Inelastic Neutron Scattering Studies: Relevance to Neutrinoless Double-β Decay

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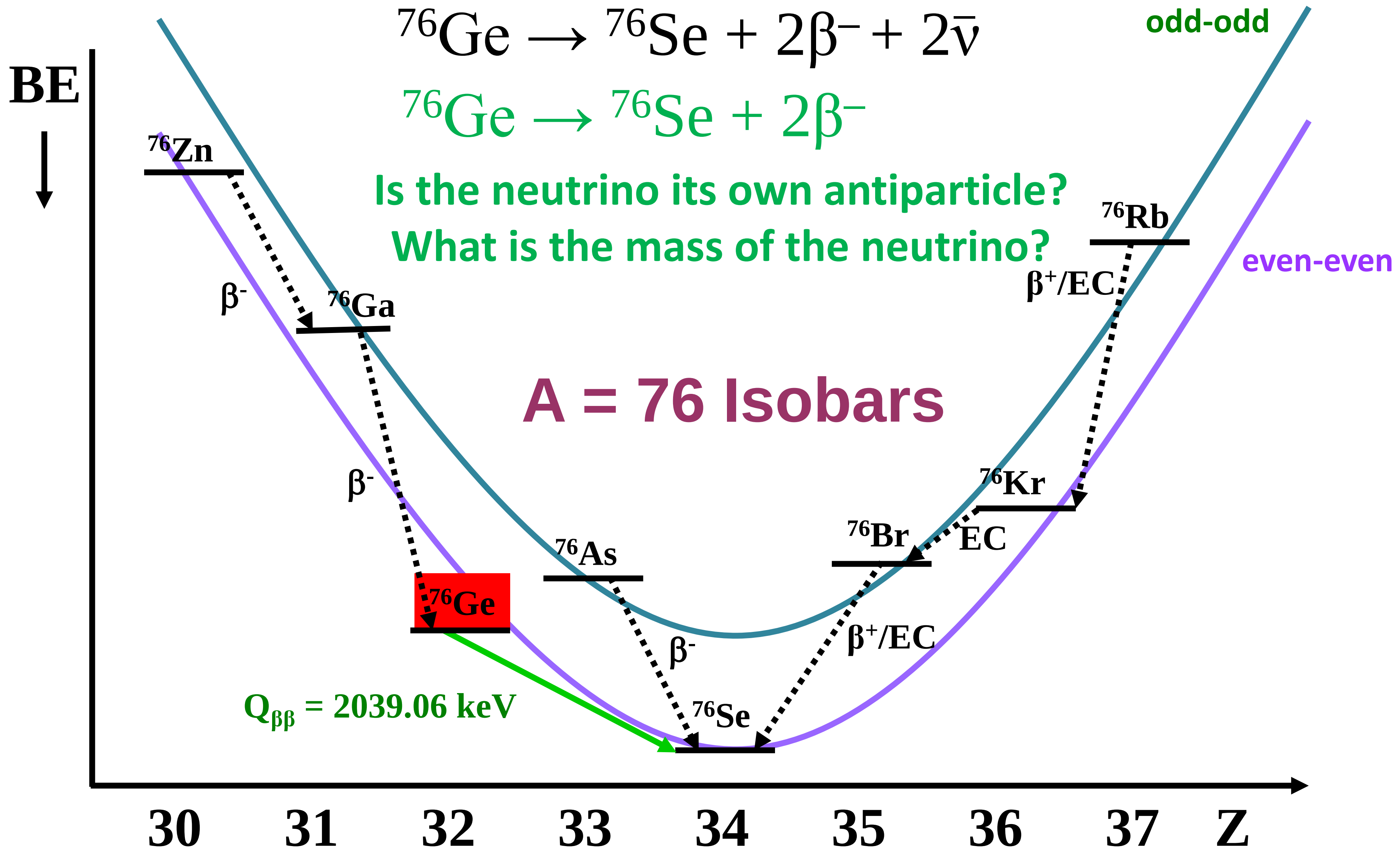
Double-β Decay

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

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

Is the neutrino its own antiparticle?

What is the mass of the neutrino?



Decay Rates of 2νββ and 0νββ

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)\left|M_{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2$$

Phase space factor

Nuclear Matrix Element

Effective Majorana neutrino mass

$$\left(T_{1/2}^{2\nu}\right)^{-1} = G_{2\nu}(Q_{\beta\beta}, Z)\left|M_{2\nu}\right|^2$$

$$T_{1/2}^{2\nu}(^{76}Ge) = 1.84\times 10^{21}\ yr$$

M. Agostini et al. (GERDA), *J. Phys. G: Nucl. Part. Phys.* **40** 035110 (2013)

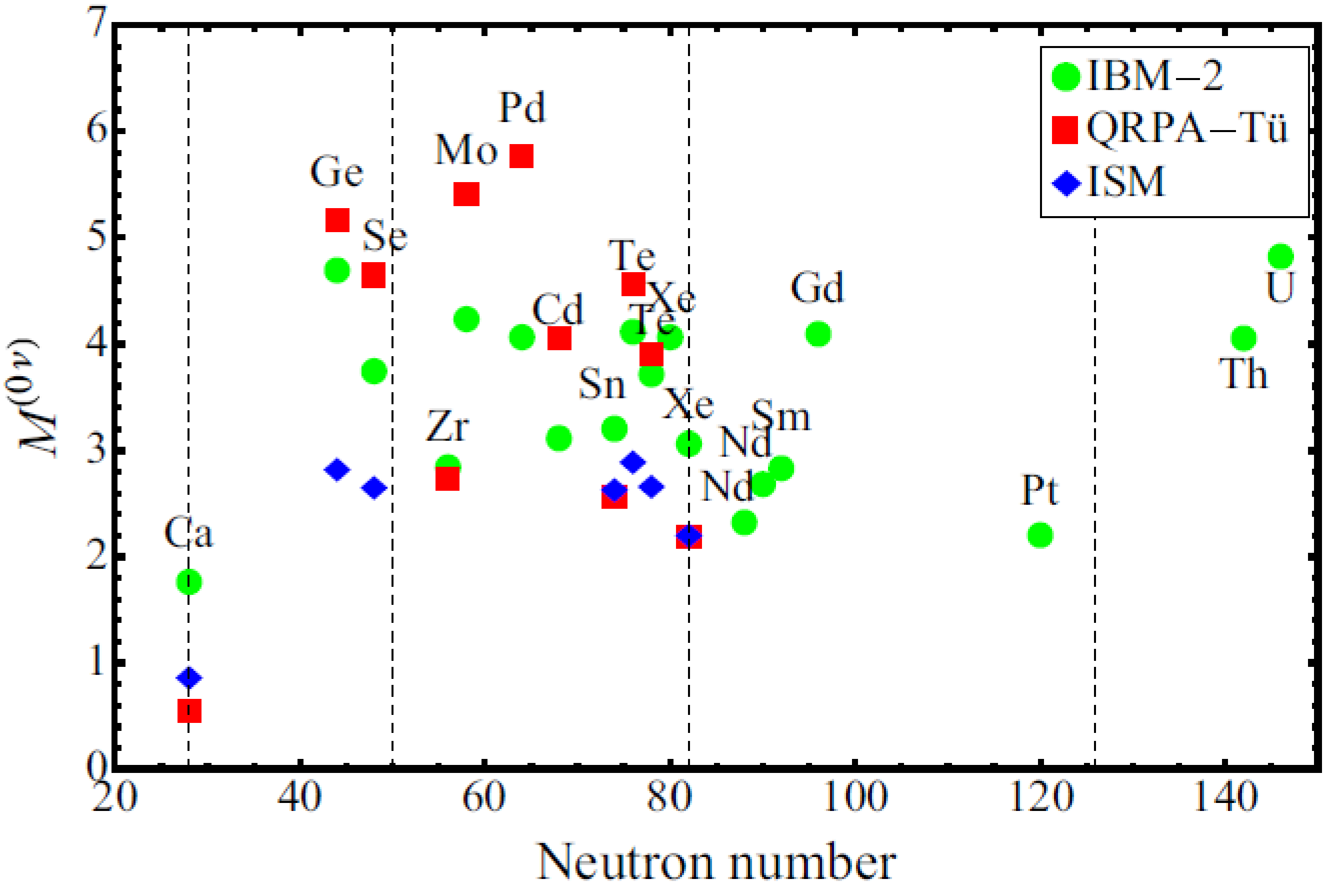
$$T_{1/2}^{0\nu}(^{76}Ge) = 1.19\times 10^{25}\ yr$$

H.V. Klapdor-Kleingrothaus, I.V. Krivoshina, A. Dietz, and O. Chkvorets, Phys. Lett. B **586**, 198 (2004)

$$T_{1/2}^{0\nu}(^{76}Ge) > 2.1\times 10^{25}\ yr$$

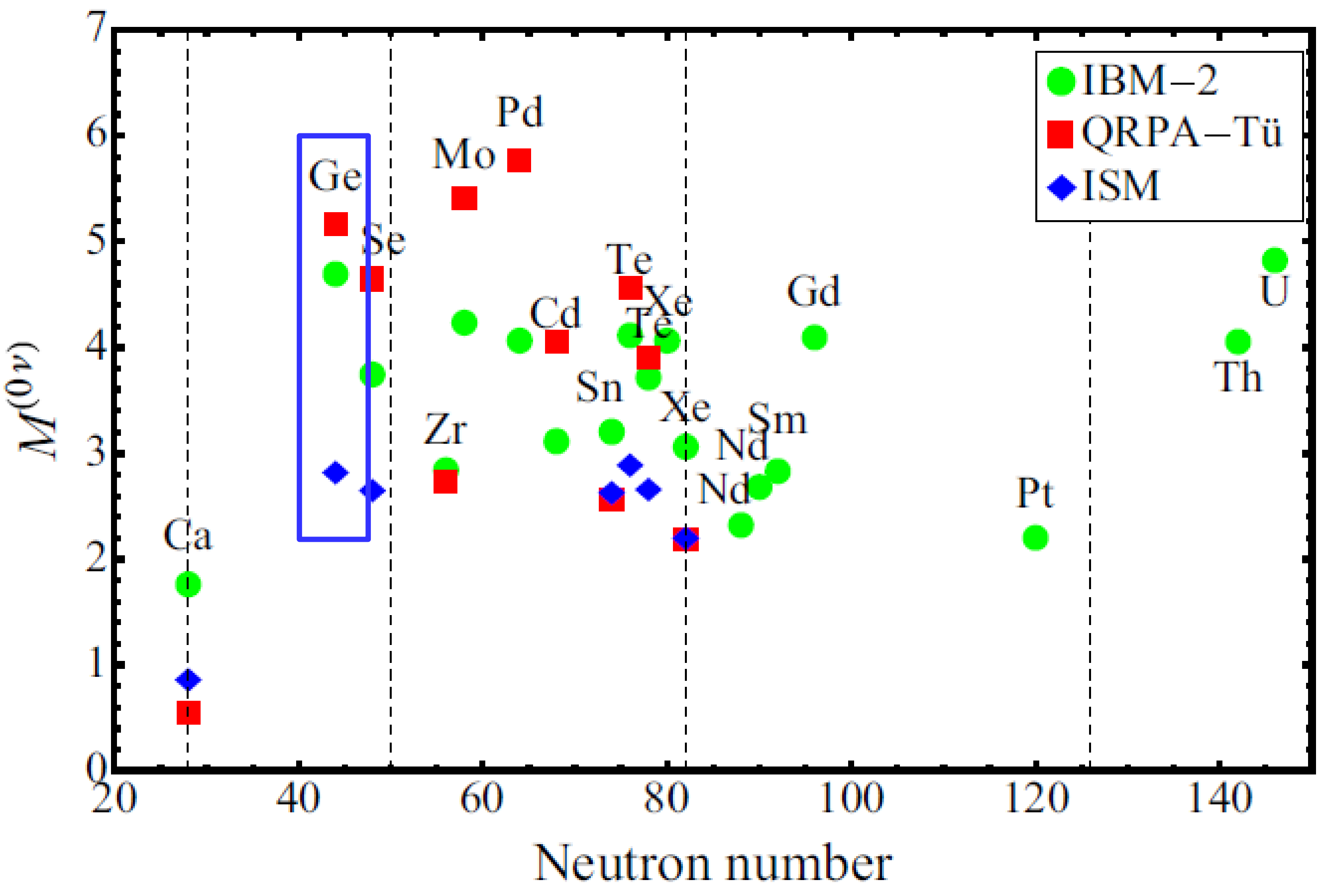
M. Agostini et al. (GERDA), PRL **111**, 122503 (2013)

Comparison of calculated nuclear matrix elements for 0νββ candidates



J. Barea, J. Kotila, and F. Iachello, Phys. Rev. 91, 034304 (2015).

Comparison of calculated nuclear matrix elements for 0νββ candidates



J. Barea, J. Kotila, and F. Iachello, Phys. Rev. 91, 034304 (2015).

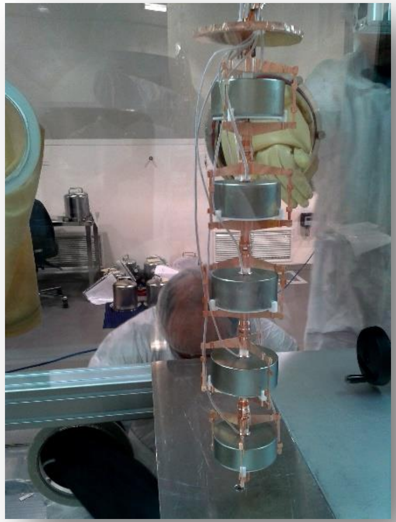
Current Searches for ^{76}Ge 0νββ

MAJORANA
DEMONSTRATOR

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

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

GERDA



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

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

INS Experiments

Monoenergetic neutrons:

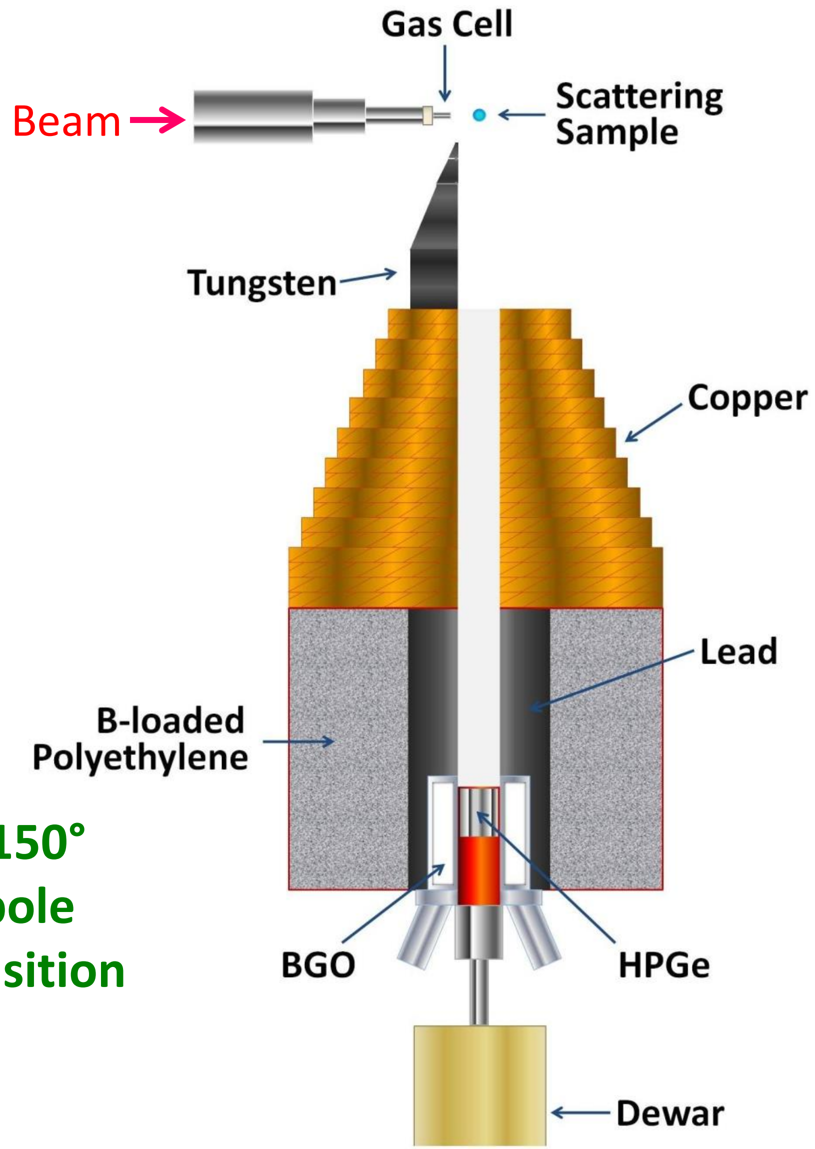
$^{3}H(p,n)^{3}He$ or $^{2}H(d,n)^{3}He$

Excitation functions

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

Angular distributions

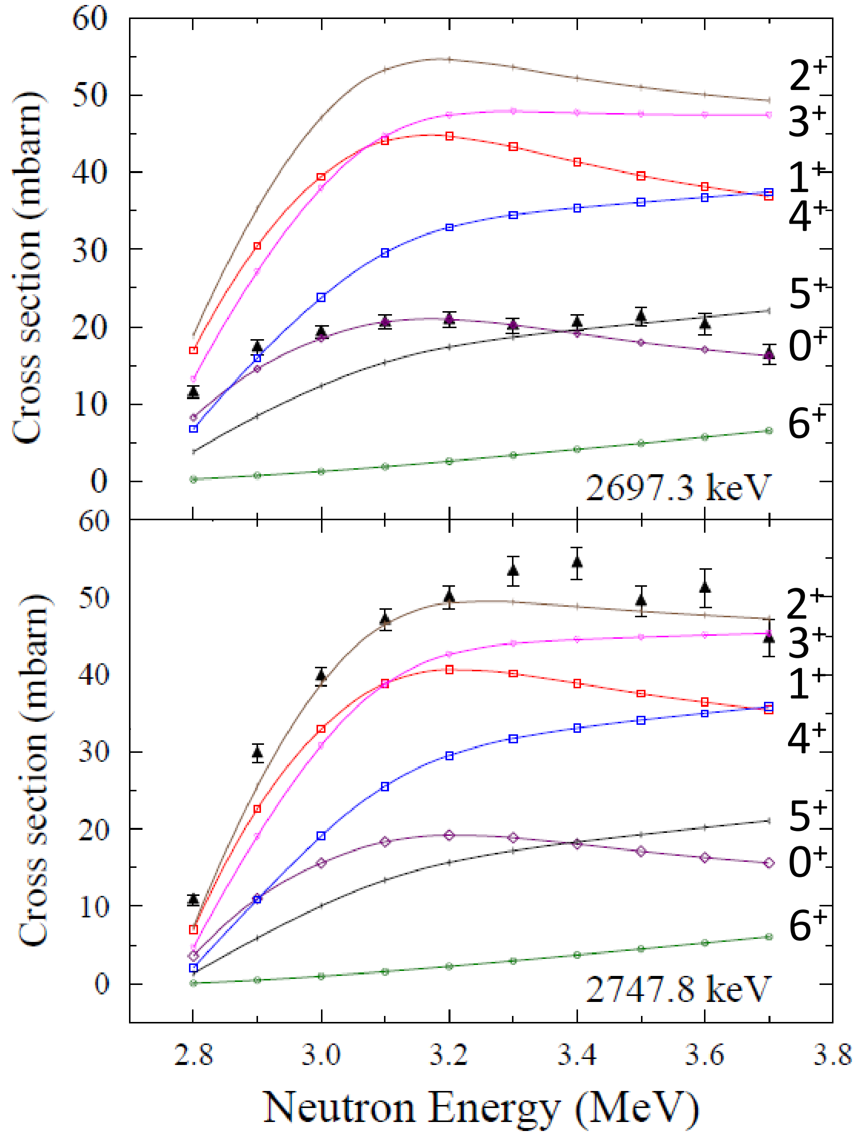
- Constant neutron energy
- Detection angle varied from 40°-150°
- Transition multipolarities, multipole mixing ratios, level lifetimes, transition probabilities

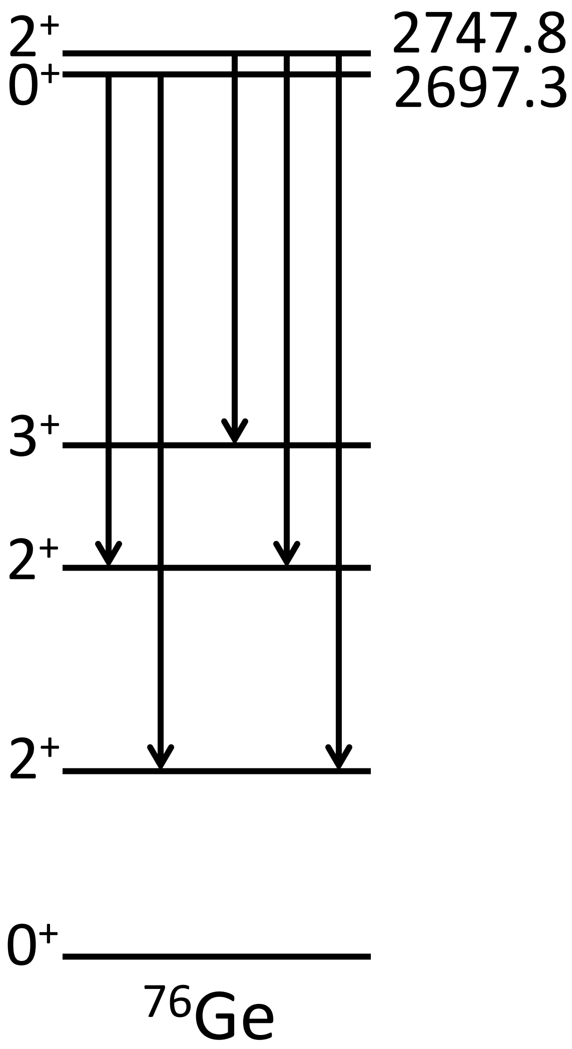


From Inelastic Neutron Scattering

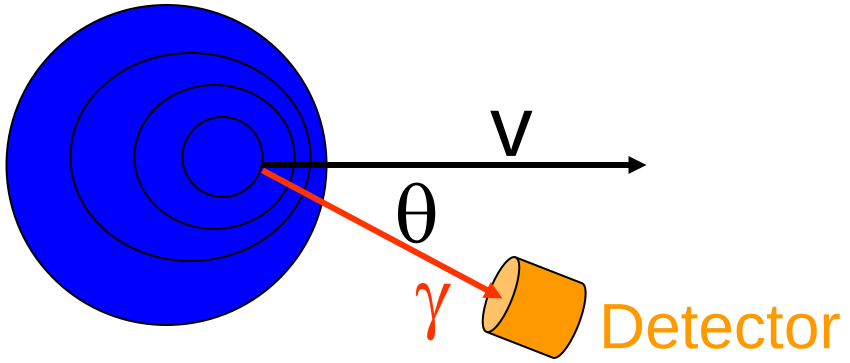
- Level scheme: J^{π}
- Transition multipolarities: E1, E2, E3, M1…
- Multipole mixing ratios: $\delta(E2/M1)$
- Level lifetimes: τ
- Transition probabilities: $B(\lambda)$
- Cross sections/Backgrounds: σ

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





Doppler-Shift Attenuation Method



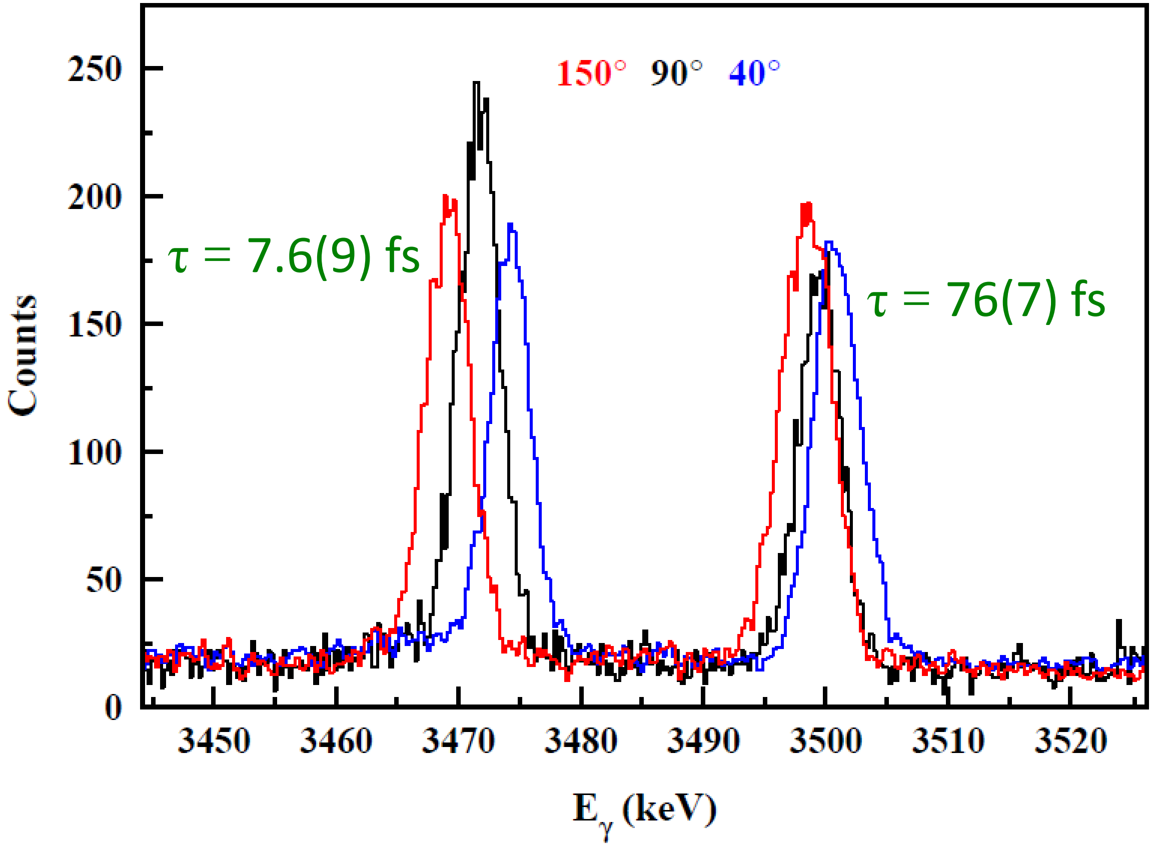
$$E(\theta) = E_\gamma\,(1 + v/c \cos\theta)$$

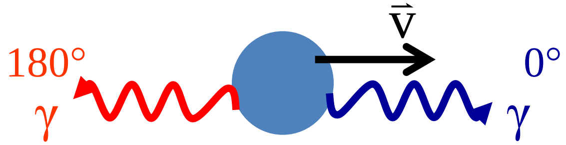
The nucleus is recoiling into a viscous medium.

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

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

Level Lifetimes: Doppler-Shift Attenuation Method (DSAM)





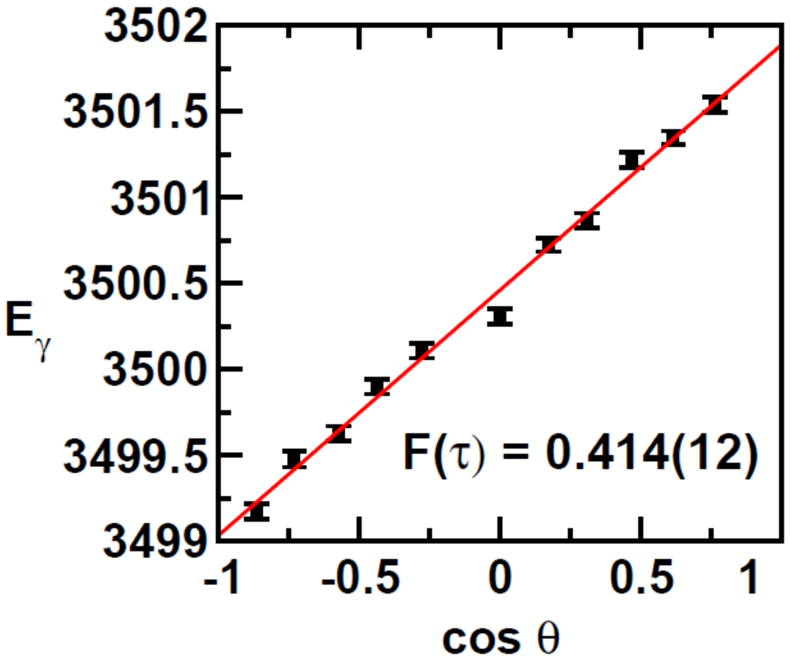
Scattered neutron causes the nucleus to recoil.

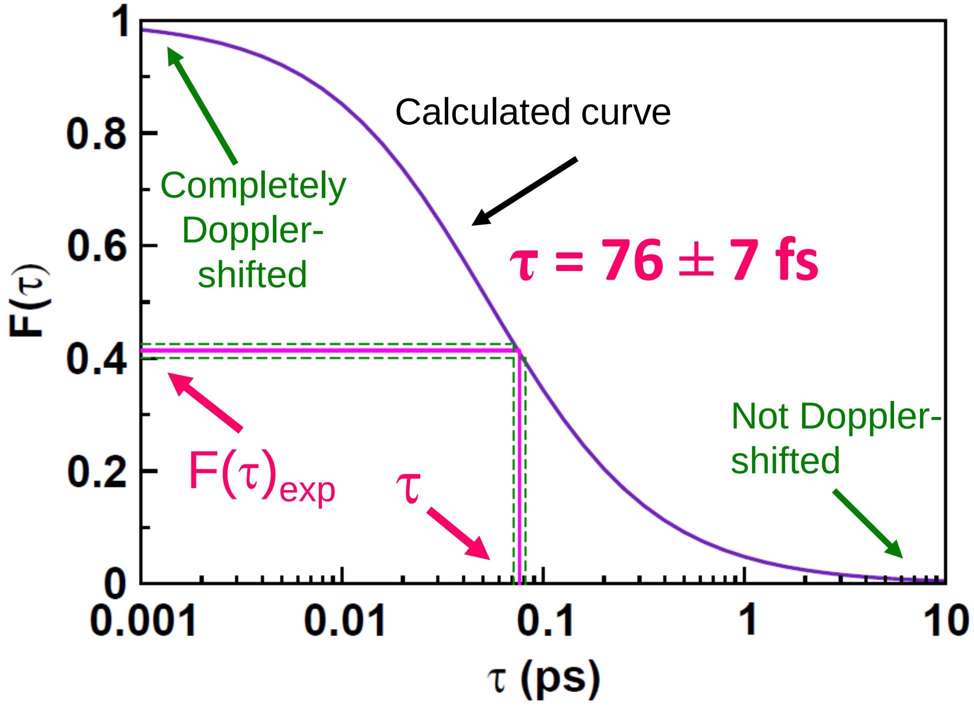
Emitted γ rays experience a Doppler shift.

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).

Why study ^{76}Ge?

It is the parent for double-β decay.

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

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

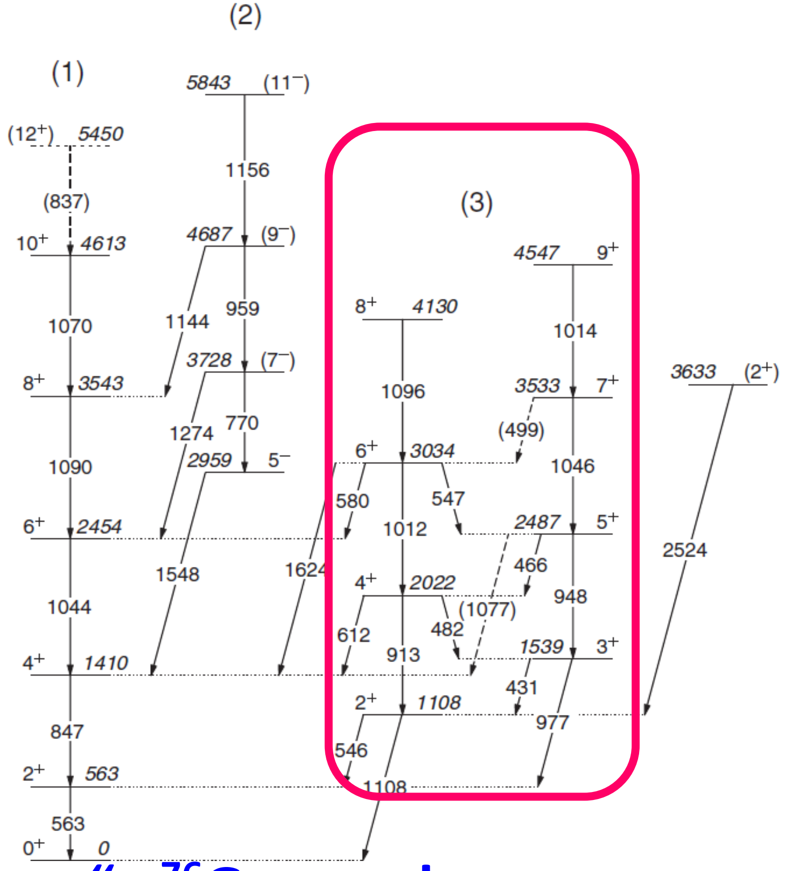
It is structurally interesting.

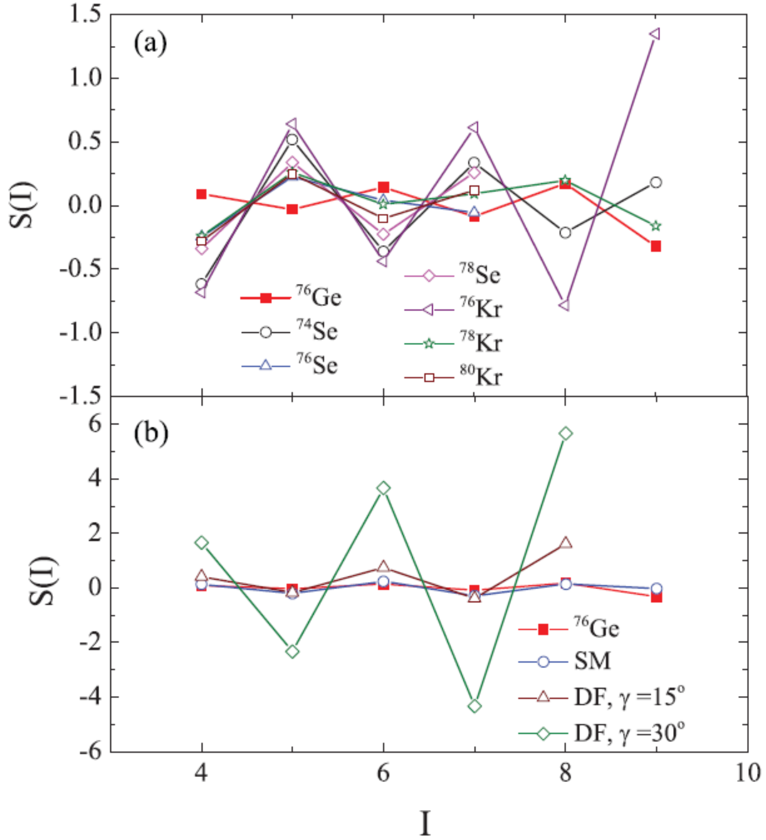
- ❑ Shape Transition
- ❑ Shape Coexistence
- ❑ Rigid Triaxiality

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

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

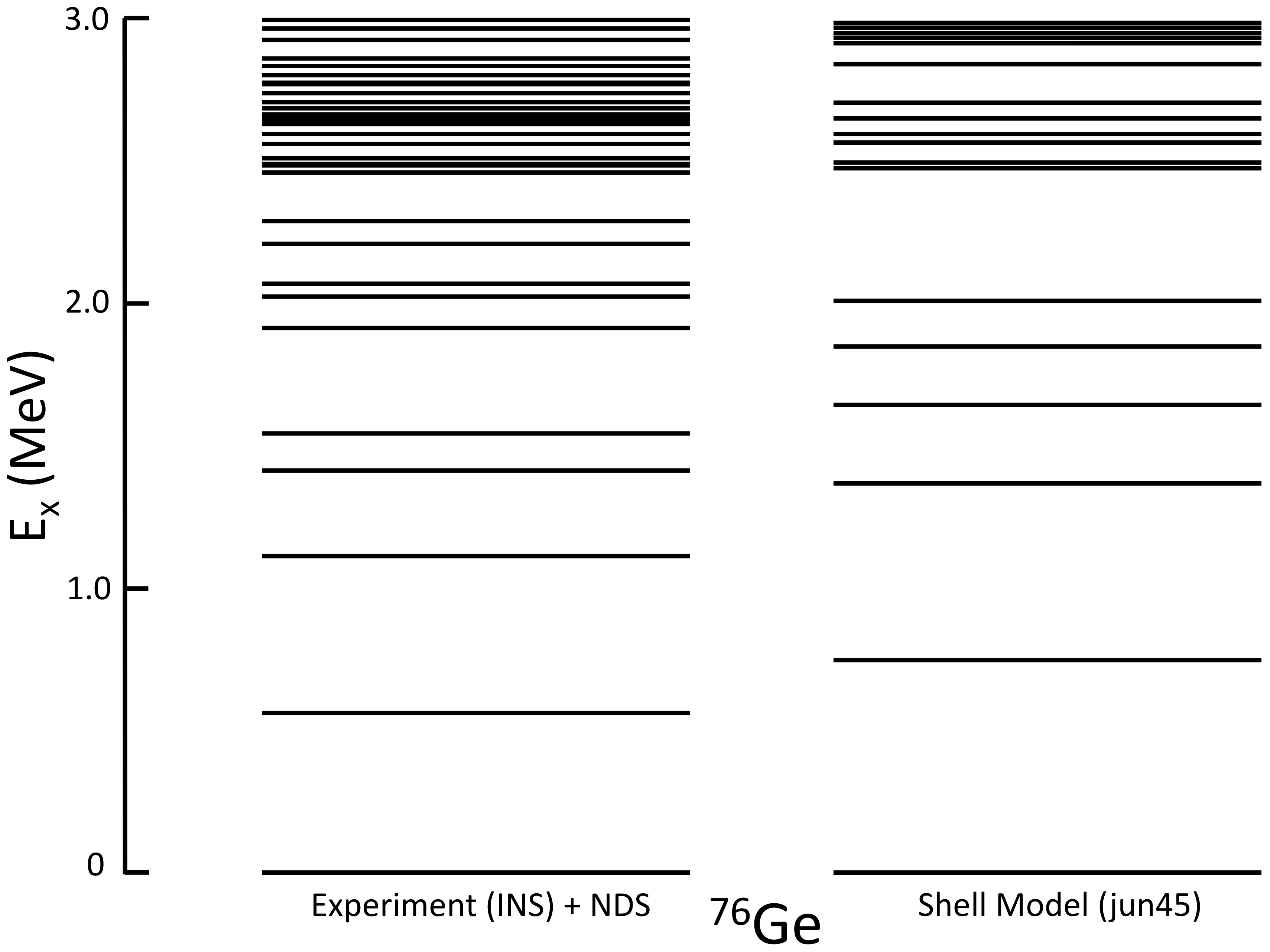
Y. Toh,[1,2] C. J. Chiara,[2,3] E. A. McCutchan,[2,4] W. B. Walters,[3] R. V. F. Janssens,[2] M. P. Carpenter,[2] S. Zhu,[2] R. Broda,[5] B. Fornal,[5] B. P. Kay,[2] F. G. Kondev,[6] W. Królas,[5] T. Lauritsen,[2] C. J. Lister,[2,*] T. Pawłat,[5] D. Seweryniak,[2] I. Stefanescu,[2,3] N. J. Stone,[7,8]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

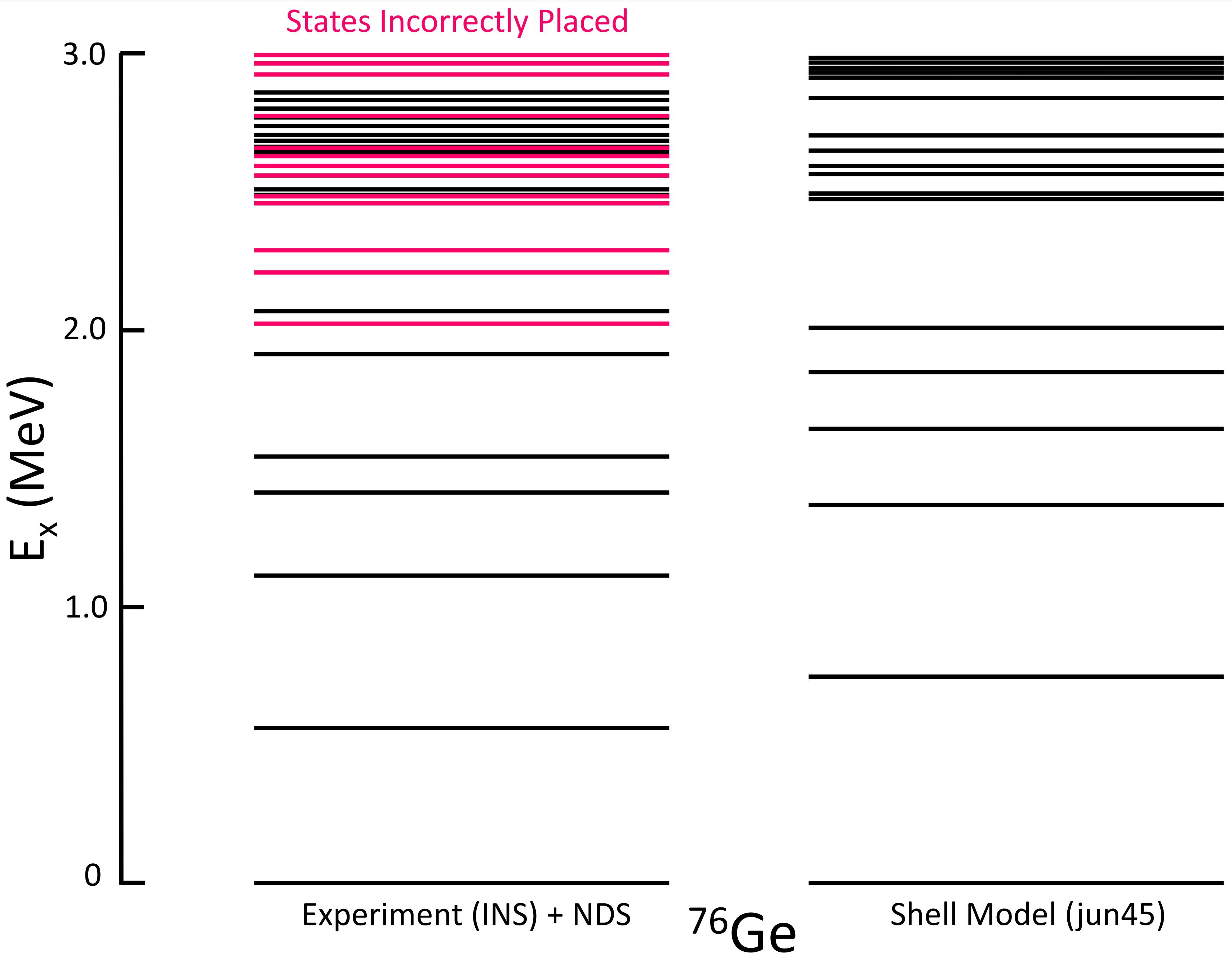




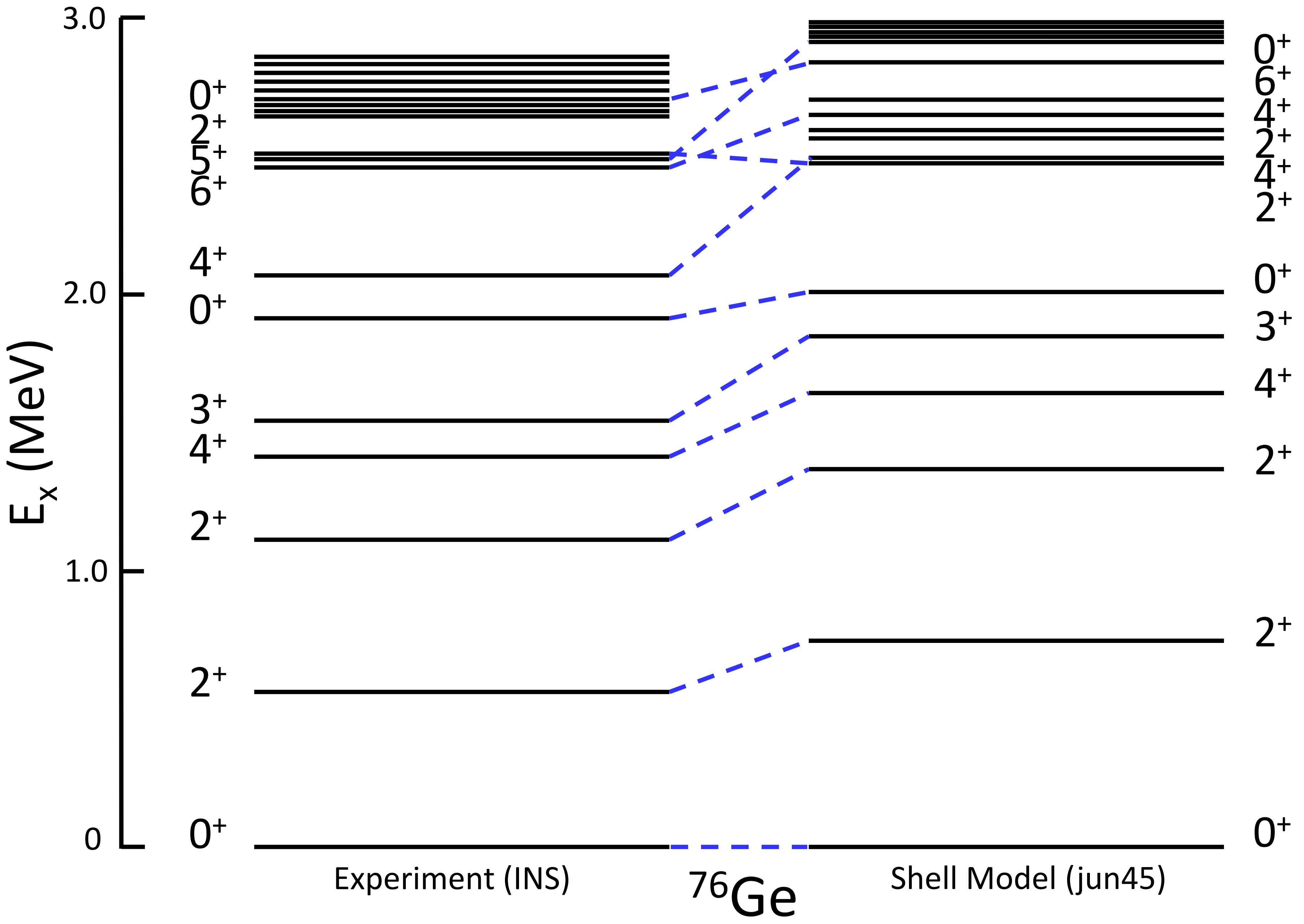
"…^{76}Ge may be a rare example of a nucleus exhibiting rigid triaxial deformation in the low-lying states."


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

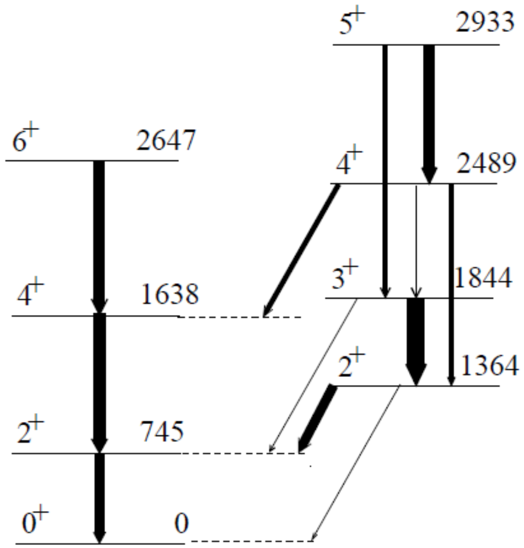

3.0
2.0
1.0
0
Ex (MeV)
Experiment (INS) + NDS
76Ge
Shell Model (jun45)



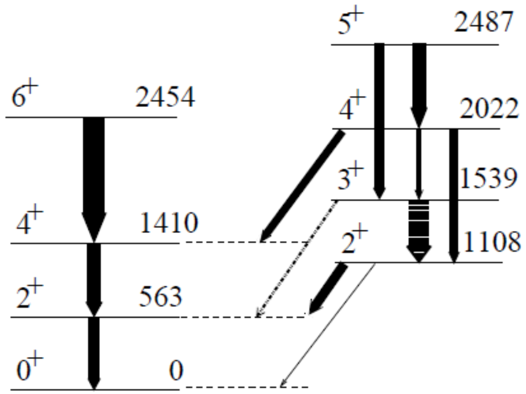
States Incorrectly Placed
3.0
2.0
1.0
0
E_x (MeV)
Experiment (INS) + NDS
^{76}Ge
Shell Model (jun45)


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

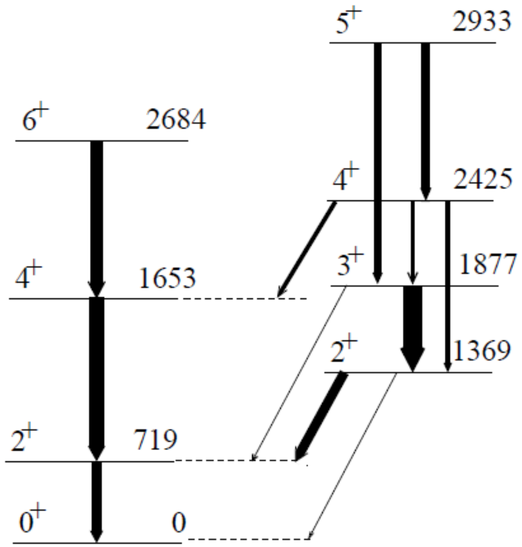
Comparison with Shell Model



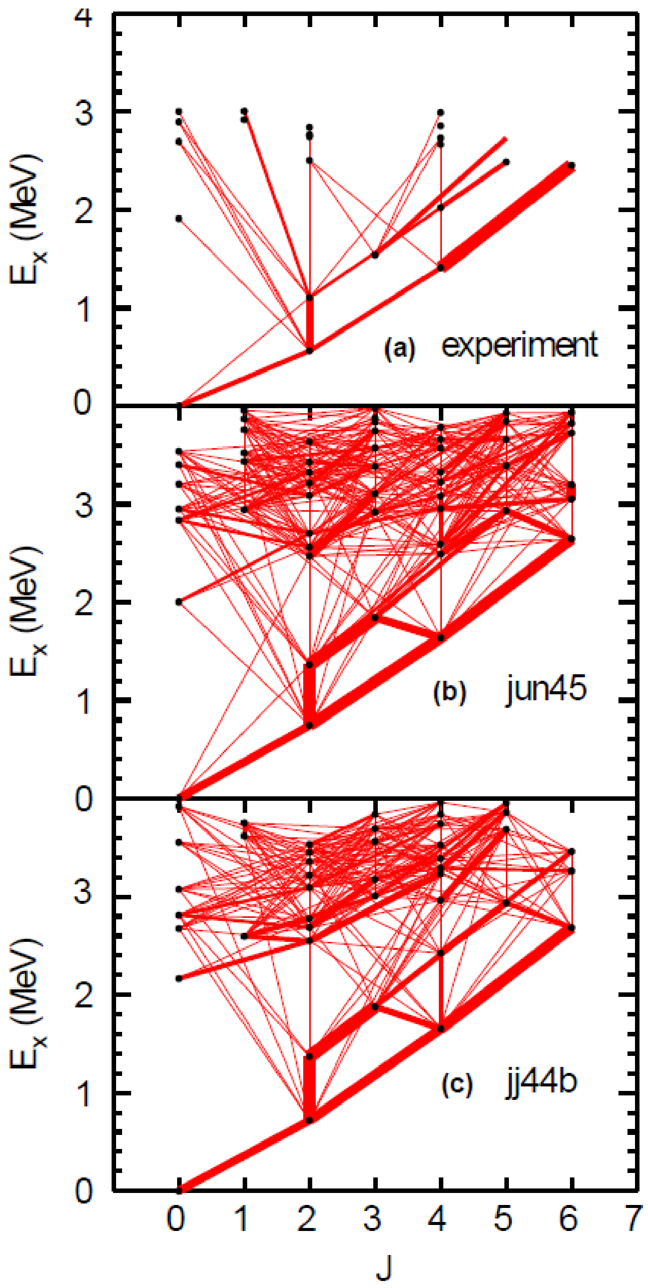
jun45

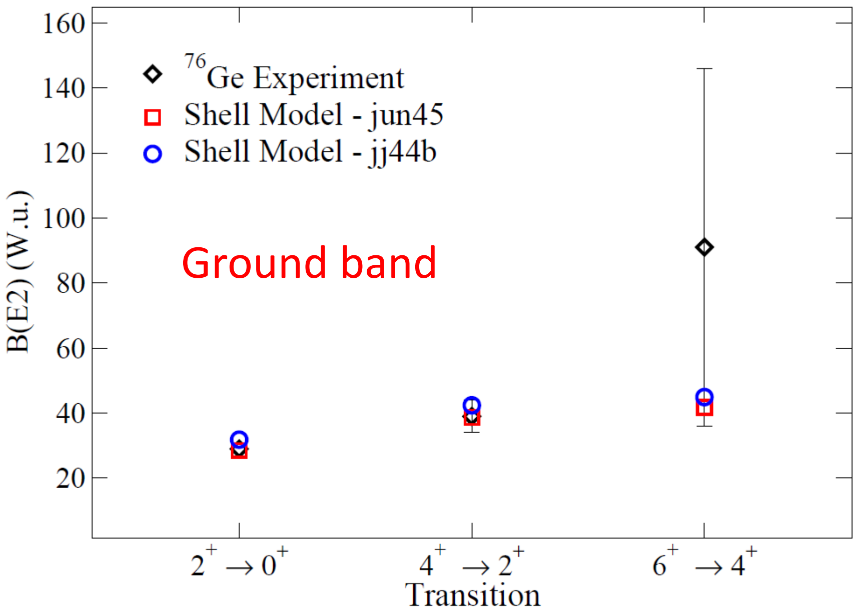


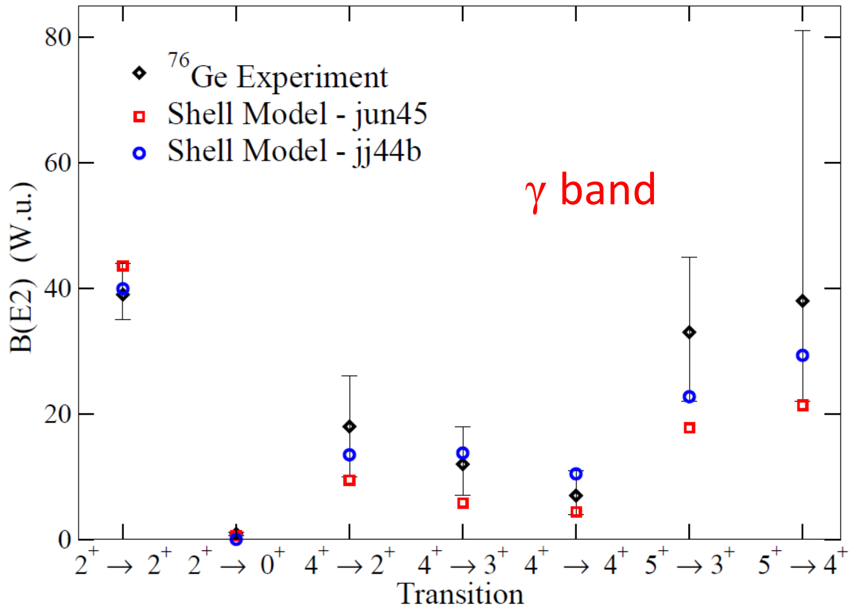
Experiment



jj44b

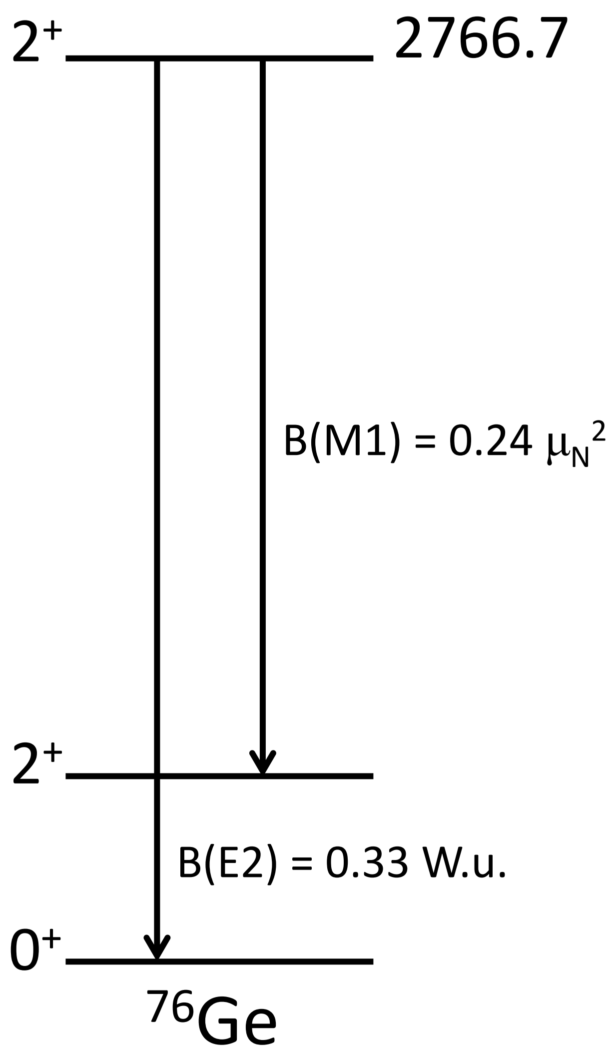


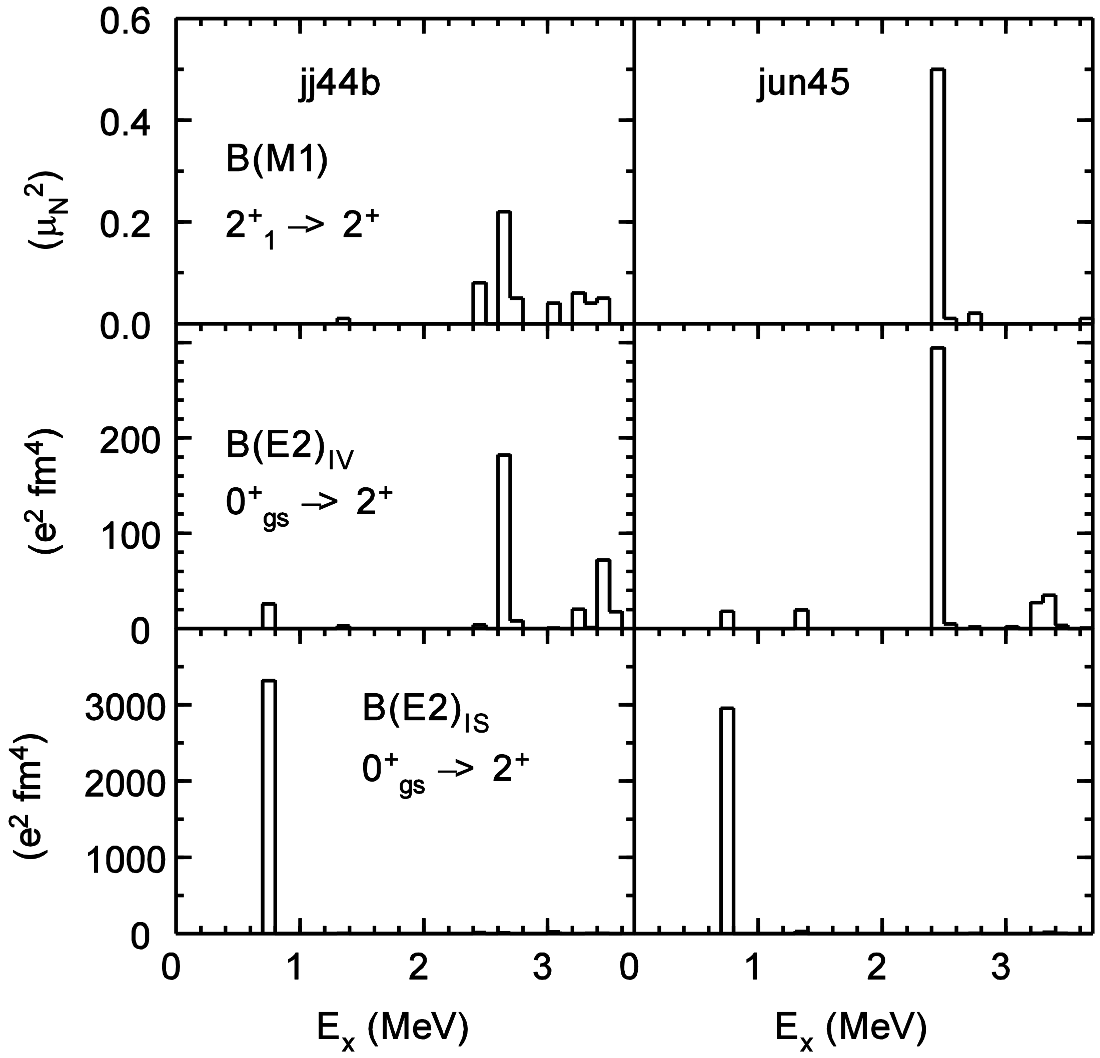




Calculations by B. A. Brown

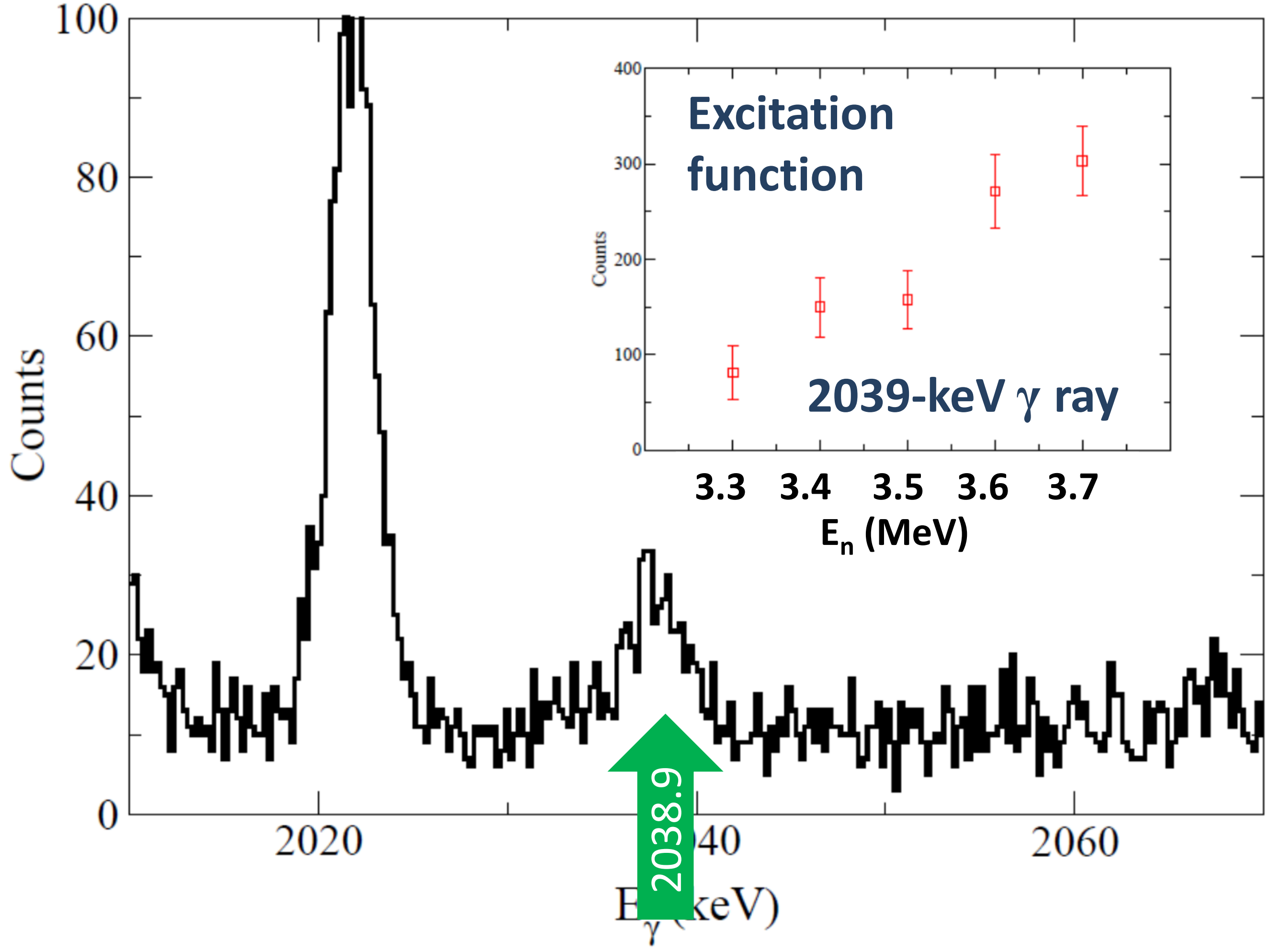
Mixed-Symmetry State





2039-keV Region in the ^{76}Ge(n,n′γ) Spectrum

E_n = 3.7 MeV



B.P. Crider et al., Phys. Rev. C 92, 034310 (2015)

$0\nu\beta\beta$ nuclei studied by INS at UKAL

^{48}Ca – J.R. Vanhoy, et al., Phys. Rev. C 45, 1628 (1992)
^{76}Ge – In progress and B.P. Crider et al., Phys. Rev. C 92, 034310 (2015)
^{76}Se – In progress
^{82}Se – Planned
^{96}Zr – G. Molnár et al., Nucl. Phys. A500, 43 (1989)
T. Belgya et al., Nucl. Phys. A500, 77 (1989)
^{96}Mo – S.R. Lesher et al., Phys. Rev. C 75, 034318 (2007)
^{116}Cd – M. Kadi et al., Phys. Rev. C 68, 031306R (2003)
^{116}Sn – S. Raman et al., Phys. Rev. C 43, 521 (1991)
^{128}Te – S.F. Hicks et al., Phys. Rev. C 86, 054308 (2012)
^{130}Te – In progress
^{130}Xe – In progress
^{136}Xe – In progress
^{136}Ba – S. Mukhopadhyay et al., Phys. Rev. C 78, 034317 (2008).
^{150}Nd – In progress
^{150}Sm – Planned

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T. J. Ross
B. P. Crider
S. Mukhopadhyay
E. E. Peters

Other Collaborators:

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J. R. Vanhoy – U.S. Naval Academy
A = 76 Collaboration – Yale, TU Darmstadt, TUNL-HIγS, ANU…

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