!

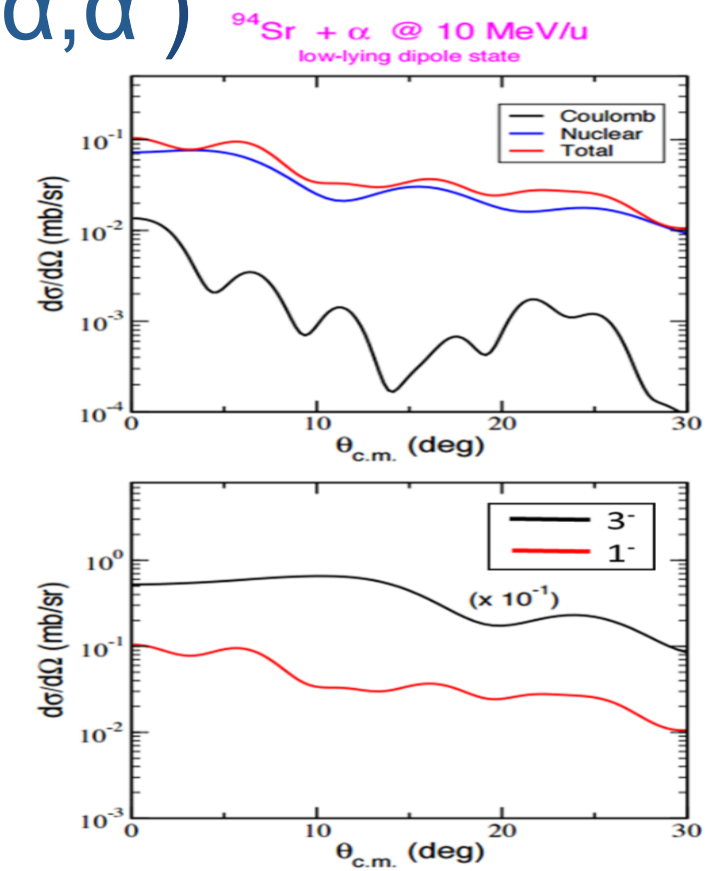


Phys. Lett. B 738, 519 (2014)

Courtesy of F.C.L. Crespi

(p,p'), (α,α')





Calculations based on semiclassical model, together with a **microscopic description of the internal structure** of the nuclei within the HF+RPA formalism

DWBA angular distributions for the system ^{94}Sr +α at 10 MeV/u incident energy calculated for the two low lying states 1− and 3− (lower panel) close in energy

FCL Crespi, E. Lanza, D. Mengoni, LoI for SPES

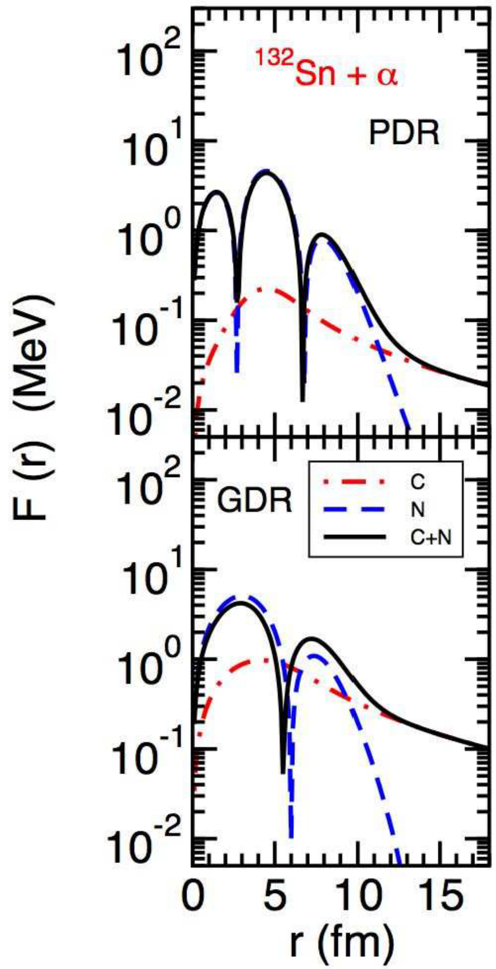
Adavantages of cryotargets for PDR

Gamma and particle spectroscopy

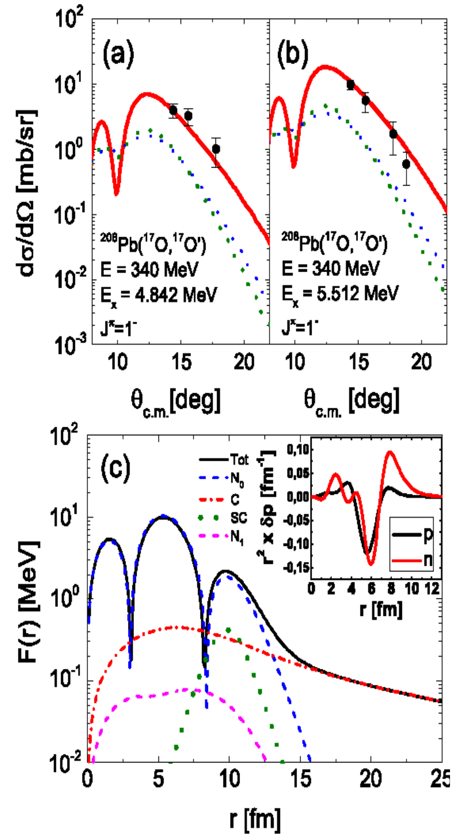
- Different probes (p,p’), (α,α’)
- γ-ray spectroscopy for angular distribution: firm multipole assignement
- Particle spectroscopy: form factors

ACTAR

- Possibility of multipole particle decomposition for unbound states ?



A .Vitturi, E. Lanza: Pramana, January 2010

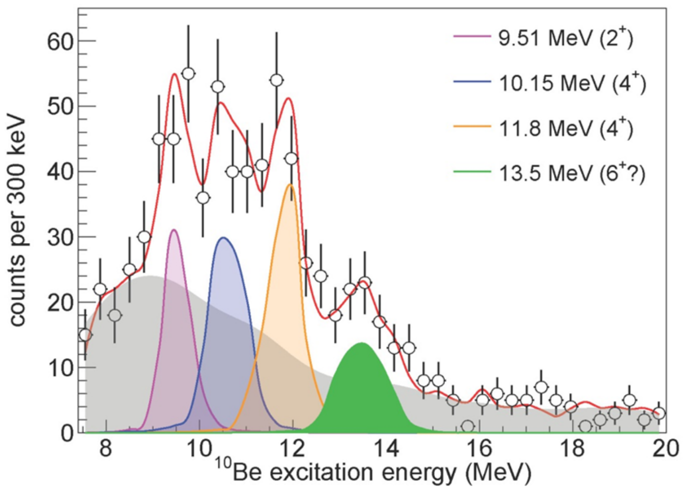


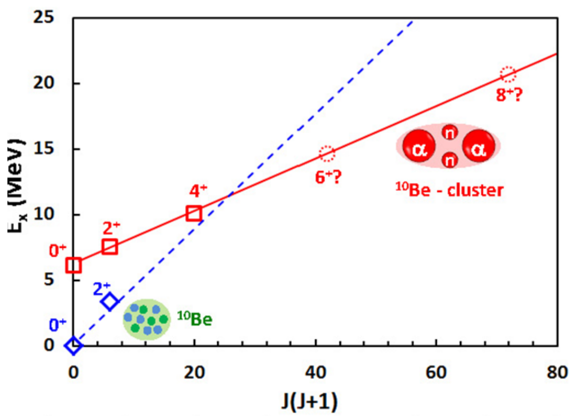
Phys. Rev. Lett. 113, 012501 (2014)

Clustering studies

Cluster states studied with cryogenic α targets

- Molecular states predicted at high excitation energies
- Cluster states in light nuclei, like ^{10}B, can be studied by (α,α') scattering
- Coincidence between the ^{4}He recoiling particle and the $^{4}He+^{6}He$ cluster break-up fragments
- Invariant mass reconstruction in the 8-16 MeV excitation energy





I. Lombardo, LoI for SPES

Conclusions

- One, two-nucleon transfer to populate single-particle and more collective (ex: intruder) states.
- Cryogenic targets necessary to combine good thickness, gamma spectroscopy, light-particle spectroscopy and heavy-ion mass spectroscopy
- Physics case mainly around shell closures to investigate shell structure in exotic regions
- New opportunities to study the PDR in neutron-rich nuclei with different probes, overcoming typical experimental uncertainties
- Other phenomena like clustering are possible to be studied in light nuclei
- Nuclear astrophysics

Table 1. Gain in the number of scattering centers $N_{\mathrm{at/cm^2}}$ between H_2 and CH_2 targets for a given energy straggling σ_{E}, and the resulting angular straggling σ_{Θ}. Calculations were done with the LISE code [12].

		Thickness (μm)	σ_{E} (keV/u)	$N_{\mathrm{at/cm^2}} 10^{20}$	σ_{Θ} (mrad)
^{1}H 1 MeV	H_2	50	8.9	2.2	13.9
	CH_2	9.26	8.9	0.7	24.9
^{1}H 5 MeV	H_2	50	7.5	2.2	2.4
	CH_2	9.359	7.5	0.7	4.4
^{3}He 3 MeV	H_2	50	6.2	2.2	9.9
	CH_2	9.42	6.2	0.7	17.9