The Nuclear Structure of ^{74}Ge from Inelastic Neutron Scattering

Erin E. Peters
University of Kentucky

UKAL 7 MV Model CN VDG (External View) – Located on U. of KY's main campus

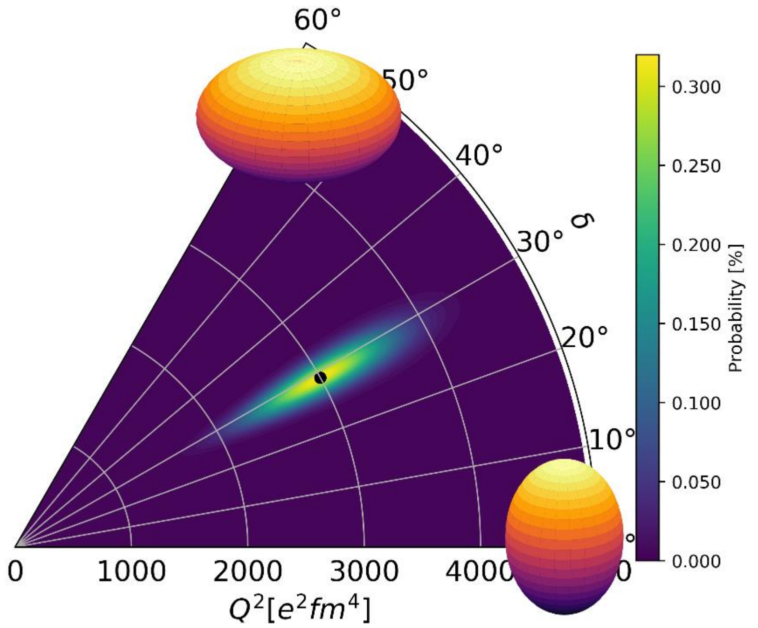
Collaboration:

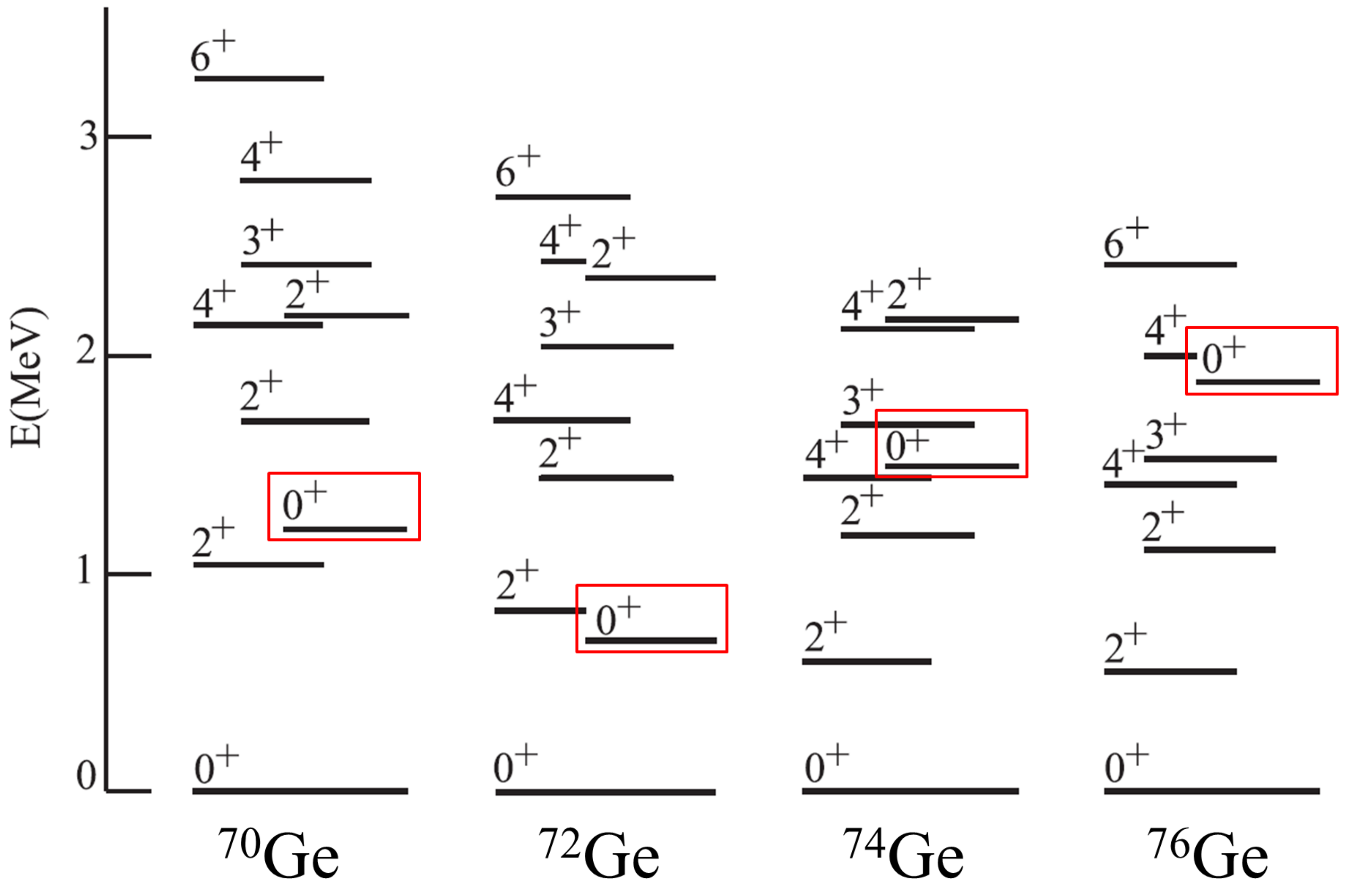
S. W. Yates – University of Kentucky
B. A. Brown – FRIB, Michigan State University
A. P. D. Ramirez – currently Lawrence Livermore National Laboratory
S. Mukhopadhyay – currently Georgia Institute of Technology

Why study the Ge isotopes?

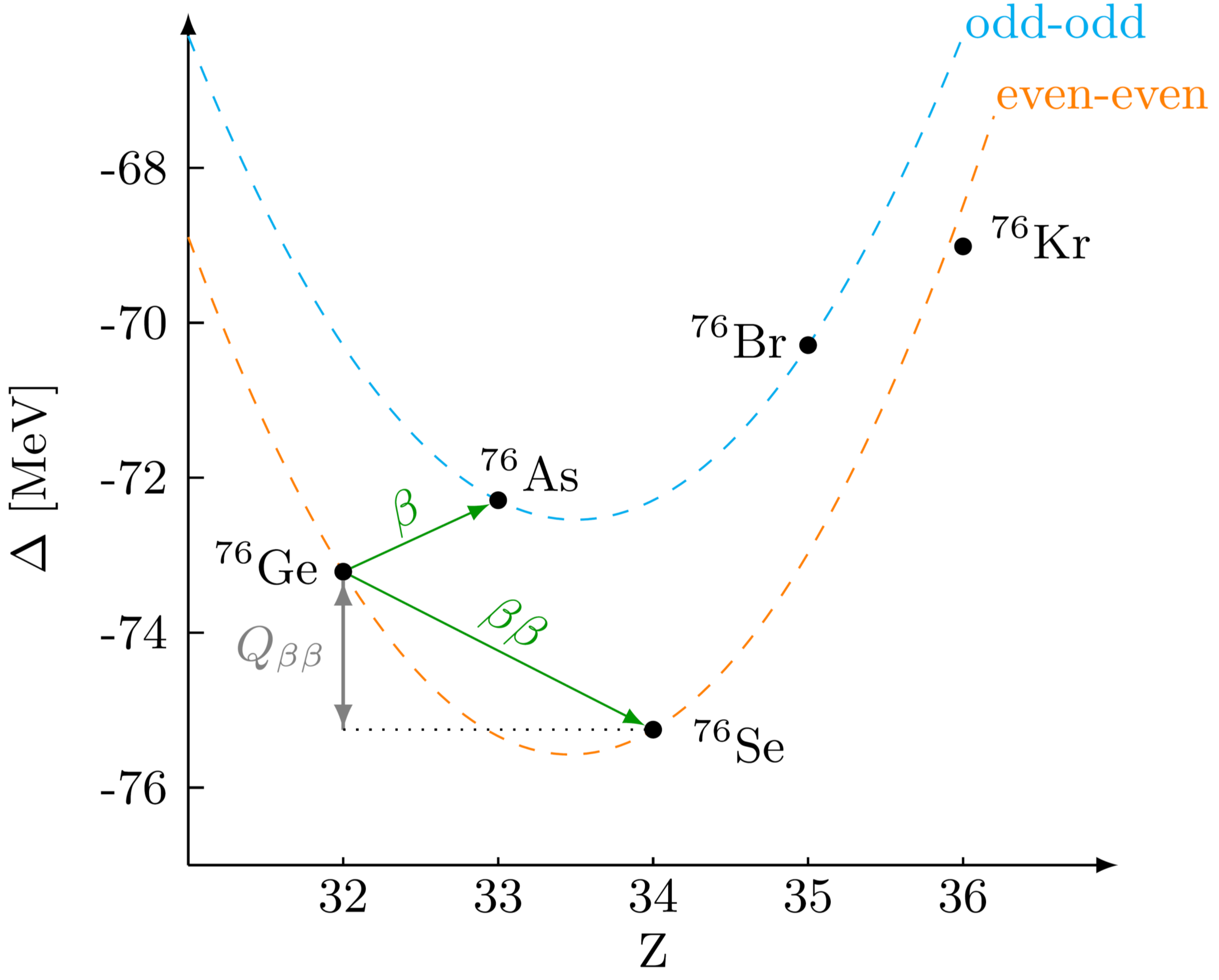
Structurally Interesting!

- Shape Transition
- Soft/Rigid Triaxiality
- Subshell Closures
- Shape Coexistence





Broader Impacts: Neutrinoless Double-beta Decay

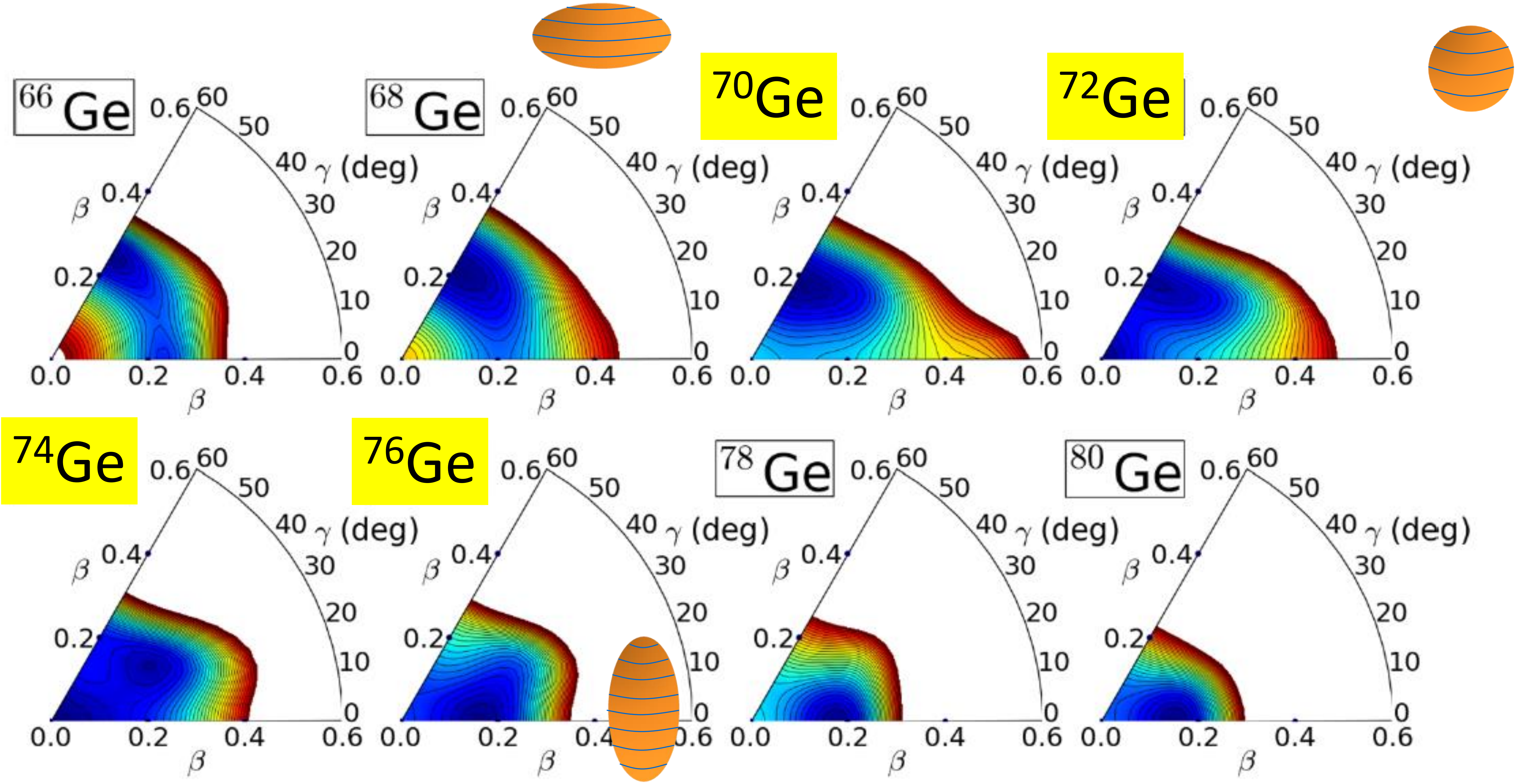


Structural Evolution of Ge

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]



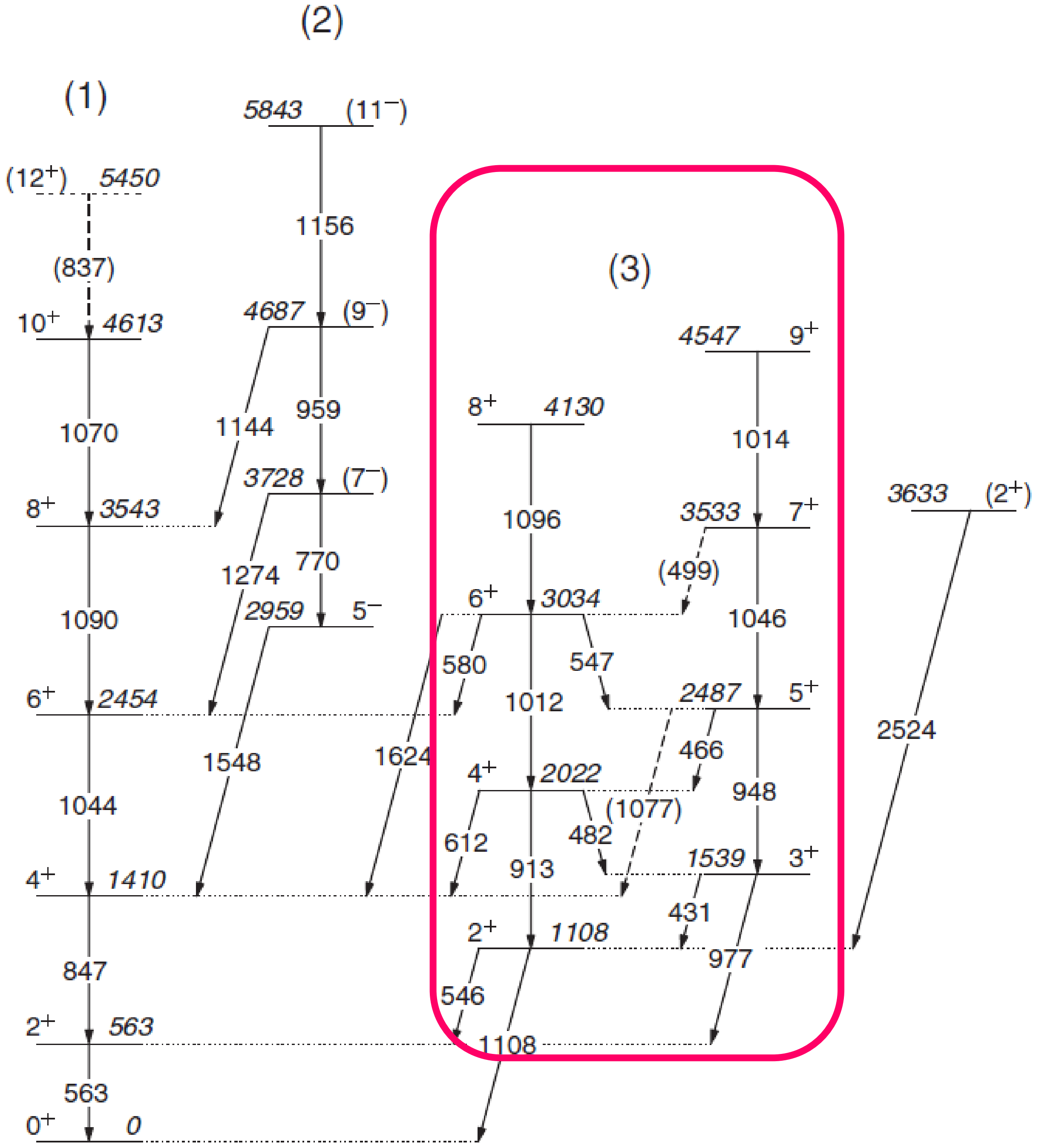
Triaxiality in ^{76}Ge

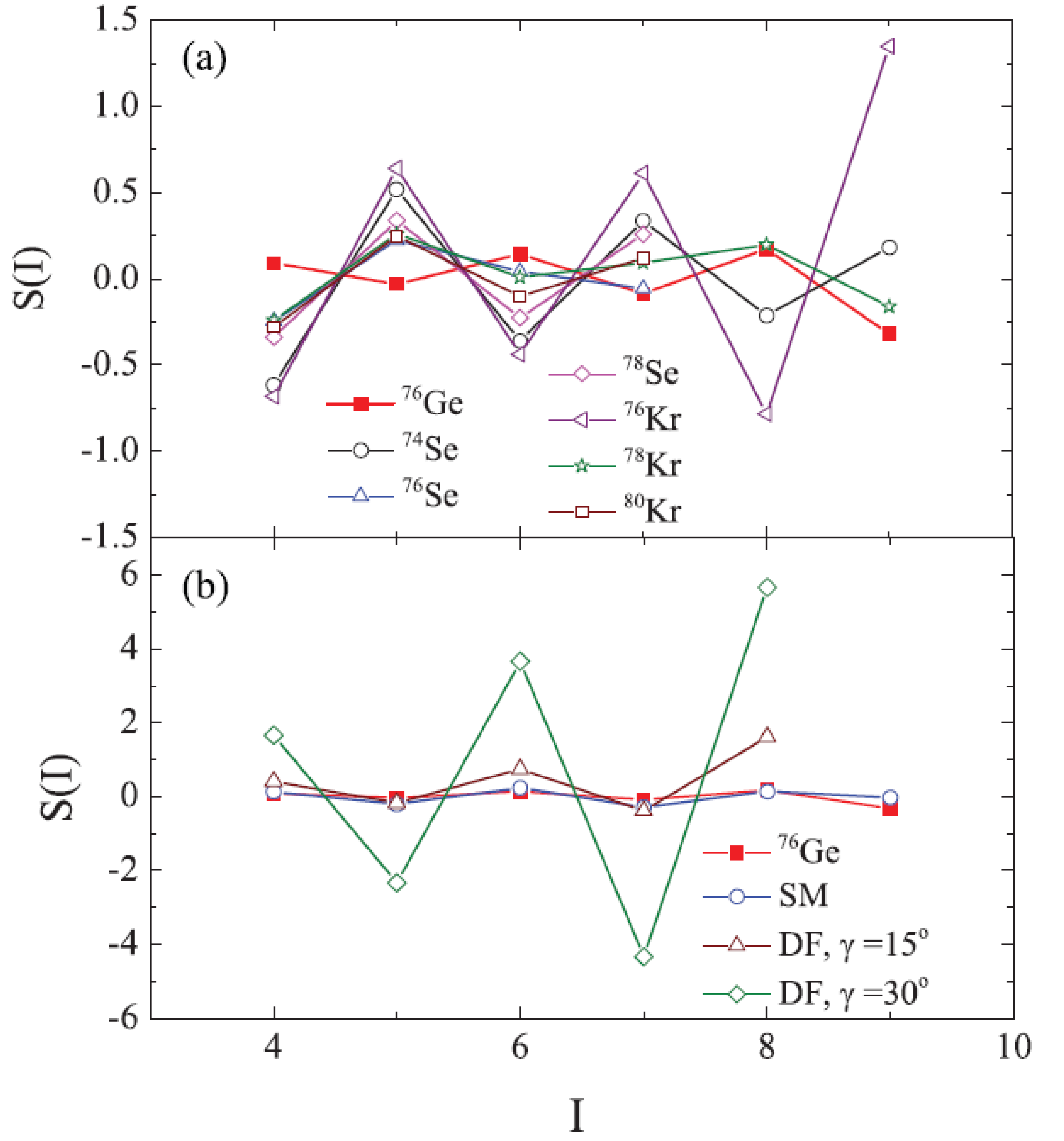
PHYSICAL REVIEW C **87**, 041304(R) (2013)

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."

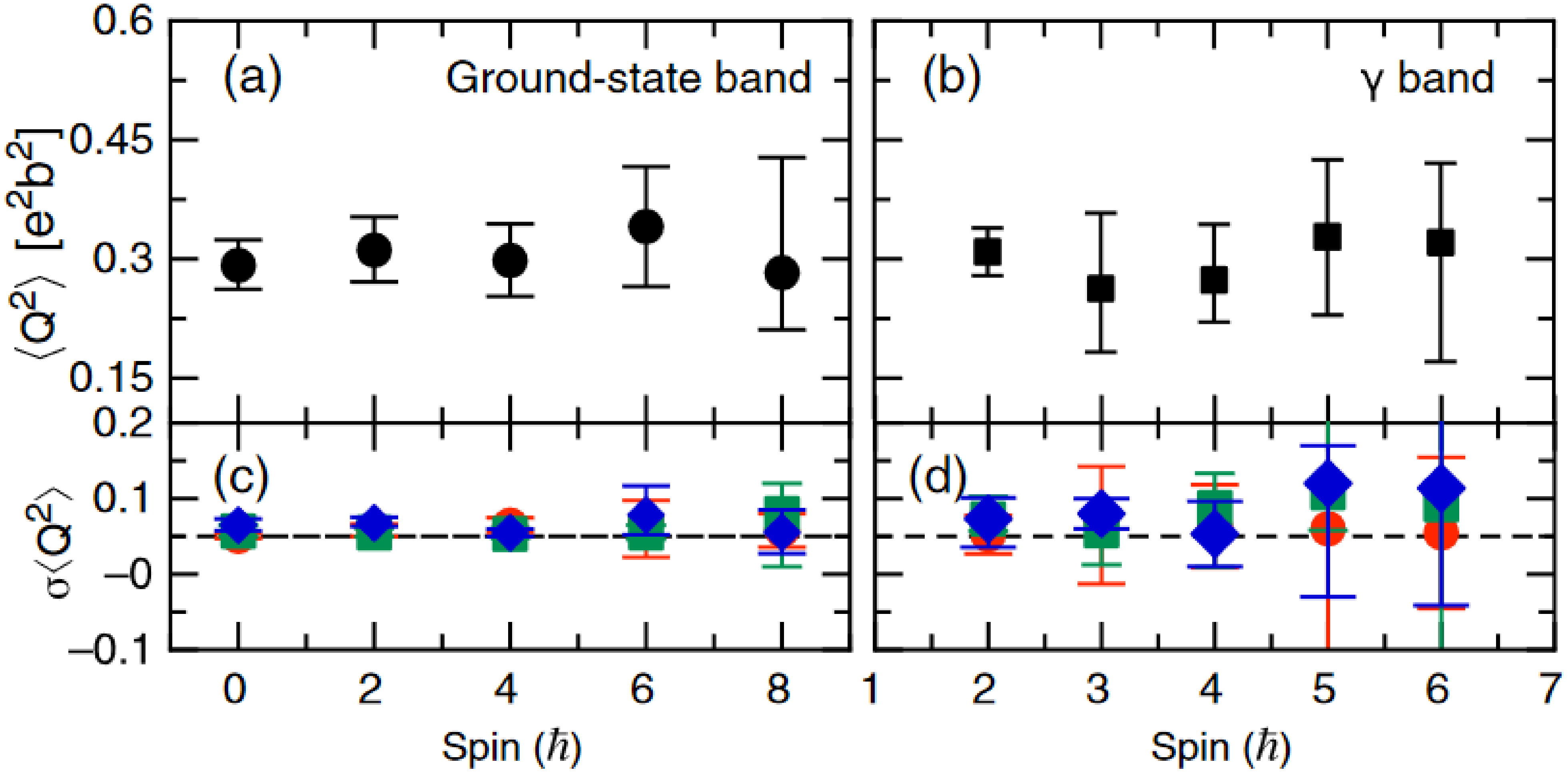




Triaxiality in ^{76}Ge

$\langle Q^2 \rangle$ ~0.28

quadrupole deformation



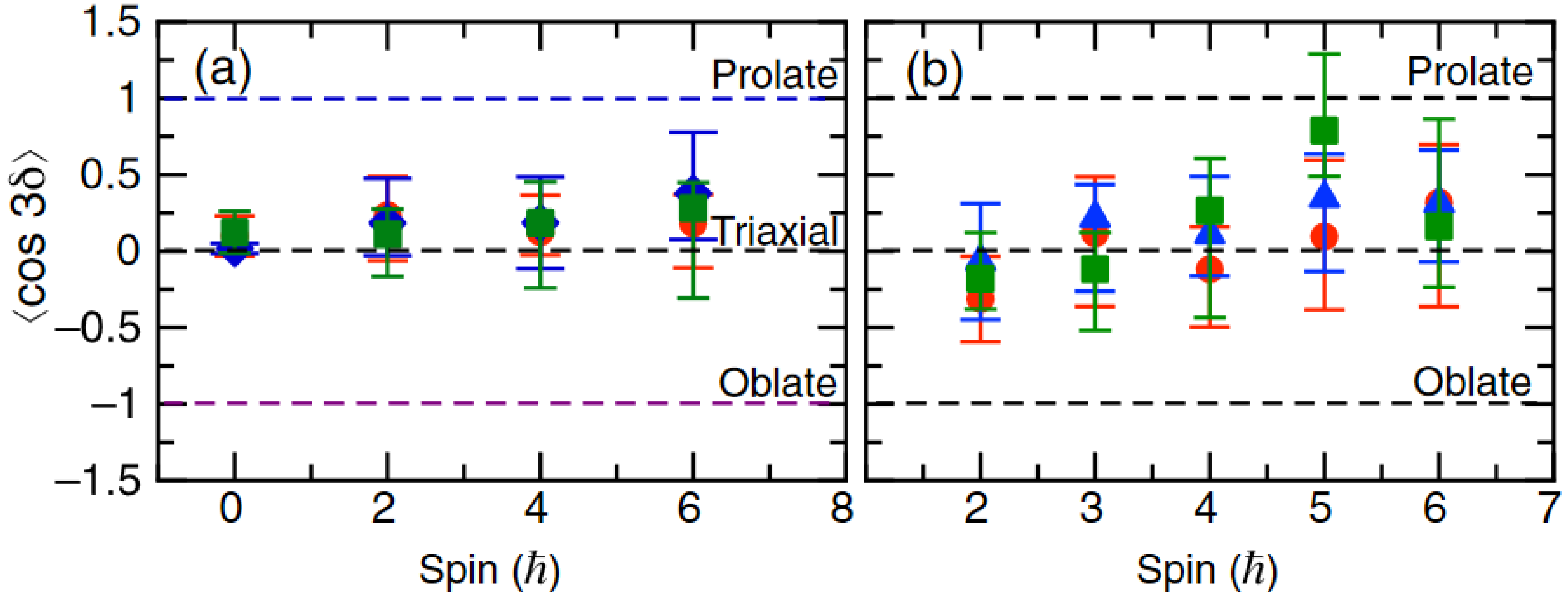
Coul. Ex. at

Argonne NATIONAL LABORATORY

A. D. Ayangeakaa et al., Phys. Rev. Lett. **123**, 102501 (2019).

$\langle \cos 3\delta \rangle$

axiality



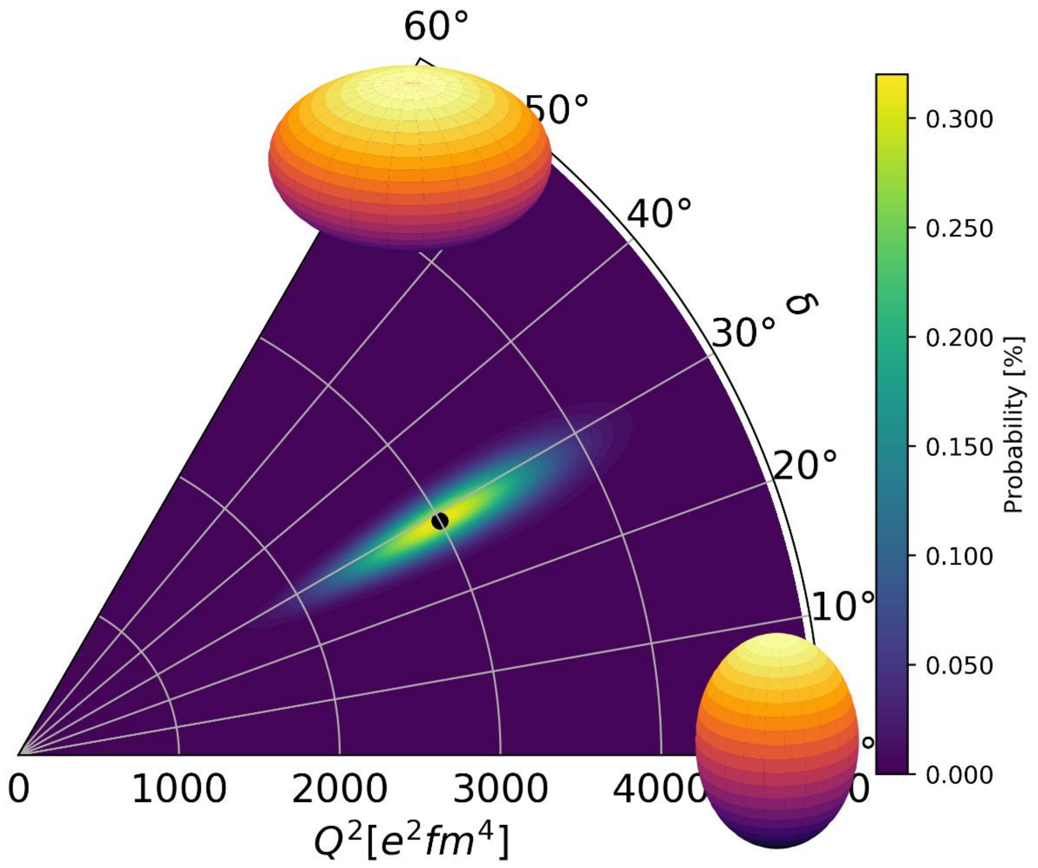
Triaxiality in ^{76}Ge

Shell-Model Calculations by **Alex Brown**

Ground-state deformations:

A.D. Ayangeakaa, et al., Phys. Rev. C 107, 044314 (2023).

Experimental result



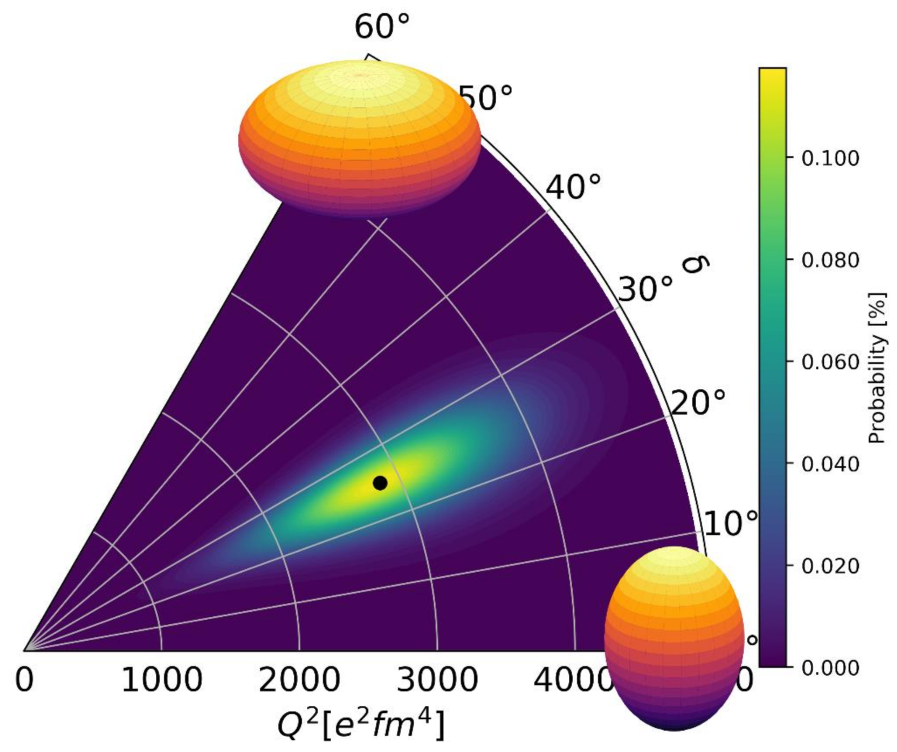
Quadrupole deformation

$\beta \approx 0.28$

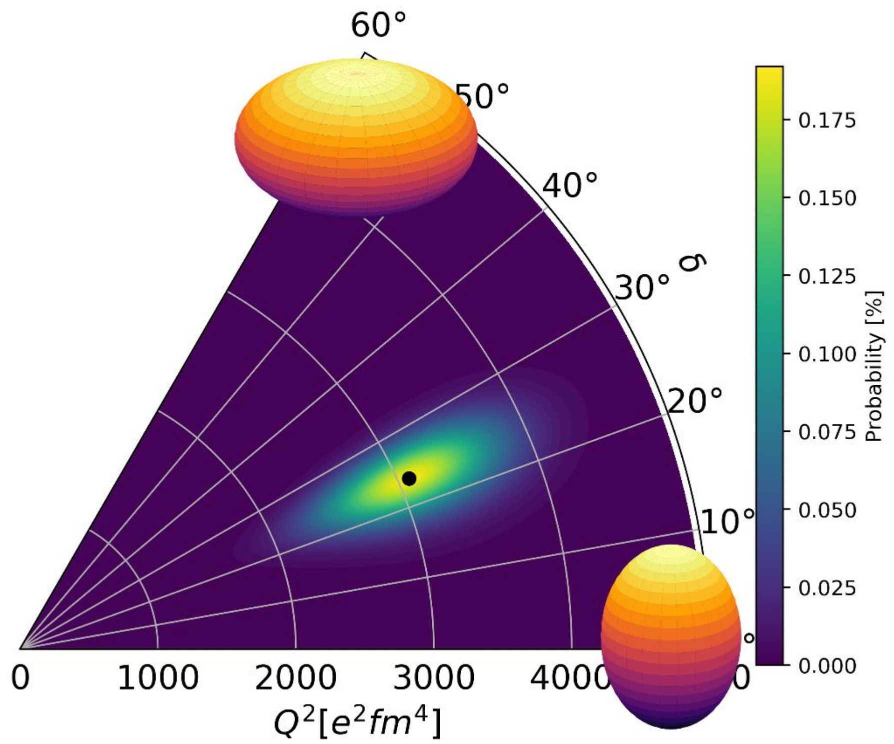
Triaxial deformation

$\gamma \approx 27^{\circ}$

jj44b Hamiltonian

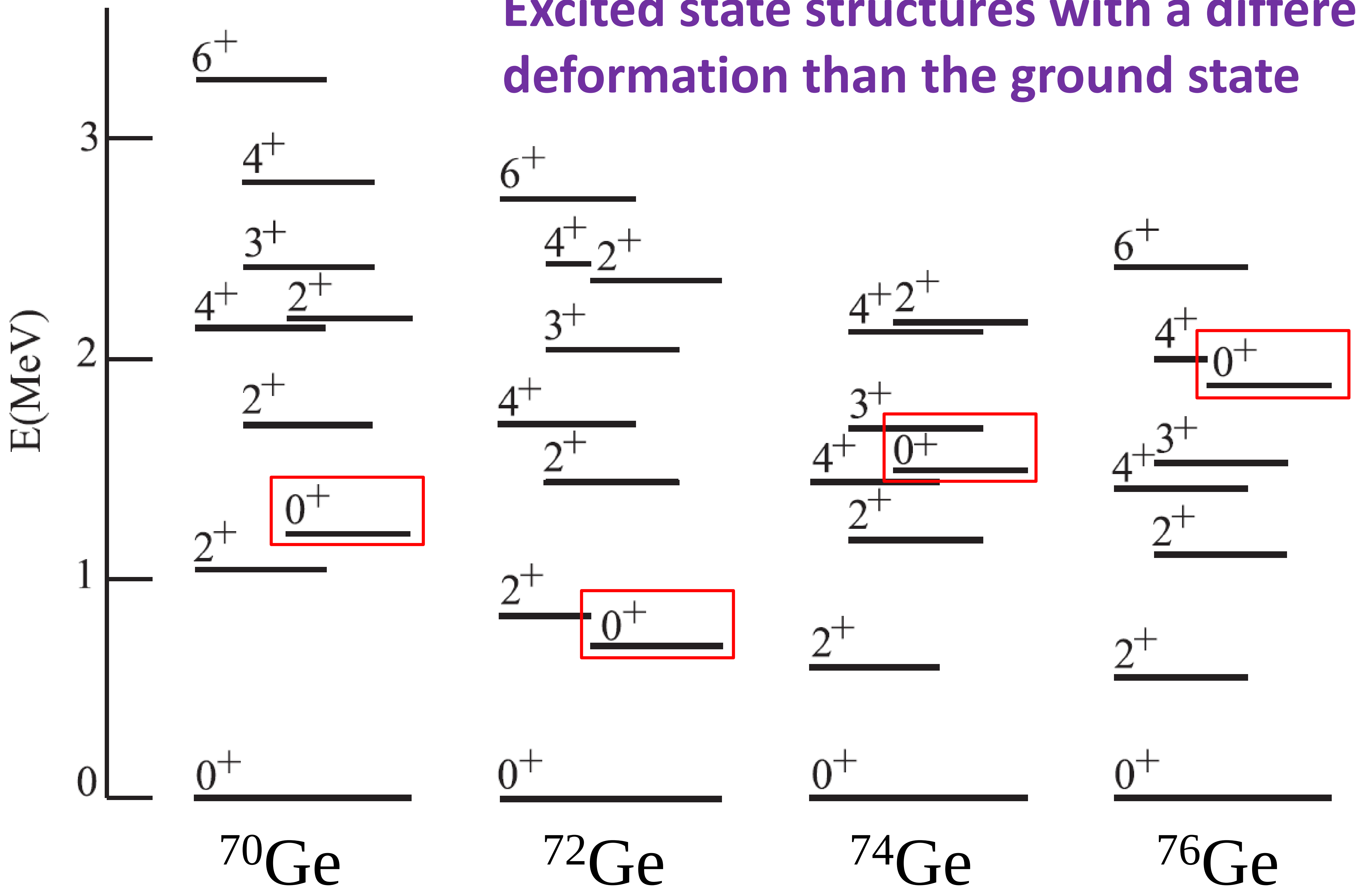


JUN45 Hamiltonian



Shape Coexistence in Ge Isotopes

Excited state structures with a different deformation than the ground state



Z. Podolyák *et al.*, Int. J. Mod. Phys. E 13, 123 (2004).
K. Heyde and J. L. Wood, Rev. Mod. Phys. 83, 1467 (2011).

Why study the Ge isotopes?

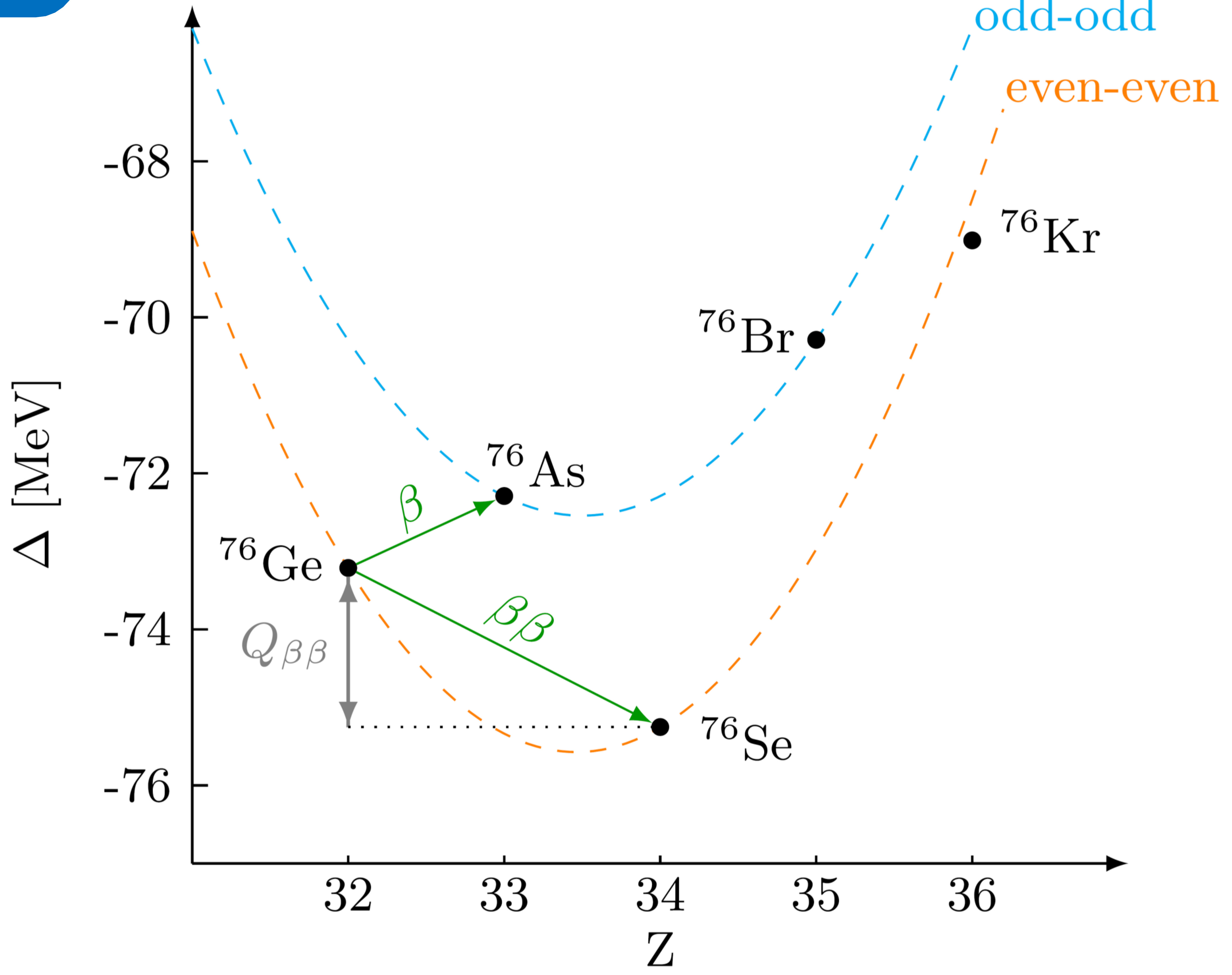
Implications for 0νββ Decay

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

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

Is the neutrino its own antiparticle?

What is the mass of the neutrino?

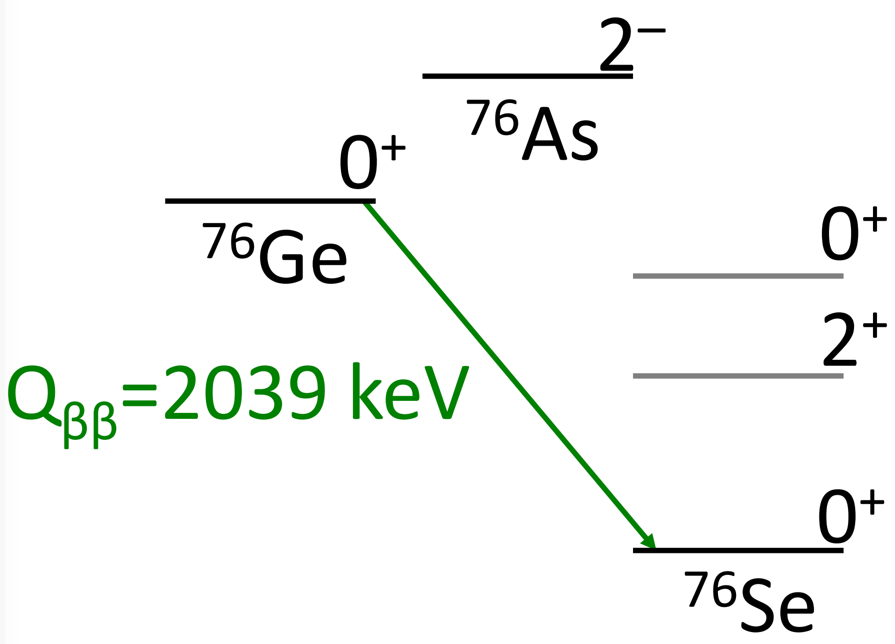


M. Agostini, et al. Rev. Mod. Phys. 95 025002 (2023).

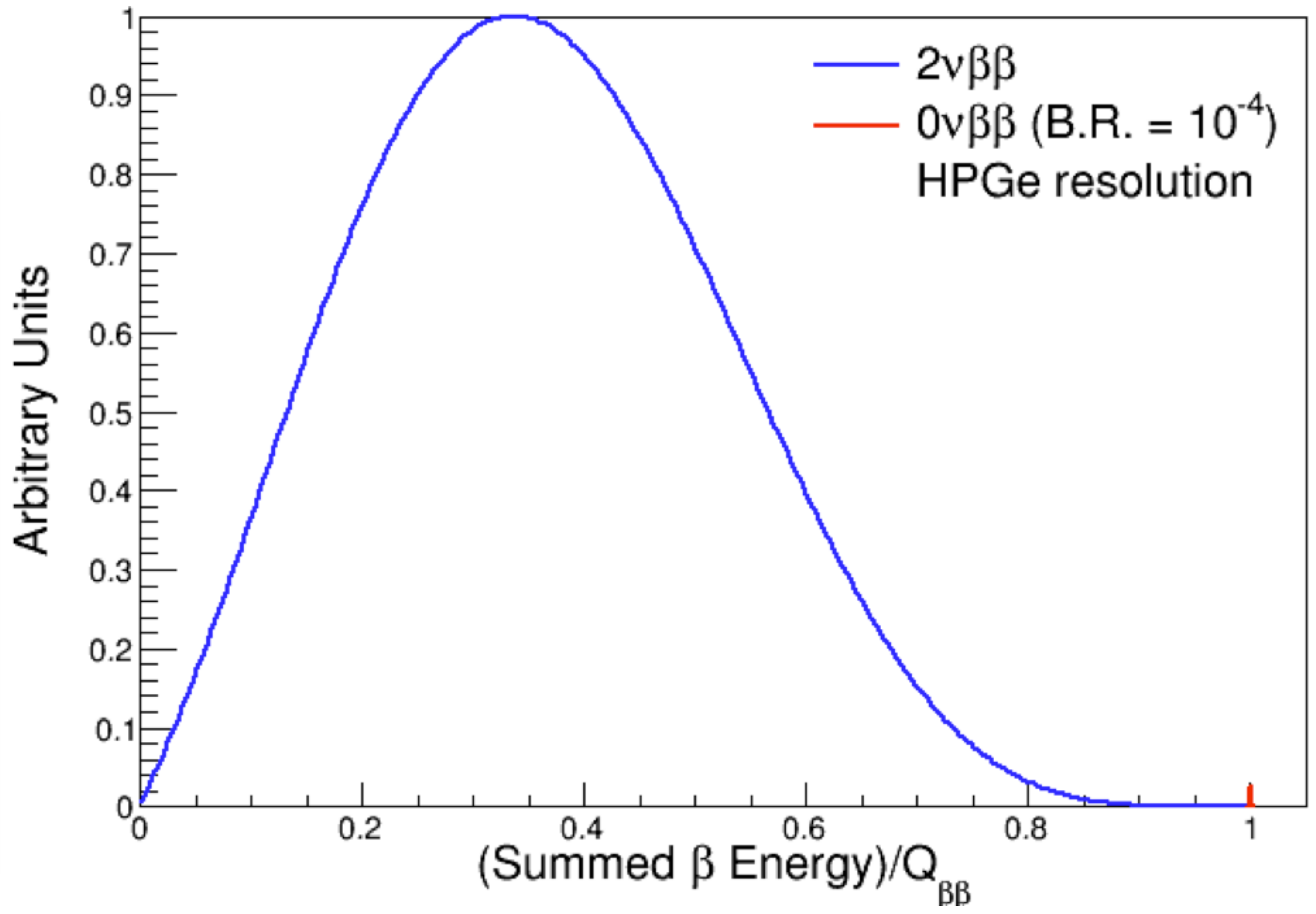
Current Searches for ^{76}Ge $0\nu\beta\beta$

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

MAJORANA DEMONSTRATOR



MAJORANA Collaboration: The simulated $0\nu\beta\beta$ signal in a high-purity germanium (HPGe) detector.



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

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

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

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

$0\nu\beta\beta$ Decay Rate

Phase Space Factor

Effective Majorana Neutrino Mass

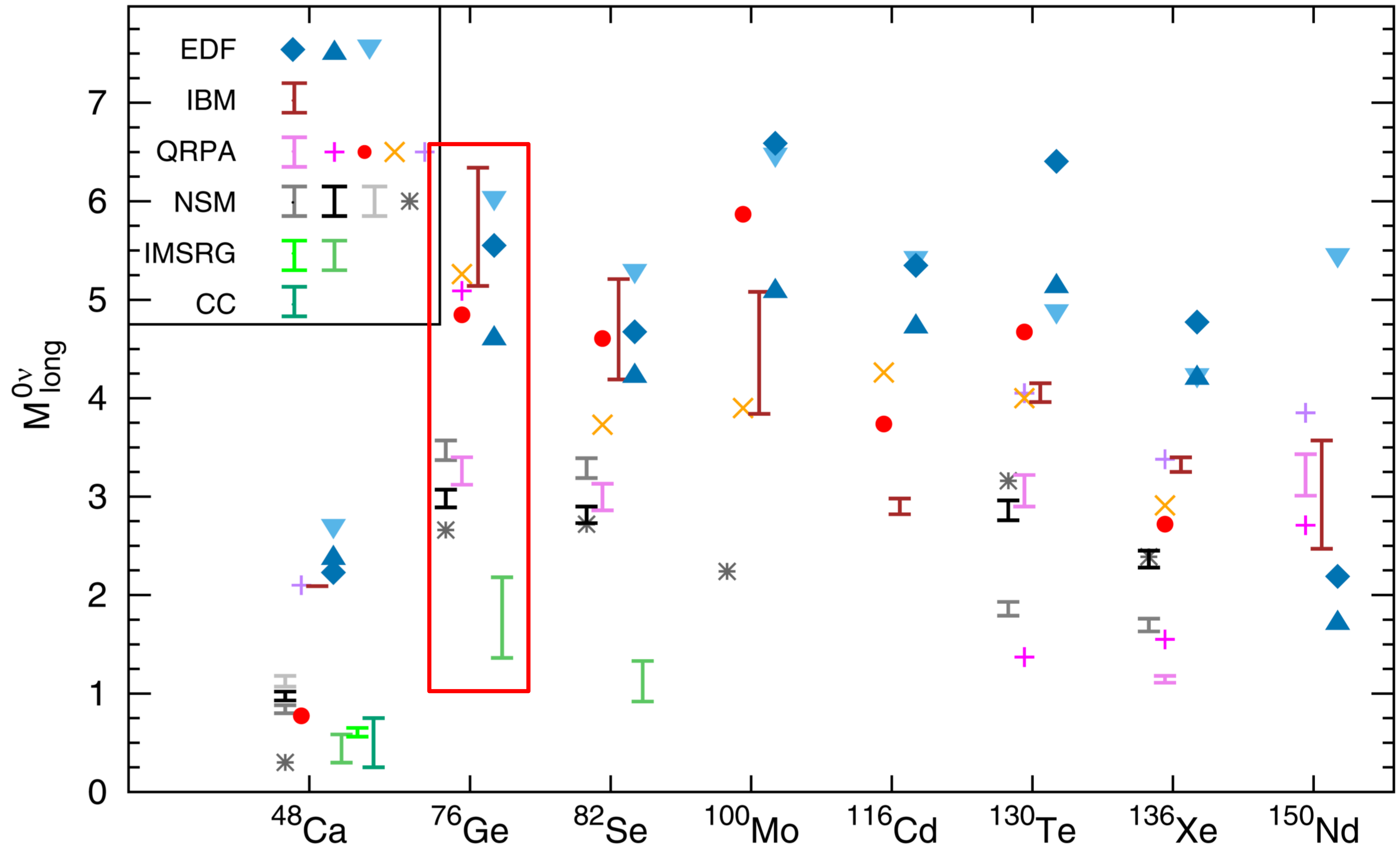
$$\left[T^{0\nu}_{1/2}\left(0^{+} \rightarrow 0^{+}\right)\right]^{-1} = G^{0\nu}(E_0, Z)\left|M^{0\nu}\right|^{2} \langle m_{\nu_e} \rangle^{2}$$

Nuclear Matrix Element from Nuclear Structure Theory

$T_{½}\,(0\nu\beta\beta) > 1.8 \times 10^{26}$ a @ 90% CL

M. Agostini et al. (GERDA), Phys. Rev. Lett. **125**, 252502 (2020).

Calculated Nuclear Matrix Elements



Experimental nuclear structure data are needed to constrain the calculations.

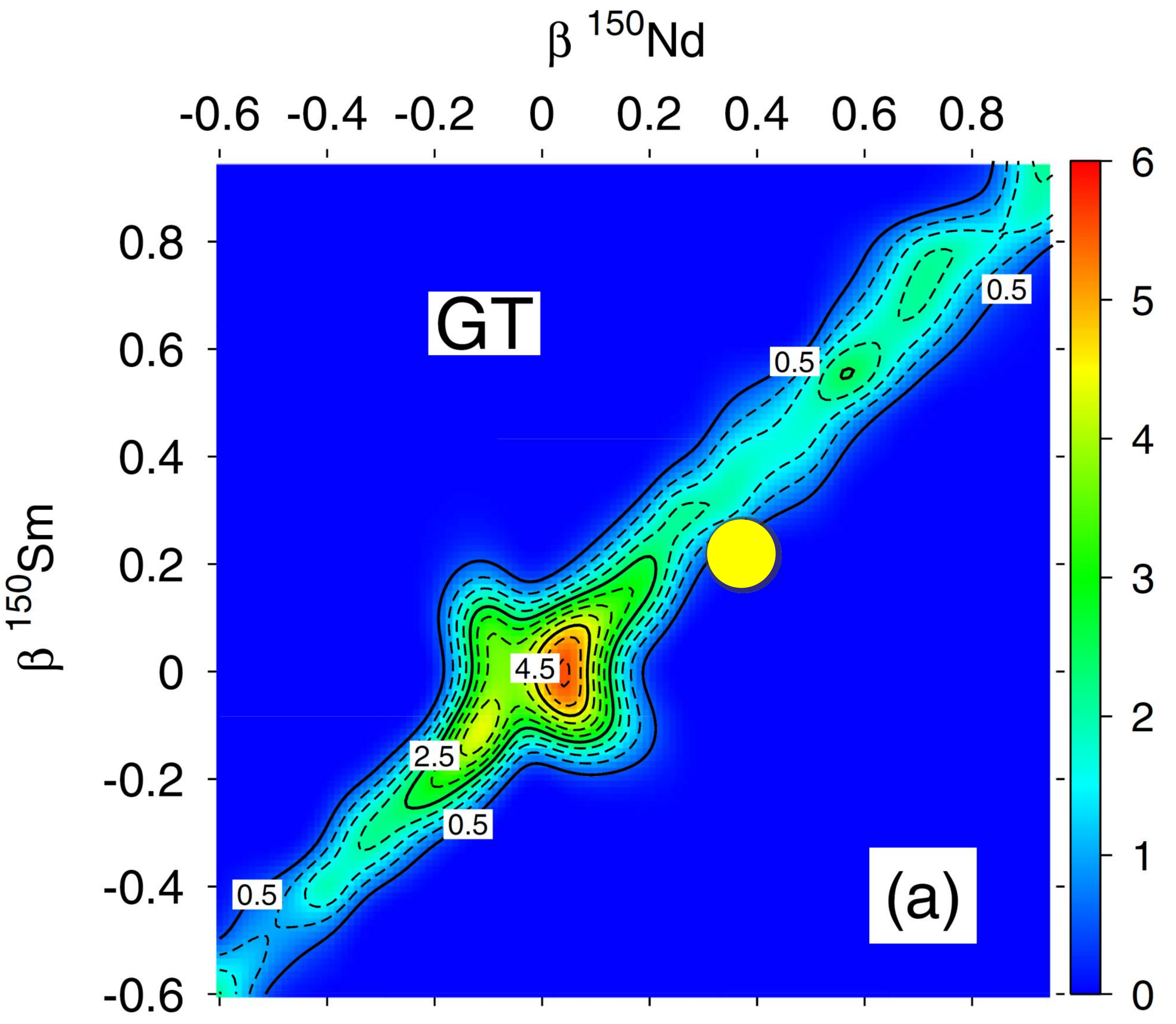
M. Agostini, G. Benato, J. A. Detwiler, J. Menéndez, and F. Vissani, Rev. Mod. Phys. 95, 025002 (2023).

Deformation and the NME

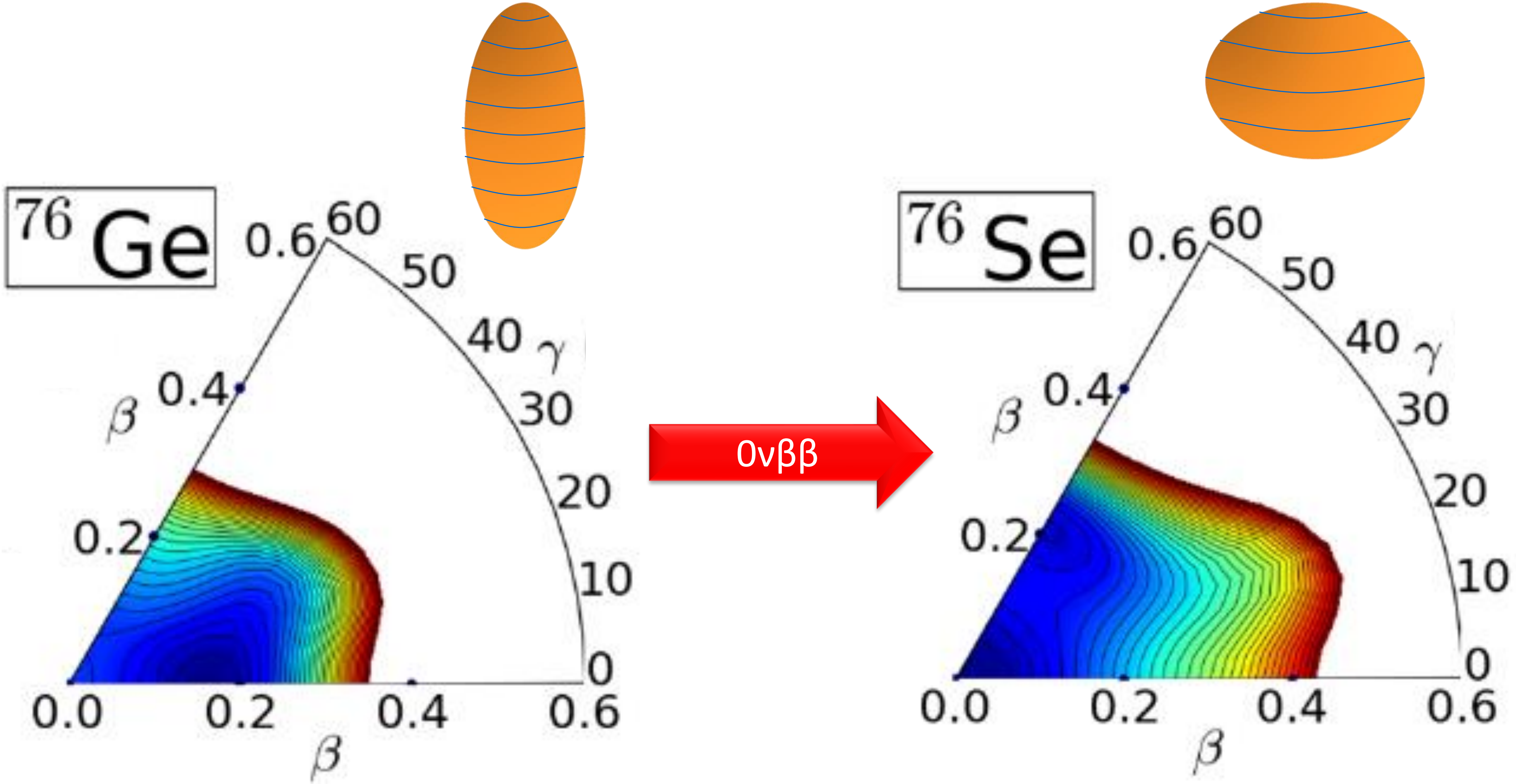
A difference in deformation between the parent and daughter decreases the NME.

Beyond-mean-field density functional theory – Gogny D1S functional

Tomás R. Rodríguez and Gabriel Martínez-Pinedo, Phys. Rev. Lett. **105**, 252503 (2010).



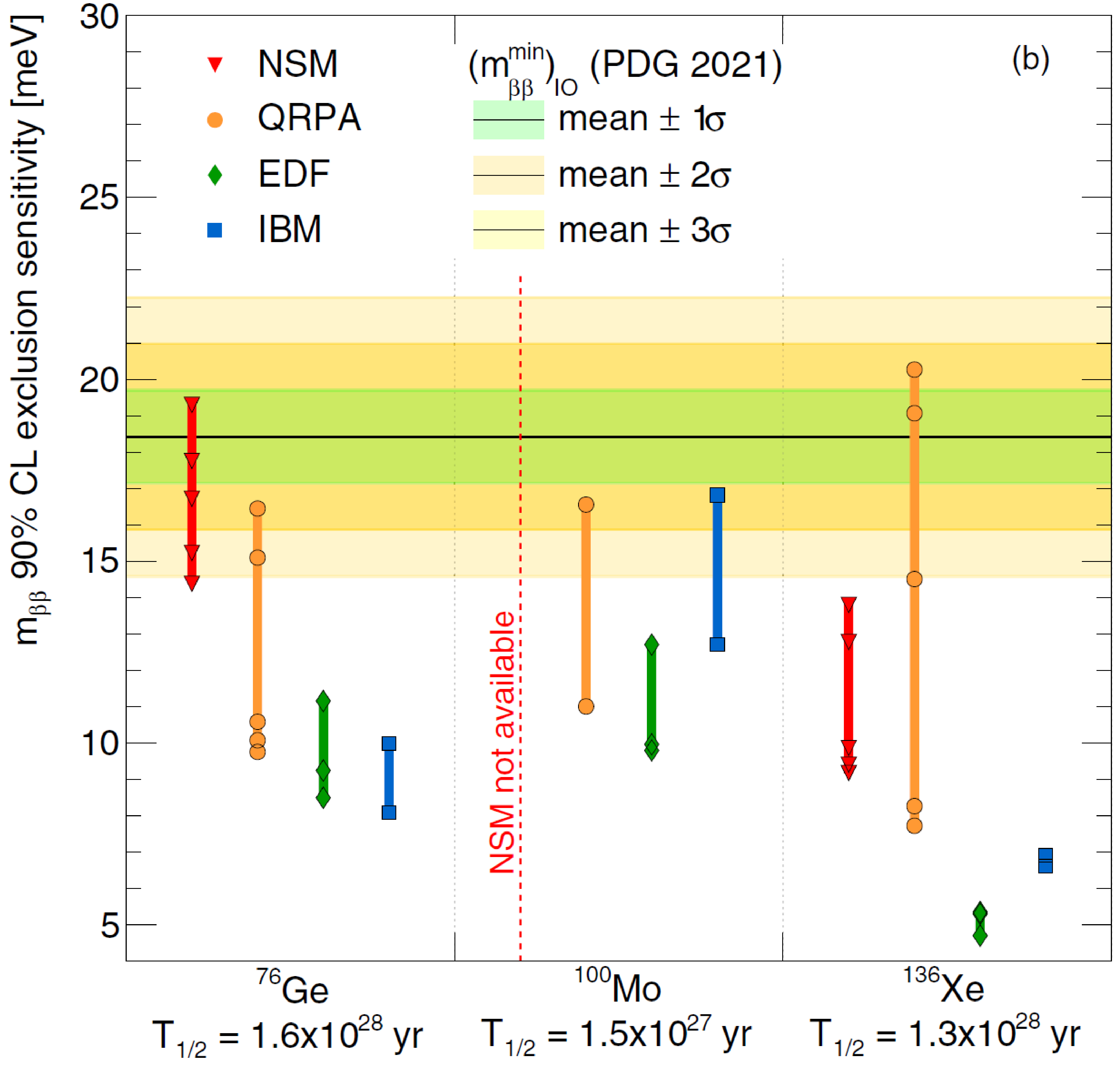
Structure of ^{76}Ge and ^{76}Se



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

The difference in deformation affects the NME.

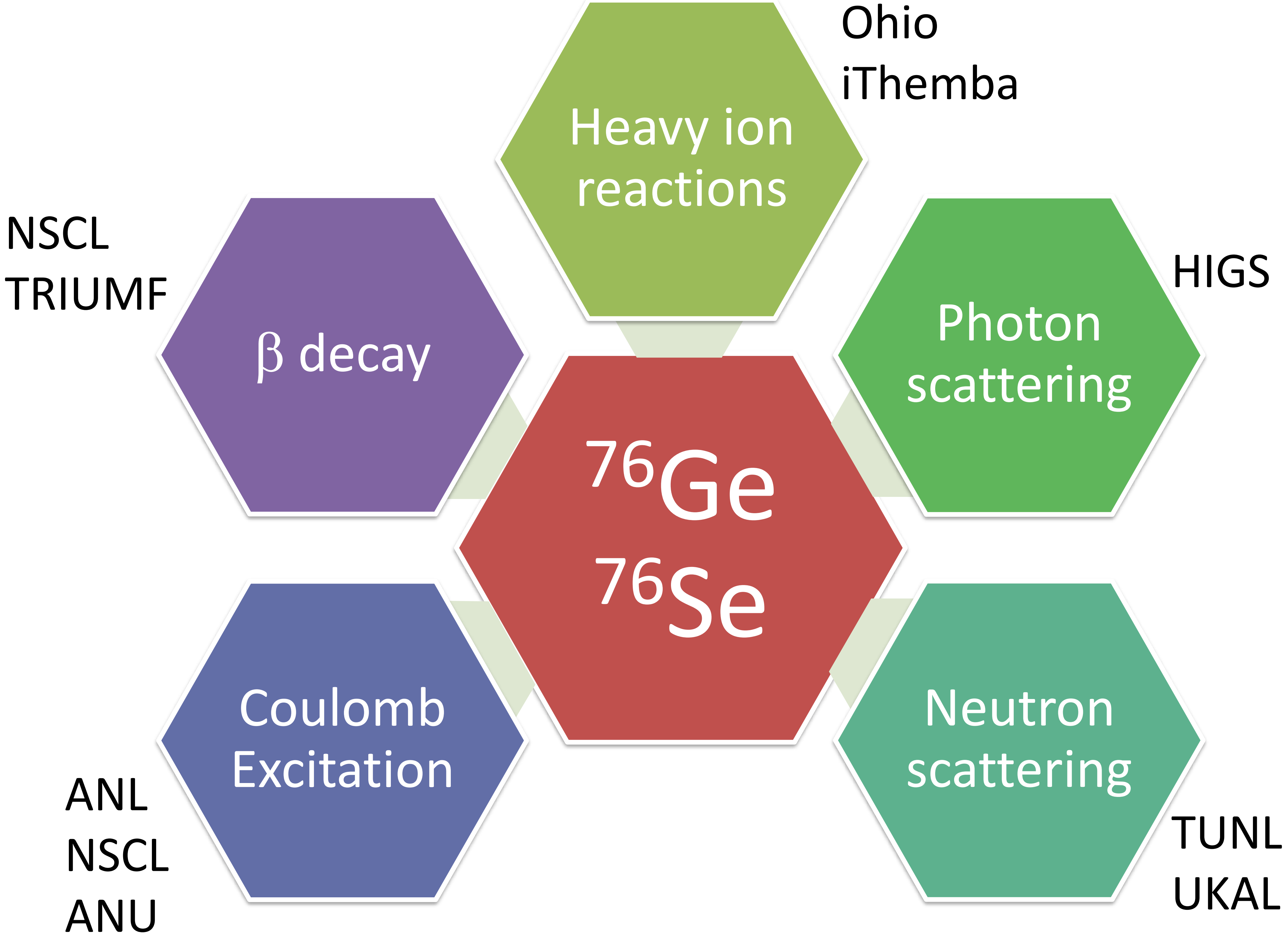
Calculated Nuclear Matrix Elements



Impact of matrix elements on discovery potential at stated sensitivities and 90% CL.

M. Agostini, et al., Phys. Rev. C 104, L042501 (2021).

Experimental Techniques



I. Detailed Nuclear Spectroscopic Data

II. Deformations

UKAL – Laboratory overview

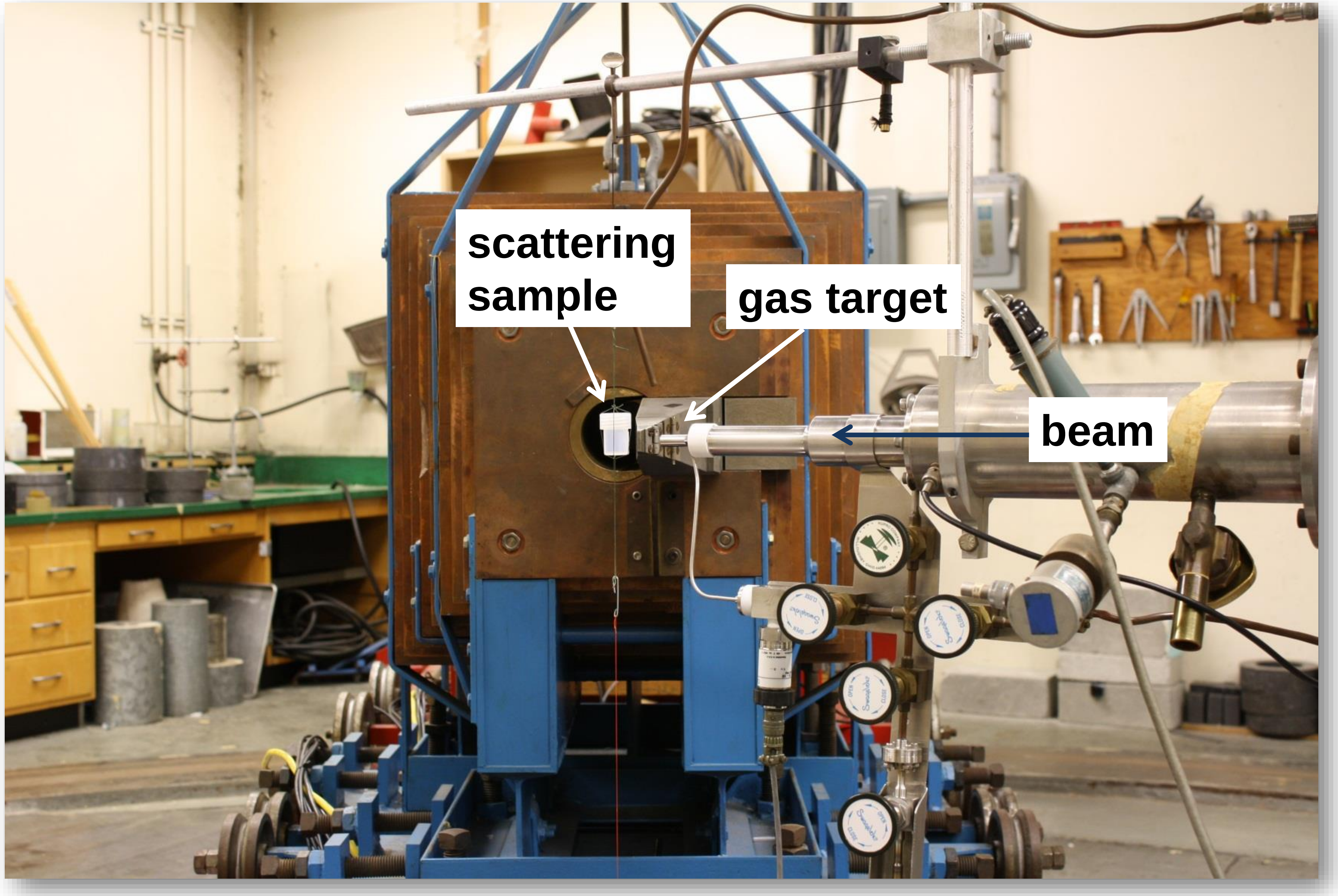
- 7 MV Model CN VDG
- p, d, ^{3}He, and α beams
- D.C. (~50 μA)
- Pulsed beams (~5 μA)
- f = 1.875 MHz
- Δt ~1 ns

UKAL – Opened in 1964
Almost 60 years of continuous operation and funding

UKAL – Laboratory overview

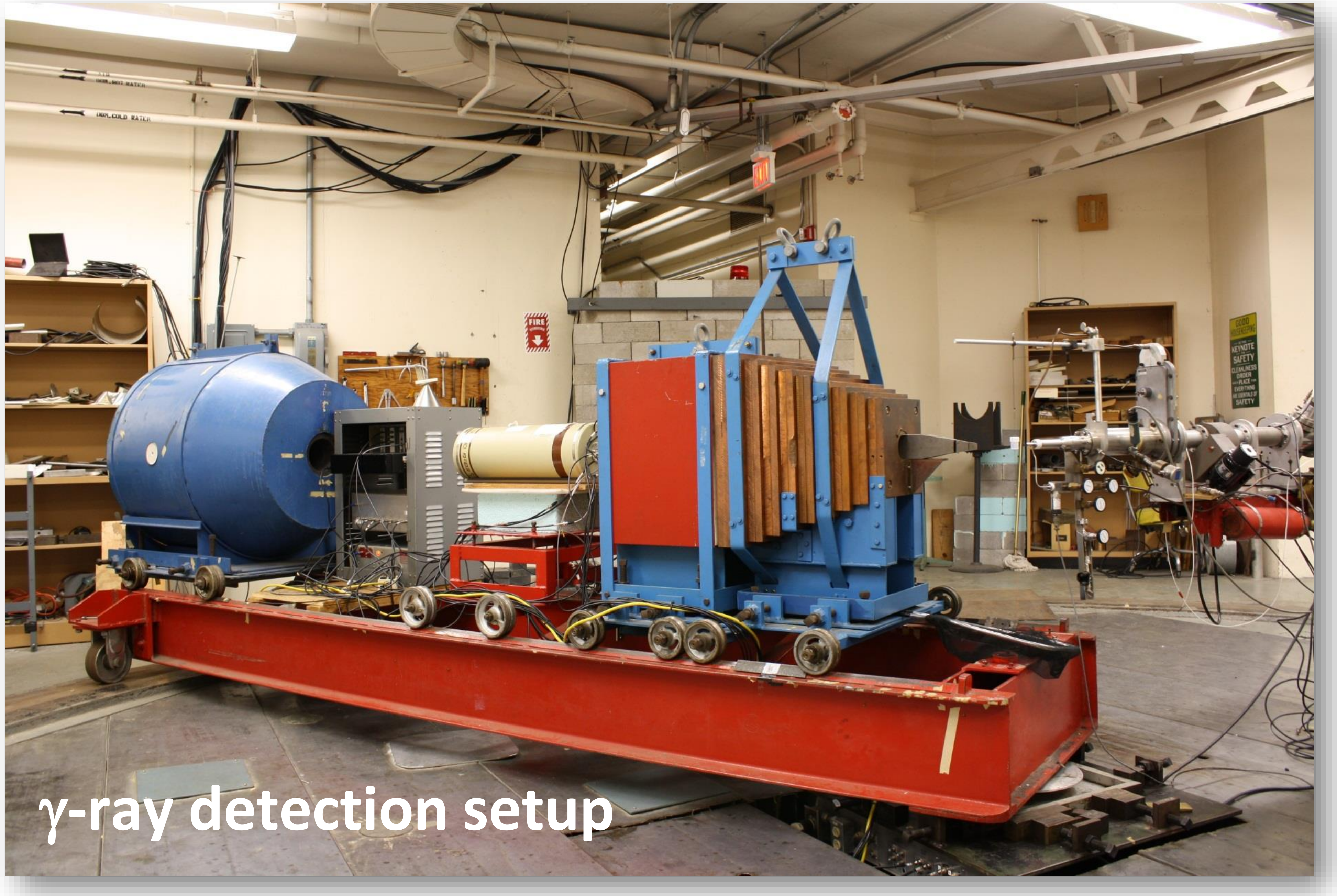
Source reactions for neutrons:

- $^3H(p,n)^3He$, Q = –0.76 MeV,
  $E_n < 5.5$ MeV
- $^2H(d,n)^3He$, Q = 3.3 MeV,
  $E_n = 4 – 9$ MeV
- $^3H(d,n)^3He$, Q = 17.5 MeV,
  $E_n = 18 – 23$ MeV
- $\Delta E < 100$ keV
- Not a true beam, more of a cone



UKAL – Laboratory overview

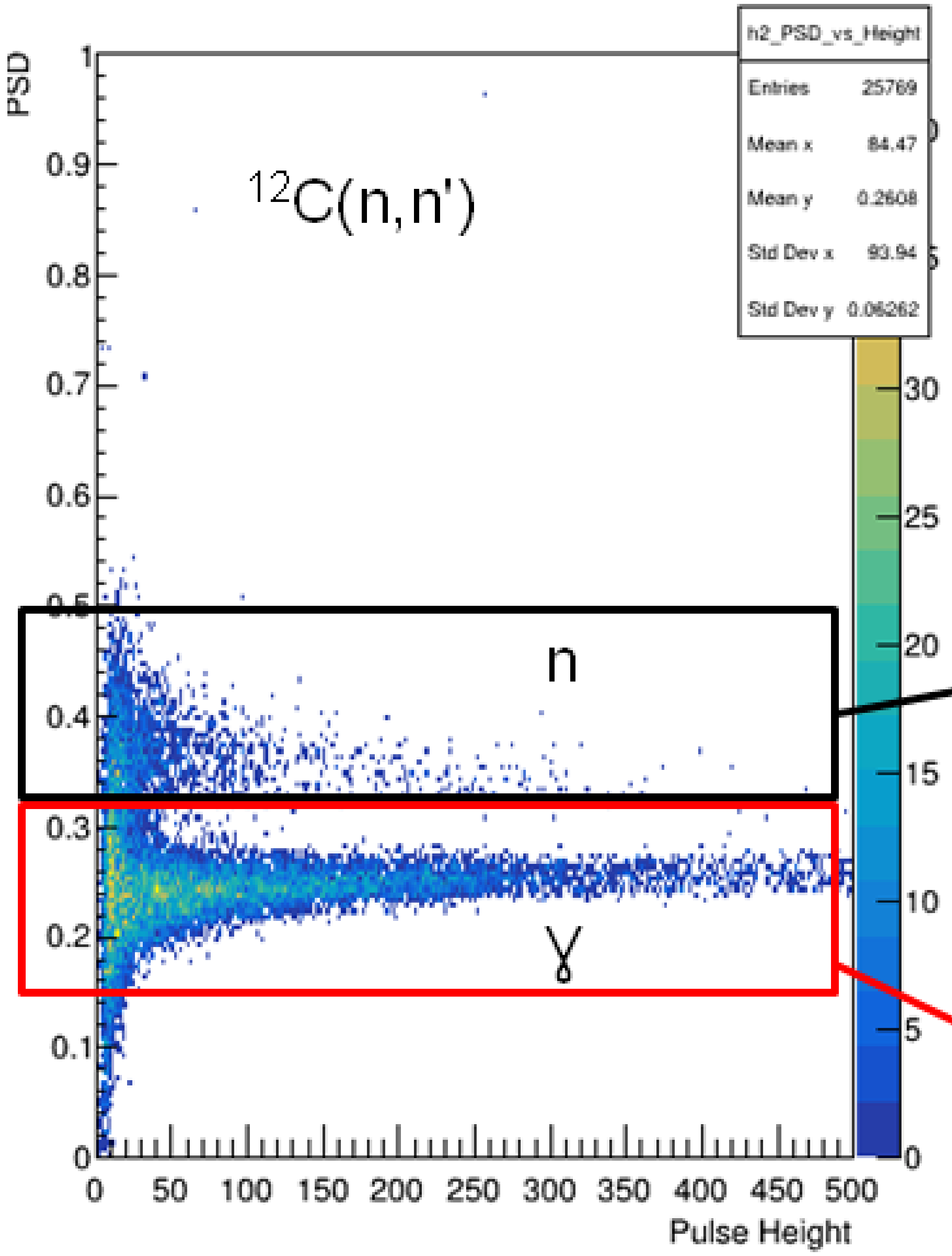
- Compton-suppressed HPGe
- Flux monitors: long counter, NE213
- More γ-ray work: S.F. Hicks, J.T.H. Dowie



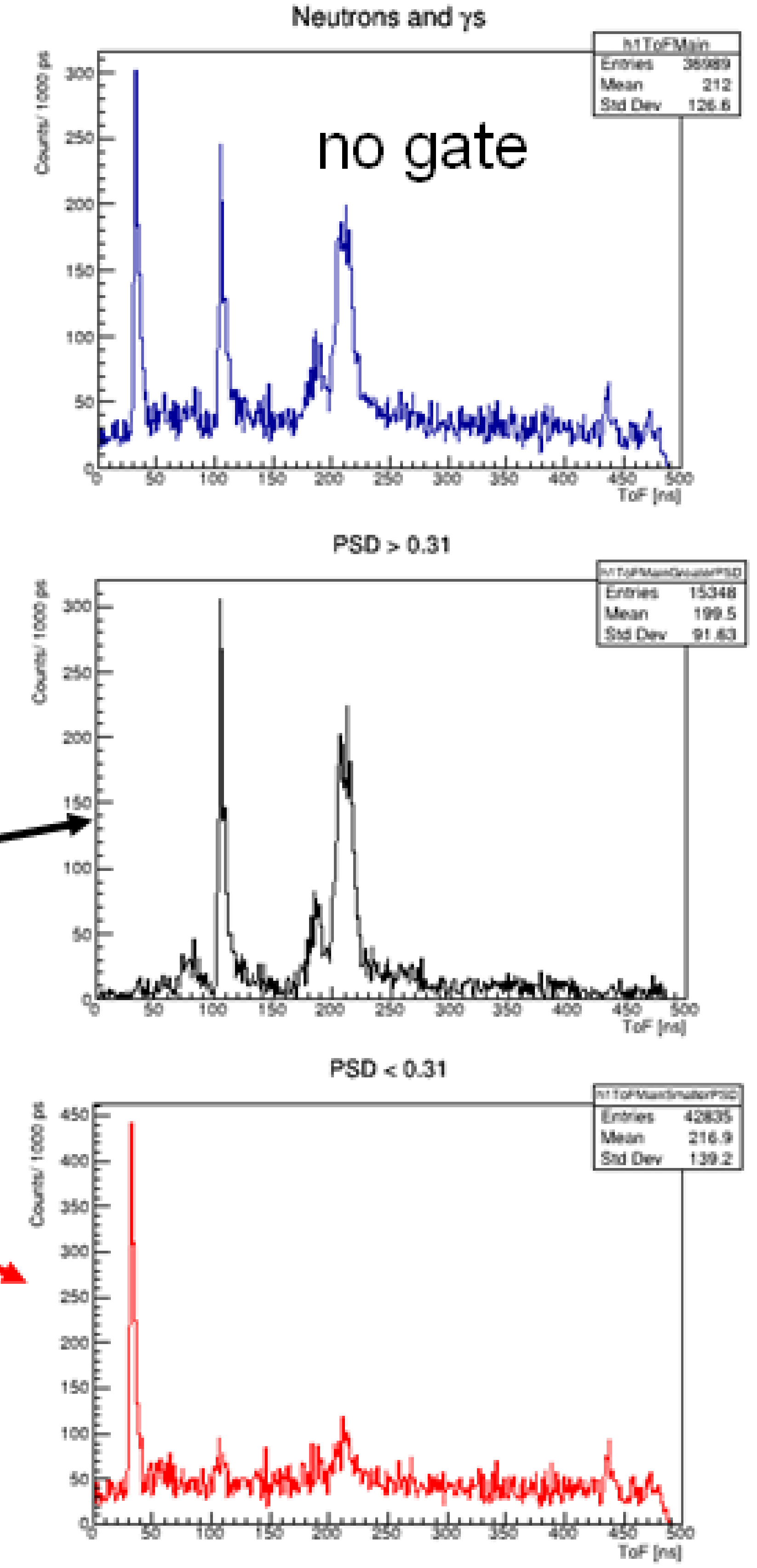
- n detection: Talk by J.R. Vanhoy
- TOF techniques with up to 4 m flight path
- C_6H_6 and C_6D_6 neutron detectors

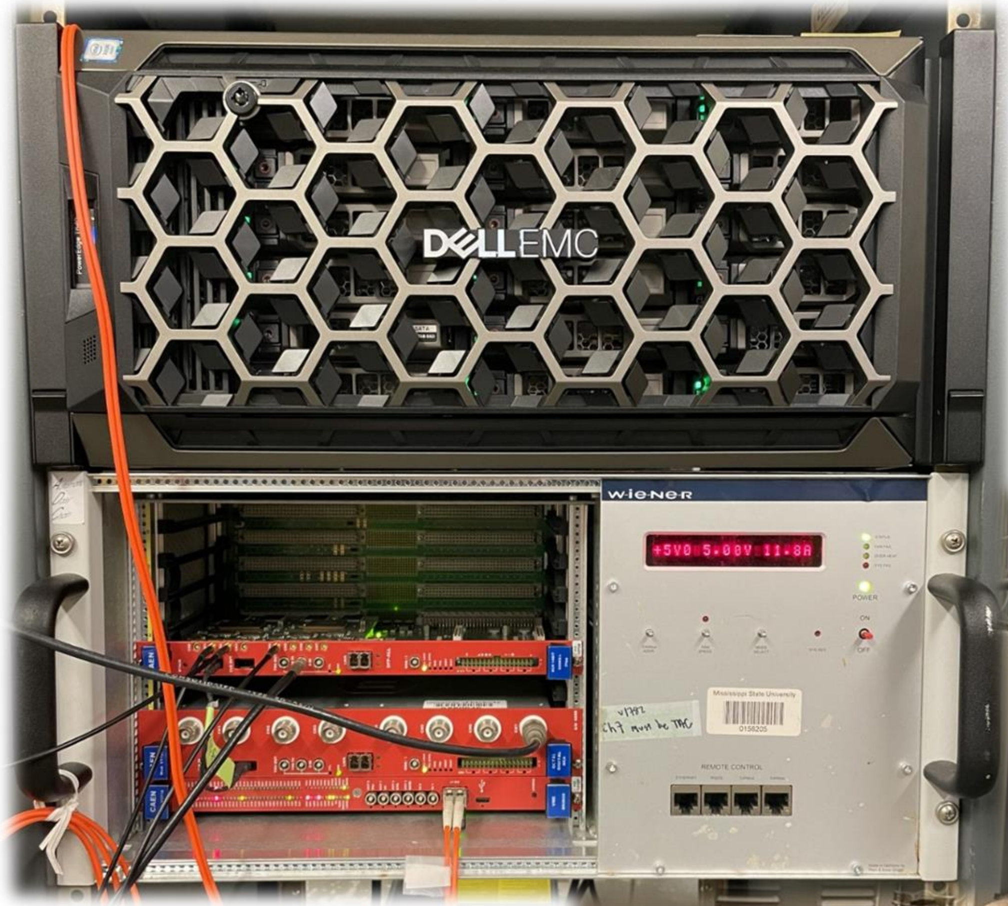
UKAL – Updated Capabilities

- New digital data acquisition system
- n detection PSD capabilities improved
- New γ-ray timing capabilities



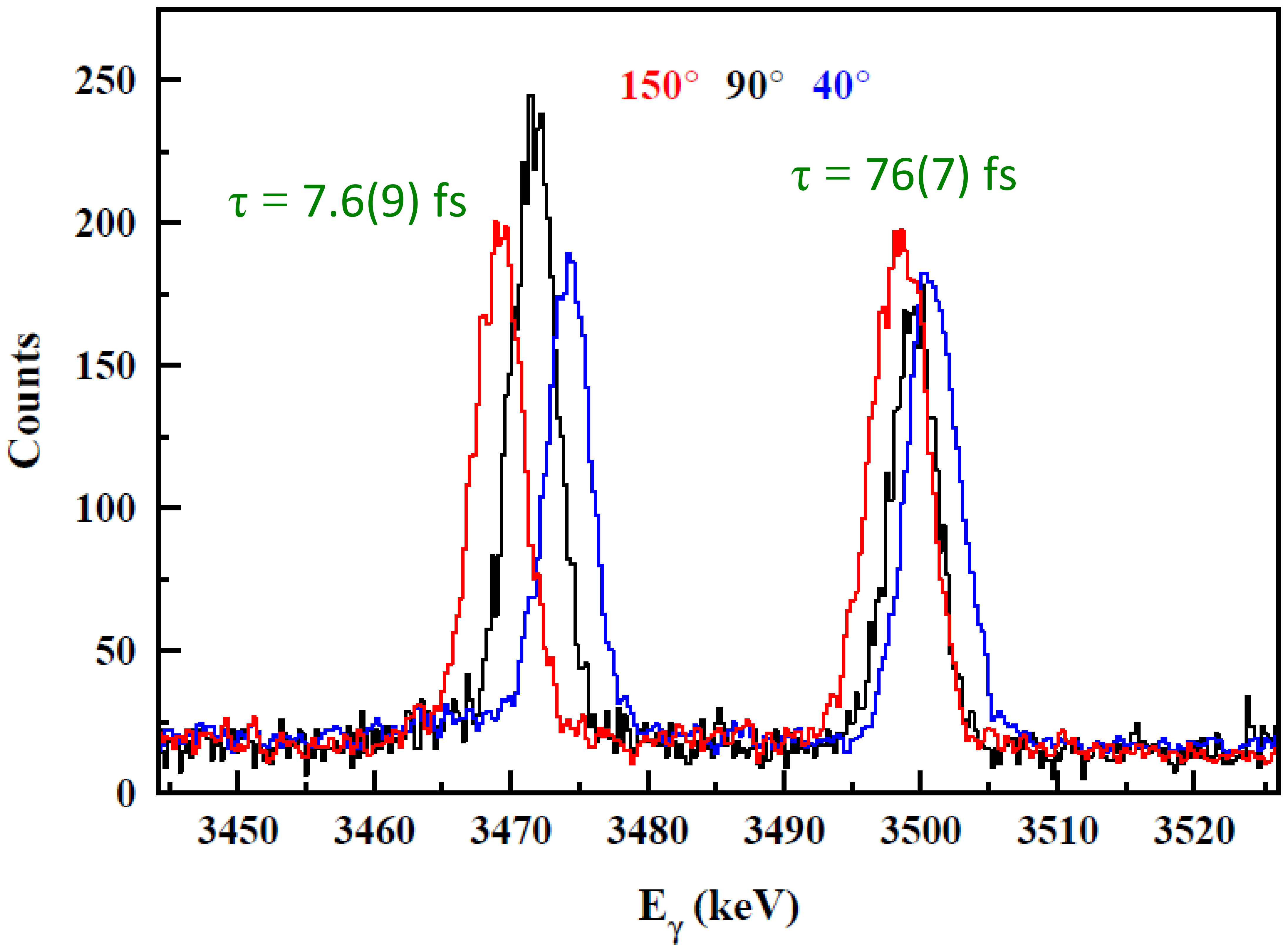
ToF = offset - (t_{Main} – $t_{Beam\ Pickoff}$) (ns)

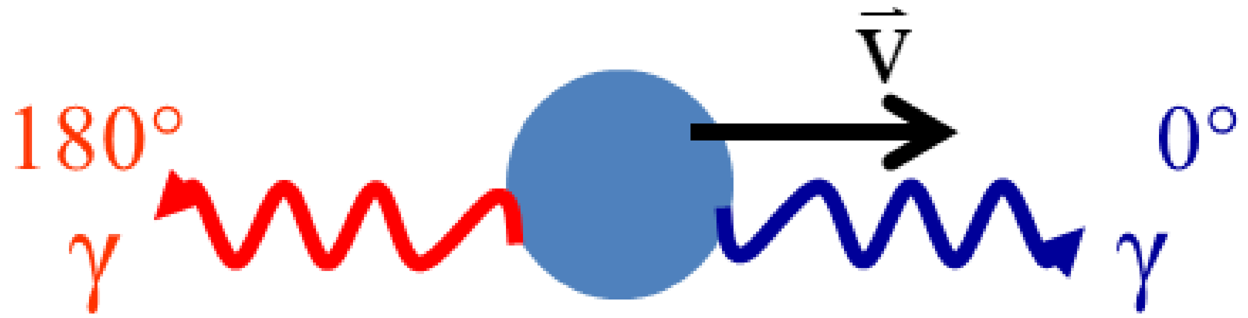




Yongchi Xiao

INS DSAM Lifetimes





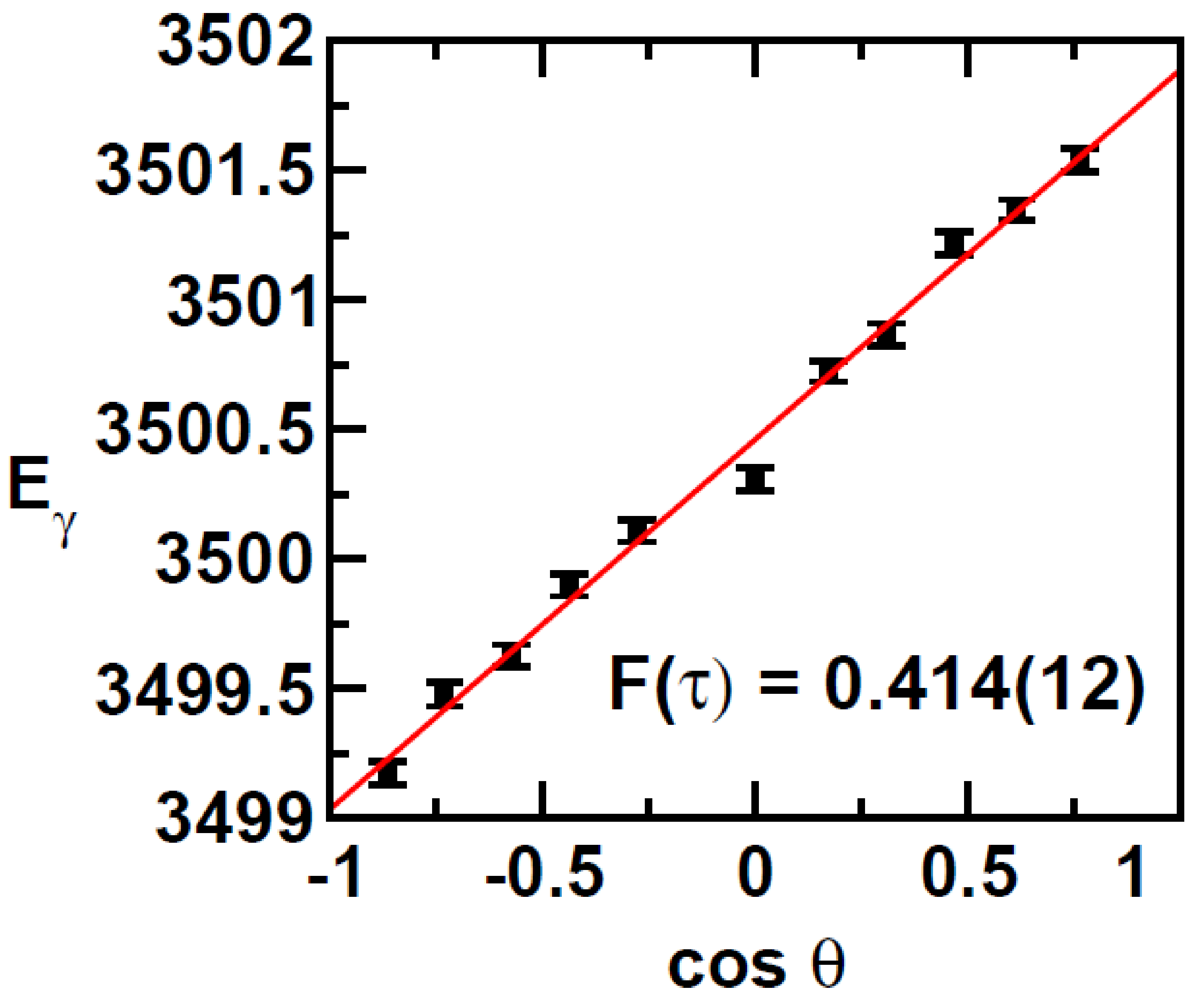
Scattered neutron causes the nucleus to recoil.

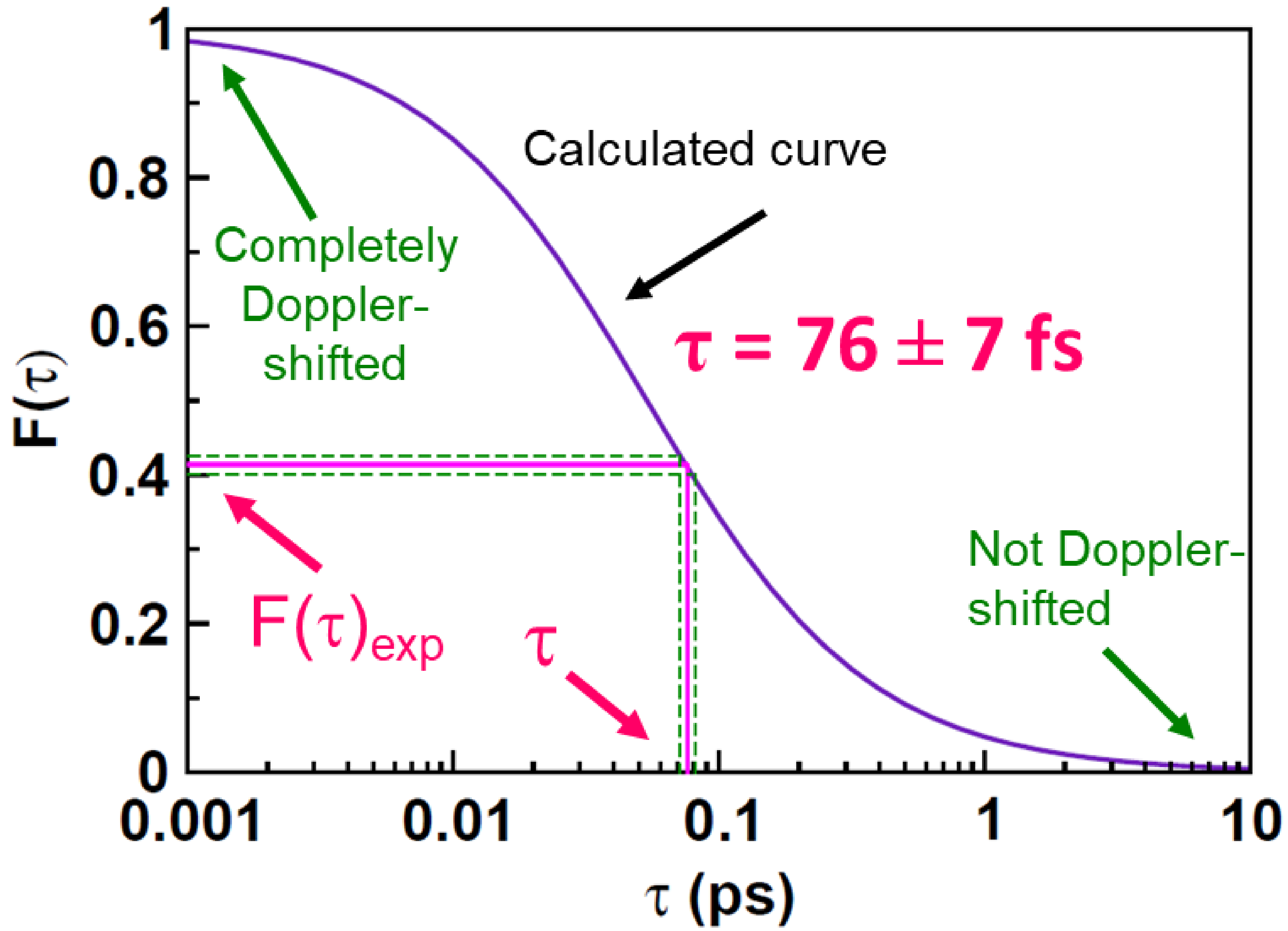
Emitted γ rays experience a Doppler shift.

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).

INS DSAM Lifetimes



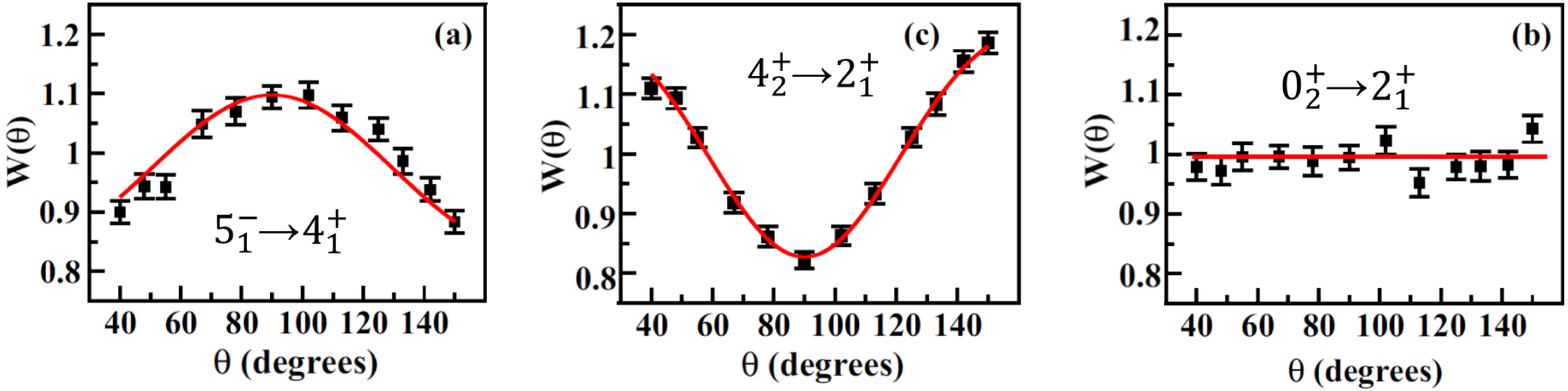


$$E_\gamma(\theta) = E_\gamma\left[1 + F_{exp}(\tau)\frac{v_{cm}}{c}\cos\theta\right]$$

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

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

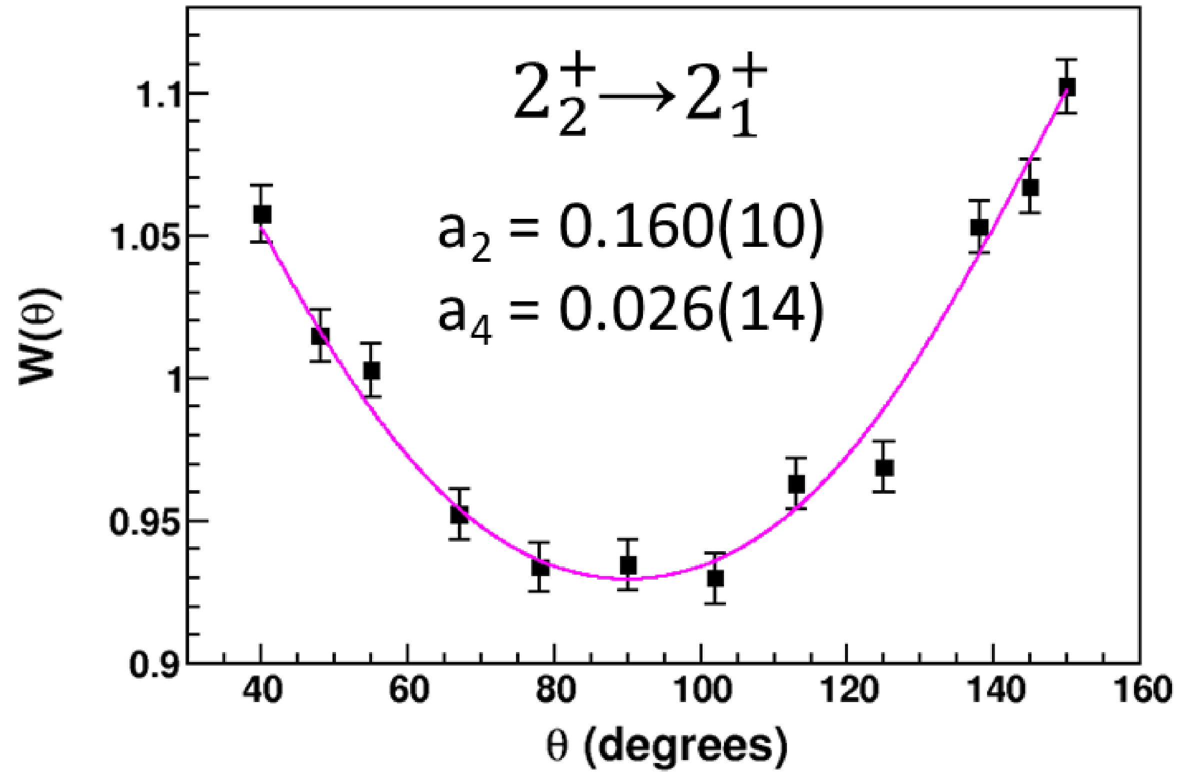
INS Angular Distributions

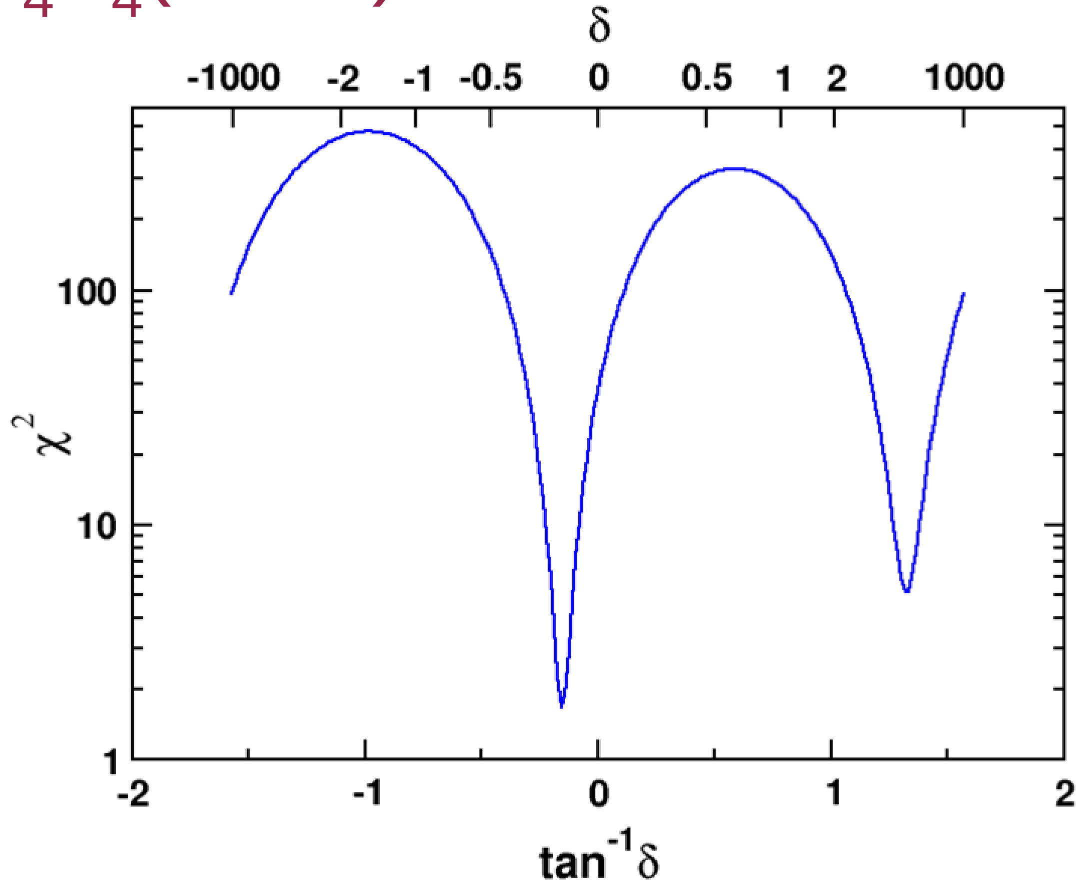


^{134}Xe

$$W(\theta) = 1 + a_2 P_2(\cos\theta) + a_4 P_4(\cos\theta)$$

Comparison with statistical model calculations to extract the E2/M1 mixing ratio



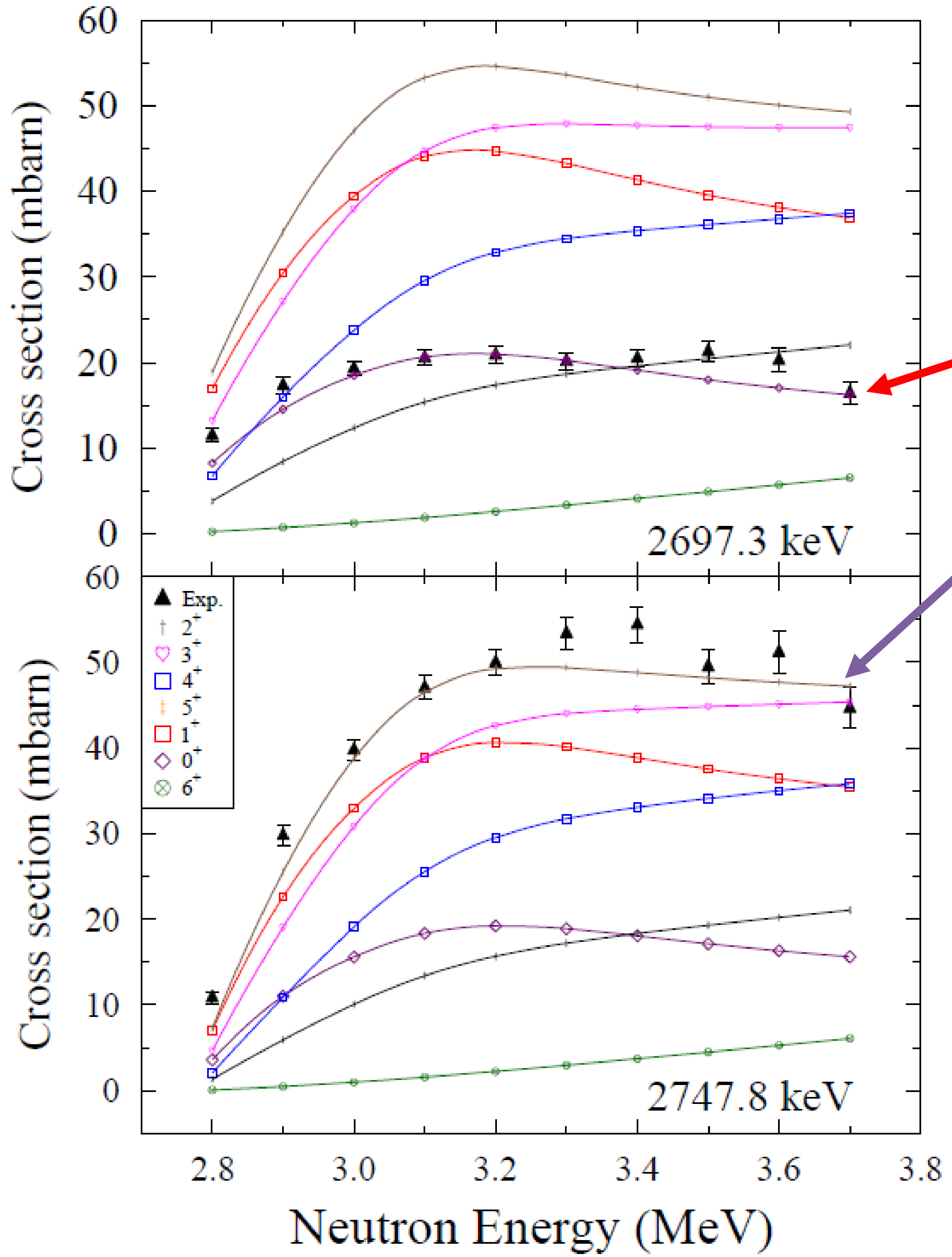


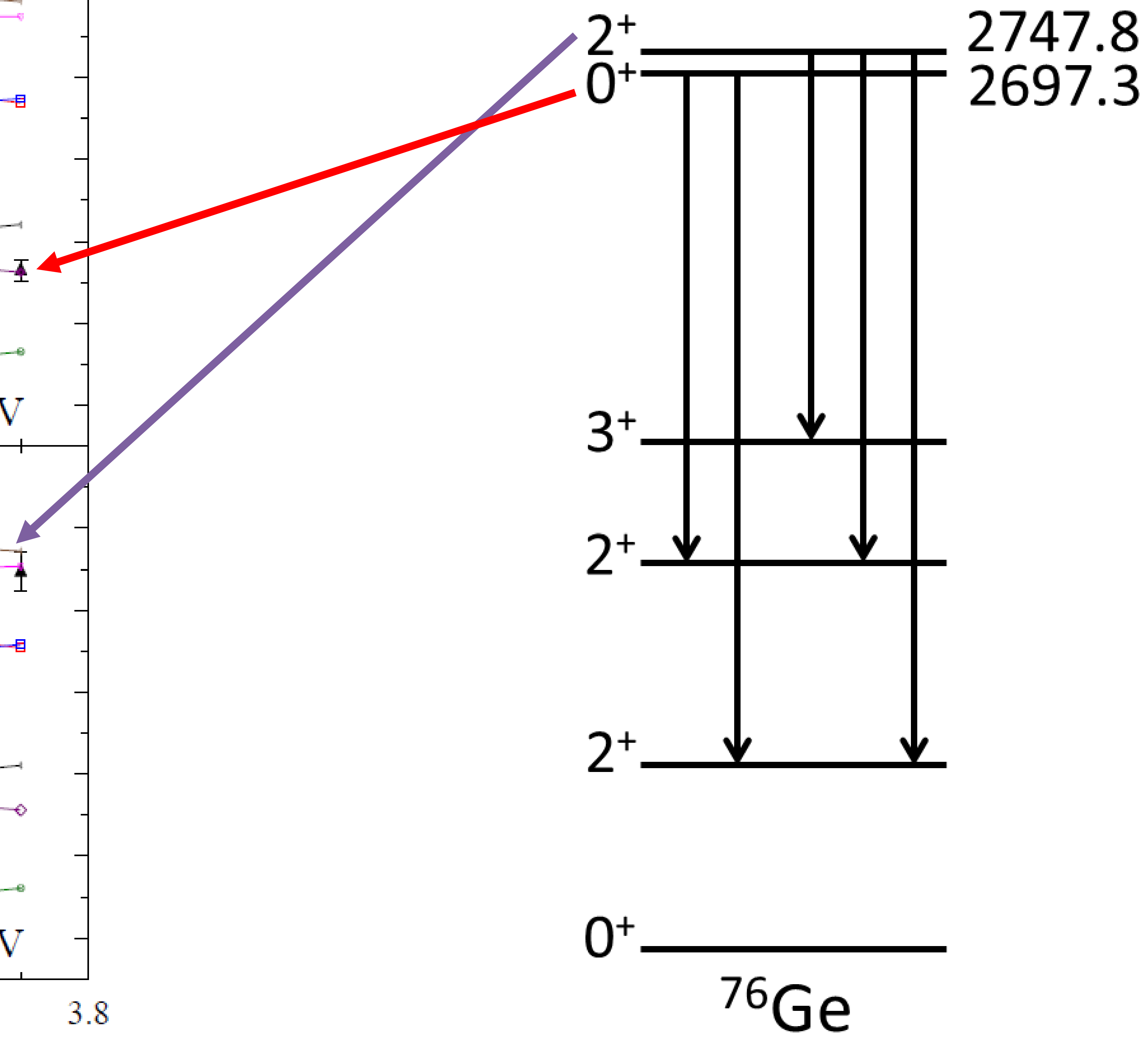
^{56}Fe

$$\delta = -0.155^{+13}_{-20}$$

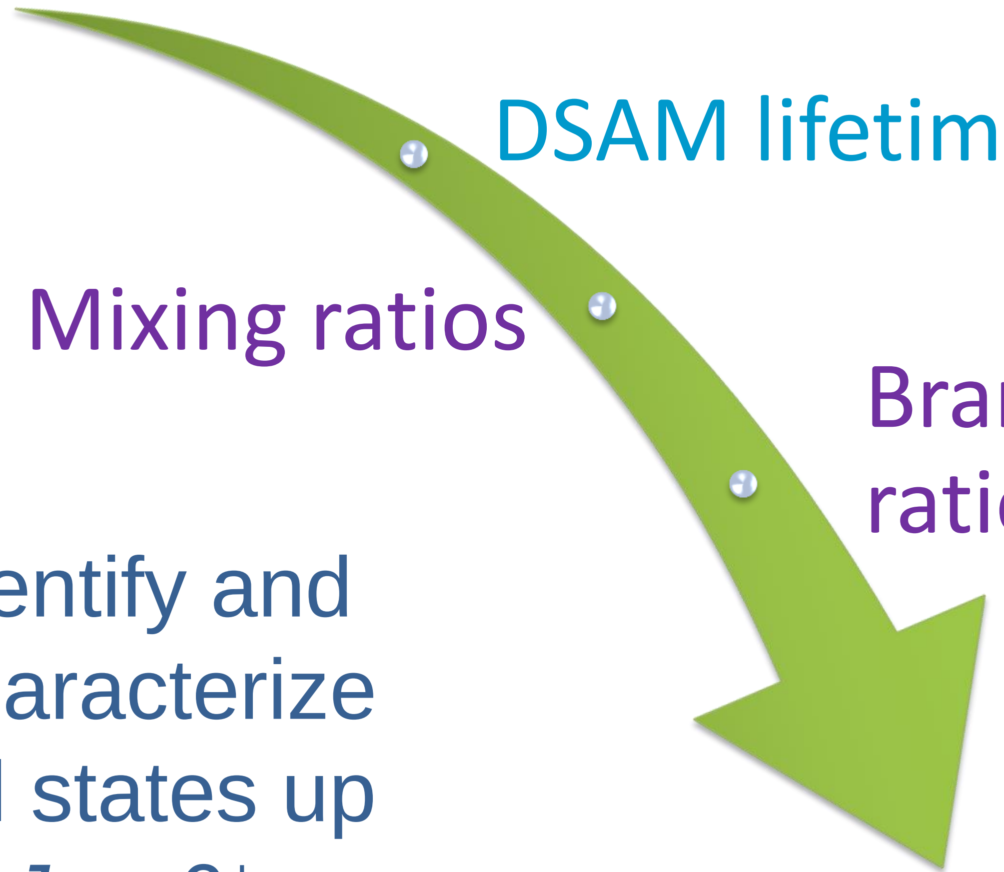
$$\delta(NNDC) = -0.18 \pm 0.01$$

INS Excitation Functions





UKAL – Inelastic Neutron Scattering



Identify and characterize **all** states up to $J^{\pi} = 6^{+}$

Transition probabilities for:

- Constraining $0\nu\beta\beta$ nuclear matrix element calculations
- Identifying shape coexistence

Inelastic Neutron Scattering Advantages:

- **No Coulomb barrier**
- **Statistical population of all states up to ~J^{π} = 6**
- **Population of non-yrast states**
- **Level lifetimes (fs-ps) measured using the Doppler-shift attenuation method**
- **Multipole mixing ratios also measured from γ-ray angular distributions**
- **Eliminate erroneous states**

A Comprehensive Approach

- Identify **all** of the excited states up to some energy (*e.g.*, 3 MeV) in as many nuclei in the region as possible, but certainly those near the nucleus of interest.
- Eliminate the **erroneous states**.
  - States are populated statistically and non-selectively in INS.
  - Thus, we see population of states with J = 0 – 4 within ~100 keV incident E_n of the level energy and states with J = 5,6 within ~400 keV.
  - If we do not find at least the most intense γ ray(s) purportedly emitted from the state at the appropriate energies, we refute the level, labeling it an "erroneous state".
  - The γ ray is likely misplaced in the level scheme.
  - Coincidence data, while very helpful, are not generally required.
- Characterize **all** of the remaining states.
- Compare these data with theoretical model calculations.

Erroneous State Example

^{74}Ge: First 10 States
2006 ENSDF Evaluation

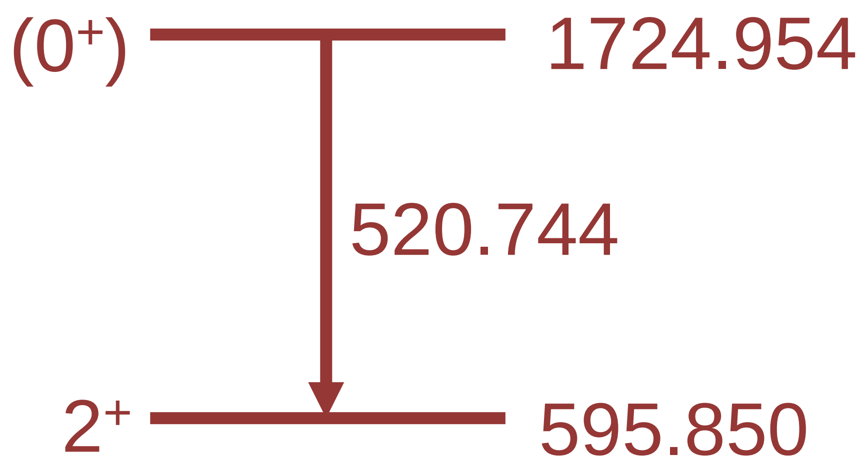
E_i(level)	J_i^π	E_γ	I_γ	E_f	J_f^π	Mult.†	δ	Comments
595.850	2^+	595.847 *6*	100	0.0	0^+	E2		B(E2)(W.u.)=33.0 *4* Mult.: from γ(pol,θ).
1204.205	2^+	608.353 *5*	100 *1*	595.850	2^+	E2+M1	+3.4 *4*	B(M1)(W.u.)=0.00099 *15*; B(E2)(W.u.)=43 *6* δ: from $\gamma\gamma(\theta)$ in ^{74}As ε decay. Other: +2.2 *3* from (n,n$'\gamma$).
		1204.208 *12*	46 *3*	0.0	0^+	E2		B(E2)(W.u.)=0.71 *11*
1463.759	4^+	867.898 *6*	100	595.850	2^+	E2		B(E2)(W.u.)=41 *3*
1482.81	0^+	887.19 *7*	100	595.850	2^+	E2		B(E2)(W.u.)=9 *+9−6*
		1482.6		0.0	0^+	E0		From ce data (1983Pa10). $I_{(\gamma+ce)}$: <0.006 from ^{74}As ε decay. q_K^2(E0/E2)<0.12, X(E0/E2)<0.052, ρ^2(E0)>0.032 (2005Ki02, evaluation).
1697.140	$(3)^+$	233.395 *12*	2.1 *2*	1463.759	4^+			
		492.936 *6*	58 *1*	1204.205	2^+	(M1+E2)	+1.3 *4*	δ: from $\gamma(\theta)$ in (n,n$'\gamma$) (1970Ch15). Other: 2.0 *+3−6* or 0.75 *+15−6* (1987Do14). Mult.: D+Q from $\gamma(\theta)$. ΔJ^π=no from placement in level scheme.
		1101.267 *12*	100 *1*	595.850	2^+	(M1+E2)	+0.34 *5*	δ: from $\gamma(\theta)$ in (n,n$'\gamma$) (1970Ch15). Other: 0.47 *5* (1987Do14). Mult.: D+Q from $\gamma(\theta)$. ΔJ^π=no from placement in level scheme.
1724.954	(0^+)	520.744 *12*	100	1204.205	2^+			
2165.259	$(3,4)^+$	468.11 *3*	6.5 *3*	1697.140	$(3)^+$			
		701.487 *6*	42.7 *3*	1463.759	4^+			
		961.055 *10*	100 *1*	1204.205	2^+	(M1(+E2))	0.01 *1*	δ: from $\gamma(\theta)$ in (n,n$'\gamma$) (1987Do14). Mult.: D+Q from $\gamma(\theta)$. ΔJ^π=no from placement in level scheme.
2197.933	2^+	715.17 *3*	35 *2*	1482.81	0^+			
		734.17 *4*	25 *4*	1463.759	4^+			
		993.67 *6*	100 *5*	1204.205	2^+	(E2+M1)	−2.8 *2*	δ: $\gamma\gamma(\theta)$ in ^{74}As ε. Mult from ΔJ^π. Mult.: D+Q from $\gamma(\theta)$. ΔJ^π=no from placement in level scheme.
		1602.0 *2*	45 *4*	595.850	2^+			
		2197.95 *8*	82 *10*	0.0	0^+			
2227.77	0^+	1021.9 *1*	38	1204.205	2^+			
		1631.89 *12*	100	595.850	2^+			
2403.5	1	2403.5 *4*		0.0	0^+			

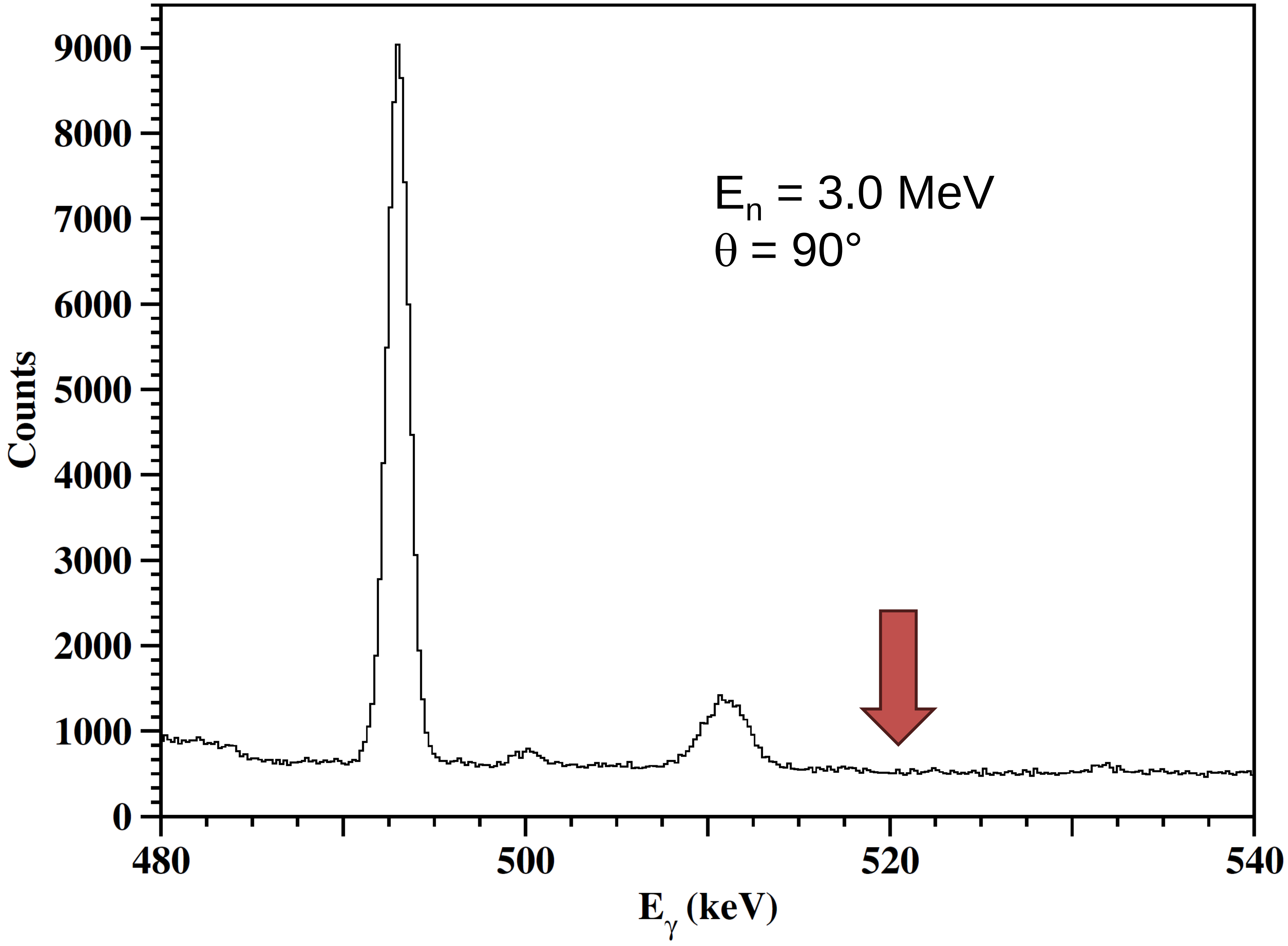
From ENSDF

Erroneous State Example

^{74}Ge

- Reported 520.744(12) keV γ ray from a 1724.954(14) keV (0^+) state





Erroneous State Example

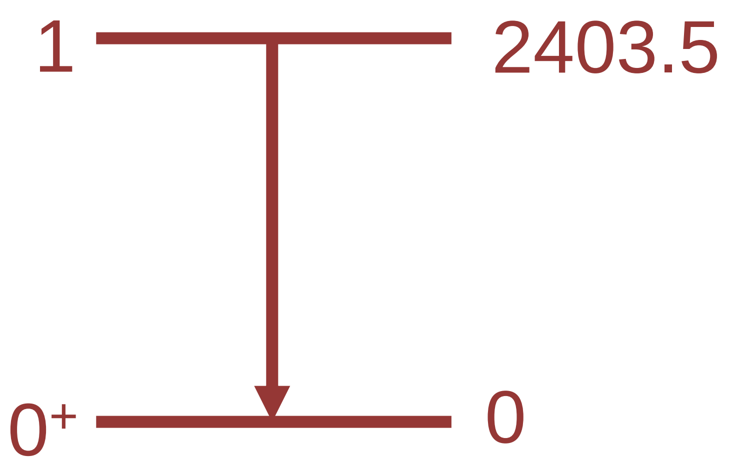
^{74}Ge: First 10 States 2006 ENSDF Evaluation

E_i(level)	J_i^π	E_γ	I_γ	E_f	J_f^π	Mult.†	δ	Comments
595.850	2^+	595.847 *6*	100	0.0	0^+	E2		B(E2)(W.u.)=33.0 *4* Mult.: from γ(pol,θ).
1204.205	2^+	608.353 *5*	100 *1*	595.850	2^+	E2+M1	+3.4 *4*	B(M1)(W.u.)=0.00099 *15*; B(E2)(W.u.)=43 *6* δ: from $\gamma\gamma(\theta)$ in ^{74}As ε decay. Other: +2.2 *3* from (n,n′γ).
		1204.208 *12*	46 *3*	0.0	0^+	E2		B(E2)(W.u.)=0.71 *11*
1463.759	4^+	867.898 *6*	100	595.850	2^+	E2		B(E2)(W.u.)=41 *3*
1482.81	0^+	887.19 *7*	100	595.850	2^+	E2		B(E2)(W.u.)=9 +*9*−*6*
		1482.6		0.0	0^+	E0		From ce data (1983Pa10). $I_{(\gamma+ce)}$: <0.006 from ^{74}As ε decay. q_K^2(E0/E2)<0.12, X(E0/E2)<0.052, ρ^2(E0)>0.032 (2005Ki02, evaluation).
1697.140	$(3)^+$	233.395 *12*	2.1 *2*	1463.759	4^+			
		492.936 *6*	58 *1*	1204.205	2^+	(M1+E2)	+1.3 *4*	δ: from $\gamma(\theta)$ in (n,n′γ) (1970Ch15). Other: 2.0 +*3*−*6* or 0.75 +*15*−*6* (1987Do14). Mult.: D+Q from $\gamma(\theta)$. ΔJ^π=no from placement in level scheme.
		1101.267 *12*	100 *1*	595.850	2^+	(M1+E2)	+0.34 *5*	δ: from $\gamma(\theta)$ in (n,n′γ) (1970Ch15). Other: 0.47 *5* (1987Do14). Mult.: D+Q from $\gamma(\theta)$. ΔJ^π=no from placement in level scheme.
1724.954	(0^+)	520.744 *12*	100	1204.205	2^+			
2165.259	$(3,4)^+$	468.11 *3*	6.5 *3*	1697.140	$(3)^+$			
		701.487 *6*	42.7 *3*	1463.759	4^+			
		961.055 *10*	100 *1*	1204.205	2^+	(M1(+E2))	0.01 *1*	δ: from $\gamma(\theta)$ in (n,n′γ) (1987Do14). Mult.: D+Q from $\gamma(\theta)$. ΔJ^π=no from placement in level scheme.
2197.933	2^+	715.17 *3*	35 *2*	1482.81	0^+			
		734.17 *4*	25 *4*	1463.759	4^+			
		993.67 *6*	100 *5*	1204.205	2^+	(E2+M1)	−2.8 *2*	δ: $\gamma\gamma(\theta)$ in ^{74}As ε. Mult from ΔJ^π. Mult.: D+Q from $\gamma(\theta)$. ΔJ^π=no from placement in level scheme.
		1602.0 *2*	45 *4*	595.850	2^+			
		2197.95 *8*	82 *10*	0.0	0^+			
2227.77	0^+	1021.9 *1*	38	1204.205	2^+			
		1631.89 *12*	100	595.850	2^+			
2403.5	1	2403.5 *4*		0.0	0^+			

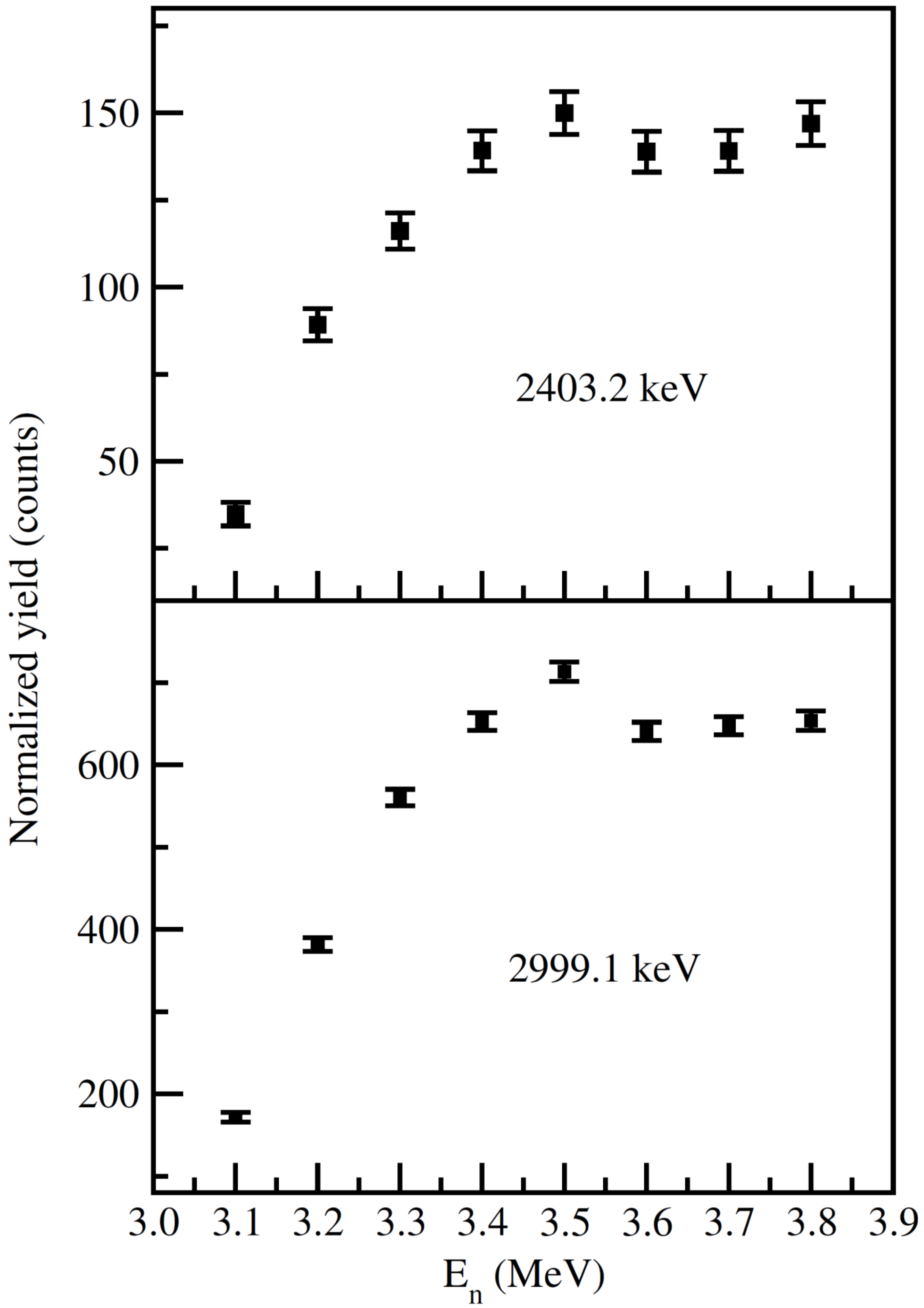
From ENSDF

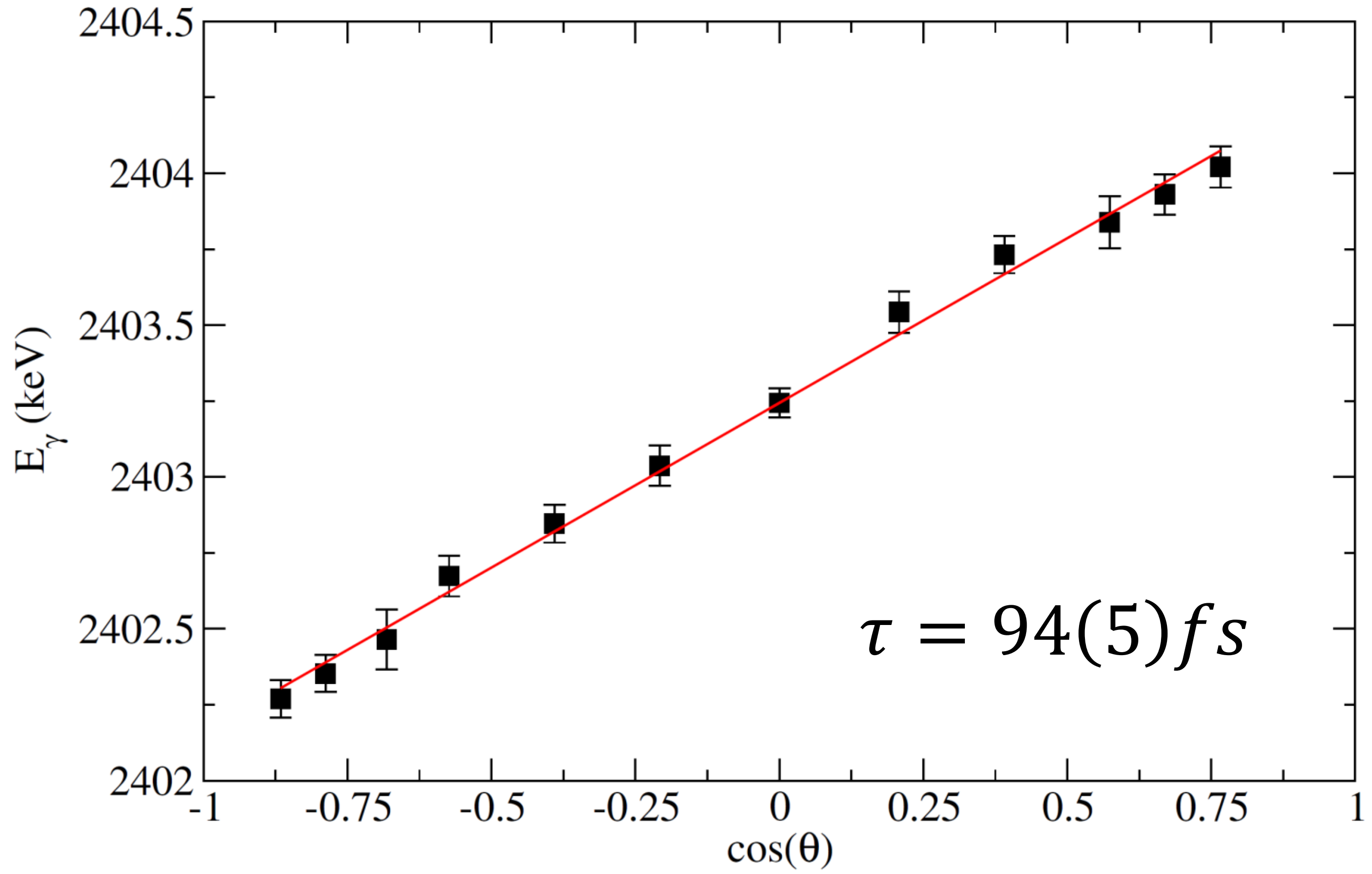
Erroneous State Example

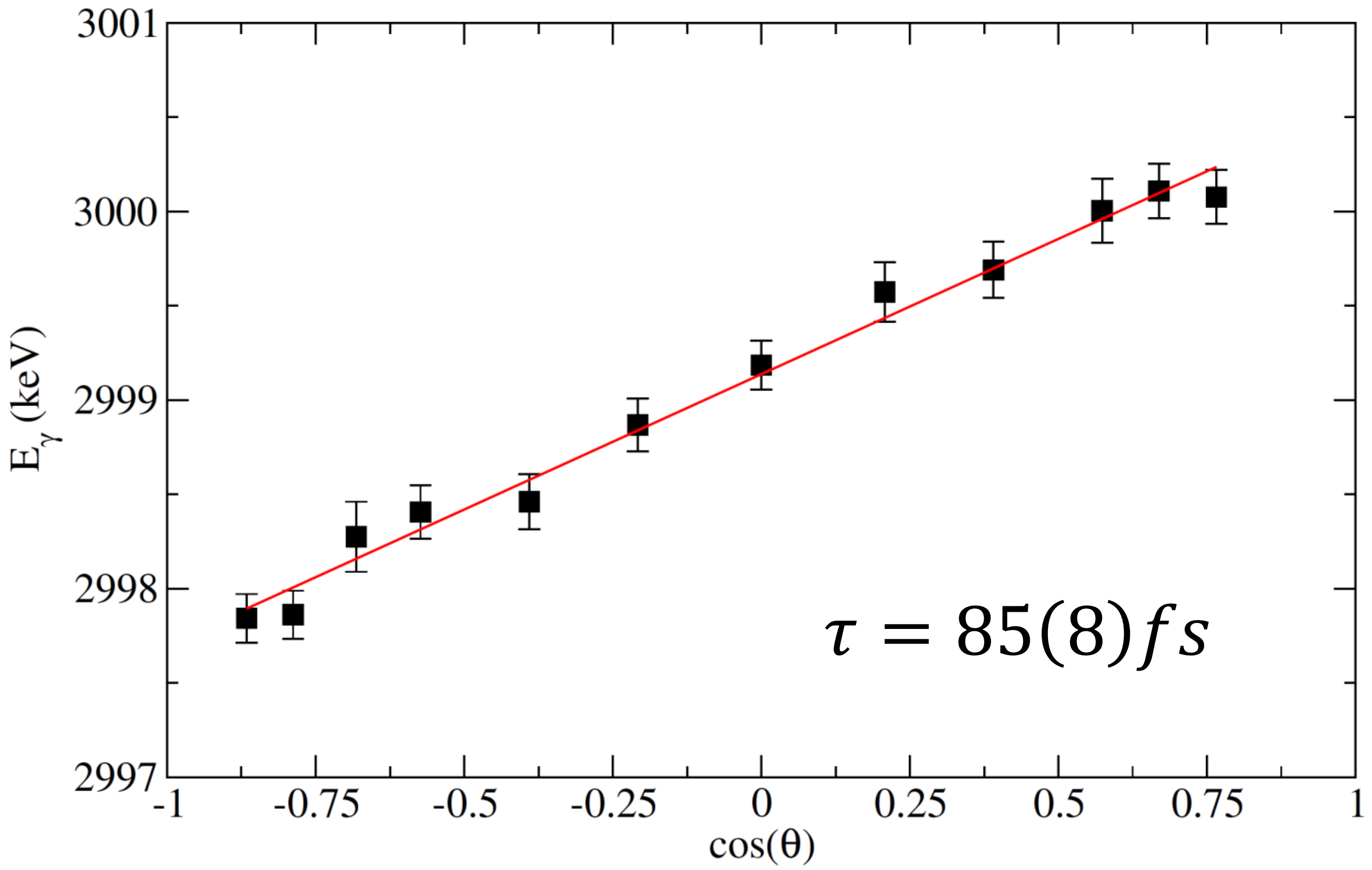
- **2403.5(4) keV γ ray was previously assigned as a ground-state transition from a spin-1 state in ^{74}Ge**



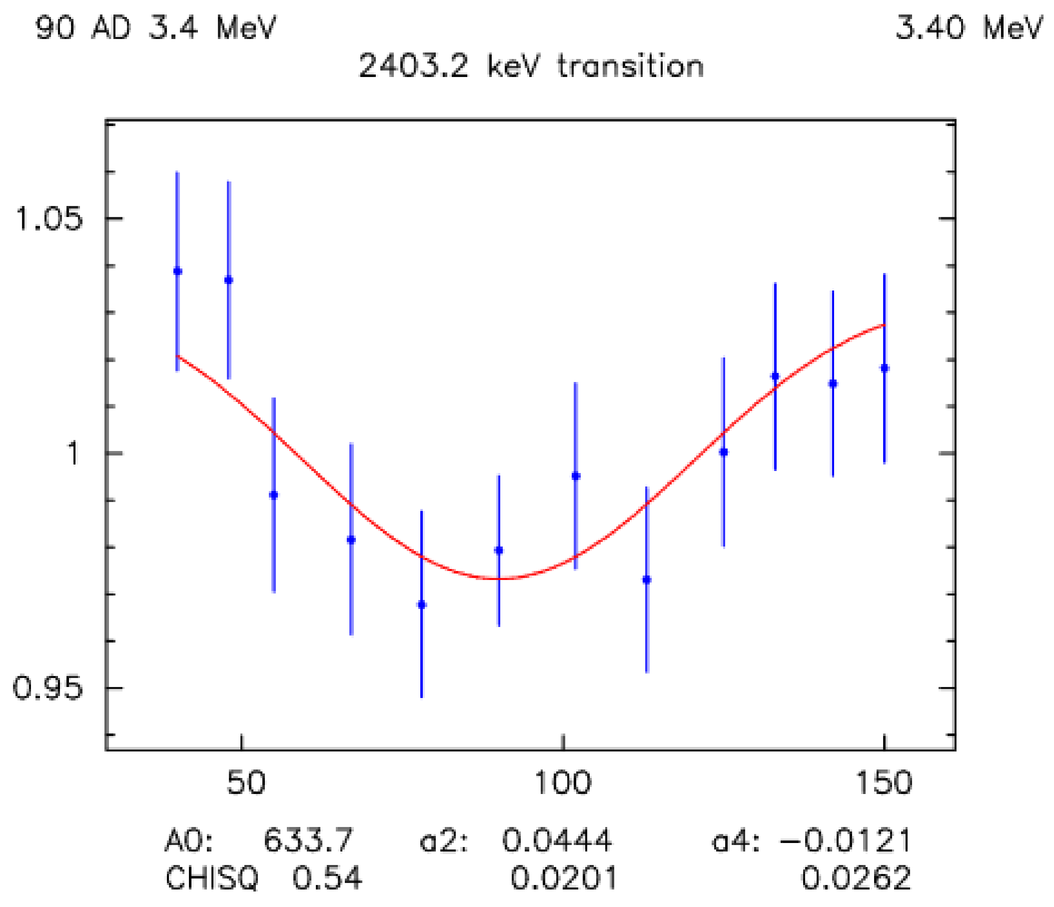
- **2999 keV γ ray is newly observed**

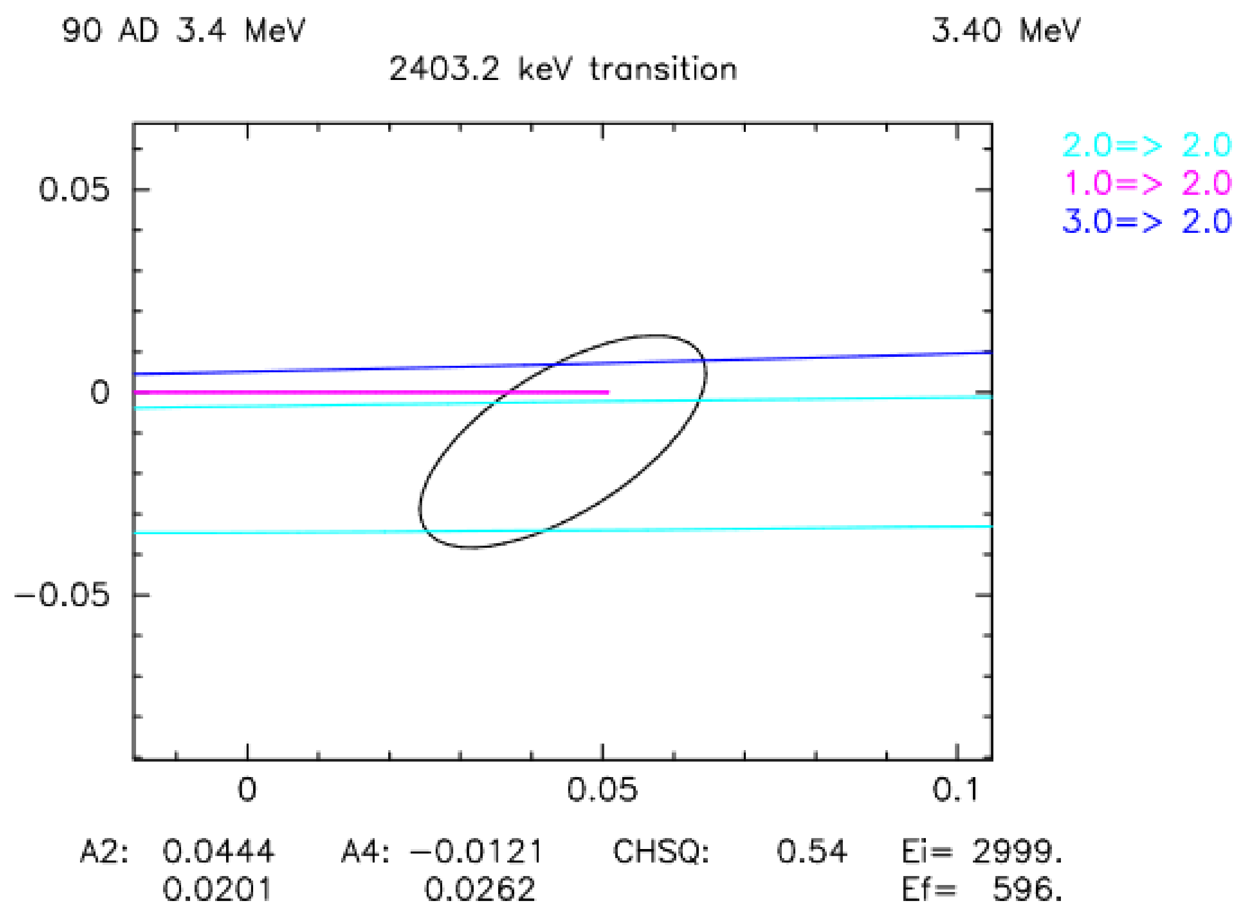


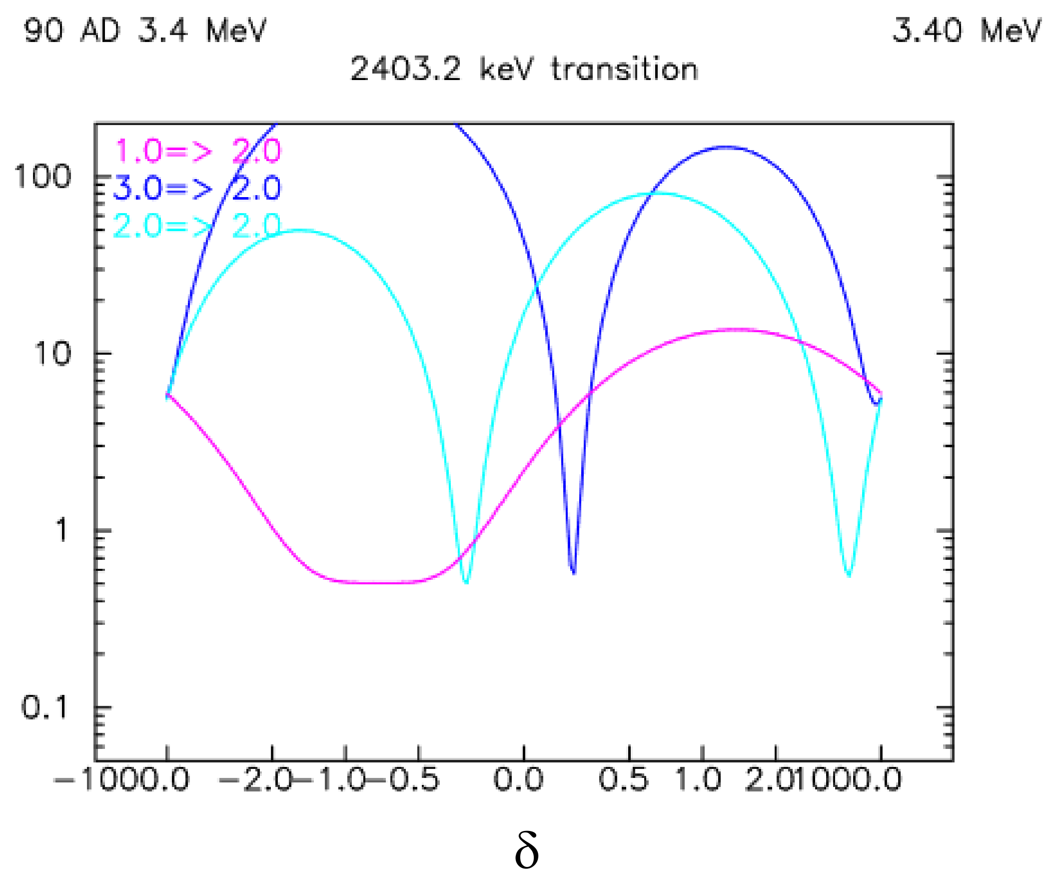


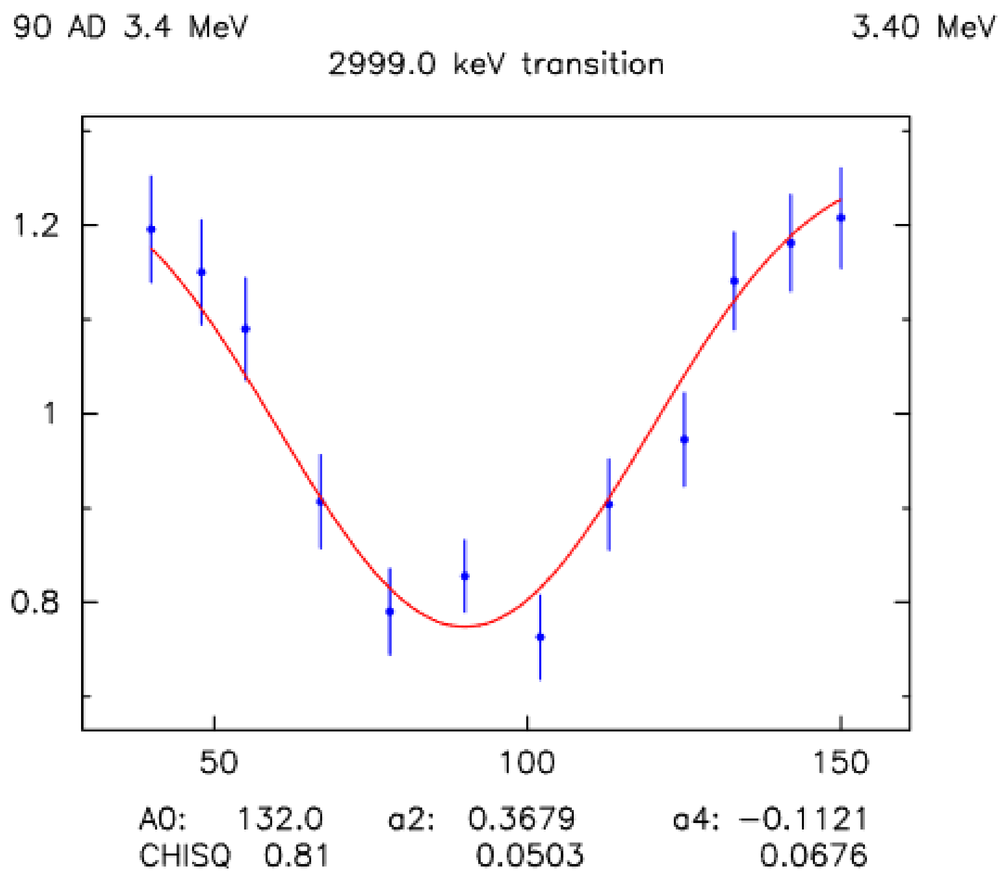


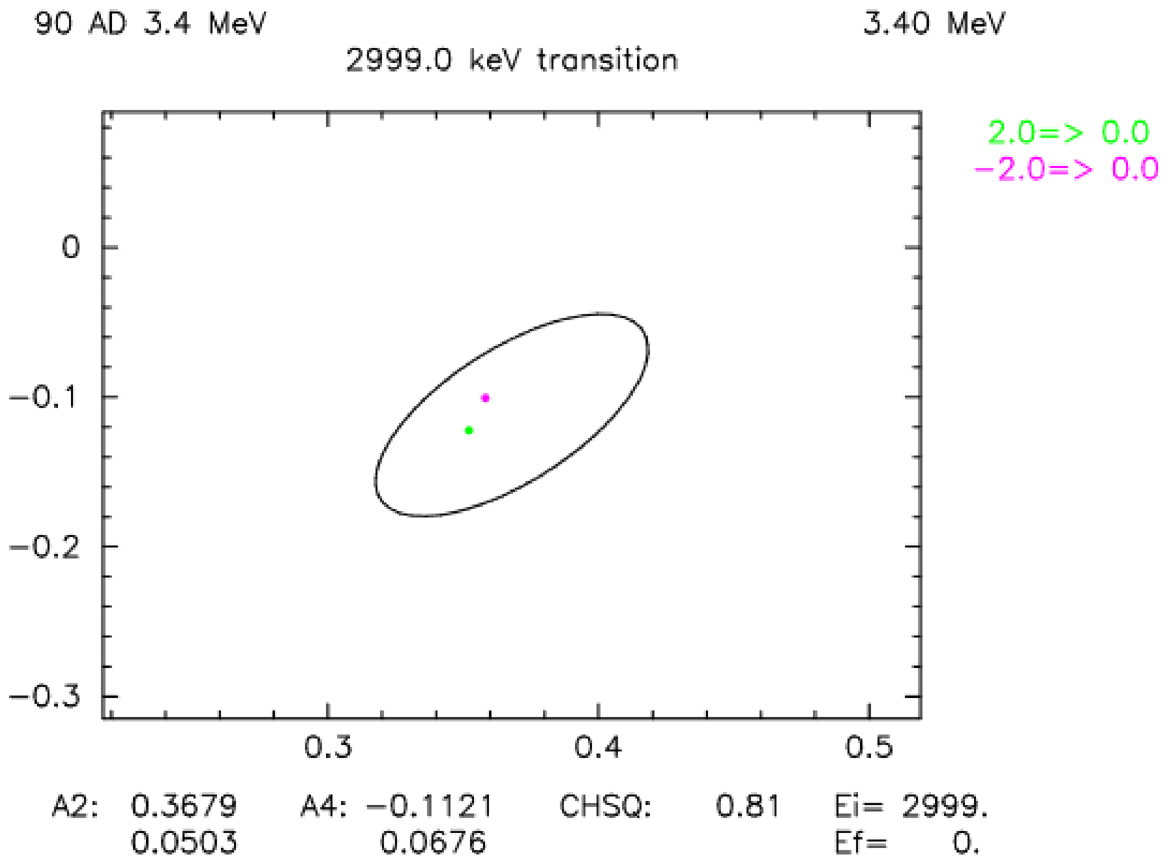
Erroneous State Example

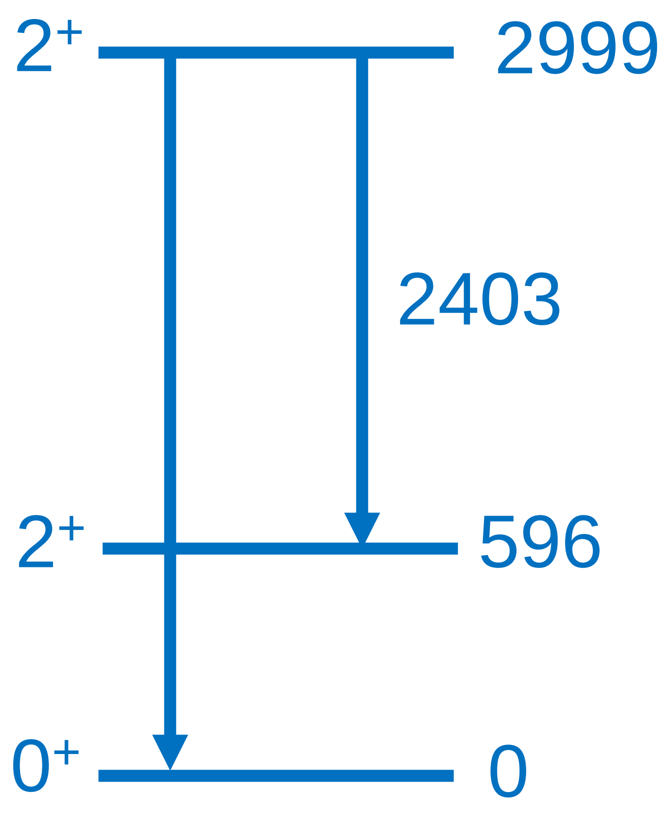










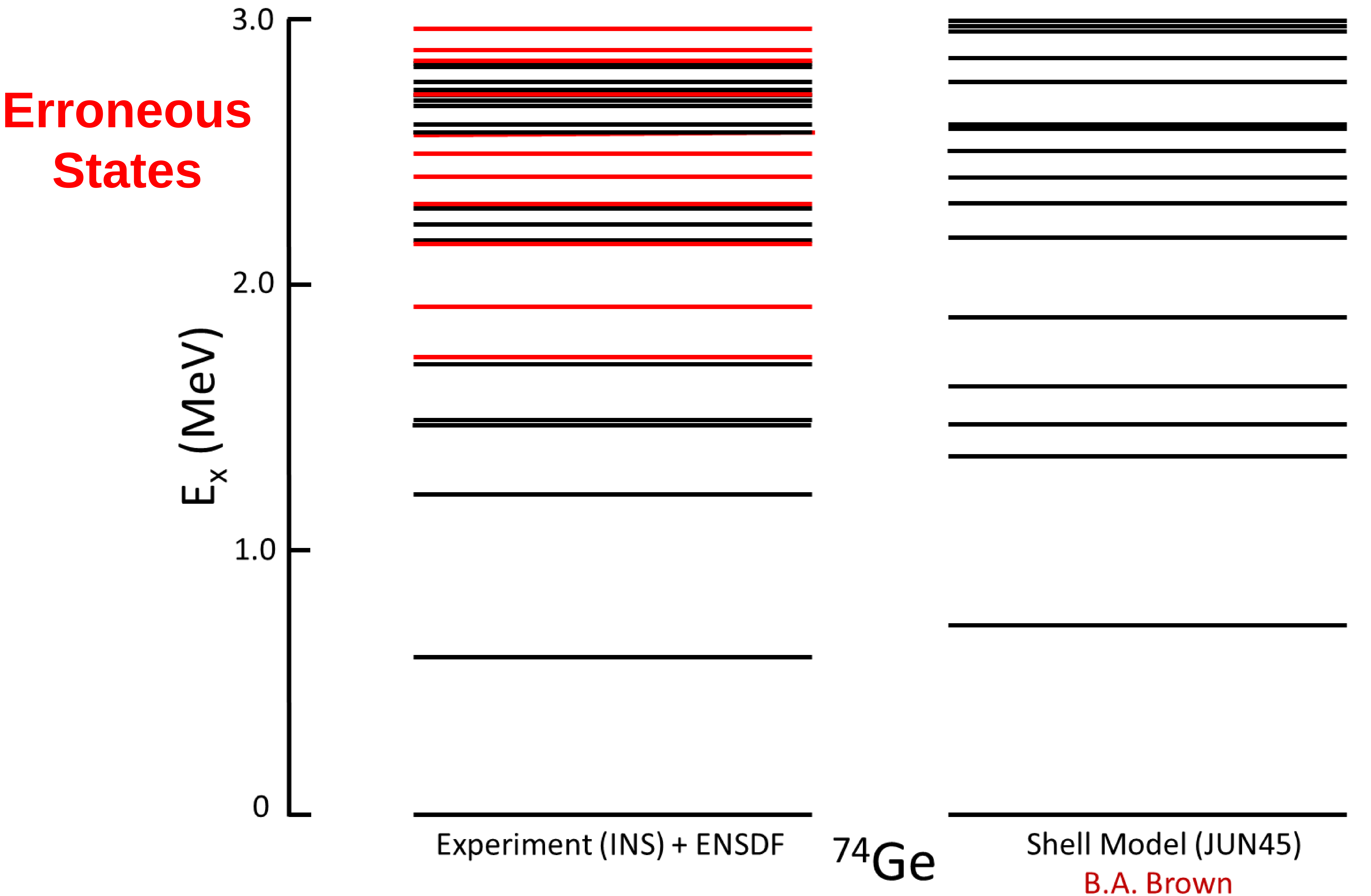


✓Excitation functions & thresholds
✓Lifetimes
✓Spins from angular distributions
✓Energies
= A consistent picture

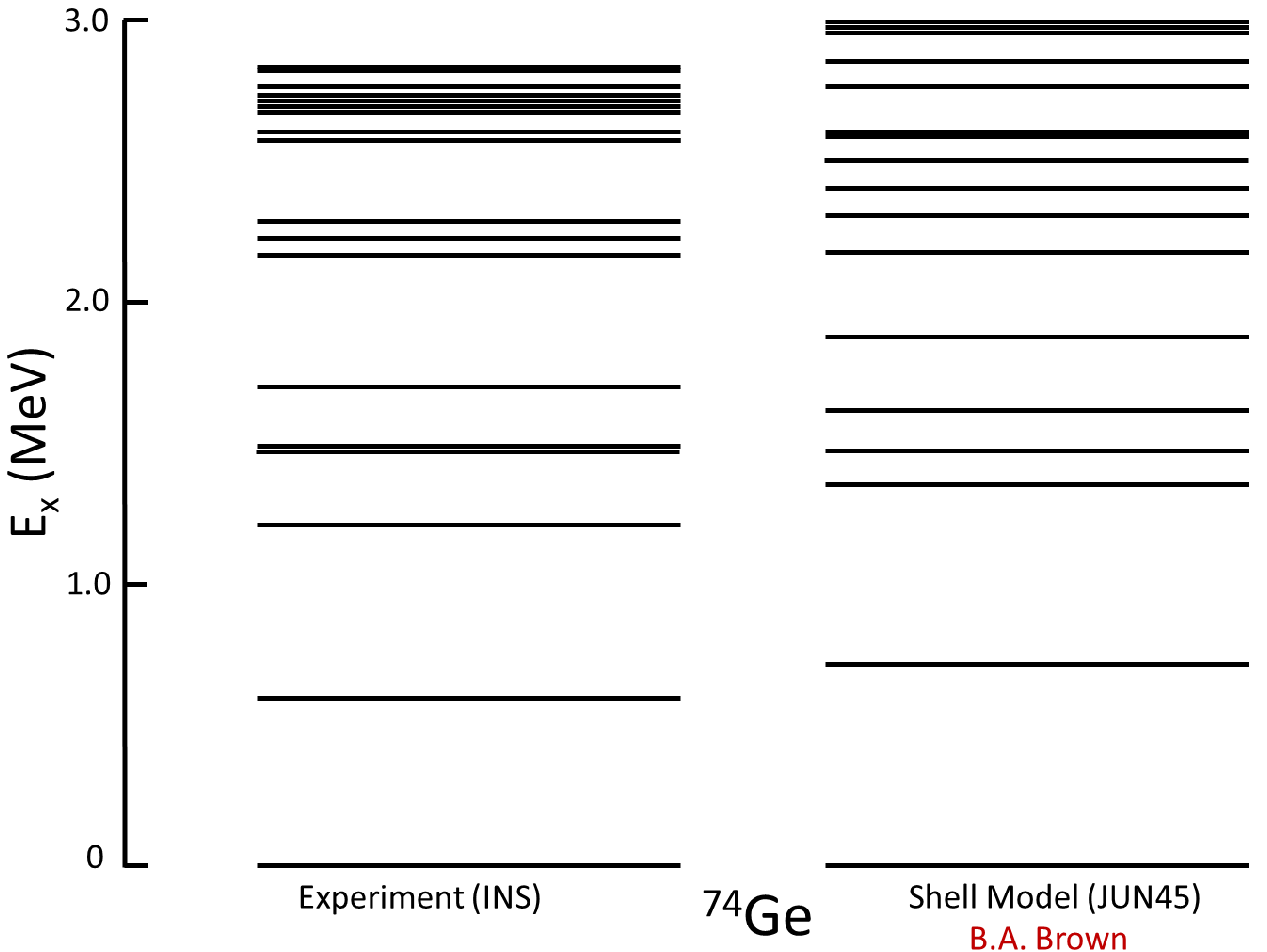
^{74}Ge(n,n`γ)


3.0
2.0
1.0
0
E_x (MeV)
Data
Theory
Experiment (INS) + ENSDF
^{74}Ge
Shell Model (JUN45)
B.A. Brown

^{74}Ge(n,n`γ)

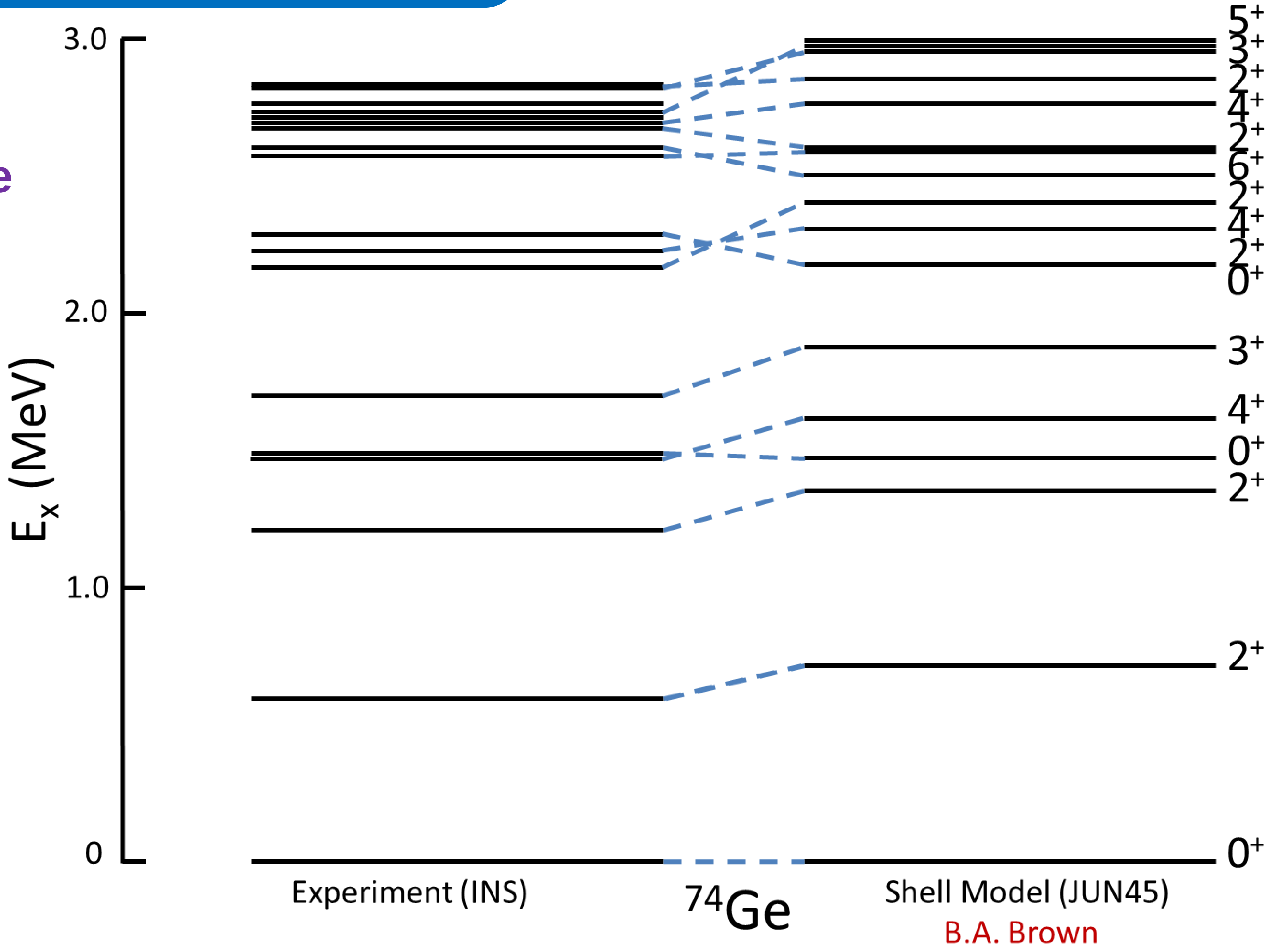

Erroneous States
3.0
2.0
1.0
0
E_x (MeV)
Experiment (INS) + ENSDF
^{74}Ge
Shell Model (JUN45)
B.A. Brown

$^{74}Ge(n,n`\gamma)$

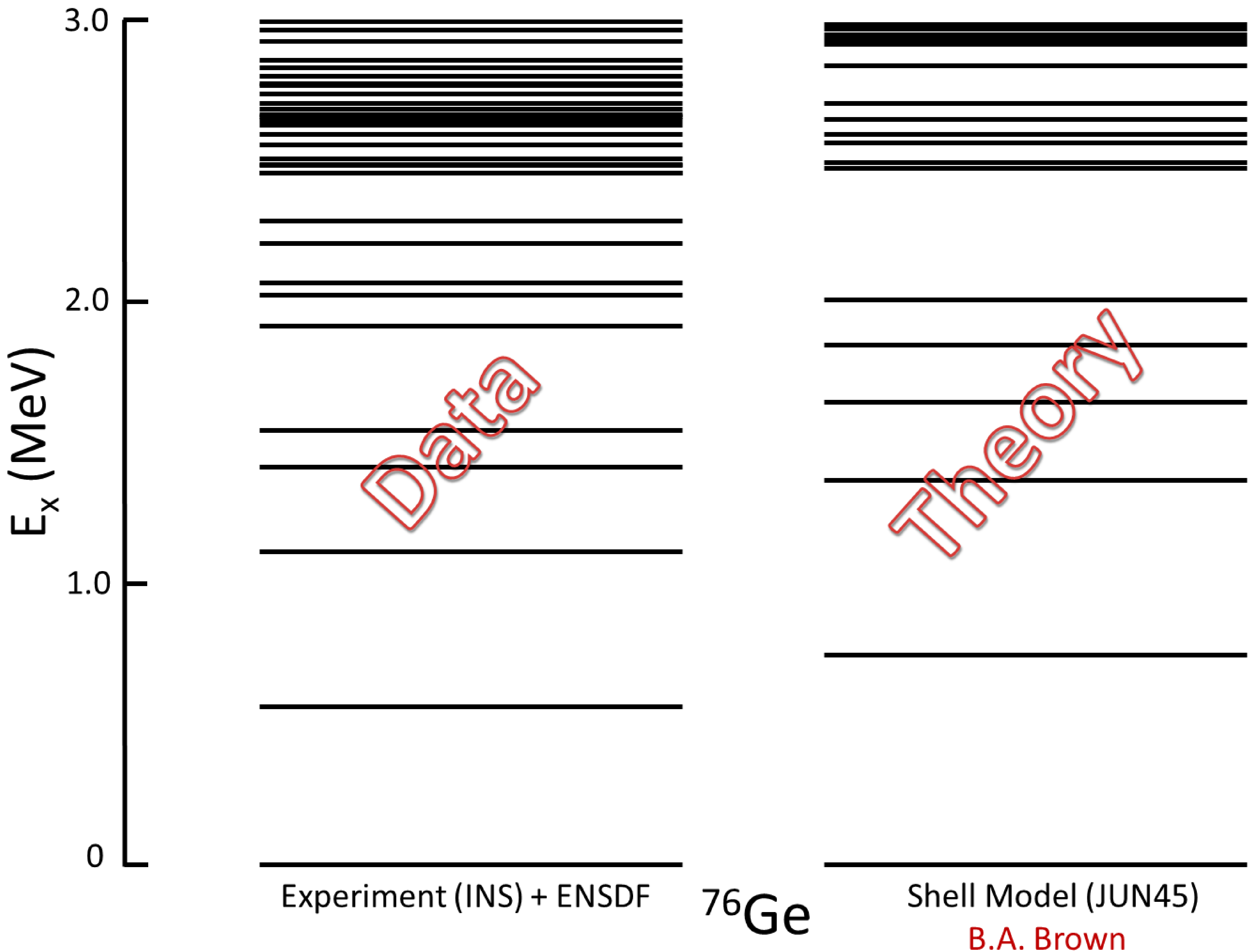


^{74}Ge(n,n`γ)

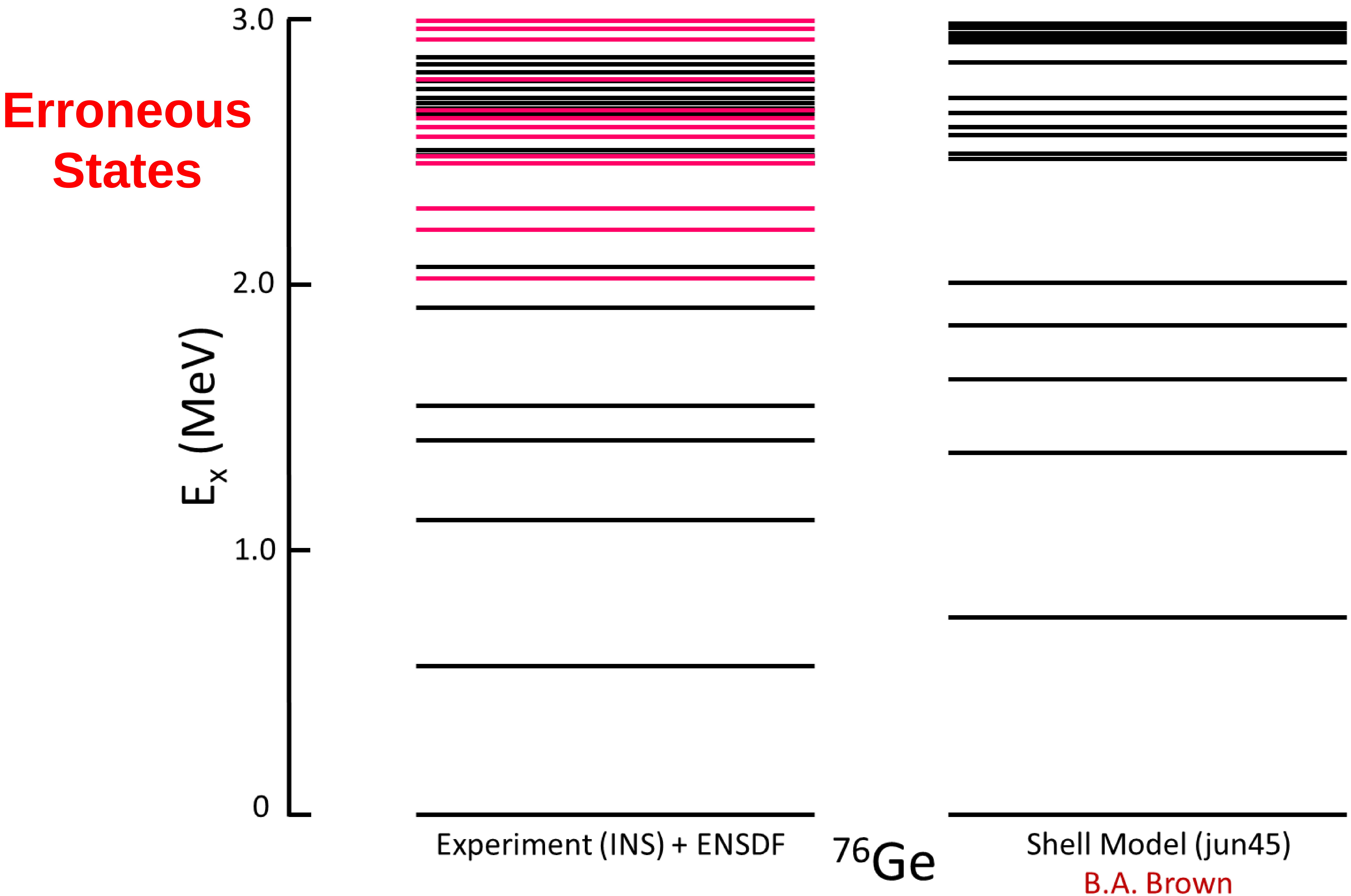
1-to-1 correspondence of theoretical & experimental levels up to ~2.8 MeV



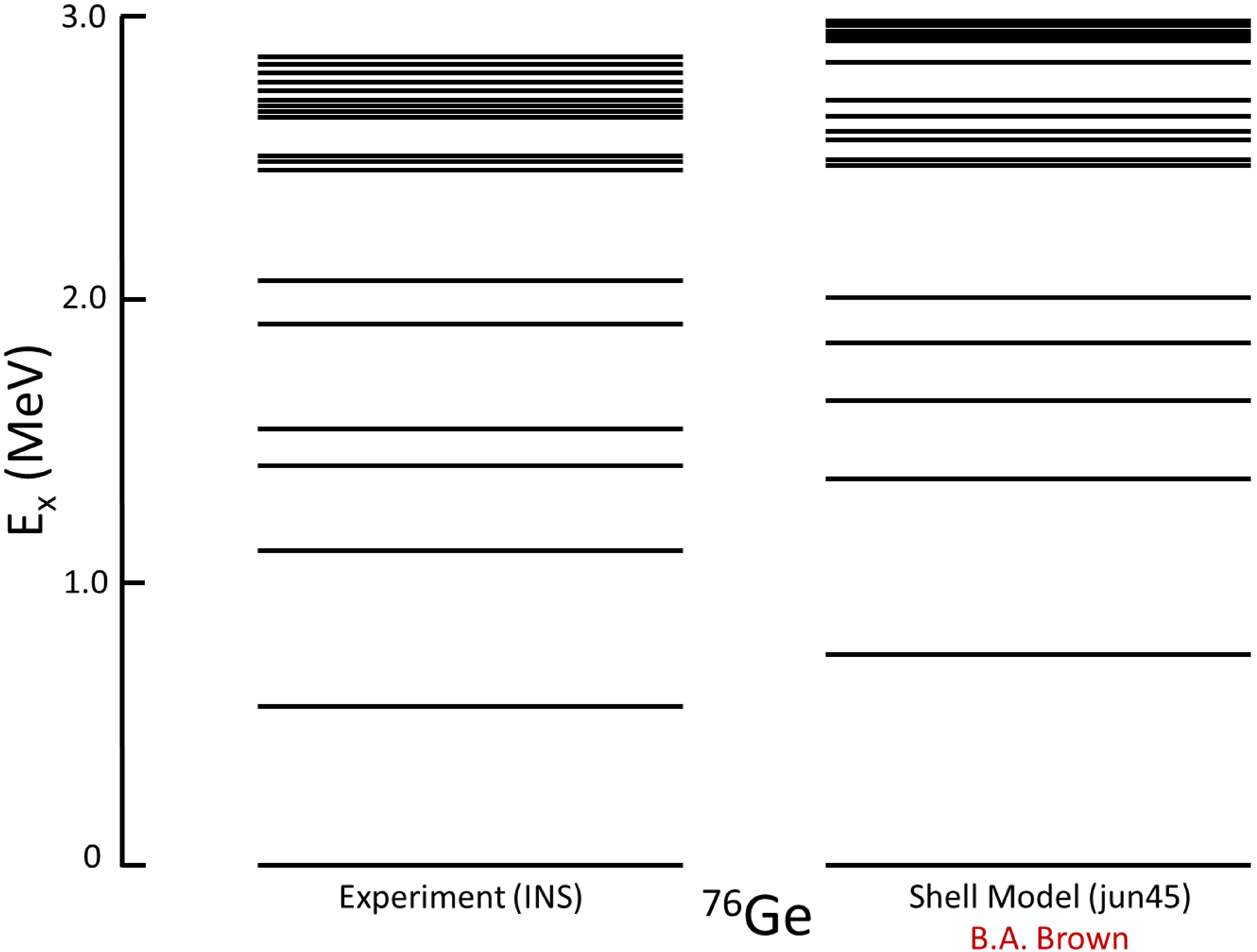
$^{76}Ge(n,n`\gamma)$



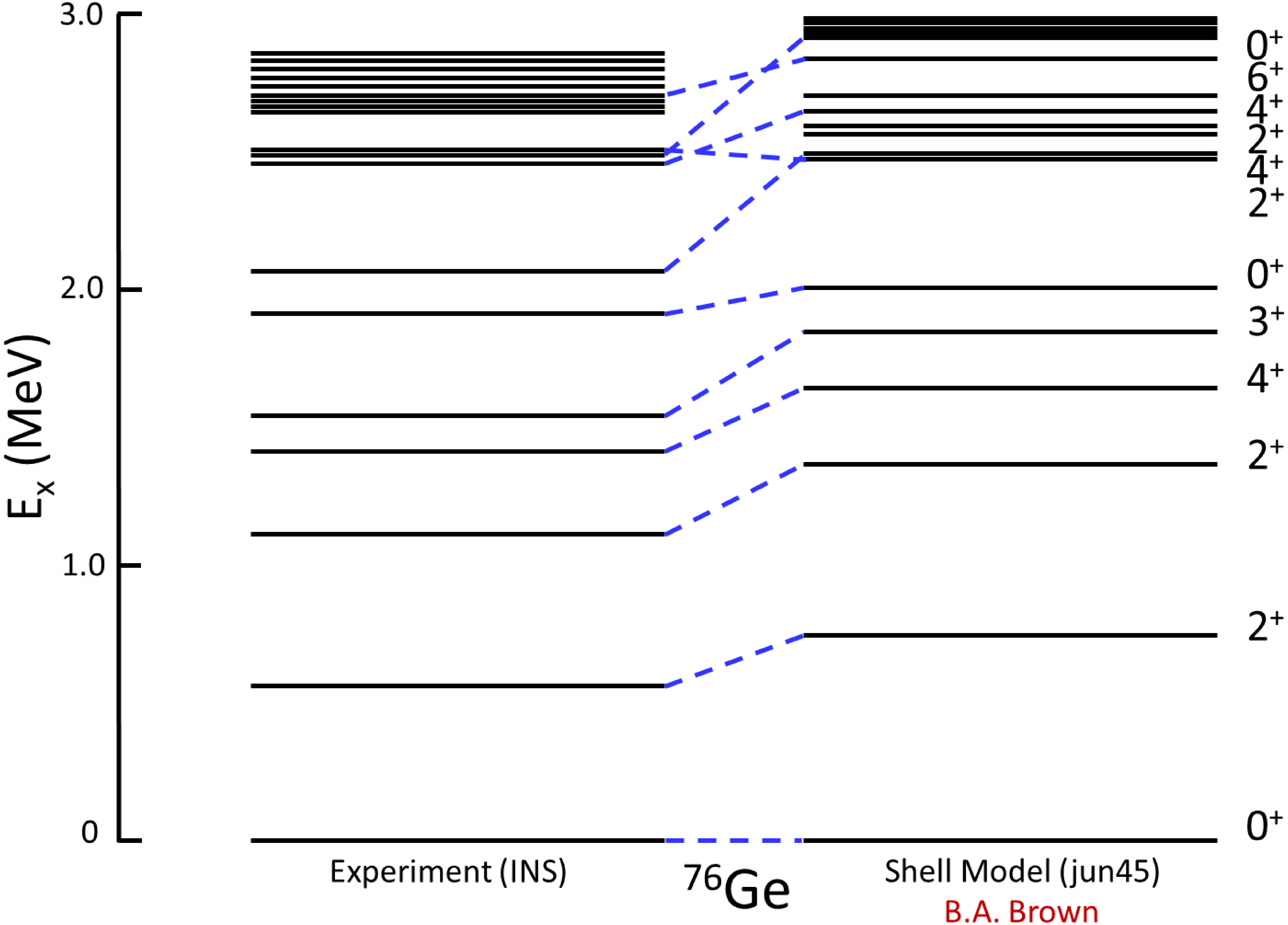
$^{76}Ge(n,n`\gamma)$



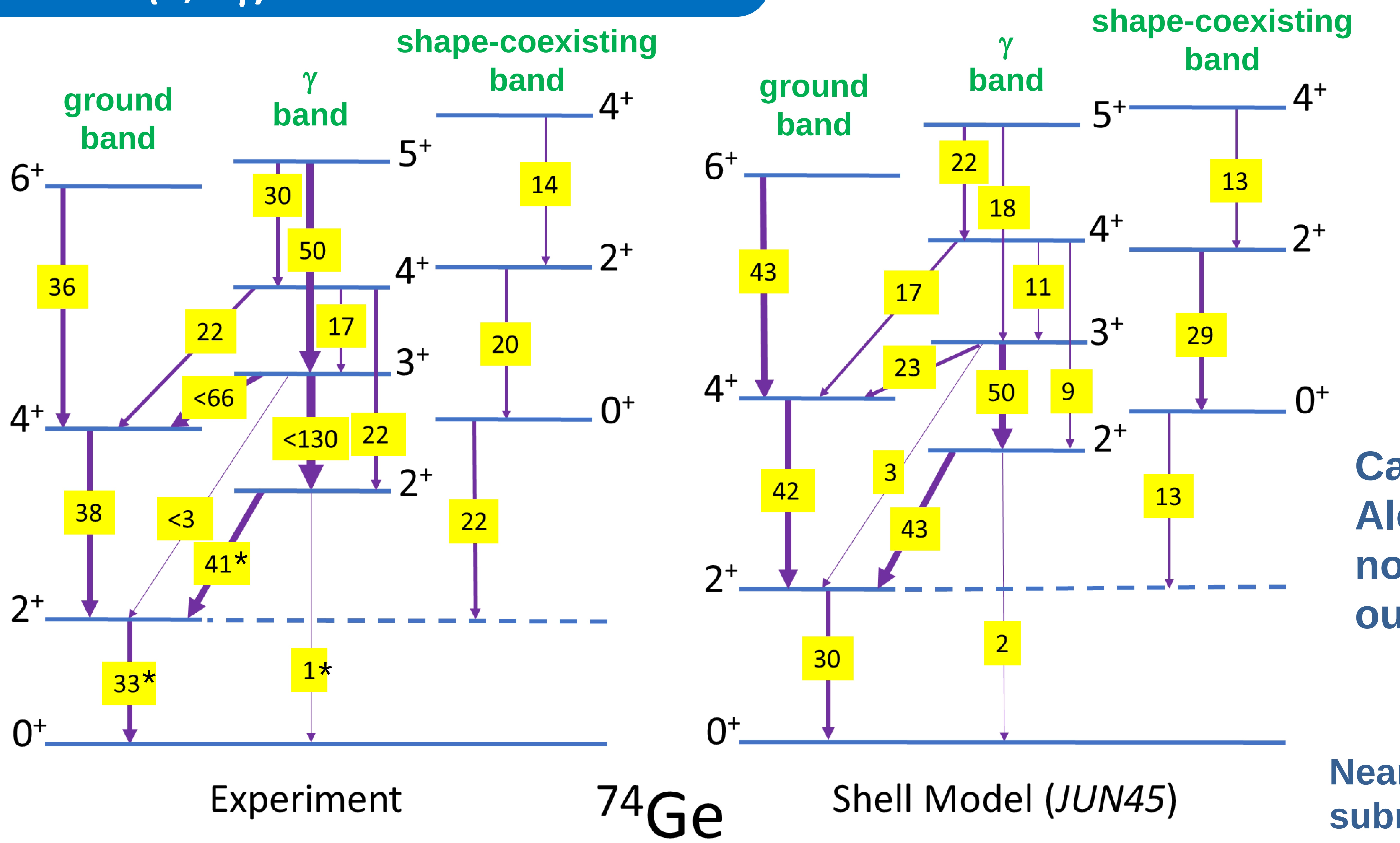
$^{76}Ge(n,n`\gamma)$



$^{76}Ge(n,n`\gamma)$



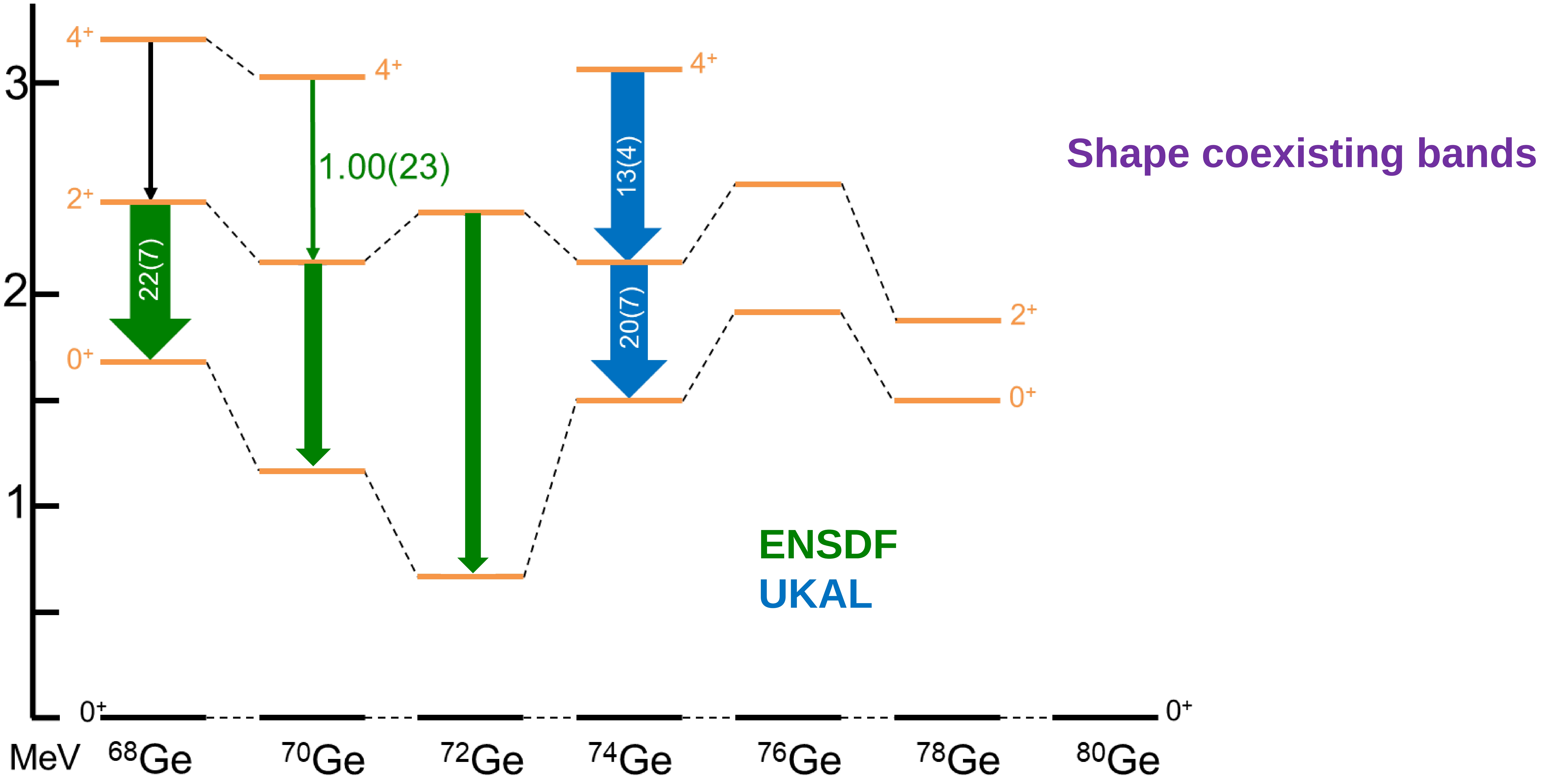
$^{74}Ge(n,n`\gamma)$



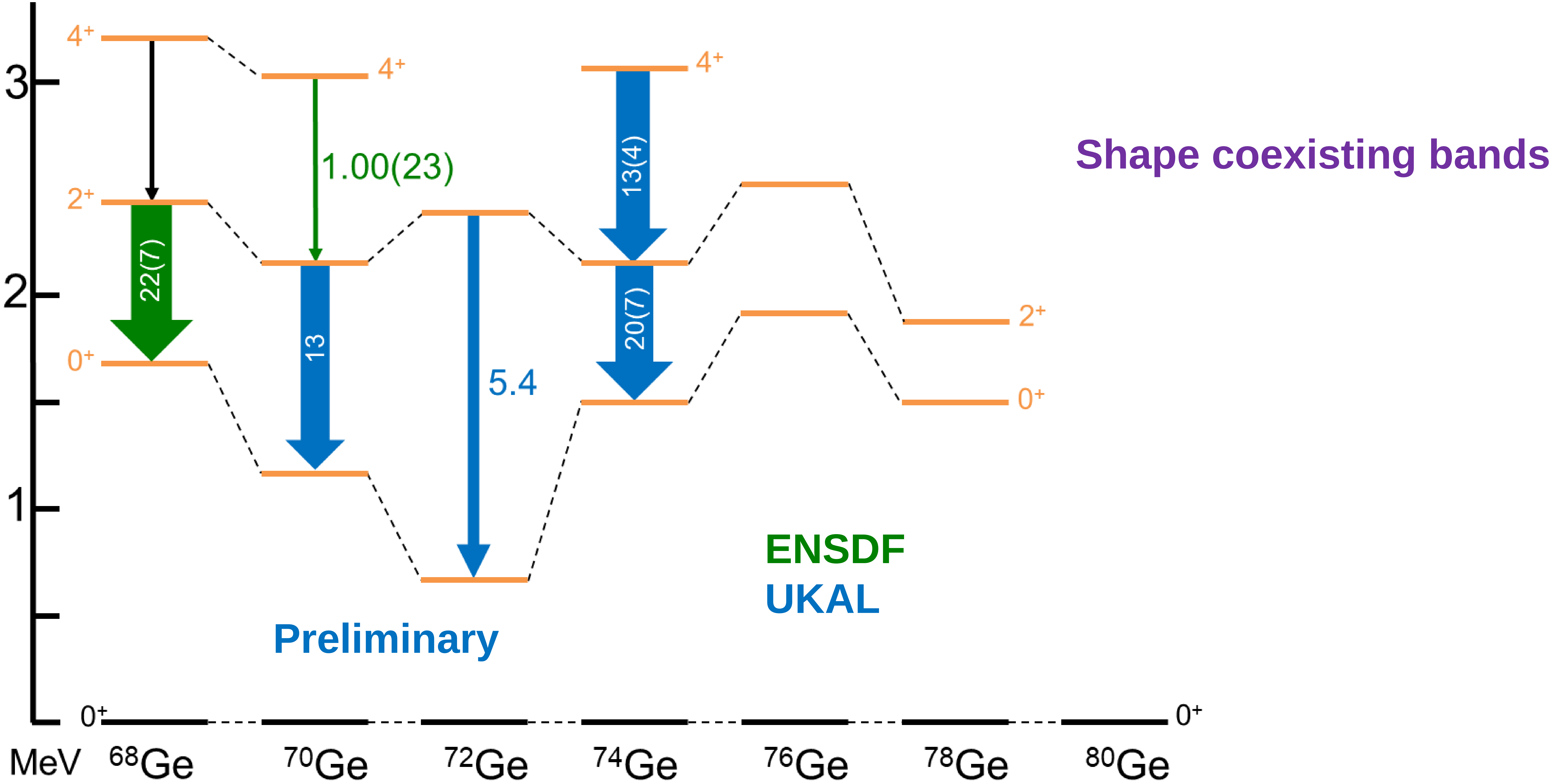
Calculations by Alex Brown with no input from our experiments

Nearly ready for submission to PRC

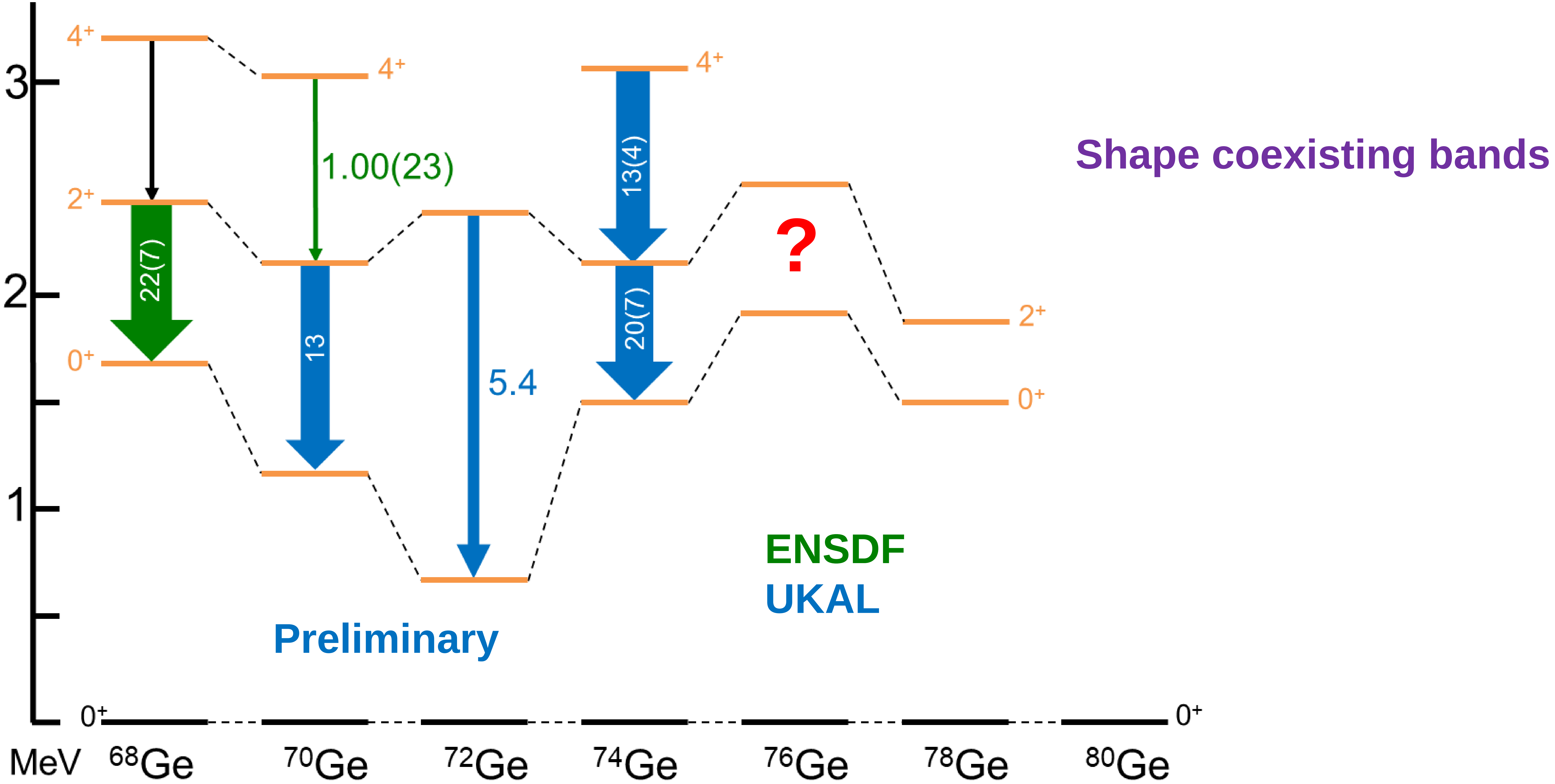
Shape Coexistence in the Ge Isotopes



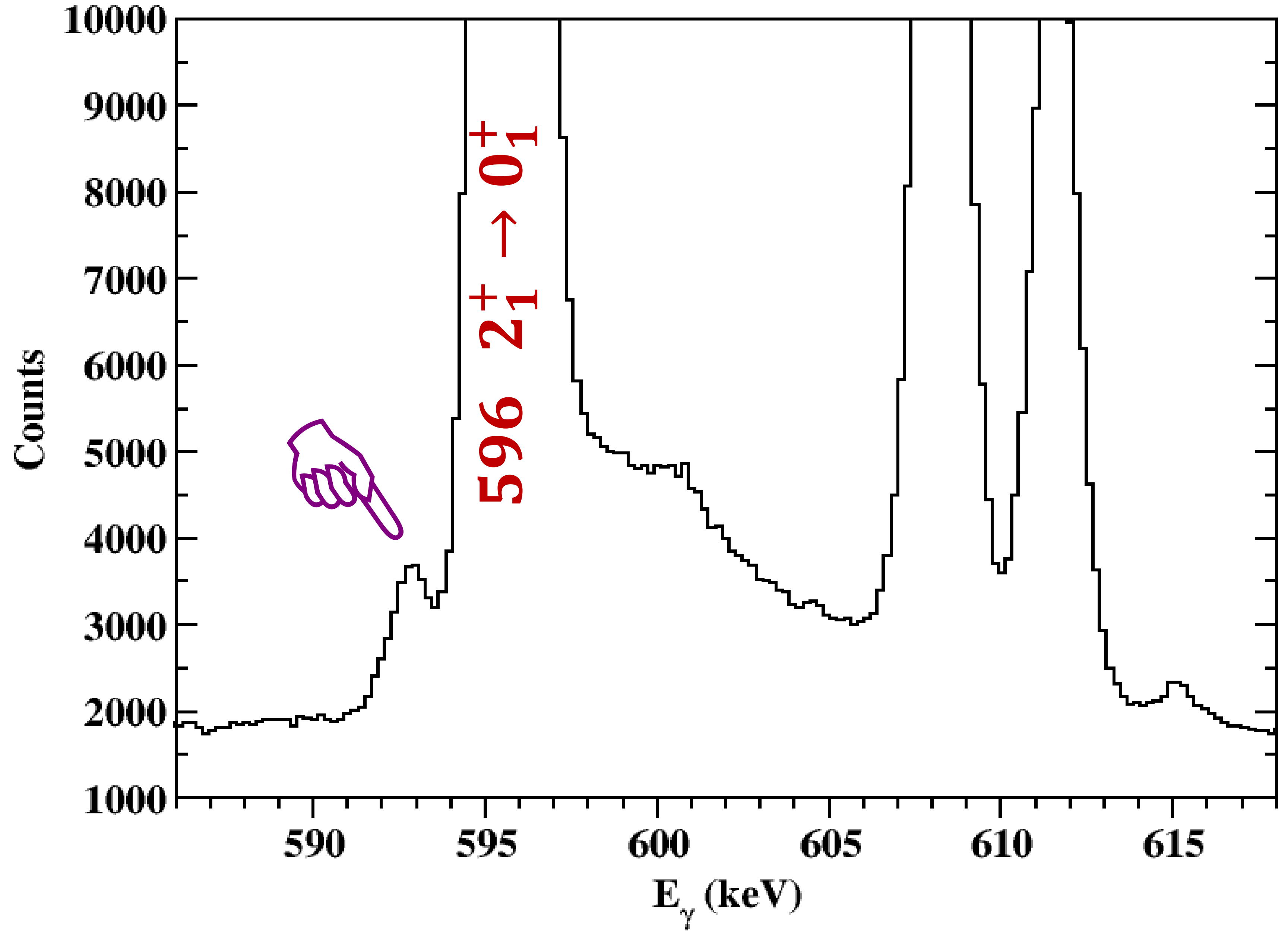
Shape Coexistence in the Ge Isotopes



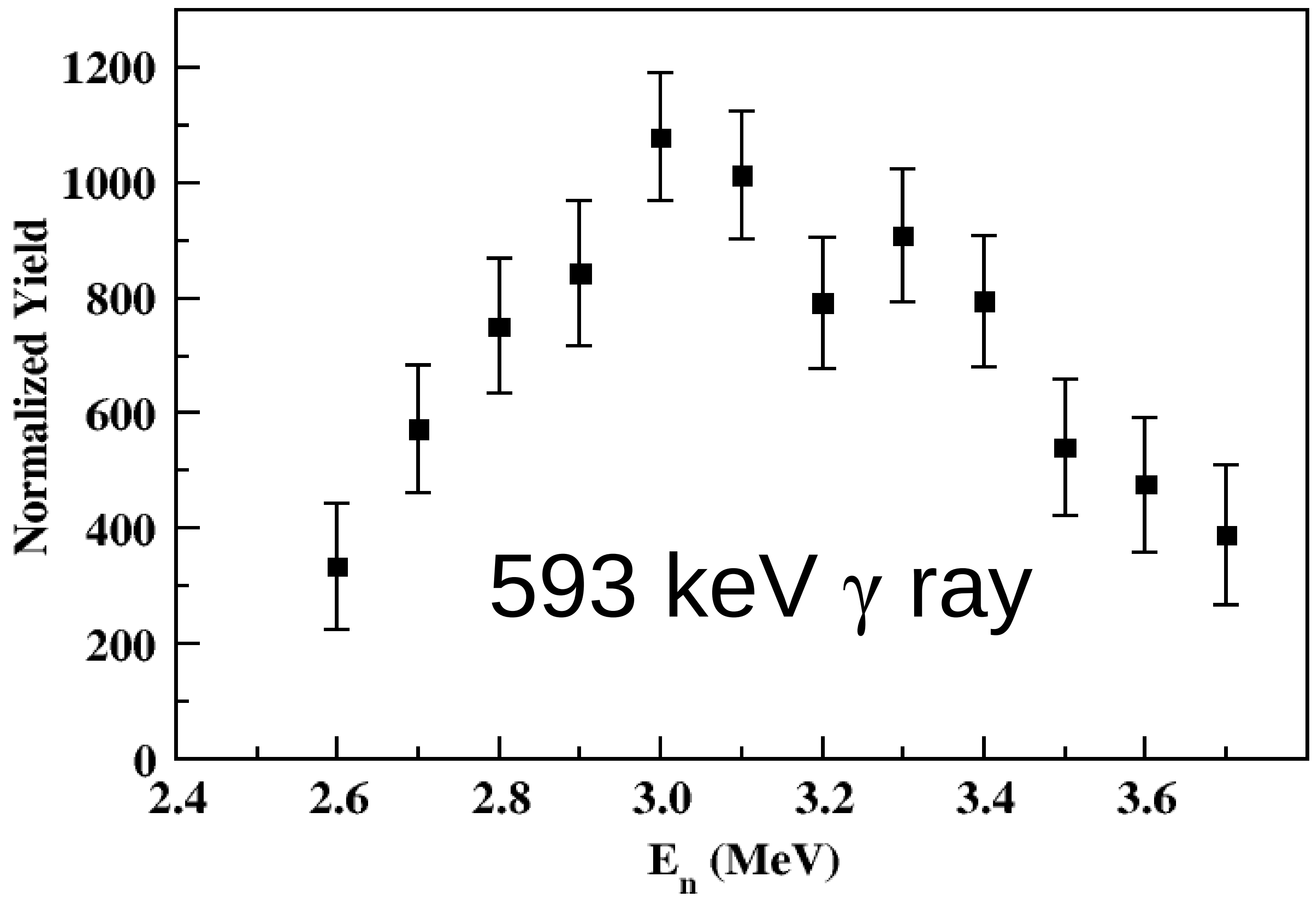
Shape Coexistence in the Ge Isotopes

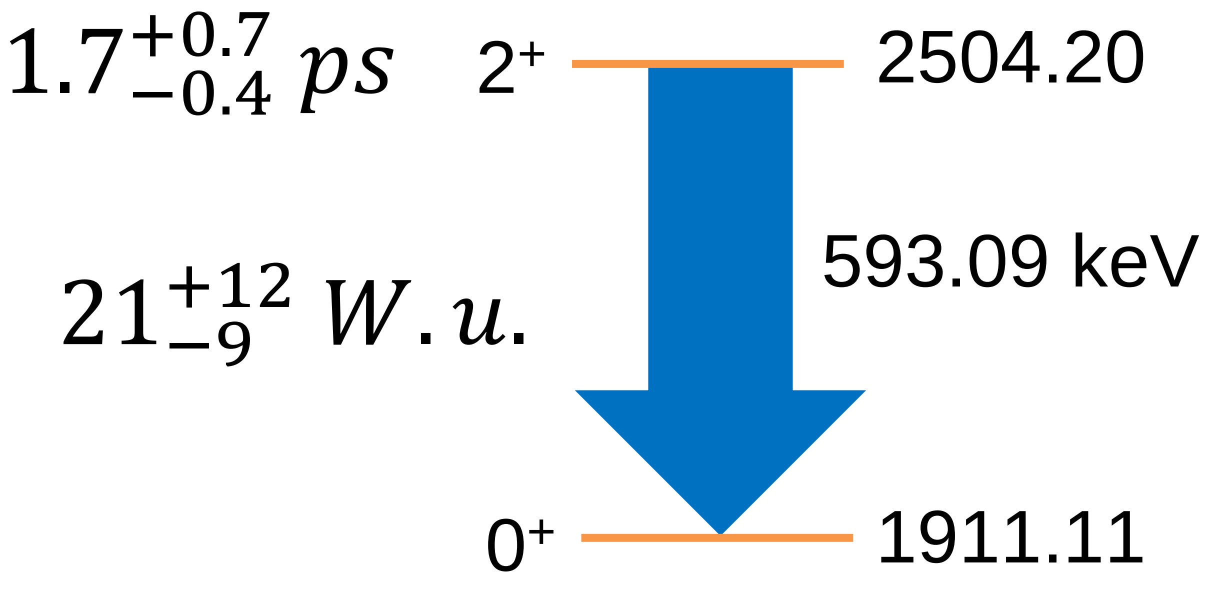


$^{76}Ge(n,n`\gamma)$

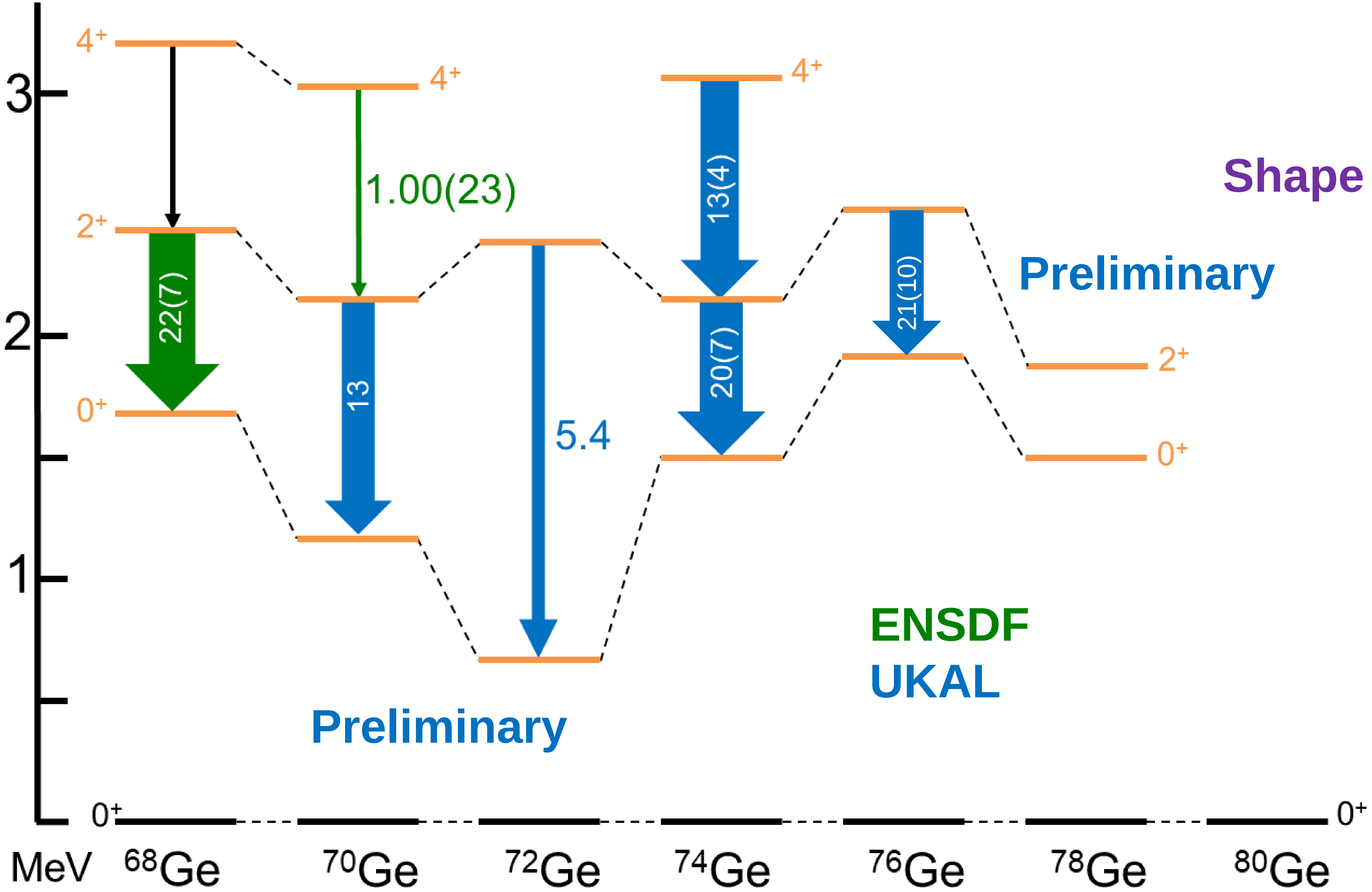


Sum of all angles
at E_n = 3 MeV

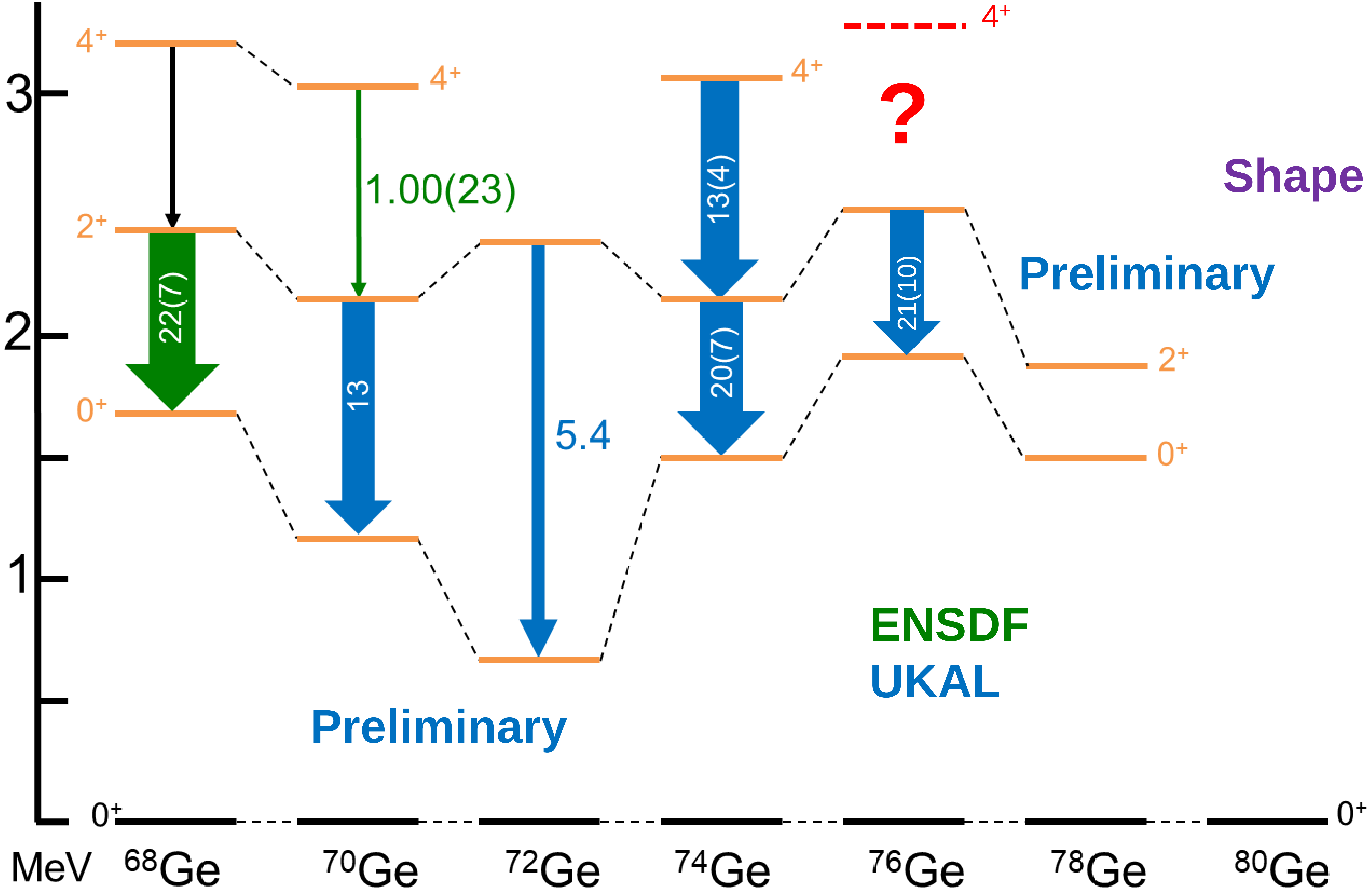




Shape Coexistence in the Ge Isotopes



Shape Coexistence in the Ge Isotopes

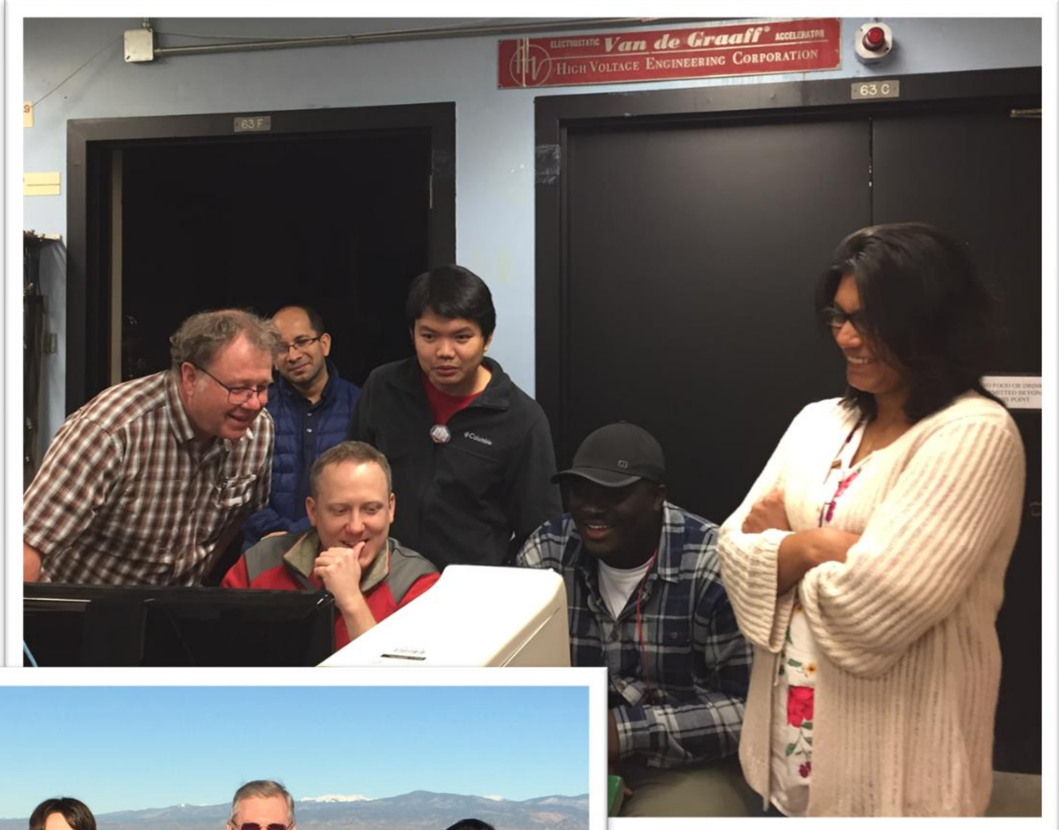


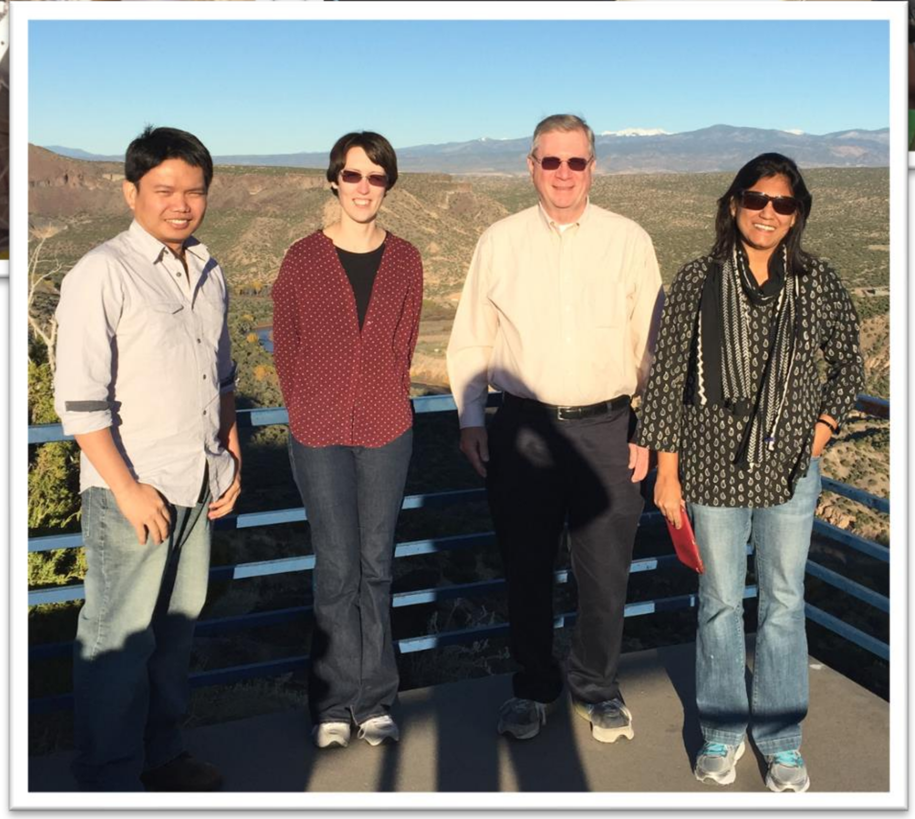
Concluding Remarks

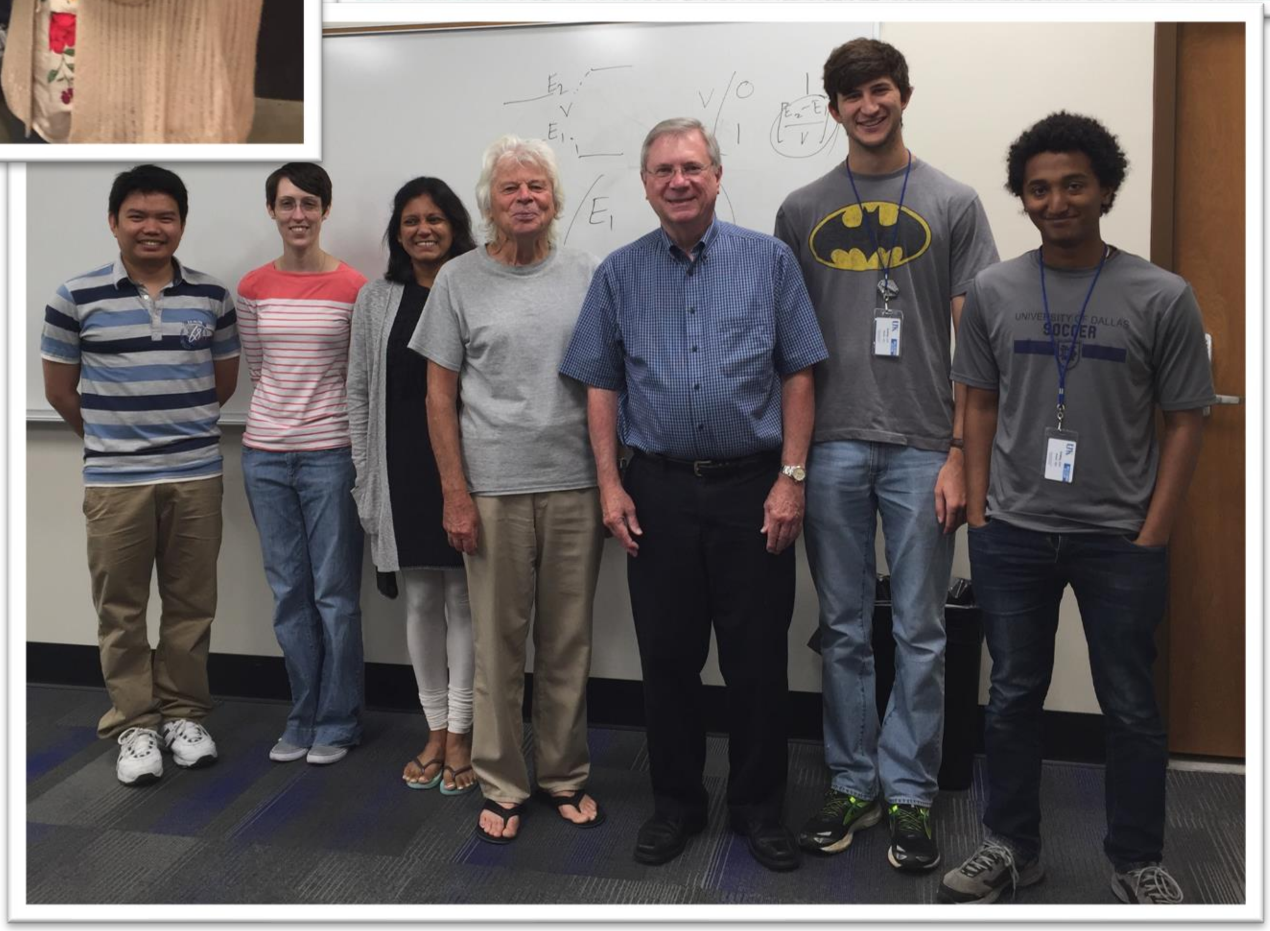
- To constrain the NME calculations for $0\nu\beta\beta$,
- Detailed spectroscopic data and knowledge of the deformations are needed.
- The nuclear structure is complex (and interesting!) for the Ge nuclei, but
- We have many different tools available and people involved in the detailed studies.

Thank you!!

- Nuclear Structure Studies are funded by the National Science foundation through grants PHY –1913028 and PHY – 2209178







https://www.pa.uky.edu/accelerator