LoI SPES

Spectroscopy studies around ^{78}Ni via transfer reactions at SPES and short term plans.

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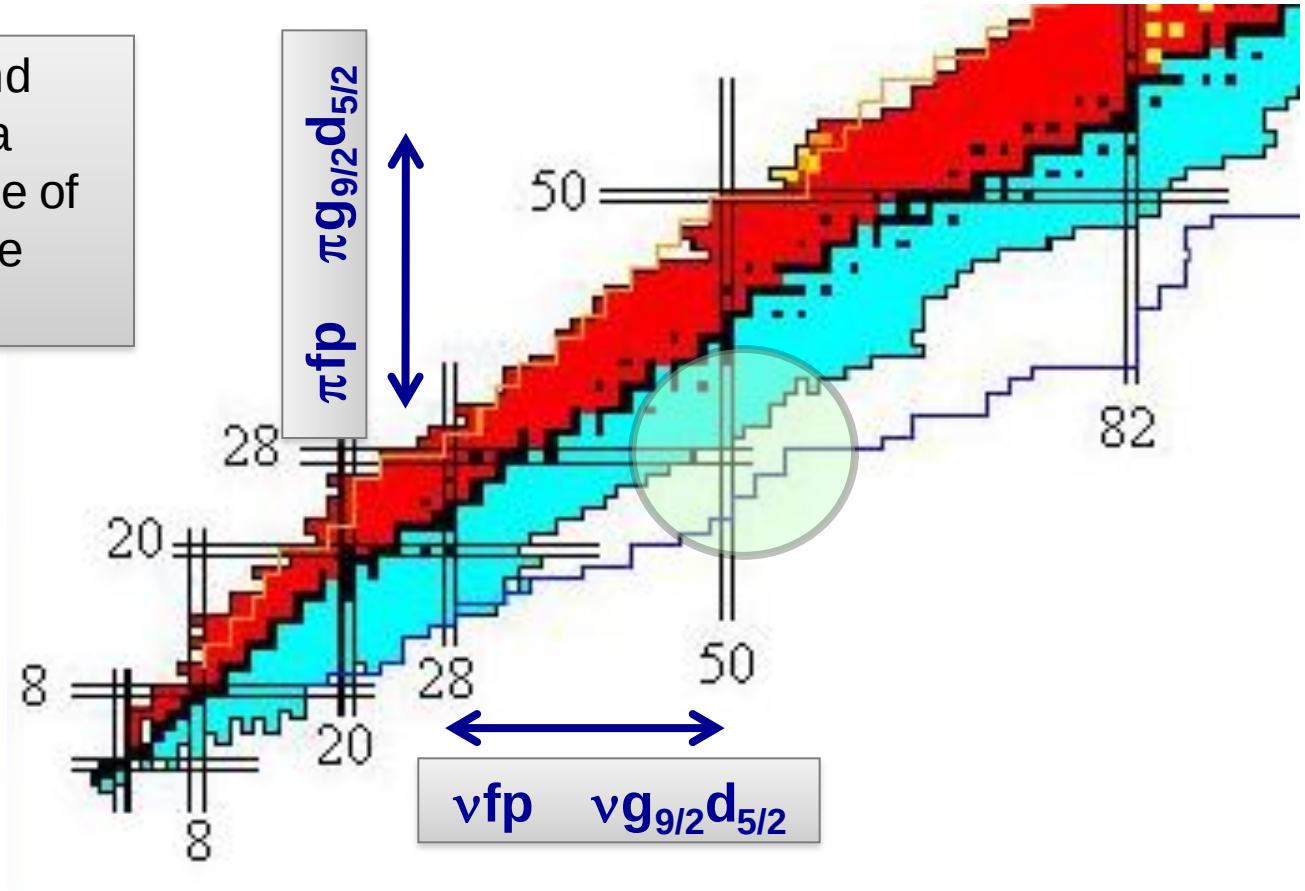
Overview

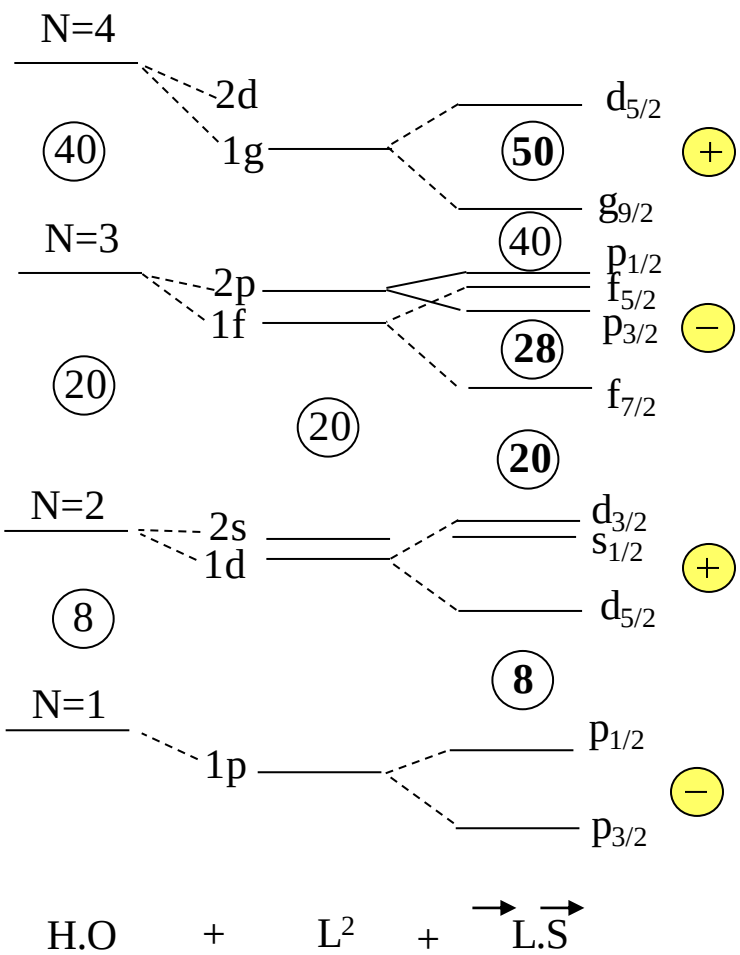
- Study of nuclei in the region of ^{78}Ni
- Physics cases and apparata for SPES
- Short term plans: ^{70}Ni(d,t)^{69}Ni at ISOLDE
- Summary/Remarks
- Possible points to consider in the discussion

Ductu naturae

Magic numbers and their evolution as a direct consequence of the character of the nuclear force.



The “spin-orbit” magic numbers



Reduction of N=50 gap by tensor force $\pi f_{5/2}$-νg
Behaviour of ^{78}Ni ?

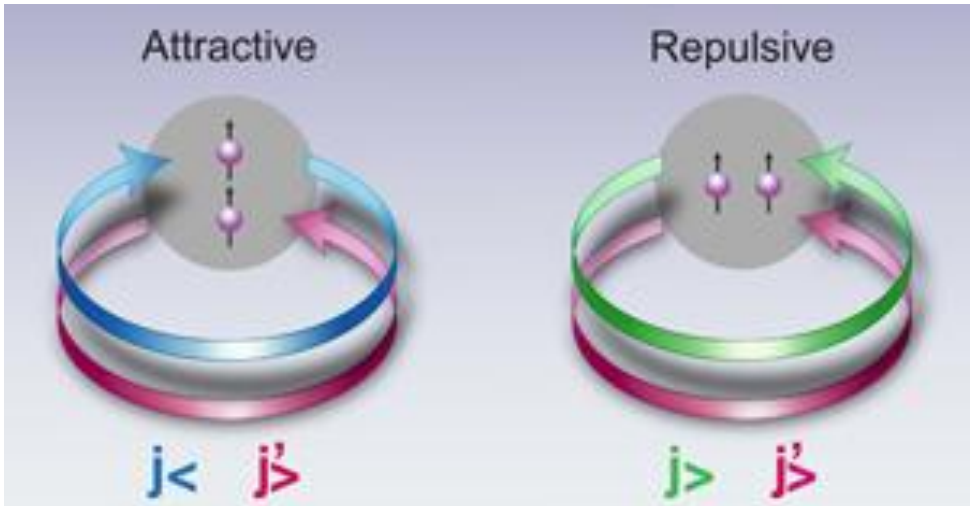
Reduction of N=28 gap by tensor force $\pi d_{3/2}$-νf
strongly deformed ^{42}Si

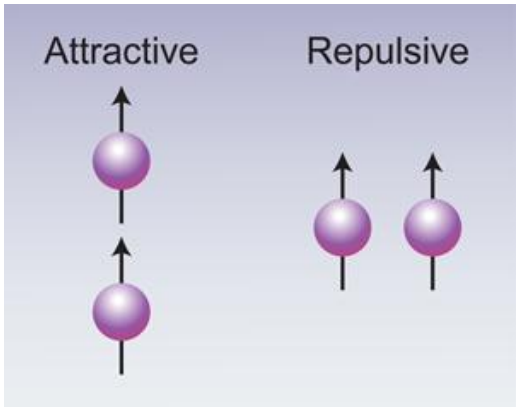
Reduction of N=20 triggered by $\pi d_{5/2}$-$\nu d_{3/2}$
Island of inversion, large collectivity

N=8 collapses at ^{12}Be
Triggered by the $\pi p_{3/2}$-$\nu p_{1/2}$ interaction

Tensor interaction

Systematic variation of effective single-particle energies due to the tensor interaction





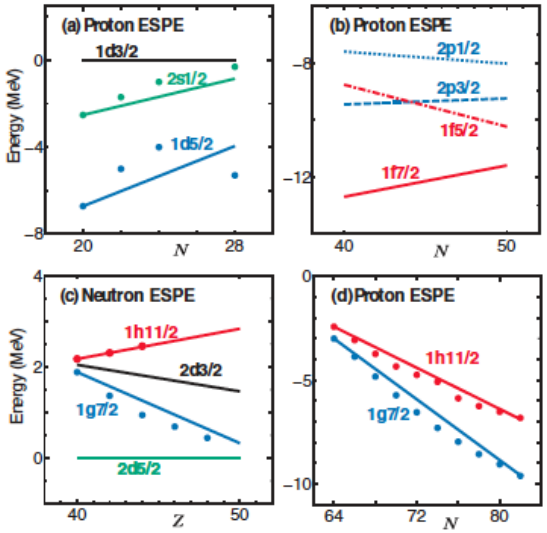
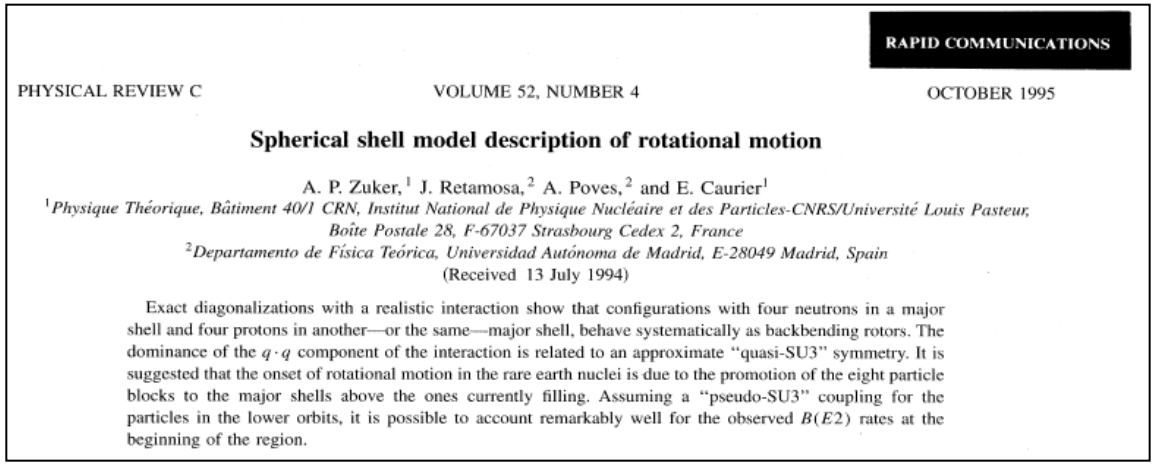


FIG. 4 (color). Proton (neutron) ESPE as a function of N (Z). Lines in (a)–(c) show the change of ESPE's calculated from the $\pi + \rho$ tensor force. Points represent the corresponding experimental data. (a) Proton ESPE's in Ca isotopes relative to $1d_{3/2}$. Points are from [13]. (b) Proton ESPE's in Ni isotopes; calculations only. See [19] for related experimental data. (c) Neutron ESPE's in $N = 51$ isotones relative to $2d_{5/2}$; points are from [21]. (d) Proton ESPE's in Sb isotopes; points are from [18]. Lines include a common shift of ESPE as well as the tensor effect (see the text).

$$\mathbf{V_T = (\tau_1 \tau_2)\,(\,[\sigma_1 \sigma_2]^{(2)}\,Y^{(2)}(\Omega)\,)\,Z(r)}$$

T. Otsuka et al. PRL 95, 232502 (2005)

Building up collectivity



RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 52, NUMBER 4 OCTOBER 1995

Spherical shell model description of rotational motion

A. P. Zuker,[1] J. Retamosa,[2] A. Poves,[2] and E. Caurier[1]
[1]*Physique Théorique, Bâtiment 40/1 CRN, Institut National de Physique Nucléaire et des Particles-CNRS/Université Louis Pasteur, Boîte Postale 28, F-67037 Strasbourg Cedex 2, France*
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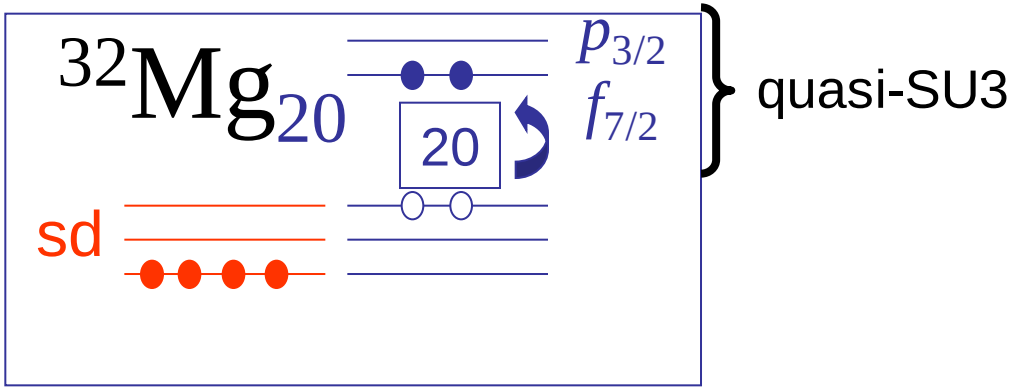
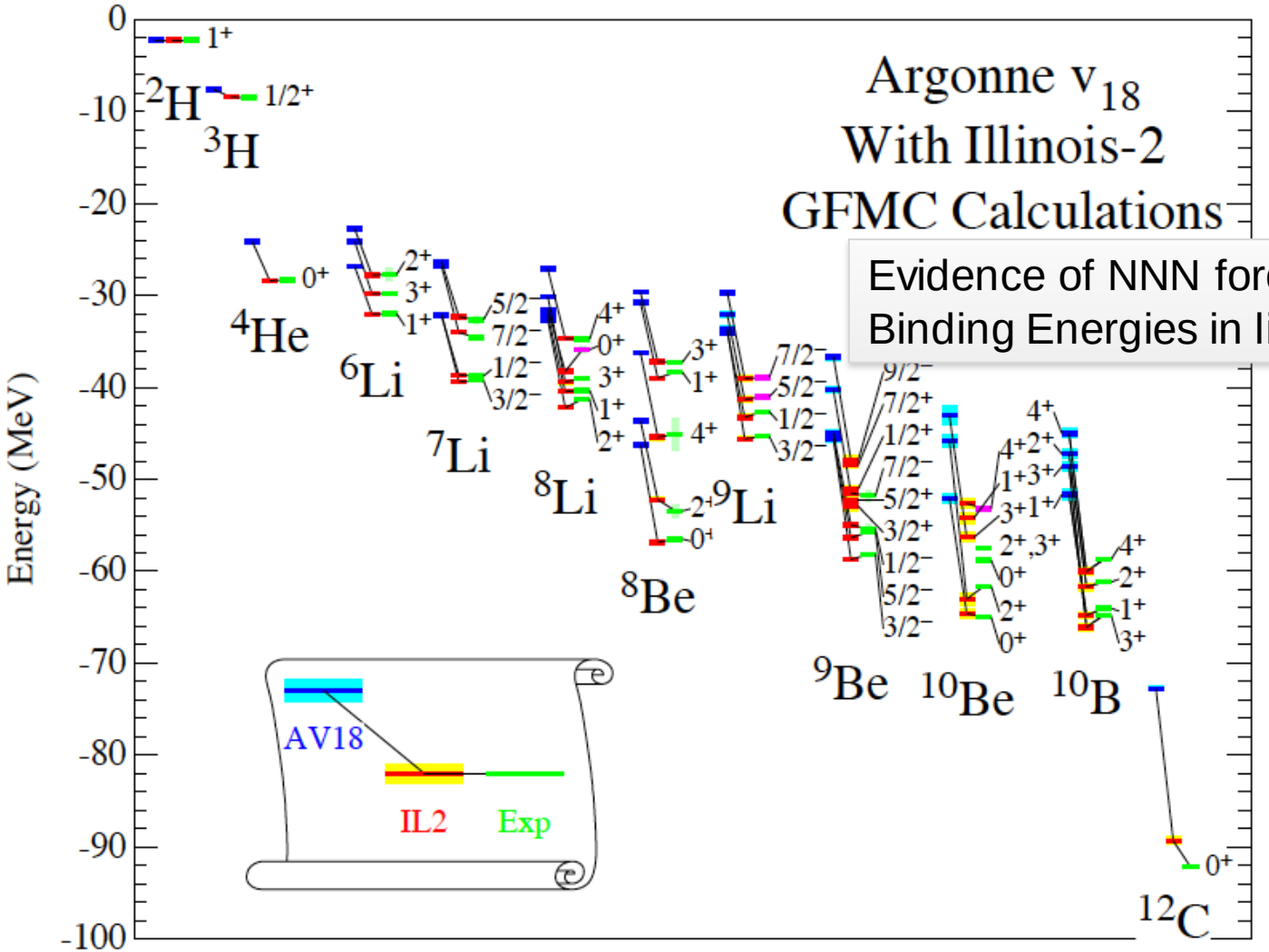
(Received 13 July 1994)

Exact diagonalizations with a realistic interaction show that configurations with four neutrons in a major shell and four protons in another—or the same—major shell, behave systematically as backbending rotors. The dominance of the $q \cdot q$ component of the interaction is related to an approximate "quasi-SU3" symmetry. It is suggested that the onset of rotational motion in the rare earth nuclei is due to the promotion of the eight particle blocks to the major shells above the ones currently filling. Assuming a "pseudo-SU3" coupling for the particles in the lower orbits, it is possible to account remarkably well for the observed $B(E2)$ rates at the beginning of the region.



Quadrupole deformation can be generated by using a quadrupole force with the central field in the subspace spanned by a sequence of $\Delta j = 2$ orbits that come lowest by the spin-orbit splitting representing this relevant subspace a quasi-SU3.

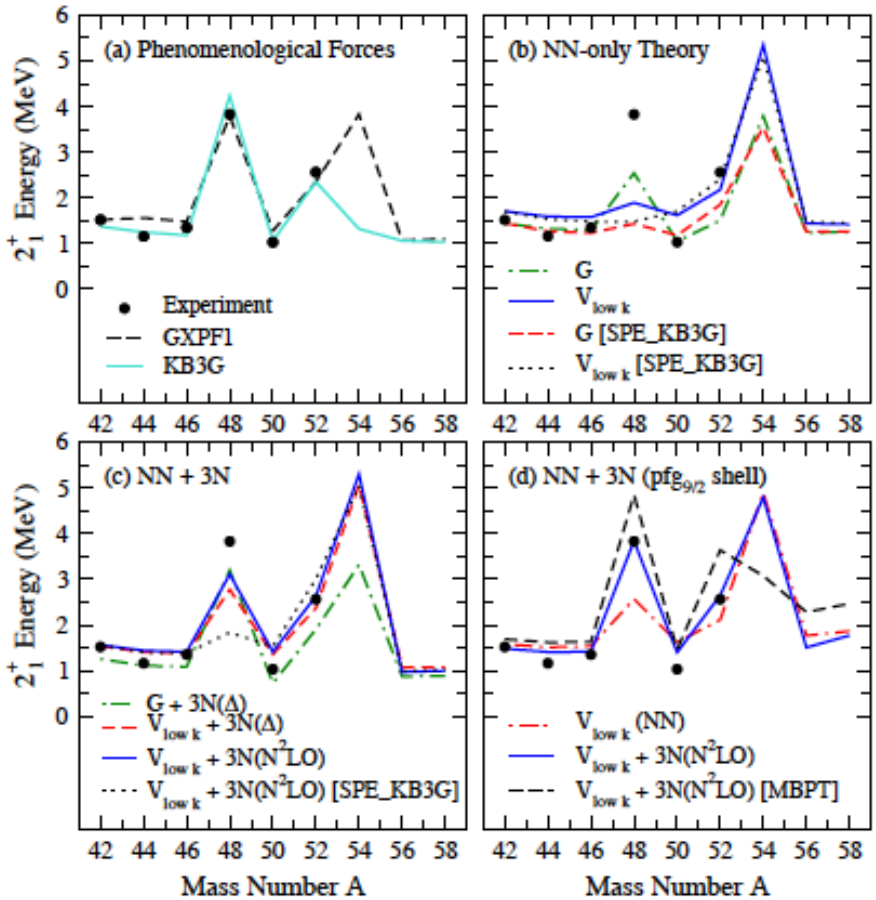
Indication of three body forces NNN



Evidence of NNN forces in the Binding Energies in light nuclei

Courtesy of C. Pipier, Argonne National lab.

NNN in the Ca region



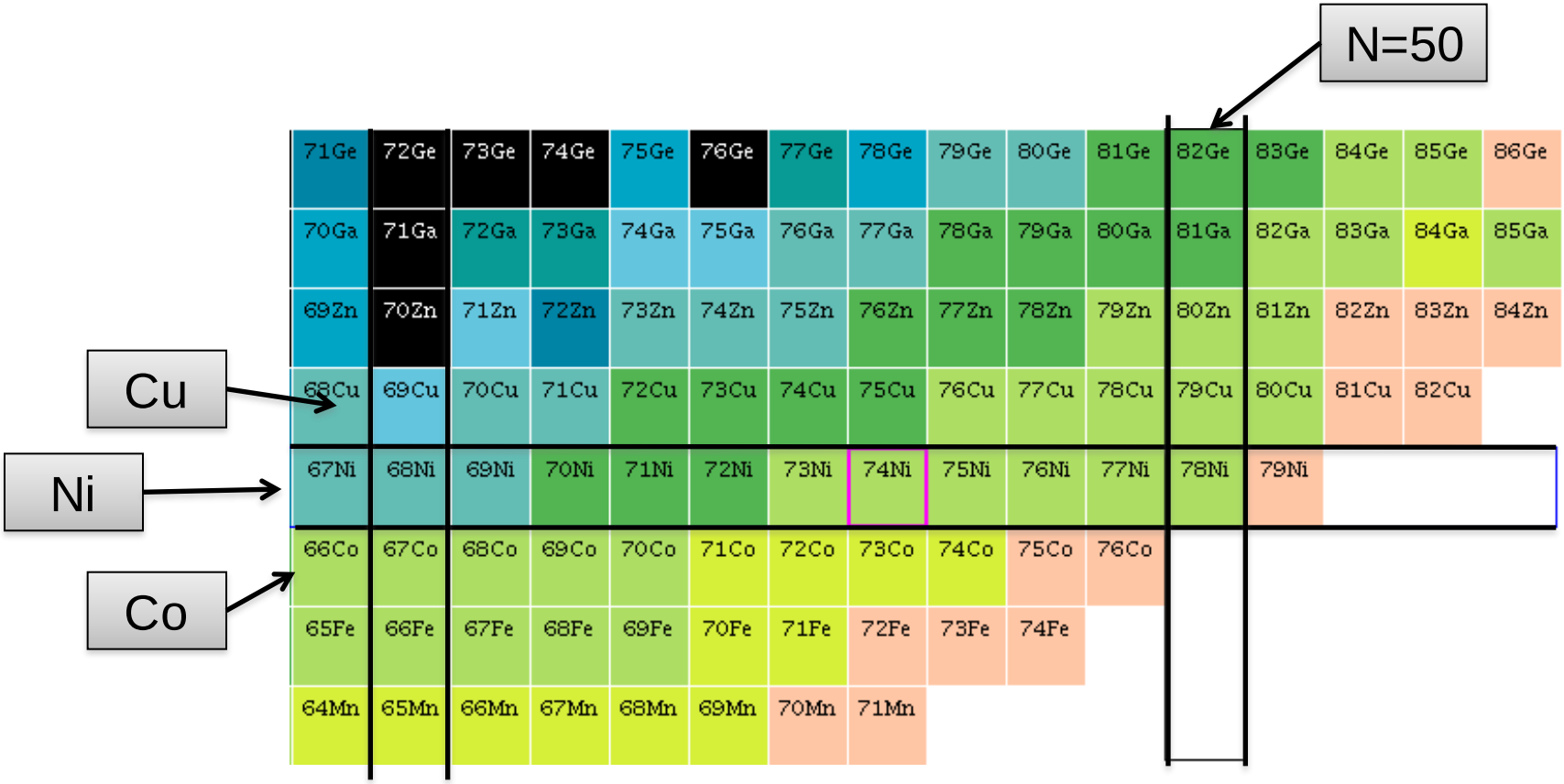
Microscopic calculations with well-established two-nucleon NN, do not reproduce N=28.

However NN and NN+3N forces predict the N=28 shell gap, but with quantitative differences.

The changes due to 3N forces are amplified in neutron-rich nuclei and will play a crucial role for matter at the extremes

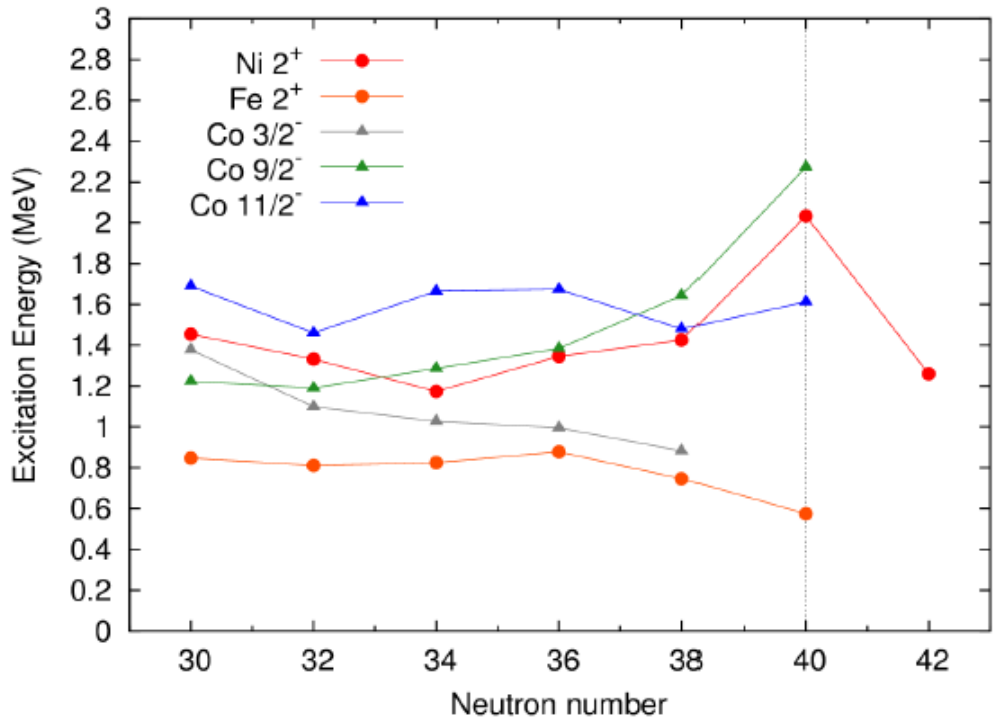
T. Otsuka et al., PRL105, 032501 (2010)
J.D. Holt et al., arXiv:1009.5984v1 (2010)

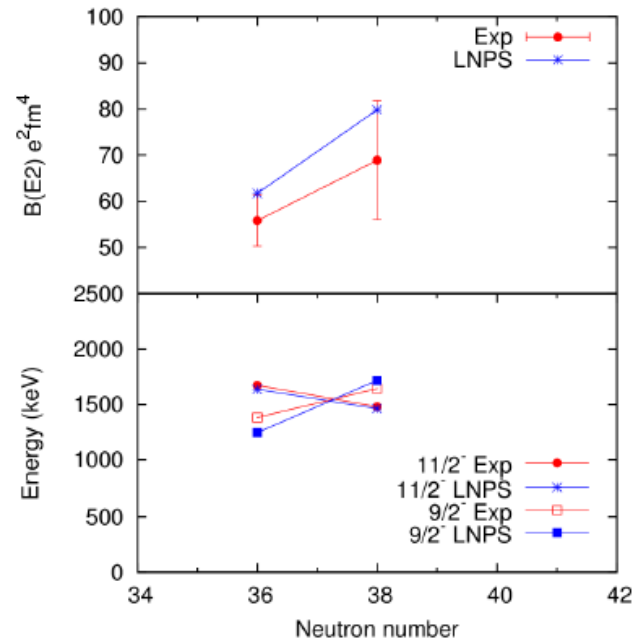
In the following …



Co isotopes, Z=27

Lifetime measurement at AGATA+PRISMA of the neutron-rich Co isotopes, a way to study the evolution of the Ni isotopes.





Co 9/2- and 11/2- states

$\pi f_{7/2}^{-1} \otimes 2^+(\mathrm{Ni})$

Co 3/2- state

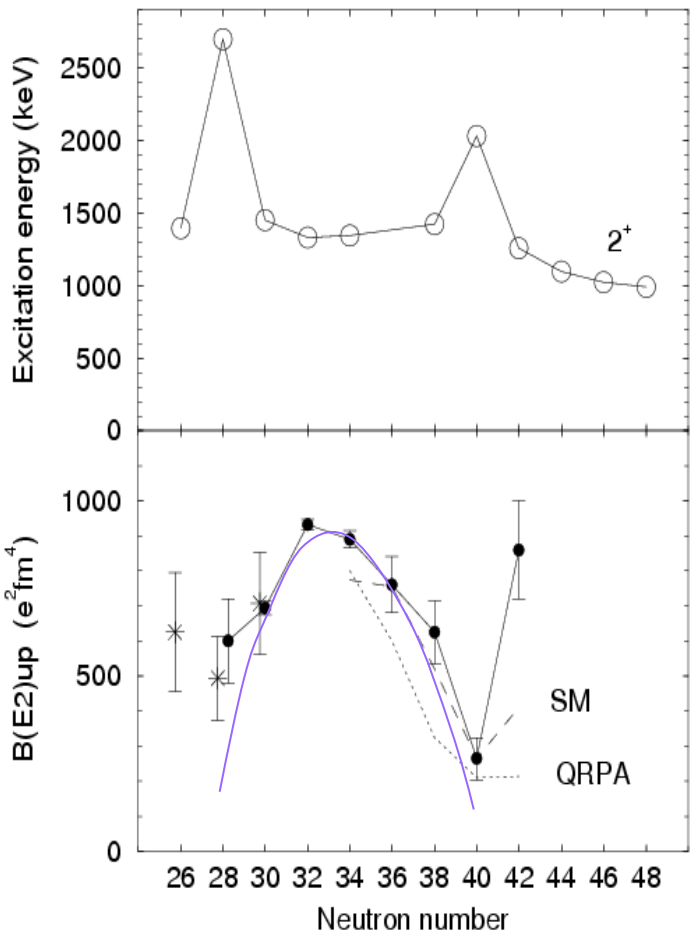
$\pi f_{7/2}^{1} \otimes 2^+(\mathrm{Fe})$

A. Dijon *et al.* PRC83, 064321 (2011)

F. Recchia *et al. to be published*

V. Modamio et al., PRC (to be submitted)

Evolution along Z=28 - ^{78}Ni



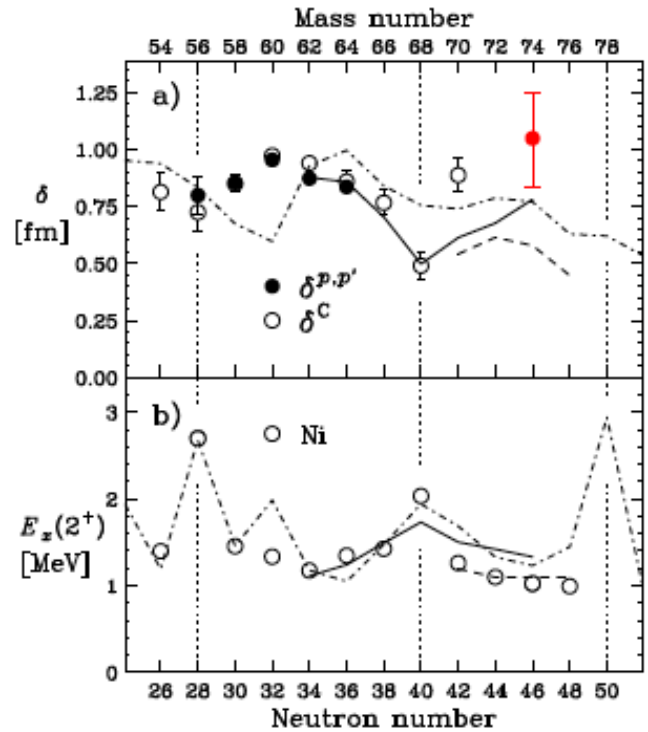


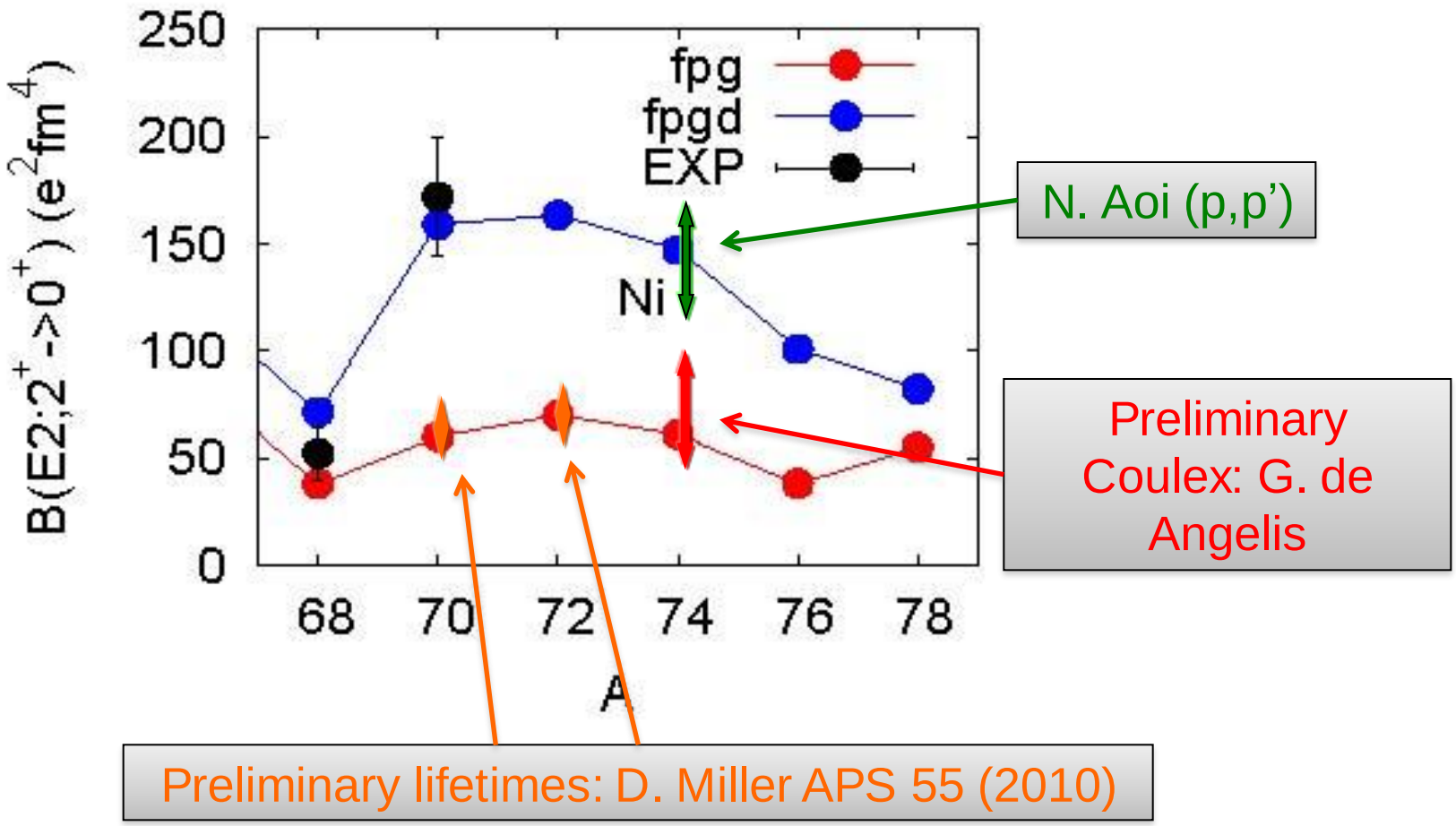
Fig. 4. (a) The δ values for Ni isotopes. The open circles show δ^C obtained from $B(E2)$ values [11,12,16,18]. The filled circles show $\delta^{p,p'}$ obtained from the proton inelastic scattering [13,47]. (b) The $E_x(2^+)$ systematics for Ni isotopes. In both figures the dashed and solid curves show the δ and $E_x(2^+)$ values from the shell-model calculations of Refs. [39] and [11], respectively. The dot-dashed curve shows the results of HFB + QRPA calculations [41].

- Softening of the Z=28 core
- Quasi-SU(3) symmetry involvement of the $d_{5/2}$ orbital to explain the collectivity

O. Sorlin et al. PRL 88 (2002) 092501
O. Perru et al. PRL 96 (2006) 232501
G. Kraus et al. PRL 73 (1994) 1773.

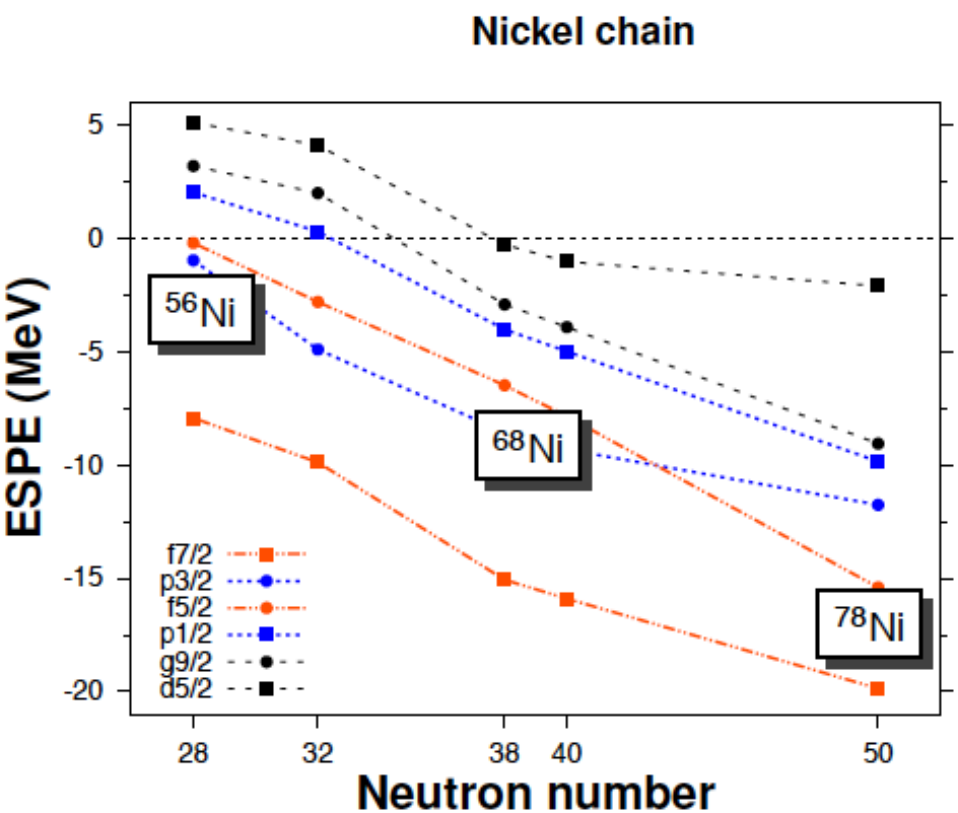
N. Aoi et al., Physics Letters B 692 (2010) 302–306

B(E2) values towards ^{78}Ni



Courtesy of K. Sieja Vietri sul Mare (2010)

ESPE towards ^{78}Ni



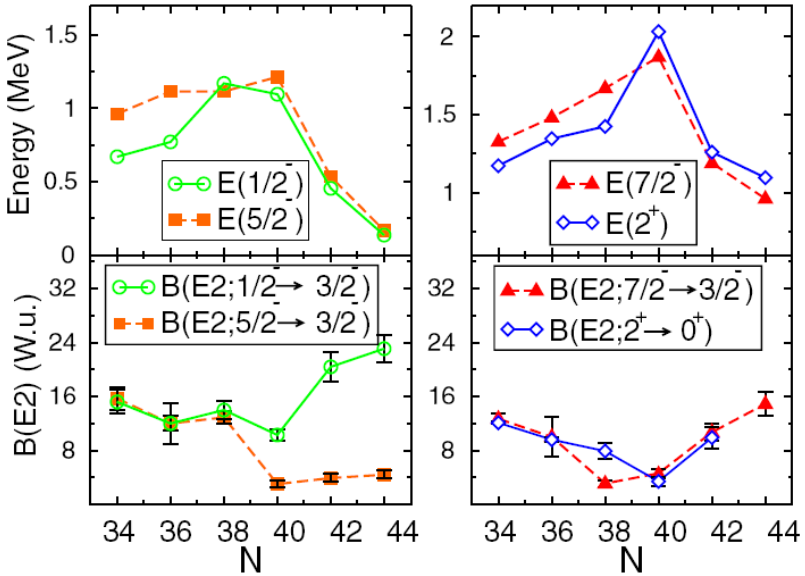
- ^{56}Ni: well doubly-magic, gap 6.5MeV
- ^{68}Ni mixture of magic and superfluid. *O.Sorlin PRL88 092501 (2002)*
- ^{78}Ni is supposes to be doubly-magic with a proton gap 5.0 MeV and neutron 4.6 MeV

The rigidity of the gap in ^{78}Ni is also an important issue in astrophysics because it is a waiting point in the r-process.

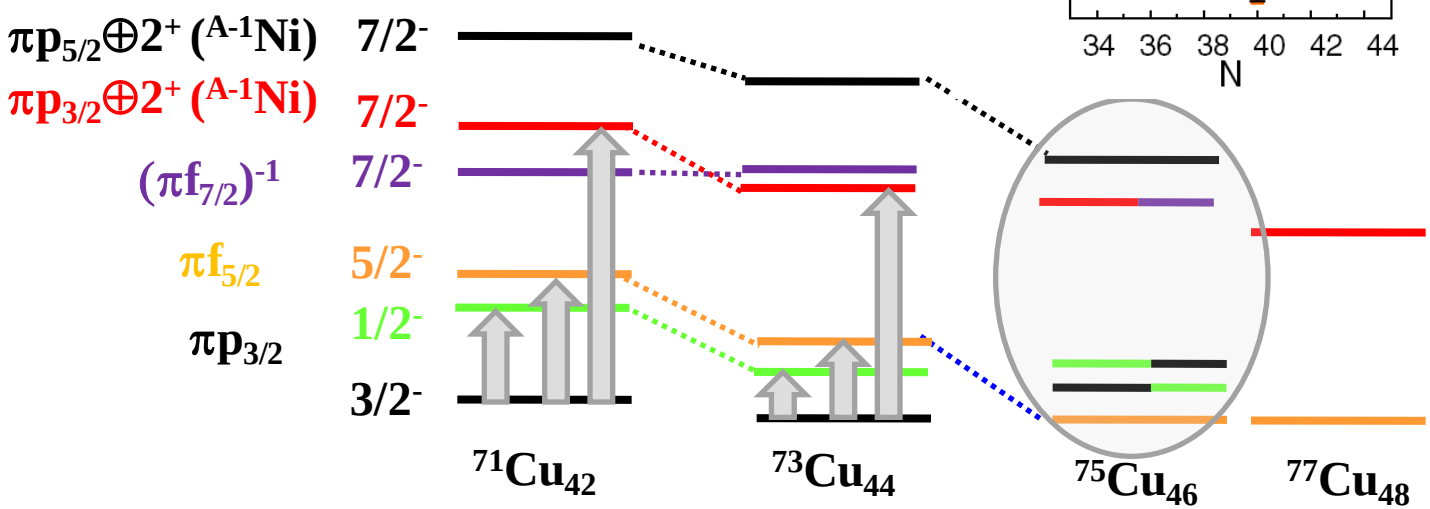
K. Sieja et al., PRC81, 061303 (2010)

Cu isotopes, Z=29

Collectivity of the $7/2_1^-$ state probe the $B(E2:0^+ \rightarrow 2^+)$ in ^{76}Ni



Magnetic moment measurement confirmed the inversion of the $f_{5/2}$ with the $p_{3/2}$ in ^{75}Cu



S. Franchoo et al., PRL 81, 3100(1998), I. Stefanescu *et al.*, PRL 100, 112502 (2008), K. Flanagan PRL, 103, 142501 (2009), J. M. Daugas PRC 81, 034304 (2010)

Along the N=50

Highly precision mass measurements

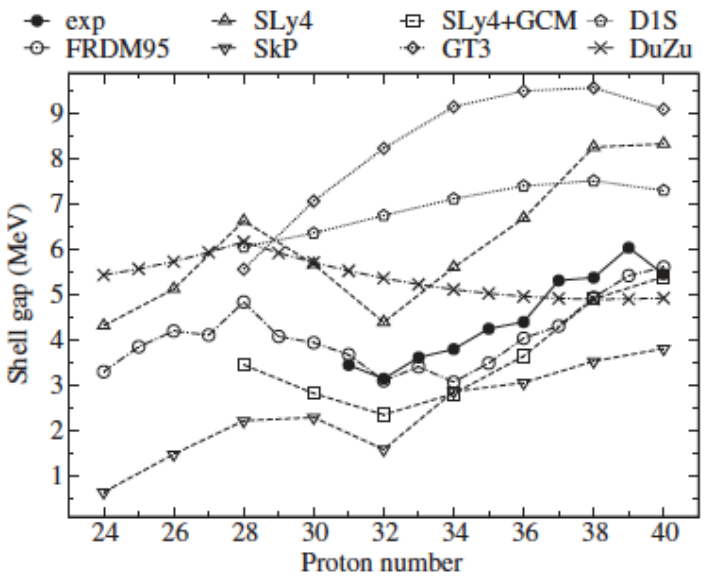


FIG. 4. Evolution of the $N = 50$ shell gap and comparison to theoretical models.

Two neutron shell gap energies

^{80}Zn Coulex

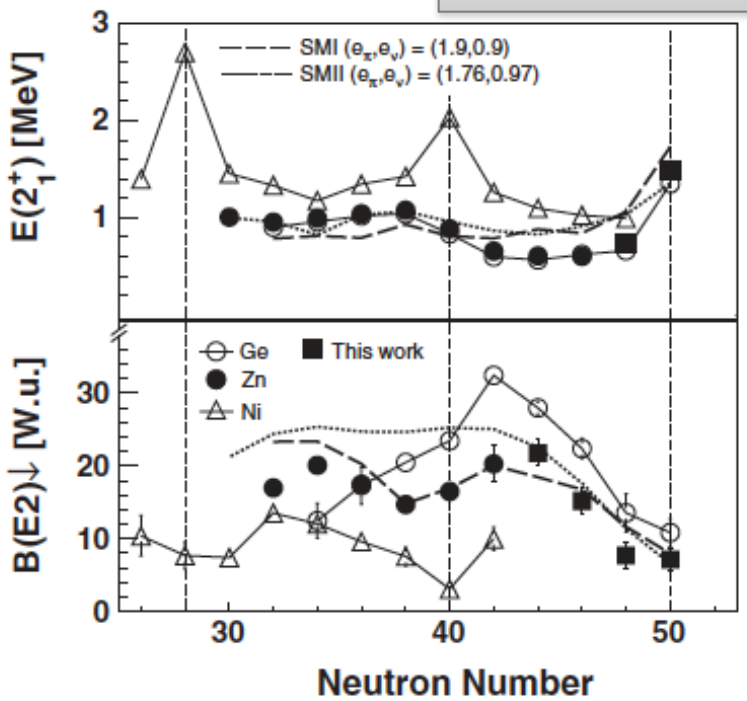
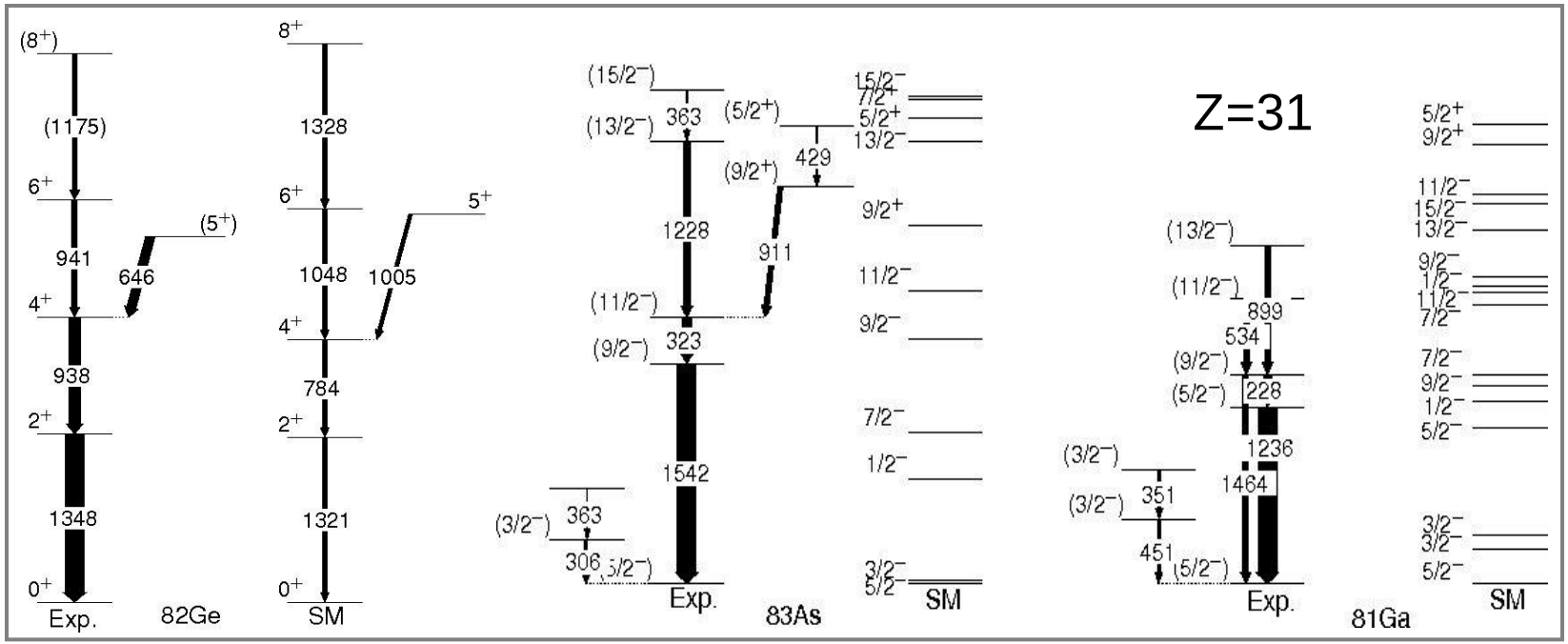


FIG. 2. $E(2_1^+)$ and $B(E2)\downarrow$ systematics for Ni ($Z = 28$), Zn ($Z = 30$), and Ge ($Z = 32$) isotopes. $B(E2)\downarrow$ values were taken from Refs. [6,7,9,10,18,30]. The dashed and dotted lines correspond to SM calculations for Zn isotopes.

J. Hakala et al., PRL101, 052502 (2008)

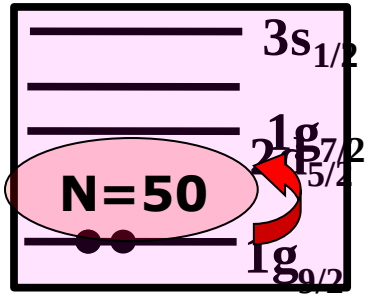
J. Van de Walle et al., PRL99, 142501 (2007)

The N=50 isotones



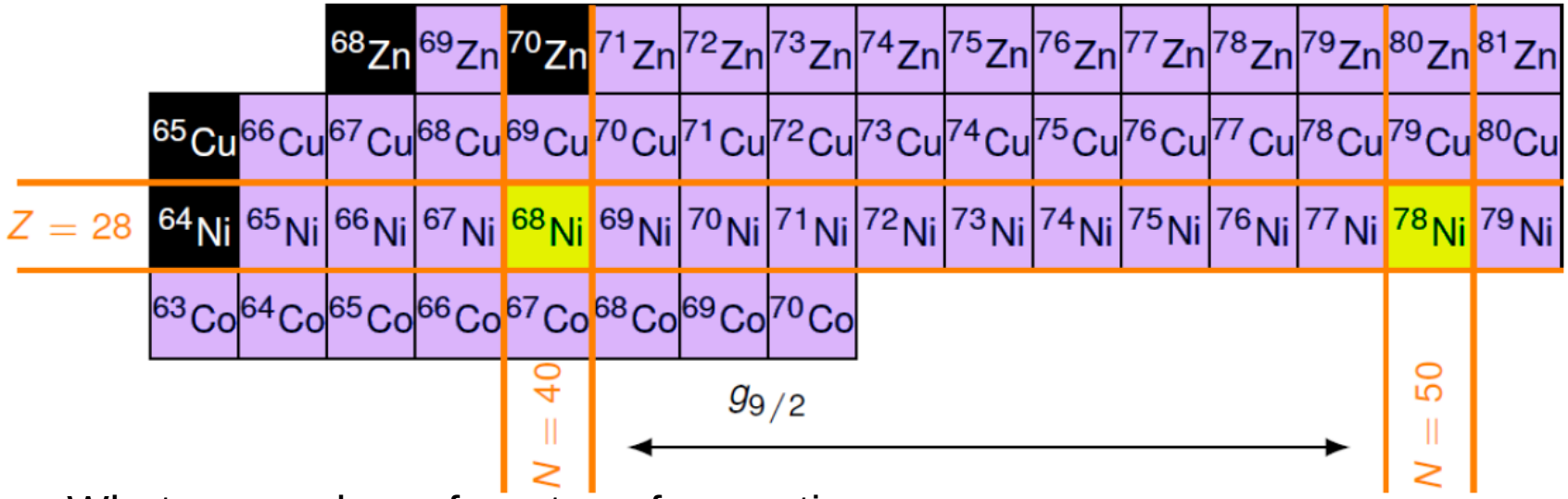
E. Sahin and G. De Angelis PLB (to be published)
Y.H. Zhang PRC70, 024301 (2004)

Shell Model calcuations: 2p-2h excitations across the N=50 shell to $2d_{5/2}$-$1g_{7/2}$-$3s_{1/2}$ (Lisetsky) for **4.7 MeV** of the shell gap value→No reduction of the shell gap



Physics cases and apparata for SPES

Transfer reactions



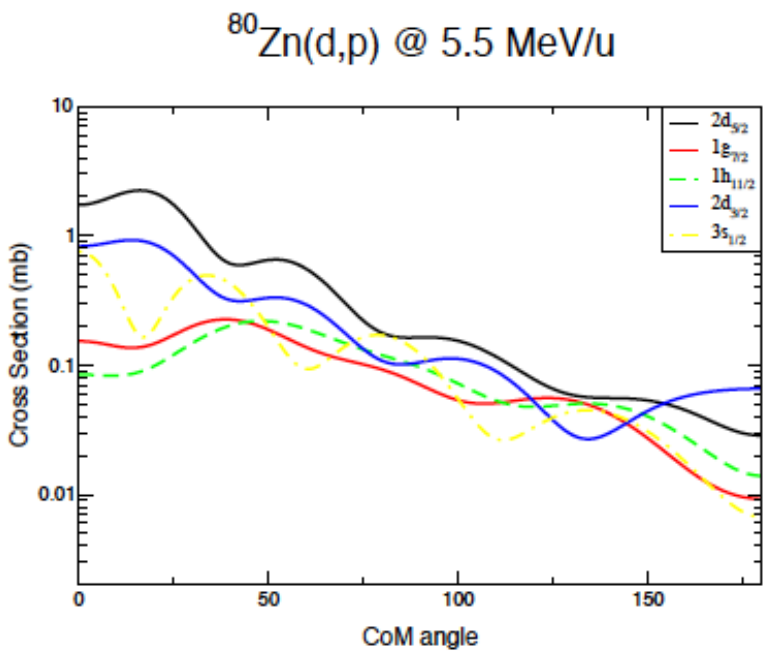
What can we learn from transfer reactions:
-Evolution of ESPE
-Spectroscopic factors, etc.

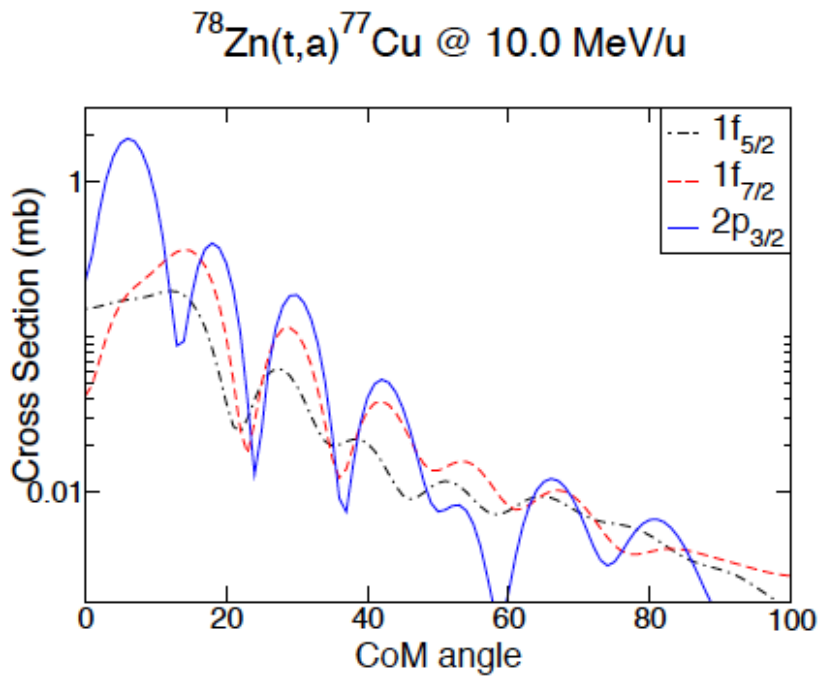
ISOLDE and GANIL:
-^{78}Zn(d,p) R. Orlandi et al., (to be published)
-^{68}Ni(d,p) G. Duchene et al., (to be published) – Thesis.
-^{66}Ni(d,p) J. Diriken et al., (to be published).
-$^{72\text{-}80}$ Zn Coulex Van de Walle *et al.*, Phys. Rev. Lett. 99 (2007)
-^{71,73,75}Cu gs μ moments K. Flanagan *et al.*, Phys. Rev. Lett. 103 (2009)
-$^{67\text{-}81}$ *Ga gs* μ moments B. Cheal *et al.*, Phys. Rev. Lett. 104 (2010)

Physics cases considered for SPES

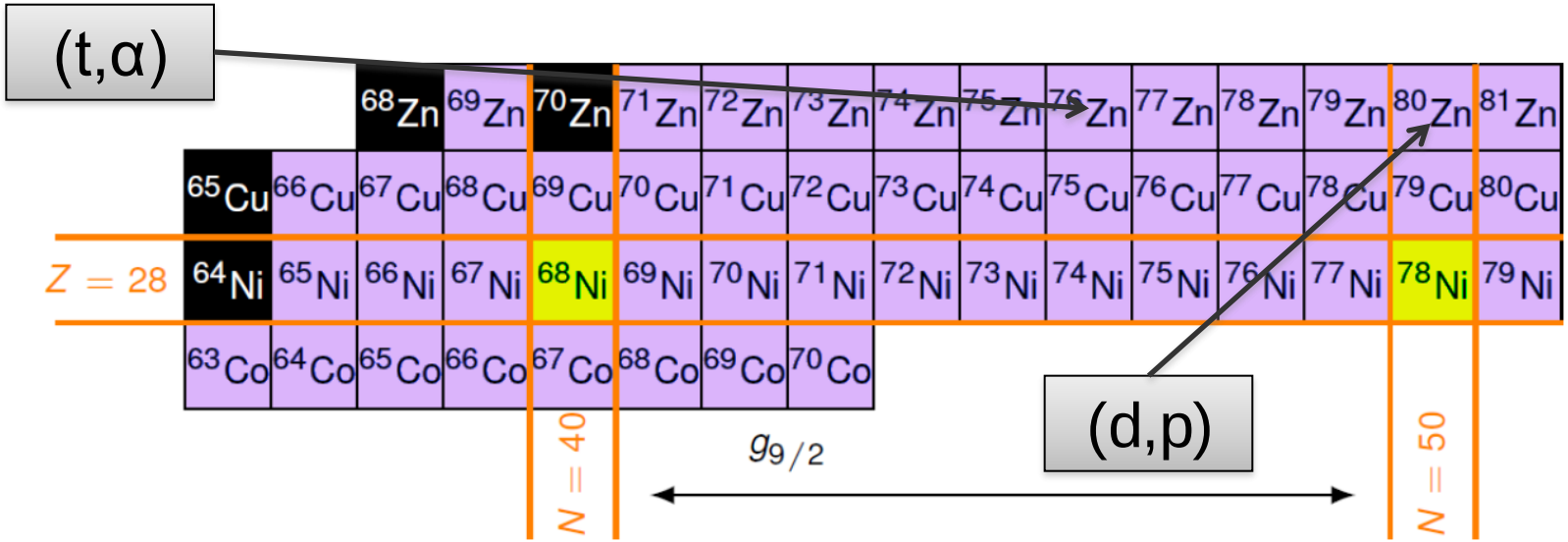
•(d,p) ^{81,82}Ga, ^{79,80}Zn – single particle orbital around N=50 $g_{9/2}$, $d_{5/2}$, $s_{1/2}$, $d_{3/2}$ and $g_{7/2}$. Gap stability

•(t,α) ^{74,76,78,80}Zn to selectively populate single proton states in odd-A ^{73,75,77,79}Cu isotopes- $p_{3/2}$, $f_{5/2}$ and $f_{7/2}$. Proton removal from the GS of Zn.





Challenges

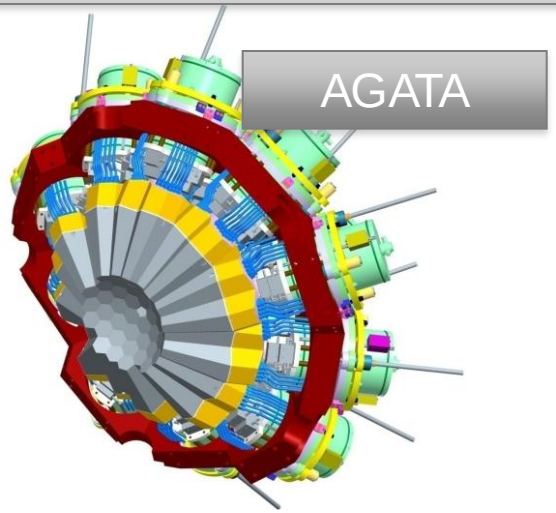


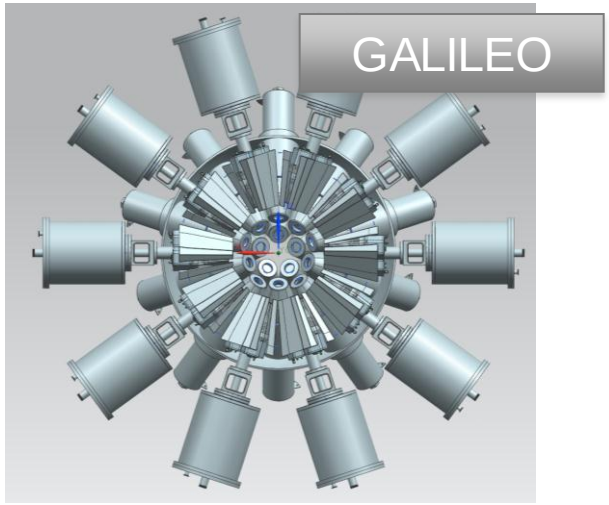
Challenges:

- Required beam ($10^5 - 10^6$ pps, purity > 40-60%)
- High-energy of secondary beams ~ 5-10MeV/u
- Tritium loaded Ti target ➔ safety issues to be considered
- Efficient instrumentation: gamma and charged particles.
- Effective interations for shell-model calculations → Energies and SF
- Cross sections calculations: DWBA calculations

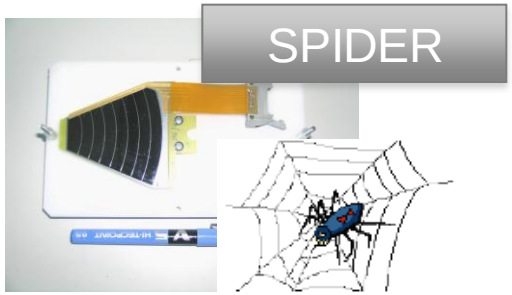
Detection systems

Gamma ray arrays





Charged particle/heavy ion detectors

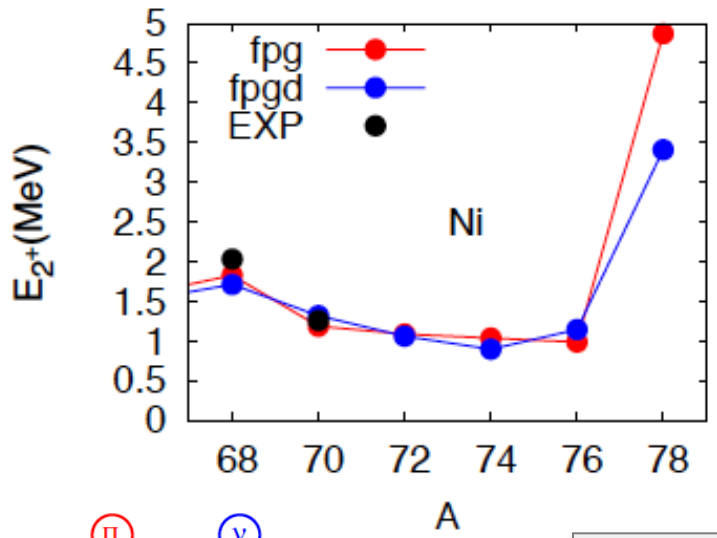


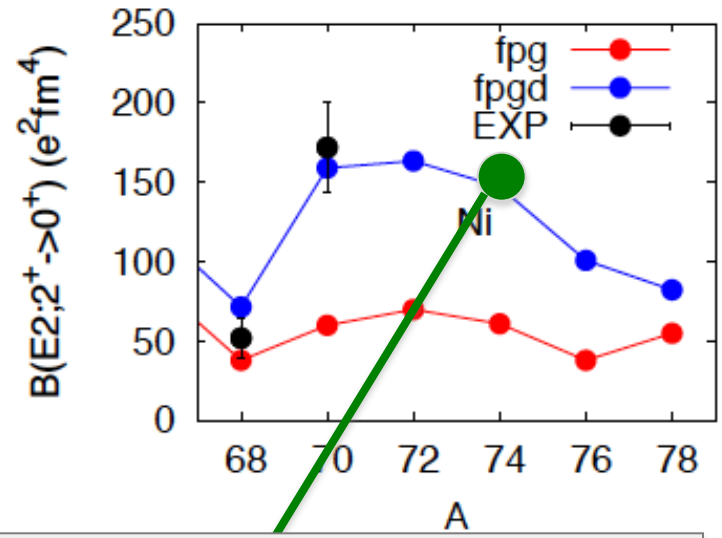
Short term plans: $^{70}Ni(d,t)^{69}Ni$ at ISOLDE

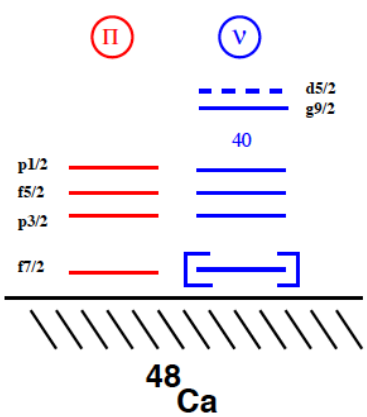
Proposal to be presented next INTC ISOLDE meeting: 31 Oct-1 Nov 2012

D. Mengoni, R. Orlandi and JJVD

Large-scale shell-model calculations







^{56}Ni-^{78}Ni

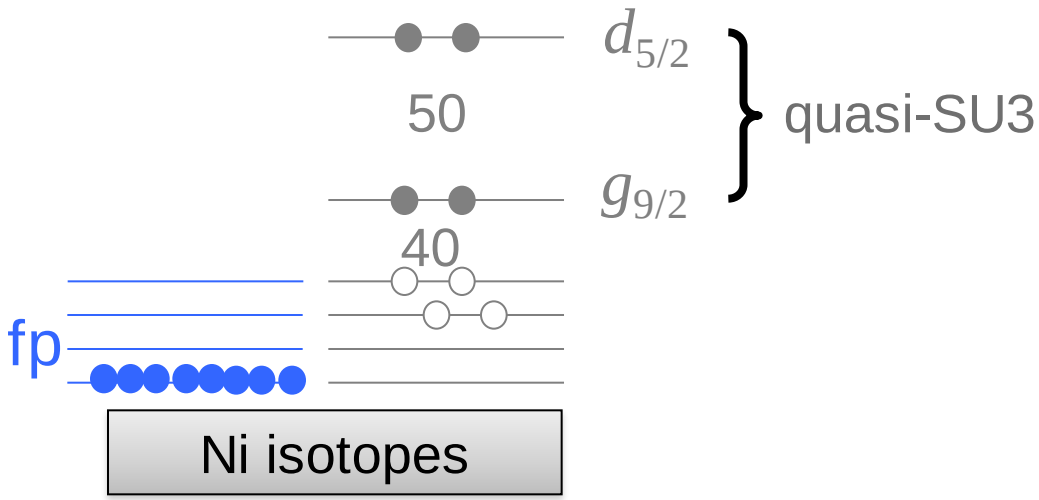
Deduced from N. Aoi PLB692 302 (2010)
δ=1.04(16) fm

- $d_{5/2}$ orbital essential to describe the B(E2) values.
- quasi-SU3 symmetry
- Region of Fe and Cr the $d_{5/2}$ orbital is essential to describe this deformation region (S. Lenzi et al., Phys. Rev. C **82**, 054301 (2010))

Courtesy of K. Sieja Vietri sul Mare (2010)

The role of the $g_{9/2}$ and $d_{5/2}$ orbitals

The GS of ^{70}Ni



GS of ^{70}Ni has according to SM calculations 0.25 particles in $d_{5/2}$

- We consider the $5/2^+$ state at 2.5 MeV (G. Duchene et al., Acta Phys. Pol.)
- The Q value of the reaction is -0.985MeV $Q(5/2^+)$=-3.485MeV

SM valence space:

- pf-shell for protons
- $f_{5/2}$,p,$g_{9/2}$,$d_{5/2}$ for neutrons.

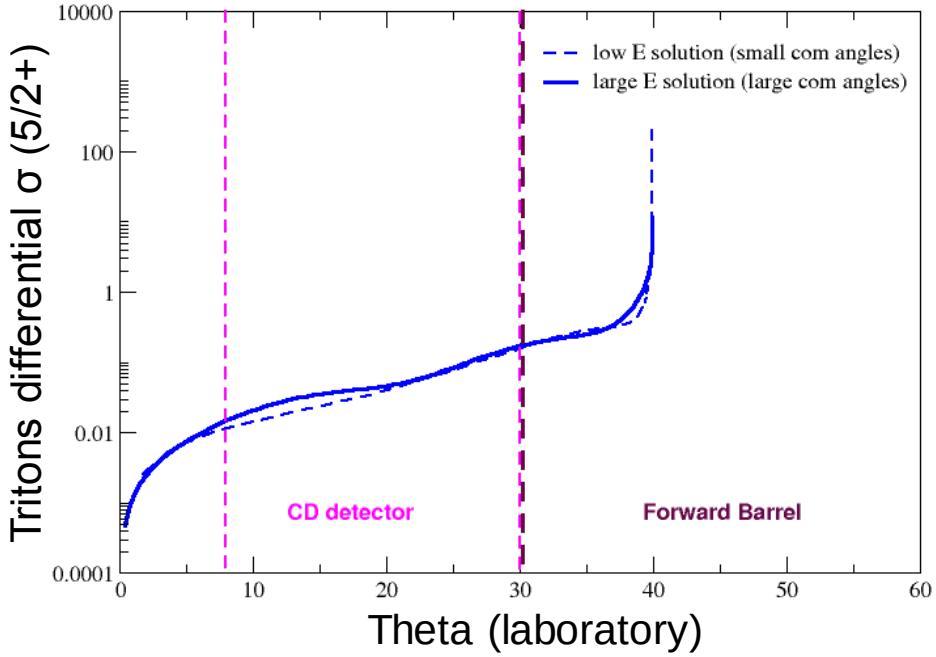
TABLE II: Occupation numbers in the 2^+ states of nickel isotopes ($Z = 28$) and the lowest excited $7/2^-$ states in copper isotopes ($Z = 29$).

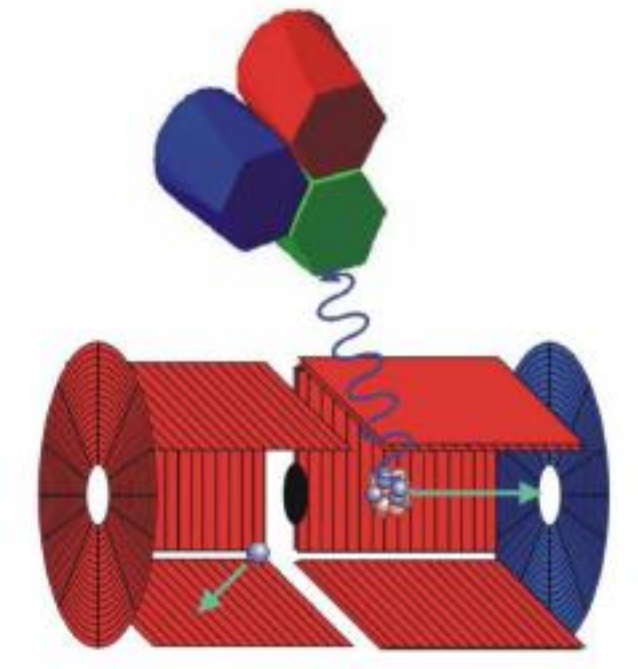
		protons				neutrons	
N	J^π	$f_{7/2}$	$f_{5/2}$	$p_{3/2}$	$p_{1/2}$	$g_{9/2}$	$d_{5/2}$
40	2^+	7.25	0.24	0.45	0.06	2.20	0.13
	$7/2^-$	6.49	1.26	0.77	0.46	3.24	0.52
	$3/2^-$	7.80	0.13	1.04	0.03	1.80	0.60
42	2^+	7.56	0.20	0.21	0.03	2.53	0.28
	$7/2^-$	7.44	0.63	0.73	0.19	3.17	0.38
	$3/2^-$	7.58	0.36	0.92	0.14	2.82	0.32
44	2^+	7.49	0.25	0.21	0.05	3.94	0.58
	$7/2^-$	7.64	0.59	0.57	0.20	3.72	0.53
	$3/2^-$	7.64	0.55	0.59	0.22	3.91	0.54
46	2^+	7.49	0.29	0.18	0.04	5.60	0.59
	$7/2^-$	7.59	0.76	0.43	0.22	5.50	0.60
	$3/2^-$	7.59	0.75	0.40	0.25	5.53	0.61
48	2^+	7.58	0.27	0.13	0.02	7.65	0.40
	$7/2^-$	7.64	1.07	0.22	0.07	7.59	0.45
	$3/2^-$	7.64	1.02	0.22	0.11	7.61	0.44
50	2^+	7.47	0.35	0.15	0.03	8.67	1.35
	$7/2^-$	6.74	2.03	0.16	0.07	9.63	0.39
	$3/2^-$	7.64	0.37	0.94	0.04	9.76	0.25

K. Sieja et al., arXiv:1201.0373v1 [nucl-th] 1 Jan 2012

Study of ^{70}Ni ground state

Calculated with TWOFNR DWBA (Igarashi)





T-REX + MINIBALL

Beam: 70Ni @ 5.5MeV/u
Target: 1 mg/cm^2 of Deuterated Polyethilene (C2D4)

Fusion evaporation of ^{12}C with ^{70}Ni (PACE4)
^{12}C+^{70}Ni → ^{82}Se → t (2n+p) + ^{79}As σ=0.14 mb → Most 2n+p and not triton

Summary

- Study of the low-lying properties of isotopes near by ^{78}Ni with the SPES beams.
- Shell evolution in the region – Tensor interaction, rigidity of the gaps when going towards ^{78}Ni
- Changes due to 3N forces are amplified in neutron-rich nuclei and will play a crucial role for matter at the extremes.
- Use of (d,p) and (t,α) reactions to study the region
- Sensitive detection systems to be used like: AGATA, GALILEO, TRACE, SPIDER
- There is no a universal technique to measure the physical properties along an isotopic chain
- Concerns: beam purity > 40%, intensity10^5-10^6, energy 10~MeV/u
- Short-term range plans: Proposal for an experiment at ISOLDE ^{70}Ni(d,t)^{69}Ni at ISOLDE

Points to consider in the discussion

- *SPES beams* → Important to know the intensity and beam purity
- *Targets* → Is there a general strategy to include radioactive targets such as tritium in the general SPES project? Who should take care of this?
- *Detector systems* → AGATA/GALILEO+TRACE ✔ Lacking any others instrumentation? For example, IC for beam purity check at the end of the line. Is there a general strategy?
- *Before SPES* → General strategy (INFN) to collaborate with other laboratories with larger experience ISOLDE/GANIL? Not only a single proposal.
- Theoretical support → Is there a more general umbrella of theoreticians working on this kind of projects? Within NuPNET?
- Etc.

Reactions and 3-body force

Study of Three-Body Force

in Nuclear Physics

- Which reactions (and systems) to study?
  - Electromagnetic interaction on 3B systems
  - 3B (and more bodies?) Bound states
  - 3B Elastic scattering in large parts of phase space
  - 3B Break-up reaction in different kinematics
  - Many-body systems → Nuclear matter

$N + d \rightarrow N + d$

$N + d \rightarrow N + N + N$

$N + d \rightarrow {}^3He({}^3H) + \gamma^{(*)}$

$\gamma^{(*)} + {}^3He({}^3H) \rightarrow N + d$

$\gamma^{(*)} + {}^3He({}^3H) \rightarrow N + N + N$

KVI

GSI

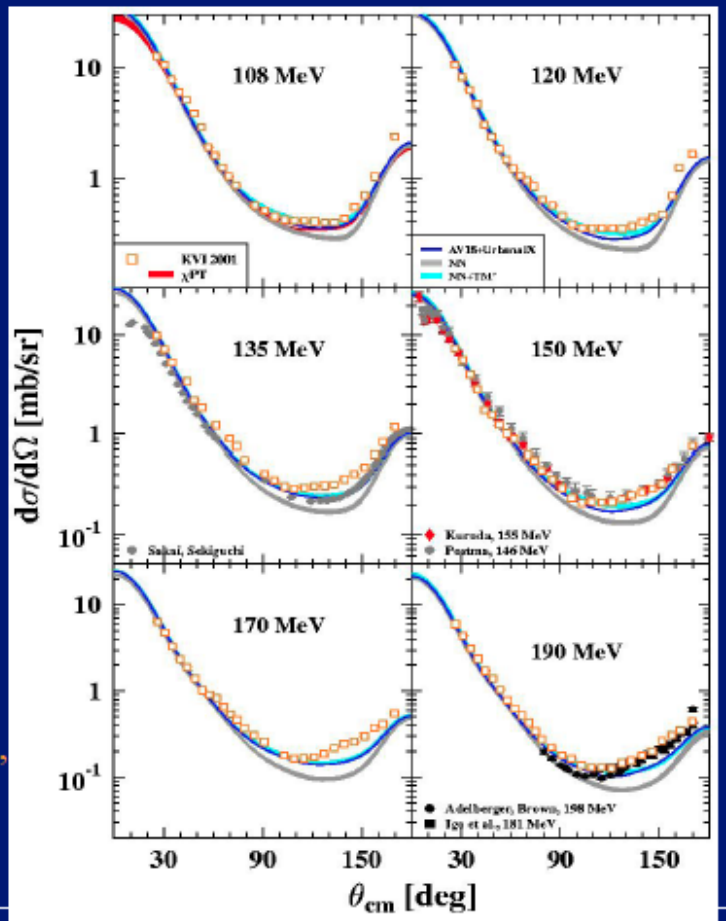
university of groningen

Courtesy of N. Kalantar-Nayestanaki

Reactions and 3-body force

pd elastic scattering cross sections

$$p + d \rightarrow p + d$$



K. Ermisch et al.,
PRC 68, 054004 (2003),
PRC 71, 064004 (2005)

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Three-nucleon forces and and their importance in three-nucleon systems and heavier nuclei

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Courtesy of N. Kalantar-Nayestanaki

^{74}Ni (p,p') measurement

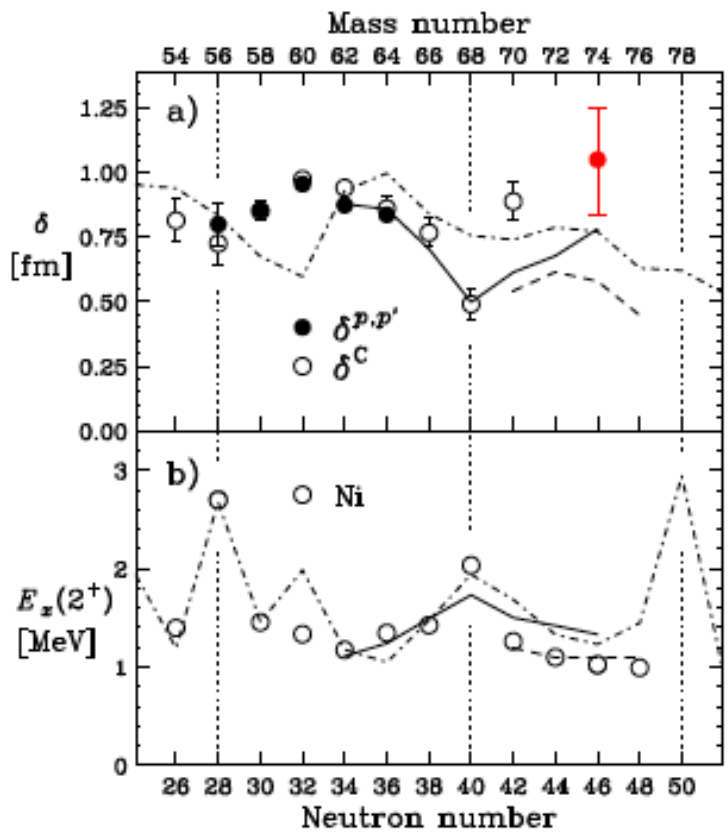

Fig. 4. (a) The δ values for Ni isotopes. The open circles show δ^C obtained from $B(E2)$ values [11,12,16,18]. The filled circles show $\delta^{p,p'}$ obtained from the proton inelastic scattering [13,47]. (b) The $E_x(2^+)$ systematics for Ni isotopes. In both figures the dashed and solid curves show the δ and $E_x(2^+)$ values from the shell-model calculations of Refs. [39] and [11], respectively. The dot-dashed curve shows the results of HFB + QRPA calculations [41].

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Enhanced collectivity in ^{74}Ni

N. Aoi [a,*], S. Kanno [b,a], S. Takeuchi [a], H. Suzuki [d], D. Bazin [c], M.D. Bowen [c], C.M. Campbell [c], J.M. Cook [c], D.-C. Dinca [c], A. Gade [c], T. Glasmacher [c], H. Iwasaki [d,c], T. Kubo [a], K. Kurita [b], T. Motobayashi [a], W.F. Mueller [c], T. Nakamura [e], H. Sakurai [d,a], M. Takashina [f,g], J.R. Terry [c], K. Yoneda [c,a], H. Zwahlen [c]

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- Softening of the Z=28 core
- Quasi-SU(3) symmetry involvement of the $d_{5/2}$ orbital to explain the collectivity

Beyond N=50 - Deformation

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Island of inversion around ^{64}Cr

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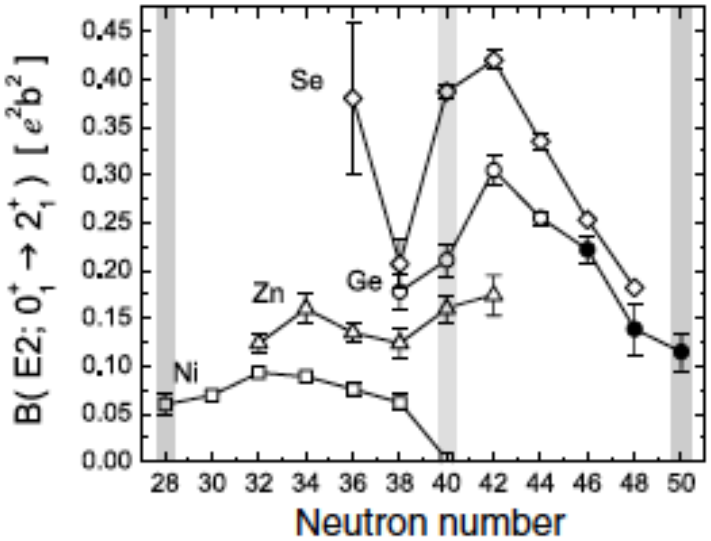
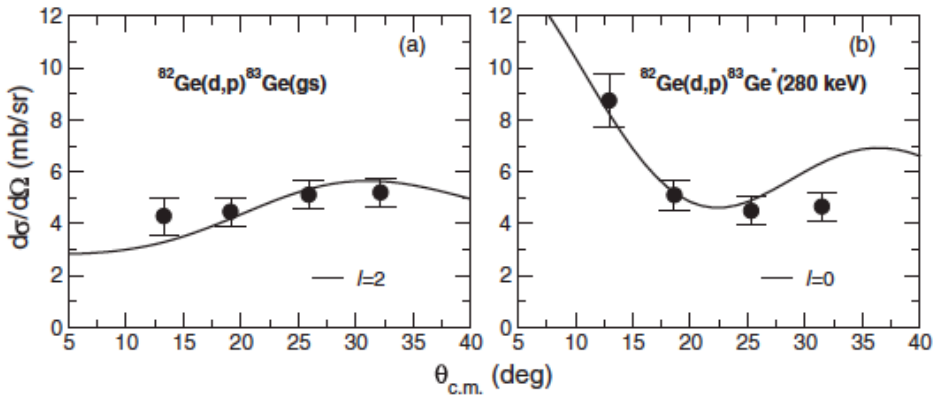
(Received 10 September 2010; published 2 November 2010)

Involvement of the quasi-SU(3) in the explanation of the deformation in the N=40 region

^{78,80,82}Ge Coulex



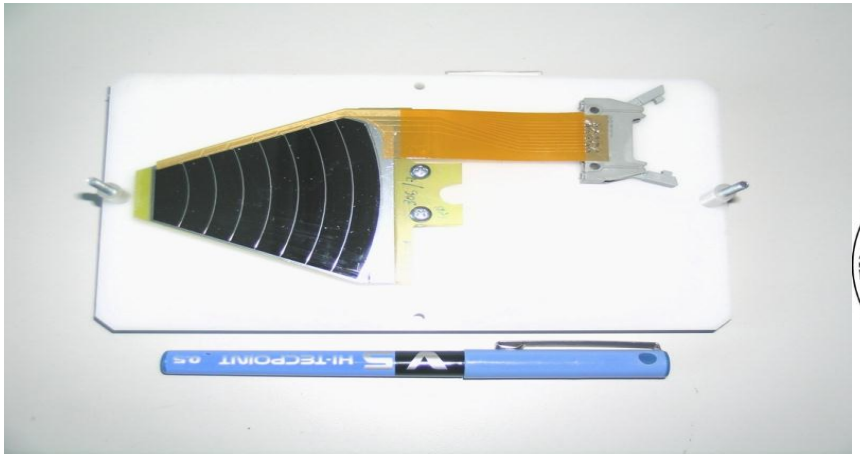
^{84}Se(d,p)^{85}Se (N=51)

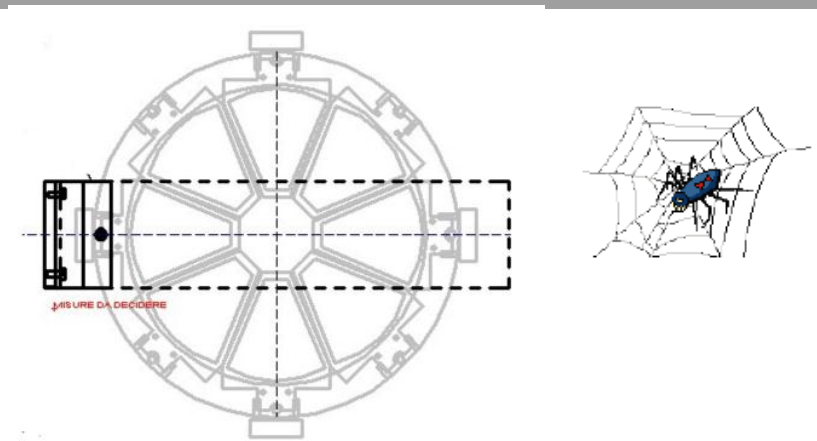


Proton angular distributions for GS and 462keV Ex

- Coulex: ^{78,80,82}Ge E. Padilla-Rodal et al., PRL94, 122501 (2005)
- Relativistic Coulex + knockout: ^{82}Ge and ^{84}Se A. Gade et al., PRC81, 064326 (2010)
- (d,p): ^{83}Ge and ^{85}Se: J.S. Thomas et al., PRC76, 044302 (2007)

The Silicon Pie Detector: SPIDER





- 8 sectors of Si strip detectors arranged in a pie-shaped array
- The front surface (junction side) is segmented into 8 strips
- The thickness of the Si detector is around 300μm
- Dead layer 50nm

θ coverage when the detector is mounted at 5 cm distance from the target: 18 to 60 degrees

Strip no.	Inner radius (mm)	Outer radius (mm)	θ_{min} (deg)	θ_{max} (deg)
1	76.7	85.0	56.9	59.5
2	68.1	76.4	53.7	56.7
3	59.5	67.9	50.0	53.6
4	50.9	59.3	45.5	49.9
5	42.4	50.7	40.3	45.4
6	33.8	42.1	34.1	40.1
7	25.2	33.6	26.7	33.9
8	16.6	25.0	18.4	26.6