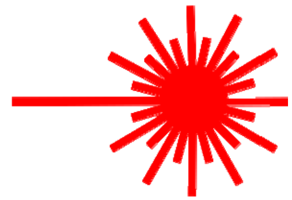
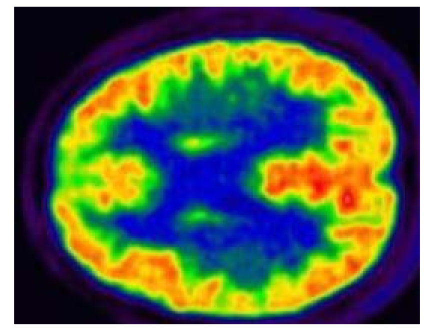
Examining the turbulent A = 100 region in light of (recent) results (from ISOLDE)



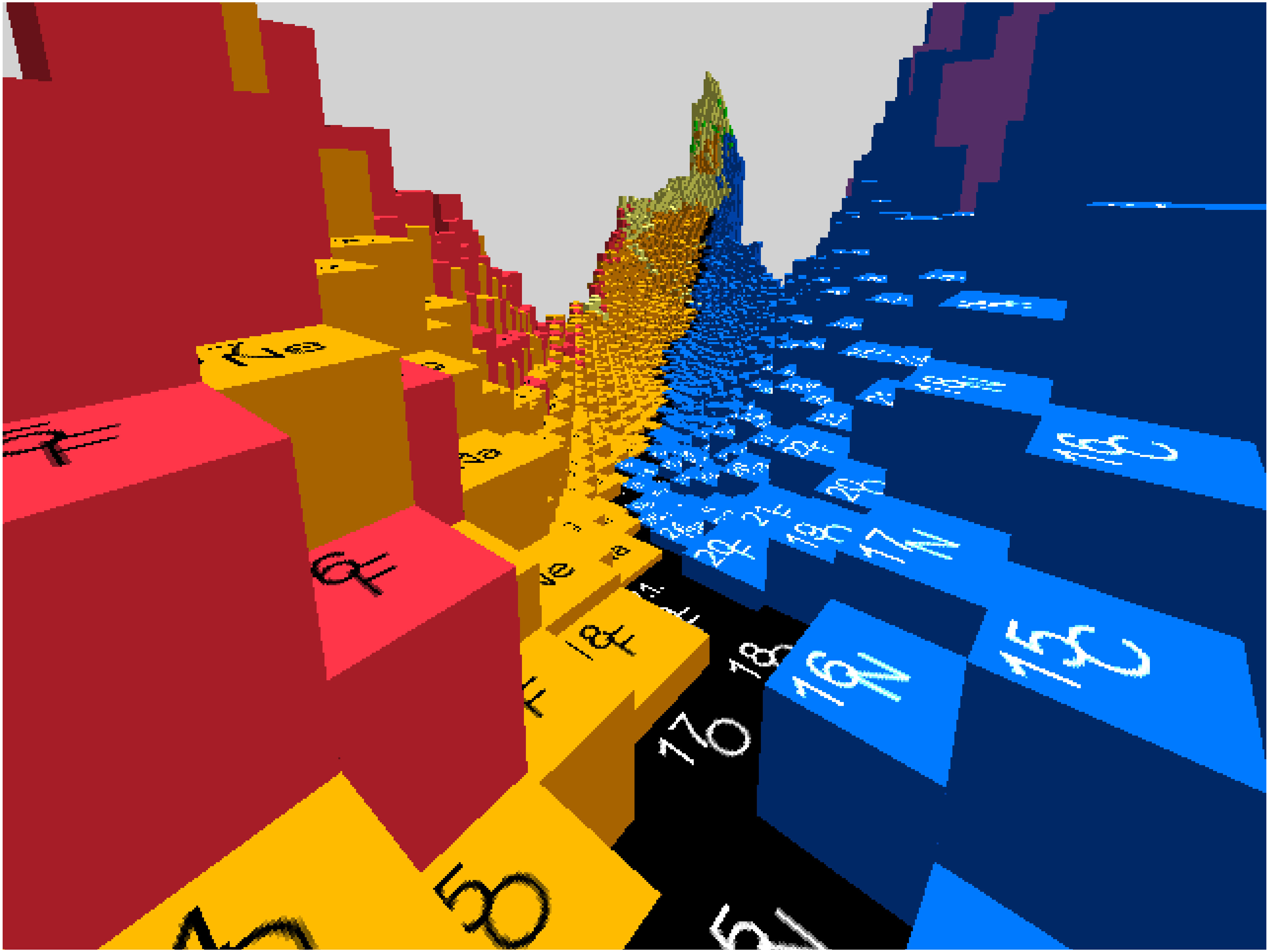
ISOLDE



David Lunney

Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse (CSNSM-IN2P3/CNRS)
Université de Paris Sud, Orsay

ISOLDE Workshop and Users Meeting, December 17-19, 2012, CERN



15C
16N
17N
16C
17O

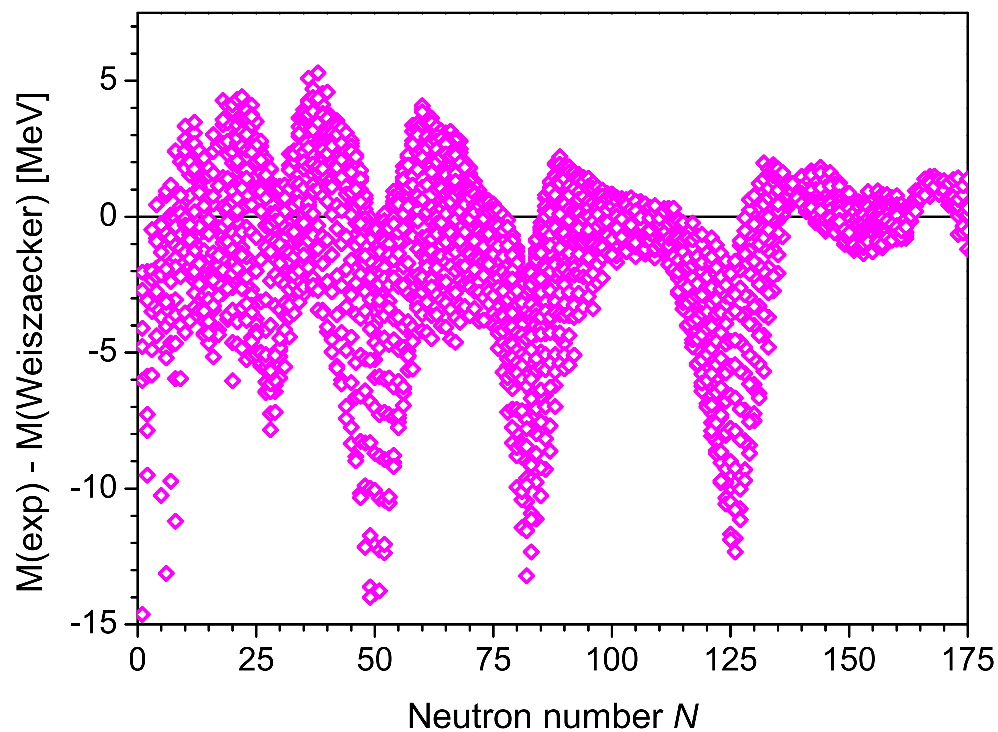
NUCLEAR GROUND-STATE MASSES AND DEFORMATIONS

P. Möller and J. R. Nix
Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545

W. D. Myers and W. J. Swiatecki
Nuclear Science Division, Lawrence Berkeley Laboratory, Berkeley, CA 94720

January 1, 1995

Famous "mic-mac" model: macroscopic liquid drip + microscopic (shell/pairing) corrections



NUCLEAR GROUND-STATE MASSES AND DEFORMATIONS

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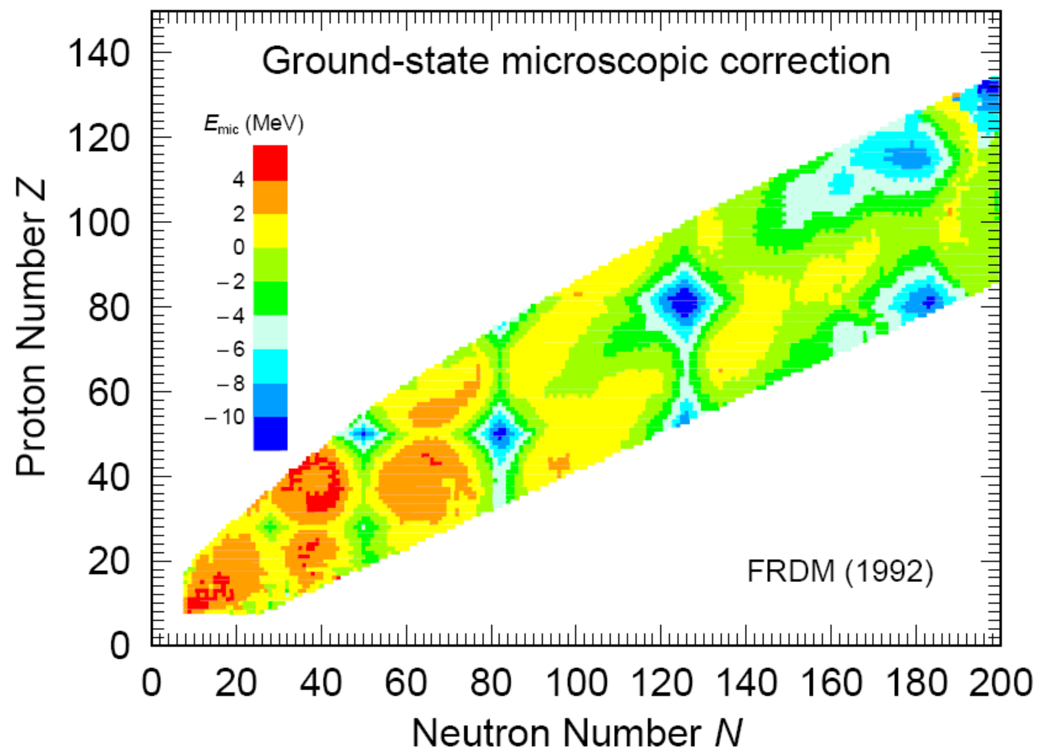
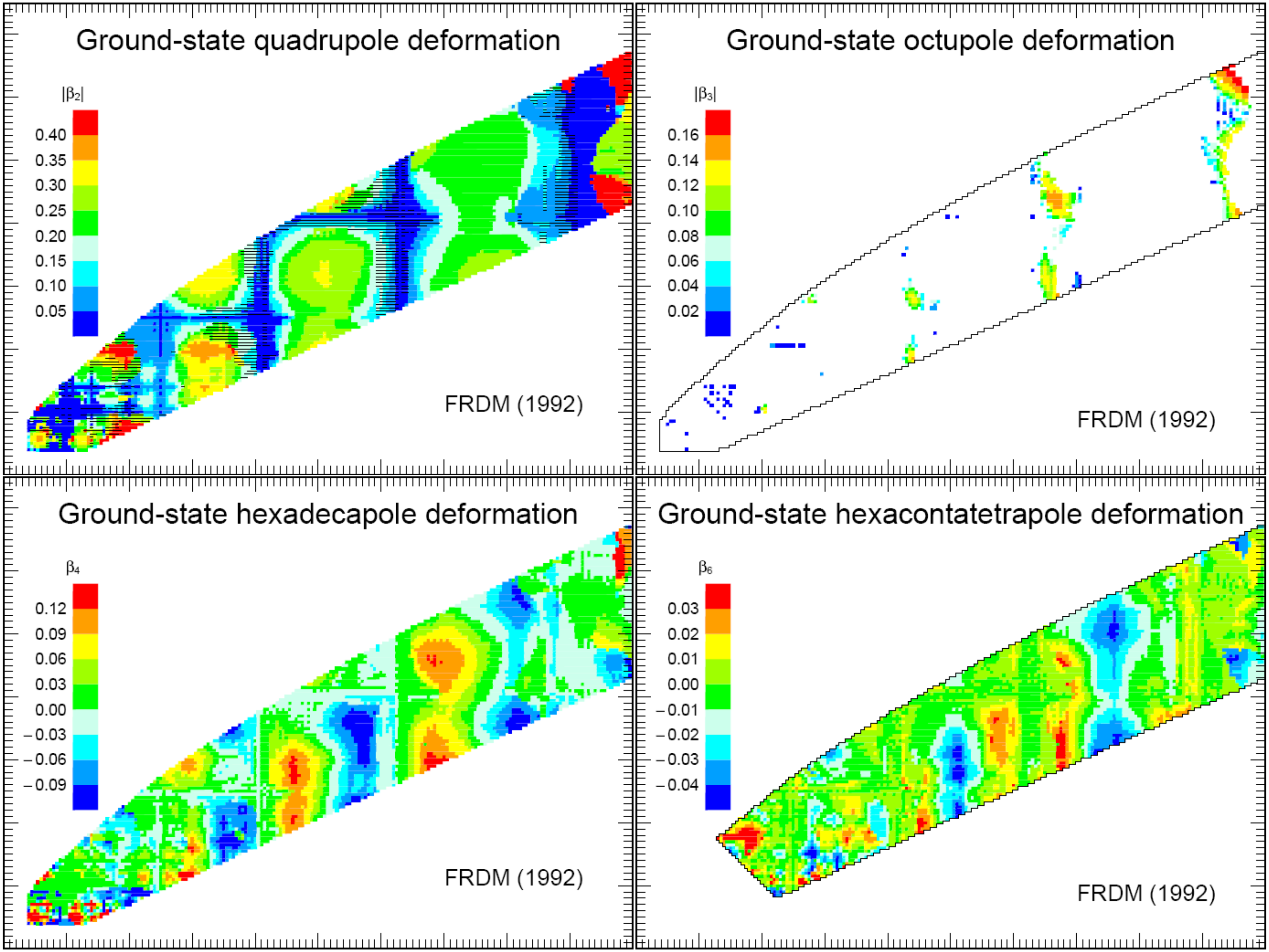


2 Models

In the macroscopic-microscopic method the total potential energy, which is calculated as a function of shape, proton number Z, and neutron number N, is the sum of a macroscopic term and a microscopic term representing the shell-plus-pairing correction. Thus, the total nuclear potential energy can be written as

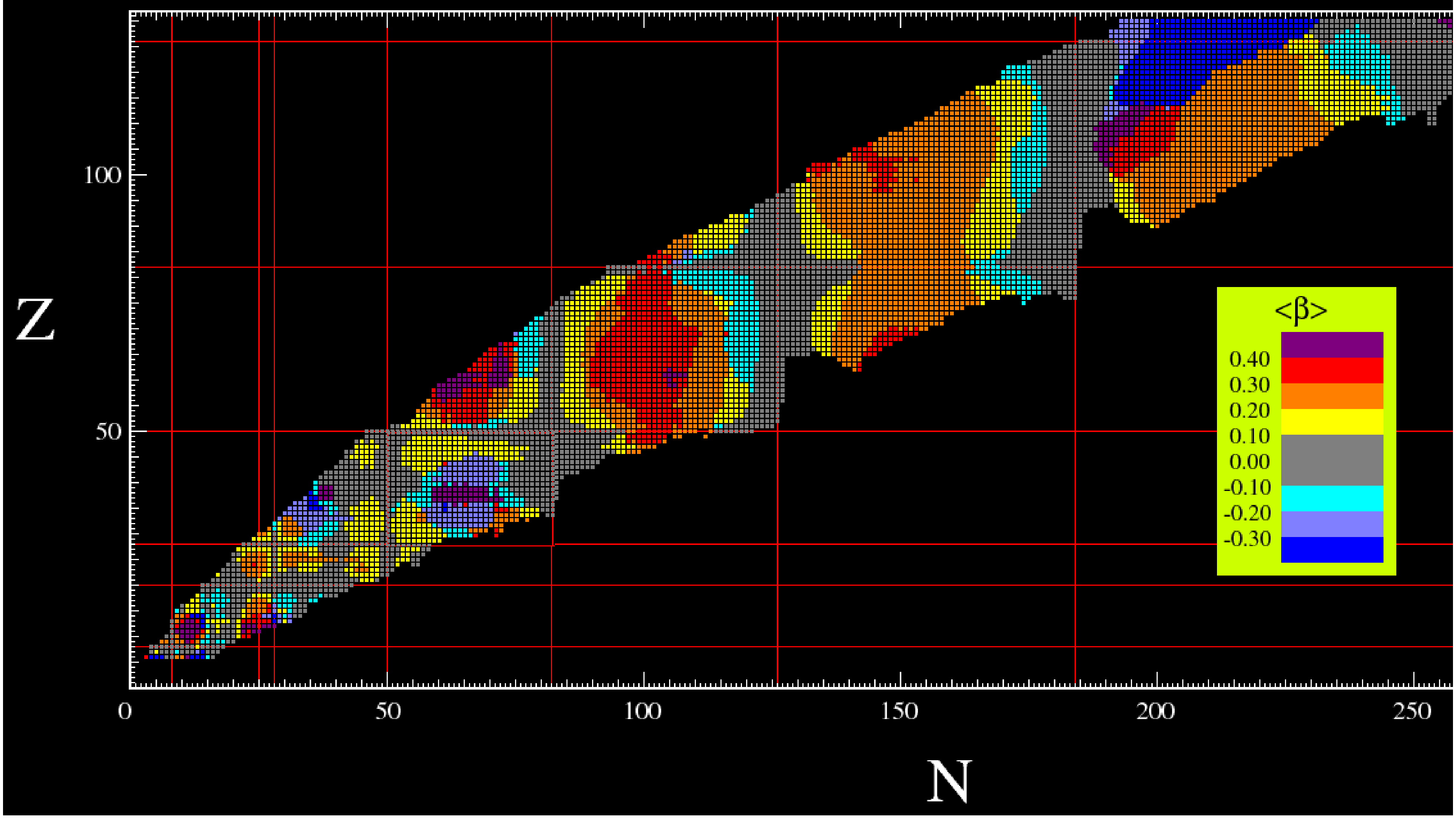
$$E_{\rm pot}(Z, N, {\rm shape}) = E_{\rm mac}(Z, N, {\rm shape}) + E_{\rm s+p}(Z, N, {\rm shape}) \quad (1)$$



Ground-state quadrupole deformation
|β2|
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
FRDM (1992)
Ground-state octupole deformation
|β3|
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
FRDM (1992)
Ground-state hexadecapole deformation
β4
0.12
0.09
0.06
0.03
0.00
−0.03
−0.06
−0.09
FRDM (1992)
Ground-state hexacontatetrapole deformation
β6
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
−0.04
FRDM (1992)

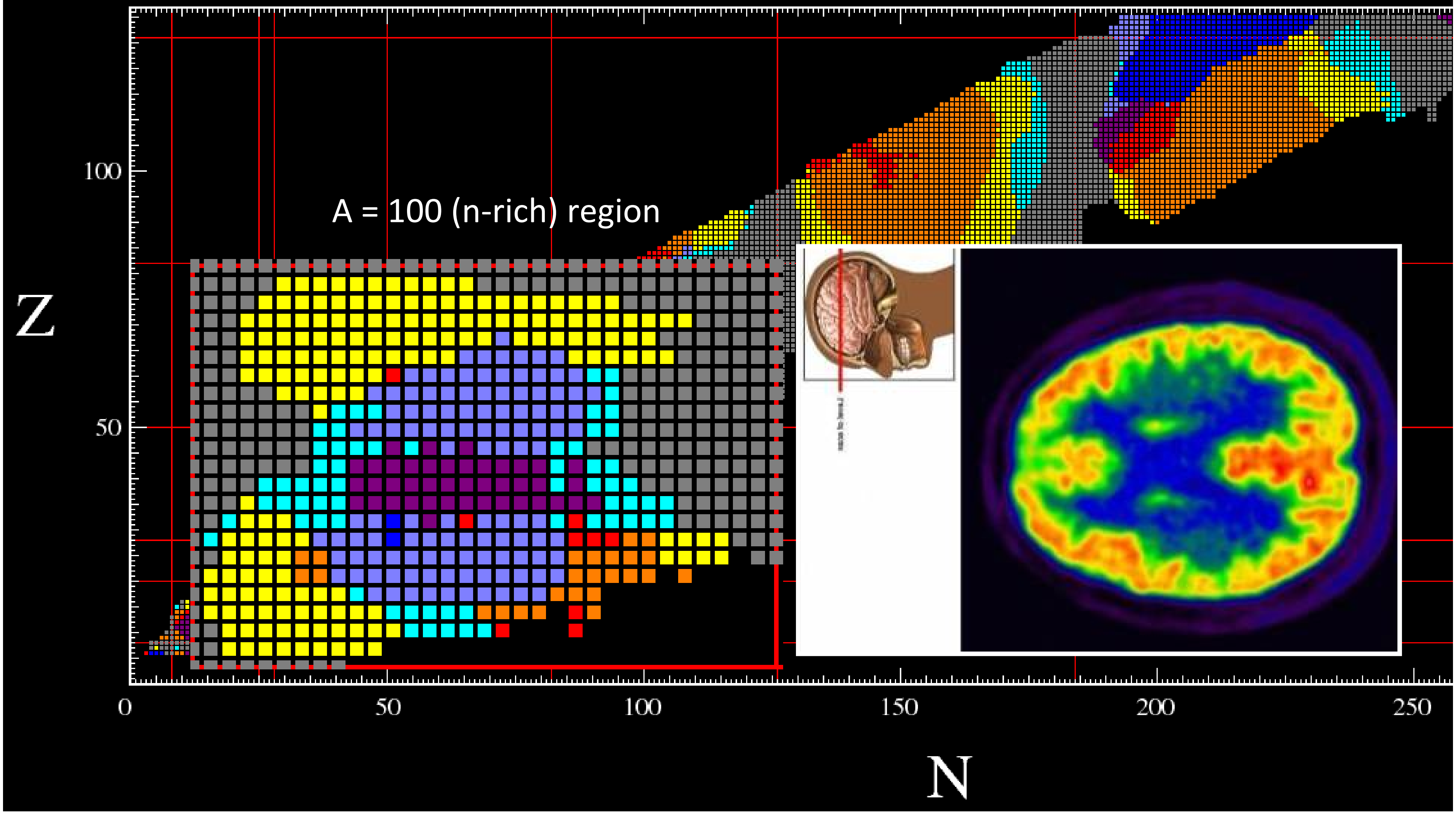
HFB – Gogny: D1S (S. Hilaire et al.)

http://www-phynu.cea.fr/

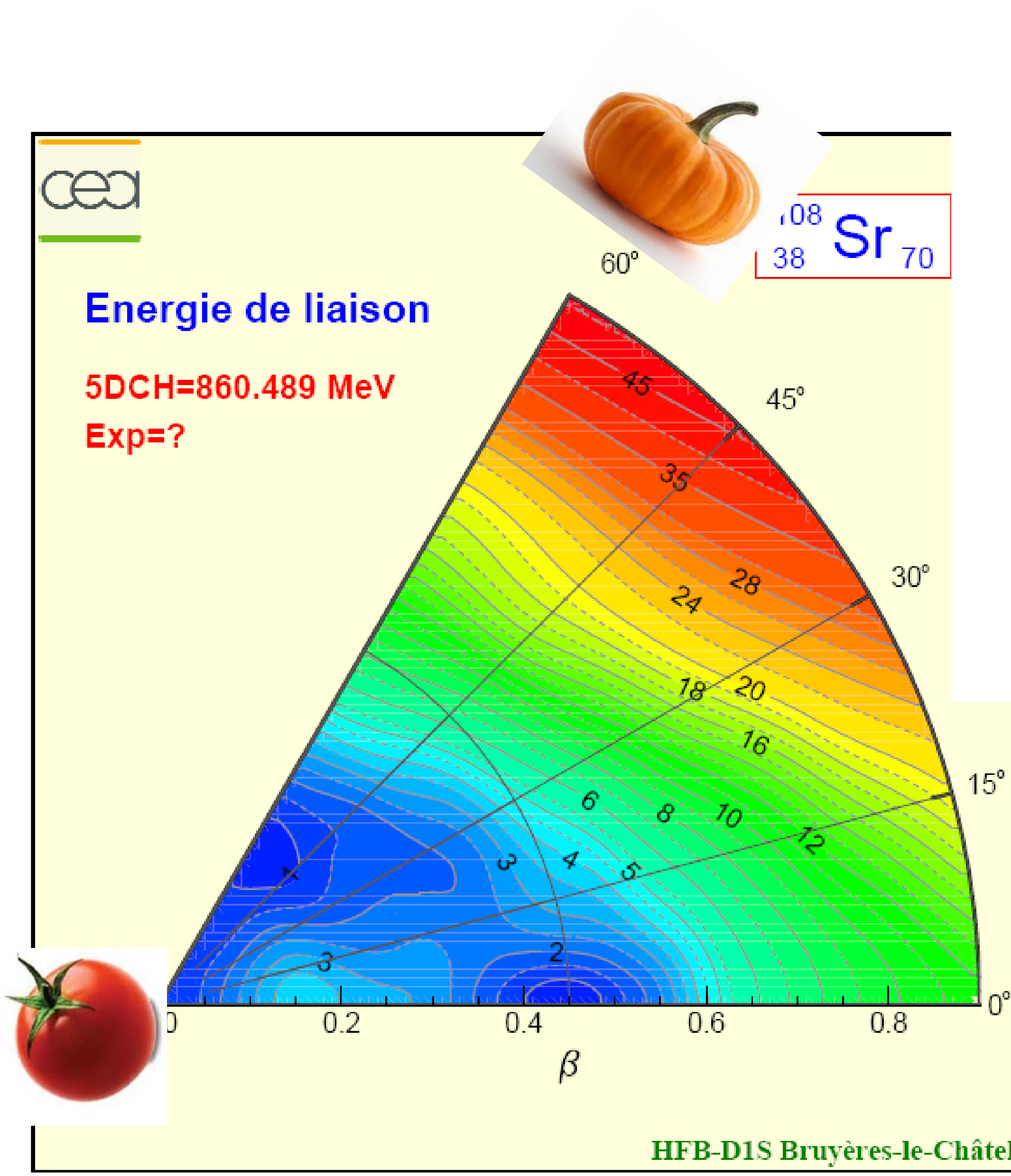


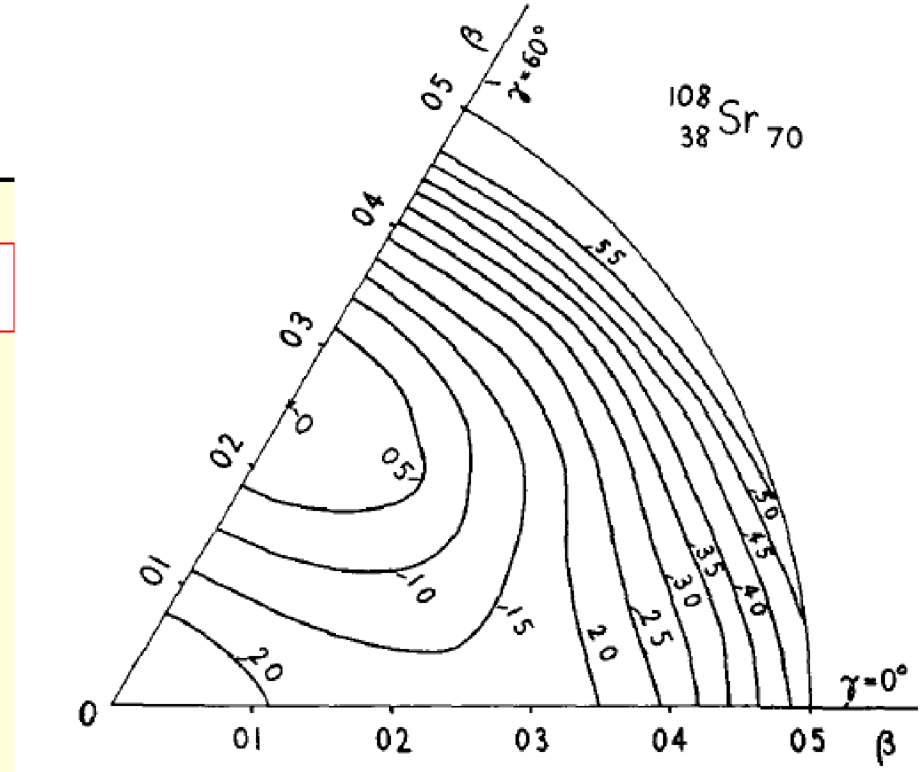
HFB – Gogny: D1S (S. Hilaire et al.)

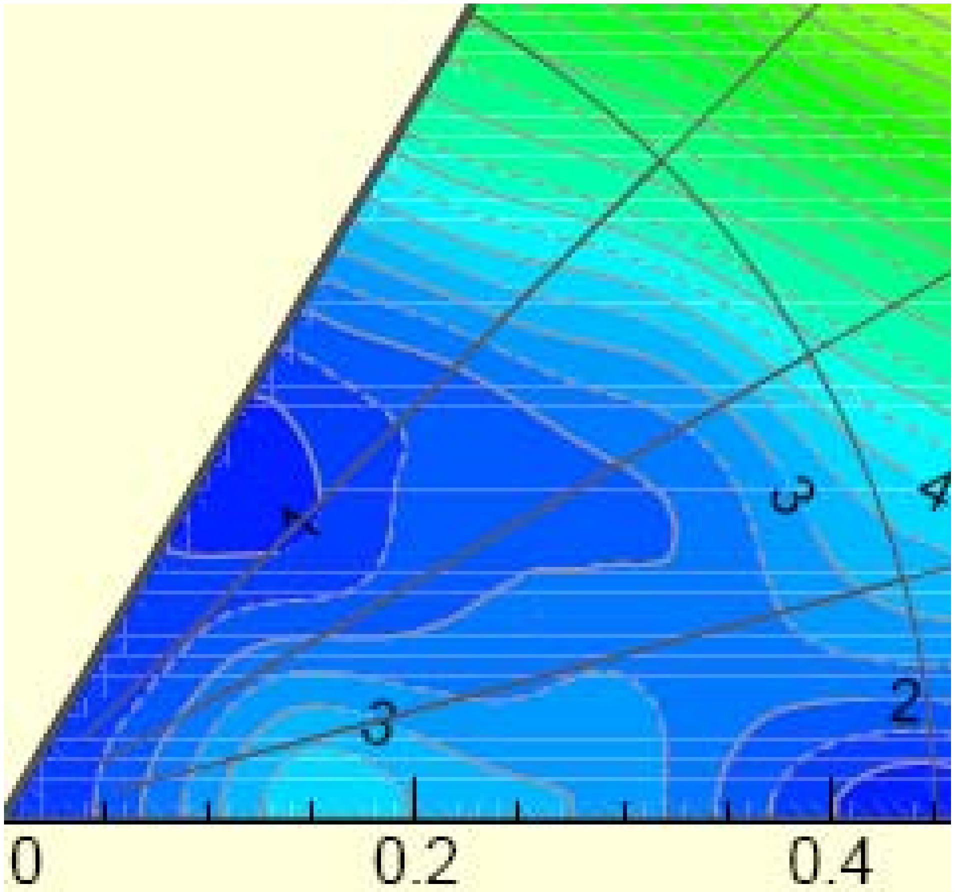
http://www-phynu.cea.fr/



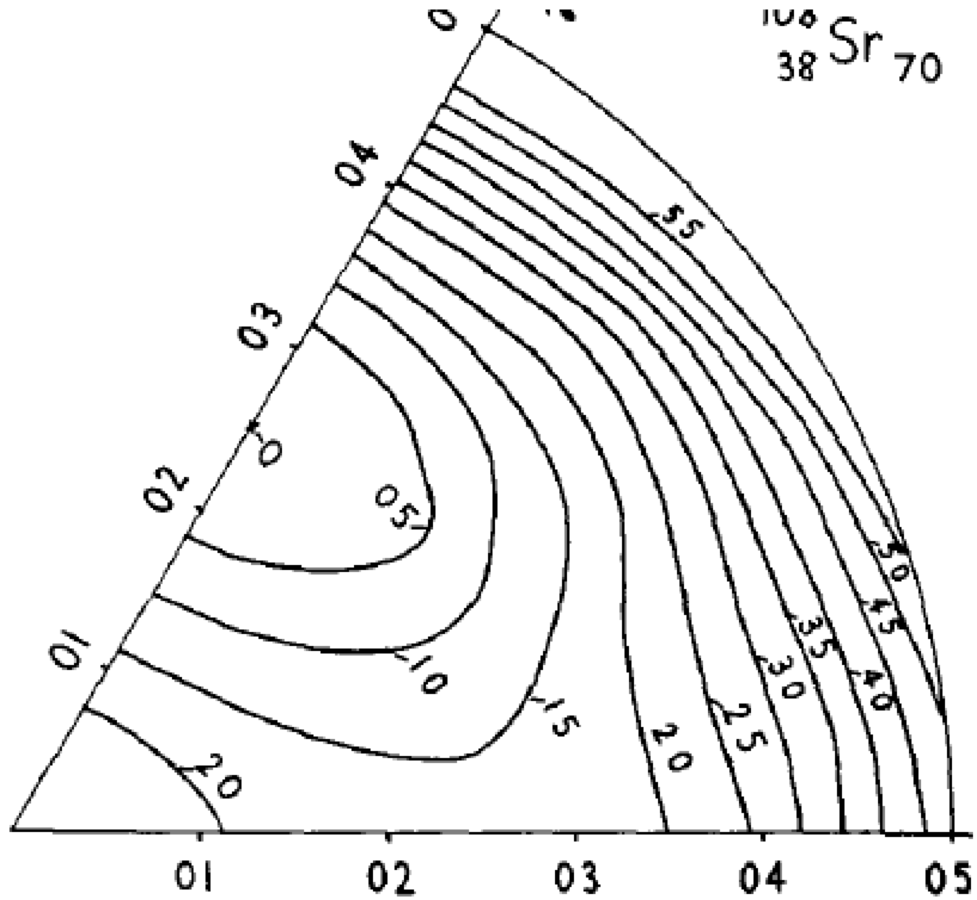
Arseniev, Sobiczewski, Soloviev, Nucl. Phys. A (1969)





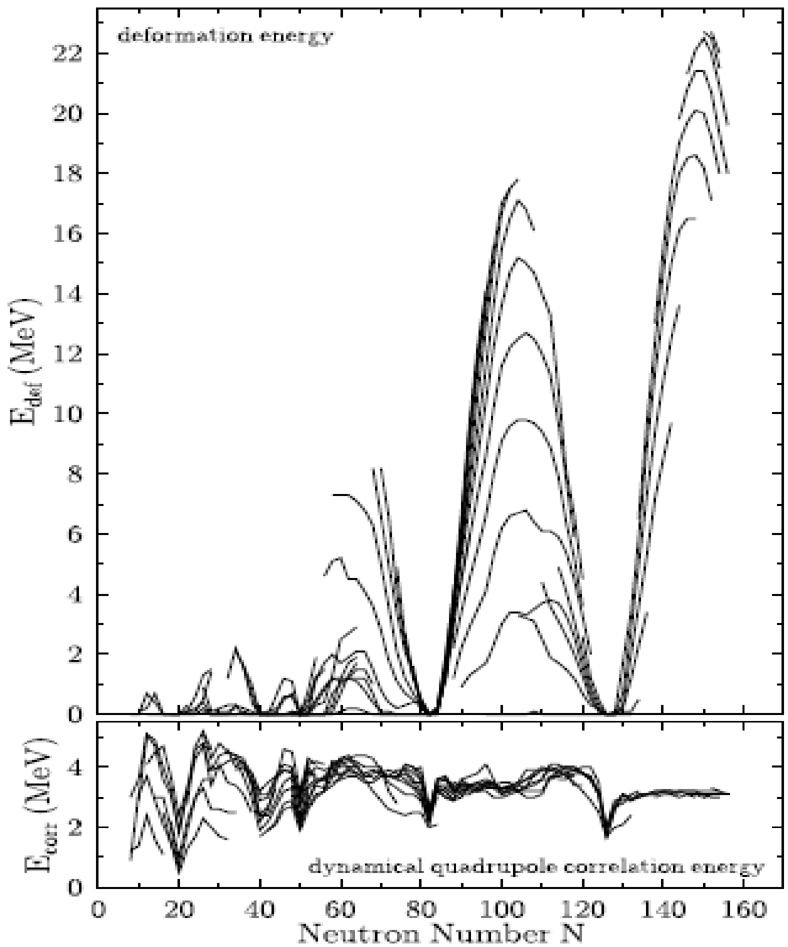


2007



1969

deformation energy



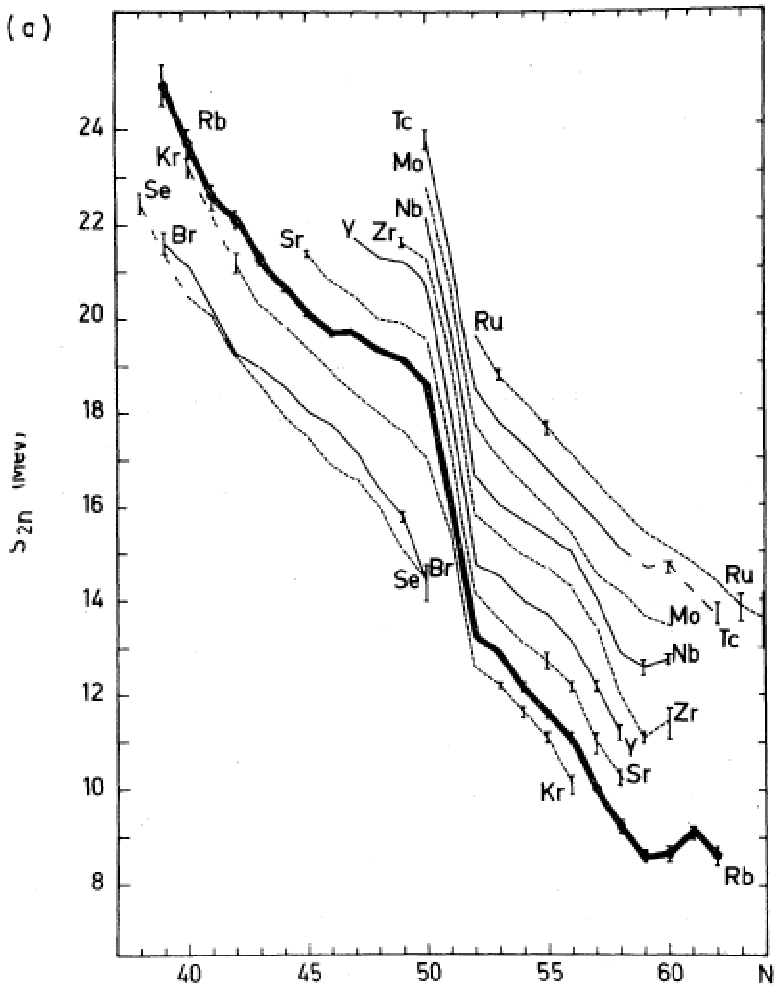
M. Bender, G. Bertsch, P.-H. Heenen (2006)

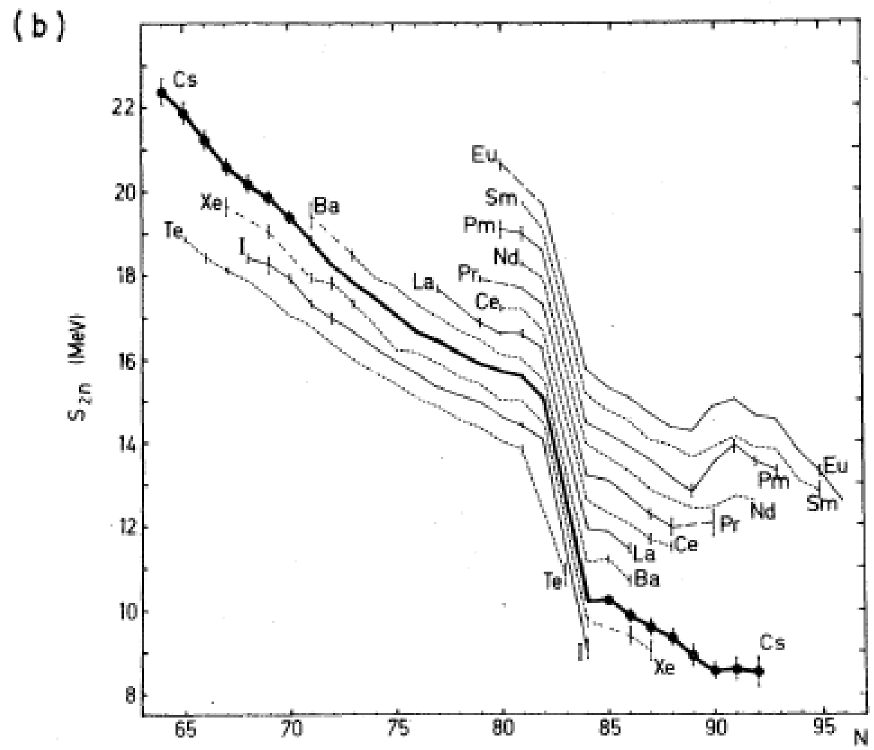
"I like middles.
It is in middles that extremes clash,
where ambiguity restlessly rules."
-John Updike

PHYSICAL REVIEW C VOLUME 19, NUMBER 4 APRIL 1979

Direct measurements of the masses of rubidium and cesium isotopes far from stability

M. Epherre, G. Audi, C. Thibault, R. Klapisch, G. Huber,* F. Touchard, and H. Wollnik†
Laboratoire René Bernas du C.S.N.S.M., Bât. 108, 91406, Orsay, France
and ISOLDE Collaboration, CERN, 1211, Geneva, Switzerland
(Received 17 July 1978)

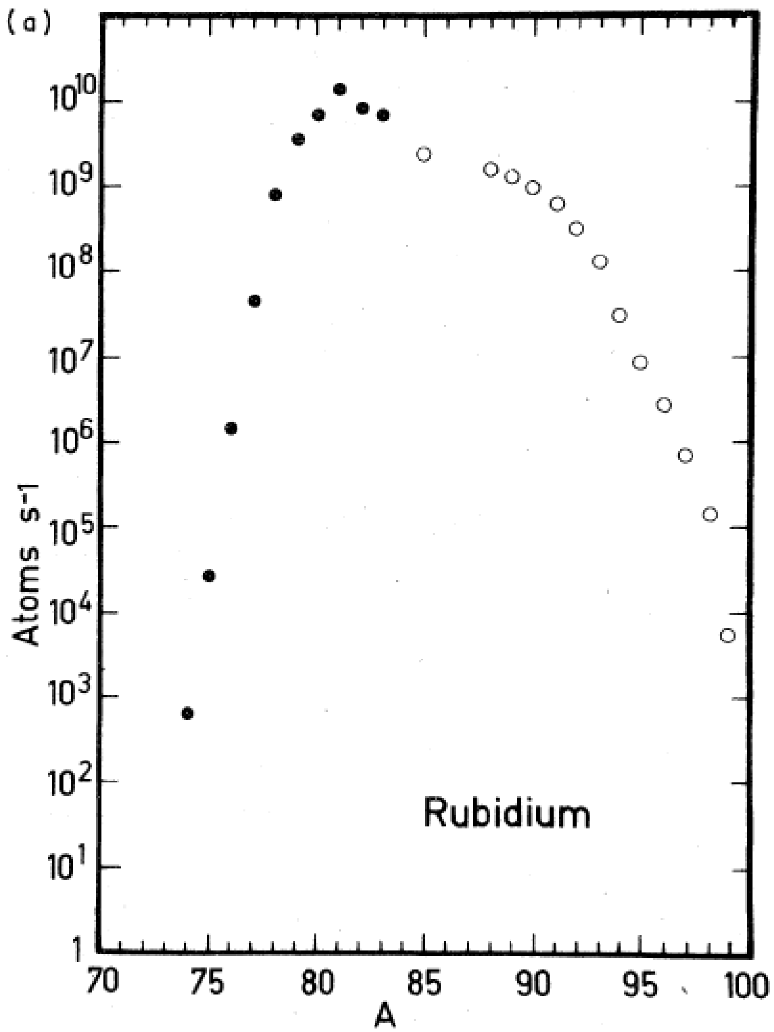


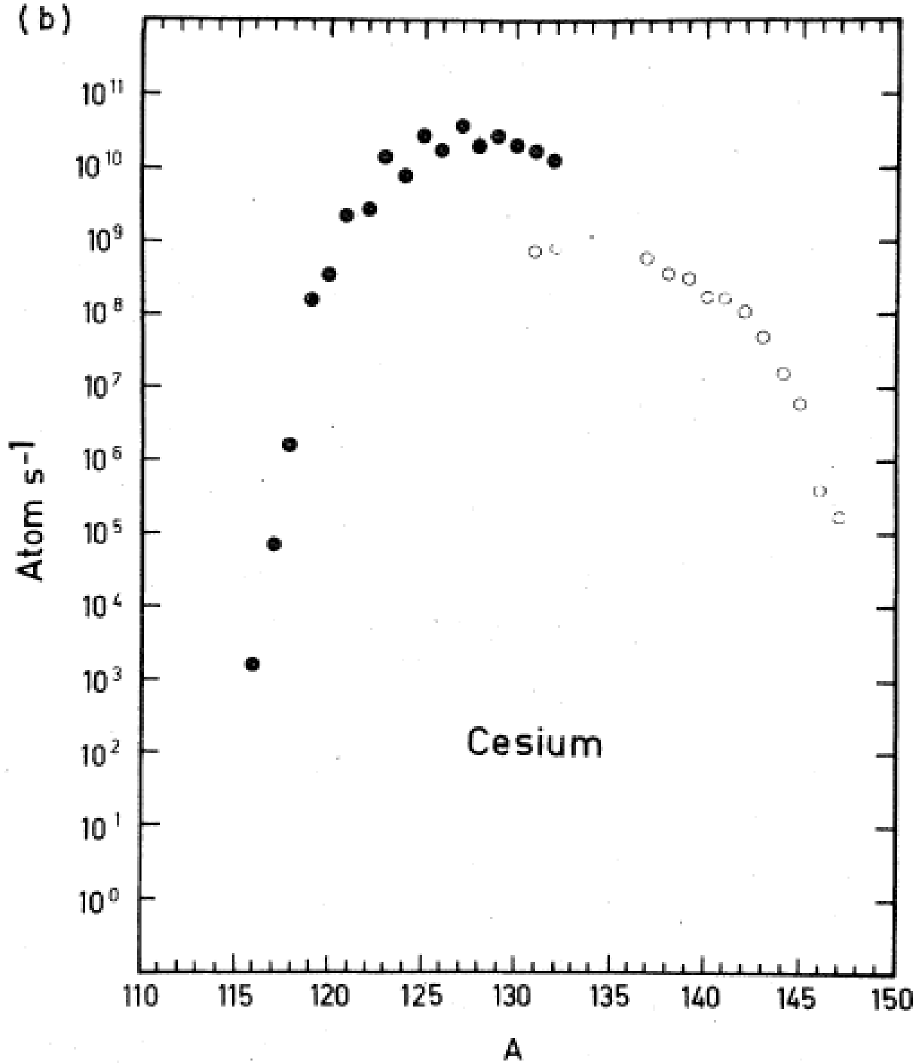


Same deduction made by Johansson (1965)
Cheifetz et al. (1970): more-often cited

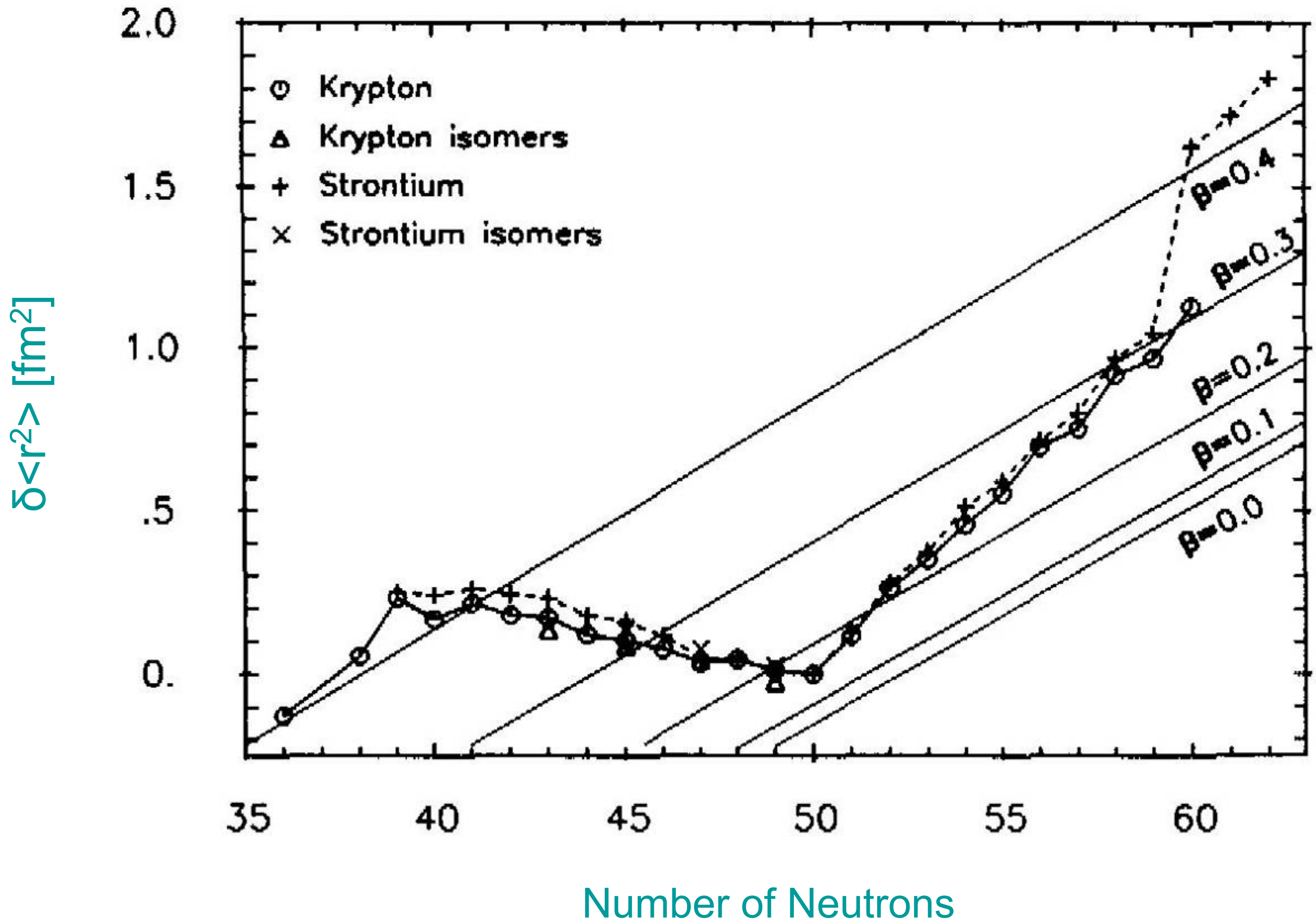
(Insufficient) mention of copious ILL contributions
(Pinston, Urban, Genevey, Simpson, et al.)

1978 SC yields (R. Neugart: the good old days!)





Early ISOLDE PSB result from COLLAPS



M. Keim (not K. Kreim!) et al., Nucl. Phys. A586 (1995) 219

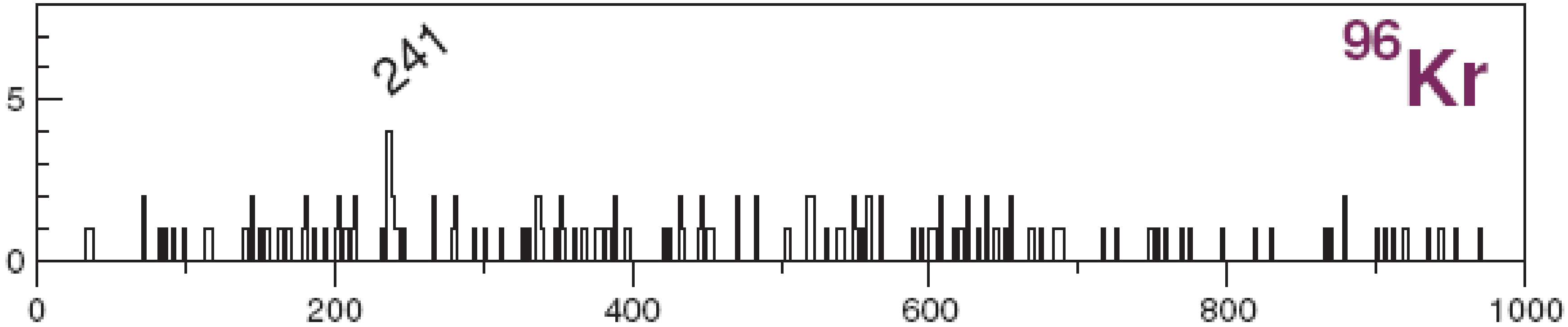
Perhaps TOO **RAPID COMMUNICATION**

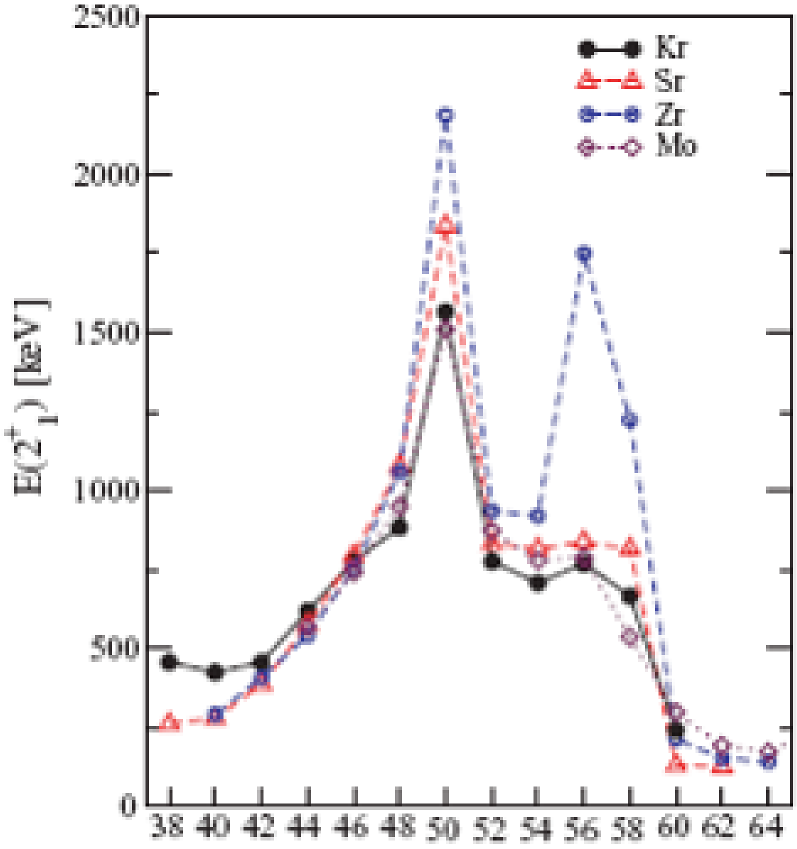
PHYSICAL REVIEW C **80**, 021301(R) (2009)

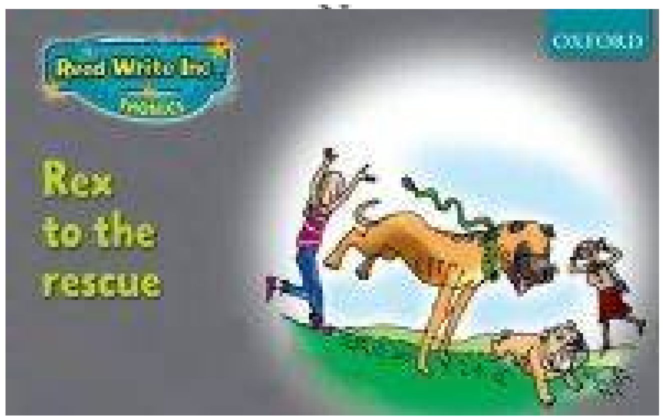
Evolution of deformation in the neutron-rich krypton isotopes: The ^{96}Kr nucleus

N. Mărginean,[1] D. Bucurescu,[1,2] C. A. Ur,[1,3] C. Mihai,[1] L. Corradi,[4] E. Farnea,[3] D. Filipescu,[1] E. Fioretto,[4] D. Ghiţă,[1] B. Guiot,[4] M. Górska,[5] M. Ionescu-Bujor,[1] A. Iordăchescu,[1] D. Jelavić-Malenica,[6] S. M. Lenzi,[3] P. Mason,[3] R. Mărginean,[1] D. Mengoni,[4] G. Montagnoli,[3] D. R. Napoli,[4] S. Pascu,[1] G. Pollarolo,[7] F. Recchia,[4] A. M. Stefanini,[4] R. Silvestri,[4] T. Sava,[1] F. Scarlassara,[3] S. Szilner,[6] and N. V. Zamfir[1]

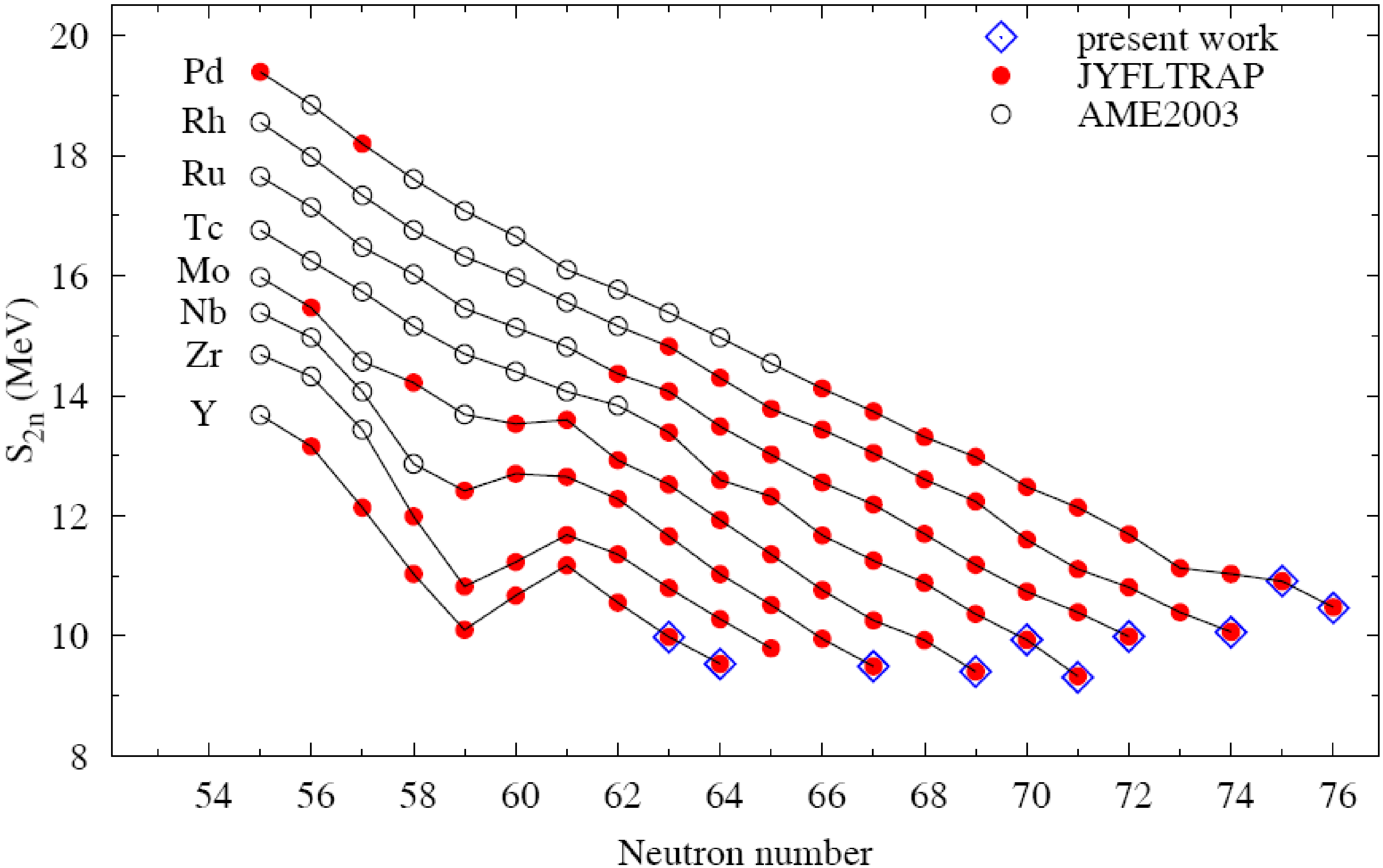
[1]*Horia Hulubei National Institute of Physics and Nuclear Engineering, R-76900 Bucharest, Romania*

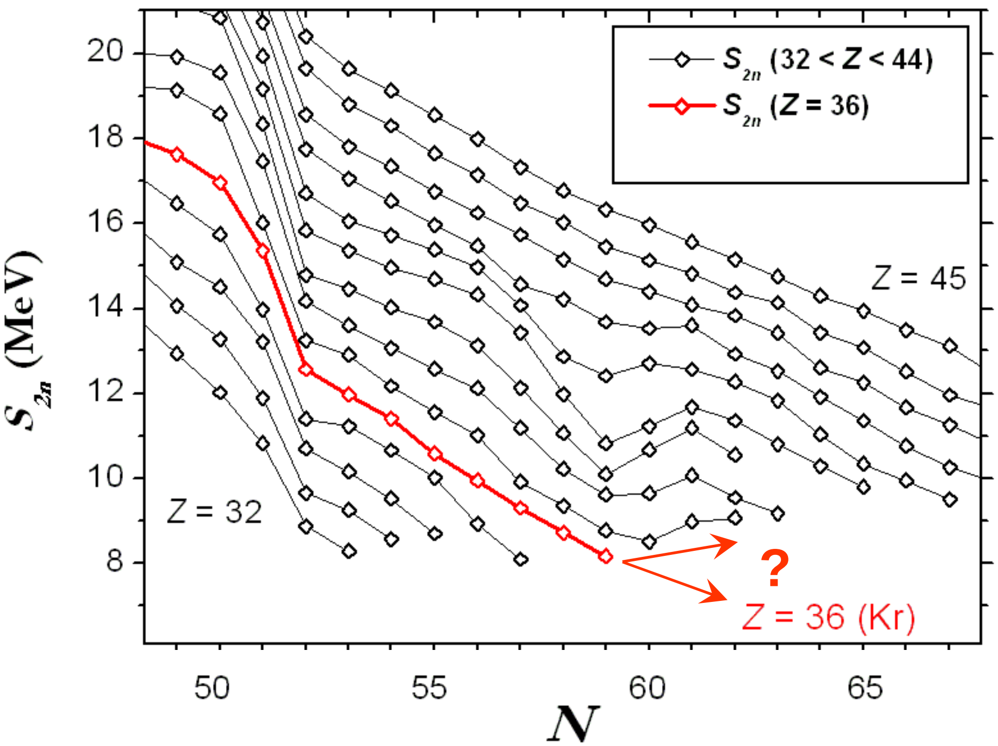






241-keV γ ray from the ^{96}Kr spectrum has been assigned to the $2_1^+ \rightarrow 0_{g.s.}^+$ transition in this nucleus. This assignment is not so straightforward. Figure 2 shows the evolution of the energy of the excited 2_1^+ state along isotopic chains, as well as that of the energies of the 2_1^+ and 4_1^+ states with the Z number from Kr to Mo. On the basis of the evolution of $E(4_1^+)$ for the $N = 60$ isotones, one could argue that the 241-keV γ ray in ^{96}Kr might be the $4^+ \rightarrow 2^+$ transition; in this case, the $2^+ \rightarrow 0^+$ transition would have an energy in the region from 103 keV (if this nucleus is a perfect rotor) to $\sim$160 keV [if it has an $E(4^+)/E(2^+)$ ratio of about 2.5], and its absence from the spectrum in Fig. 1 appears to correlate with the strong suppression of the 145 keV $2^+ \rightarrow 0^+$ transition of ^{98}Sr (we note, however, that the 145-keV transition is weak not only because of the detection efficiency but also due to the 2.8-ns half-life of the 2^+ state). This solution, solely based on the extrapolation of the energy of the $4^+ \rightarrow 2^+$ transition is, nevertheless, difficult to support. First, extrapolating in such a region of sudden changes is dangerous; such an energy for the 2_1^+ state would be one of the lowest known in the region, indicating a rather large deformation (and therefore a very sudden structure change). Second, if we look at the behavior in the $N = 58$ and $N = 56$ isotones, one can see that the trend of the Kr isotopes is similar to that of the Mo isotopes, which, applied to $N = 60$, recommends the assignment of the 241-keV γ ray to the 2^+ state. Third, as it will be discussed below, both experimental laser spectroscopy results and all existing theoretical predictions for ^{96}Kr indicate a moderate deformation, which roughly corresponds to this value for the 2^+ state energy. We thus prefer this later assignment, but it remains as a task of future $\gamma\gamma$-coincidence spectroscopy to prove that.

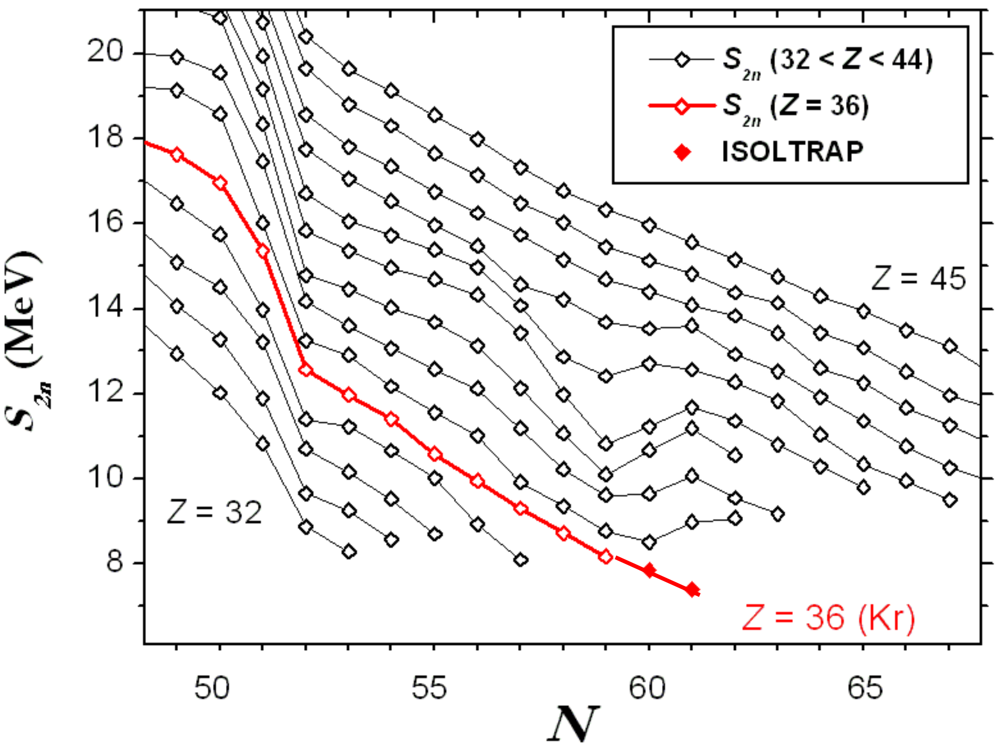

present work
JYFLTRAP
AME2003
Pd
Rh
Ru
Tc
Mo
Nb
Zr
Y
S_{2n} (MeV)
Neutron number
20
18
16
14
12
10
8
54
56
58
60
62
64
66
68
70
72
74
76



Famous shape transition at A = 100

^{97,98}Kr masses: critical point?

S. Naimi et al. (ISOLTRAP) have the answer!



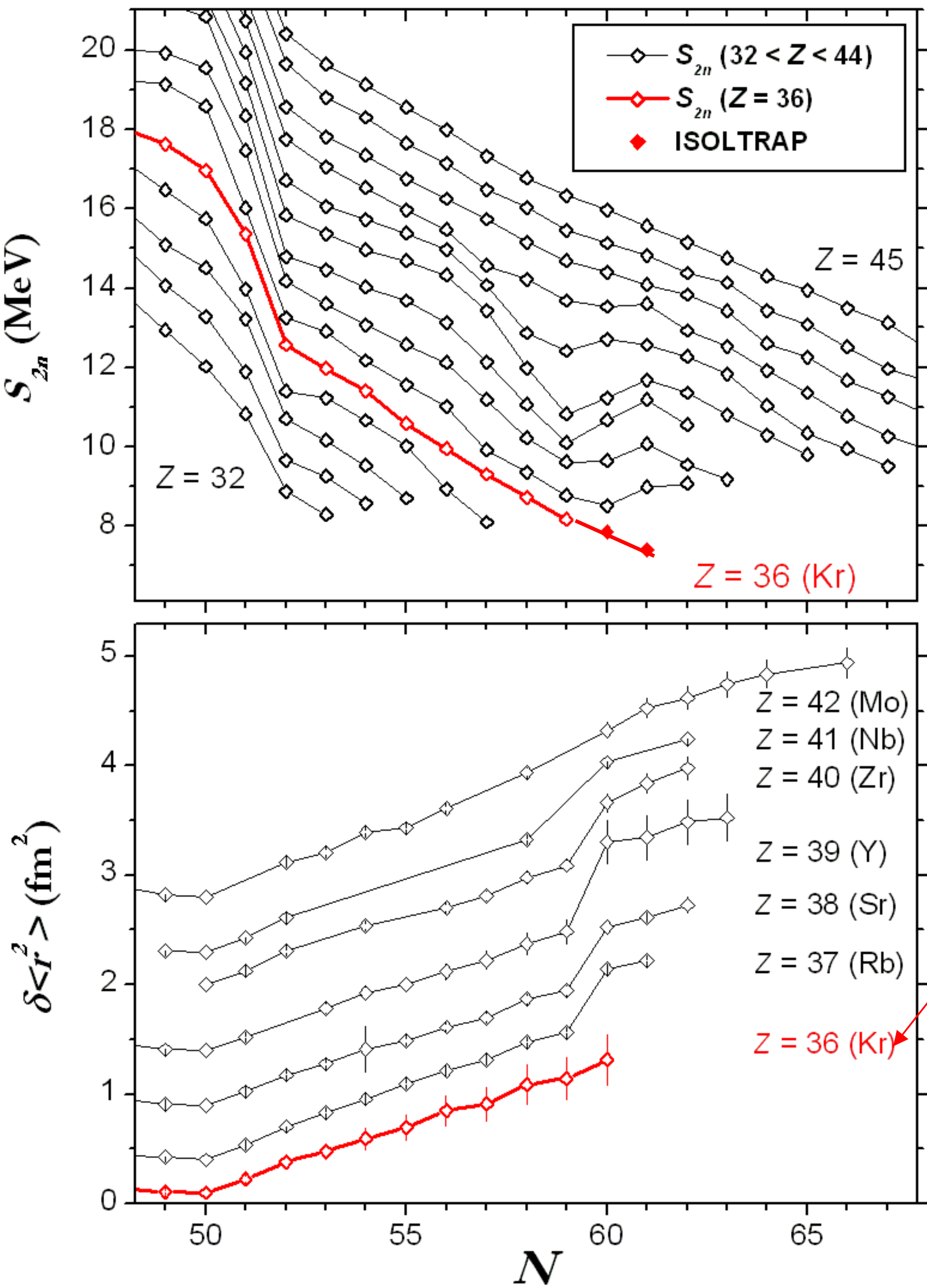
PRL 105, 032502 (2010) PHYSICAL REVIEW LETTERS week ending 16 JULY 2010

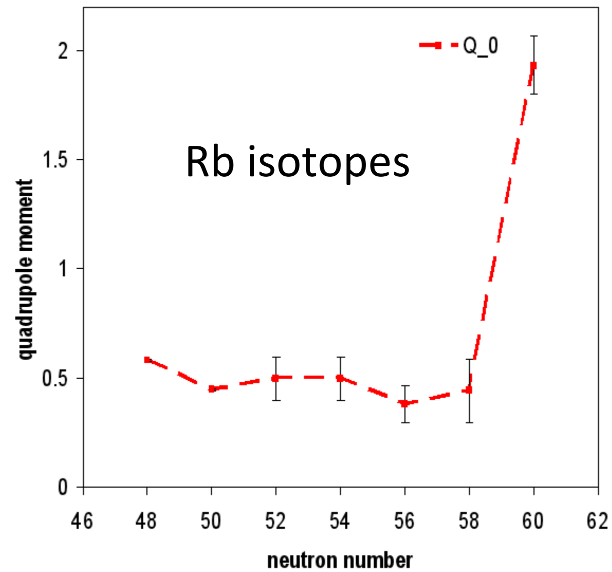
Critical-Point Boundary for the Nuclear Quantum Phase Transition Near A = 100 from Mass Measurements of ^{96,97}Kr

S. Naimi,[1] G. Audi,[1] D. Beck,[2] K. Blaum,[3] Ch. Böhm,[3] Ch. Borgmann,[3] M. Breitenfeldt,[4,*] S. George,[3,†] F. Herfurth,[2] A. Herlert,[5] M. Kowalska,[3] S. Kreim,[3] D. Lunney,[1,‡] D. Neidherr,[6] M. Rosenbusch,[4] S. Schwarz,[7] L. Schweikhard,[4] and K. Zuber[8]
[1]*CSNSM-IN2P3-CNRS, Université de Paris Sud, 91405 Orsay, France*

^{97,98}Kr masses

S. Naimi et al. (ISOLTRAP)
"New critical point for the A = 100 nuclear quantum phase transition"
Phys. Rev. Lett. 105 (2010) 032502





comparison with charge radii

[16] G. Audi, A.H. Wapstra, C. Thibault, Nucl. Phys. A 729, 337 (2003).
[17] P. Delahaye *et al.*, Phys. Rev. C 74, 034331 (2007).
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[21] C. Thibault *et al.*, Phys. Rev. C 23, 2720 (1981).
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[27] F.C. Charlwood *et al.*, Phys. Lett. B 674, 23 (2009).

Evidence for a Smooth Onset of Deformation in the Neutron-Rich Kr Isotopes

M. Albers,[1,2,*] N. Warr,[1] K. Nomura,[3] A. Blazhev,[1] J. Jolie,[1] D. Mücher,[4] B. Bastin,[5] C. Bauer,[6] C. Bernards,[1] L. Bettermann,[1] V. Bildstein,[4,7] J. Butterworth,[8] M. Cappellazzo,[1] J. Cederkäll,[9] D. Cline,[10] I. Darby,[5] S. Das Gupta,[11] J. M. Daugas,[12] T. Davinson,[13] H. De Witte,[5] J. Diriken,[5,14] D. Filipescu,[15] E. Fiori,[16] C. Fransen,[1] L. P. Gaffney,[17] G. Georgiev,[16] R. Gernhäuser,[4] M. Hackstein,[1] S. Heinze,[1] H. Hess,[1] M. Huyse,[5] D. Jenkins,[8] J. Konki,[18] M. Kowalczyk,[19] T. Kröll,[6] R. Krücken,[4,20] J. Litzinger,[1] R. Lutter,[21] N. Marginean,[15] C. Mihai,[15] K. Moschner,[1] P. Napiorkowski,[19] B. S. Nara Singh,[8] K. Nowak,[4] T. Otsuka,[3,22,23] J. Pakarinen,[9] M. Pfeiffer,[1] D. Radeck,[1] P. Reiter,[1] S. Rigby,[17] L. M. Robledo,[24] R. Rodríguez-Guzmán,[25] M. Rudigier,[1] P. Sarriguren,[25] M. Scheck,[6,17] M. Seidlitz,[1] B. Siebeck,[1] G. Simpson,[26] P. Thöle,[1] T. Thomas,[1] J. Van de Walle,[27] P. Van Duppen,[5] M. Vermeulen,[8] D. Voulot,[9] R. Wadsworth,[8] F. Wenander,[9] K. Wimmer,[4,23] K. O. Zell,[1] and M. Zielinska[19]

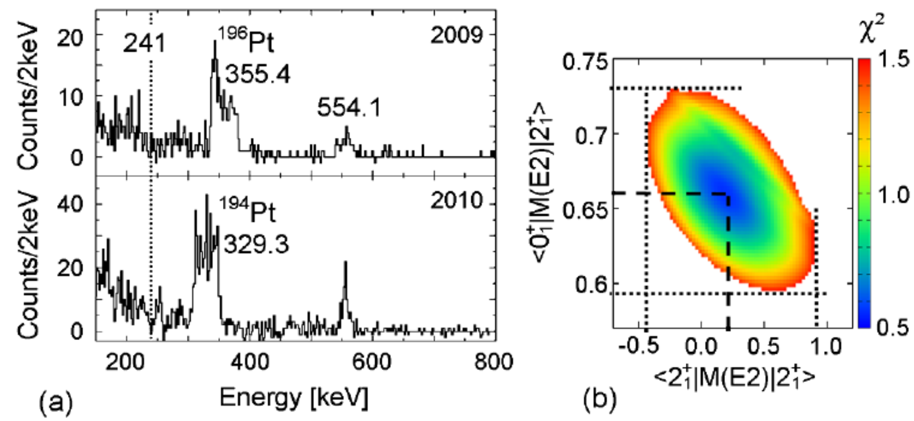
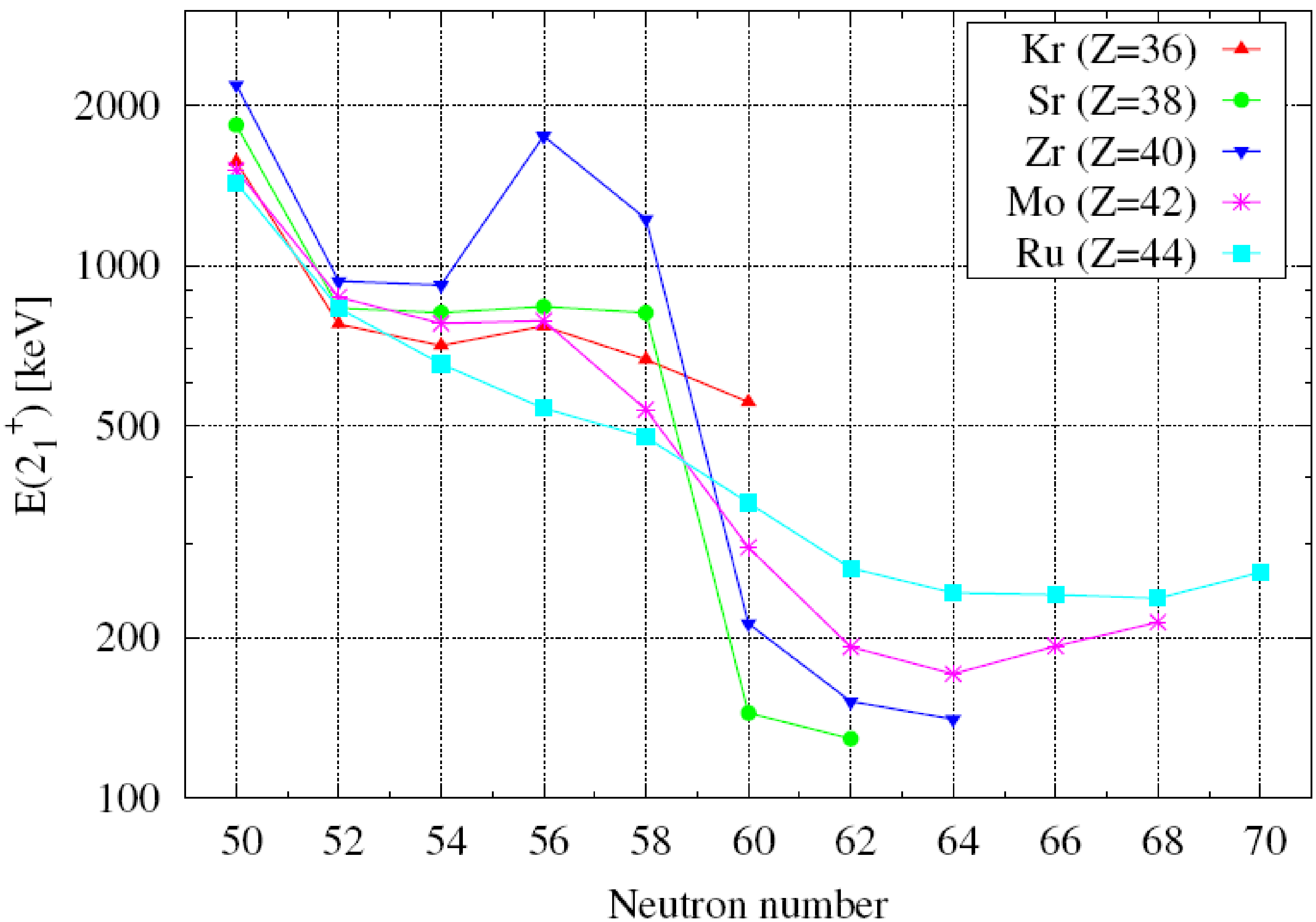


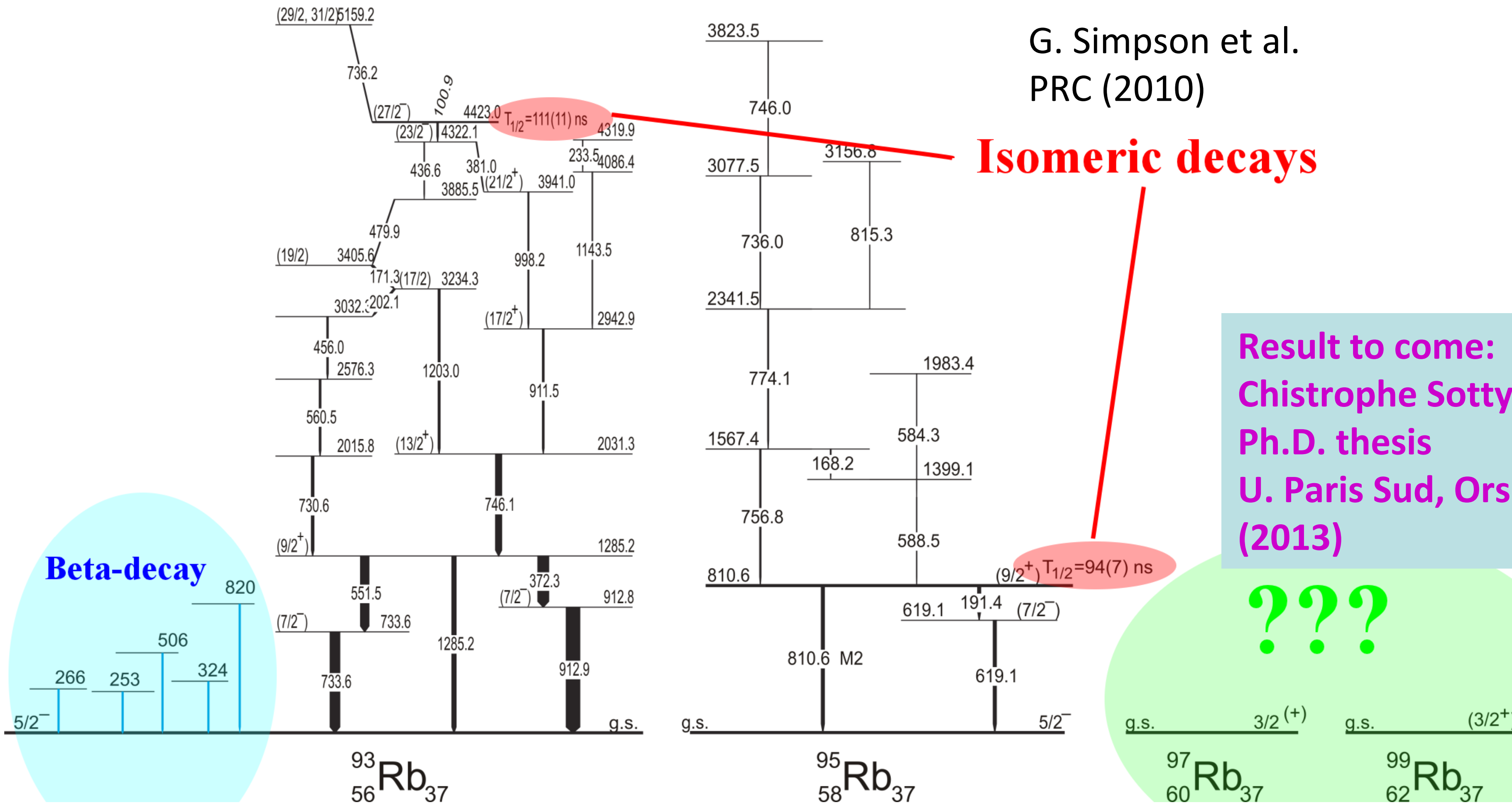
FIG. 2 (color online). (a): Particle-gated and background-subtracted γ spectra with the ^{96}Kr beam on the ^{196}Pt target in 2009 (upper panel) and on the ^{194}Pt target in 2010 (lower panel), both Doppler corrected for mass $A = 96$. (b): 1σ contour of the χ^2 surface with respect to the diagonal and the transitional matrix elements of the 2_1^+ state in ^{96}Kr.



Kr (Z=36)
Sr (Z=38)
Zr (Z=40)
Mo (Z=42)
Ru (Z=44)
2000
1000
500
200
100
$E(2_1^+)$ [keV]
50
52
54
56
58
60
62
64
66
68
70
Neutron number

REX-MINIBALL Experimental results – n-rich Rb

G. Simpson et al.
PRC (2010)



Result to come:
Chistrophe Sotty,
Ph.D. thesis
U. Paris Sud, Orsay
(2013)

Also the Sr coulex from E. Clément

M. Albers et al.

PRL **108,** 062701 (2012) PHYSICAL RE

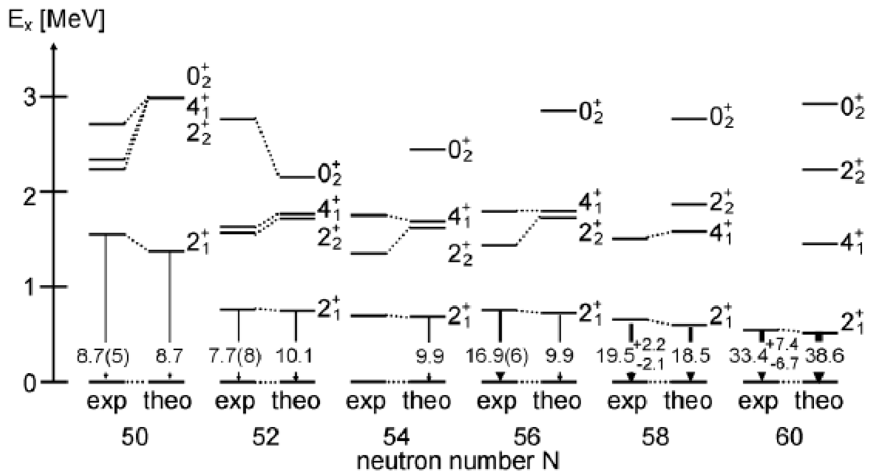
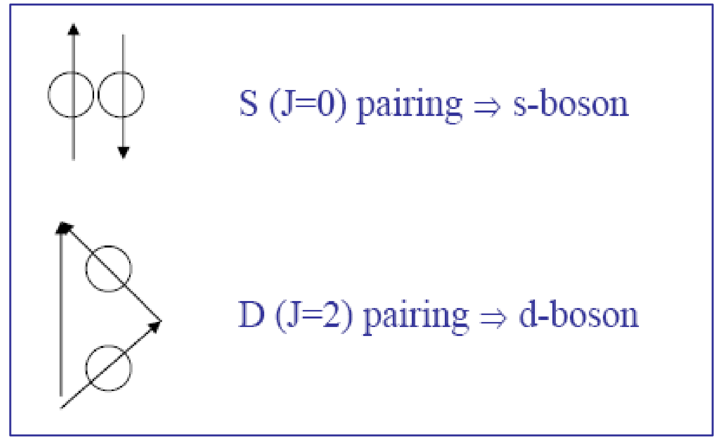
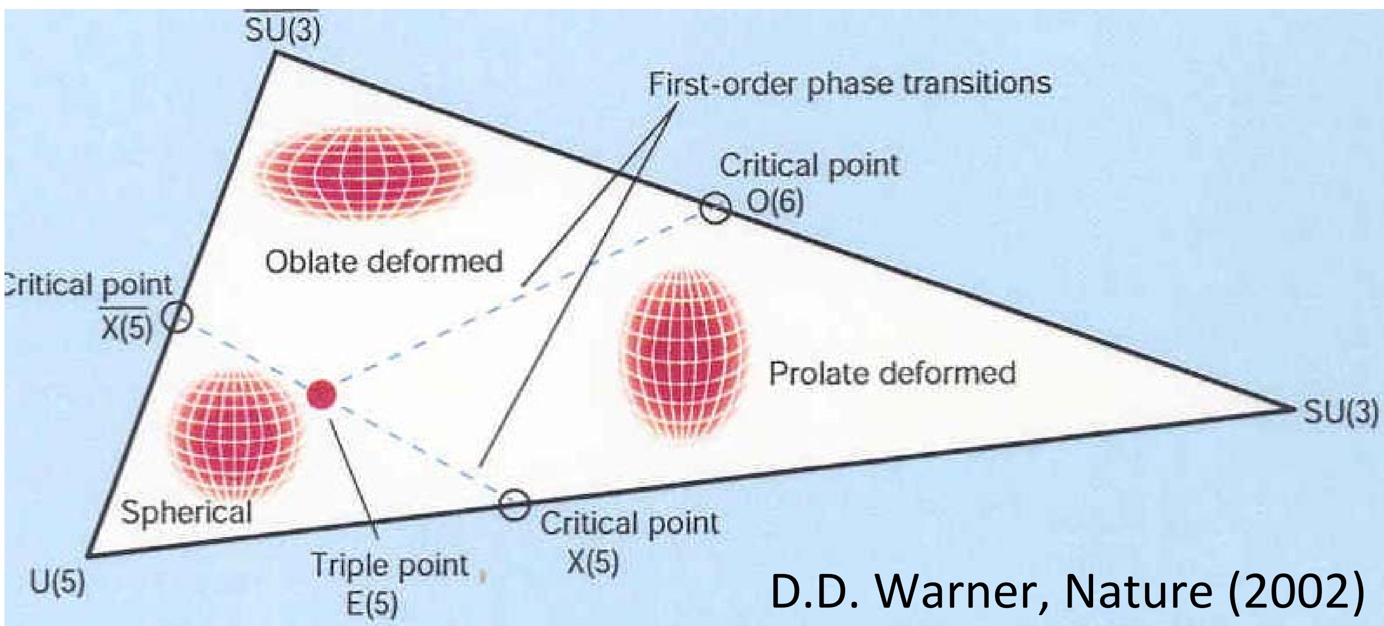


FIG. 5. Experimental and theoretical excitation energies of excited 0_2^+, 2_1^+, 2_2^+, and 4_1^+ states in the Kr isotopes with $50 \leq N \leq 60$. The experimental $B(E2; 2_1^+ \rightarrow 0_1^+)$values are taken from [9,31] and this Letter and are given in W.u..

Interacting Boson Model

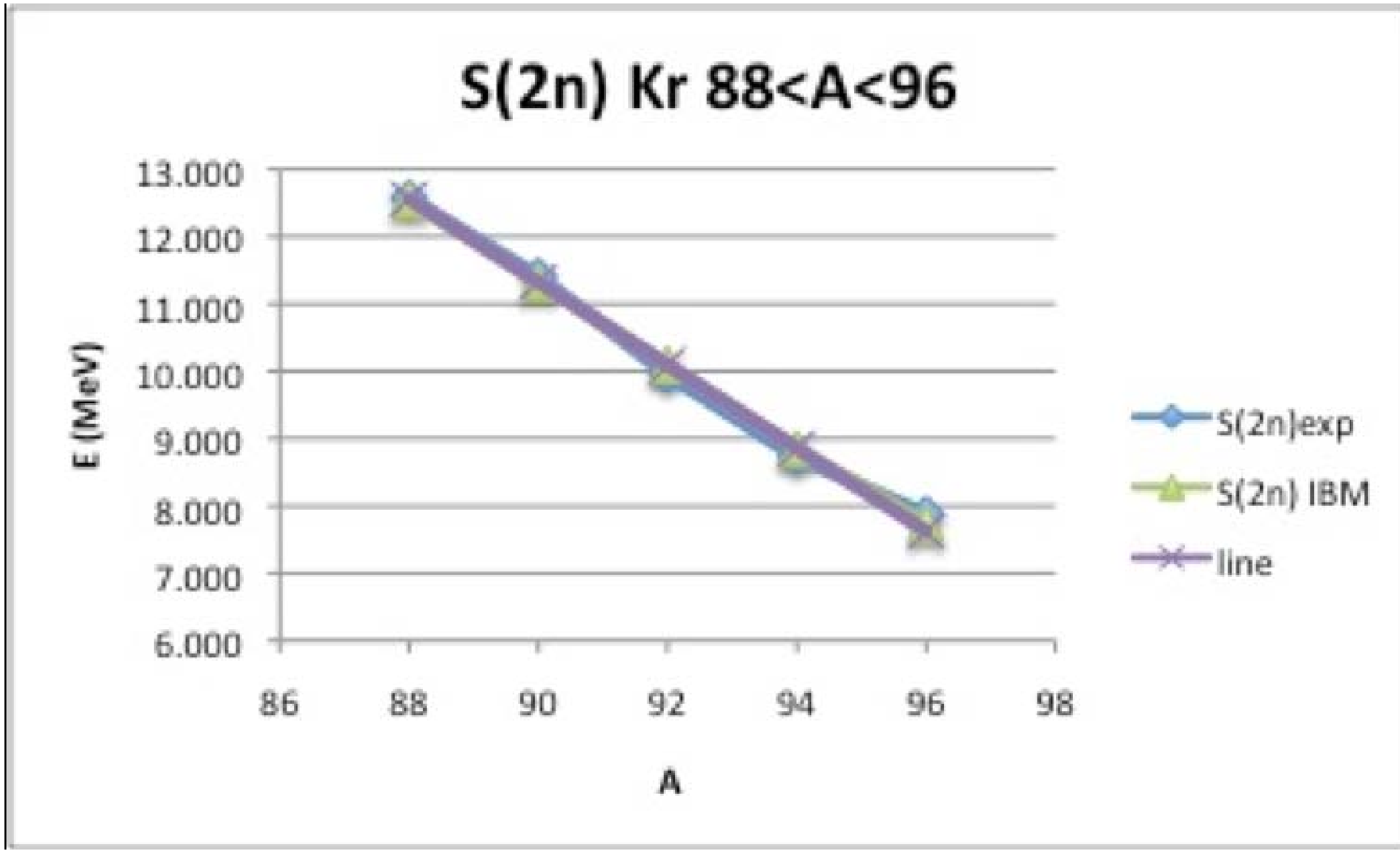




D.D. Warner, Nature (2002)

Effective boson number: A new approach for predicting separation energies with the IBM1, applied to Zr, Kr, Sr isotopes near A=100

N. Paul, P. Van Isacker, J.E. Garcia Ramos, A. Aprahamian



Parametrize an IBM Hamiltonian and relate masses to spectra

to (probably) appear (2013)

Physics Letters B 691 (2010) 202–207

Contents lists available at ScienceDirect

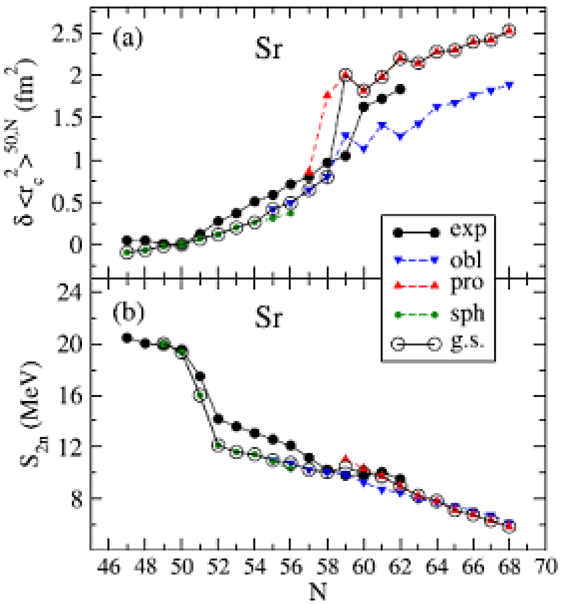
Physics Letters B

www.elsevier.com/locate/physletb

Charge radii and structural evolution in Sr, Zr, and Mo isotopes

R. Rodríguez-Guzmán[a], P. Sarriguren[a,*], L.M. Robledo[b], S. Perez-Martin[b,1]

[a] Instituto de Estructura de la Materia, CSIC, Serrano 123, E-28006 Madrid, Spain
[b] Departamento de Física Teórica, Módulo 15, Universidad Autónoma de Madrid, 28049 Madrid, Spain



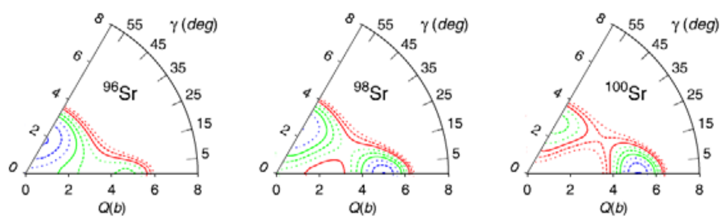


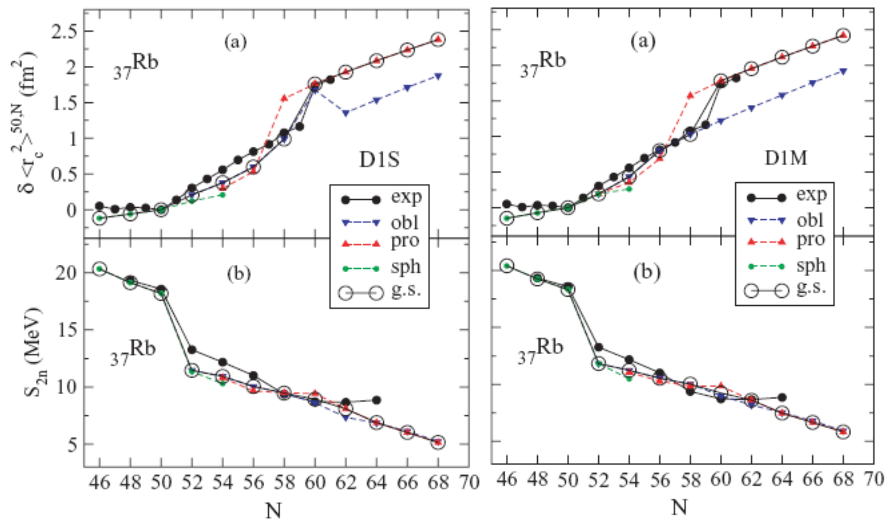
Fig. 4. Q–γ planes for ^{96,98,100}Sr isotopes with the Gogny-D1S interaction. The contour lines extend from the minimum up to 2 MeV higher in steps of 0.25 MeV.

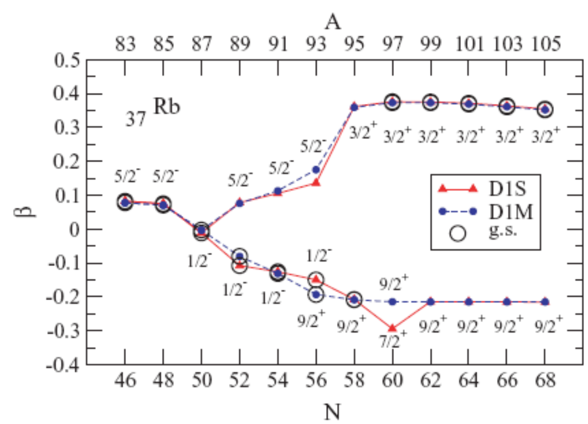
RAPID COMMUNICATIONS

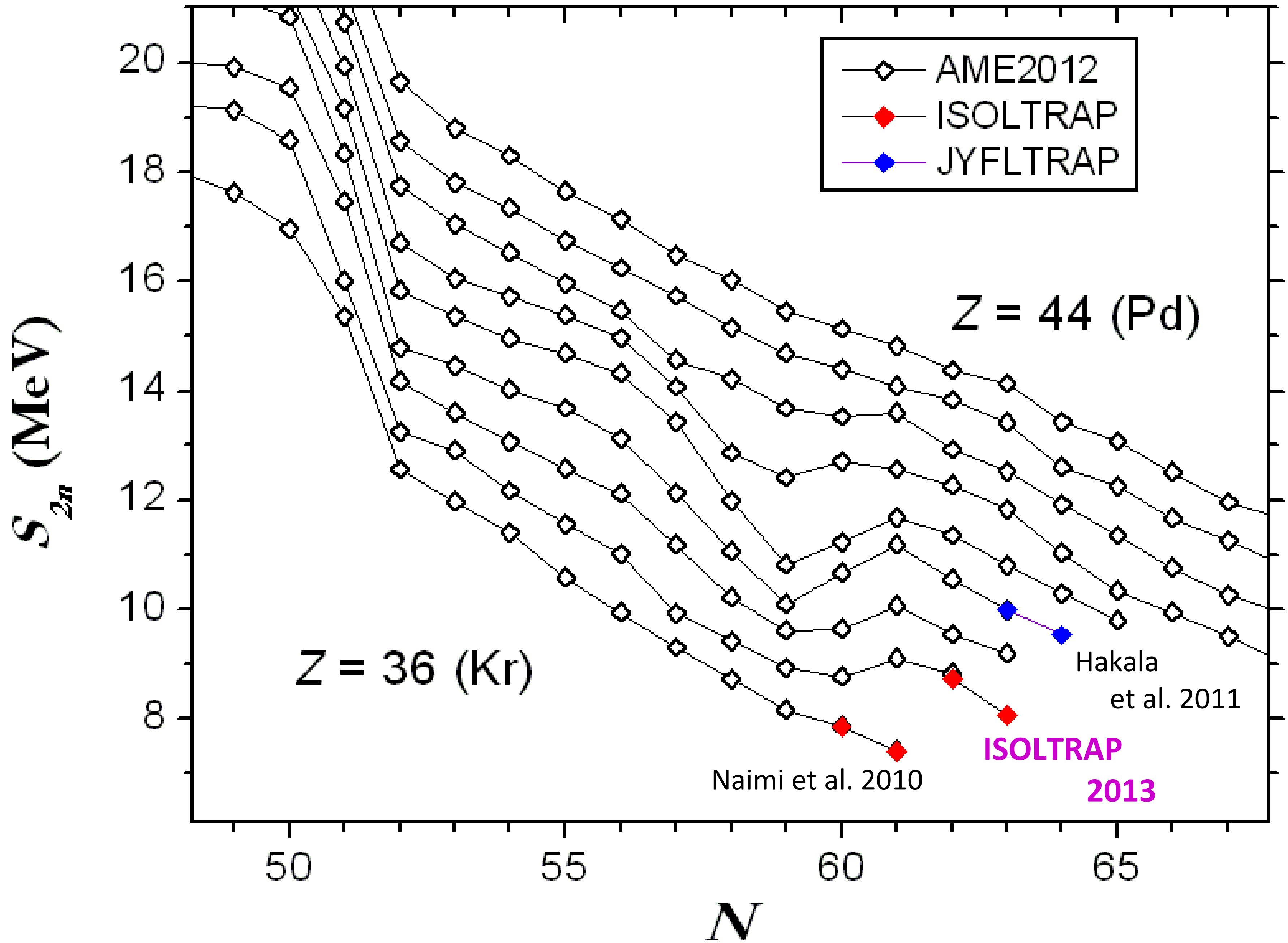
PHYSICAL REVIEW C **82**, 061302(R) (2010)

Signatures of shape transitions in odd-*A* neutron-rich rubidium isotopes

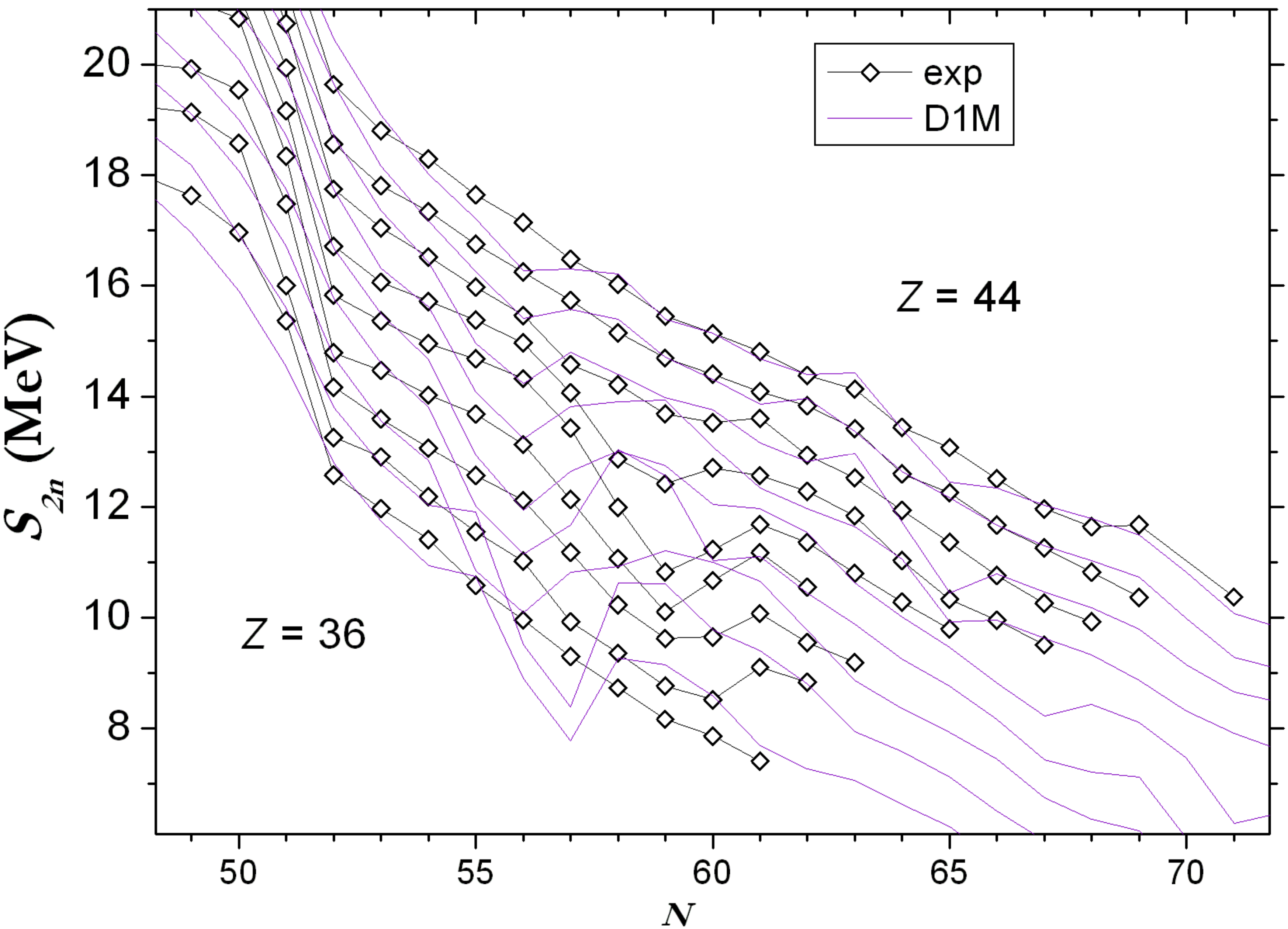
R. Rodriguez-Guzman,[1] P. Sarriguren,[1] and L. M. Robledo[2]
[1]Instituto de Estructura de la Materia, CSIC, Serrano 123, E-28006 Madrid, Spain
[2]Departamento de Física Teórica, Módulo 15, Universidad Autónoma de Madrid, E-28049 Madrid, Spain
(Received 3 November 2010; published 9 December 2010)



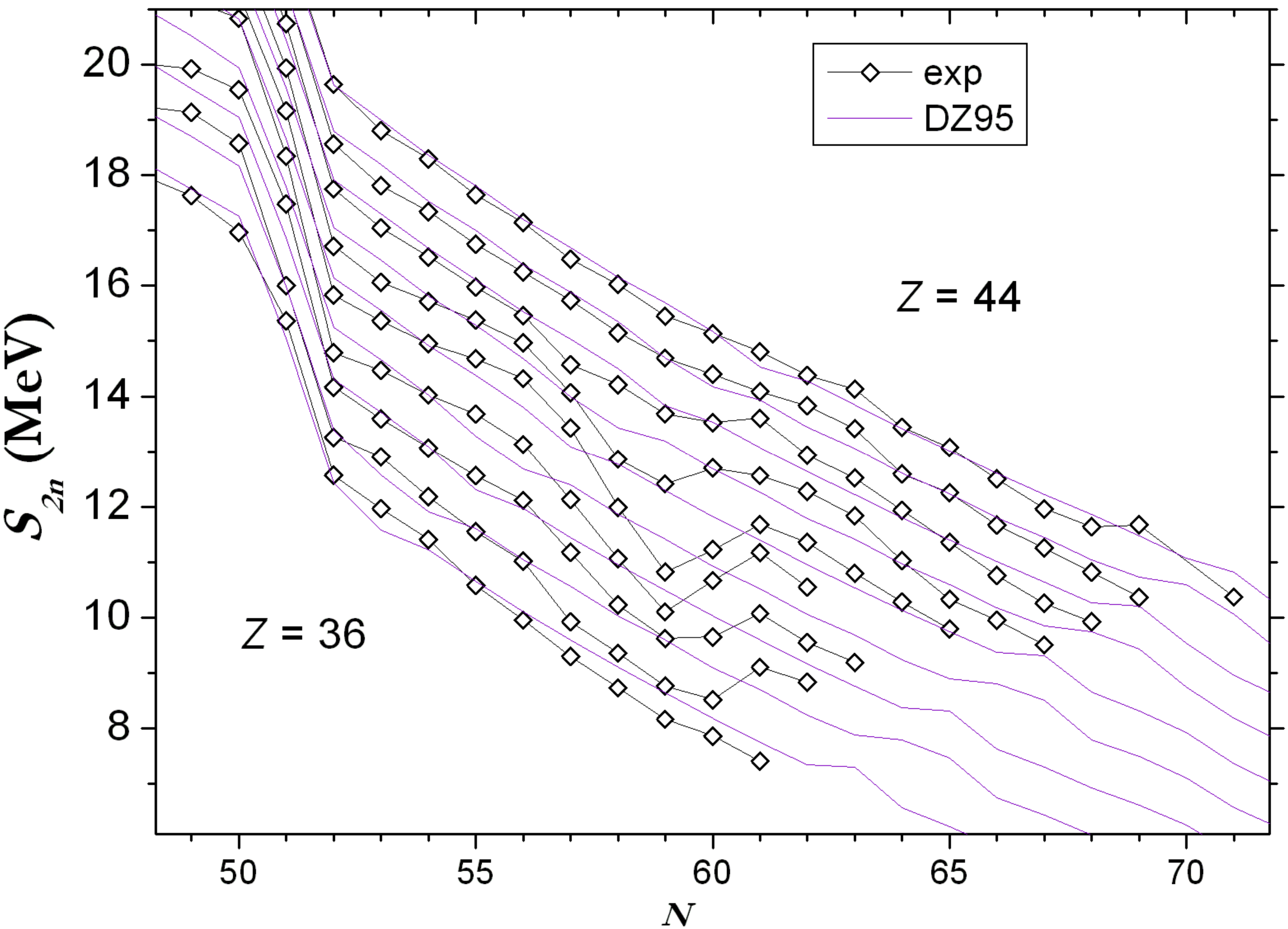




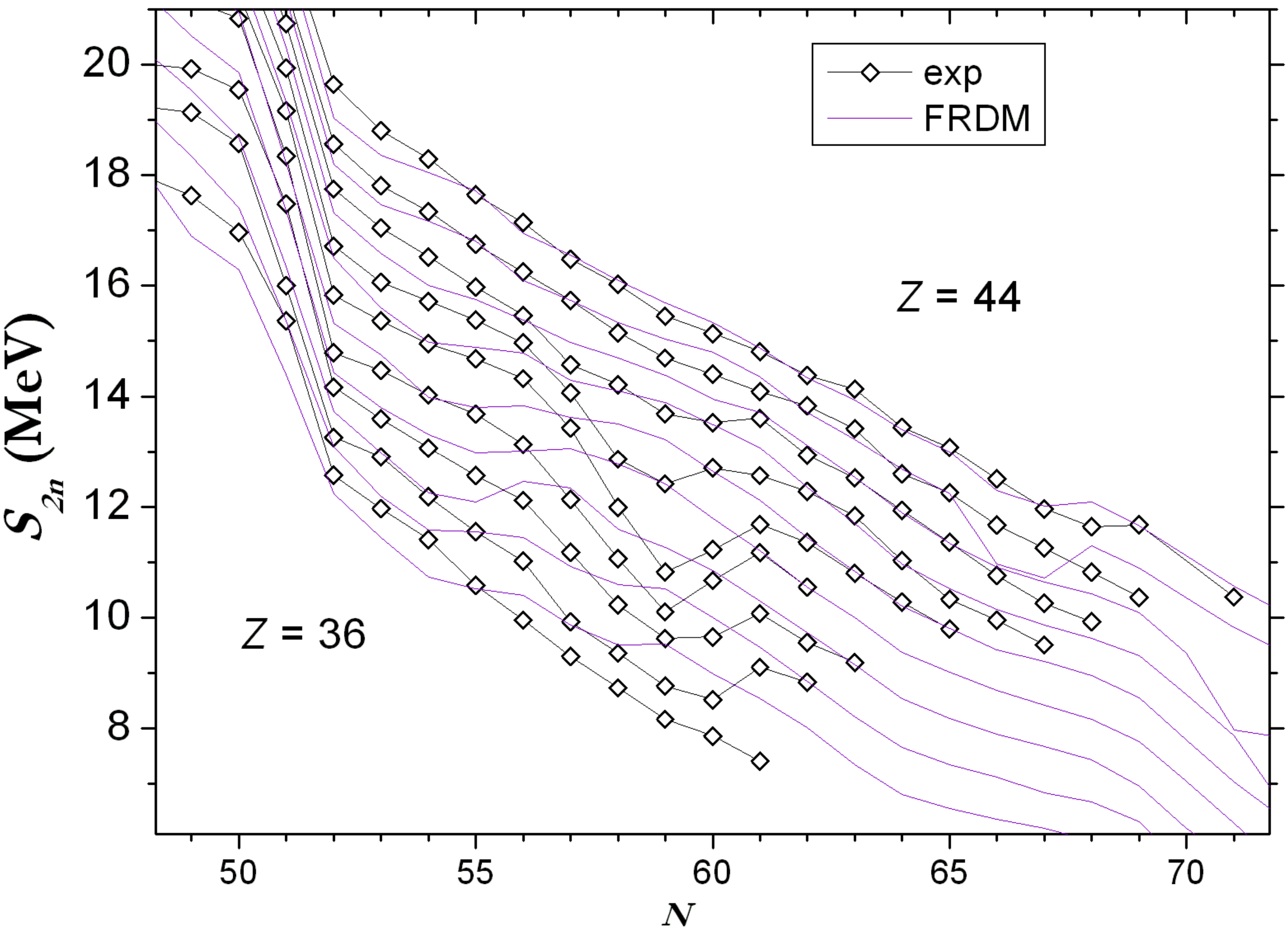
AME2012
ISOLTRAP
JYFLTRAP
Z = 44 (Pd)
Z = 36 (Kr)
Hakala
et al. 2011
ISOLTRAP
2013
Naimi et al. 2010
S2n (MeV)
N
20
18
16
14
12
10
8
50
55
60
65



exp
D1M
Z = 44
Z = 36
S_{2n} (MeV)
N
20
18
16
14
12
10
8
50
55
60
65
70



exp
DZ95
Z = 44
Z = 36
20
18
16
14
12
10
8
50
55
60
65
70
S_2n (MeV)
N



exp
FRDM
Z = 44
Z = 36
S_{2n} (MeV)
N
20
18
16
14
12
10
8
50
55
60
65
70

Conclusion

Binding energies (and charge radii) give important indications
Spectroscopy, e.g. to probe 2+ state energies, is needed to find the cause
We make assumptions while holding the hand of theory

This region is a nice example of different techniques bringing different observables
Also the source of a variety of theoretical approaches (necessary for interpretation)

ISOLDE is a nice microcosm:
experiments on ground-states (isoltrap and collaps) mesh with spectroscopy (miniball).

That's one small step for neutron number,
one giant leap for nuclear shape!

...thanks for staying!