States, Levels, and Excitations in Weakly Bound Nuclei

*This material is based upon work supported by (among many others) the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under Contract Number DE-AC02-06CH11357.

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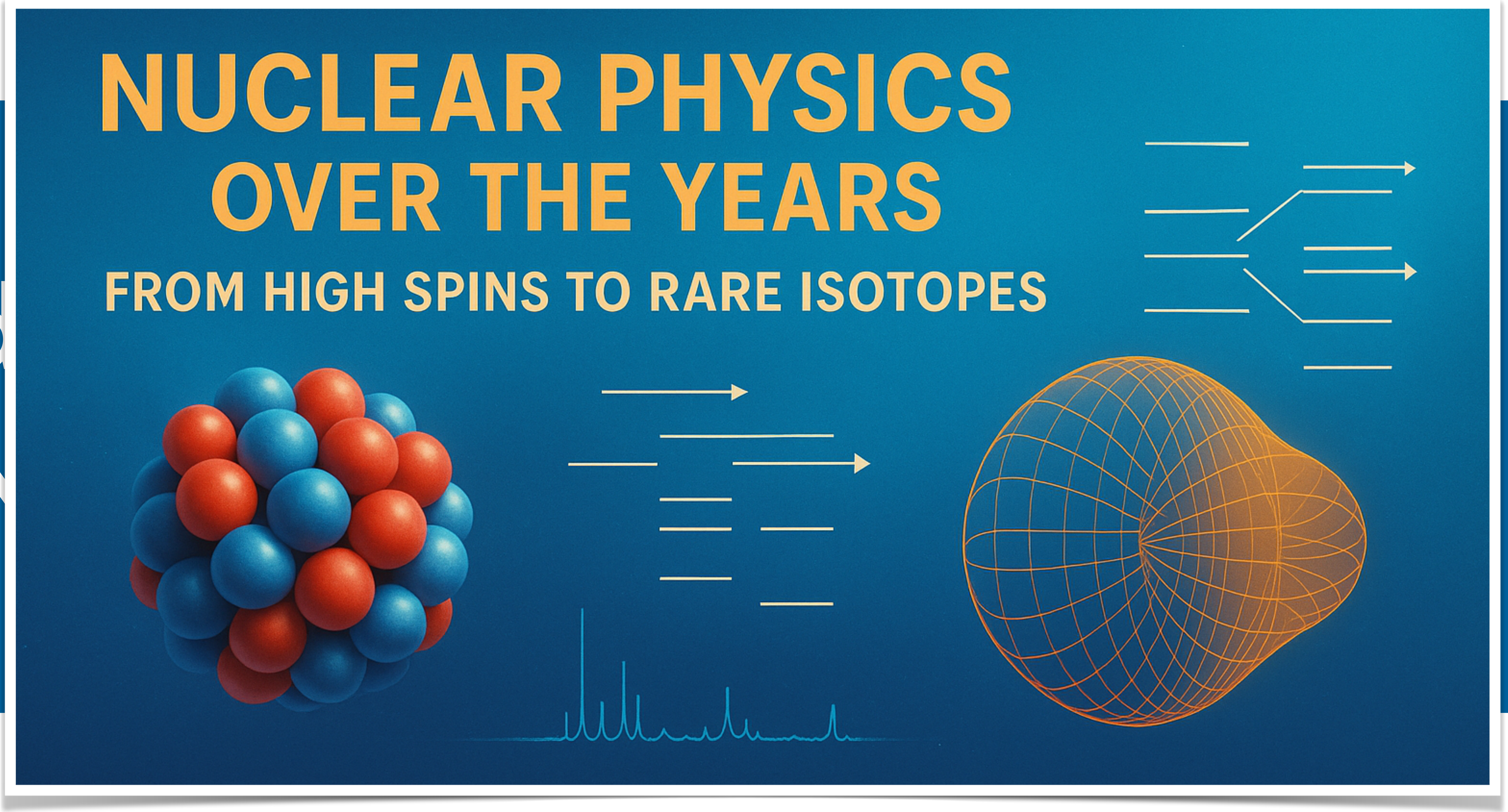
States, Levels, and
in Weakly Bound N



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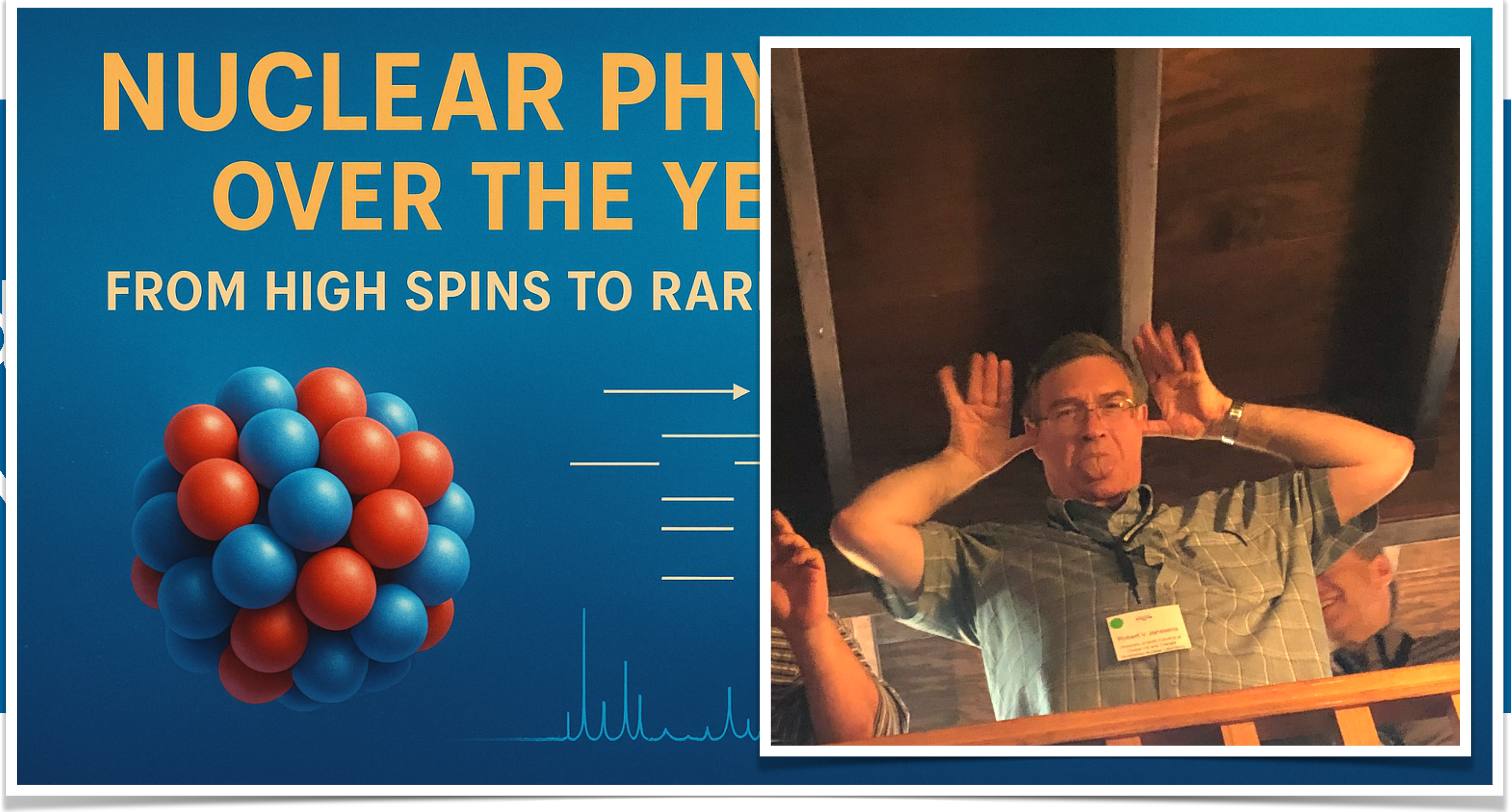

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Levels, States, and Excitations …

Robert has a fantastic writing aesthetic, from which I learned a lot … also, even as Division director, he would have manuscripts red with ink on your chair before you arrived the day after emailing him

PHYSICAL REVIEW C **80**, 017301 (2009)

Properties of excited states in ^{77}Ge

B. P. Kay,[1] C. J. Chiara,[1,2,3] J. P. Schiffer,[1] F. G. Kondev,[2] S. Zhu,[1] M. P. Carpenter,[1] R. V. F. Janssens,[1] T. Lauritsen,[1] C. J. Lister,[1] E. A. McCutchan,[1] D. Seweryniak,[1] and I. Stefanescu[1,3,4]
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(Received 30 April 2009; published 2 July 2009)

Most of the excited states in ^{77}Ge are known from transfer-reaction data: the most quantitative information is provided by the ^{76}Ge$(d,p)^{77}$Ge reaction using a polarized deuteron beam [4], where the vector analyzing powers and angular distributions of outgoing protons yield spin and parity information. From this study the following excited states had been assigned spin and parity: 159.70($1/2^-$), 224.9($9/2^+$), 504.8($5/2^+$), 629.4($3/2^-$), 884.3($5/2^+$), 1250.4($1/2^+$), 1385.0($5/2^+$), 1536($1/2^+$), 1777($1/2^+$), and 1804($3/2^+$) keV. No sign was seen of the 492-keV level, which could not be resolved next to the strongly populated 505-keV state, in that experiment. This

Also, Fig. 1 would “show”, Fig. 2 would “demonstrate”, Fig. 3 would “display”, Fig. 4 would “present”, etc., … he was also a disciplined user of hyphens …

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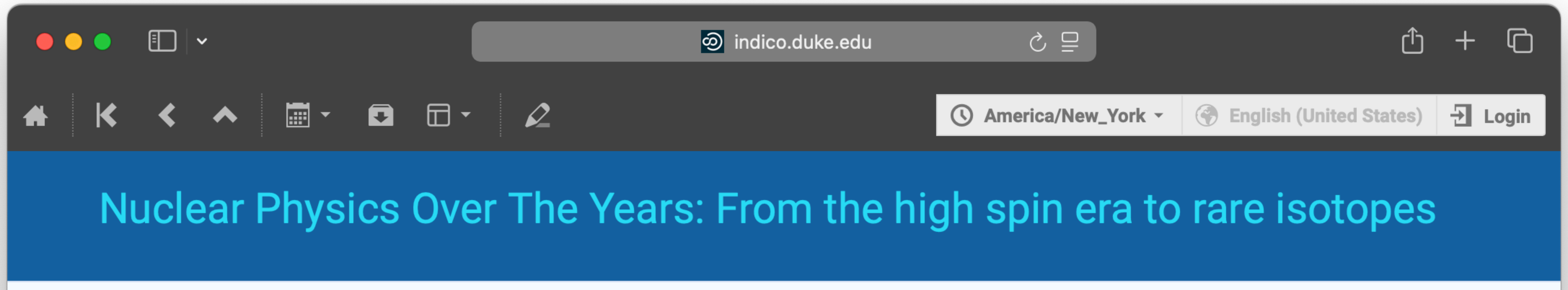

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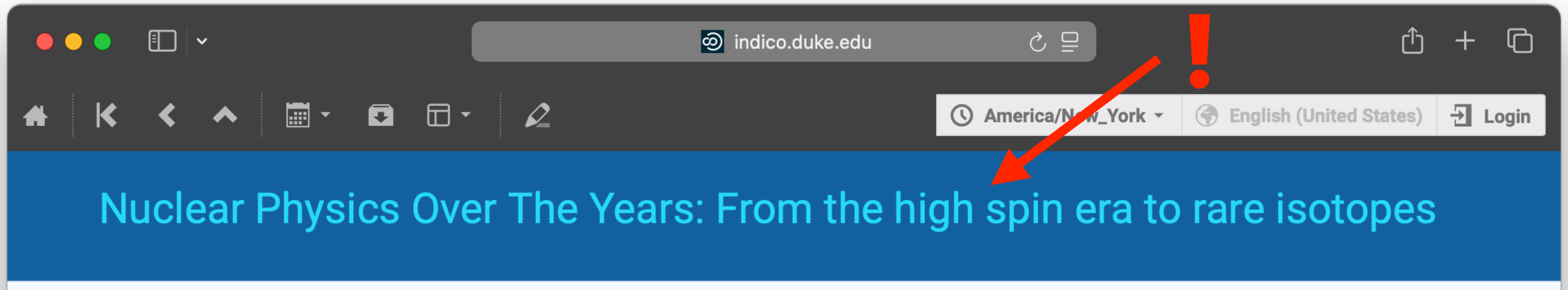

RVFJ and me

Robert technically hired me TWICE …

Sep. '81	Nov. '81	……..	2005	2007	2010	2013	……	2025
RVFJ starts at ANL	BPK born		RVFJ/ Gade at NSCL	Postdoc (RVFJ acting DD)	BPK to York	Return to ANL (RVFJ DD)		Celebrations

I impressed Robert with my eating at first. In East Lansing, he personally paid for and watched me eat a giant slice of NY cheesecake in awe … I would go on to impress the likes of Ben Mottelson with my ability to consume (sadly, not my physics)!

PHYSICAL REVIEW C **73**, 037309 (2006)

Spectroscopy of the odd-odd *fp*-shell nucleus ^{52}Sc from secondary fragmentation

A. Gade,[1] R. V. F. Janssens,[2] D. Bazin,[1] B. A. Brown,[1,3] C. M. Campbell,[1,3] M. P. Carpenter,[2] J. M. Cook,[1,3] A. N. Deacon,[4] D.-C. Dinca,[1,3] S. J. Freeman,[4] T. Glasmacher,[1,3] B. P. Kay,[4] P. F. Mantica,[1,5] W. F. Mueller,[1] J. R. Terry,[1,3] and S. Zhu[2]
[1]National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA
[2]Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA
[3]Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA
[4]Department of Physics and Astronomy, Schuster Laboratory, University of Manchester, Manchester M13 9PL, United Kingdom
[5]Department of Chemistry, Michigan State University, East Lansing, Michigan 48824, USA
(Received 17 January 2006; published 22 March 2006)

PHYSICAL REVIEW C **74**, 021302(R) (2006)

Cross-shell excitation in two-proton knockout: Structure of ^{52}Ca

A. Gade,[1,2] R. V. F. Janssens,[3] D. Bazin,[1] B. A. Brown,[1,2] C. M. Campbell,[1,2] M. P. Carpenter,[3] J. M. Cook,[1,2] A. N. Deacon,[5] D.-C. Dinca,[1,2] B. Fornal,[4] S. J. Freeman,[5] T. Glasmacher,[1,2] P. G. Hansen,[1,2] B. P. Kay,[5] P. F. Mantica,[1,6] W. F. Mueller,[1] J. R. Terry,[1,2] J. A. Tostevin,[7] and S. Zhu[3]
[1]National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA
[2]Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA
[3]Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA
[4]Institute of Nuclear Physics, Polish Academy of Science, PL-31342 Cracow, Poland
[5]School of Physics and Astronomy, Schuster Laboratory, University of Manchester, Manchester M13 9PL, United Kingdom
[6]Department of Chemistry, Michigan State University, East Lansing, Michigan 48824, USA
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(Received 23 March 2006; published 16 August 2006)

PHYSICAL REVIEW C **74**, 047302 (2006)

One-neutron knockout in the vicinity of the $N = 32$ sub-shell closure: ^{9}Be(^{57}Cr,^{56}Cr+γ)X

A. Gade,[1,2] R. V. F. Janssens,[3] D. Bazin,[1] B. A. Brown,[1,2] C. M. Campbell,[1,2] M. P. Carpenter,[3] J. M. Cook,[1,2] A. N. Deacon,[4] D.-C. Dinca,[1,2] S. J. Freeman,[4] T. Glasmacher,[1,2] M. Horoi,[5] B. P. Kay,[4] P. F. Mantica,[1,6] W. F. Mueller,[1] J. R. Terry,[1,2] J. A. Tostevin,[7] and S. Zhu[3]
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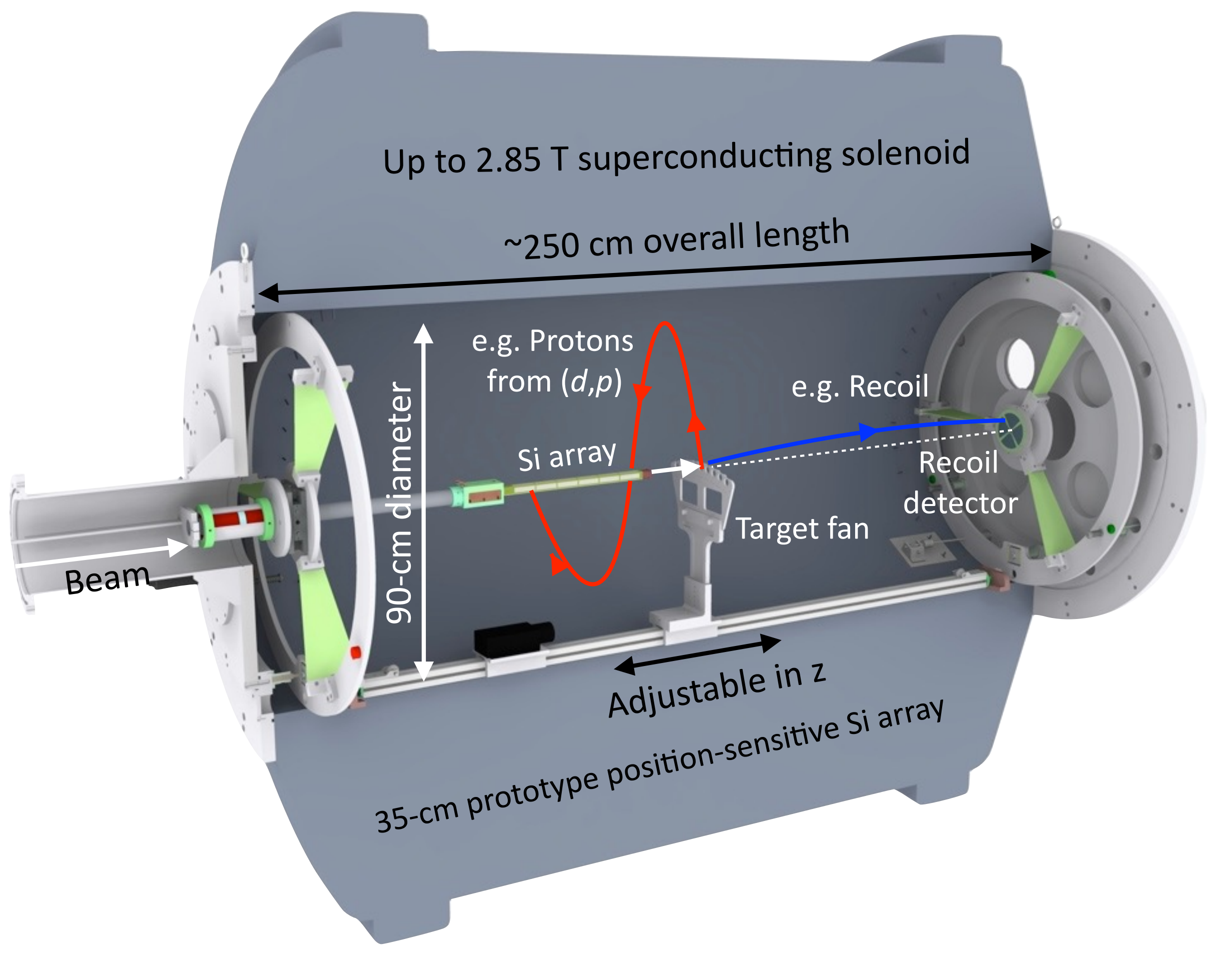
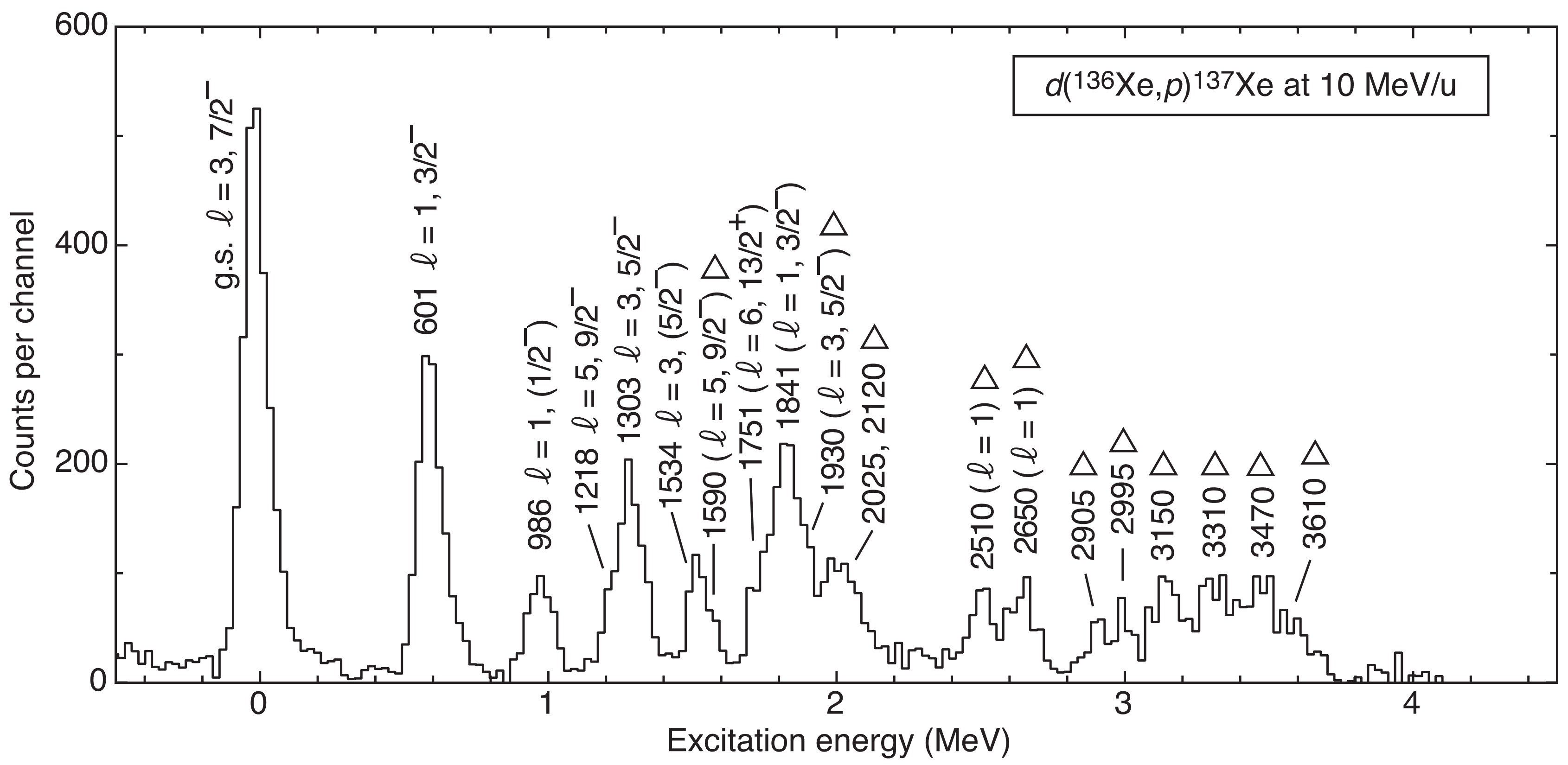
[6]Department of Chemistry, Michigan State University, East Lansing, Michigan 48824, USA
[7]Department of Physics, School of Electronics and Physical Sciences, University of Surrey, Guildford, Surrey GU2 7XH, United Kingdom
(Received 22 May 2006; published 11 October 2006)

RVFJ and energy/vision/mentorship

Robert created an energy at Argonne like no other … I was fortunate enough to be at Argonne in my early career at a very special time

Robert, likely with a little nudge here and there from John, hired me and Calem to energize the transfer-reaction program at Argonne with the advent of HELIOS, the in-flight beam program, and CARIBU, and the FRIB era …





Physics Highlight

Bridging Nuclear Shells: Neutron s-States are Different

Neutron excitations with zero angular momentum (ℓ = 0) exhibit a tendency to linger below the binding threshold, with a reluctance to become unbound from the nucleus. Their behavior near the threshold of binding is qualitatively different from neutron excitations with any other value of angular momentum, or indeed any proton excitation (Fig. 1). Recently [1], it was shown that the variation in binding energy of states with zero (ℓ = 0) and two (ℓ = 2) units of angular momentum, in isotopes of helium to oxygen with neutron numbers between 5 and 10, can be described in simple geometrical terms, hitherto not fully appreciated.

The experimental data (Fig. 2, left) reveal the striking correlation between energy differences ($E_{\ell=0} - E_{\ell=2}$) of these states with respect to the energy of ℓ = 2 neutrons, used as a reference. The trend is in excellent agreement with calculations that take into consideration simple geometric aspects of the nuclear potential [1]. Some of these data were obtained in recent measurements at ATLAS using the HELIOS spectrometer to study transfer reactions in inverse kinematics. The 'left-over' differences, which are quite small, are likely due to the action of a well-understood interaction: the tensor force (Fig. 2, right). The lingering of neutron zero-angular momentum states is associated with an increase in radius of loosely bound states that give rise to neutron halos, and leads one to speculate the existence of heavier halo nuclei, for example, around ^{78}Ni.

Ref [1]; C.R. Hoffman, B.P Kay, and J.P. Schiffer, arXiv:1311.1556 and submitted to Phys. Rev. Lett.

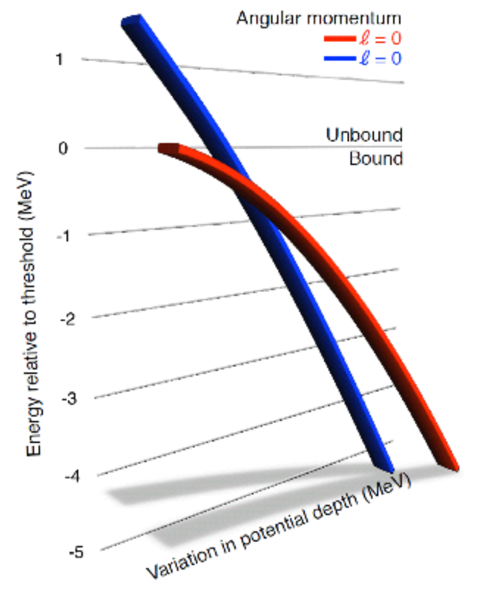


Fig1: Energy of excitations with 0 and 2 units of angular momentum in a simple potential.

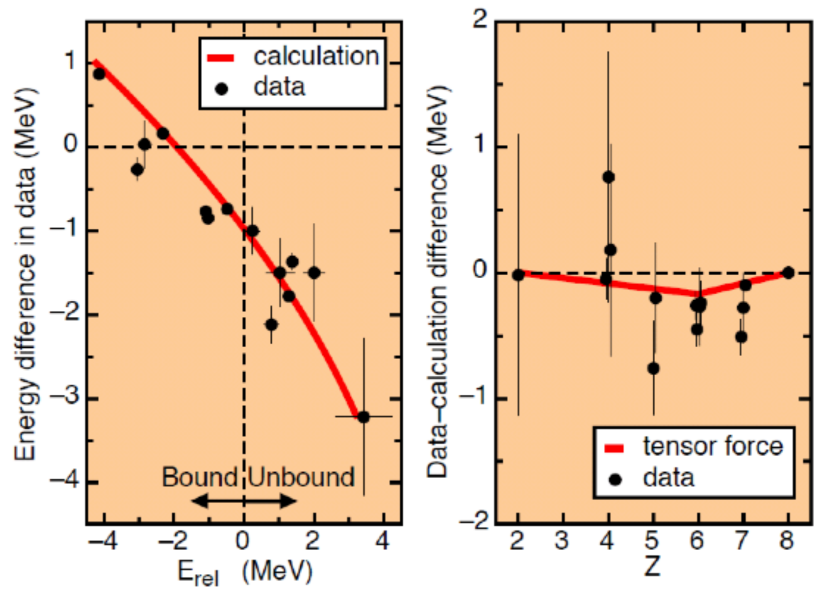
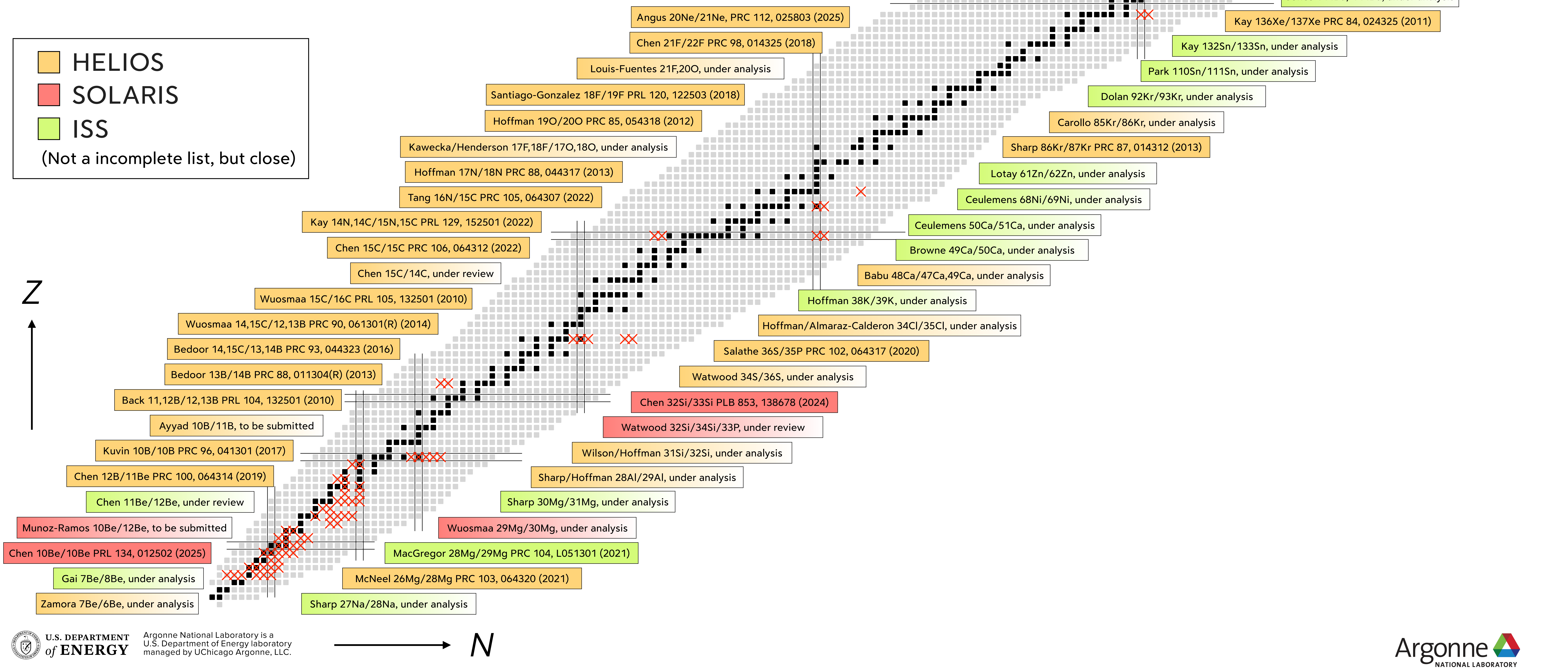


Fig 2: Trend in the data compared to calculations (left), and the remaining difference (right)

Point of contact: Robert V.F. Janssens, Phone: 2-8426

(Aside) I’m not going to mention HELIOS … much …

Solenoidal spectrometers have proven to be a highly versatile approach to studying nuclear reactions for structure, astrophysics, and applications



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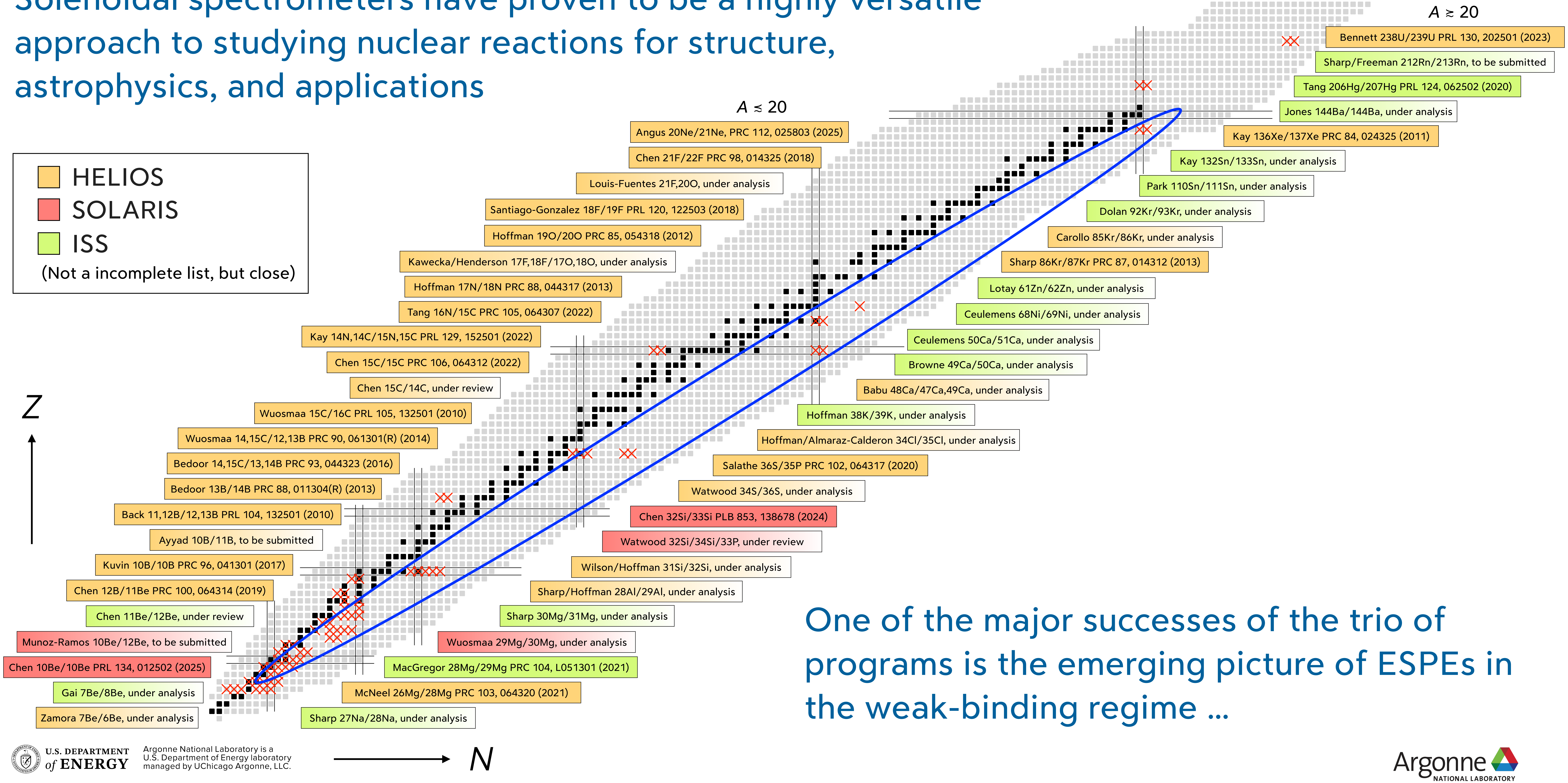

One of the major successes of the trio of programs is the emerging picture of ESPEs in the weak-binding regime …

(Aside) I'm not going to mention ^{132}Sn … much …

Longstanding fascination with ^{132}Sn as an extreme example of a doubly magic nucleus

SINGLE-PARTICLE STATES AROUND DOUBLE-MAGIC ^{132}Sn

J. Blomqvist,
Research Institute of Physics, S-104 05 Stockholm.

Abstract

Double-magic ^{132}Sn exhibits the strongest shell closure of any observed single-nucleus. The experimental data on single-particle states in the surrounding nuclei ^{131}In, ^{131}Sn, ^{133}Sn and ^{133}Sb are reviewed. Single-particle energies are calculated with a standard Woods-Saxon potential, and corrections resulting from a comparison with the ^{208}Pb region are applied.

1. The shell closure in ^{132}Sn

This implies that nuclear reaction studies are essentially excluded. The nearest approach [5] seems to be the ^{136}Xe(d,^{3}He) reaction which leads to ^{135}I, 3 protons away from ^{132}Sn. The production method for ^{132}Sn and its closest neighbours is in practice limited to fission of actinides, in which case the heavy fragment has a reasonable chance to end up near ^{132}Sn. Spectroscopic studies of specific fission fragments have so far required the use of mass separation to clear up the spectra.

The presently known levels in ^{132}Sn are shown in Fig.2.

J. Blomqvist, 4th International Conference on Nuclei Far From Stability, CERN-81-09-V2 (1981)

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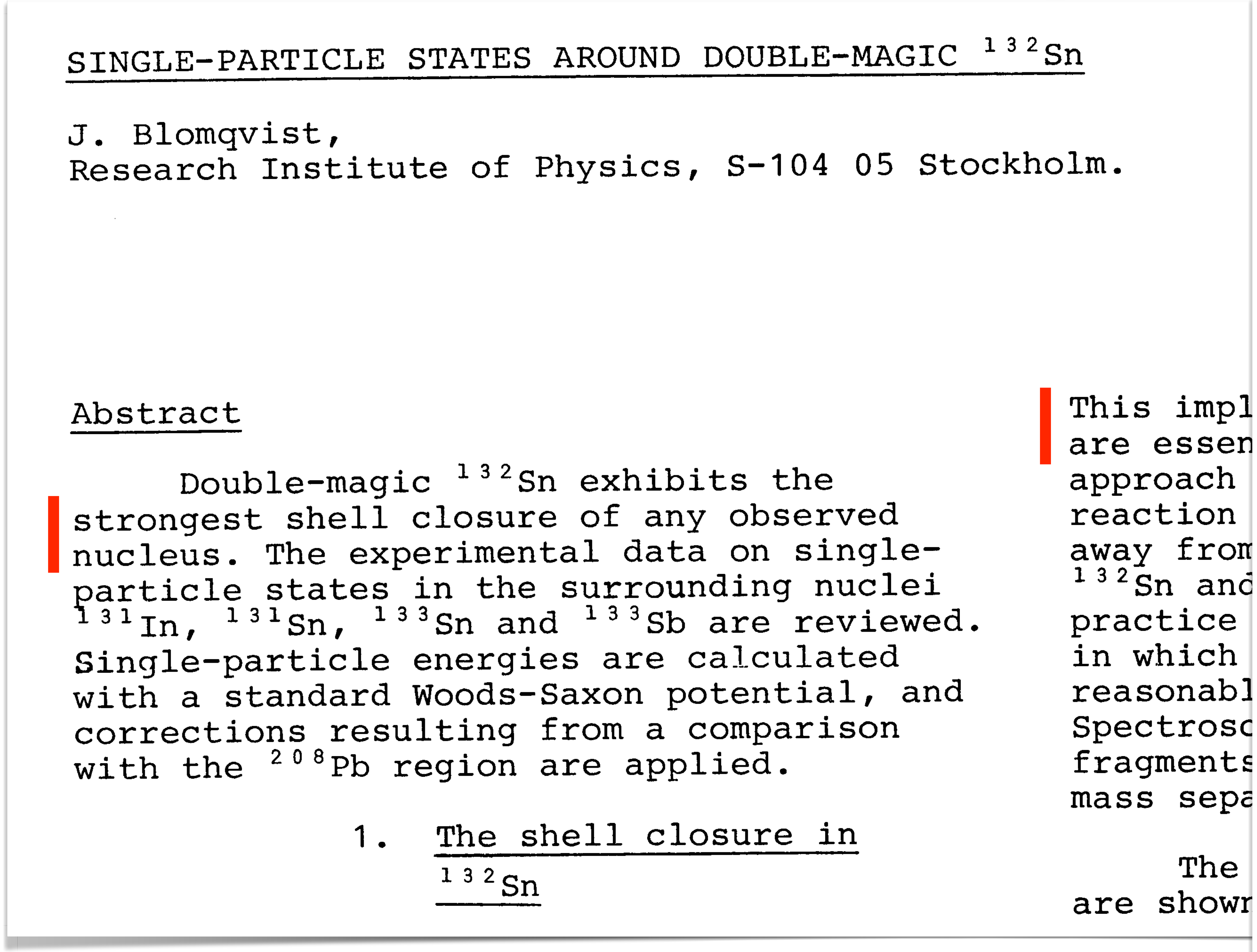

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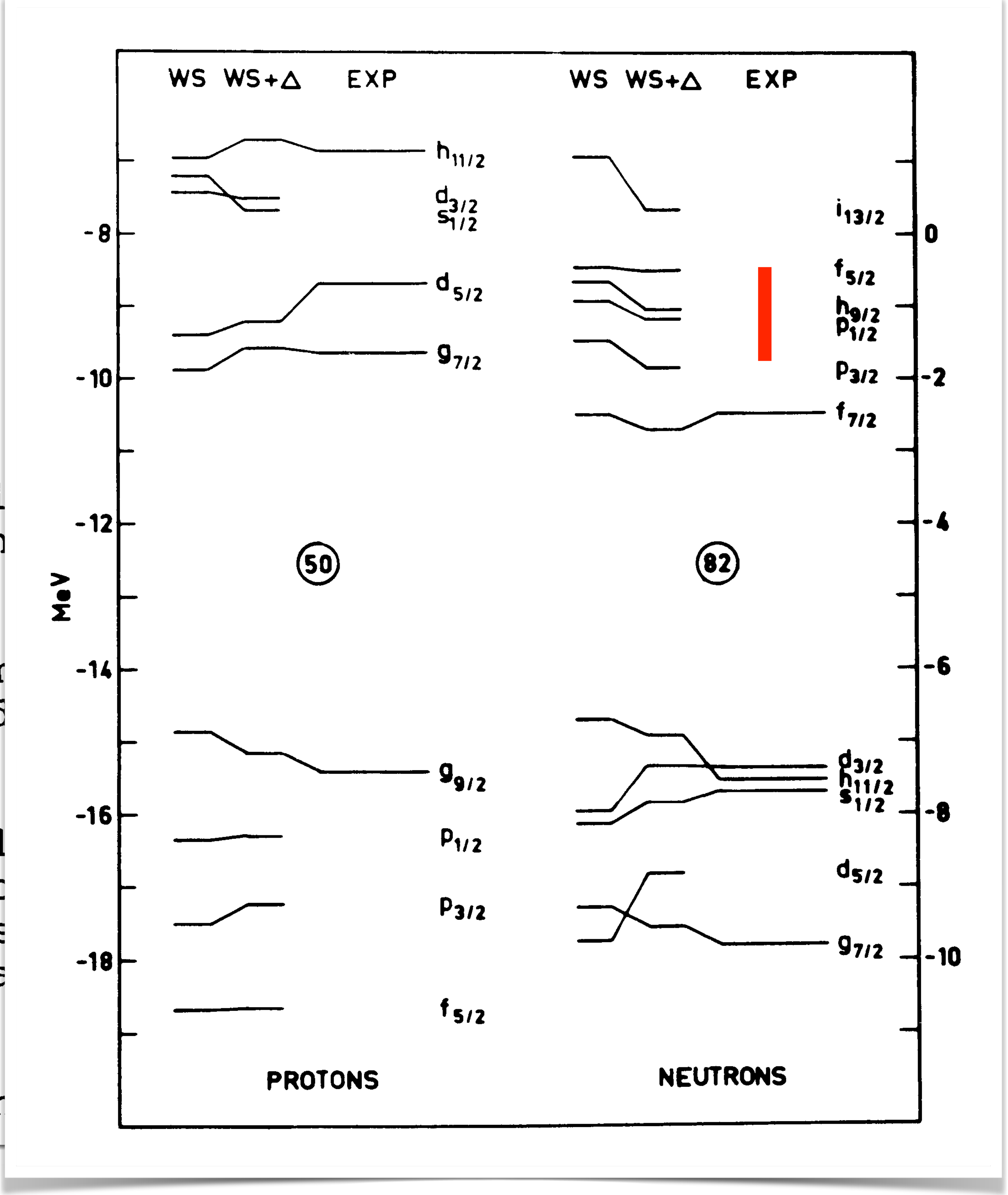

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Longstanding fascination with ^{132}Sn as an extreme example of a doubly magic nucleus

SINGLE-PAR

J. Blomqvi
Research I

Abstract

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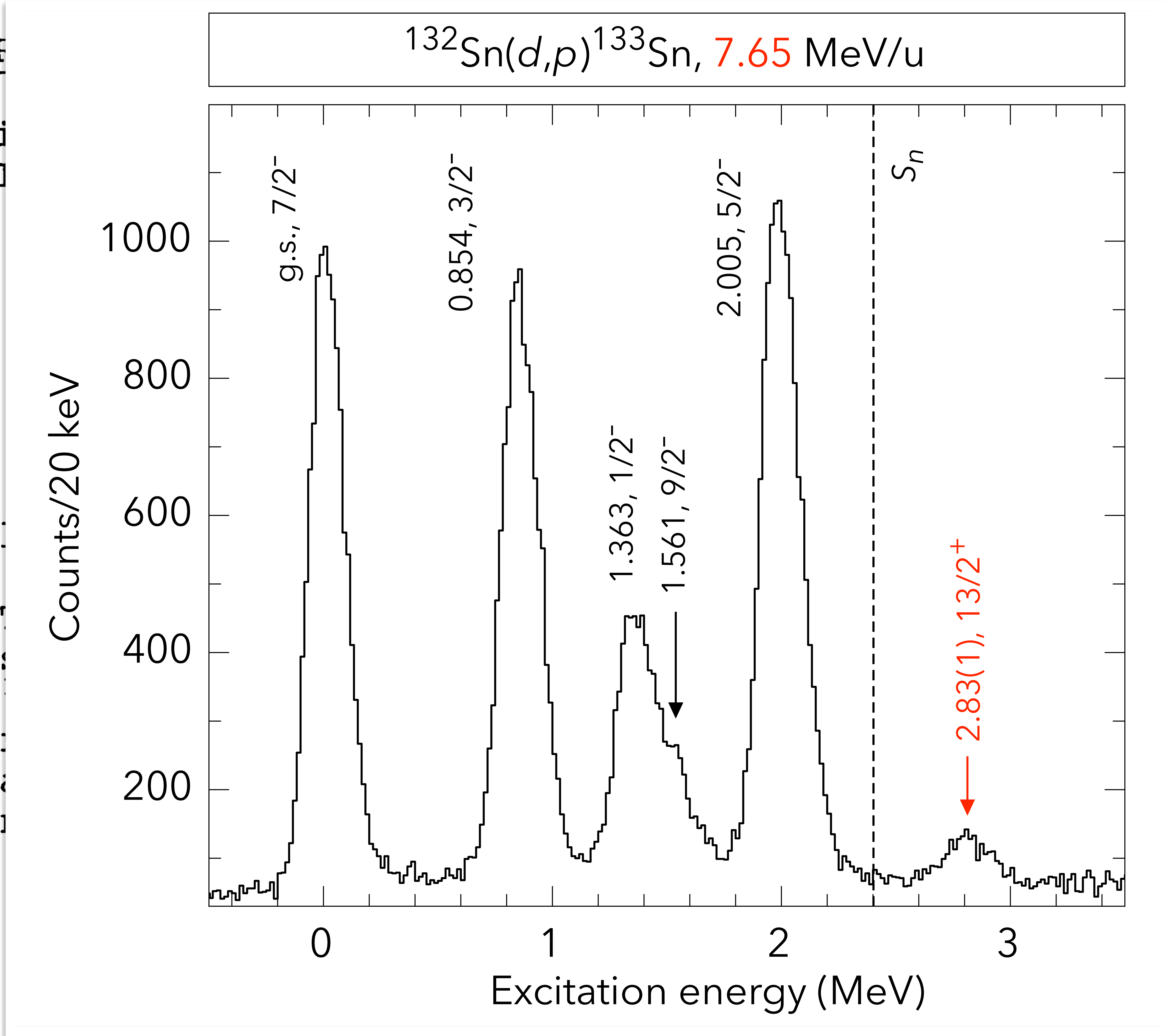
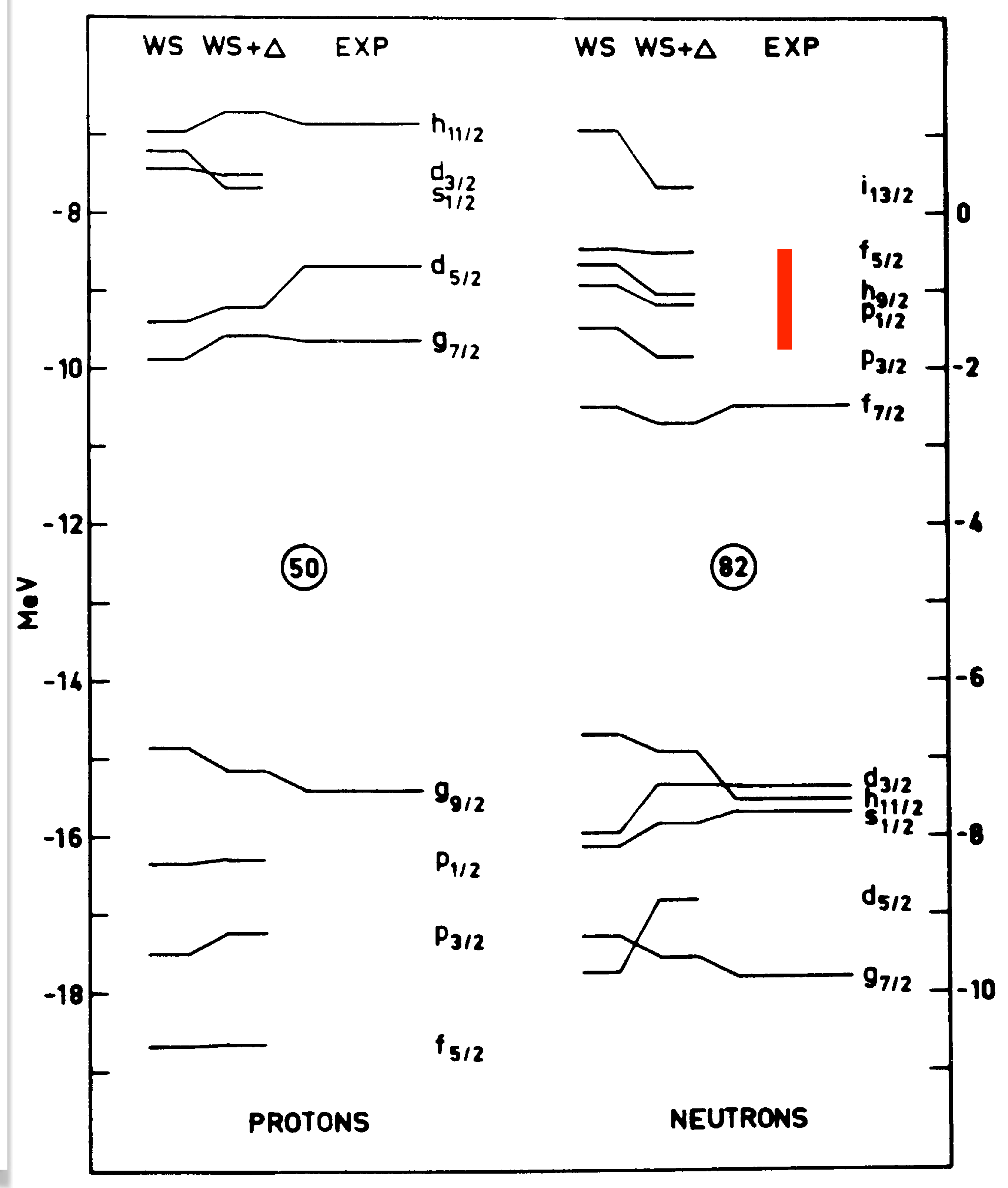


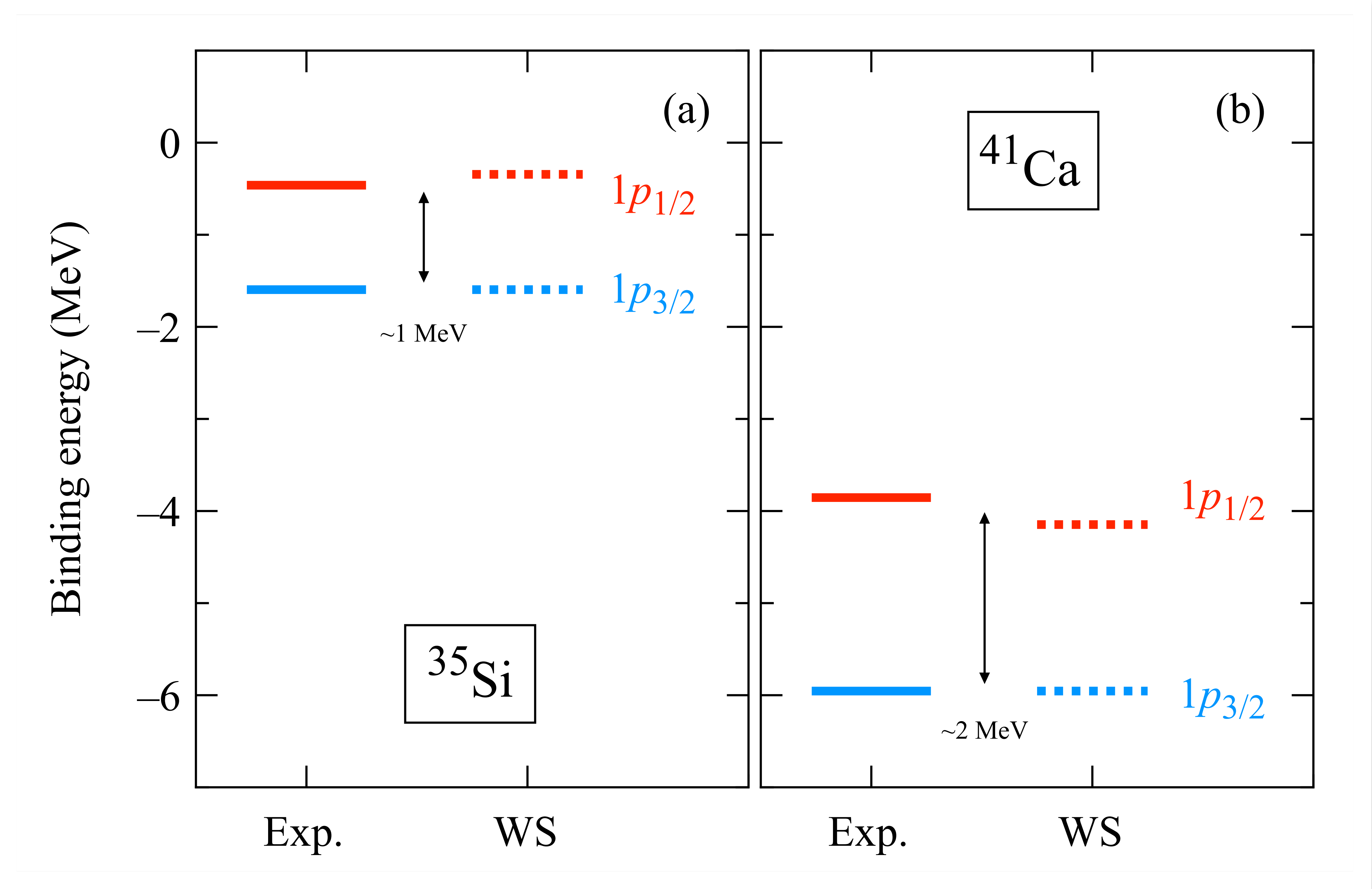


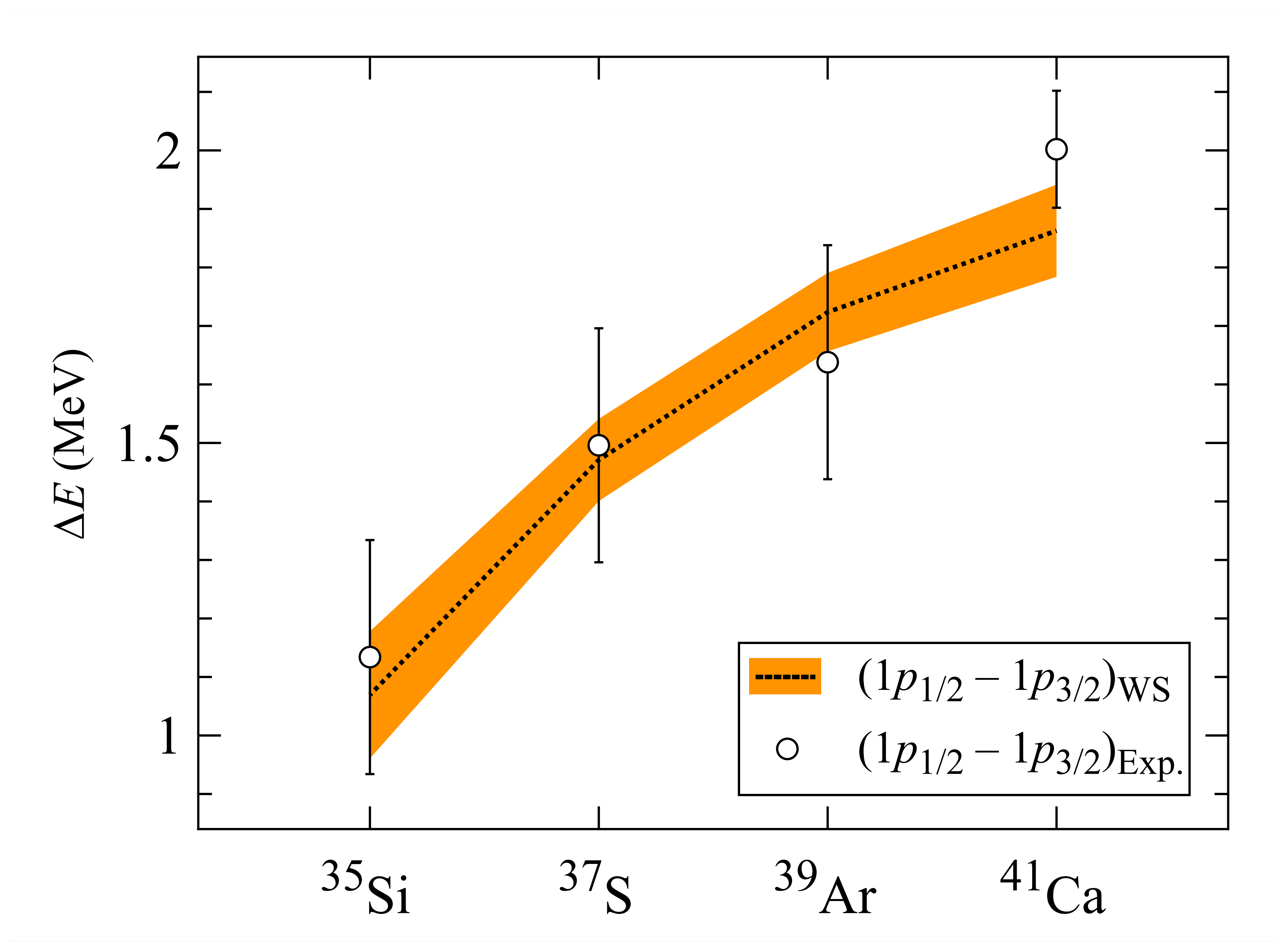
J. Blomqvist, 4th International Conference on Nuclei Far From Stability, CERN-81-09-V2 (1981)

The bubble nucleus story and weak binding

Essentially wholly described by simple geometrical considerations

****SO strength not changed****

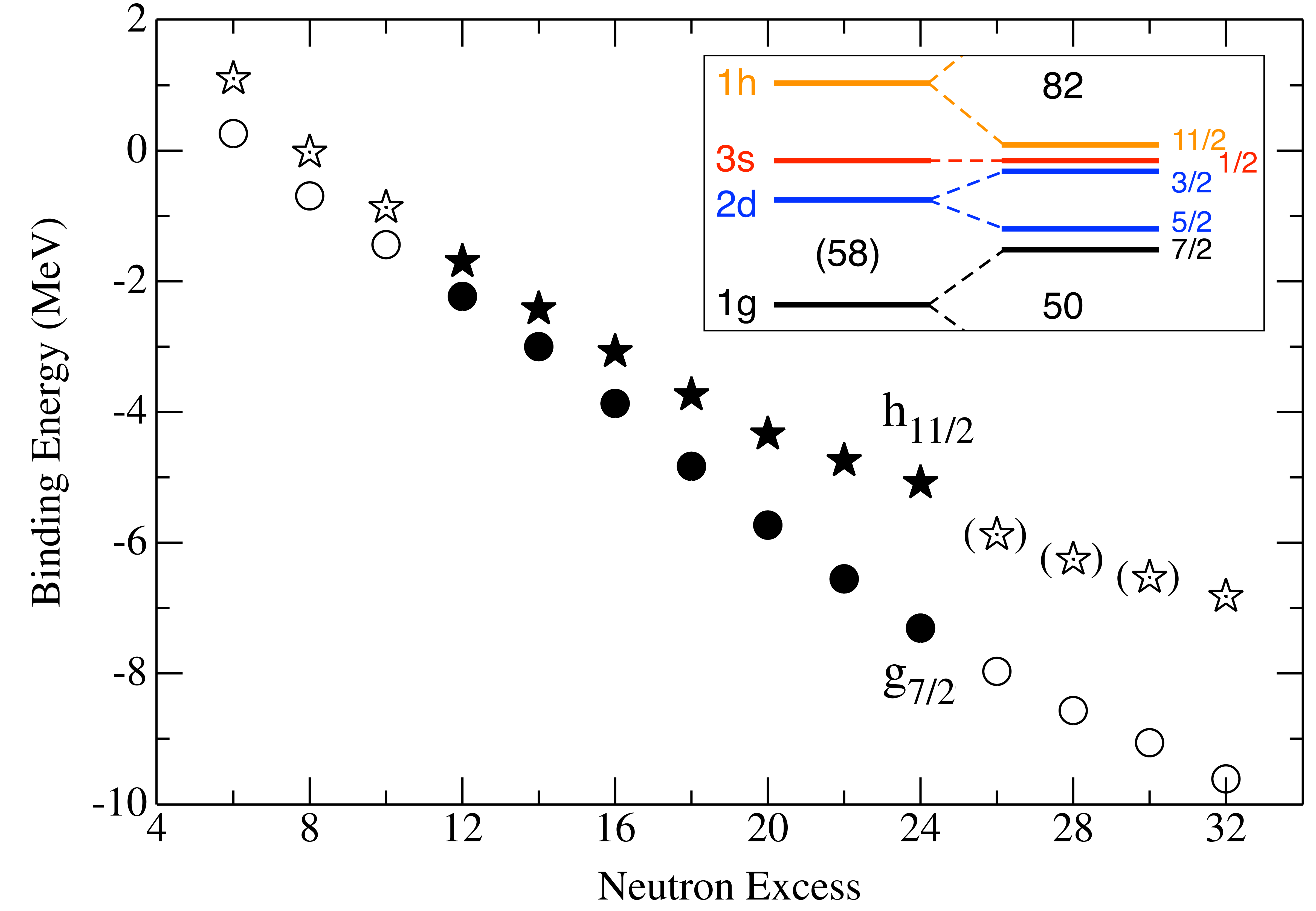


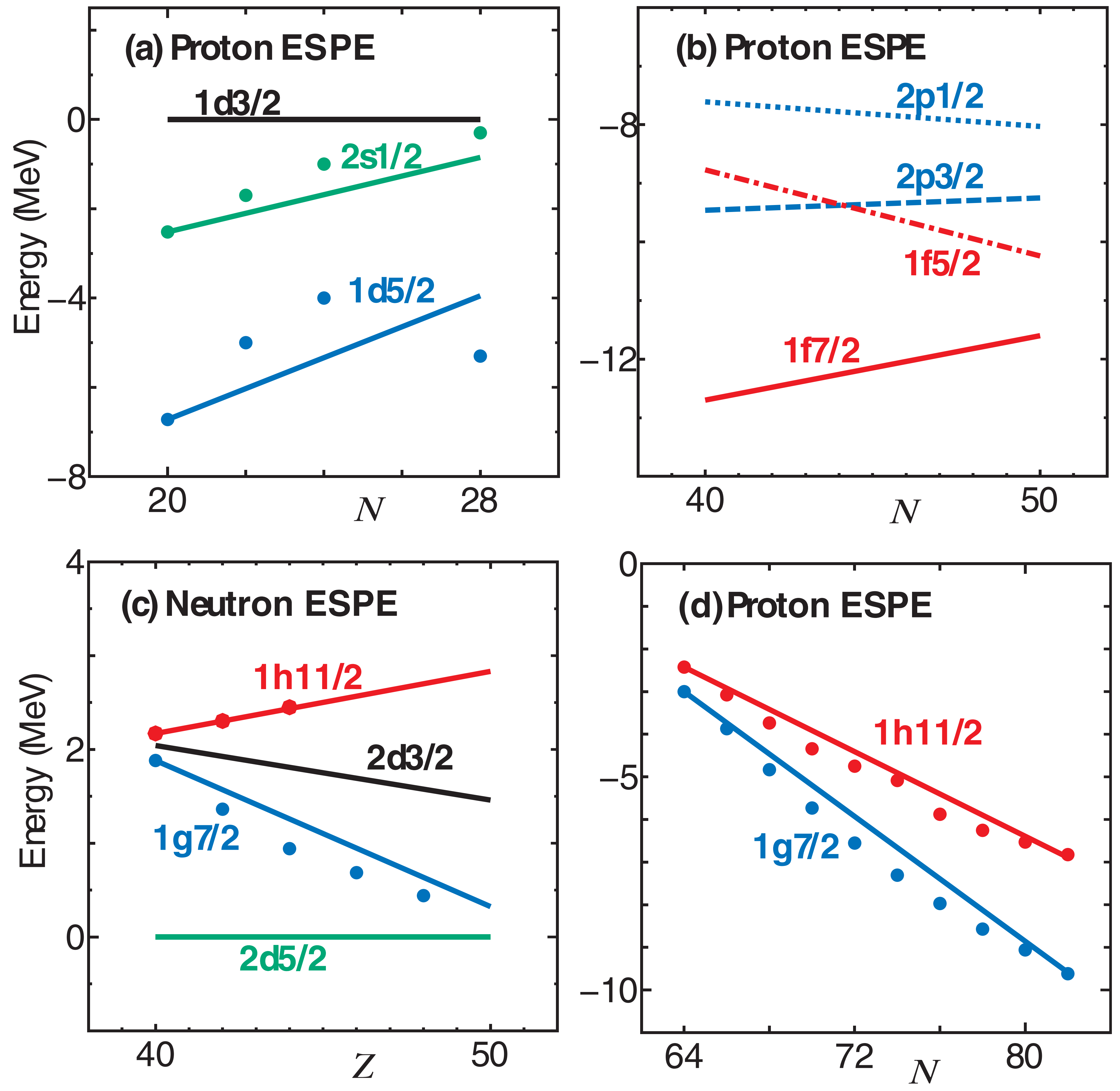


BPK *et al.*, Phys. Rev. Lett. **119**, 182502 (2017)

Changes in the spin-orbit interaction (with neutron excess) ?

The question has been asked many times in response to experimental data. One of my favorite Argonne examples …



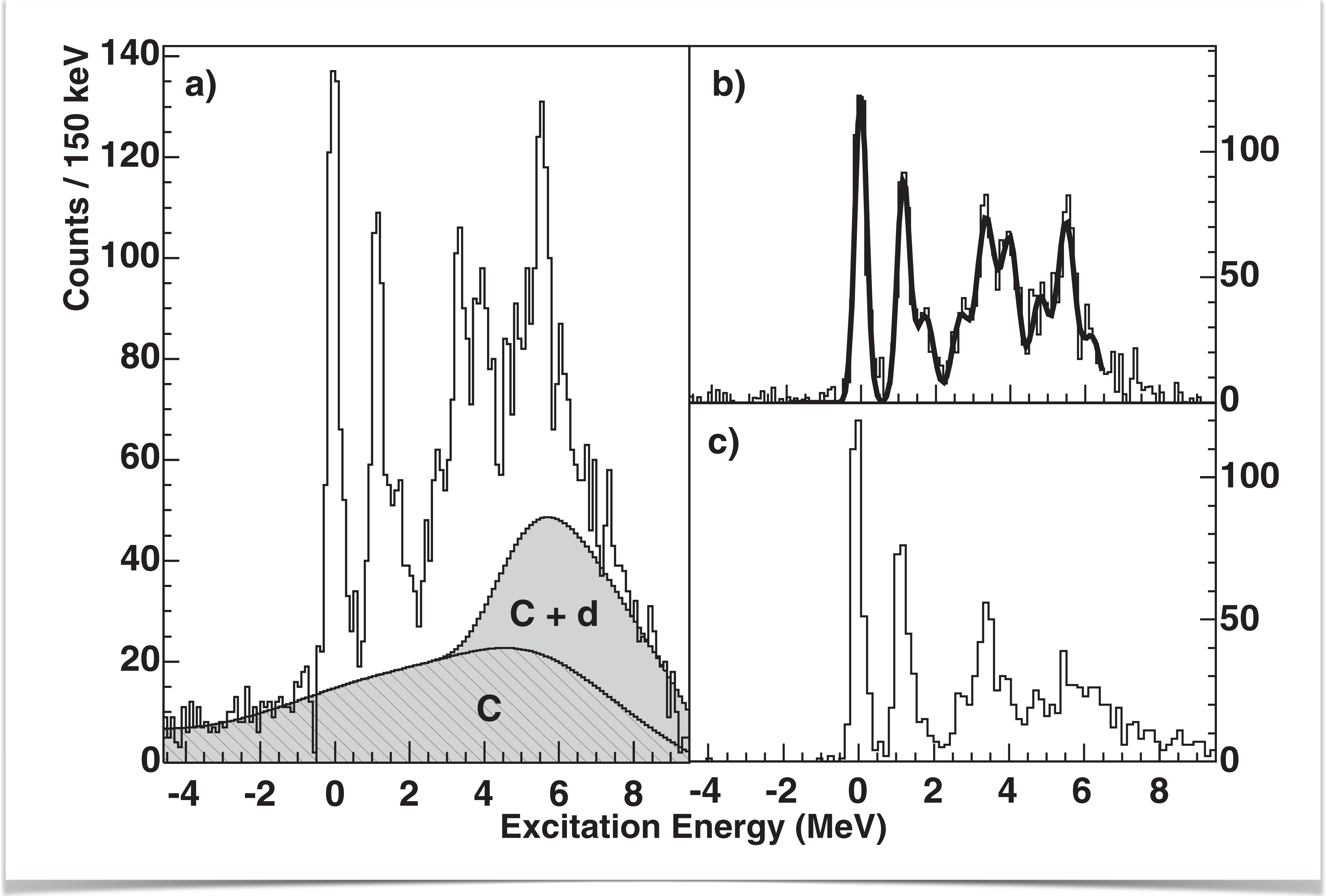


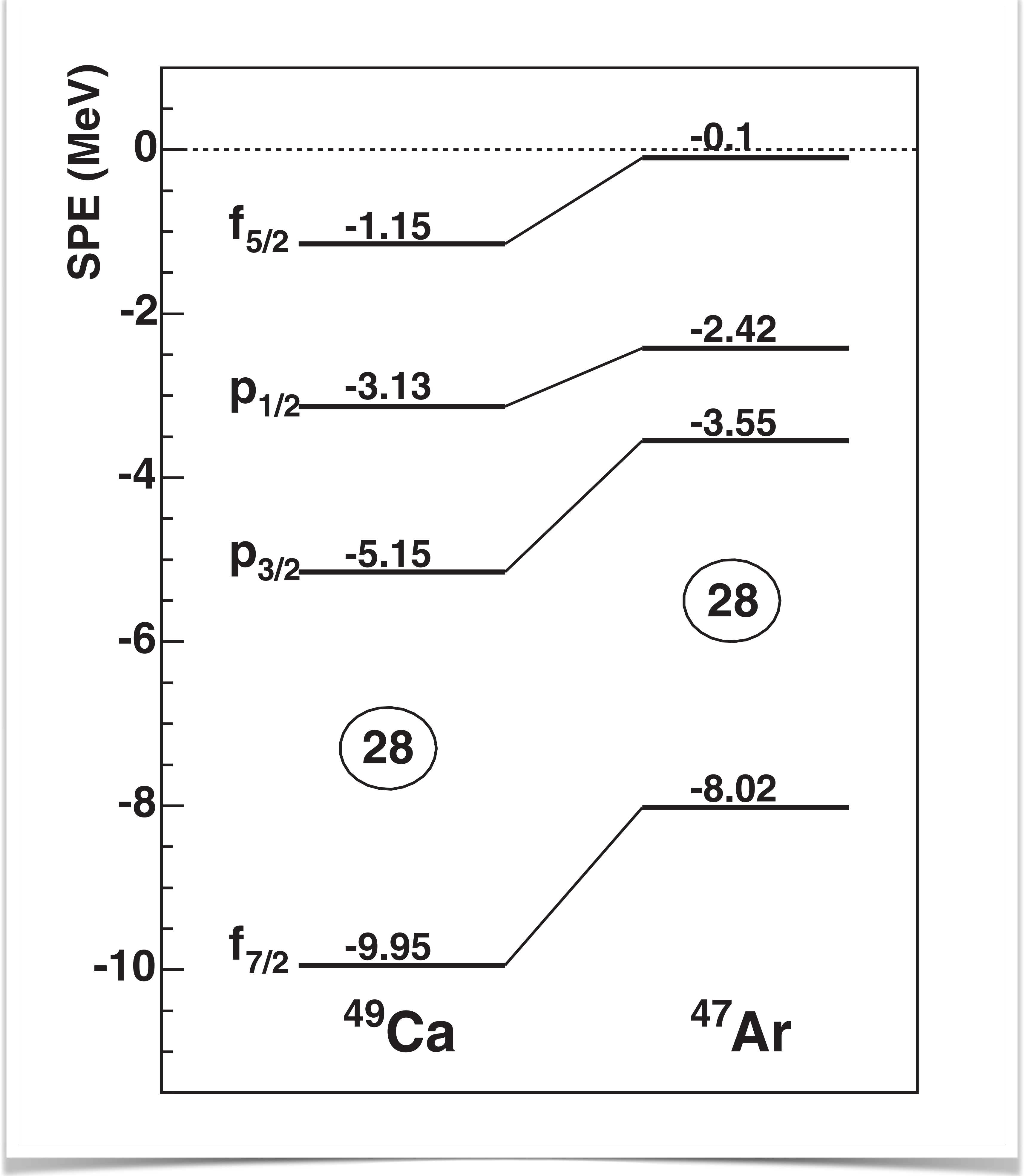
J. P. Schiffer *et al.*, Phys. Rev. Lett. **92**, 162501 (2004)

T. Otsuka *et al.*, Phys. Rev. Lett. **95**, 232502 (2005)

Changes in the spin-orbit interaction (with neutron excess) ?

A reduction of spin-orbit splittings at N = 28 … and consequence of pn interactions or a modification in the proton density?





L. Gaudefroy *et al.*, Phys. Rev. Lett. **97**, 092501 (2006)

Gerhart Mairle's SO scalings

Table 1
List of spin–orbit splittings ϵ_{so}.

Nucleus	Protons			Neutrons		
	nl	ϵ_{so}/MeV	ref.	nl	ϵ_{so}/MeV	ref.
^{12}C	1p	8.24	[8,9]	1p	8.52	[8]
^{16}O	1p	6.88	[10,11]	1p	6.72	[10,11,12]
^{40}Ca	1d	6.74	[13]	1d	6.74	[13,14]
				2p	2.10	[13,14]
^{48}Ca				1f	8.91	[15]
				2p	1.87	[15]
$A=60$ [a]	1d	5.78	[1]			
	1f	6.89	[1]			
	2p	1.54	[1]			
^{90}Zr	1f	6.27	[16]	1g	7.86	[16,17]
				2p	1.16	[16,17]
				2d	2.38	[16,17]
^{116}Sn	1g	6.39	[18,19]			
	2d	1.72	[18,19]			
^{140}Ce				1h	6.46	[20,21]
				2d	1.67	[20,21]
				3p	0.69	[20,21]
^{144}Sm	1g	5.83	[18,22]			
^{208}Pb	1h	5.55	[23,24]	1i	6.38	[23,24]
	2d	1.32	[23,24]	2f	1.85	[23,24]
	2f	1.72	[23,24]	2g	2.49	[23,24]
				3d	0.97	[23,24]

[a] Mean values of ϵ_{so} found in the vicinity of ^{56}Ni.

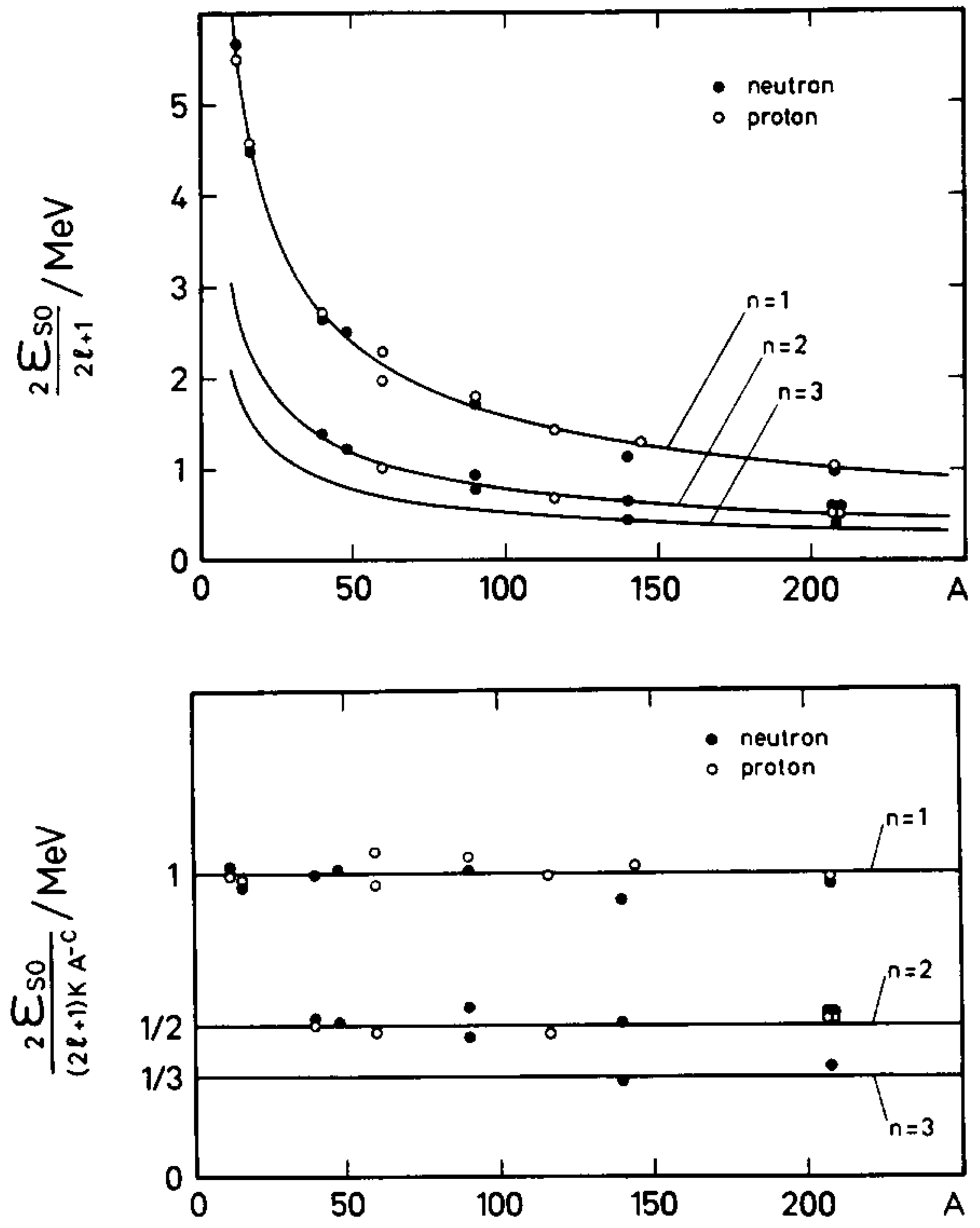


Fig. 1. Reduced spin–orbit splittings for different main quantum numbers n. The A-dependence is the result of the fit shown in fig. 2 corresponding to $g(A)=kA^{-c}$.

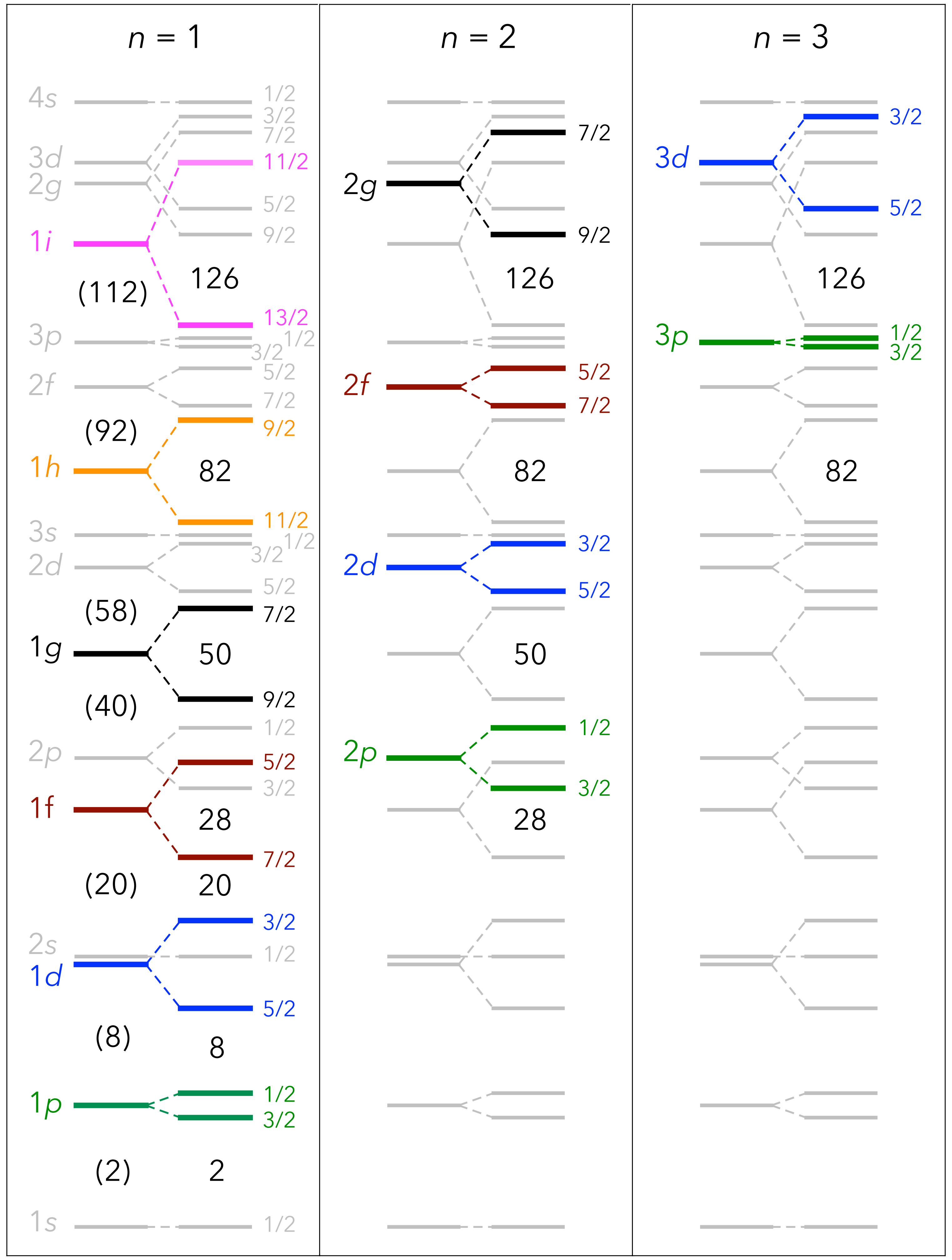
58 data points, surprisingly not many more even today (perhaps another 20-30 or so)

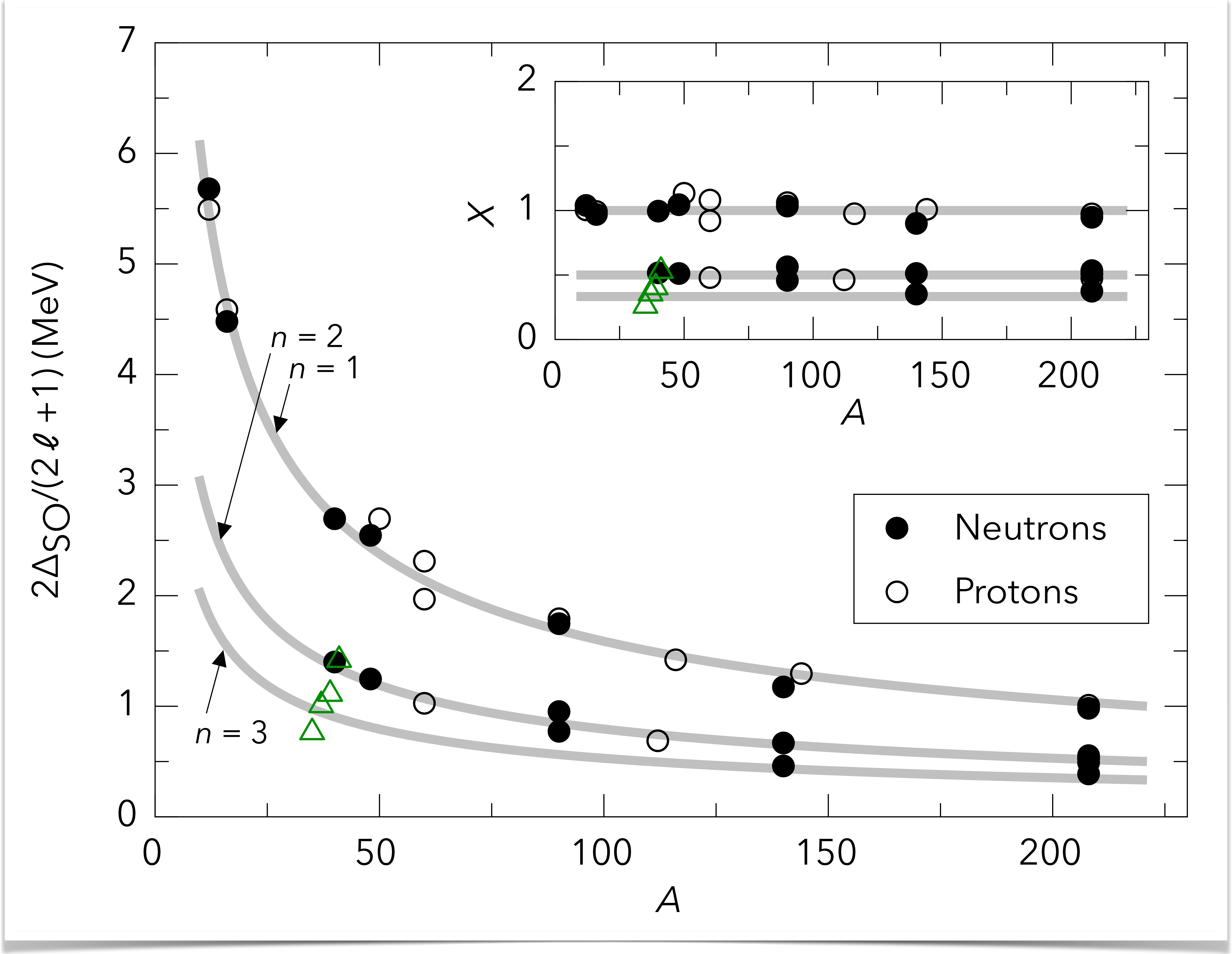
(Note: we already knew Δ_{SO} ~ $-20(l.s)A^{-2/3}$ … B&M)

G. Mairle, Phys. Lett. B **304**, 39 (1993)

Mairle and the *p* states

Many recent discussions on spin-orbit partners … and weak binding

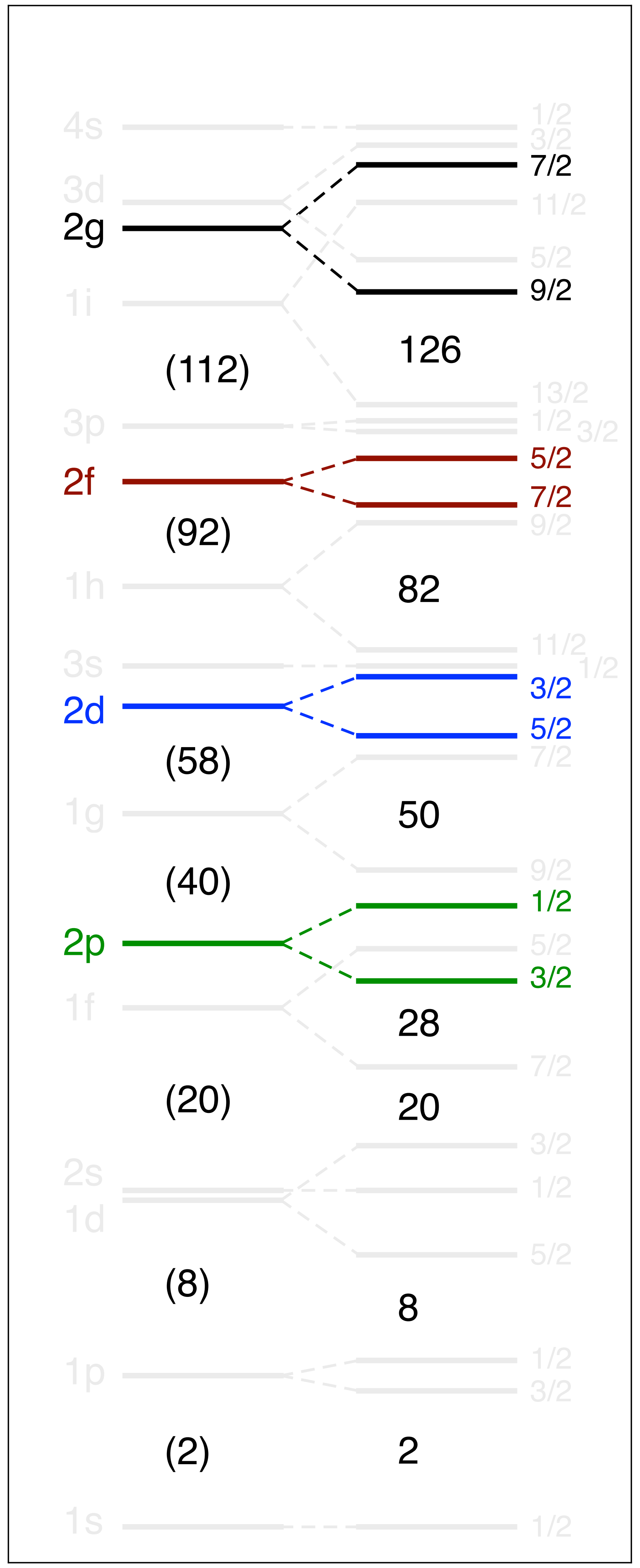


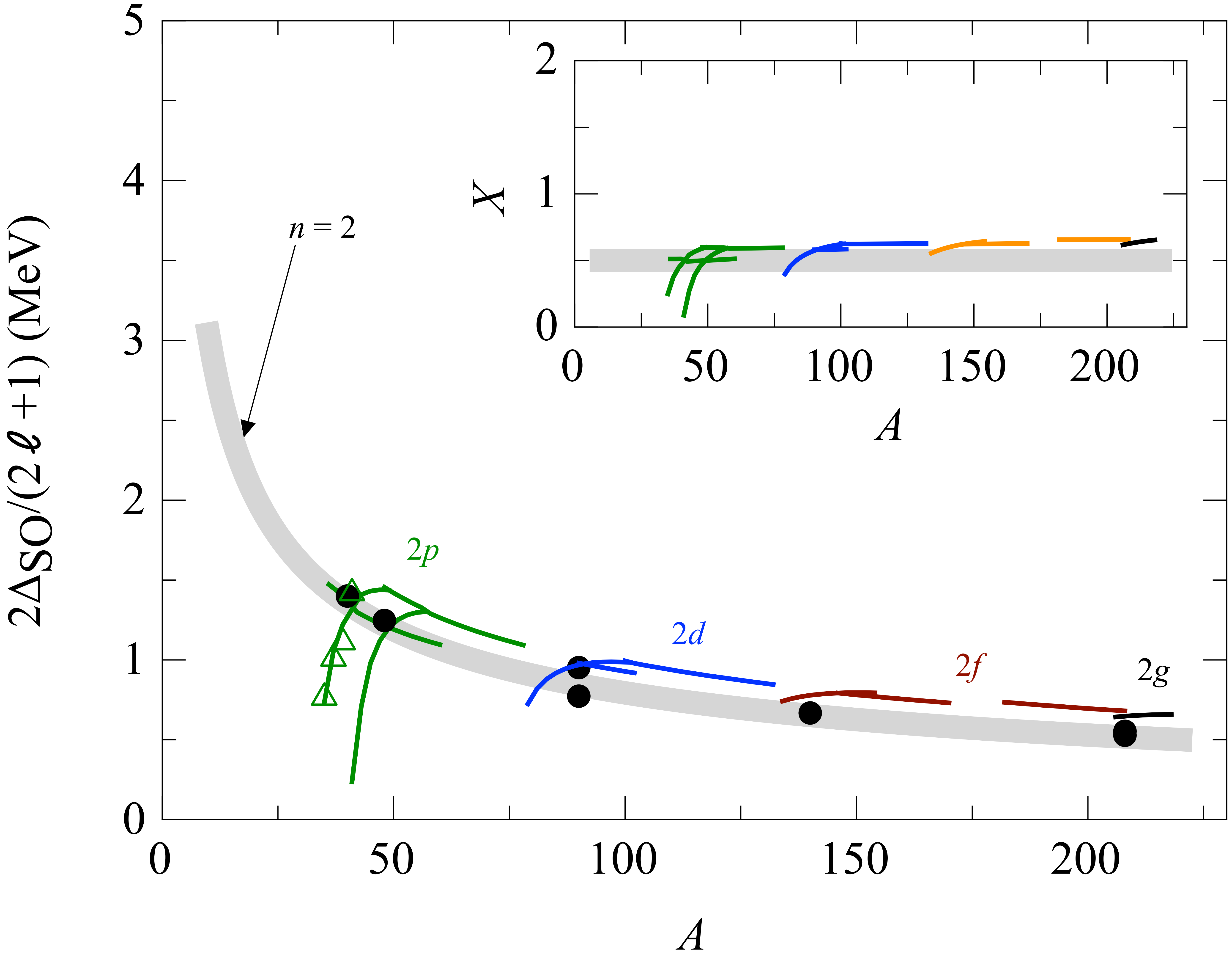


G. Mairle, Phys. Lett. B **304**, 39 (1993) | BPK *et al.*, Phys. Rev. Lett. **119**, 182502 (2017) | A. Mutschler *et al.*, Nat. Phys. **13**, 152 (2017)

Mairle versus WS calculations?

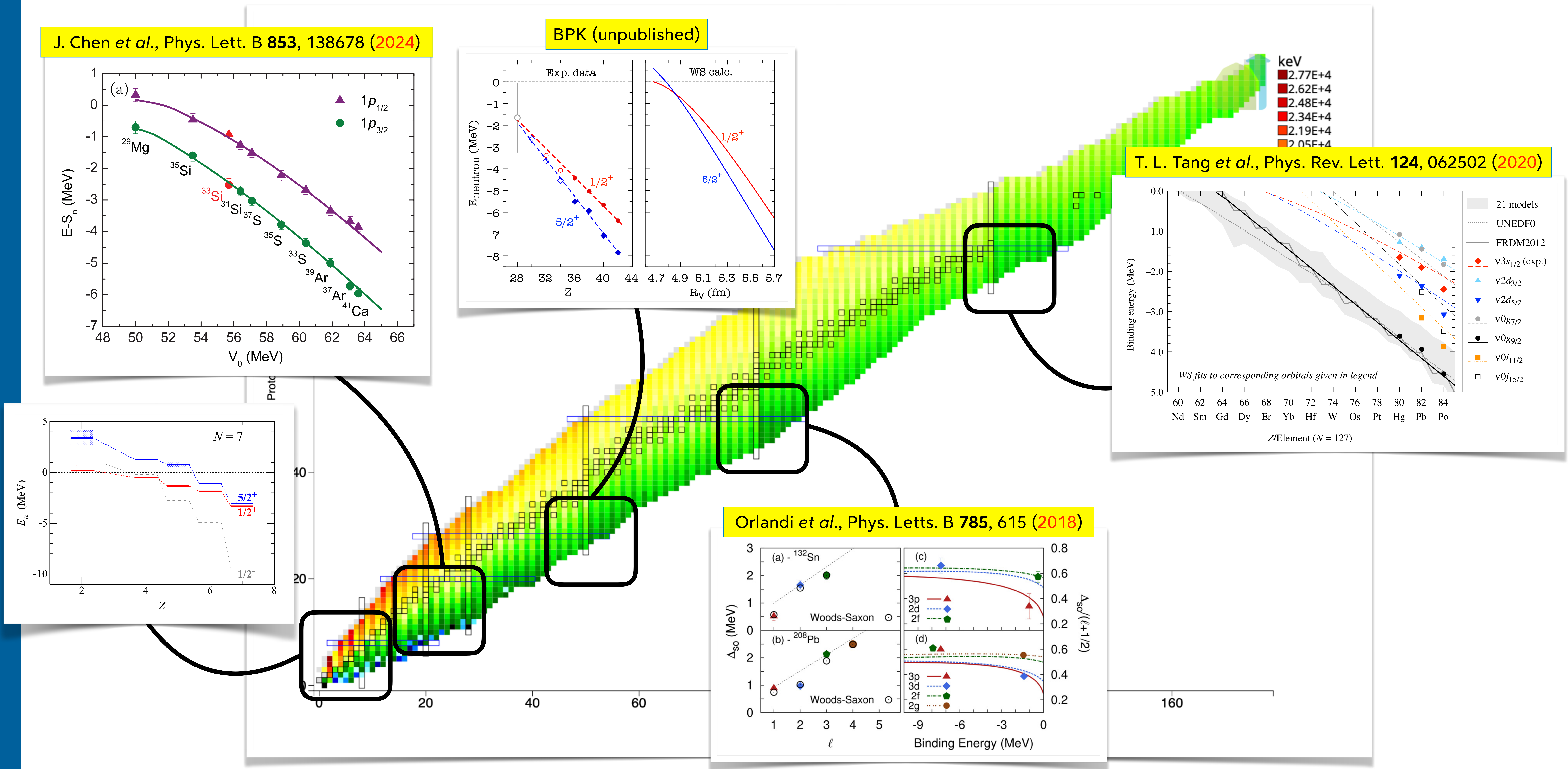
Using an “effective” WS parameterization, strong deviations from Mairle seen near threshold





N. Schwierz, I. Wiendenhöver, and A. Volya, arXiv:0709.3525, A. Volya, http://www.volya.net.

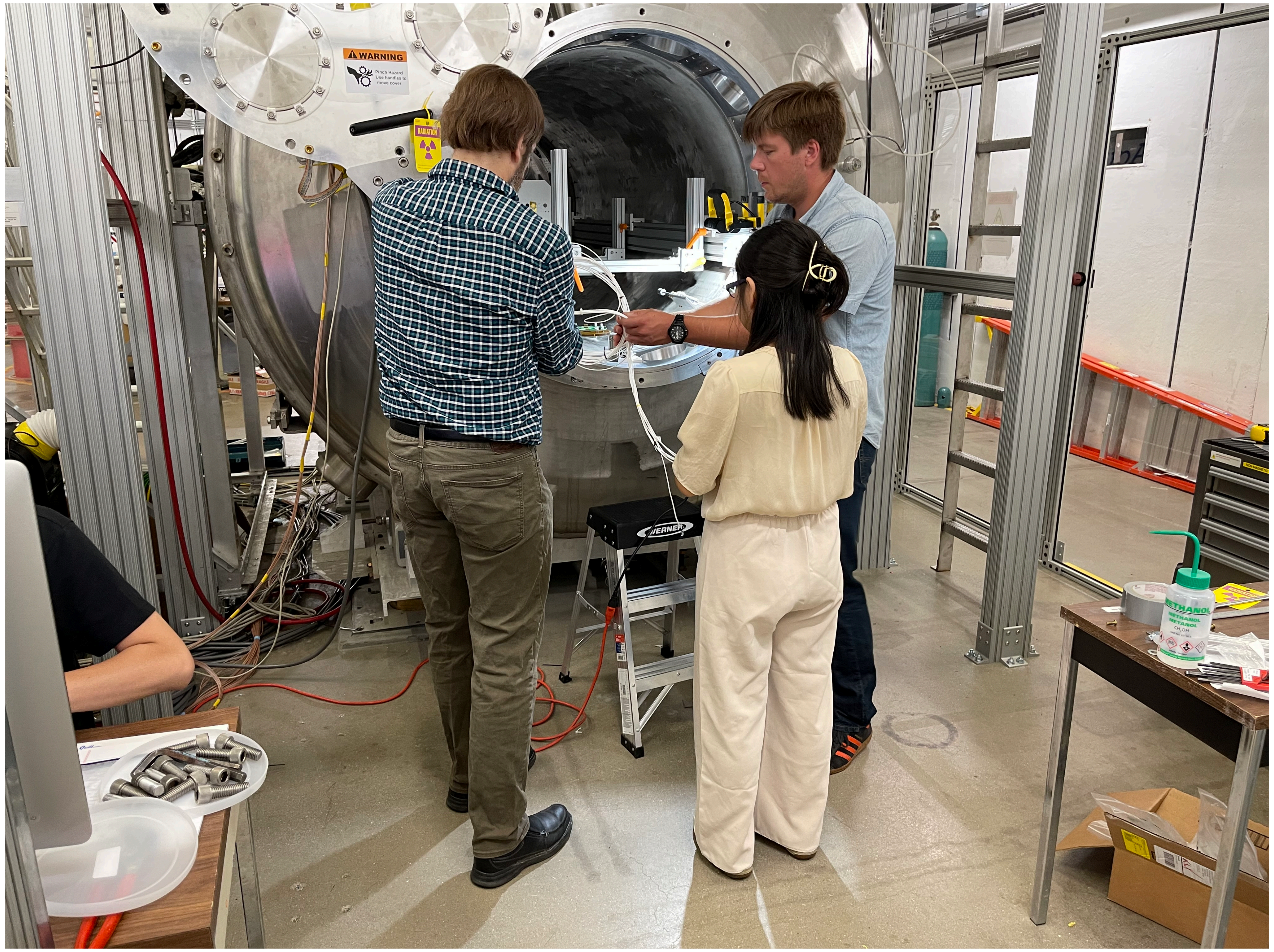
Weak binding across the chart … universal effect?

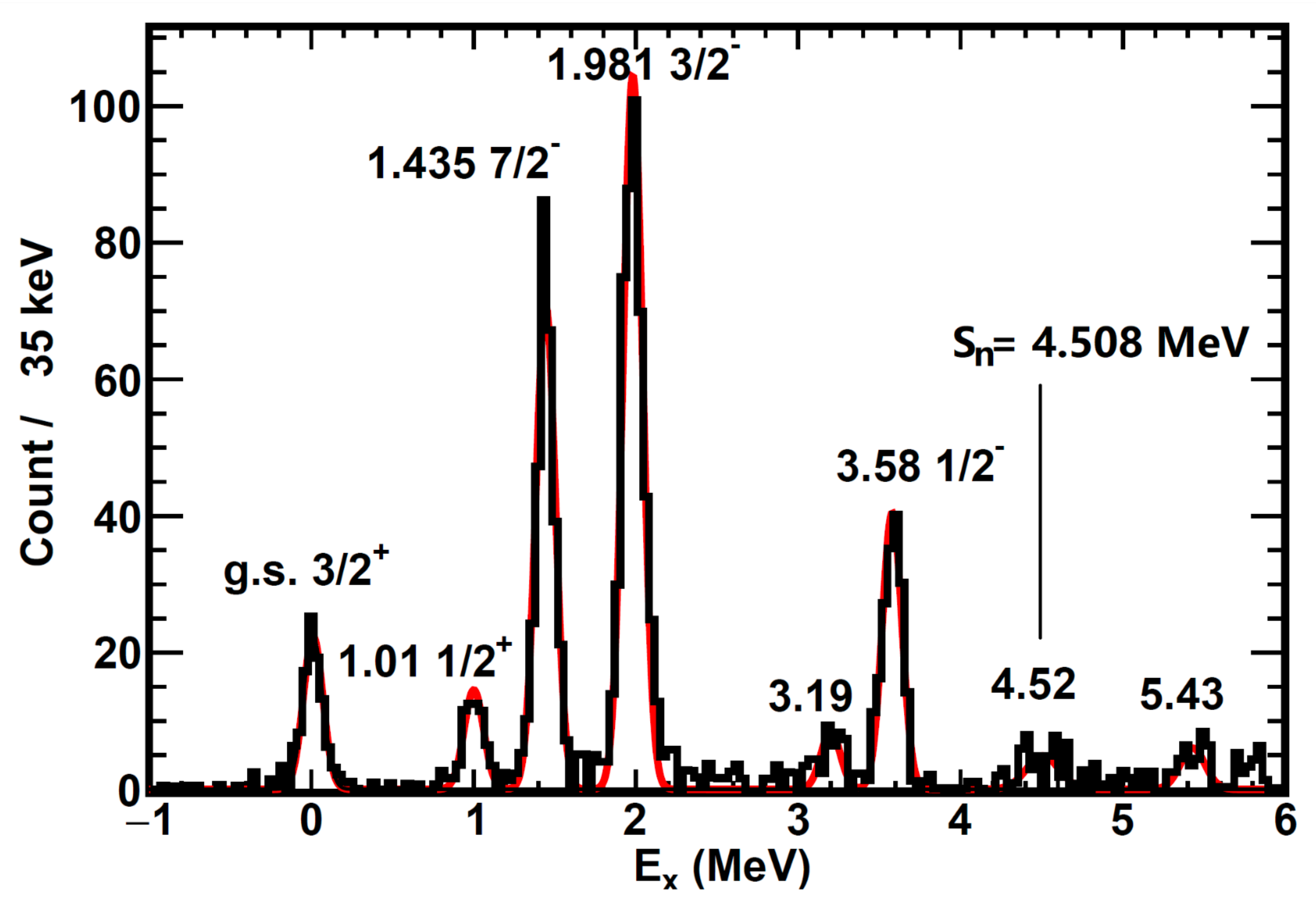


https://www.nndc.bnl.gov/nudat3/, filtering on S_n

Chen *et al.* and SOLARIS

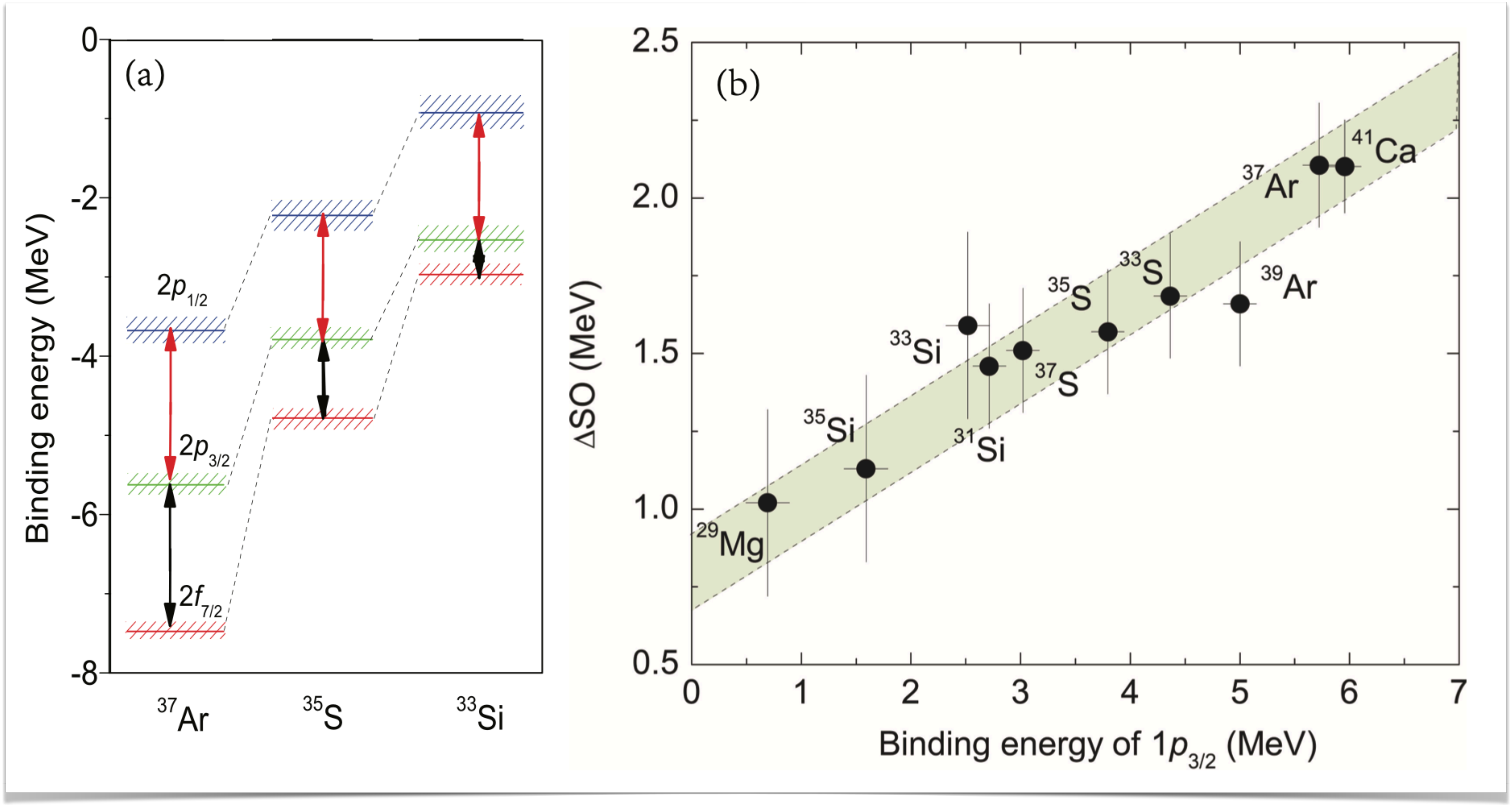
^{32}Si beam at 8.3 MeV/u, ~1e5 pps, 90% purity, 120 µg/cm² CD_2 target





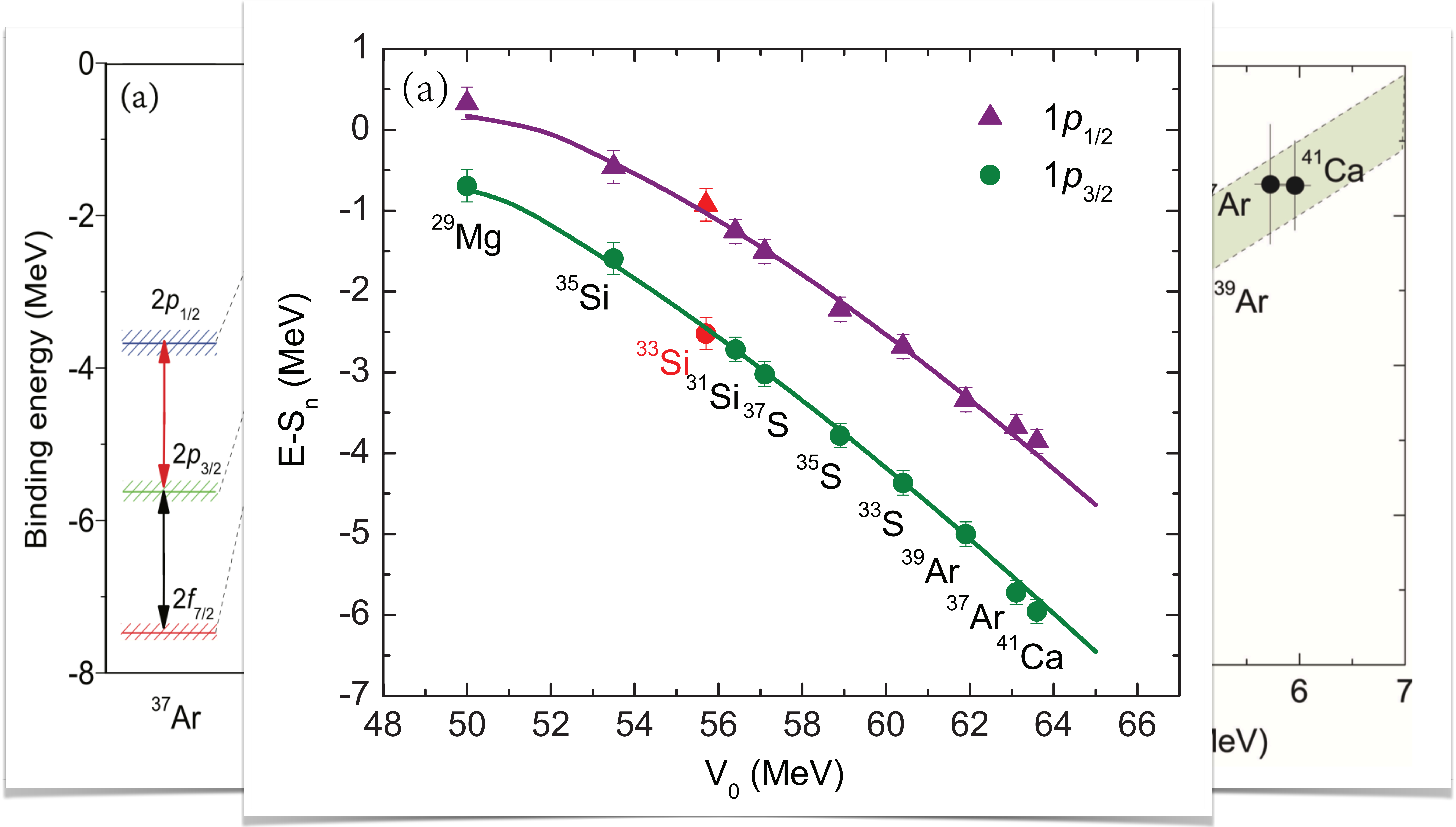
J. Chen *et al.*, Phys. Lett. B **853**, 138678 (2024)

A regionally smooth trend, no abrupt changes



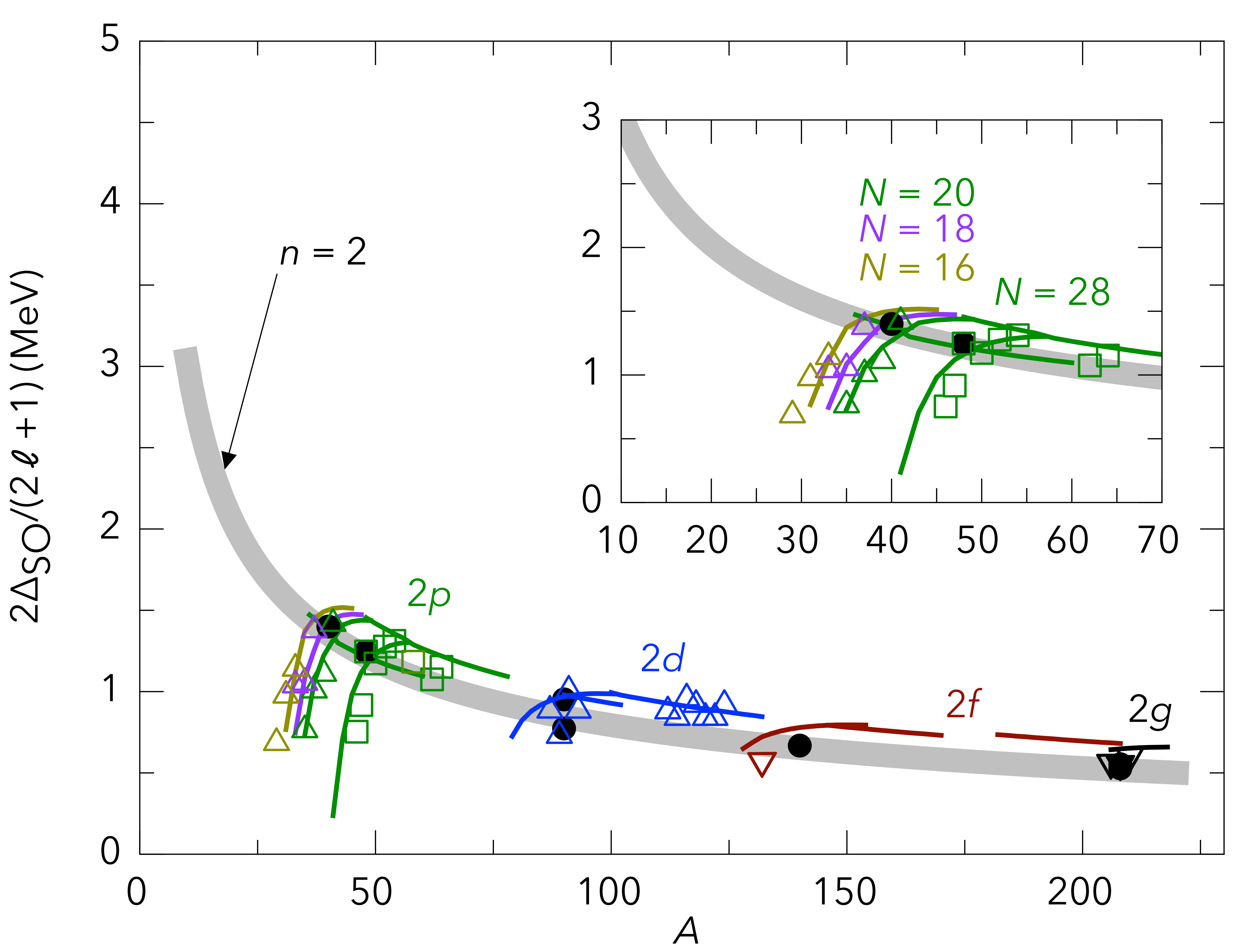
J. Chen *et al.*, Phys. Lett. B **853**, 138678 (2024)

A regionally smooth trend, no abrupt changes



J. Chen *et al.*, Phys. Lett. B **853**, 138678 (2024)

Available *n* = 2 data since Mairle



N = 16, 18, 20

J. Chen *et al.*, Phys. Lett. B **853**, 138678 (2024)

P. MacGregor *et al.*, Phys. Rev. C **104**, L138678 (2021)

BPK *et al.*, Phys. Rev. Lett. **119**, 182502 (2017)

N = 28

L. Riley *et al.*, Phys. Rev. C **103**, 064309 (2021), ibid. 106, 064308 (2022), **108**, 044306 (2023)

L. Gaudefroy *et al.*, Phys. Rev. Lett. **97**, 092501 (2006)

C. J. Paxman *et al.*, Phys. Rev. Lett. **134**, 162504 (2025)

N = 50

D. K. Sharp *et al.*, Phys. Rev. C **87**, 014312 (2013)

Z = 50

S. V. Szwec *et al.*, Phys. Rev. C **104**, 054308 (2021)

N = 82

K. Jones *et al.*, Nature (London) **465**, 454 (2010)

R. Orlandi *et al.*, Phys. Rev. Lett. B **785**, 615 (2018)

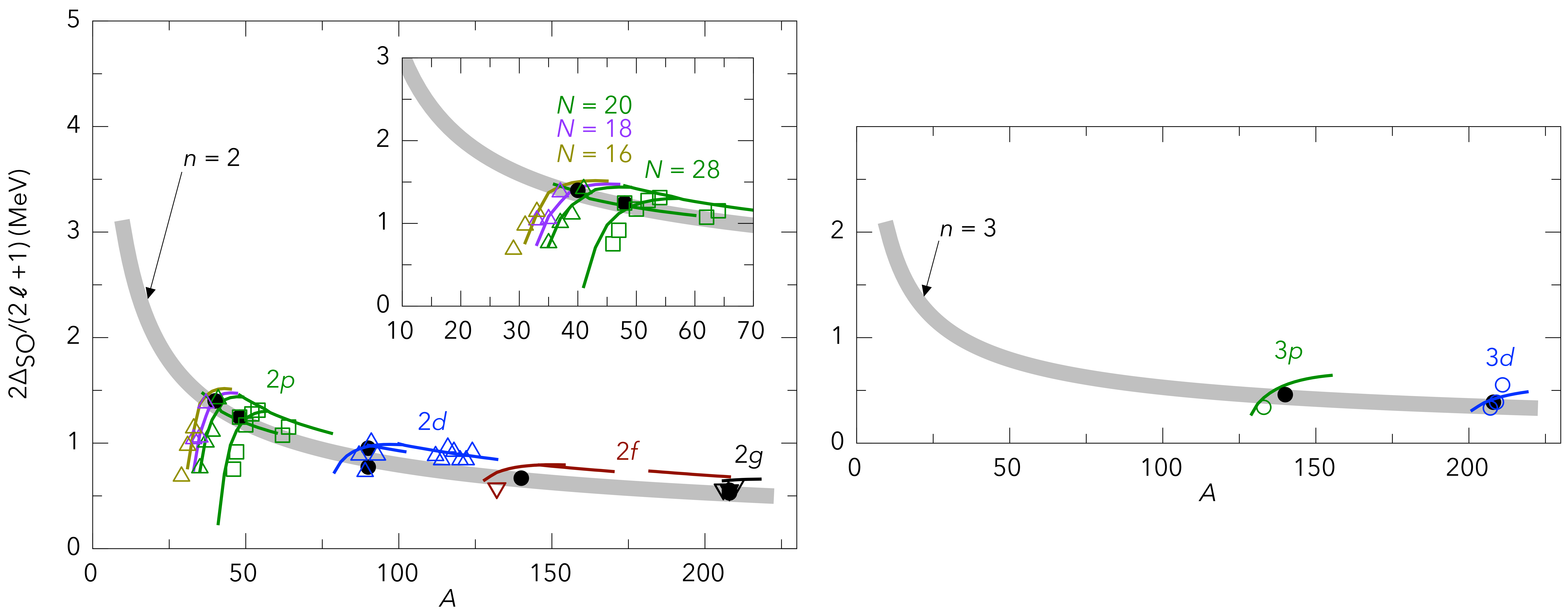
N = 126

T. L. Tang *et al.*, Phys. Rev. Lett. **124**, 062502 (2020)

M. Dierkes *et al.*, to be published

A universal fate for SO partners?

There is limited new data available since Mairle's work (58 SO partners … perhaps 20-30 more). Much of it is around *N* ~ 20 … and likely more to come in the coming year or so



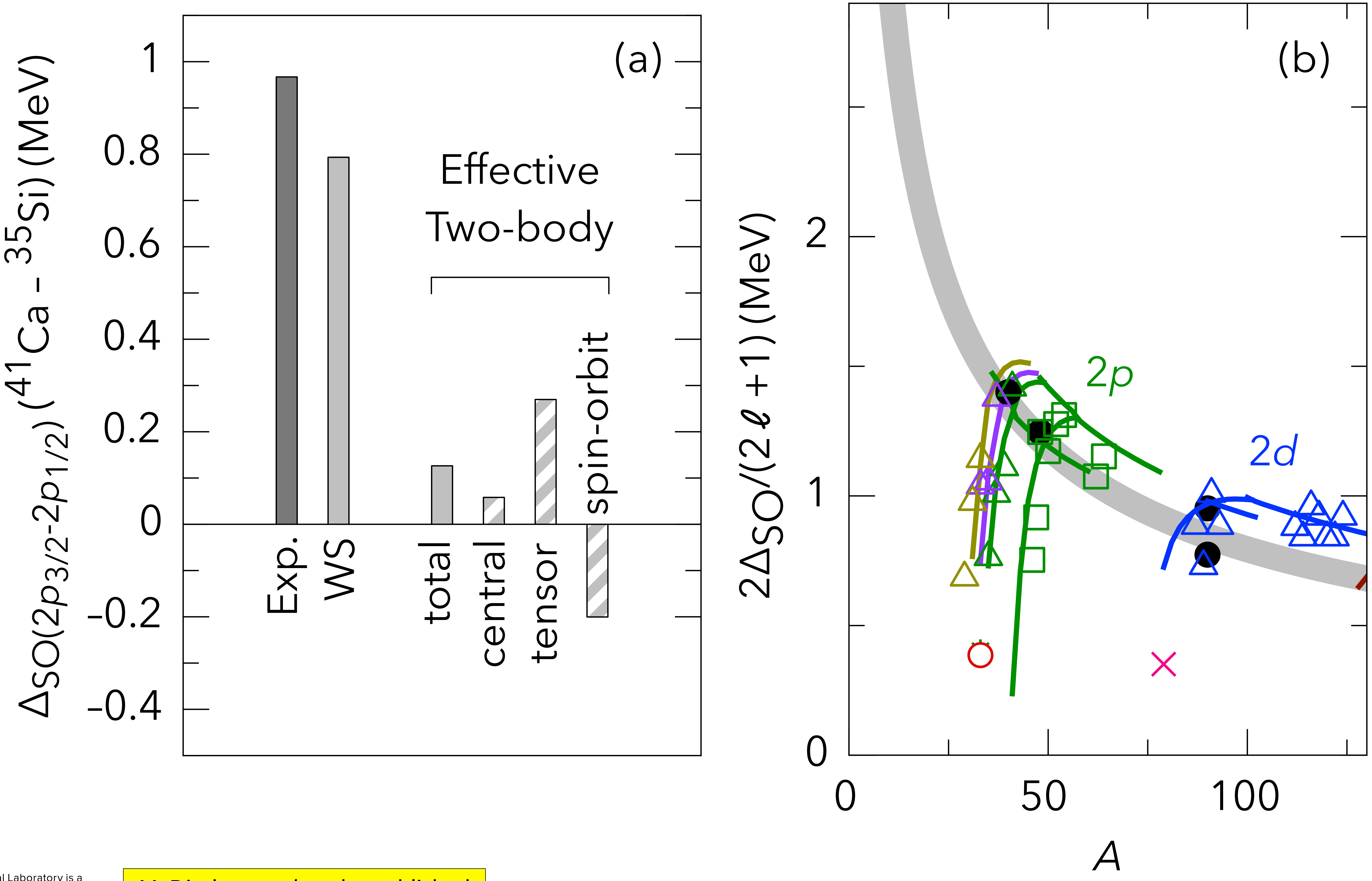
M. Dierkes *et al.*, to be published

R. Orlandi *et al.*, Phys. Lett. B **785**, 615 (2018)

O. Sorlin *et al.*, Phys. Lett. B **809**, 135740 (2020)

Other effects?

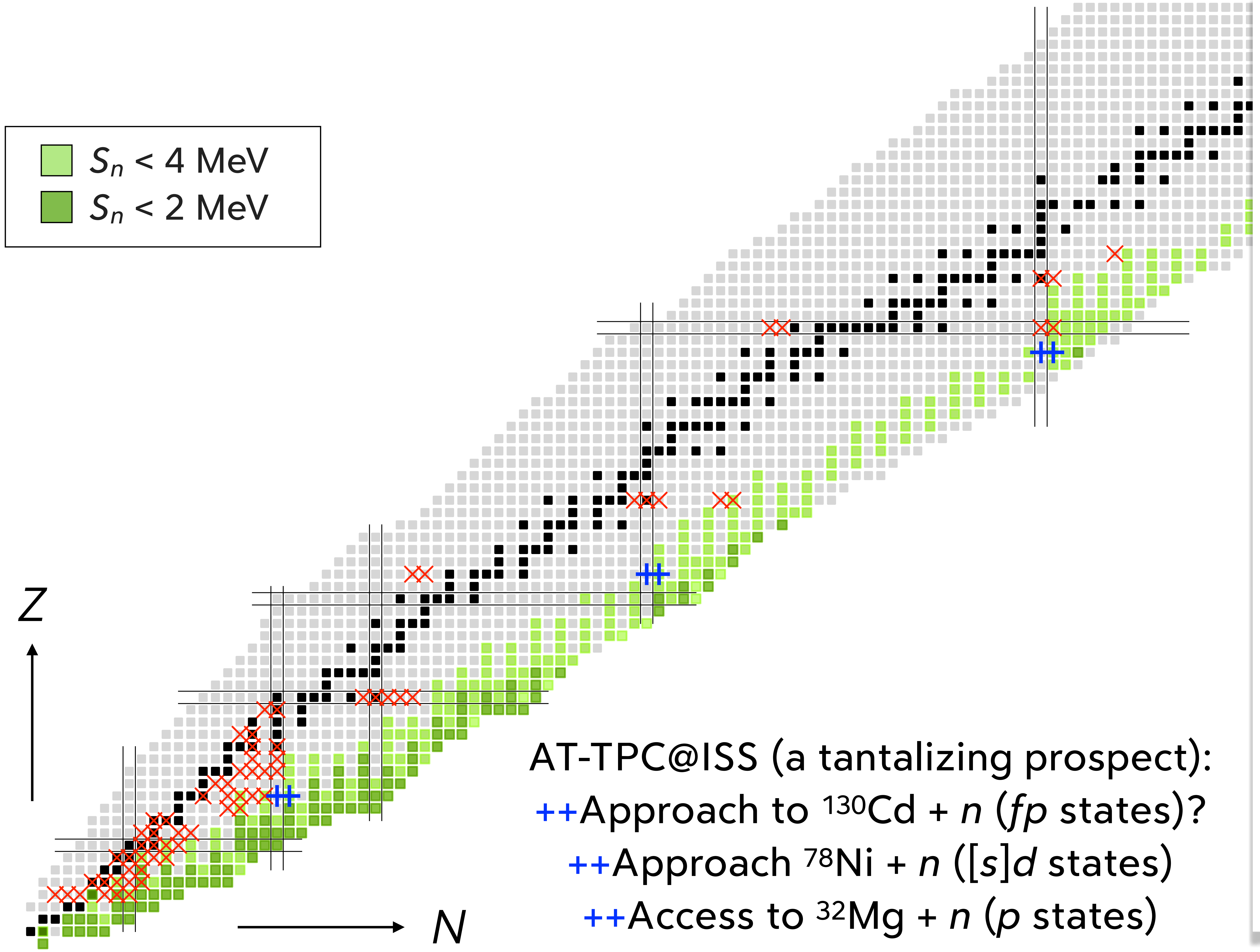
While it is tempting to say it must be driven by other effects, it is not obvious at this point



M. Dierkes *et al.*, to be published

A universal fate for SO partners?

The current generation of RIB facilities are weak-binding playgrounds …

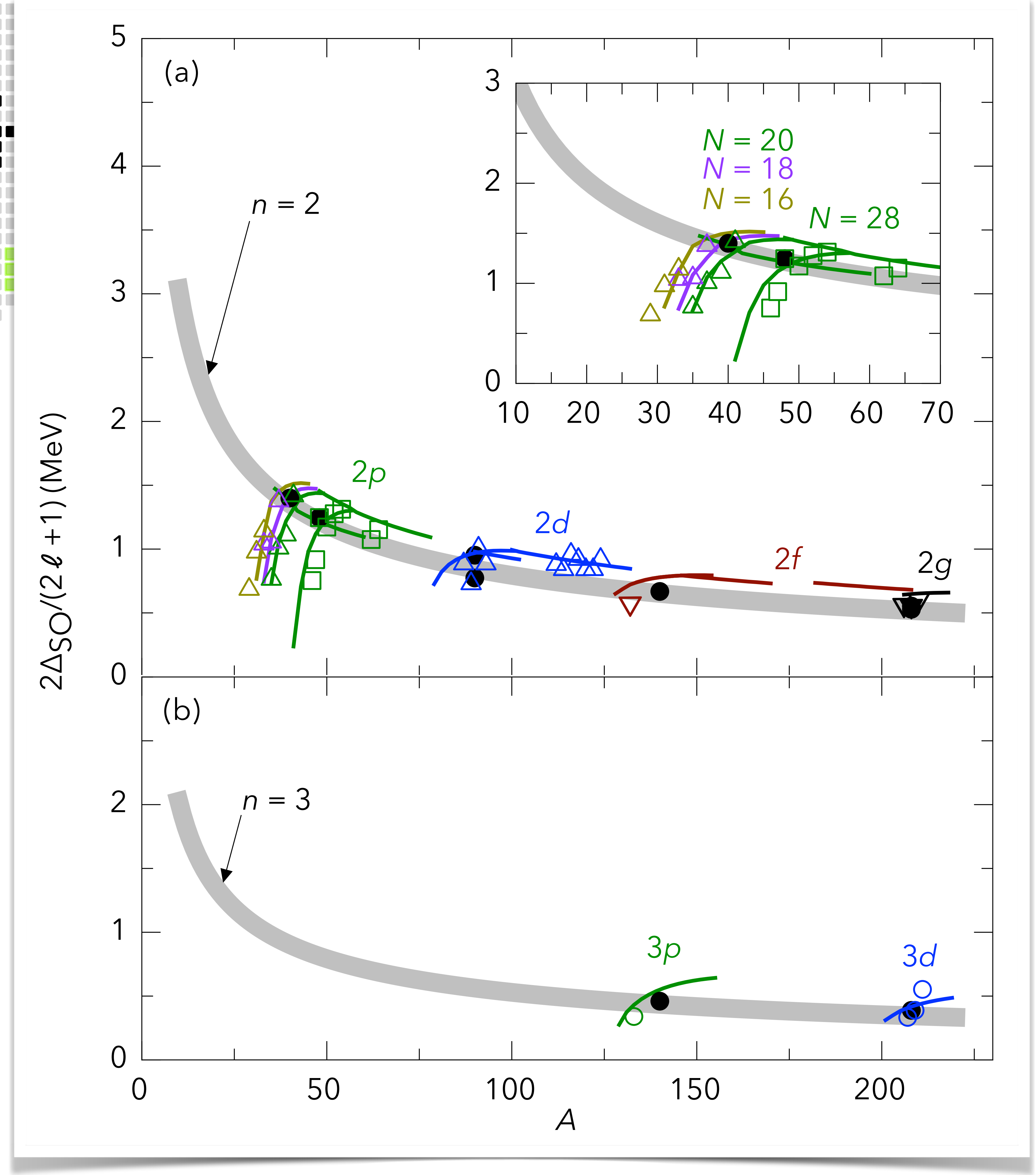


AT-TPC@ISS (a tantalizing prospect):

++Approach to ^{130}Cd + *n* (*fp* states)?

++Approach ^{78}Ni + *n* ([*s*]*d* states)

++Access to ^{32}Mg + *n* (*p* states)



S_n values from AME2020 | Figure on the right: M. Dierkes *et al.*, to be published

1959

Argonne NATIONAL LABORATORY

Spin-orbit splittings in the presence of weak binding

M. W. Dierkes,[1] A. R. Ficek,[1] S. J. Freeman,[2,3] P. Jurzyk,[1] W. M. Kane,[1] B. P. Kay,[4,*] N. Krumdick,[1] D. F. Krzysiak,[1] A. J. McNulty,[1] J. M. Perretta,[1] B. M. Sagon,[1] X. A. Sekiya,[1] and A. Valenti[1]

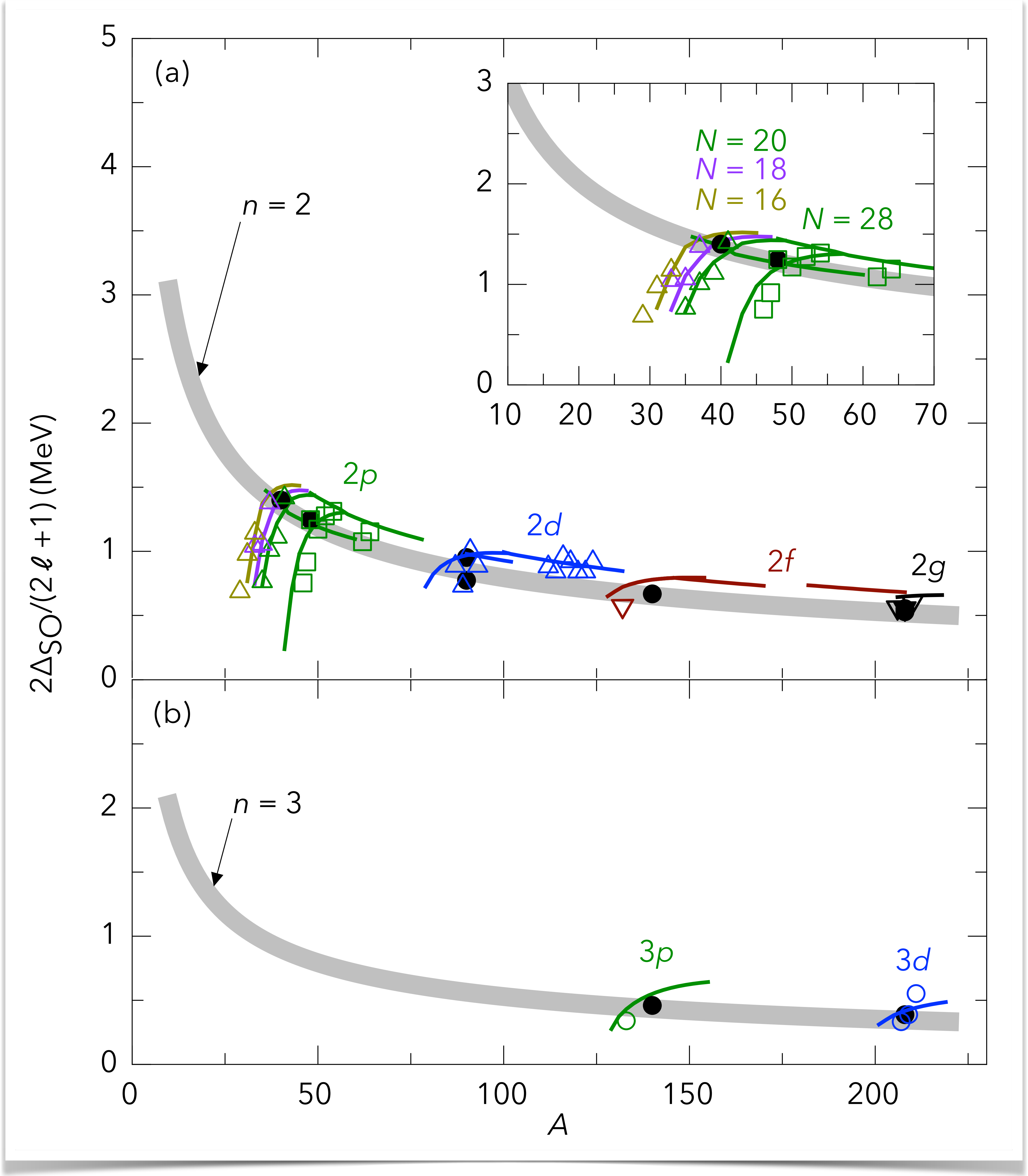
[1] *Lockport Township High School, Lockport, Illinois 60441, USA*
[2] *ISOLDE, CERN, CH-1211 Geneva 23, Switzerland*
[3] *Department of Physics, University of Manchester, M13 9PL Manchester, United Kingdom*
[4] *Physics Division, Argonne National Laboratory, Lemont, Illinois 60439, USA*

And so …

FRIB, and similar facilities, are weak-binding playgrounds … that is the physics of the coming decades. We are starting to see some emerging phenomena

The evolution of ESPEs has been astonishingly instructive in informing our understanding of nuclear structure. The fact they seem to 'sit of top' of other features is not yet obvious. The weak binding effect, a major topic of study, seems to be ubiquitous.

Revisiting Mairle's scalings has permitted another way of demonstrating this … the results are quite emphatic (and seemingly predictive).



And so …

FRIB, and similar facilities, are weak-binding playgrounds … that is the physics of the coming decades. We are starting to see some emerging phenomena

The evolution of ESP
instructive in informi
structure. The fact th
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ubiquitous.

I (we) wholeheartedly thank you (RVFJ) for all the wonderful opportunities you have given me (and us). I hope I have gone some way towards justifying those hirings many years ago …

Revisiting Mairle's scalings has permitted another way of demonstrating this … the results are quite emphatic (and seemingly predictive).