Neutron single-particle states towards ^{78}Ni: ^{80}Ga(d,p)^{81}Ga

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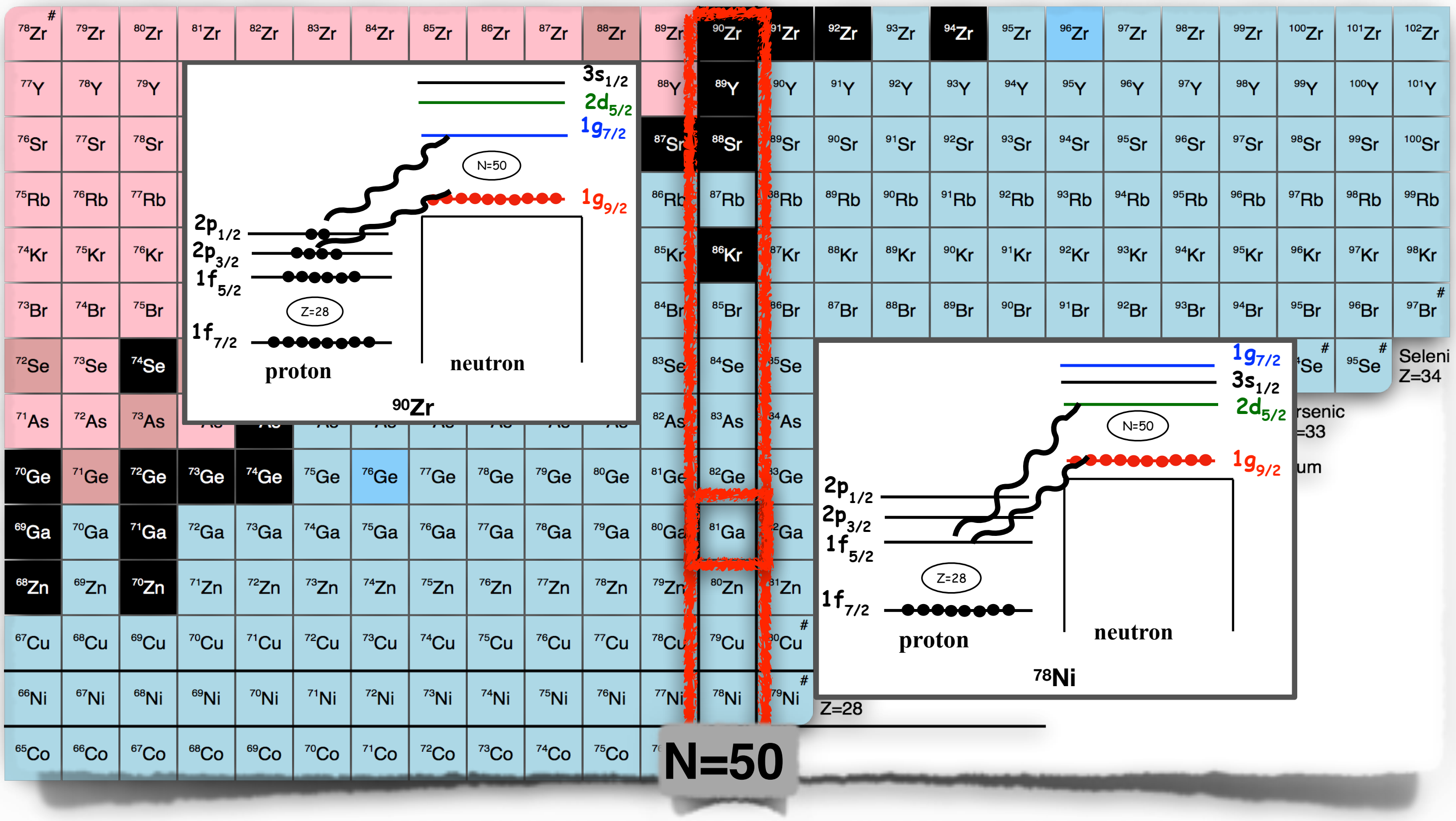
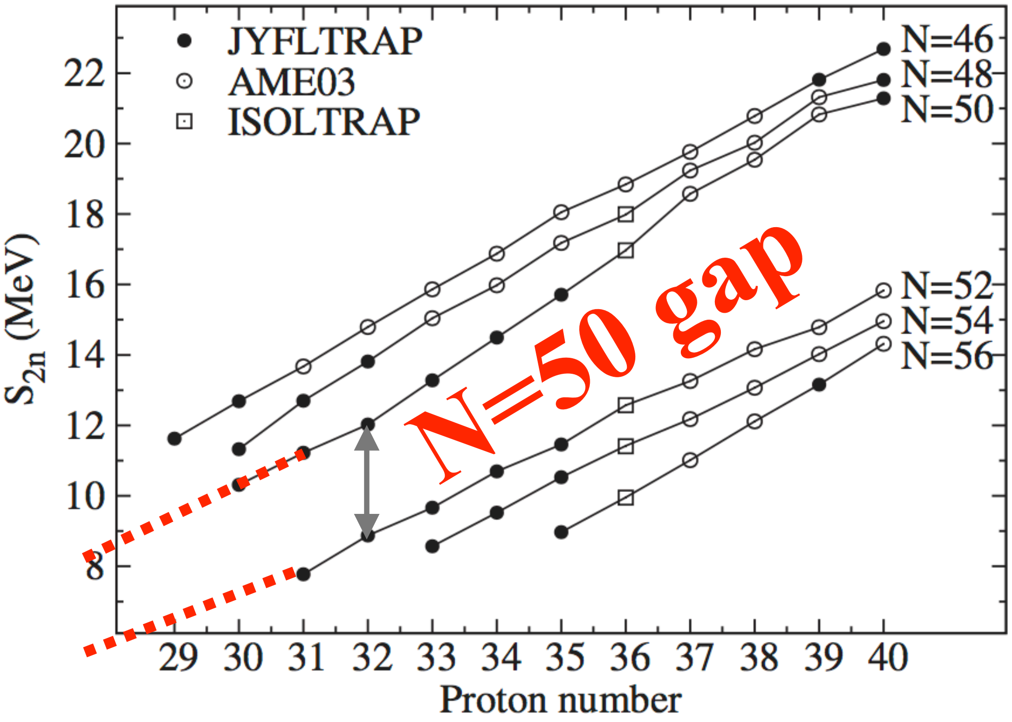
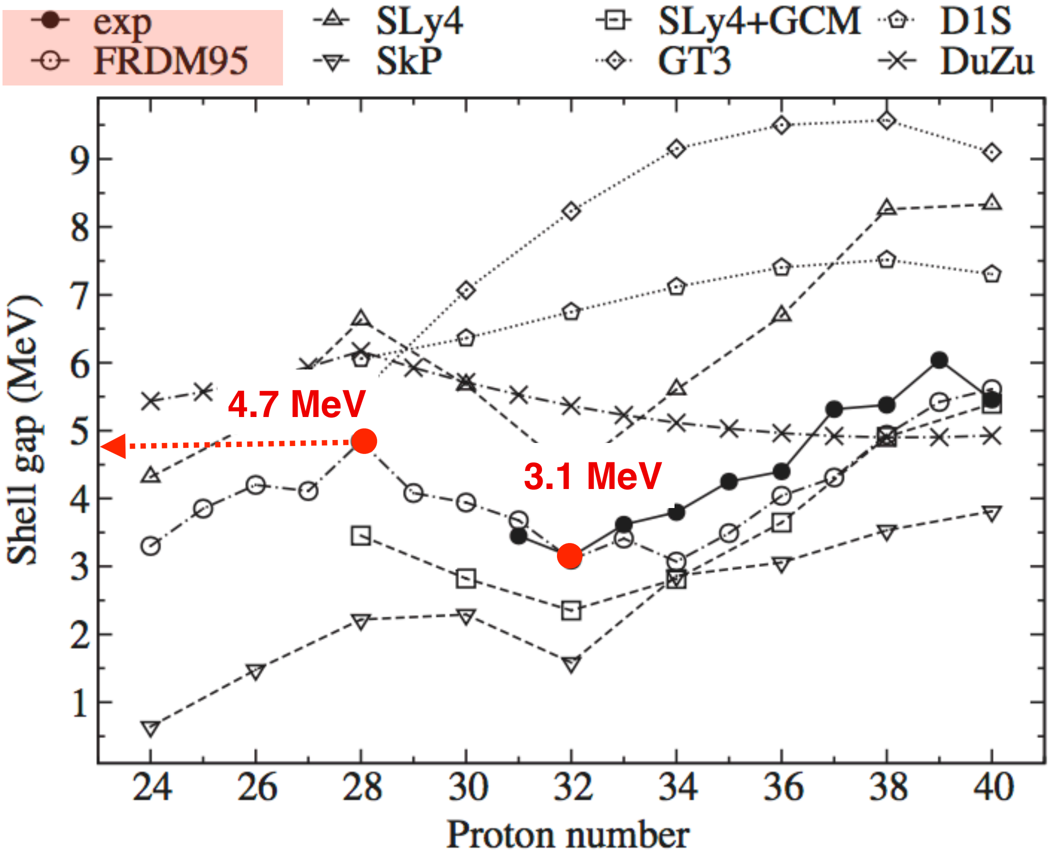
**University of Oslo, Oslo, Norway*
***INFN- Laboratori Nazionali di Legnaro, LNL, Padova, Italy*
****University of Surrey, Guildford, United Kingdom*



1. Evolution of the N=50 shell gap from the mass measurements

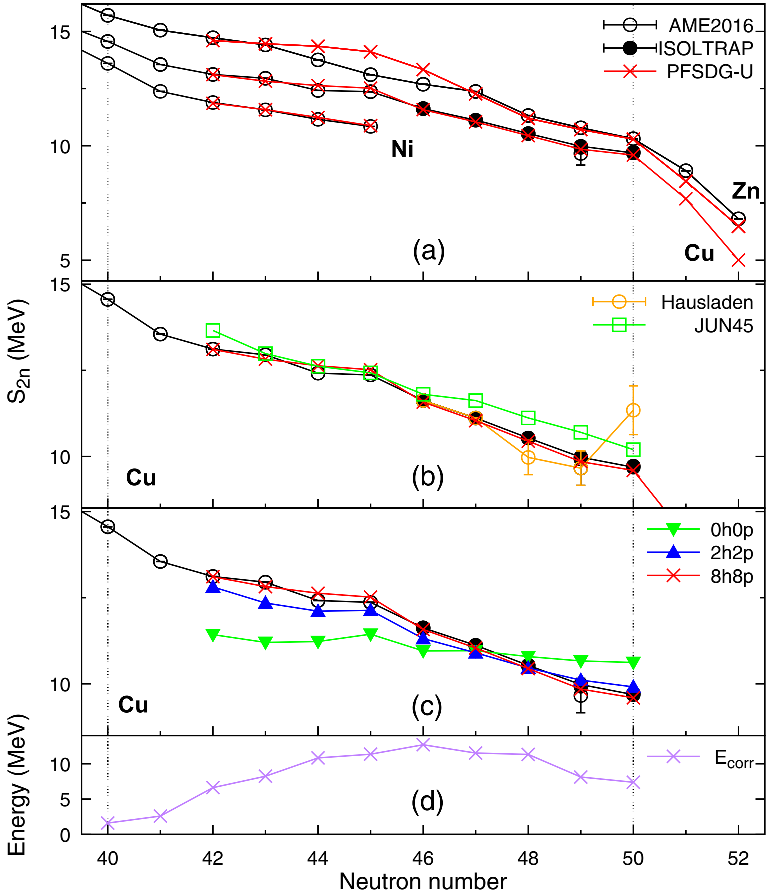




Next critical masses:
$^{82}\mathrm{Zn}$, $^{\cancel{77,79},81}\mathrm{Cu}$, $^{76,78,80}\mathrm{Ni}$

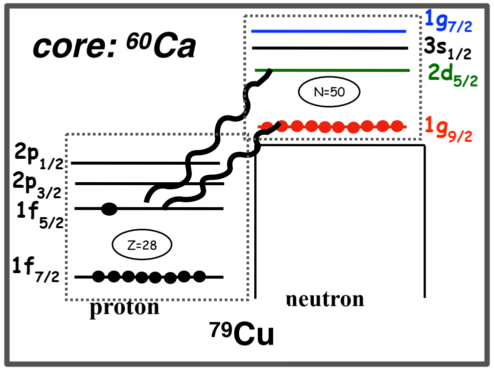
J. Hakala et al., Phys. Rev. Lett. 101, 052502 (2008)

2. Recent mass measurements at ISOLDE : $^{75-79}$Cu



A. Welker et al., PRL 119, 192502 (2017).

PFSDG-U interaction:
F. Nowacki et al., PRL 117, 272501 (2016).



Monopole interaction

■Proton-neutron interactions, primarily between proton 1f$_{5/2}$ and neutron 1g$_{9/2}$.

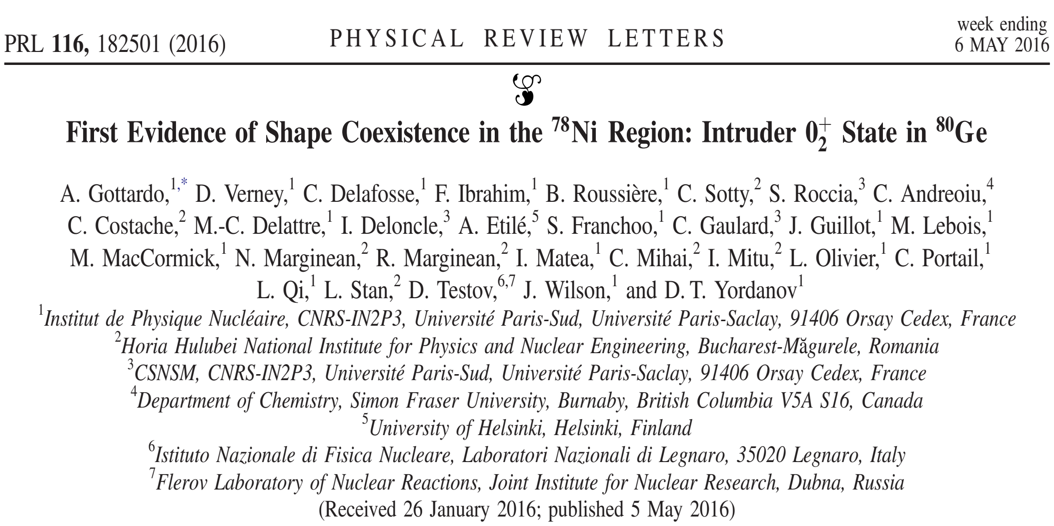
■N=50 shell gap changes from 6.7 MeV at Z=40 to 4.9 MeV at Z=28

Multipole interactions

■ Excitations of both protons and neutrons above the major gaps are necessary to reproduce observables in the ^{78}Ni region

■ *Shape coexistence in ^{78}Ni through the 2p-2h excitations*

3. Shape coexistence in N=50 isotones:


PRL **116,** 182501 (2016) PHYSICAL REVIEW LETTERS week ending 6 MAY 2016

First Evidence of Shape Coexistence in the ^{78}Ni Region: Intruder 0_2^+ State in ^{80}Ge

A. Gottardo,[1,*] D. Verney,[1] C. Delafosse,[1] F. Ibrahim,[1] B. Roussière,[1] C. Sotty,[2] S. Roccia,[3] C. Andreoiu,[4] C. Costache,[2] M.-C. Delattre,[1] I. Deloncle,[3] A. Etilé,[5] S. Franchoo,[1] C. Gaulard,[3] J. Guillot,[1] M. Lebois,[1] M. MacCormick,[1] N. Marginean,[2] R. Marginean,[2] I. Matea,[1] C. Mihai,[2] I. Mitu,[2] L. Olivier,[1] C. Portail,[1] L. Qi,[1] L. Stan,[2] D. Testov,[6,7] J. Wilson,[1] and D. T. Yordanov[1]

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[2] *Horia Hulubei National Institute for Physics and Nuclear Engineering, Bucharest-Măgurele, Romania*
[3] *CSNSM, CNRS-IN2P3, Université Paris-Sud, Université Paris-Saclay, 91406 Orsay Cedex, France*
[4] *Department of Chemistry, Simon Fraser University, Burnaby, British Columbia V5A S16, Canada*
[5] *University of Helsinki, Helsinki, Finland*
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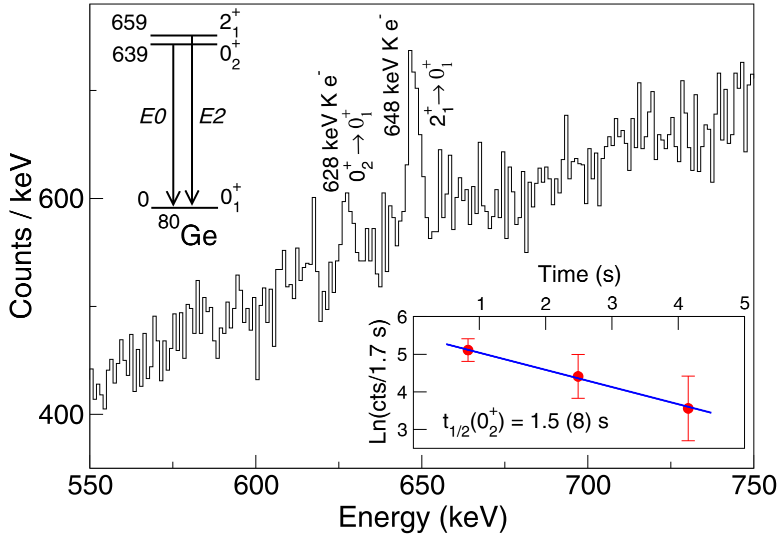
[7] *Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research, Dubna, Russia*

(Received 26 January 2016; published 5 May 2016)

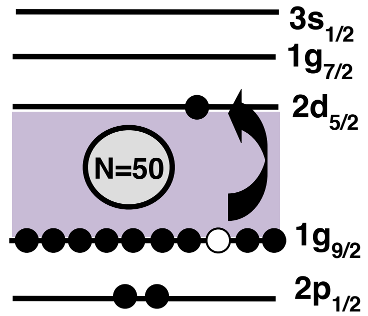


- A second 0^+ state at 639 keV in ^{80}Ge (N=48) has been interpreted as an $\nu(2p - 2h)$ excitation across N = 50.
- The first evidence of the shape coexistence in the N=50 region.
- The energy of the 0^+_2 intruder state due to this *2p-2h* excitation could be determined via:

$$E_{0_2^+} = \underline{2(E_{\nu d_{5/2}} - E_{\nu g_{9/2}})} + \Delta E^{\nu\nu}_{\text{pair}} + \Delta E^{\pi\nu}_{M} + \Delta E^{\pi\nu}_{Q},$$

J. L. Woodet al, Phys. Rep. 215, 101 (1992).

4. 1p-1h Excitations



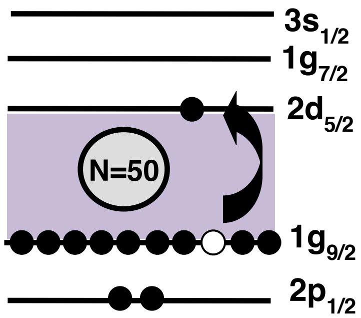
$\nu g_{9/2}^{-1} \otimes \nu d_{5/2}^{+1}$

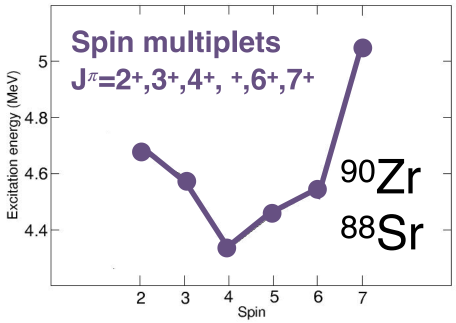
1p-1h excitations between neutron $1g_{9/2}$ and $2d_{5/2}$ orbitals provide the essential ingredients

- to the monopole component of the NN interaction in order to determine the size of the N=50 gap
- to a better understanding of the correlation effects which can cause to a possible IOI and shape coexistence in the ^{78}Ni mass region

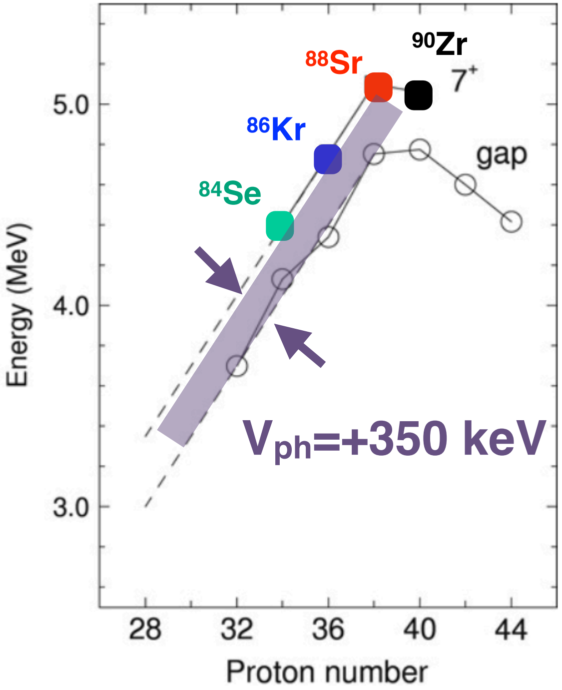
Main purpose of the present proposal is to study <u>1p-1h</u> excitations in the N=50 isotones starting from ^{81}Ga.

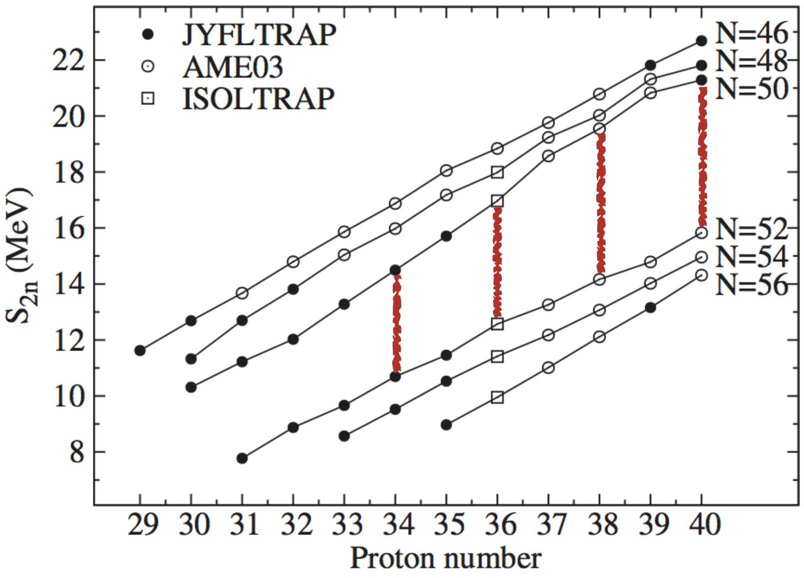
3. 1p-1h Excitations





7+ states from γ-ray spectroscopy

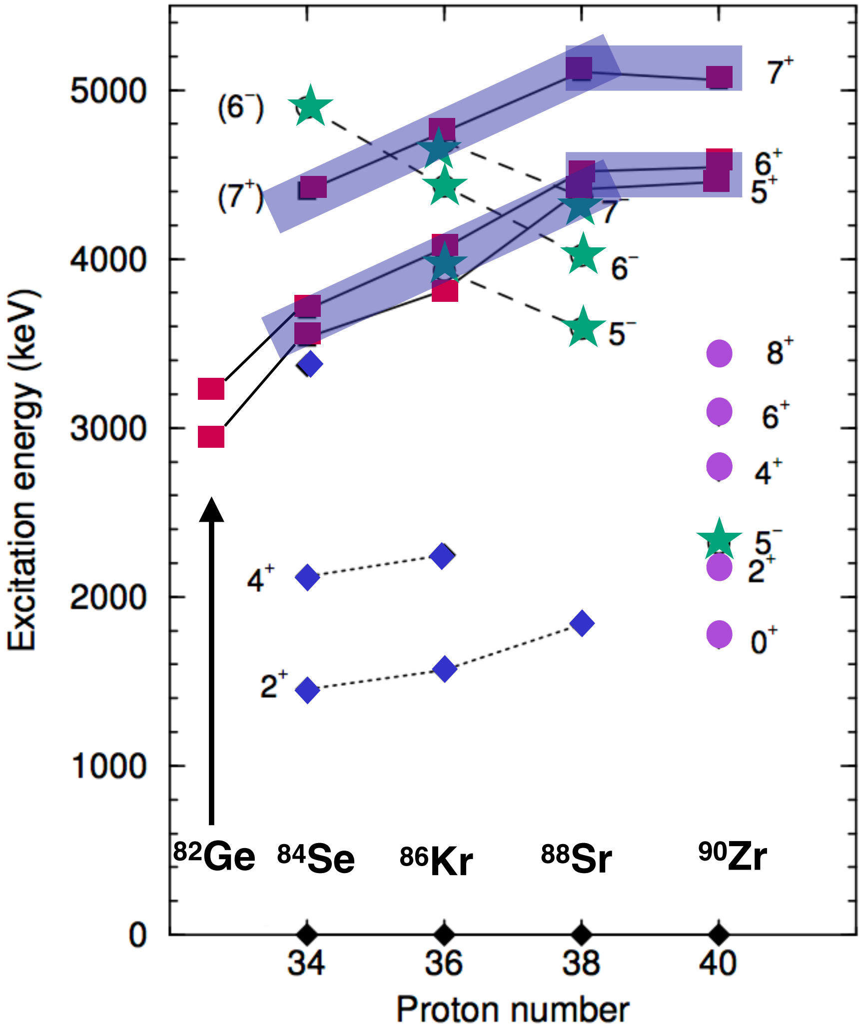




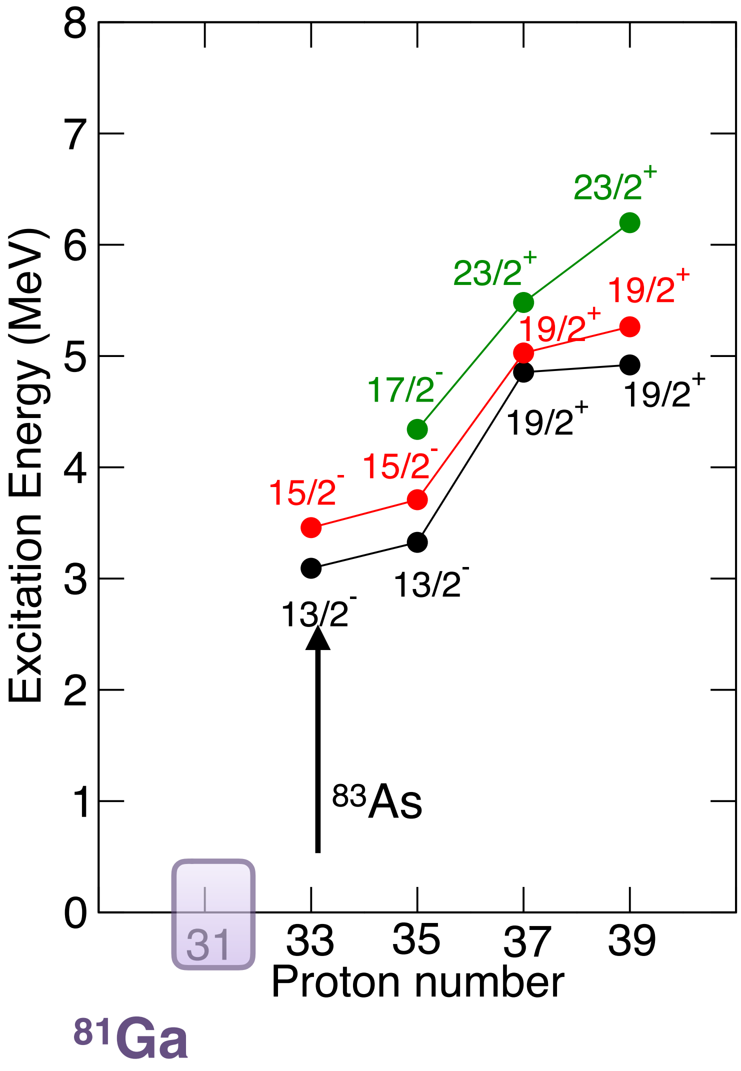
O. Sorlin, M.-G. Porquet,
Prog.in Part. and Nuc. Phys. 61 (2008) 602

J. Hakala et al., Phys. Rev. Lett.
101, 052502 (2008)

EVEN-A N=50 Isotones



ODD-A N=50 Isotones



T. Rząca-Urban et al., Phys. Rev. C 76, 027302 (2007)

A. Prévost, et al., Eur Phys. J. A 22 (2004) 391.

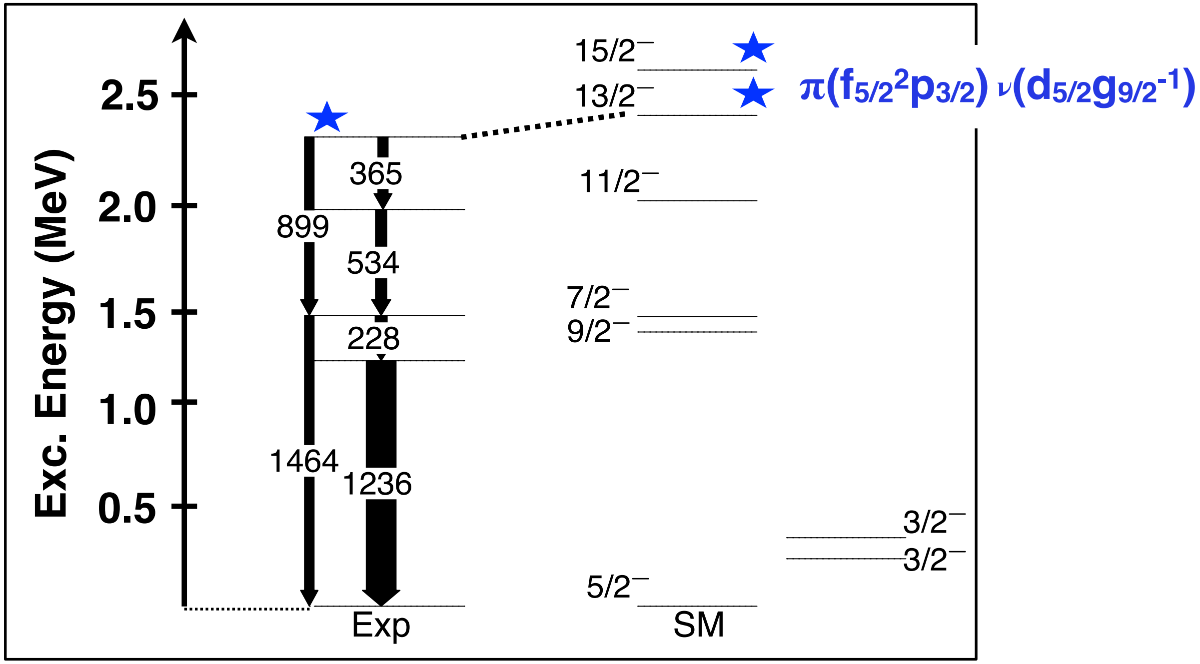
ES et al.,Nucl. Phys. A 893, 1-12 (2012)

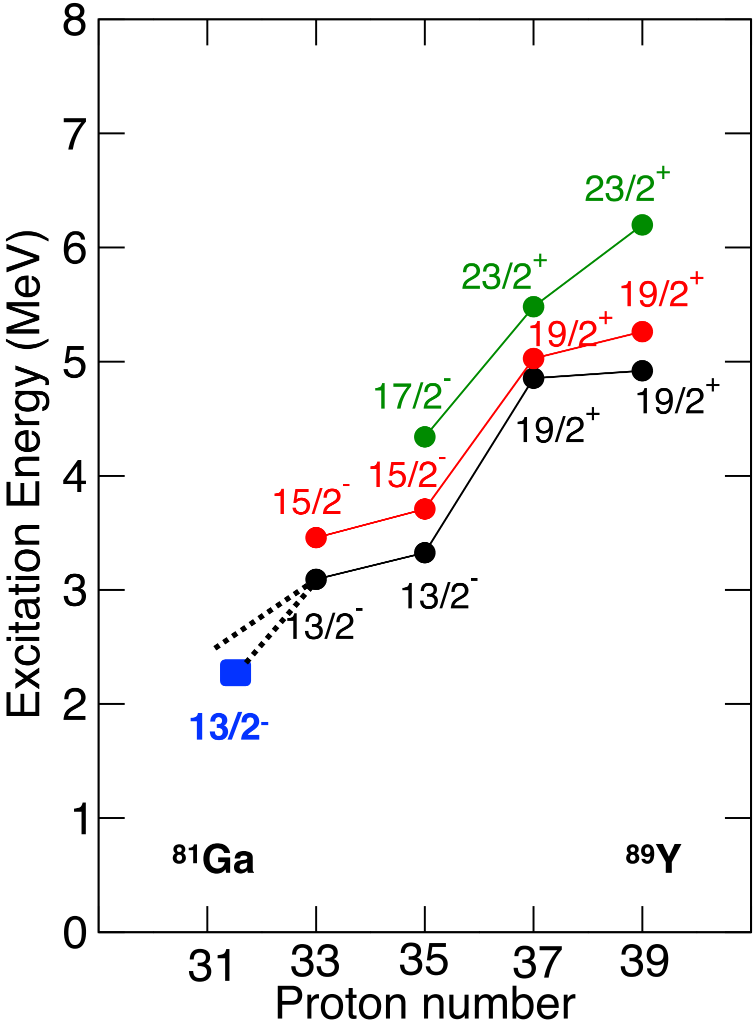
We propose to measure the neutron particle-hole states in ^{81}Ga via one-neutron transfer reaction in inverse kinematics: ^{80}Ga(d,p)^{81}Ga

- It will be the most exotic case along the N=50 nuclei in which neutron core states will be identified through *1p-1h* excitations.
- We aim to study the N=50 shell gap evolution closer to Z=28 via spectroscopy.
- Selection of *1p-1h* states will help us to understand the expected correlations and to predict states due to neutron *2p-2h* excitations
- Prediction of such *2p-2h* states can be subject to further experimental campaigns at ISOLDE.
- If successful, in the future the same method can be applied to ^{80}Zn, the next member of the N=50 chain close to ^{78}Ni

^{81}Ga: the most exotic odd-A N=50 isotope accessible to n-p excitations

★ p-h excitation across the neutron gap





Multi-nucleon transfer reaction at LNL, Italy

^{82}Se + ^{238}U E(^{82}Se)=515 MeV

CLARA γ array coupled to

PRISMA magnetic spectrometer

$\Theta_{PRISMA}=\Theta_{Grazing}=64^{\circ}$

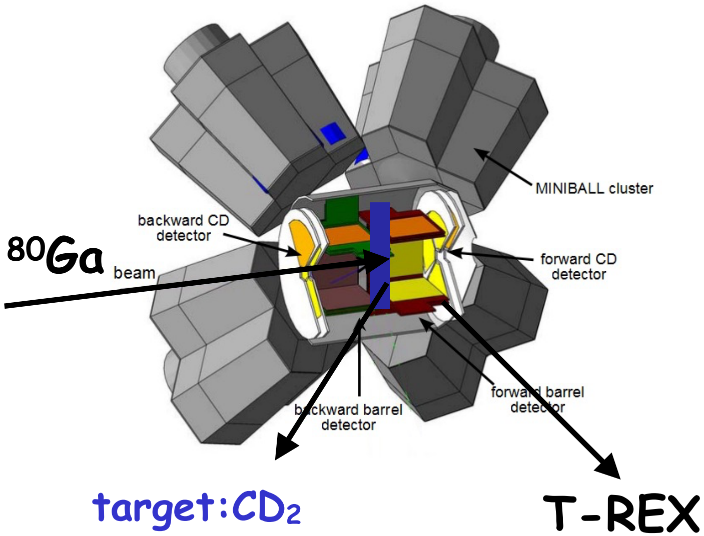
ES et al.,Nucl. Phys. A 893, 1 (2012)

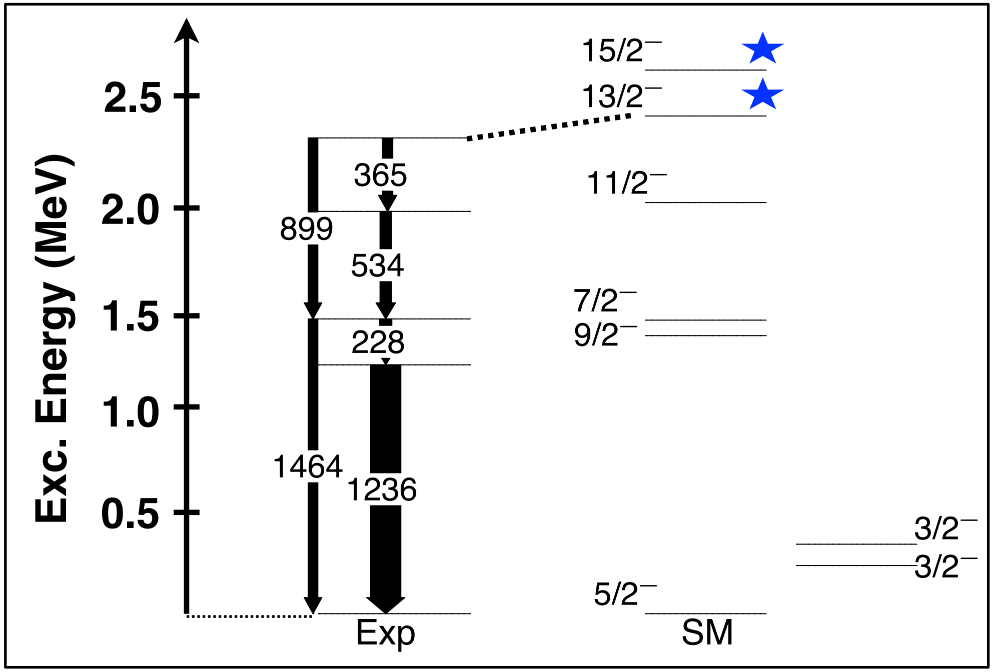
Proposed Experiment

^{80}Ga(*d,p*)^{81}Ga inverse kinematics

^{80}Ga + CD_2 @ E(^{80}Ga)=500 MeV

MINIBALL

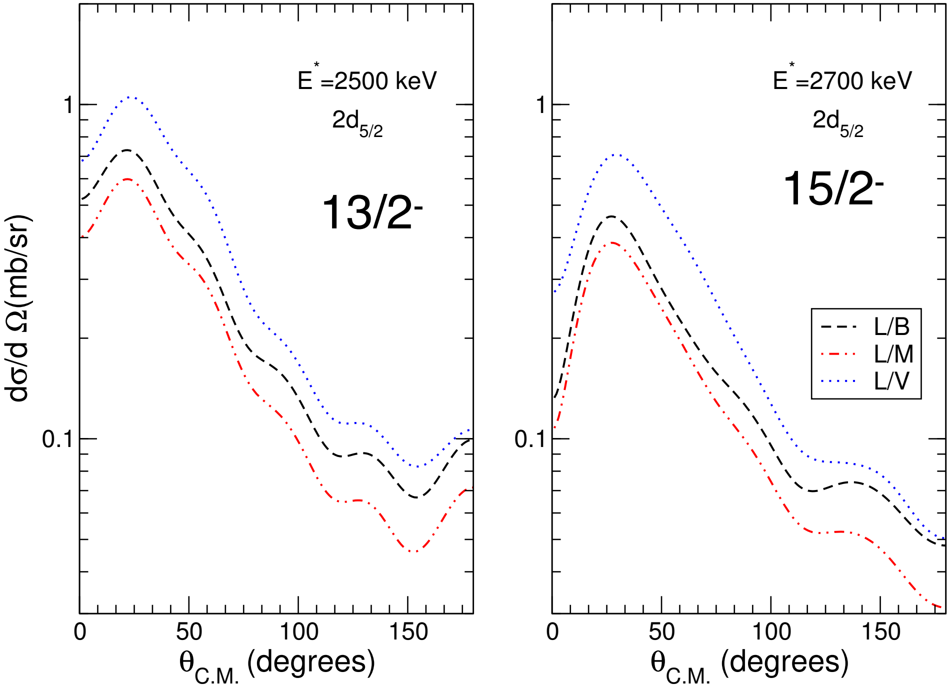




^{81}Ga

Beam time request

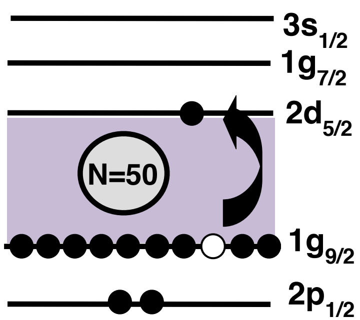
Beam energy (^{80}Ga)	500 MeV (6.25 MeV/nuc)
Beam intensity on target	1.4 x10^4 pps
Initial beam intensity	3.5 x10^5 pps
proton beam current	2 microA
Transmission on MINIBALL beam line	2%
Target thickness (CD_2)	1 mg/cm^2
Cross sections	DWBA via FRESCO



$\pi(f_{5/2}^2 p_{3/2})\ \nu(d_{5/2} g_{9/2}^{-1})$

$13/2^-$,$15/2^-$,$17/2^-$,$19/2^-$,$21/2^-$,$23/2^-$

Focus:
***l*=2 transfer**



$\nu g_{9/2}^{-1} \otimes \nu d_{5/2}^{+1}$

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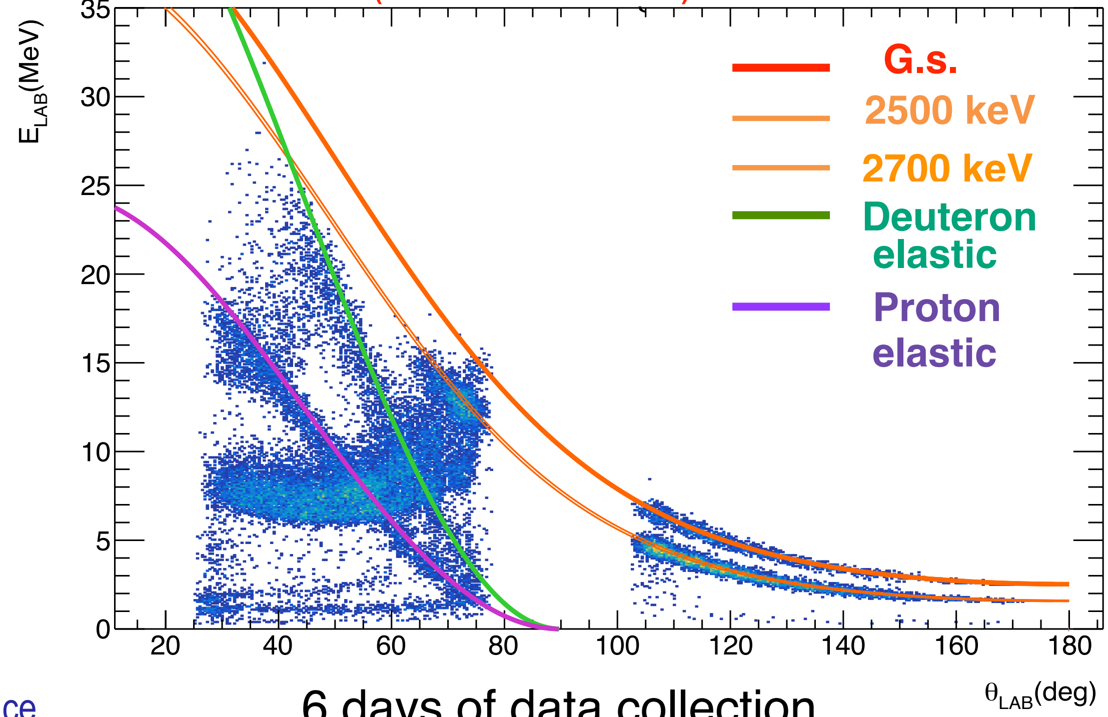
- Initial beam intensity	3.5 x10^{5} pps
- proton beam current	2 microA
- Transmission on MINIBALL beam line	2%
Target thickness (CD$_2$)	1 mg/cm^2
Cross sections	DWBA via FRESCO
MINIBALL efficiency at 1.3 MeV	8%
TREX efficiency for protons	25 % (G4 Simulations)



6 days of data collection

Simulations: Adrien Matta
Institut de Physique Nucléaire, CNRS-IN2P3, France

Beam time request

Beam energy (^{80}Ga)	500 MeV (6.25 MeV/nuc)
Beam intensity on target	1.4 x10^4 pps
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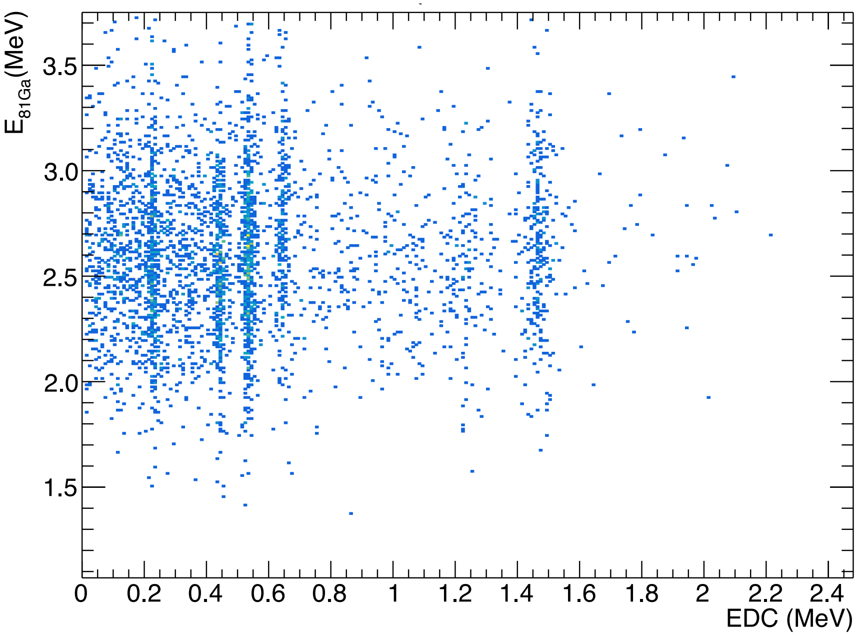

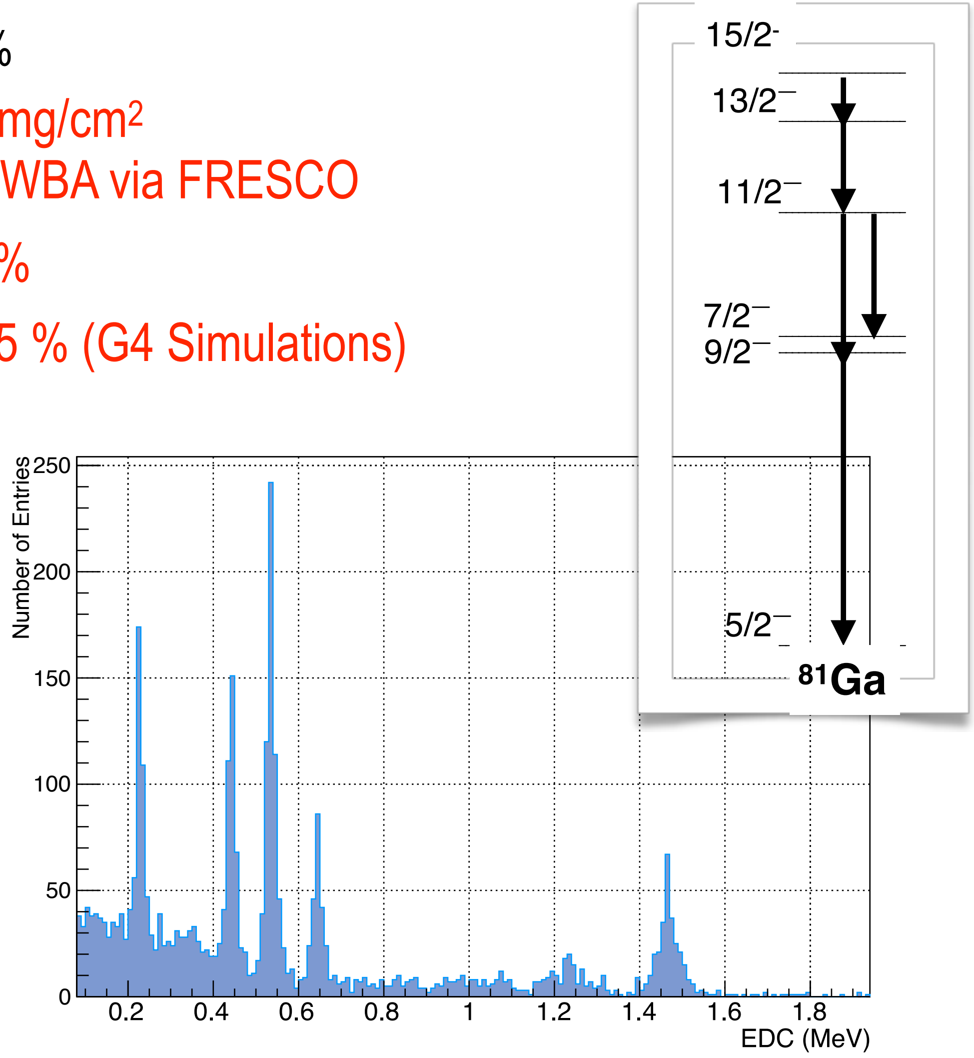

6 days of data collection

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proton beam current	2 microA
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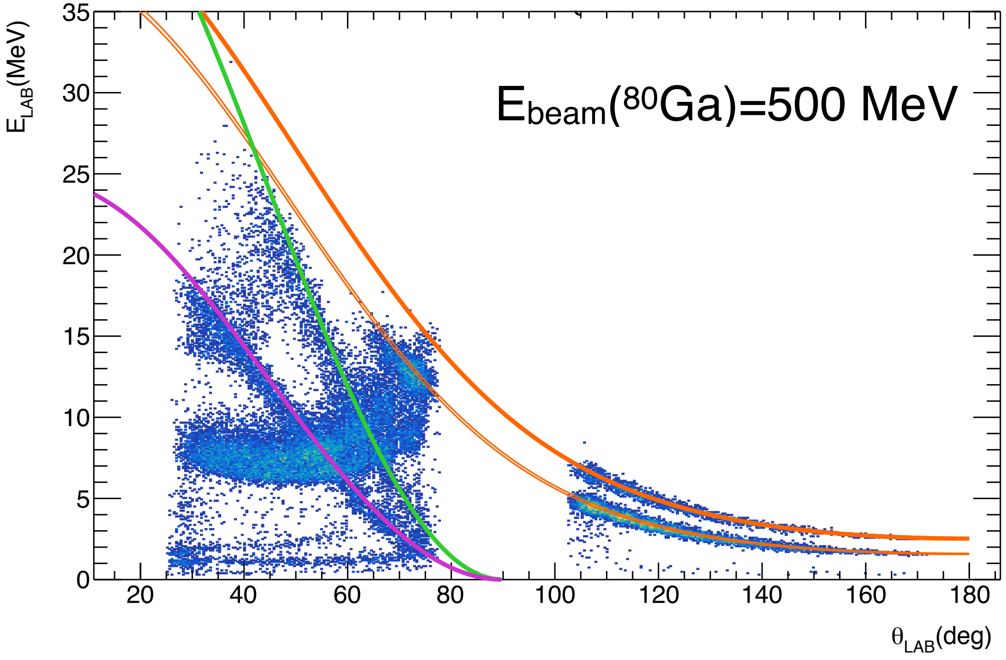
Target thickness (CD_2)	1 mg/cm^2
Cross sections	DWBA via FRESCO
MINIBALL efficiency at 1.3 MeV	8%
TREX efficiency for protons	25 % (G4 Simulations)

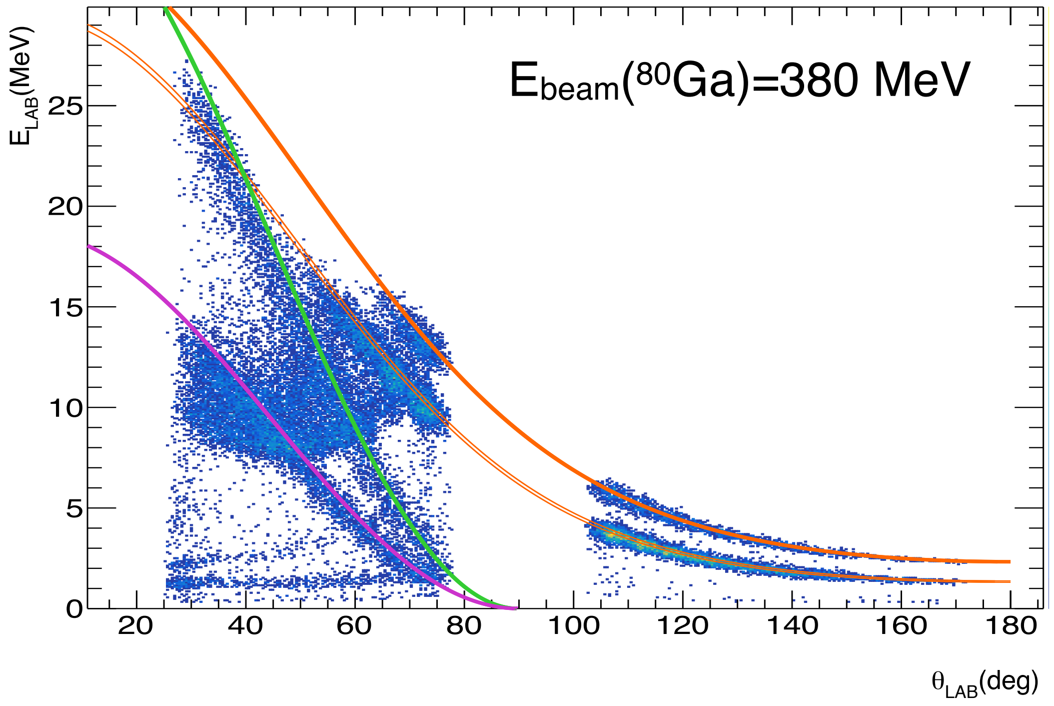
Total 3700 proton events will be obtained for the excited states at 2500 and 2700 keV (1800 events for each) in 6 days of beam time.

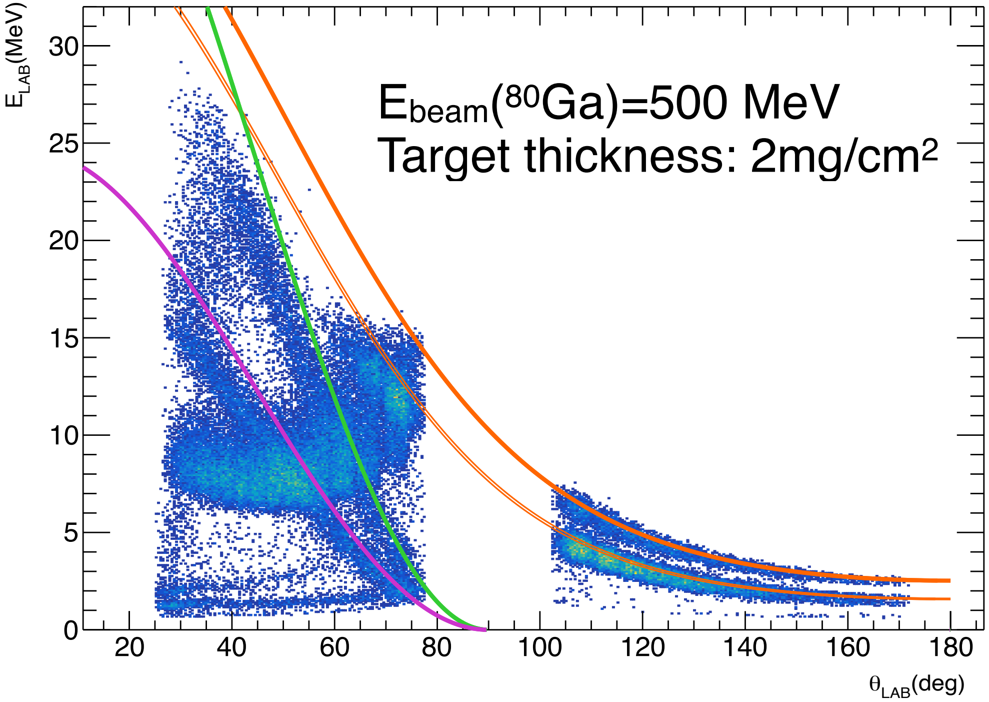
TOTAL: 18 shifts for physical runs + 3 shifts for beam preparation

Thank you

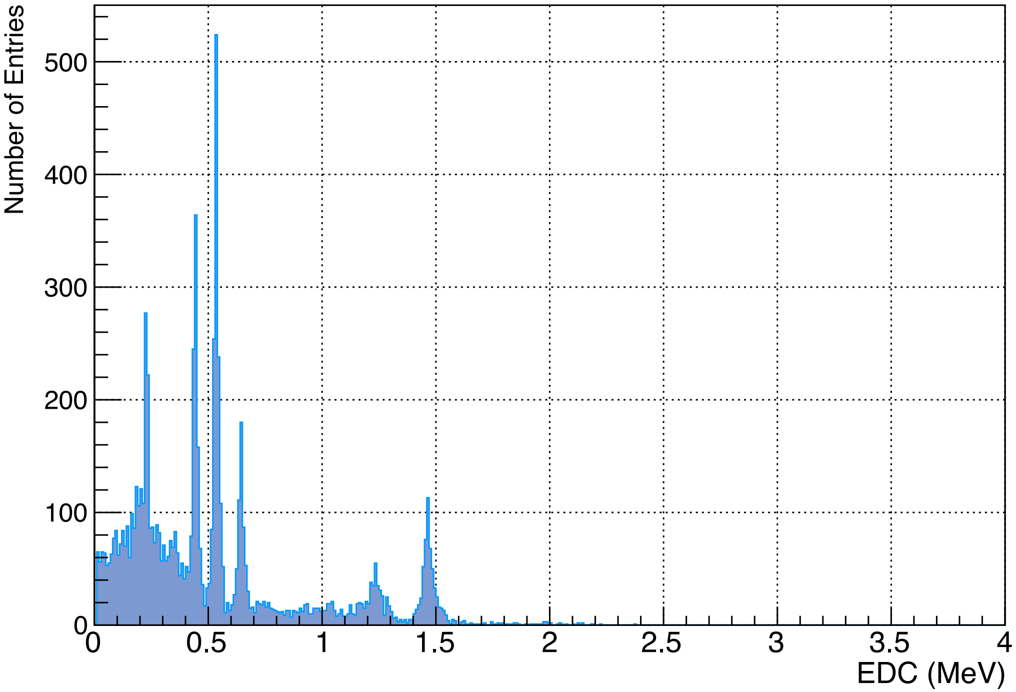
Additional slides


E_LAB(MeV)
35
30
25
20
15
10
5
0
20
40
60
80
100
120
140
160
180
θ_LAB(deg)
E_beam(80Ga)=500 MeV


E_LAB(MeV)
25
20
15
10
5
0
20
40
60
80
100
120
140
160
180
θ_LAB(deg)
E_beam(80Ga)=380 MeV



E_{LAB}(MeV)
30
25
20
15
10
5
0
20
40
60
80
100
120
140
160
180
θ_{LAB}(deg)
$E_{beam}(^{80}Ga)$=500 MeV
Target thickness: 2mg/cm^2



Number of Entries
500
400
300
200
100
0
0
0.5
1
1.5
2
2.5
3
3.5
4
EDC (MeV)

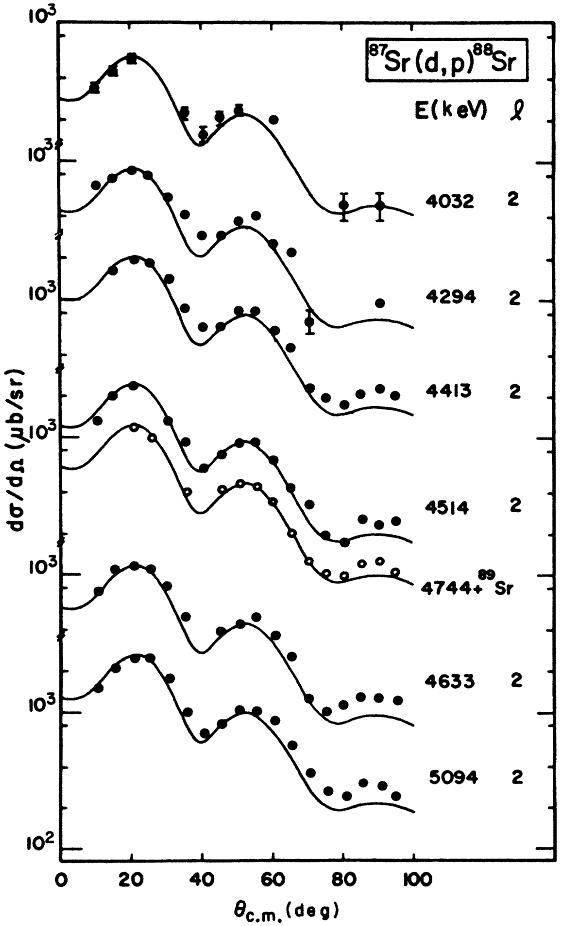


FIG. 8. Measured differential cross sections and DWBA fits for $l=2$ transitions. All fits are based on NLFR calculations using L/B parameters.

TABLE V. Summary of (d,p) results for levels in ^{88}Sr.

Level No.[a]	E^* (keV)	Cosman and Slater[a] l	Cosman and Slater[a] G_{lJ}[c]	This experiment[b] l	This experiment[b] G_{lj}^{88}	This experiment[b] G_{lj}^{89}	This experiment[b] J^π (assumed)[d]	This experiment[b] S_{lj}^{88}
1	(1836)	2	0.126	2	(0.13)		2^+	0.25
5	4032	2	0.279	2	0.35		2^+	0.71
6	4294	2	0.376	2	0.53		4^+	0.59
7	4413	2	0.875	2	1.18		$[5]^+$	1.07
8	(4450)	2	0.083	(2)	(~0.10)		$[4]^+$	(0.11)
10	4514	2	1.080	2	1.31		$[6]^+$	1.00
12	4633	2	0.564	2	0.68		$[3]^+$	0.97
13	4744	2	0.805	2	0.14	5.86	$[4]^+$	0.28(0.16)
17	5094	2	1.040	2	1.33		$[7]^+$	0.89
			5.228		5.75	5.86		
15	4873[e]	0	0.230	0	0.24[e]		$[4]^+$	0.26[e]
21	5416	0	0.105	0	0.13		$[5]^+$	0.12
22	5466	0	0.563	0	0.61		4^+	0.67
23	(5506)	0	0.027	(0)	<0.01			
25	5729	0	0.789	0	0.94		$[5]^+$	0.85
26	(5780)	0	0.405	0	0(±0.03)	1.92		
32	(6214)	0	0.031	(0)	(~0.03)			
			2.150		1.95	1.92		

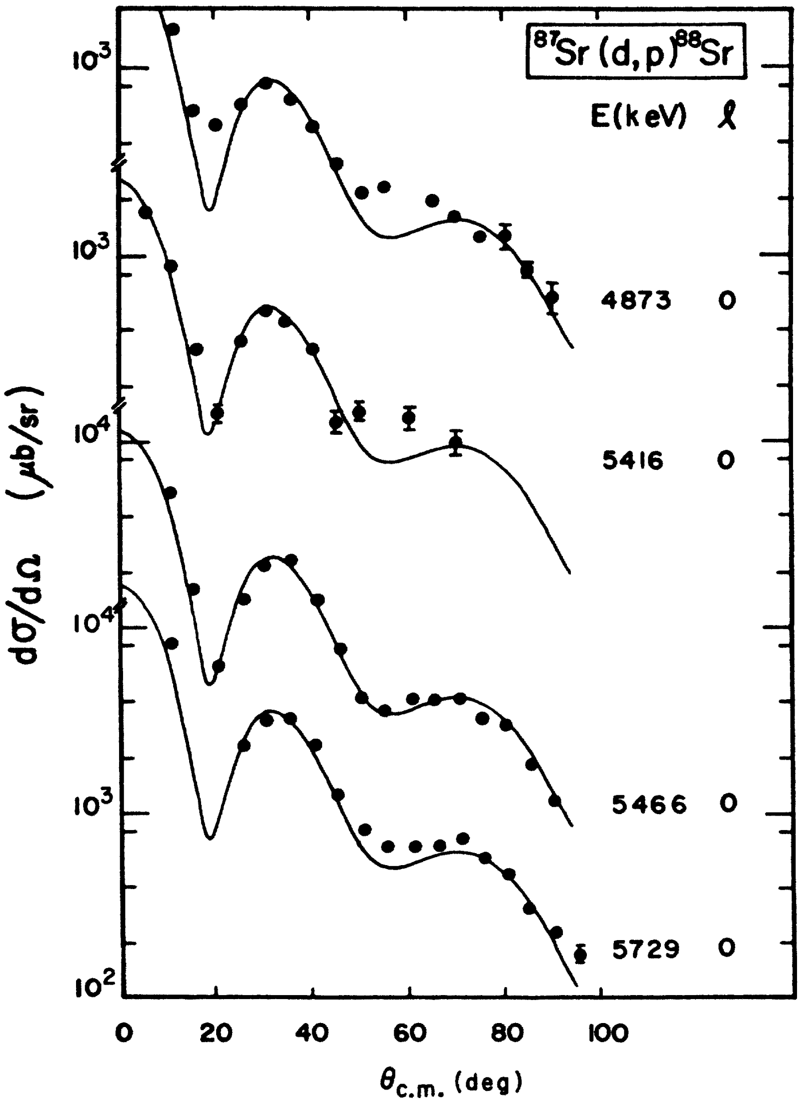
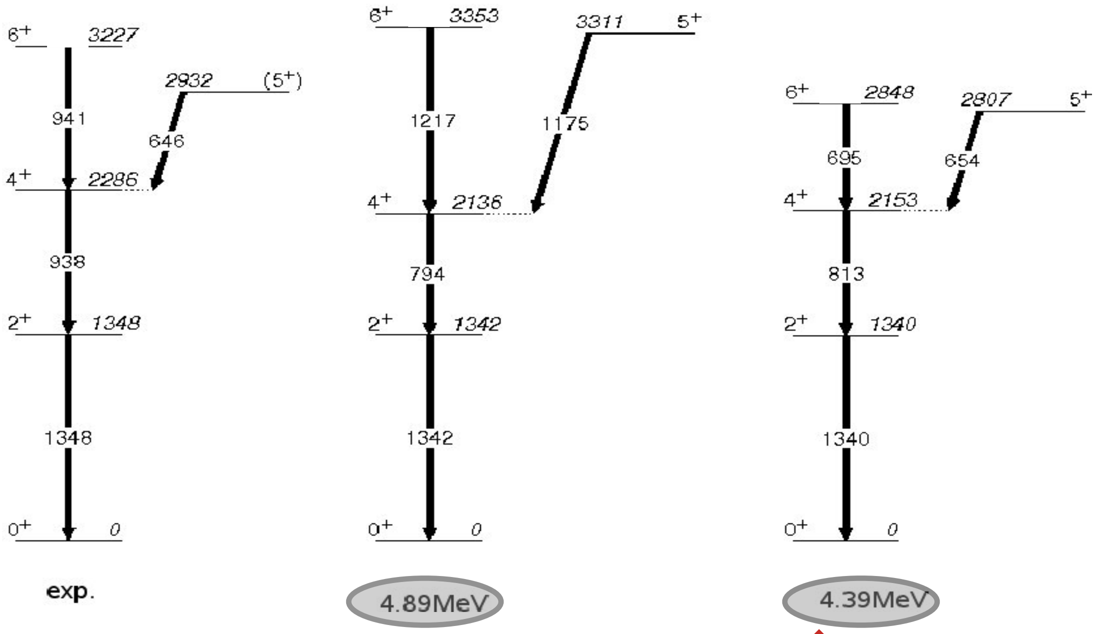


FIG. 9. Measured differential cross sections and DWBA fits for $l = 0$ transitions. All fits are based on NLFR calculations using L/B parameters.

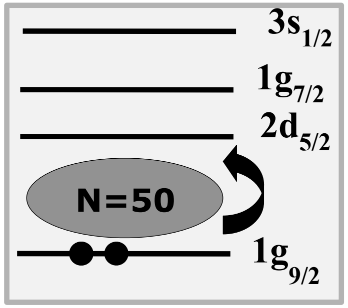
Low-lying states are mainly based on proton excitations

Information can be derived from high spin states

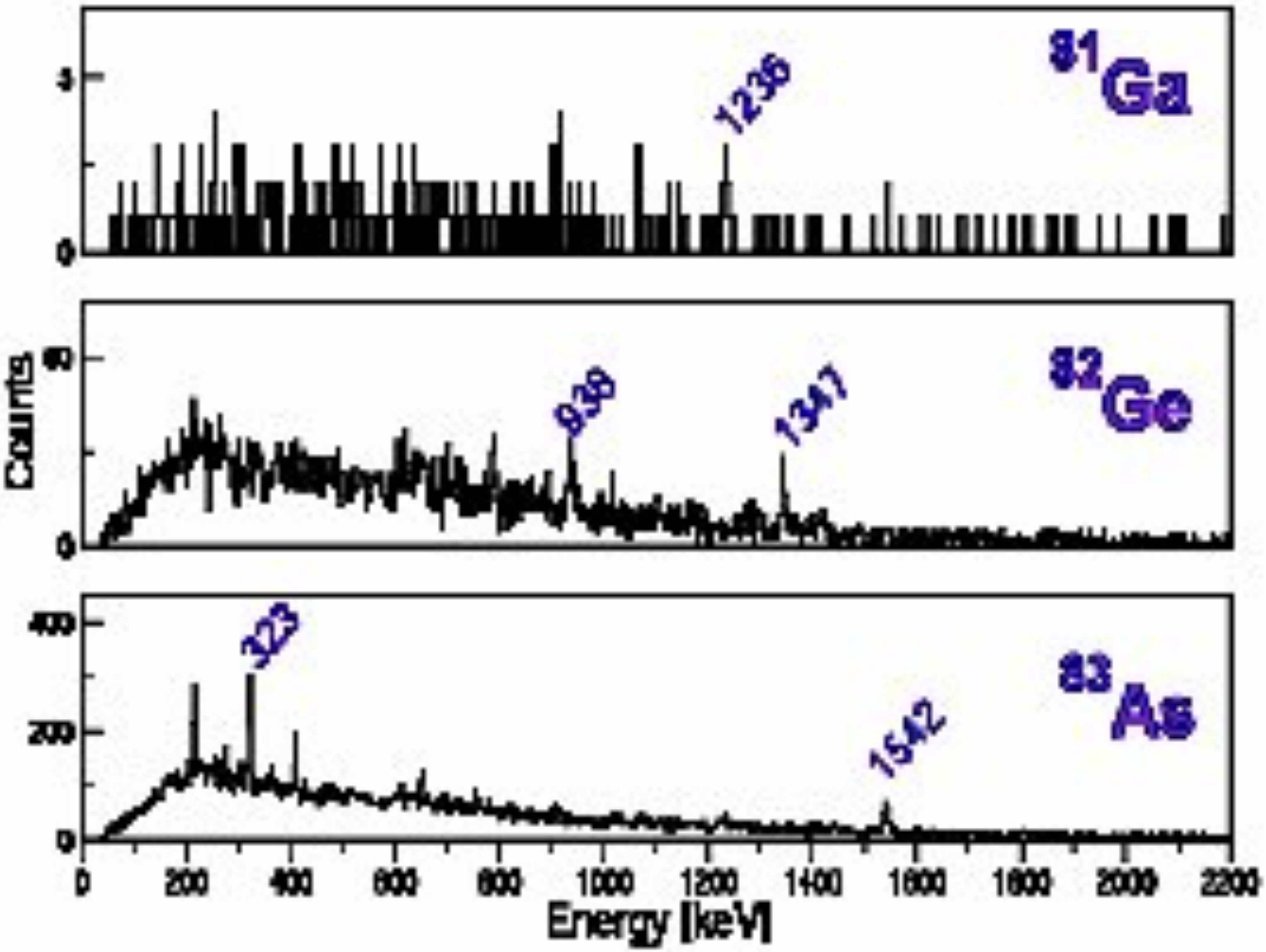
^{82}Ge

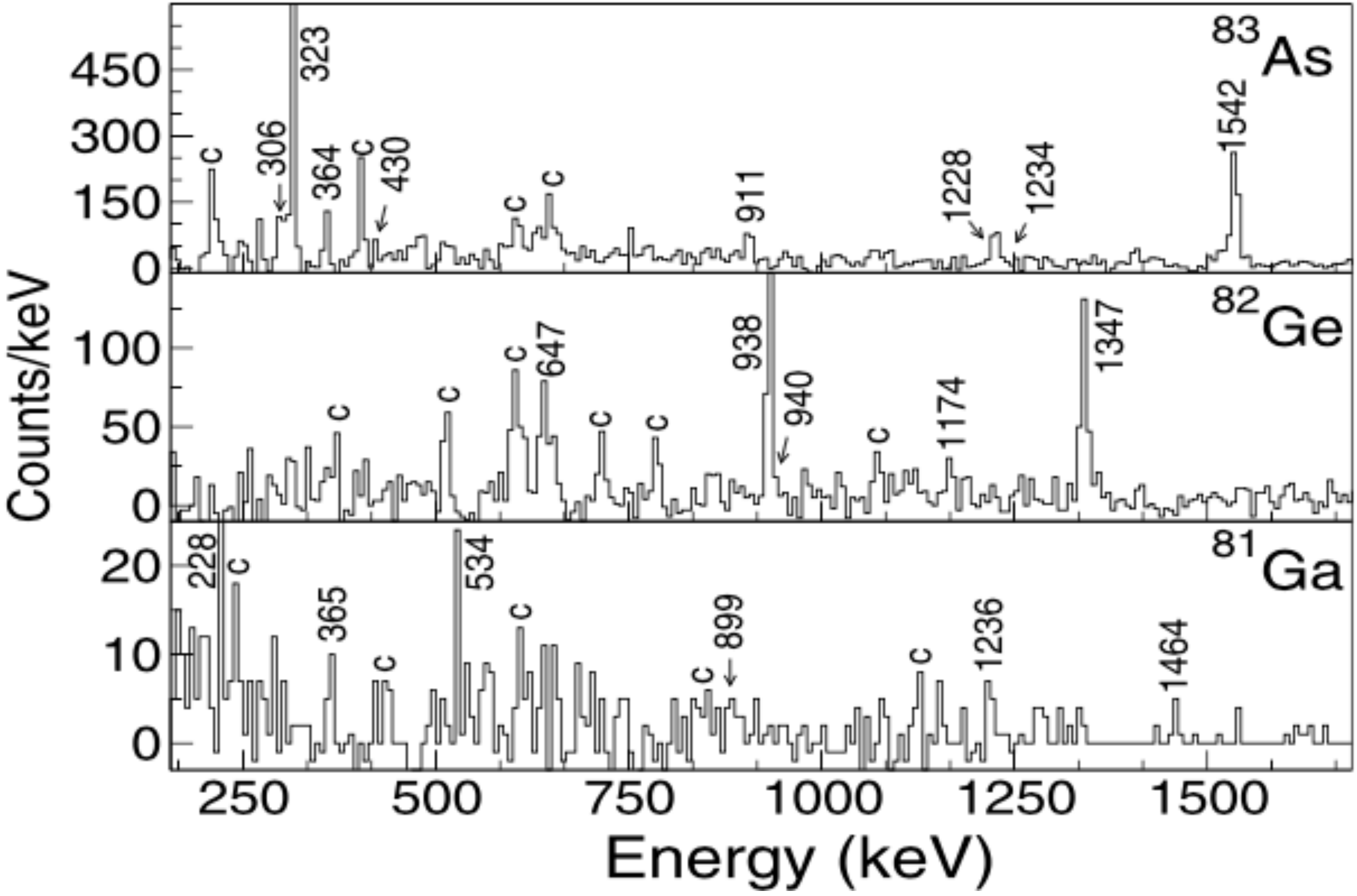


4.7 MeV



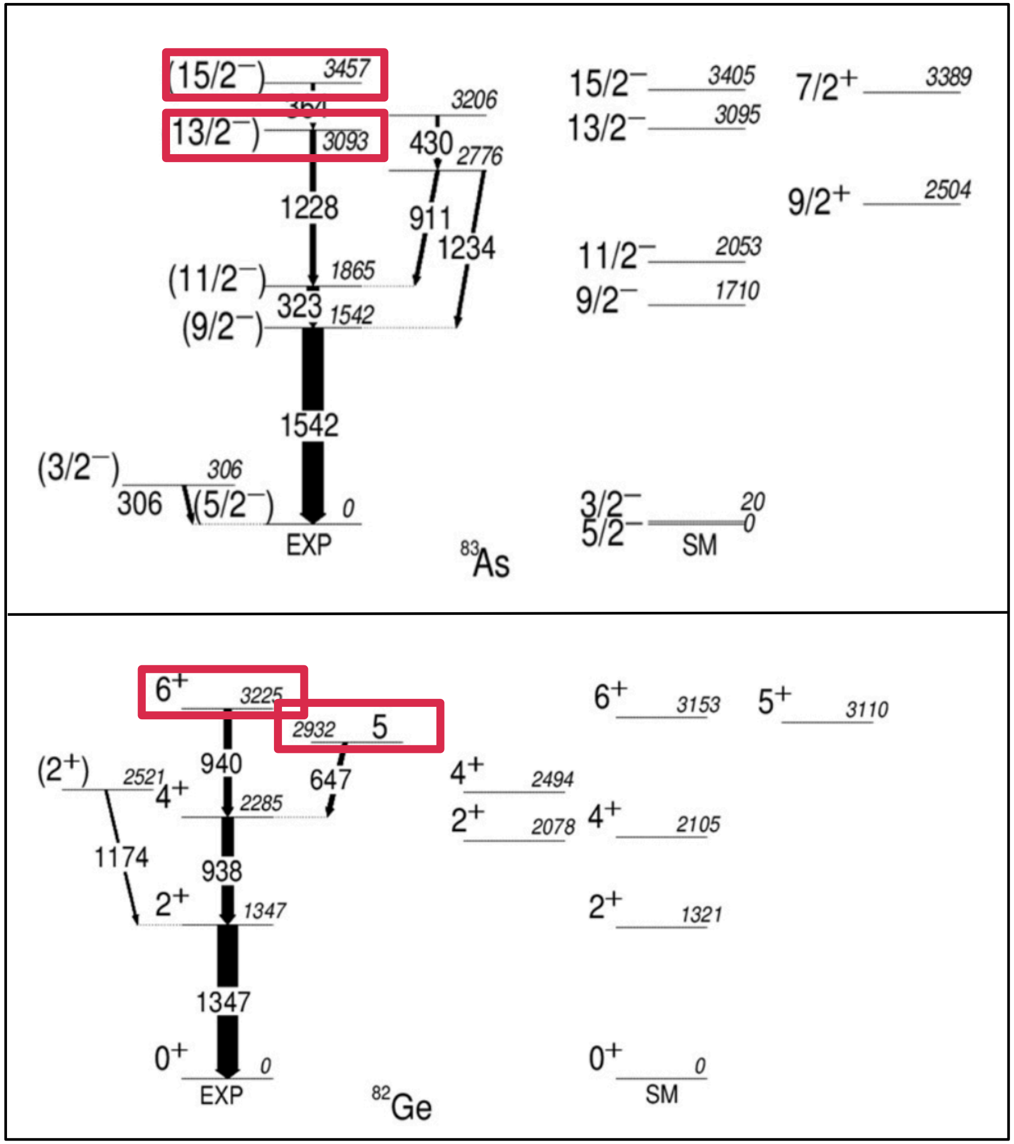
2p-2h excitations across the N=50shell to $2d_{5/2}$-$1g_{7/2}$-$3s_{1/2}$ for different shell gap values


5
0
81Ga
1236
50
0
82Ge
939
1347
Counts
400
200
0
83As
323
1542
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
Energy [keV]



Counts/keV
Energy (keV)
83As
82Ge
81Ga
0
150
300
450
0
50
100
0
10
20
250
500
750
1000
1250
1500
c
306
323
364
c
430
c
c
911
1228
1234
1542
c
c
c
c
647
c
c
938
940
c
1174
1347
228
c
365
c
534
c
c
899
c
1236
1464

Equivalent of 5+,6+ states in ^{82}Ge is found to be 13/2-, 15/2- in ^{83}As



SM Calculations:

A.F. Lisetskiy, B.A. Brown, M. Horoi, H. Grawe, Phys. Rev. C 70 (2004) 044314.

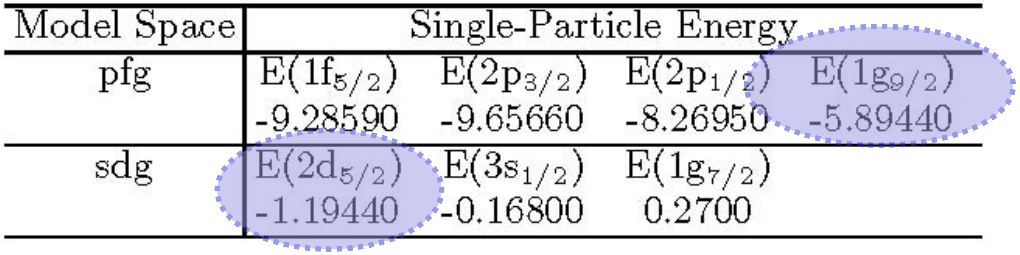
Interaction: JJ4B + SDI

Model spaces: *pfg9+sdg*

Inert Core nucleus: ^{56}Ni

Tensor interactions are included

The SPEs relative to the ^{56}Ni core have been derived from the SPEs with respect to the doubly-magic ^{78}Ni core.

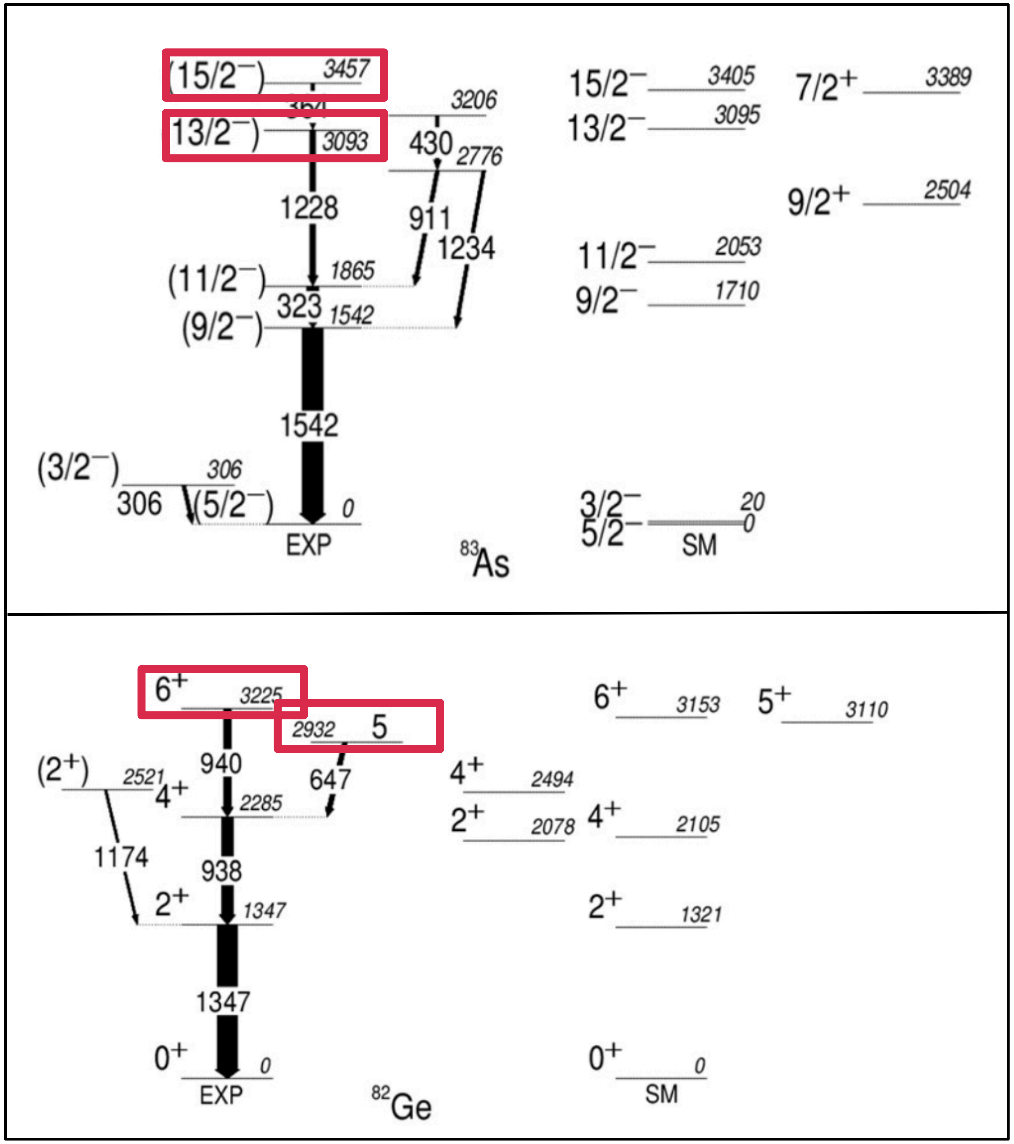


Model Space	Single-Particle Energy			
pfg	$E(1f_{5/2})$ -9.28590	$E(2p_{3/2})$ -9.65660	$E(2p_{1/2})$ -8.26950	$E(1g_{9/2})$ -5.89440
sdg	$E(2d_{5/2})$ -1.19440	$E(3s_{1/2})$ -0.16800	$E(1g_{7/2})$ 0.2700	

$$\boxed{E(\nu d_{5/2} - \nu g_{9/2}) = \text{parameter}}$$

ES et al.,Nucl. Phys. A 893, 1-12 (2012)

Equivalent of 5$^+$,6$^+$ states in ^{82}Ge is found to be 13/2$^-$, 15/2$^-$ in ^{83}As



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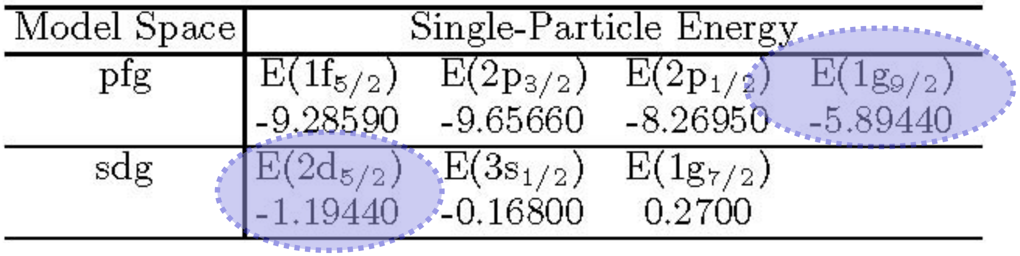
Inert Core nucleus: ^{56}Ni

Tensor interactions are included

The SPEs relative to the ^{56}Ni core have been derived from the SPEs with respect to the doubly-magic ^{78}Ni core.

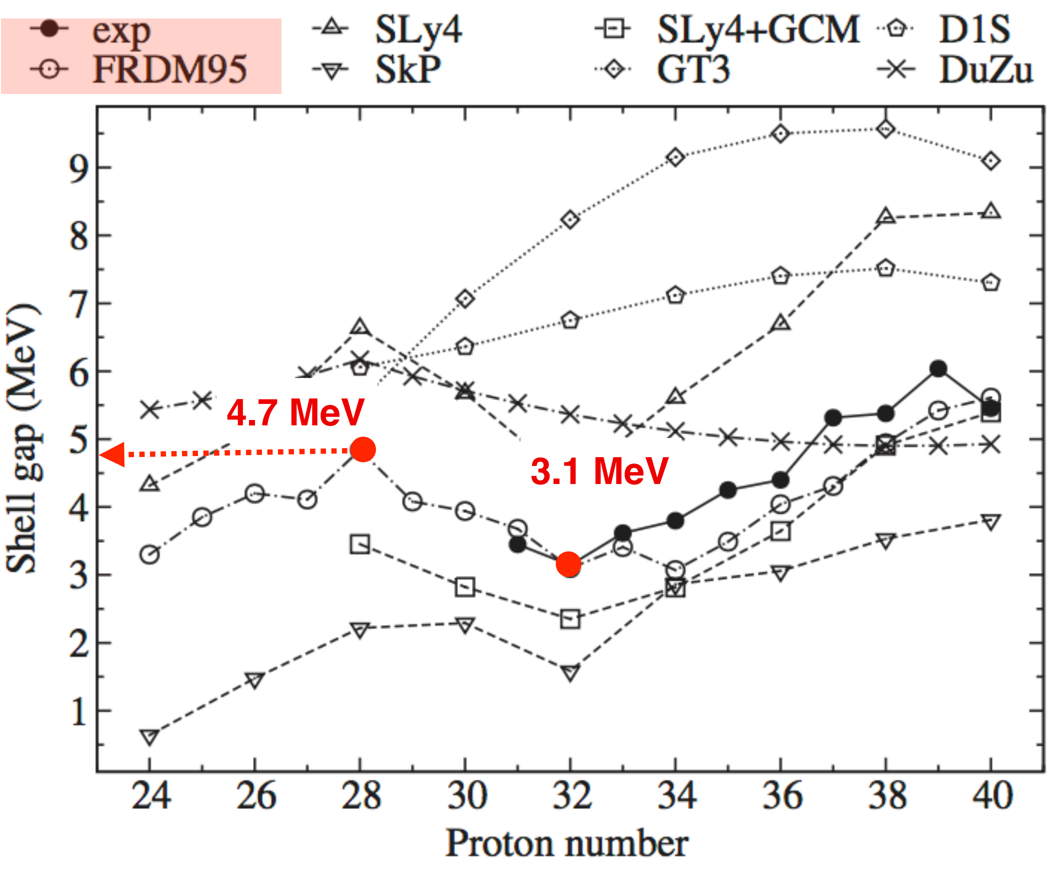


Model Space	Single-Particle Energy			
pfg	$E(1f_{5/2})$ -9.28590	$E(2p_{3/2})$ -9.65660	$E(2p_{1/2})$ -8.26950	$E(1g_{9/2})$ -5.89440
sdg	$E(2d_{5/2})$ -1.19440	$E(3s_{1/2})$ -0.16800	$E(1g_{7/2})$ 0.2700	

$$E(\nu d_{5/2} - \nu g_{9/2}) = 4.7(3)\ \text{MeV}$$

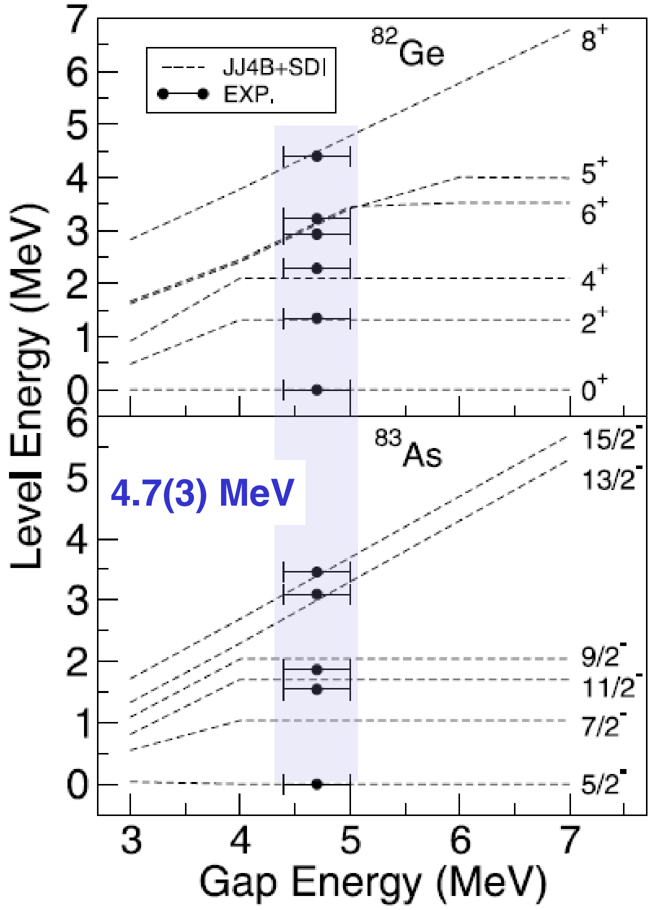
ES et al.,Nucl. Phys. A 893, 1-12 (2012)

Extrapolated Gap Value at Z=28 from mass difference: 4.7 MeV



J. Hakala et al., Phys. Rev. Lett. 101, 052502 (2008)

Gap Value at Z=28 from spectroscopy: 4.7(3) MeV



Gap Value at Z=32(^{82}Ge)

$E(\nu d_{5/2} - \nu g_{9/2})$ -V_{monopole}=4.7-1.1=**3.6(3) MeV**

ES et al.,Nucl. Phys. A 893, 1-12 (2012)