Probing Low-Spin Nuclear Structure with Fast Neutrons: Relevance to 0νββ Decay

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University of Kentucky

SSNET 2017

Gif sur Yvette

6 November 2017

Inelastic Neutron Scattering – (n,n′γ)

Monoenergetic neutrons:

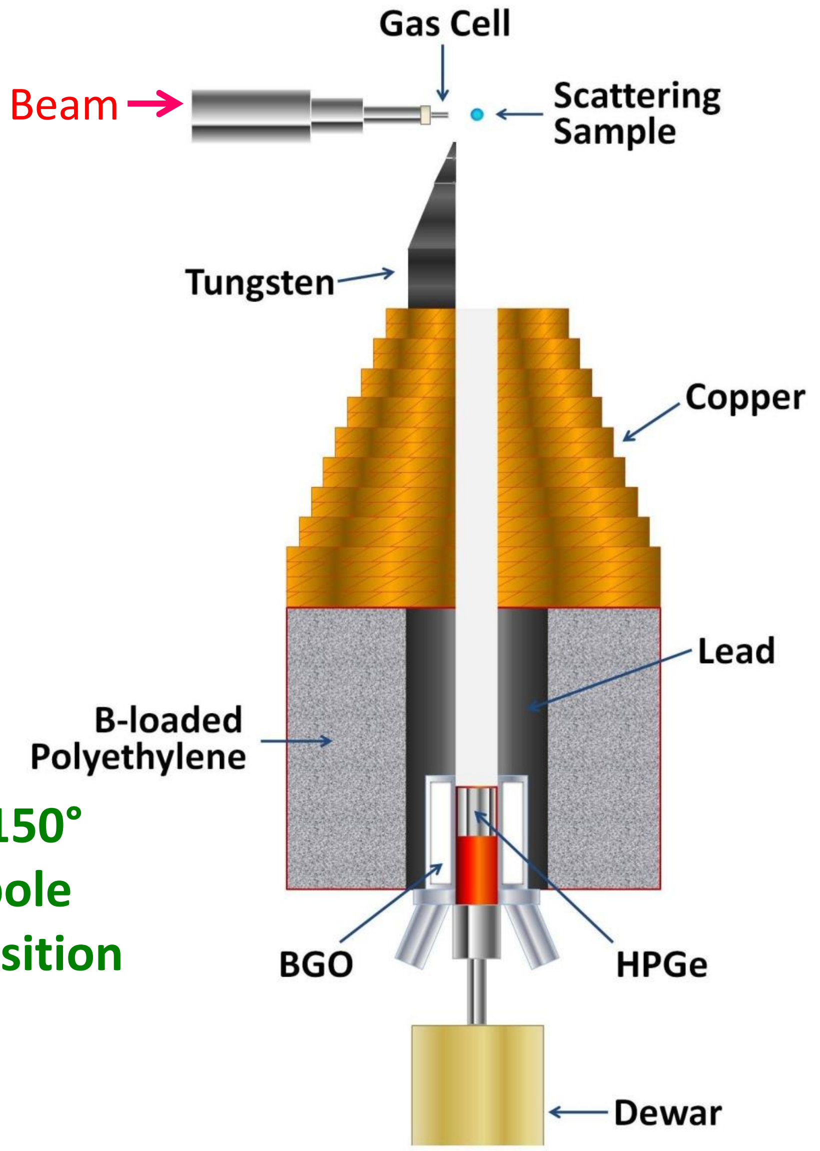
$^{3}H(p,n)^{3}He$ or $^{2}H(d,n)^{3}He$

Excitation functions

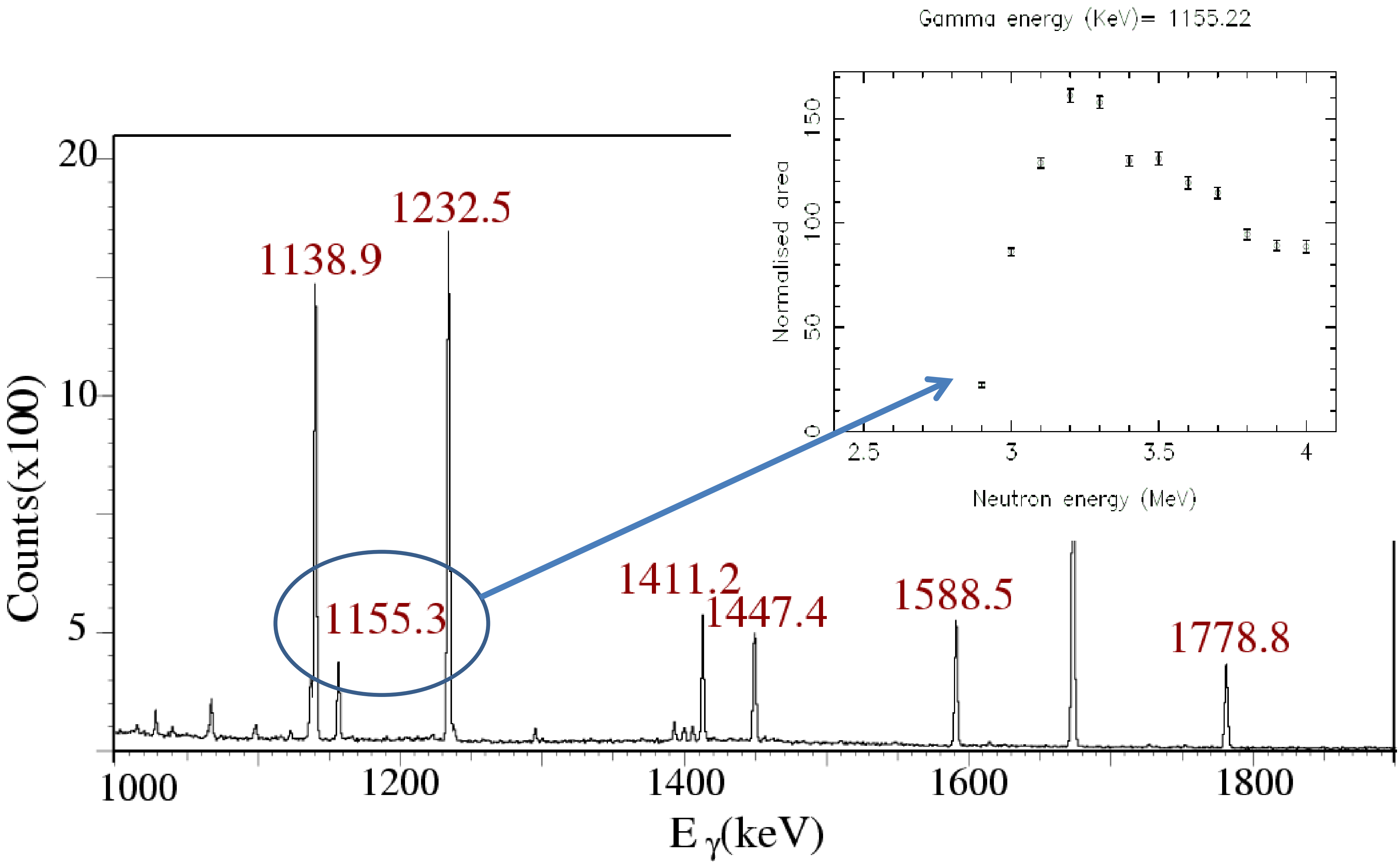
- Vary neutron energy
- Detection angle constant
- Build level scheme
- Cross sections

Angular distributions

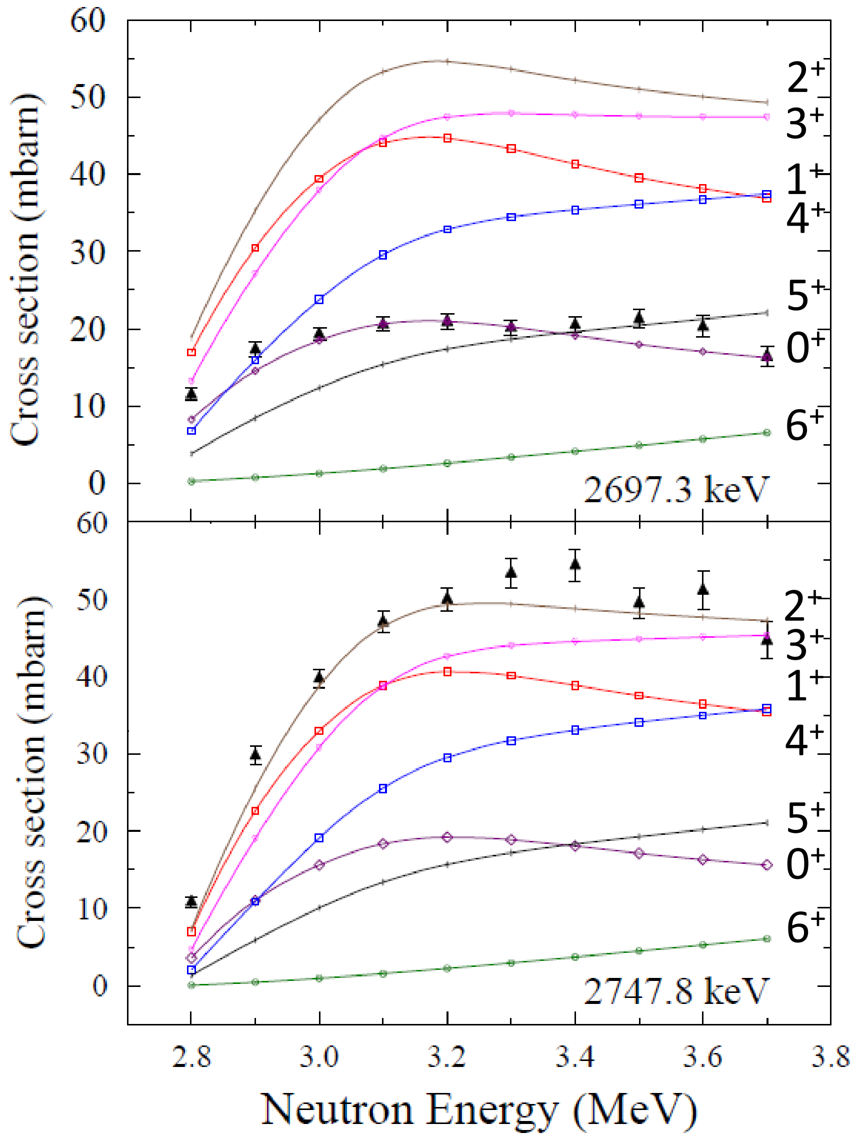
- Constant neutron energy
- Detection angle varied from 40°-150°
- Transition multipolarities, multipole mixing ratios, level lifetimes, transition probabilities

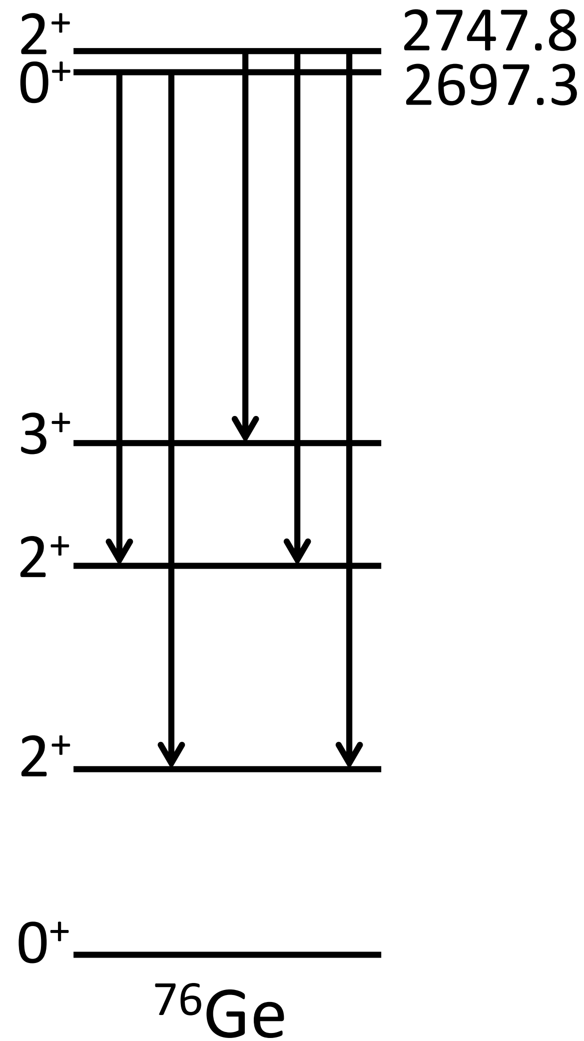


$^{94}Zr(n,n'\gamma)$ **Compton suppressed** **TOF Gating**

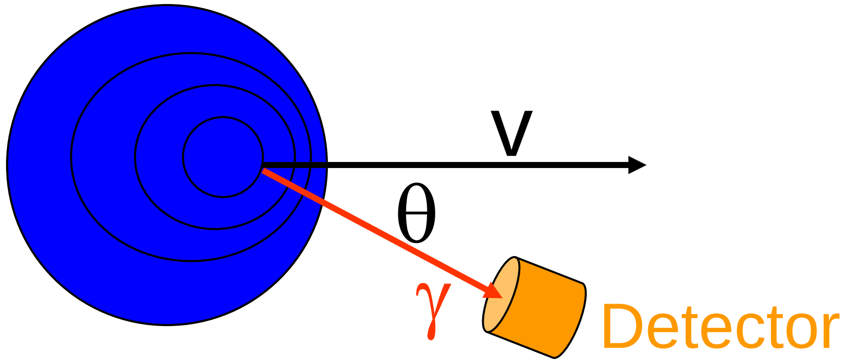


$^{76}Ge(n,n'\gamma)$ Excitation Functions





Doppler-Shift Attenuation Method



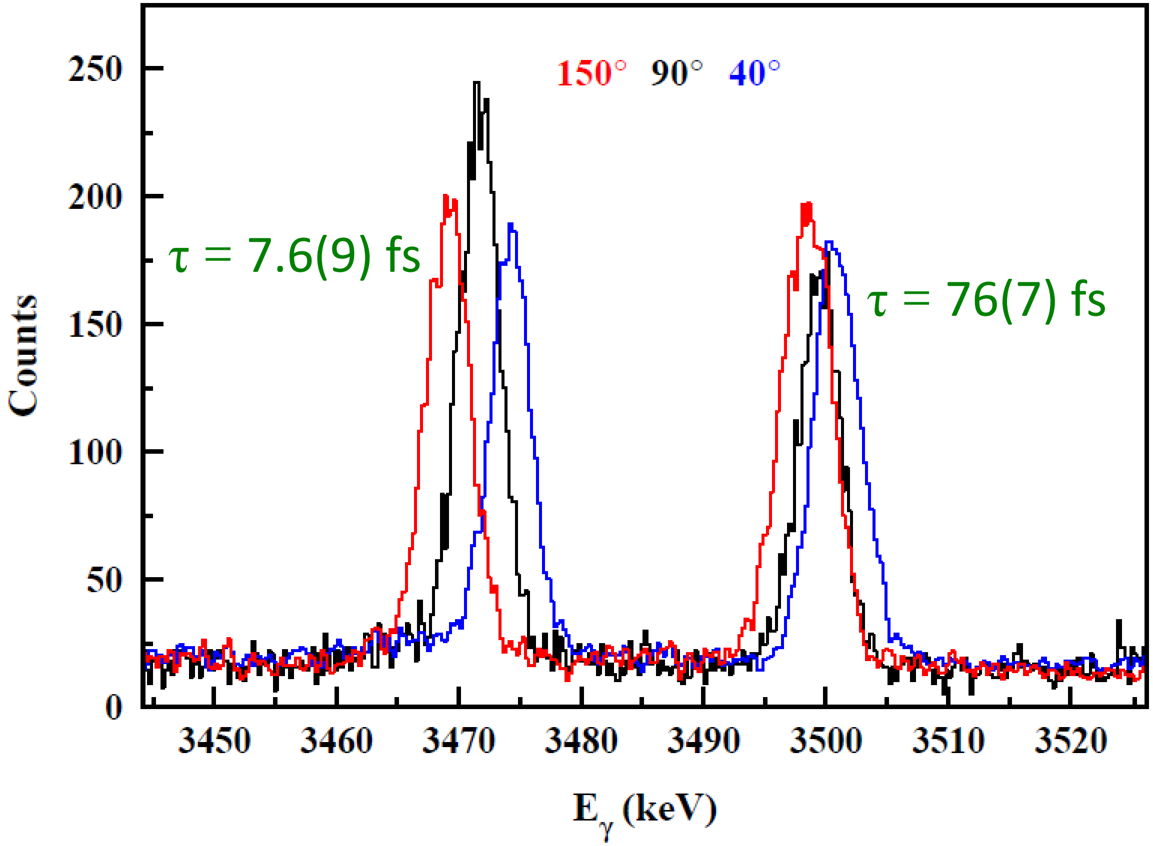
$E(\theta) = E_\gamma\,(1 + v/c \cos\theta)$

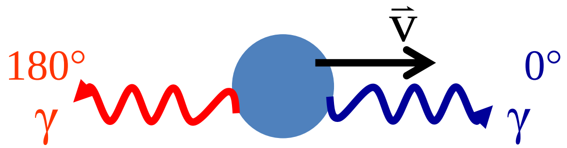
The nucleus is recoiling into a viscous medium.

$v \rightarrow v(t) = F(t)v_{max}$

$E(\theta) = E_\gamma\,(1 + \mathbf{F(\tau)}\, v/c \cos\theta)$

Level Lifetimes: Doppler-Shift Attenuation Method (DSAM)





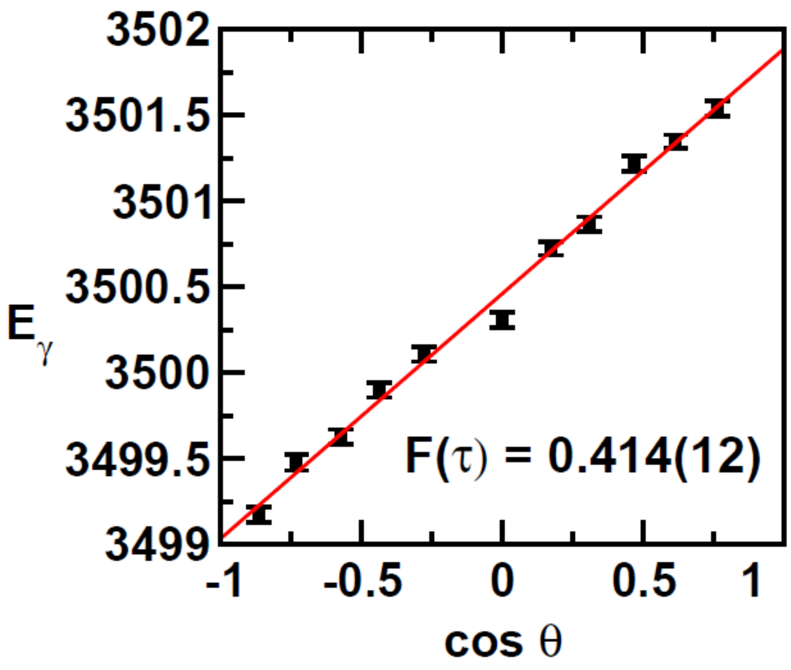
Scattered neutron causes the nucleus to recoil.

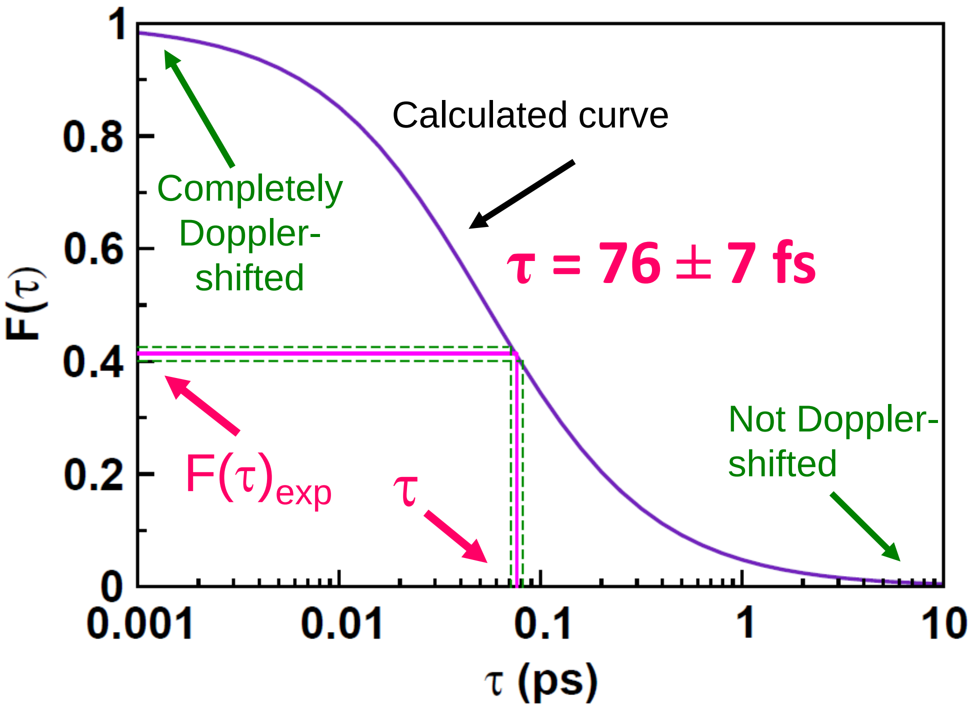
Emitted γ rays experience a Doppler shift.

Level lifetimes in the femtosecond region can be determined.

T. Belgya, G. Molnár, and S.W. Yates, Nucl. Phys. A607, 43 (1996).
E.E. Peters *et al.*, Phys. Rev. C 88, 024317 (2013).

DSAM





$$E_\gamma(\theta) = E_\gamma\left[1 + F_{exp}(\tau)\frac{v_{cm}}{c}\cos\theta\right]$$

K.B. Winterbon, Nucl. Phys. **A246**, 293 (1975).

T. Belgya, G. Molnár, and S. W. Yates, Nucl. Phys. A607, 43 (1996).

Inelastic Neutron Scattering with Accelerator-Produced Neutrons

(n,n′γ)

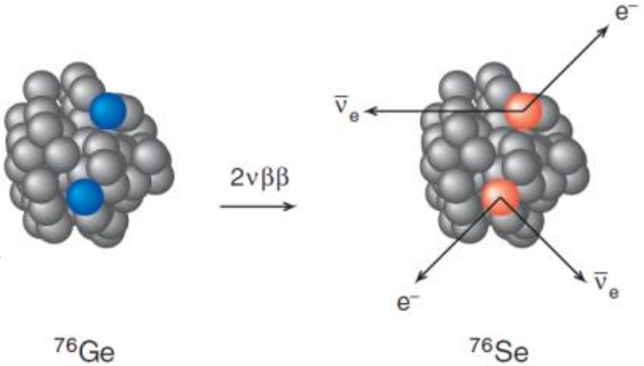
- ☞ No Coulomb barrier/variable neutron energies
- ☞ Excellent energy resolution (γ rays detected)
- ☞ Nonselective, but limited by angular momentum
- ☞ Lifetimes by Doppler-shift attenuation method (DSAM)
  - T. Belgya, G. Molnár, and S.W. Yates, Nucl. Phys. **A607**, 43 (1996)
  - E.E. Peters *et al*., Phys. Rev. C **88**, 024317 (2013).
- ☞ Gamma-gamma coincidence measurements
  - C.A. McGrath *et al*., Nucl. Instrum. Meth. **A421**, 458 (1999)
  - E. Elhami *et al*., Phys. Rev. C **78**, 064303 (2008)
- ☟ Limited to stable and long-lived nuclei
- ☟ Large amounts of enriched isotopes desirable

Why study ^{76}Ge and ^{76}Se?

They are the parent and daughter of double-β decay.

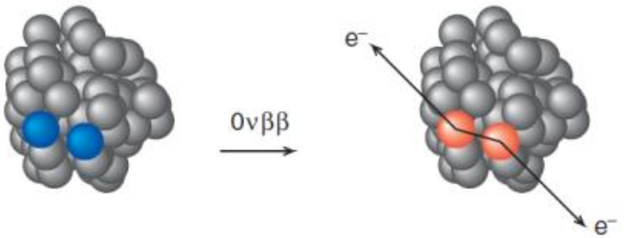
$$^{76}Ge \rightarrow {}^{76}Se + 2\beta^- + 2\bar{\nu}$$

$$T_{1/2}^{2\nu}(^{76}Ge) = 1.926 \pm 0.094 \times 10^{21}\ yr$$



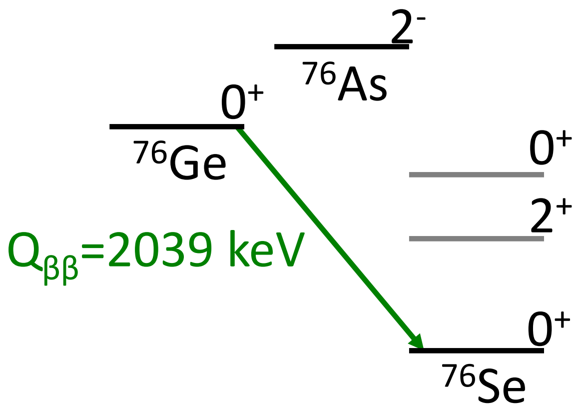
$$^{76}Ge \rightarrow {}^{76}Se + 2\beta^- \quad ?$$

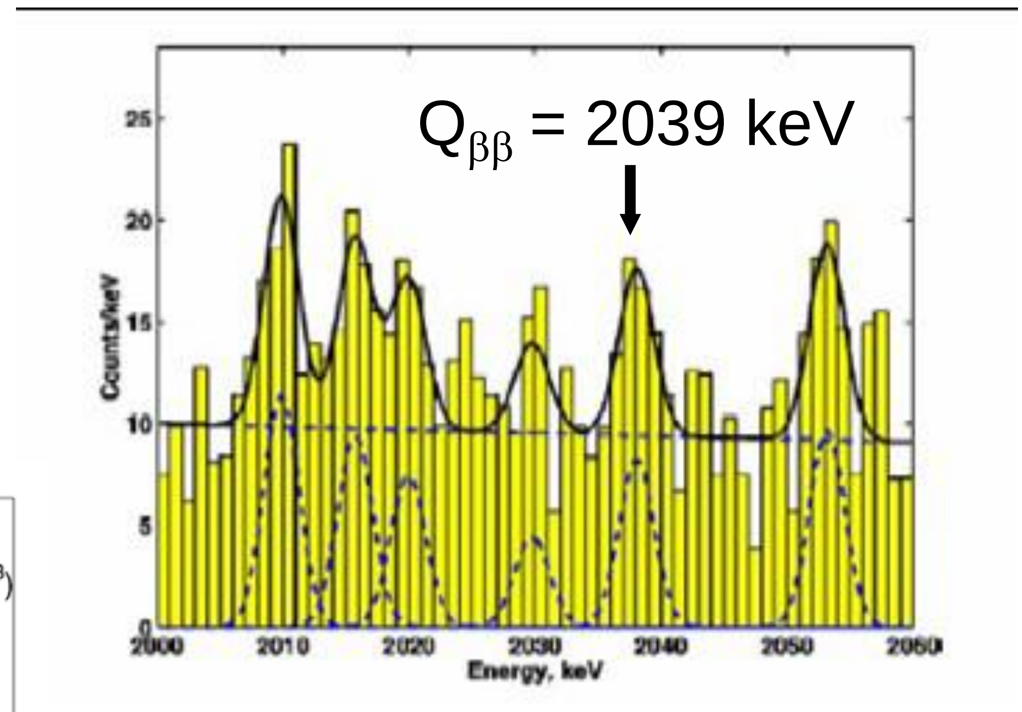
$$T_{1/2}^{0\nu}(^{76}Ge) > 5.3 \times 10^{25}\ yr$$

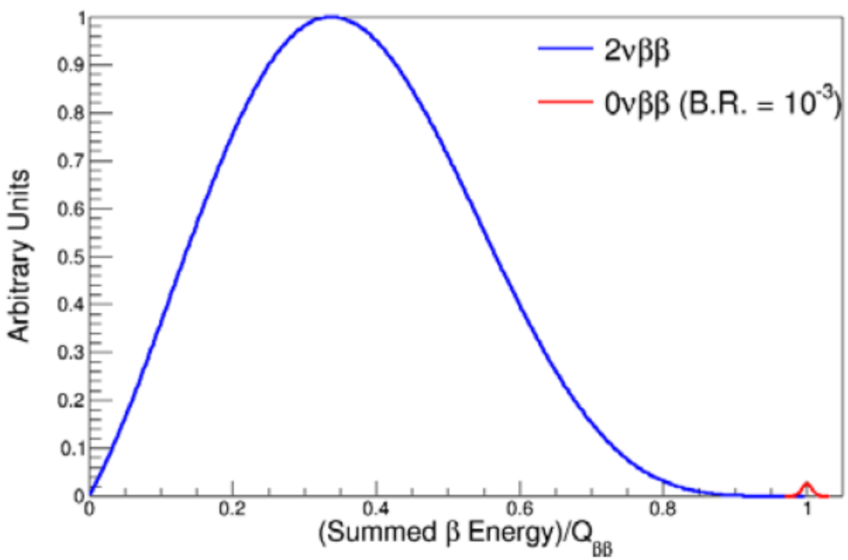


M. Agostini et al. (GERDA), Nature **544**, 47 (2017)

Experimental Signature of 0νββ



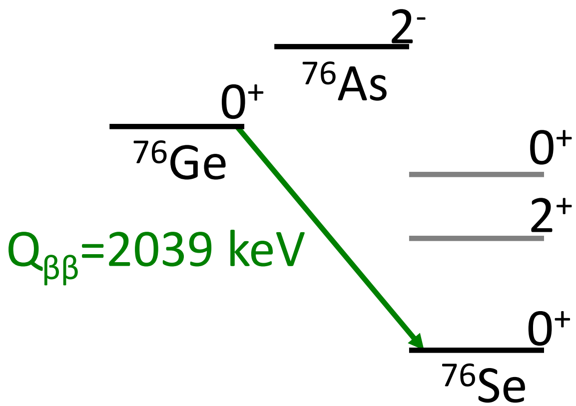


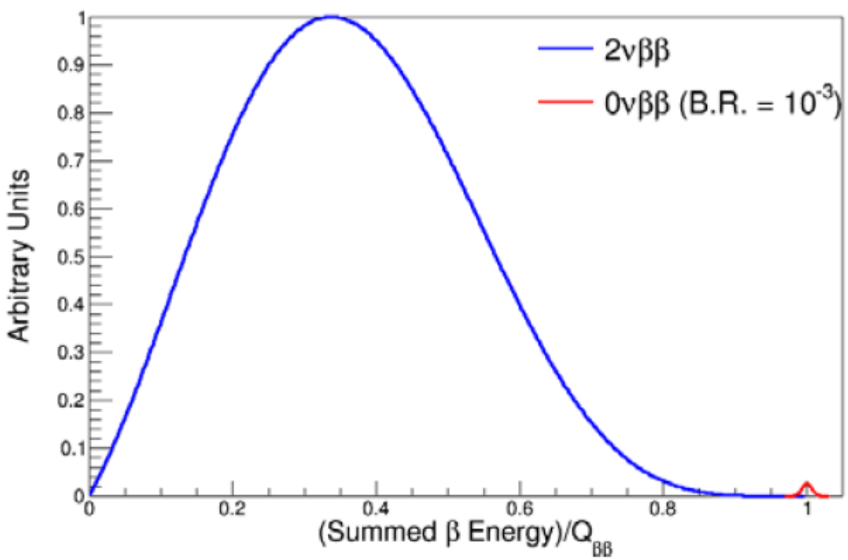


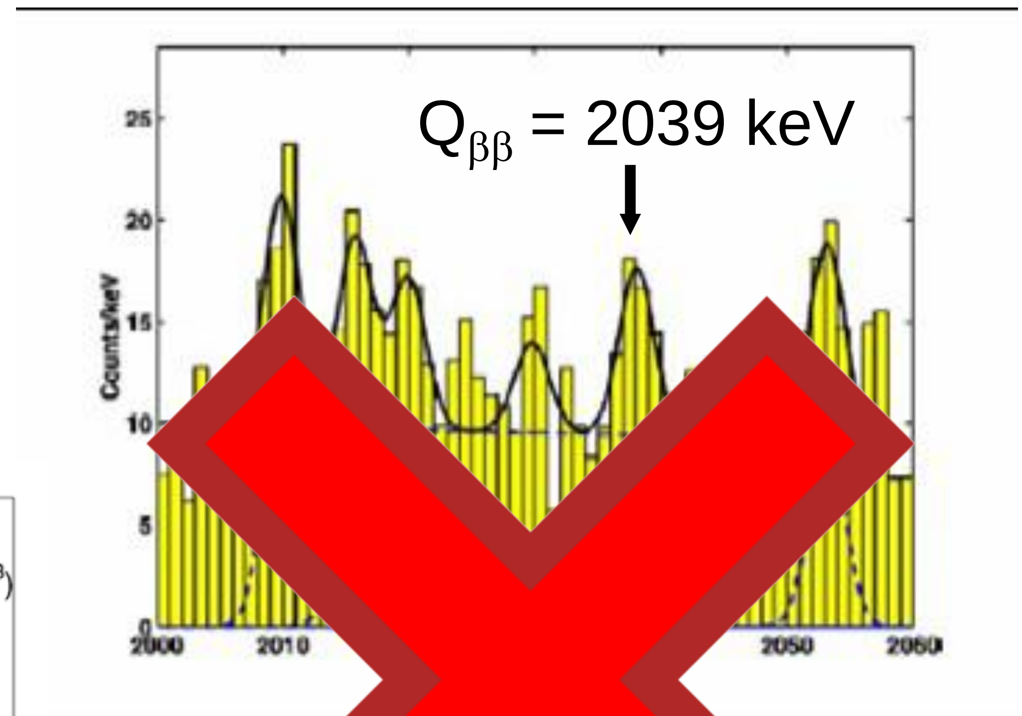
H.V. Klapdor-Kleingrothaus, I.V. Krivoshina, A. Dietz, and O. Chkvorets, Phys. Lett. **B586**, 198 (2004)

$$T_{1/2}^{0\nu}(^{76}Ge) = 1.19 \times 10^{25}\ yr$$

Experimental Signature of 0νββ







H.V. Klapd ... Krivoshina,
A. Diet ... tt.
B58 ...)

$$T_{1/2}^{0\nu}(\ldots e) = 1.19 \times 10 \ldots yr$$

Current Searches for ^{76}Ge 0νββ

MAJORANA DEMONSTRATOR

30 kg 86% ^{76}Ge + 10 kg ^{nat}Ge
SURF, SD, USA

http://neutrino.lbl.gov/majorana.htm

ββ
GERDA

40 kg 86% ^{76}Ge
Gran Sasso, Italy

http://www.mpi-hd.mpg.de/gerda/

MAJORANA + GERDA → LEGEND (tonne-scale ^{76}Ge 0νββ search)

0νββ Decay Rate

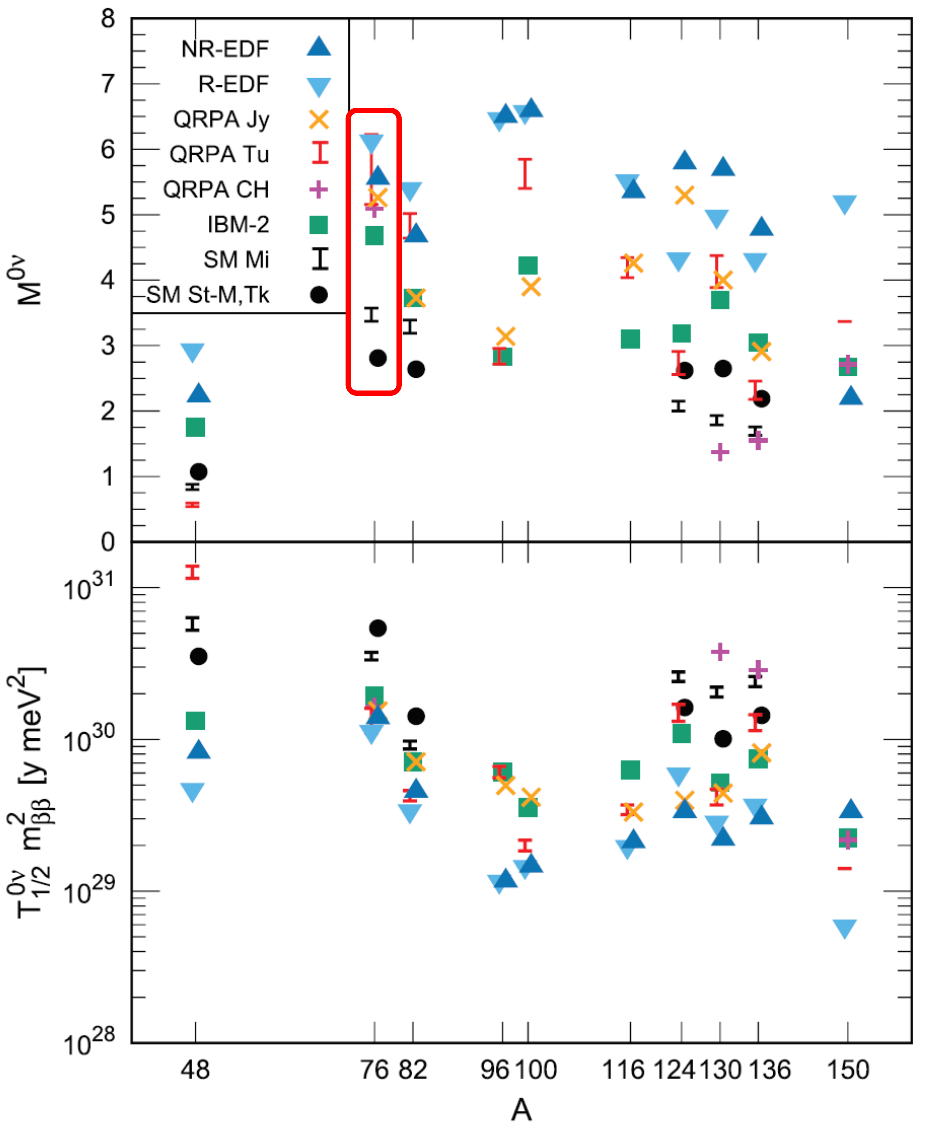
Nuclear Matrix Element

$$\left[T_{1/2}^{0\nu}\left(0^{+}\rightarrow 0^{+}\right)\right]^{-1}=G^{0\nu}(E_{0},Z)\left|M^{0\nu}\right|^{2}\left\langle m_{\nu_{e}}\right\rangle^{2}$$

Phase Space Factor

Effective Majorana Neutrino Mass

Comparison of calculated nuclear matrix elements for 0νββ candidates



Jonathan Engel and Javier Menéndez, Rep. Prog. Phys. **80**, 046301 (2017)

Why study ^{76}Ge and ^{76}Se?

They are the parent and daughter of double-β decay.

$$^{76}\mathrm{Ge} \longrightarrow {}^{76}\mathrm{Se} + 2\beta^{-} + 2\bar{\nu}$$

$$^{76}\mathrm{Ge} \longrightarrow {}^{76}\mathrm{Se} + 2\beta^{-} \quad ?$$

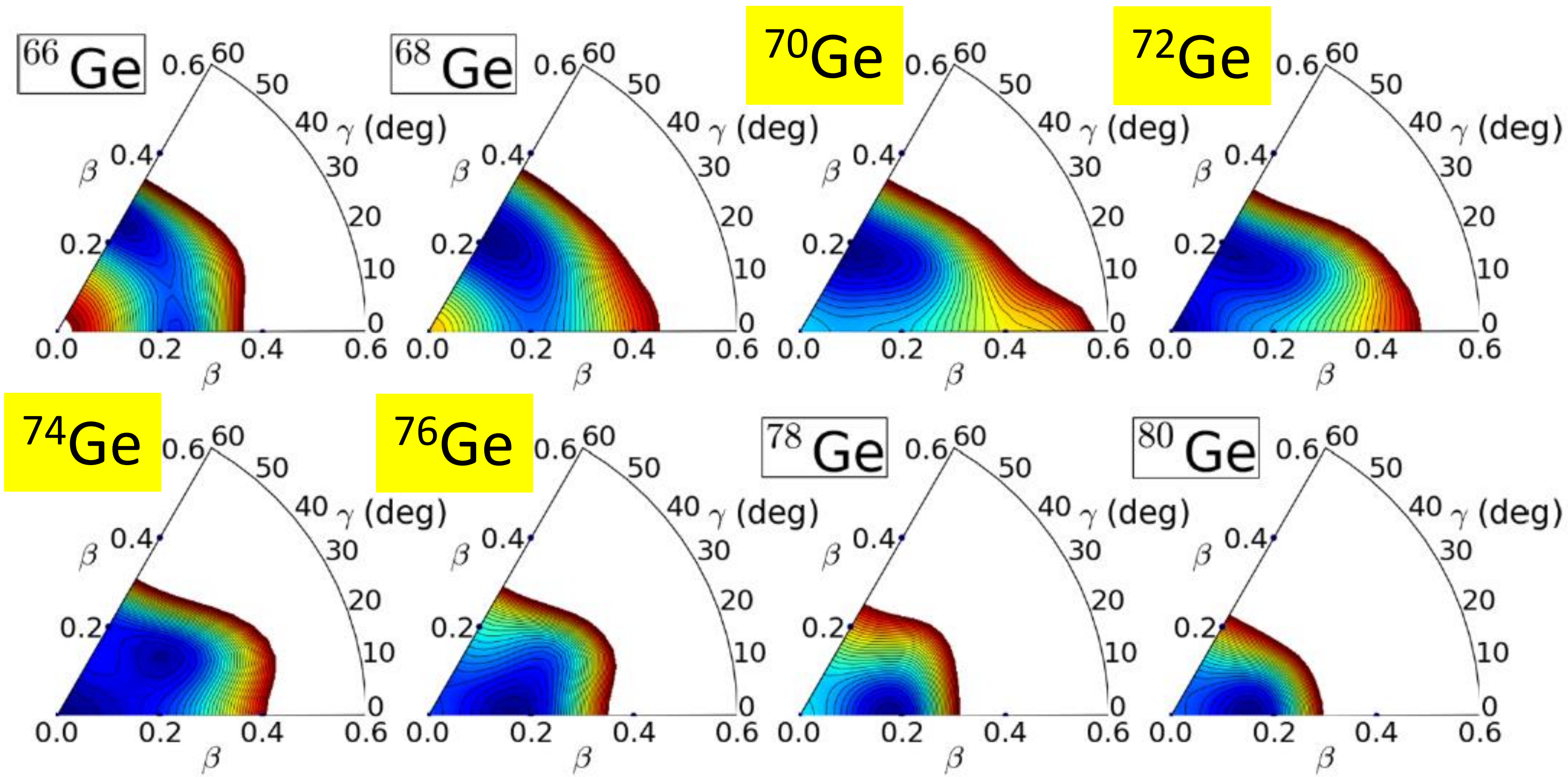
They are structurally interesting.

- Shape Transition
- Shape Coexistence
- Soft/Rigid Triaxiality

PHYSICAL REVIEW C **95**, 064310 (2017)

Structural evolution in germanium and selenium nuclei within the mapped interacting boson model based on the Gogny energy density functional

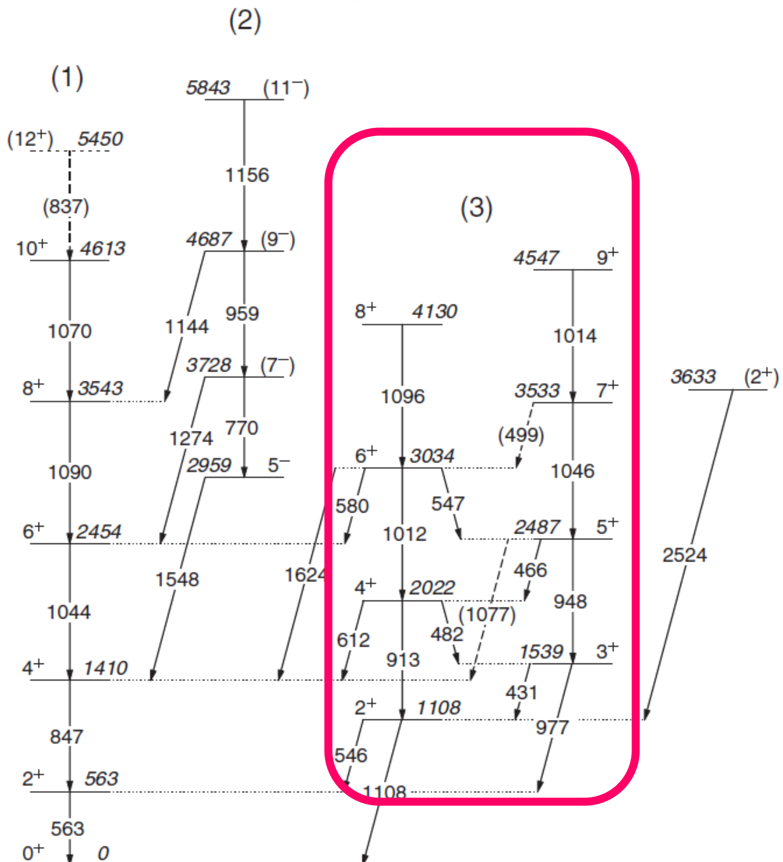
K. Nomura,[1,2] R. Rodríguez-Guzmán,[3] and L. M. Robledo[4]

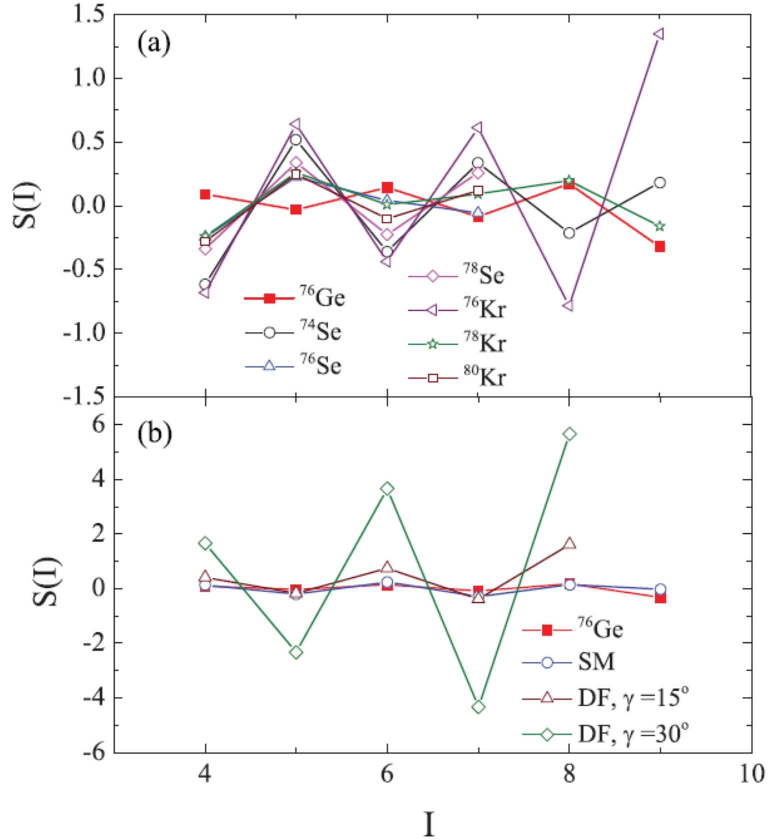


PHYSICAL REVIEW C **87**, 041304(R) (2013)

Evidence for rigid triaxial deformation at low energy in ^{76}Ge

Y. Toh,[1,2] C. J. Chiara,[2,3] E. A. McCutchan,[2,4] W. B. Walters,[3] R. V. F. Janssens,[2] M. P. Carpenter,[2] S. Zhu,[2] R. Broda,[5] B. Fornal,[5] B. P. Kay,[2] F. G. Kondev,[6] W. Królas,[5] T. Lauritsen,[2] C. J. Lister,[2,*] T. Pawłat,[5] D. Seweryniak,[2] I. Stefanescu,[2,3] N. J. Stone,[7,8] J. Wrzesiński,[5] K. Higashiyama,[9] and N. Yoshinaga[10]





“…^{76}Ge may be a rare example of a nucleus exhibiting rigid triaxial deformation in the low-lying states.”

Physics Letters B 734 (2014) 308–313

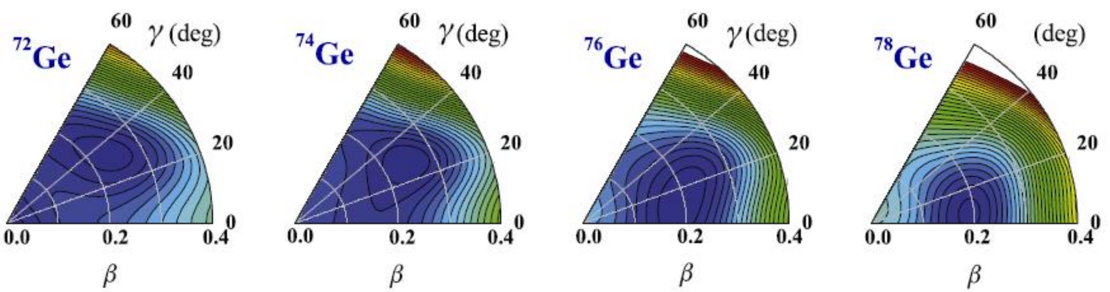
Contents lists available at ScienceDirect

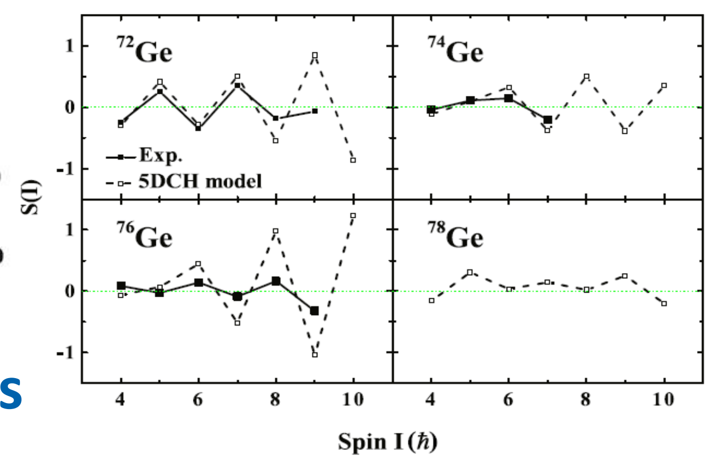
Physics Letters B

www.elsevier.com/locate/physletb

Spectroscopy of ^{74}Ge: From soft to rigid triaxiality

J.J. Sun [a], Z. Shi [b], X.Q. Li [a,*], H. Hua [a,*], C. Xu [a], Q.B. Chen [a], S.Q. Zhang [a], C.Y. Song [b], J. Meng [a], X.G. Wu [c], S.P. Hu [c], H.Q. Zhang [c], W.Y. Liang [a], F.R. Xu [a], Z.H. Li [a], G.S. Li [c], C.Y. He [c], Y. Zheng [c], Y.L. Ye [a], D.X. Jiang [a], Y.Y. Cheng [a], C. He [a], R. Han [a], Z.H. Li [a], C.B. Li [c], H.W. Li [c], J.L. Wang [c], J.J. Liu [c], Y.H. Wu [c], P.W. Luo [c], S.H. Yao [c], B.B. Yu [c], X.P. Cao [c], H.B. Sun [d]





“ …^{74}Ge is found to be the crucial nucleus marking the triaxial evolution from soft to rigid in Ge isotopes.”

PHYSICAL REVIEW C **89**, 044325 (2014)

Microscopic analysis of shape evolution and triaxiality in germanium isotopes

T. Nikšić, P. Marević, and D. Vretenar
Physics Department, Faculty of Science, University of Zagreb, 10000 Zagreb, Croatia

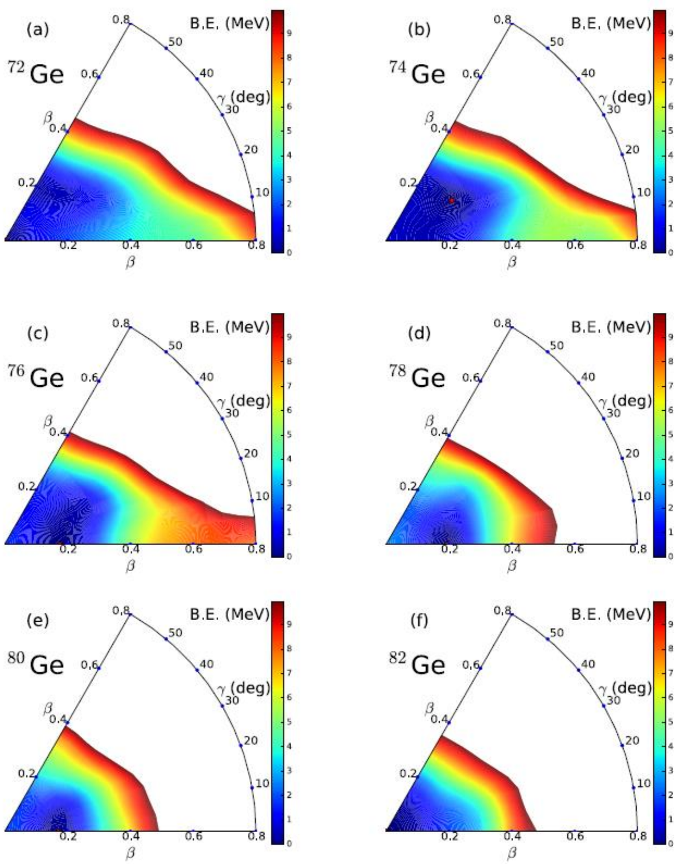
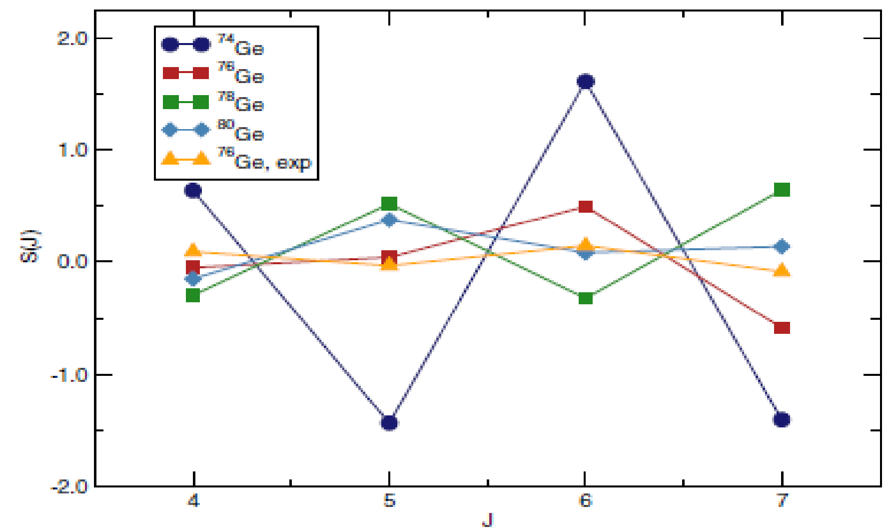


FIG. 1. (Color online) Self-consistent RHB triaxial energy surfaces of even-even Ge nuclei in the β-γ plane ($0 \leqslant \gamma \leqslant 60°$). For each nucleus energies are normalized with respect to the binding energy of the absolute minimum.

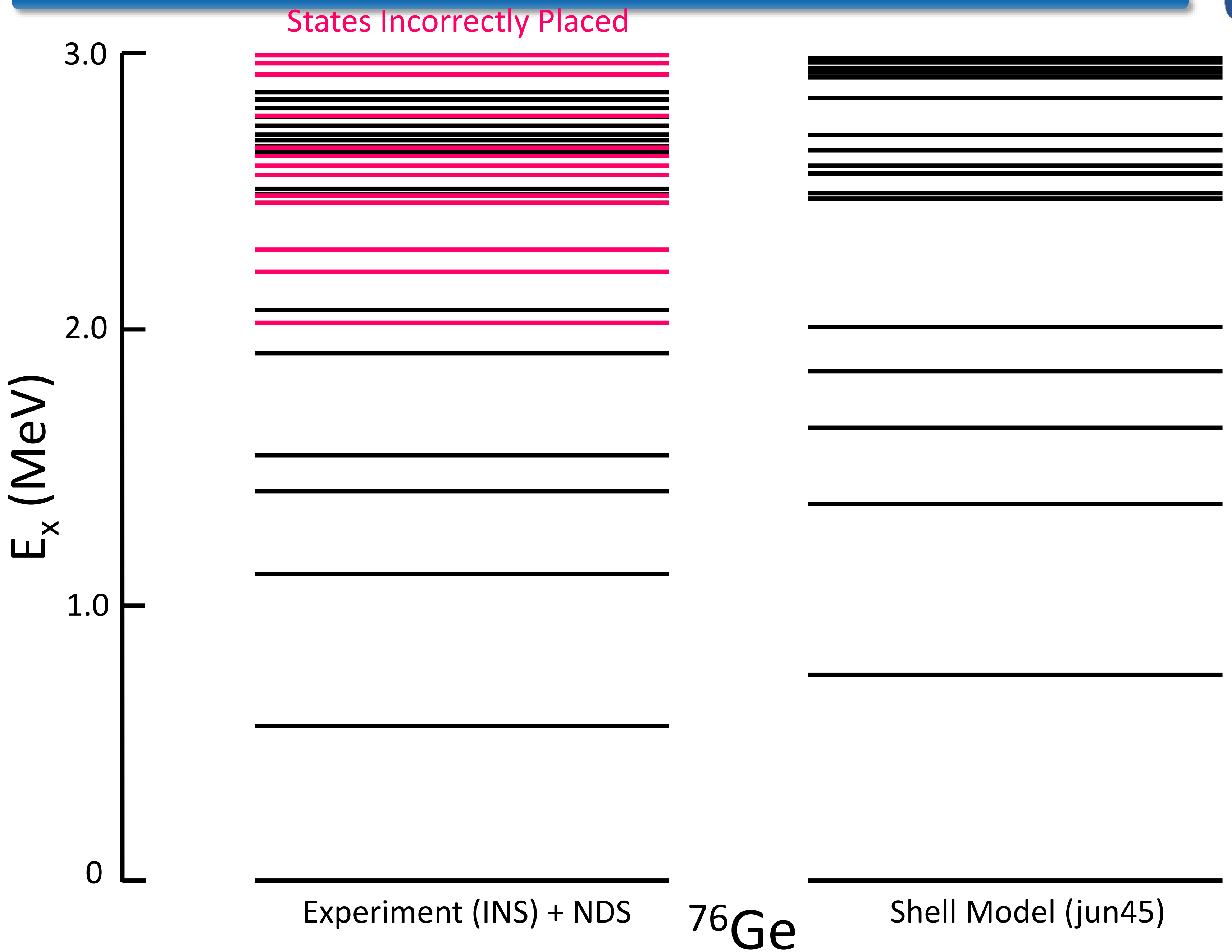


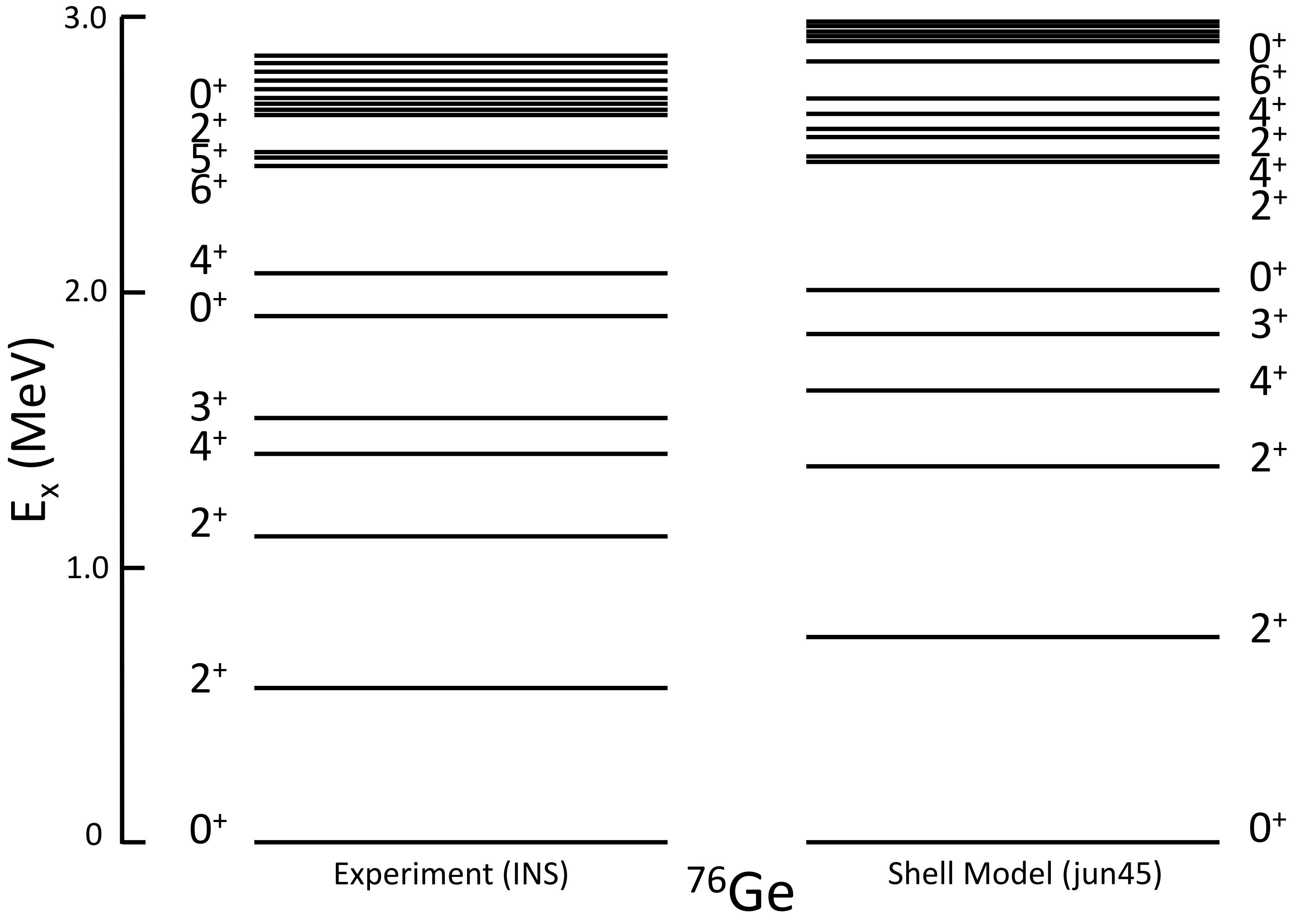
"The mean-field potential of ^{76}Ge appears to be γ soft. Collective correlations drive the nucleus toward triaxiality but do not stabilize a rigid triaxial shape."

Inelastic Scattering of Fast Neutrons with γ-ray Detection

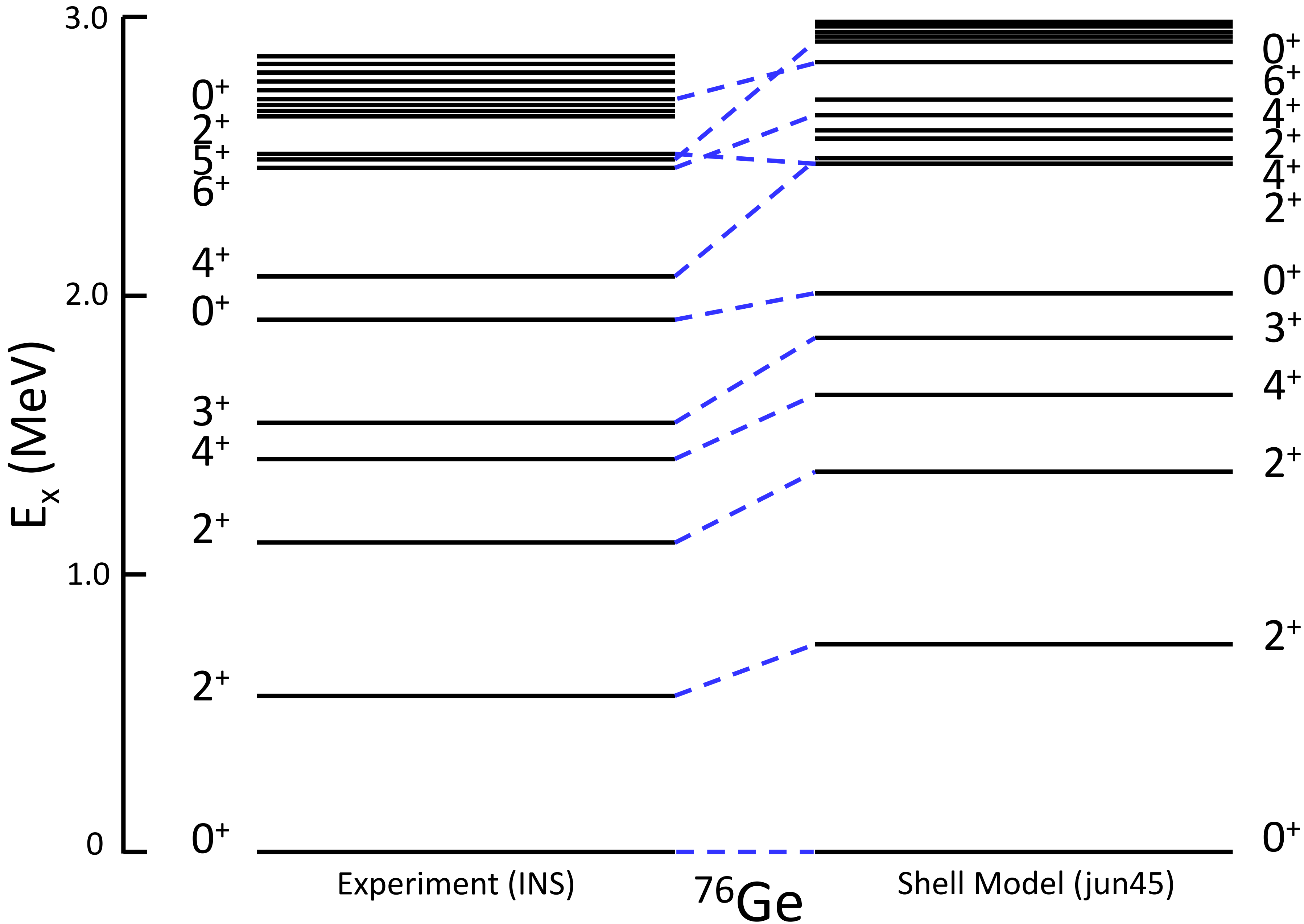
- Level scheme: J^{π}
- Transition multipolarities: E1, E2, E3, M1…
- Multipole mixing ratios: $\delta(E2/M1)$
- Level lifetimes: τ
- Transition probabilities: $B(\lambda)$
- Cross sections/Backgrounds: σ


3.0
2.0
1.0
0
E_x (MeV)
Data
Theory
Experiment (INS) + NDS
^{76}Ge
Shell Model (jun45)


States Incorrectly Placed
3.0
2.0
1.0
0
E_x (MeV)
Experiment (INS) + NDS
^{76}Ge
Shell Model (jun45)



3.0
2.0
1.0
0
E_x (MeV)
0^+
2^+
5^+
6^+
4^+
0^+
3^+
4^+
2^+
2^+
0^+
Experiment (INS)
^{76}Ge
0^+
6^+
4^+
2^+
4^+
2^+
0^+
3^+
4^+
2^+
2^+
0^+
Shell Model (jun45)


3.0
2.0
1.0
0
E_x (MeV)
0+
2+
5+
6+
4+
0+
3+
4+
2+
2+
0+
Experiment (INS)
^{76}Ge
Shell Model (jun45)
0+
6+
4+
2+
4+
2+
0+
3+
4+
2+
2+
0+

PHYSICAL REVIEW C **95**, 014327 (2017)

Nuclear structure of ^{76}Ge from inelastic neutron scattering measurements and shell model calculations

S. Mukhopadhyay,[1,2,*] B. P. Crider,[1] B. A. Brown,[3,4] S. F. Ashley,[1,2] A. Chakraborty,[1,2,†] A. Kumar,[1,2] M. T. McEllistrem,[1] E. E. Peters,[2] F. M. Prados-Estévez,[1,2] and S. W. Yates[1,2]

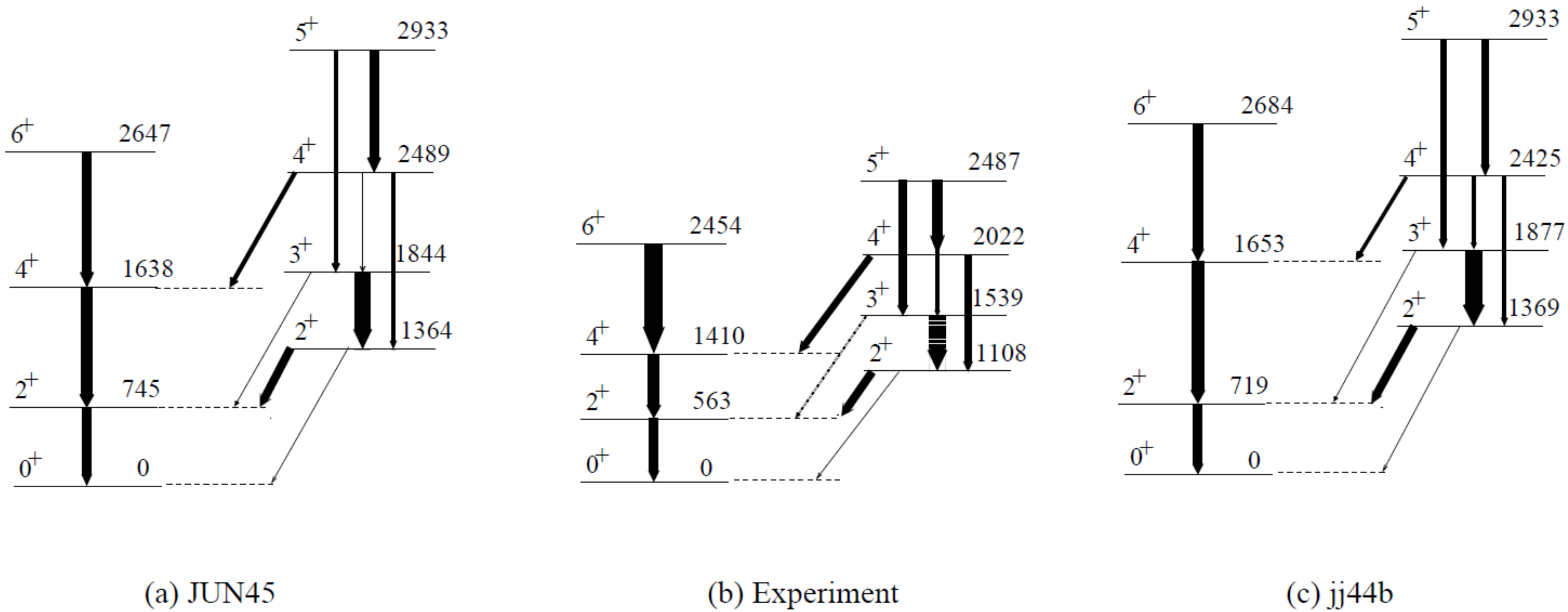
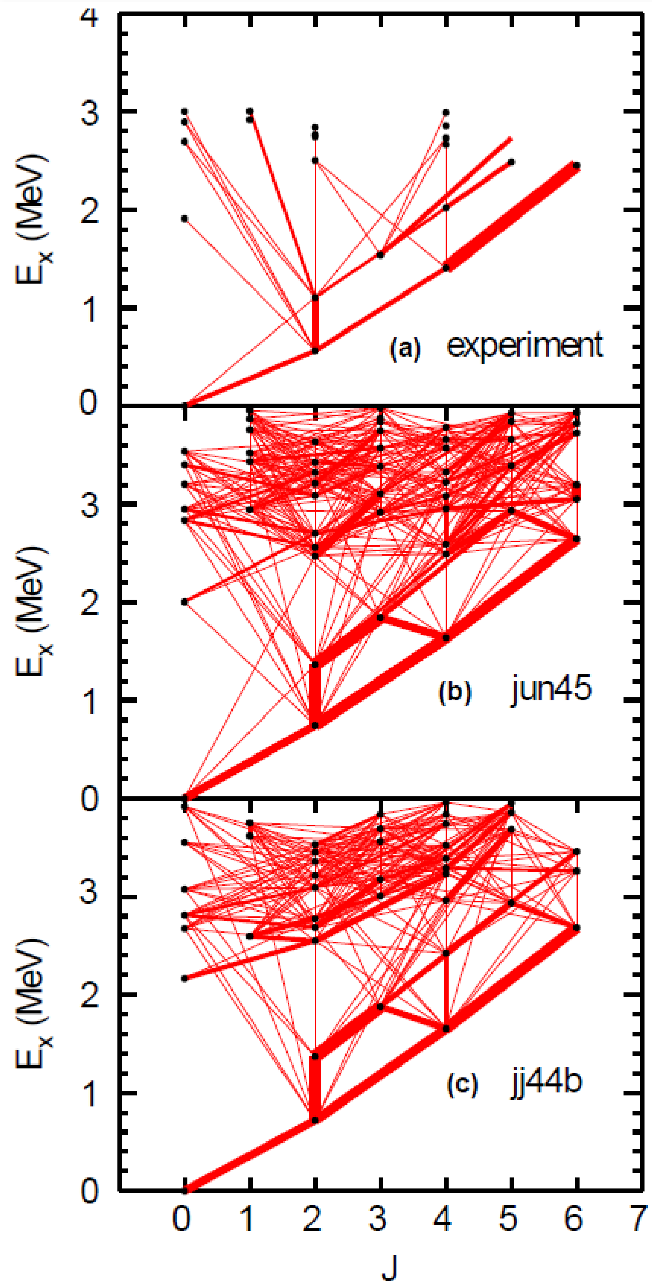
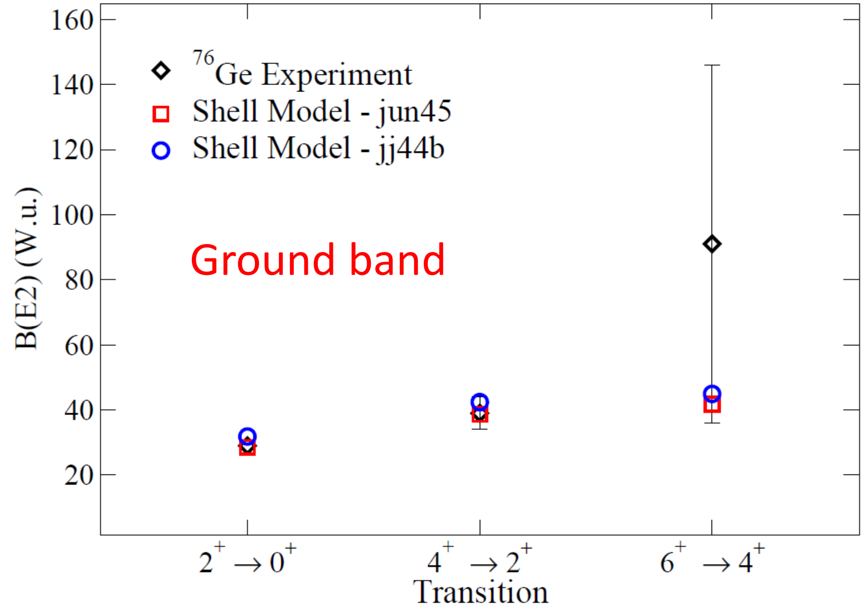
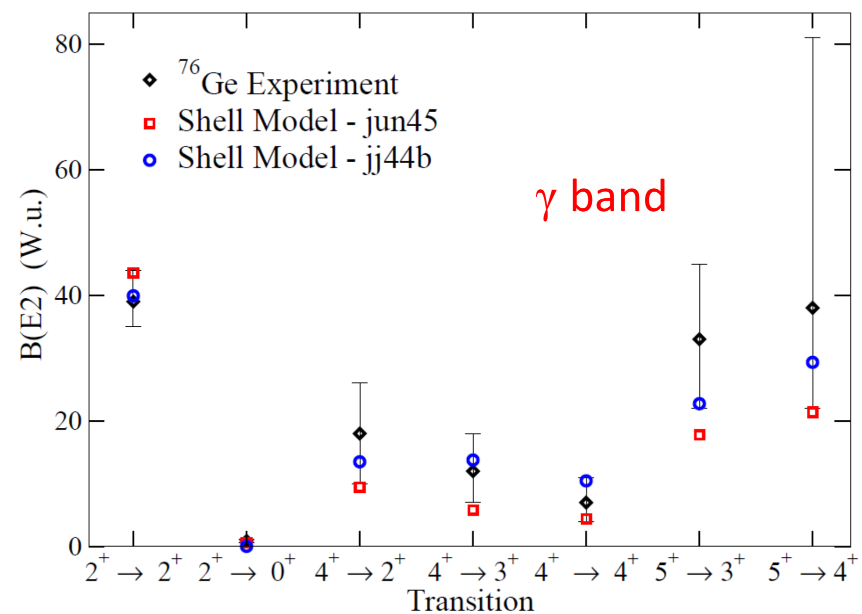


FIG. 7. Partial level scheme of ^{76}Ge from shell model calculations [(a) and (c)] and experiment (b) . The thicknesses of the solid arrows are proportional to the B(E2)s. Dashed arrows indicate that the level lifetime was not determined and the B(E2)s are calculated using the lifetime from shell-model calculations.





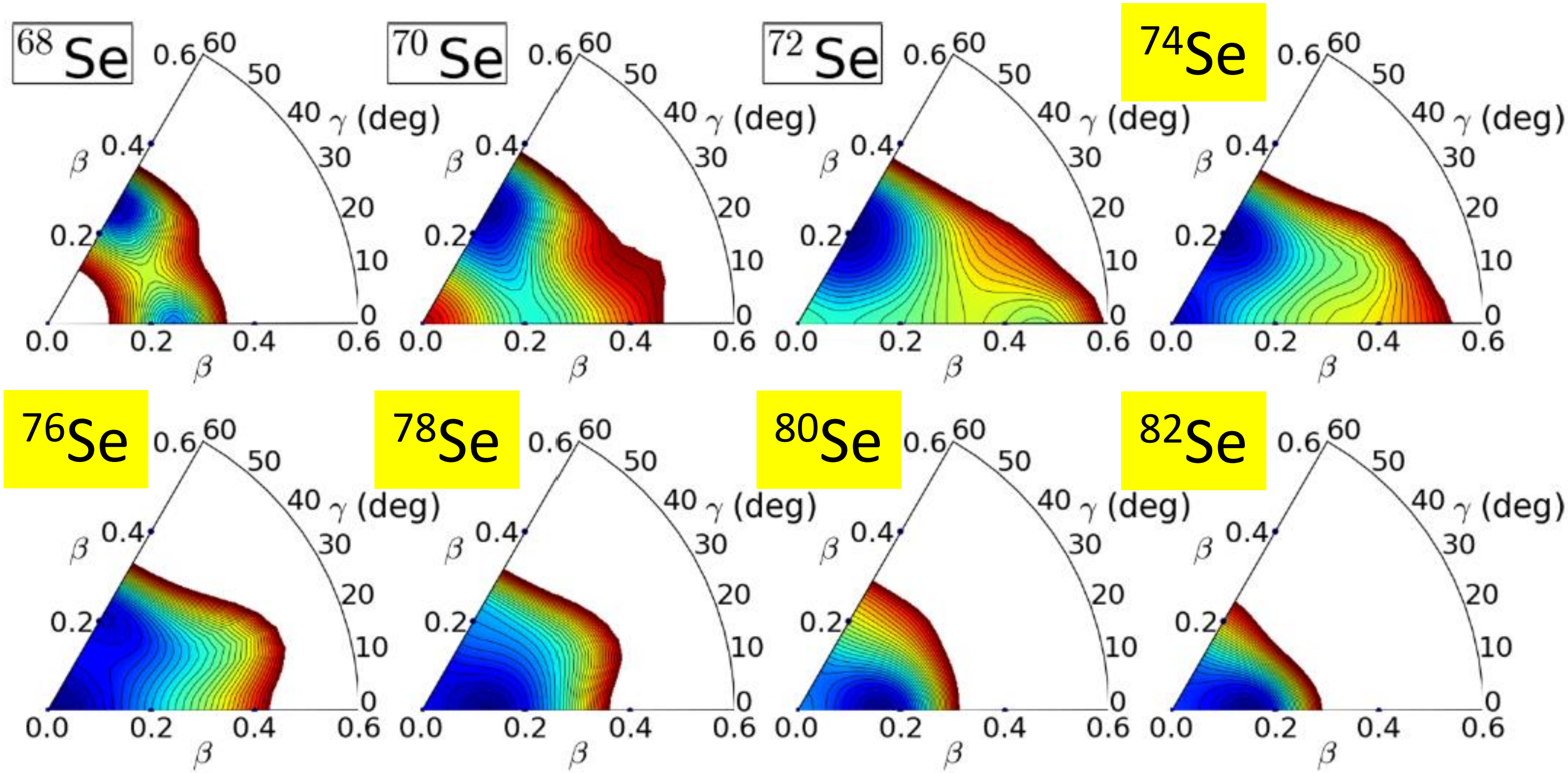


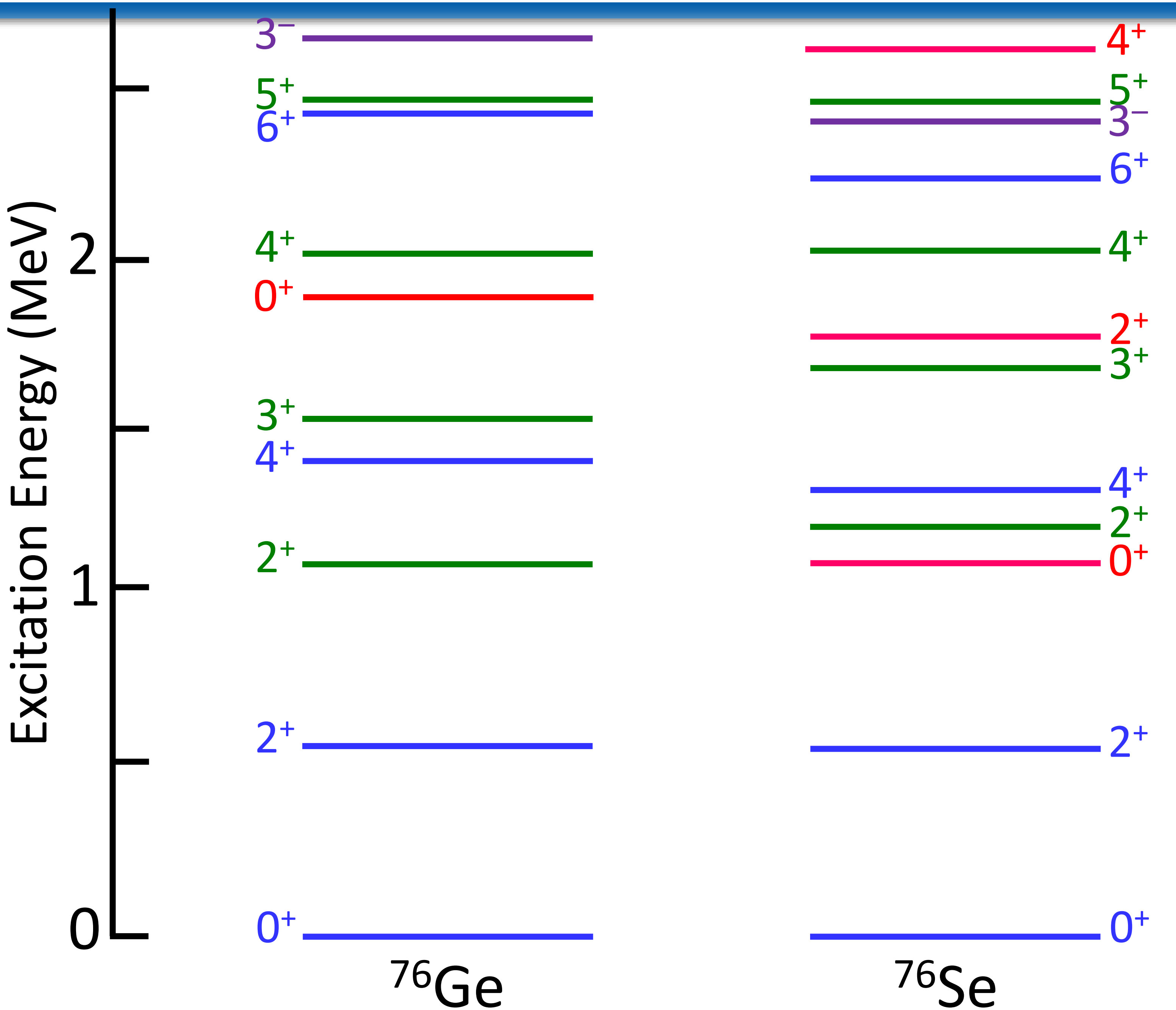
Calculations by B. A. Brown

PHYSICAL REVIEW C **95**, 064310 (2017)

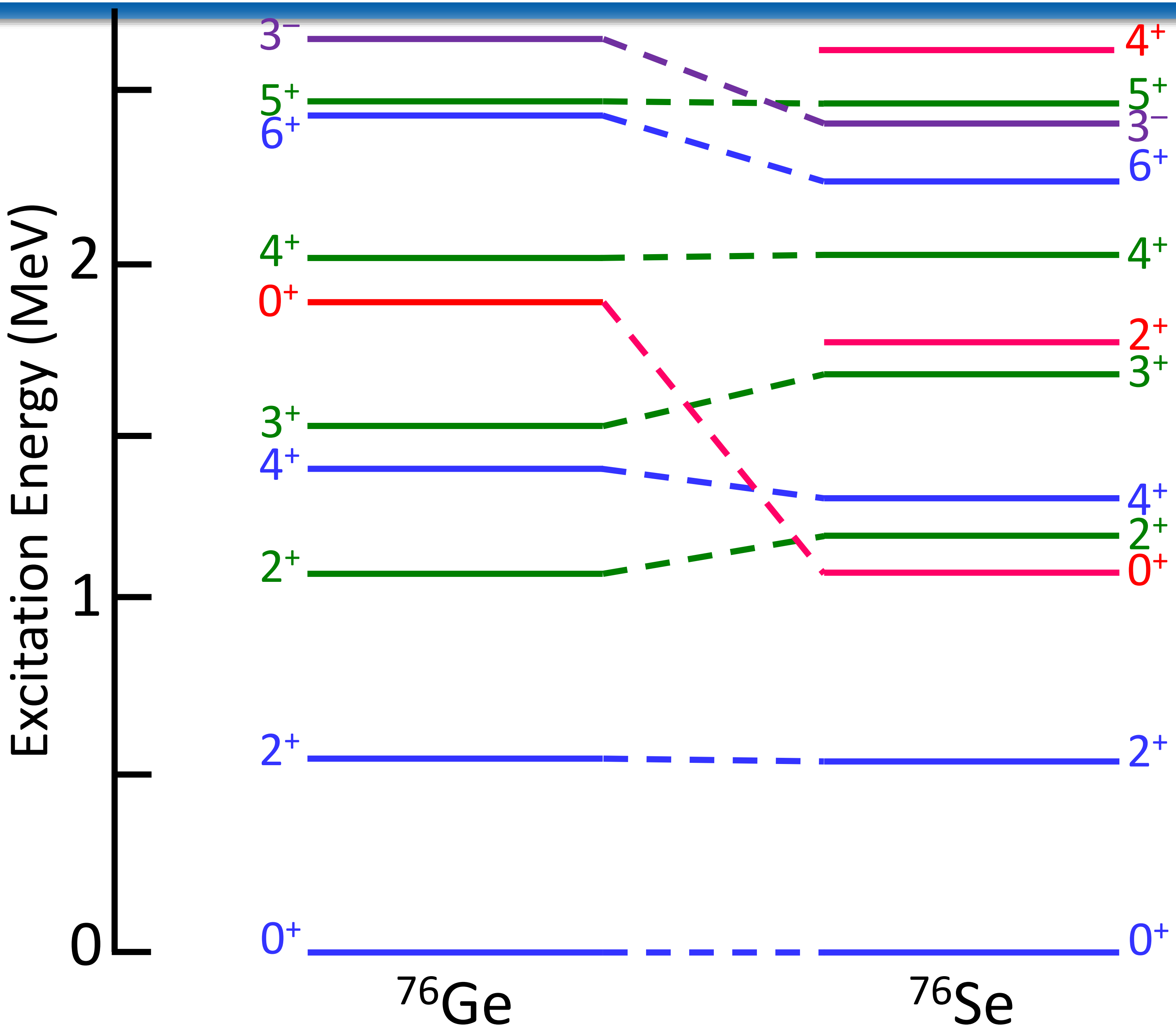
Structural evolution in germanium and selenium nuclei within the mapped interacting boson model based on the Gogny energy density functional

K. Nomura,[1,2] R. Rodríguez-Guzmán,[3] and L. M. Robledo[4]

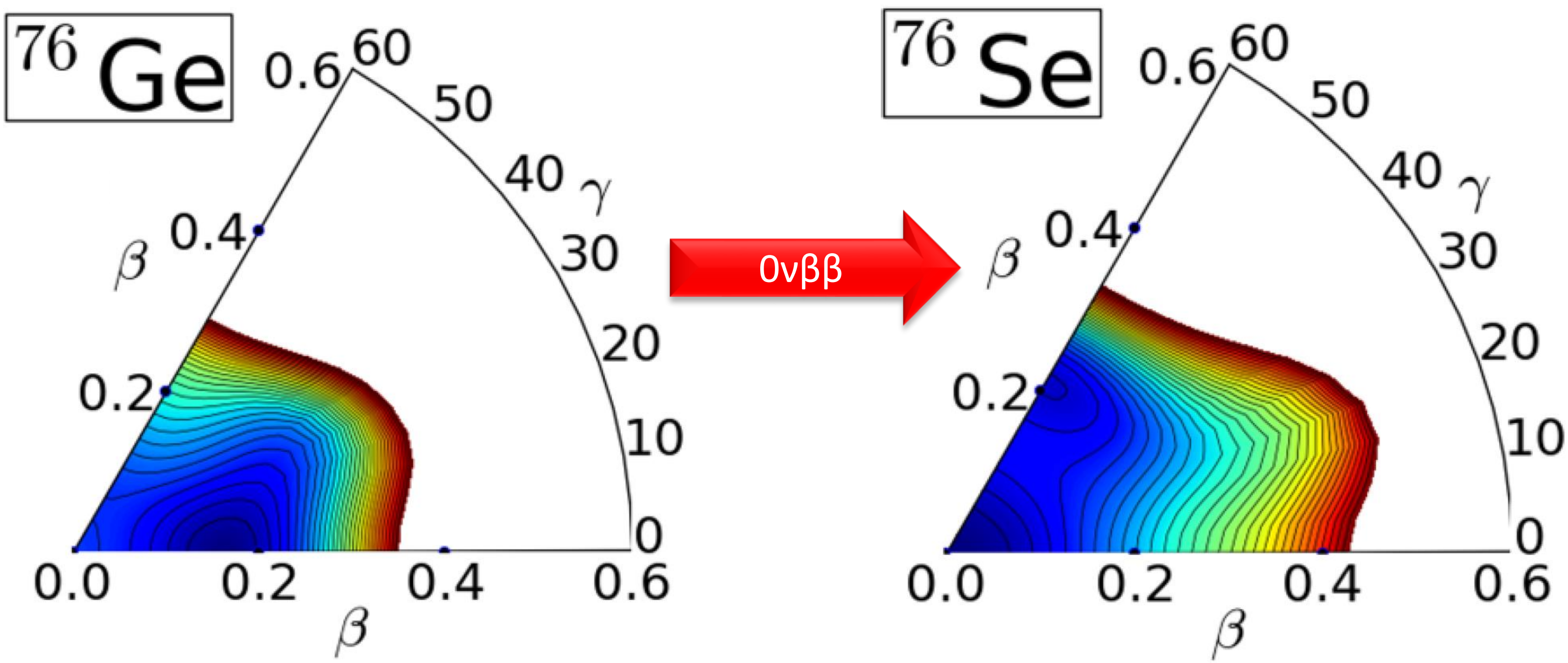




Excitation Energy (MeV)
0
1
2
3−
5+
6+
4+
0+
3+
4+
2+
2+
0+
76Ge
4+
5+
3−
6+
4+
2+
3+
4+
2+
0+
2+
0+
76Se


Excitation Energy (MeV)
0
1
2
3−
5+
6+
4+
0+
3+
4+
2+
2+
0+
4+
5+
3−
6+
4+
2+
3+
4+
2+
0+
2+
0+
76Ge
76Se

Neutrinoless Double-β Decay of ^{76}Ge



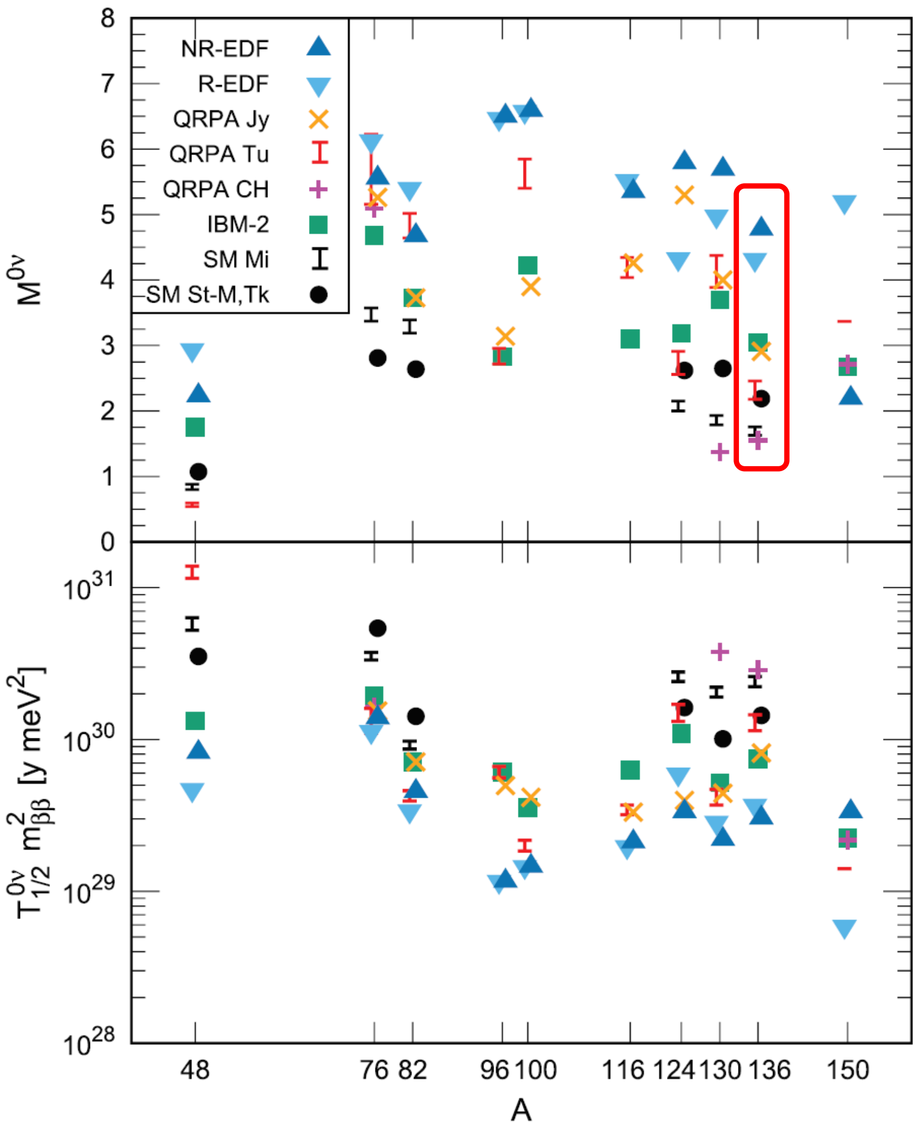
R. Nomura, K. Rodríguez-Guzmán, and L.M. Robledo, Phys. Rev. C **95**, 064310 (2017)

0νββ of ^{136}Xe

Detectors can be made from liquid xenon, high-pressure xenon, and xenon dissolved in liquid scintillator.

- ❑ **EXO-200**, Enriched Xenon Observatory, 200 kg, single-phase liquid xenon detector
- ❑ **nEXO**, 5-tonne "conventional" low-background liquid xenon detector
- ❑ **KamLAND-Zen** (KamLAND ZEro-Neutrino double beta decay), Xe-loaded liquid scintillator
- ❑ **NEXT**, a high-pressure gas xenon TPC

Comparison of calculated nuclear matrix elements for 0νββ candidates



Jonathan Engel and Javier Menéndez, Rep. Prog. Phys. **80**, 046301 (2017)

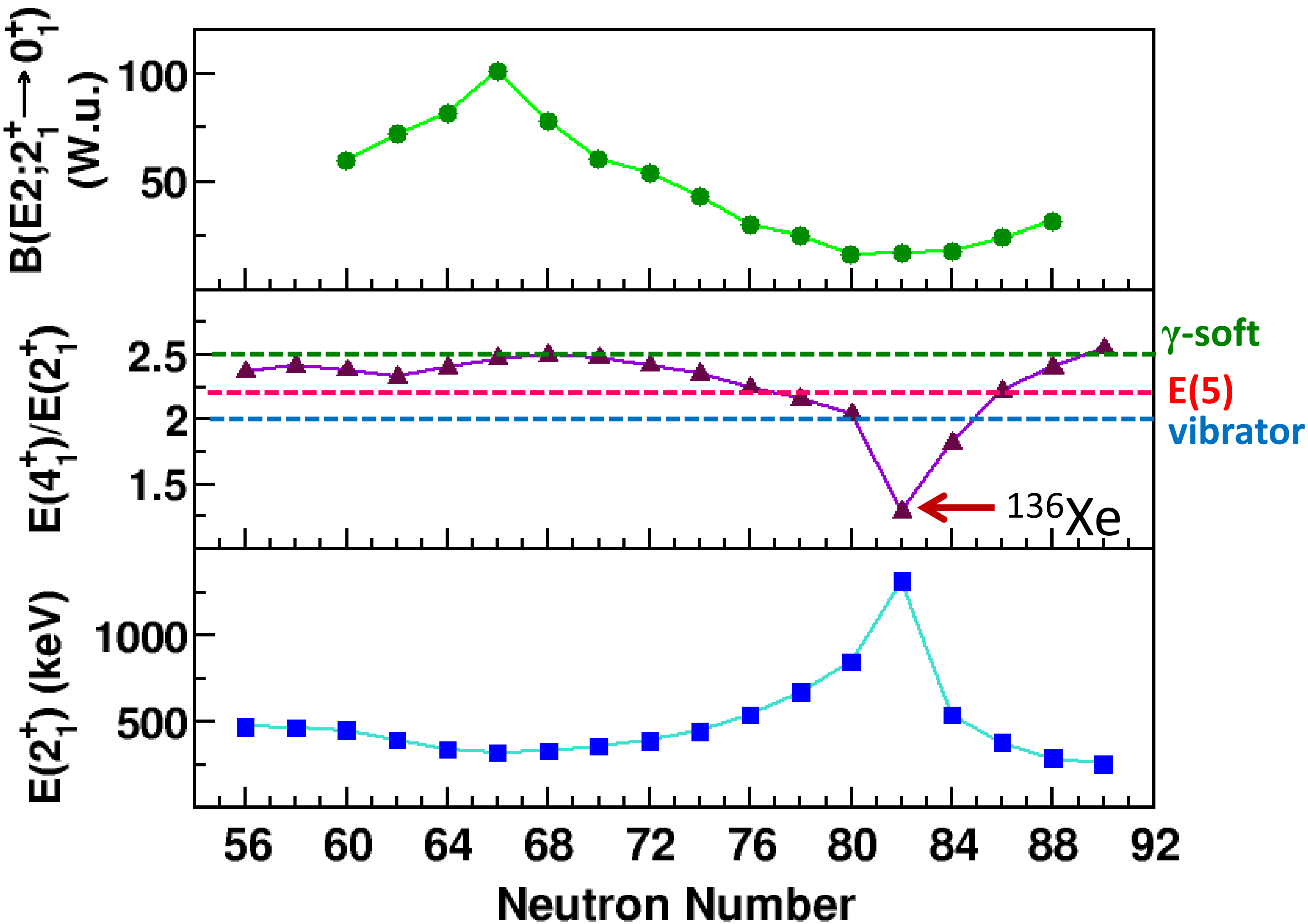
University of Kentucky Experiments

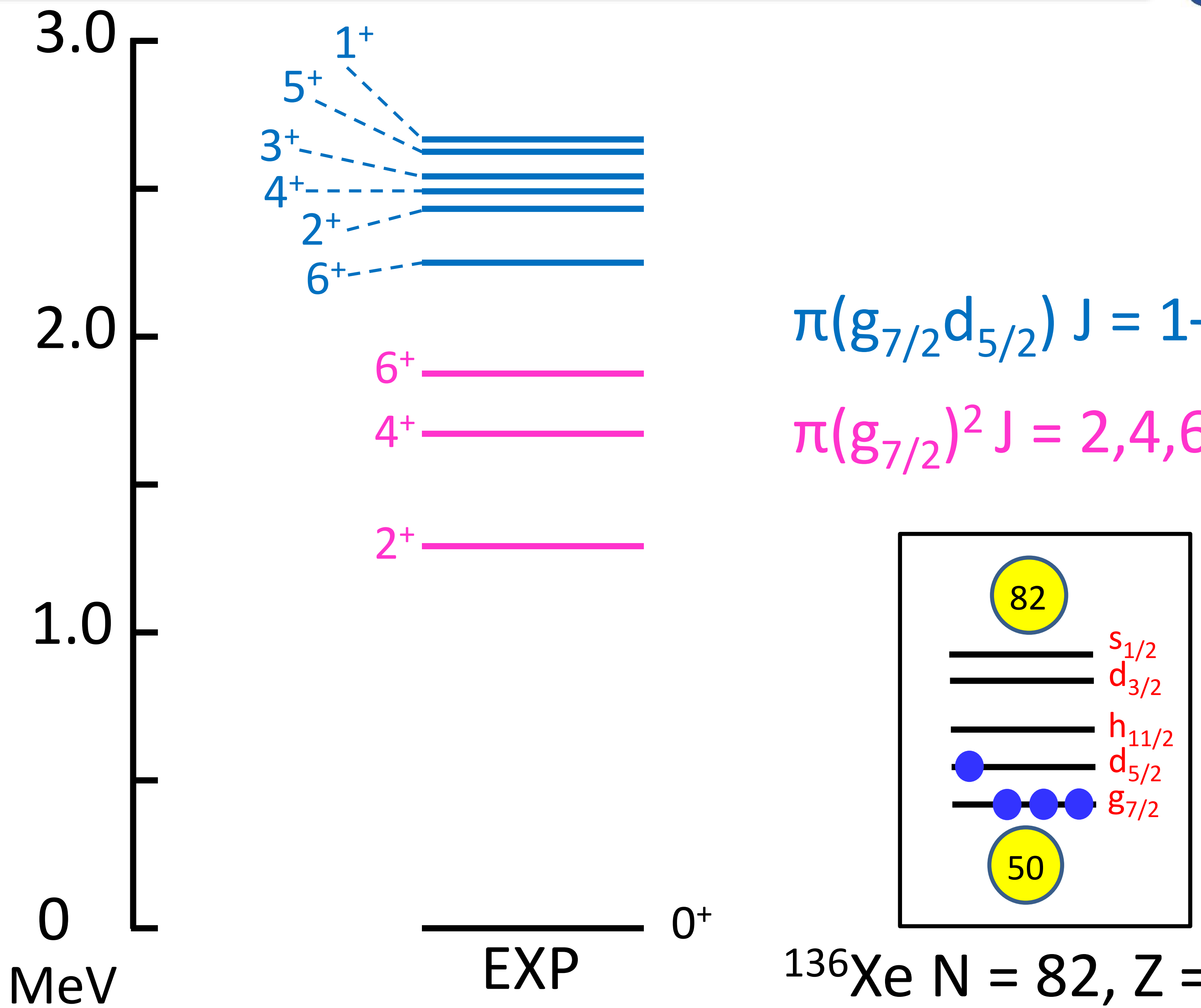
- Inelastic neutron scattering — (n,n'γ)
  - Allows determination of:
    - Level scheme
      - Population of non-yrast states
    - Transition multipolarities
    - Multipole mixing ratios
    - Level lifetimes by DSAM
      - Minimize effects of feeding
    - Transition probabilities

XeF_2 in Teflon® vial

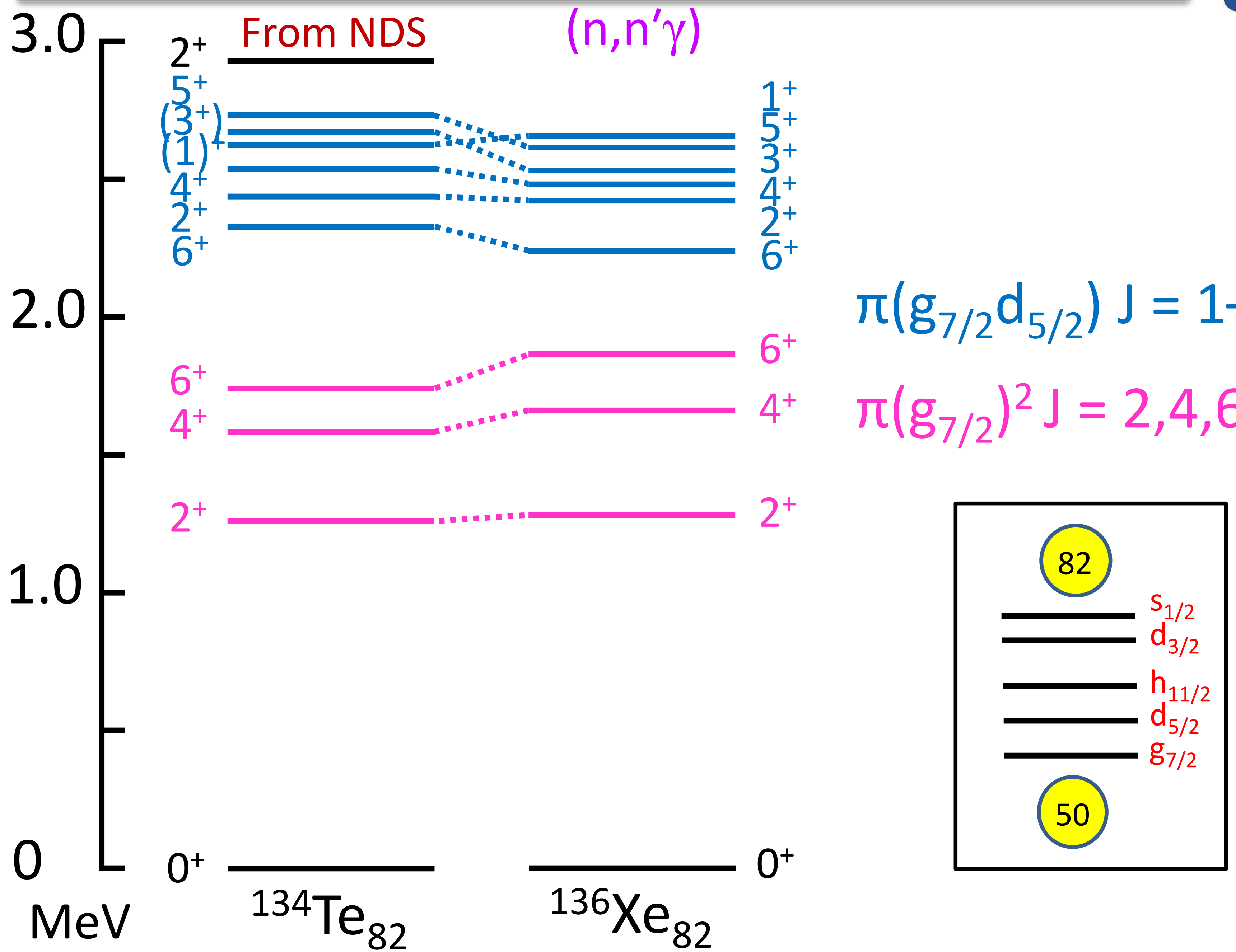
- Solid XeF_2 samples of >99.9% $^{130, 132, 134, 136}Xe$
  - Highly enriched, solid targets not used previously

Xe Systematics





^{136}Xe N = 82, Z = 54



3.0
2.0
1.0
0
MeV
From NDS
(n,n′γ)
2+
5+
(3+)
(1)+
4+
2+
6+
6+
4+
2+
0+
1+
5+
3+
4+
2+
6+
6+
4+
2+
0+
134Te82
136Xe82
π(g7/2d5/2) J = 1–6
π(g7/2)2 J = 2,4,6
82
s1/2
d3/2
h11/2
d5/2
g7/2
50

0νββ nuclei studied by INS at UKAL

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