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

Steven W. Yates

University of Kentucky Accelerator Laboratory
50 years 1964-2014

TRIUMF Double-β Decay Workshop
13 May 2016

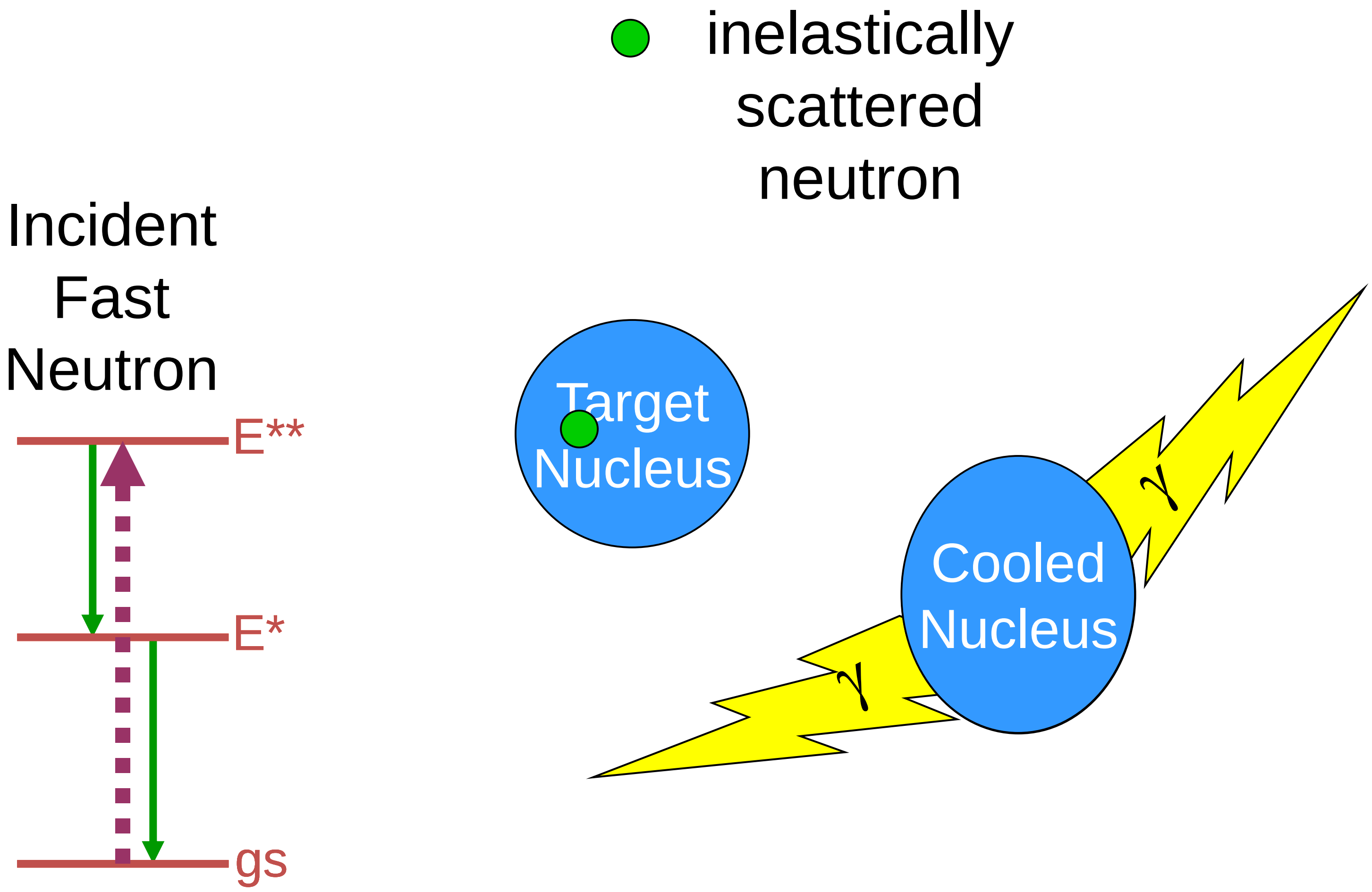
Questions

What experimental data should theory reproduce so we trust neutrinoless double-beta decay predictions?

What existing experimental data is most useful for constraining the various theory ingredients, and what are the most crucial unmeasured quantities?

Are excited state properties important?

Inelastic Neutron Scattering



(n,n'γ) reaction

From Inelastic Neutron Scattering

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

INS Experiments

Monoenergetic neutrons:

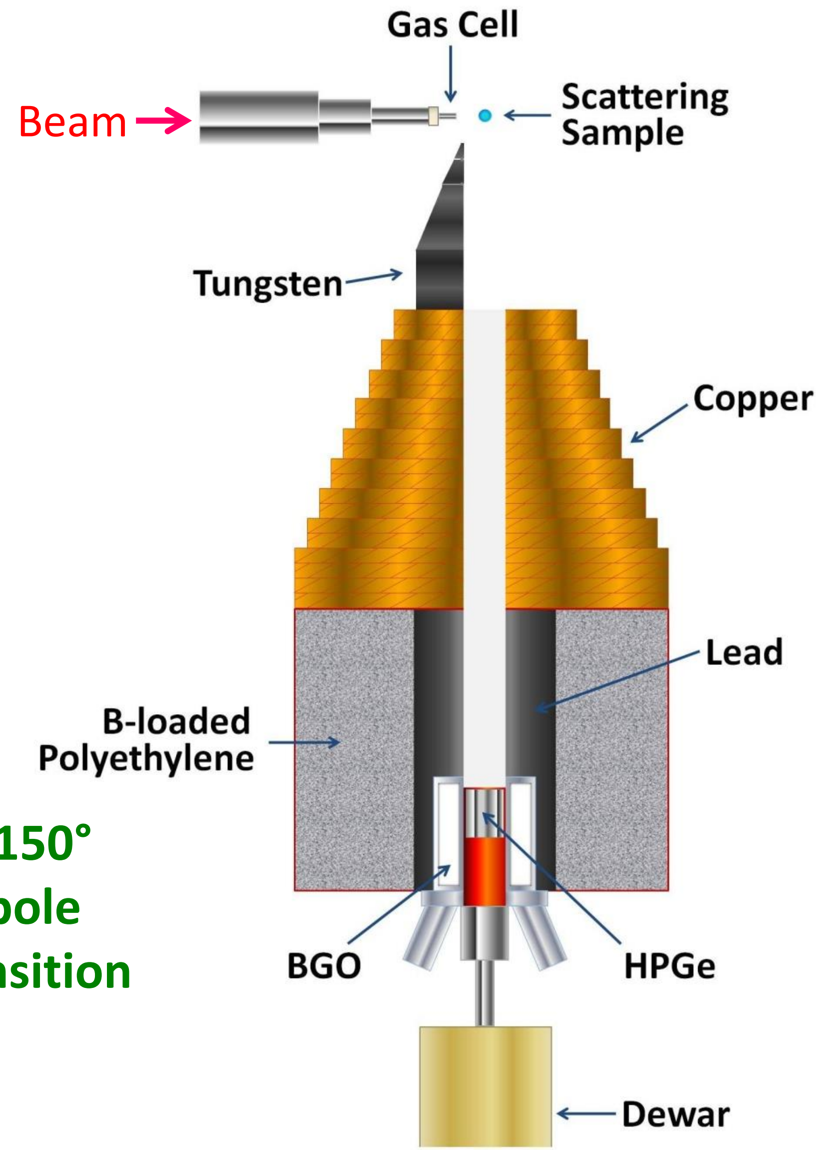
$^{3}H(p,n)^{3}He$ or $^{2}H(d,n)^{3}He$

Excitation functions

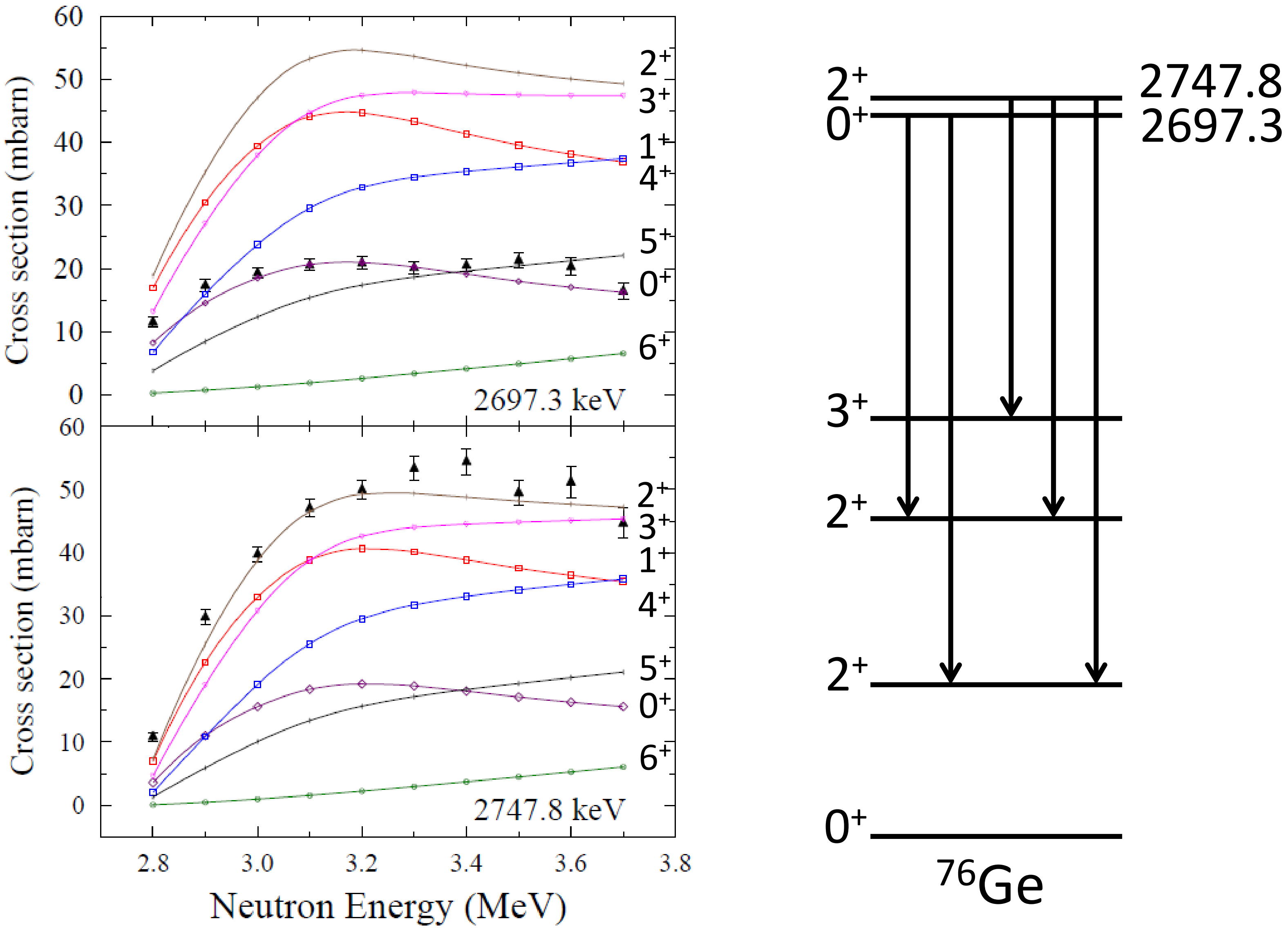
- Vary neutron energy
- Detection angle constant
- Build level scheme
- Cross sections

Angular distributions

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



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



INS Experiments

Monoenergetic neutrons:

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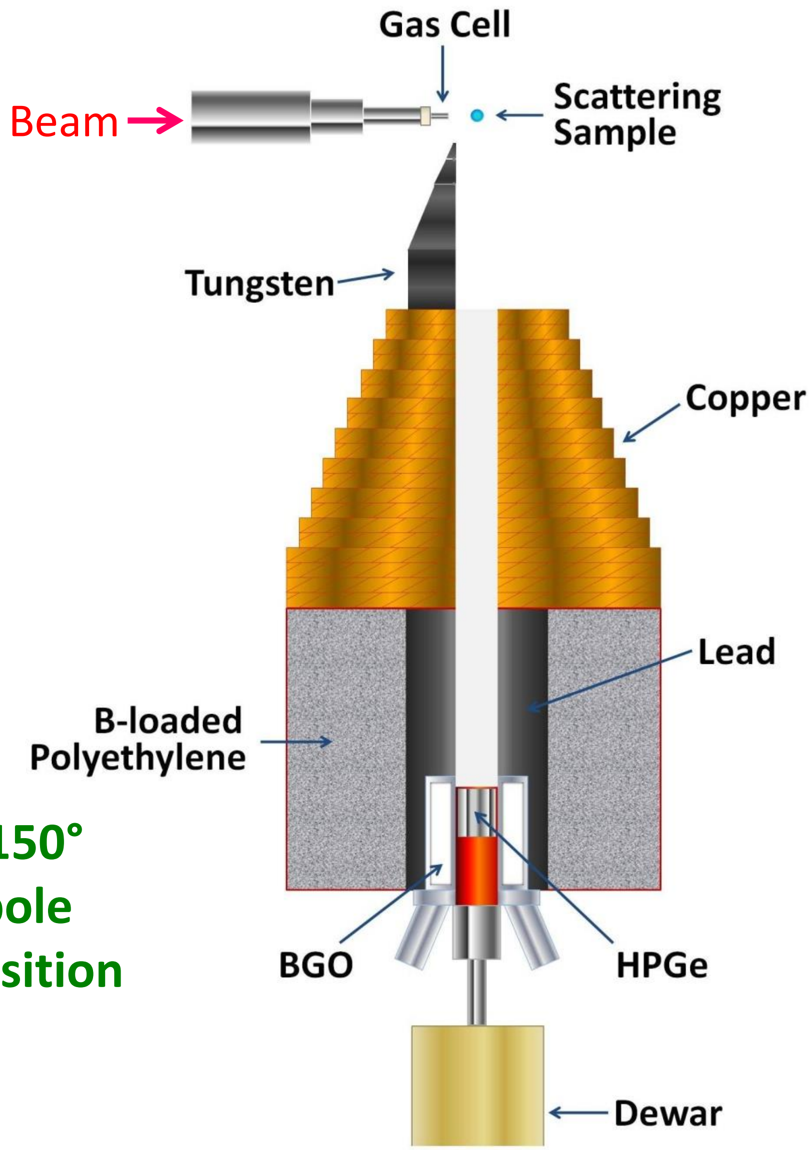

Excitation functions

- Vary neutron energy
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Angular distributions

- Constant neutron energy
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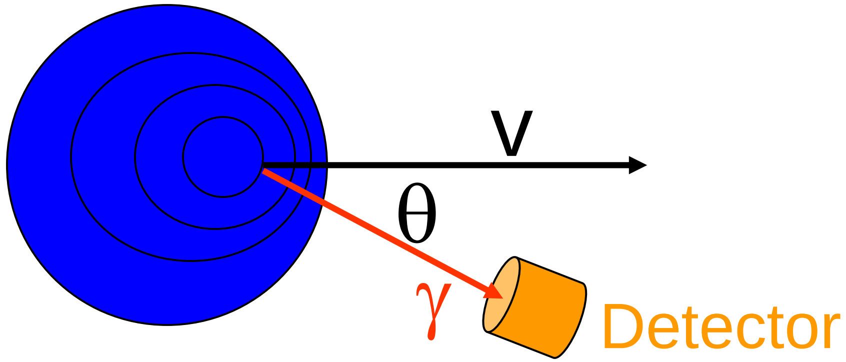
- Transition multipolarities, multipole mixing ratios, level lifetimes, transition probabilities

Doppler-Shift Attenuation Method



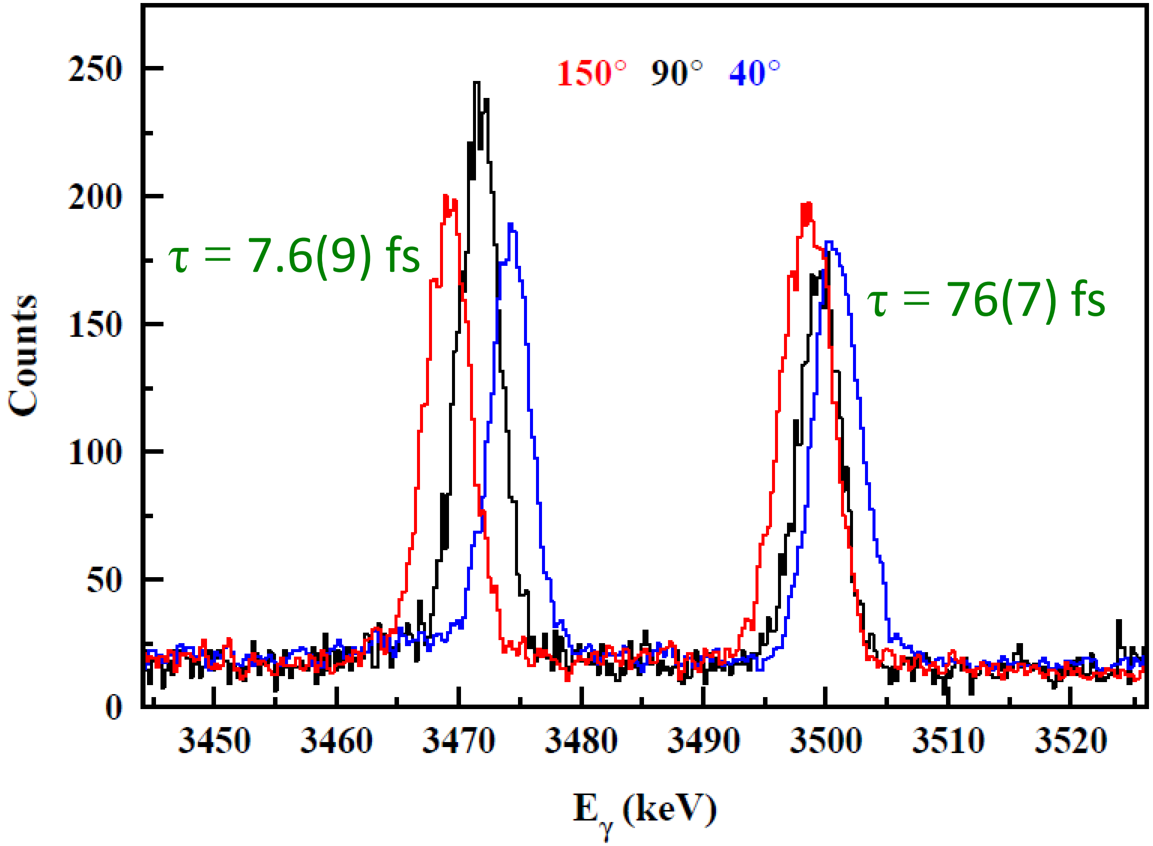
$$E(\theta) = E_\gamma\,(1 + v/c\,\cos\theta)$$

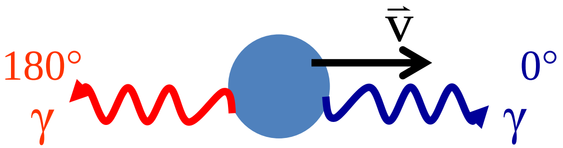
The nucleus is recoiling into a viscous medium.

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

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

Level Lifetimes: Doppler-Shift Attenuation Method (DSAM)





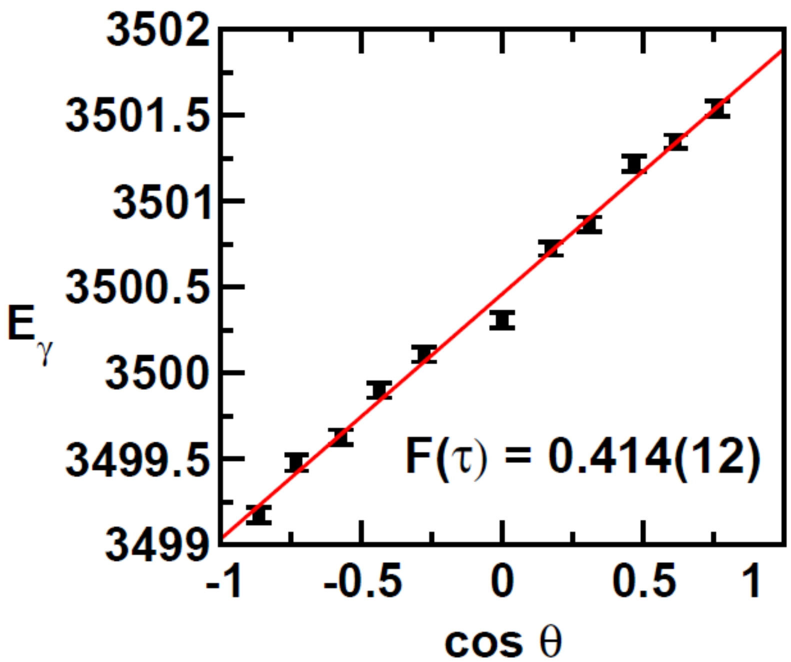
Scattered neutron causes the nucleus to recoil.

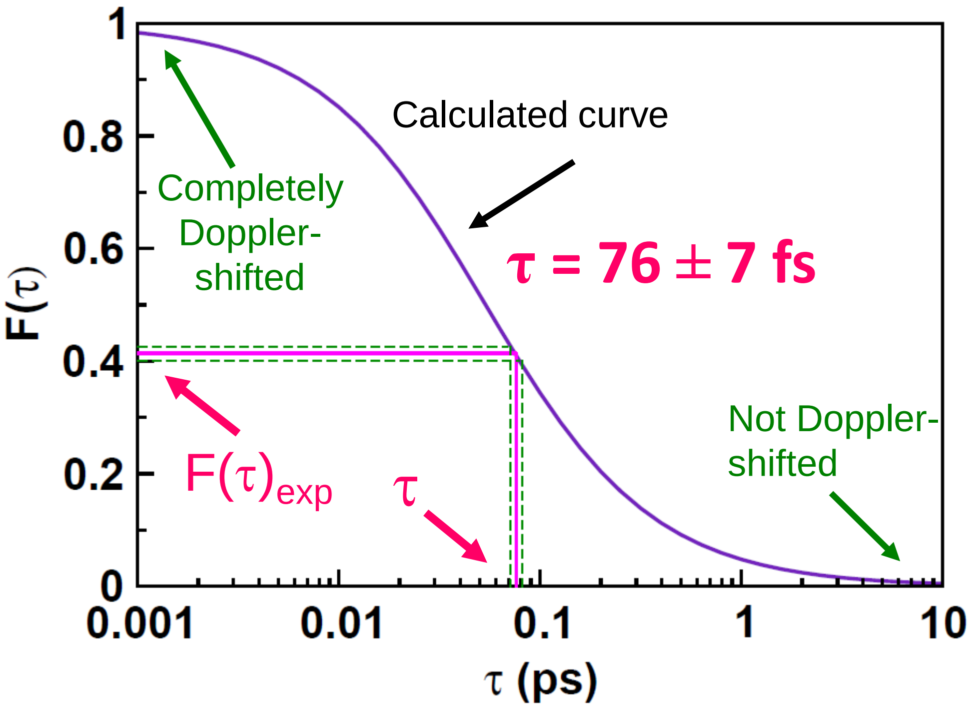
Emitted γ rays experience a Doppler shift.

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

- ☞ 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 nuclei
- 👎 Large amounts of enriched isotopes required

Why study ^{76}Ge?

It is the parent for double-β decay.

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

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

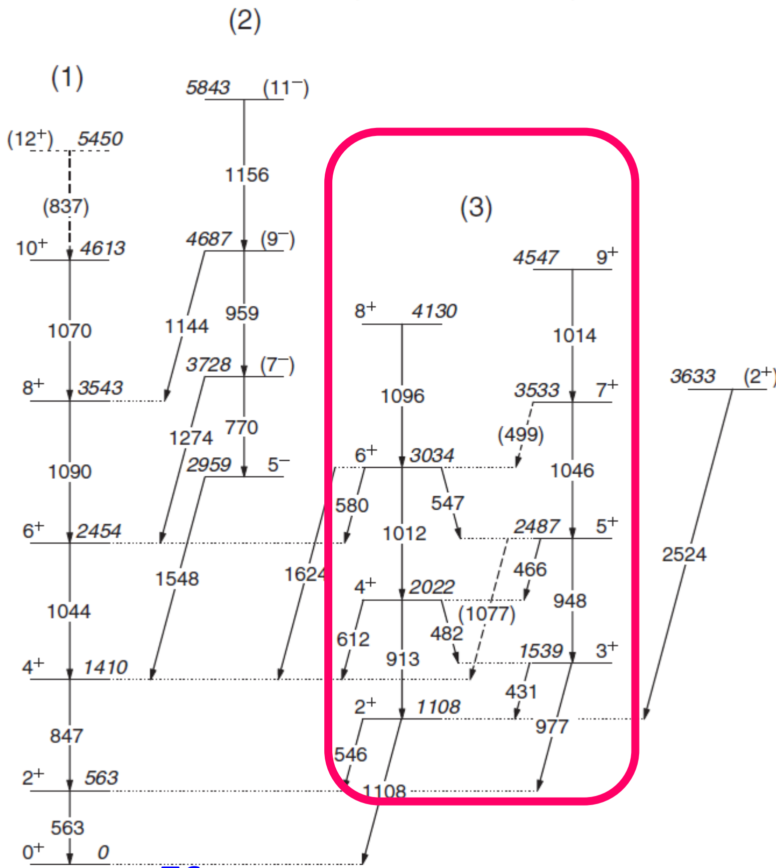
It is structurally interesting.

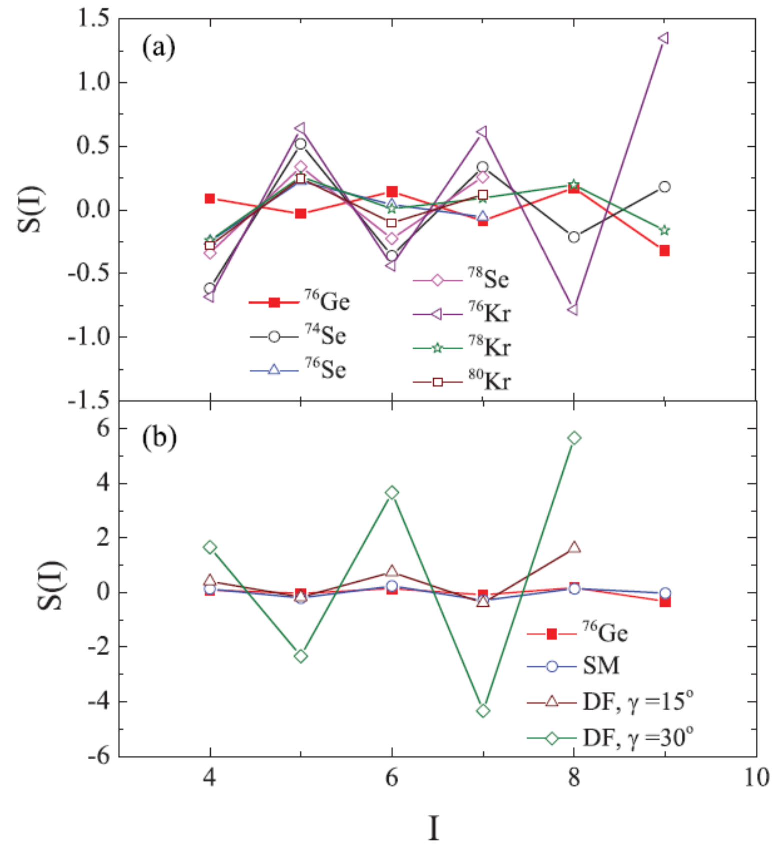
- ❑ Shape Transition
- ❑ Shape Coexistence
- ❑ Rigid Triaxiality

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."

Physics Letters B 734 (2014) 308–313

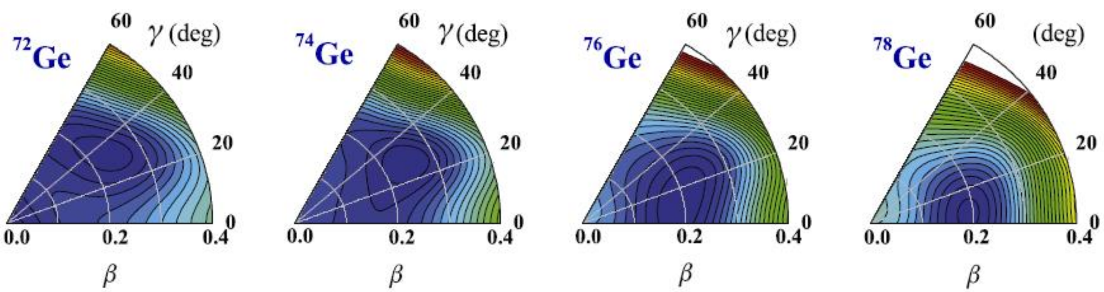
Contents lists available at ScienceDirect

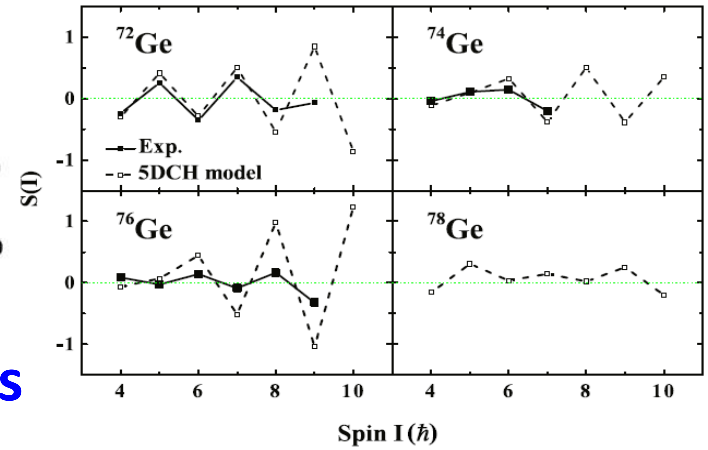
Physics Letters B

www.elsevier.com/locate/physletb

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

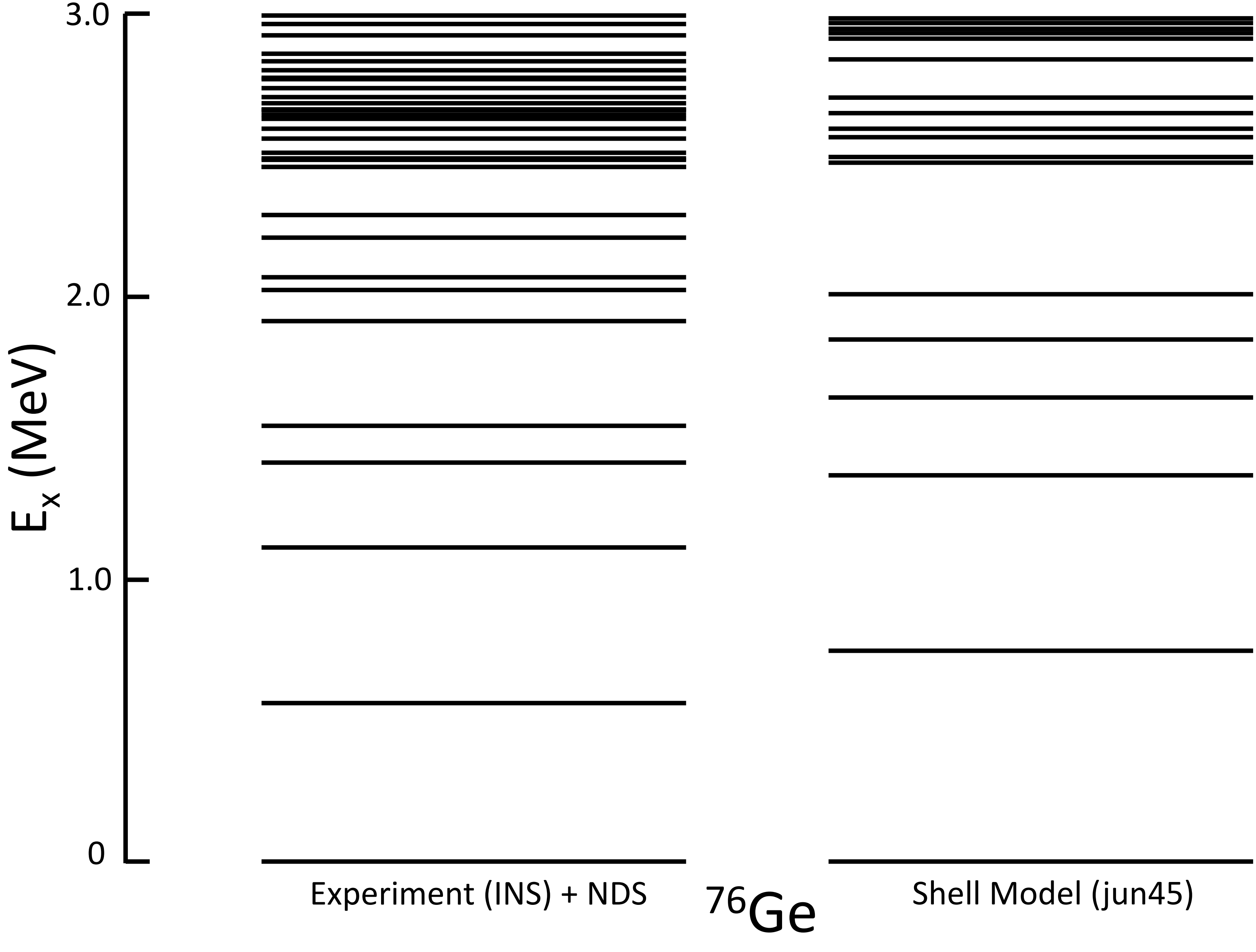
J.J. Sun [a], Z. Shi [b], X.Q. Li [a,*], H. Hua [a,*], C. Xu [a], Q.B. Chen [a], S.Q. Zhang [a], C.Y. Song [b], J. Meng [a], X.G. Wu [c], S.P. Hu [c], H.Q. Zhang [c], W.Y. Liang [a], F.R. Xu [a], Z.H. Li [a], G.S. Li [c], C.Y. He [c], Y. Zheng [c], Y.L. Ye [a], D.X. Jiang [a], Y.Y. Cheng [a], C. He [a],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



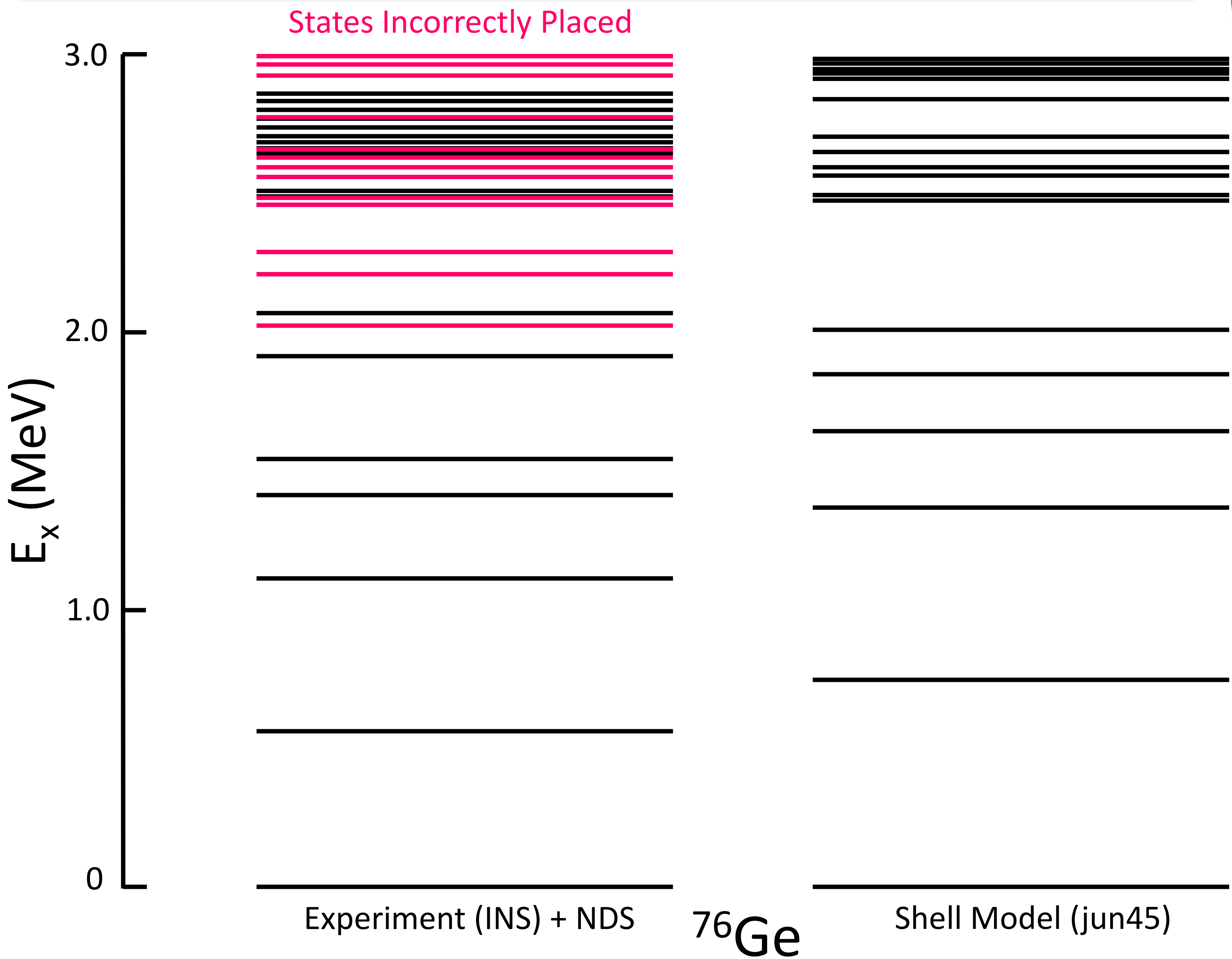


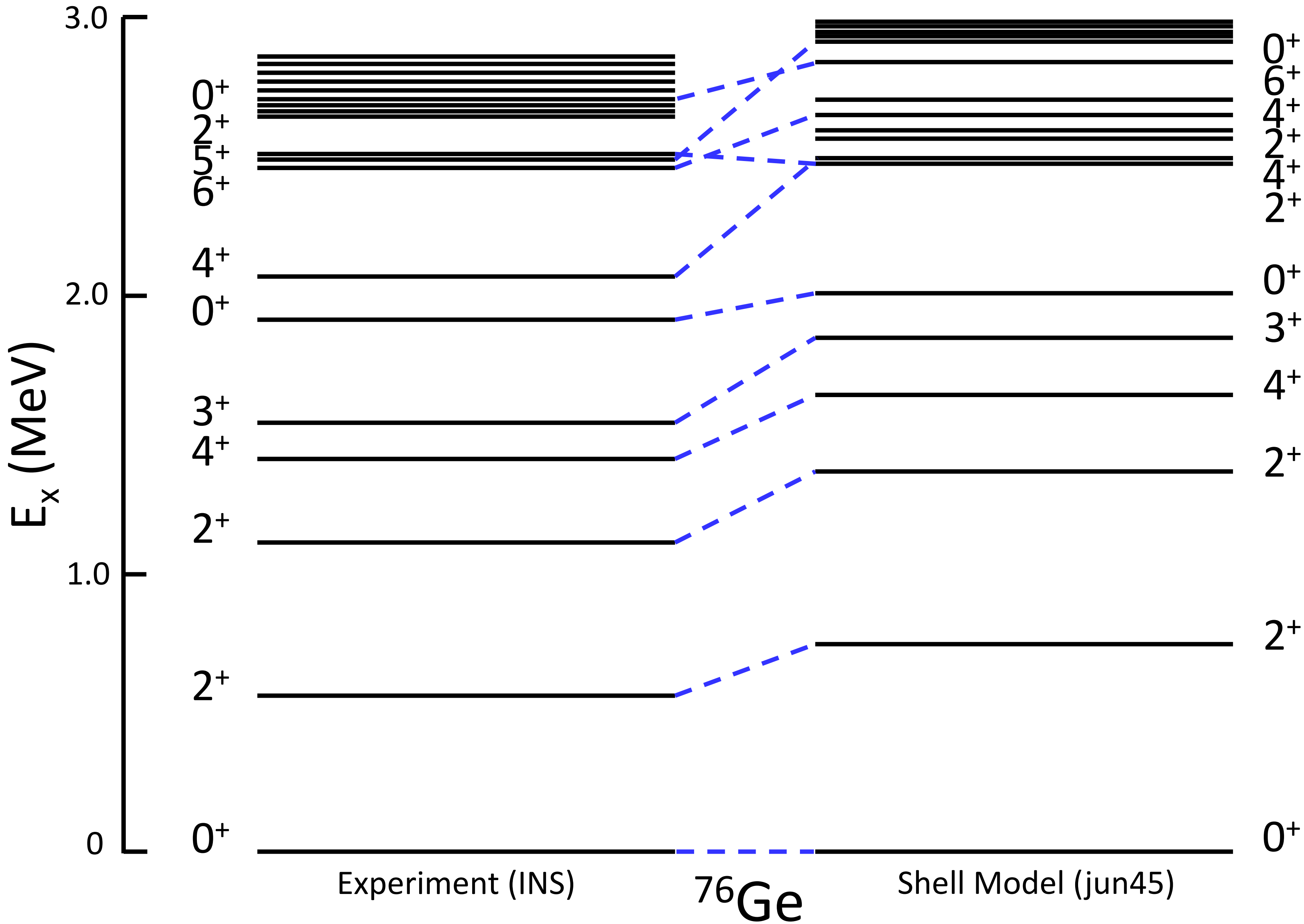
“ …^{74}Ge is found to be the crucial nucleus marking the triaxial evolution from soft to rigid in Ge isotopes.”


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

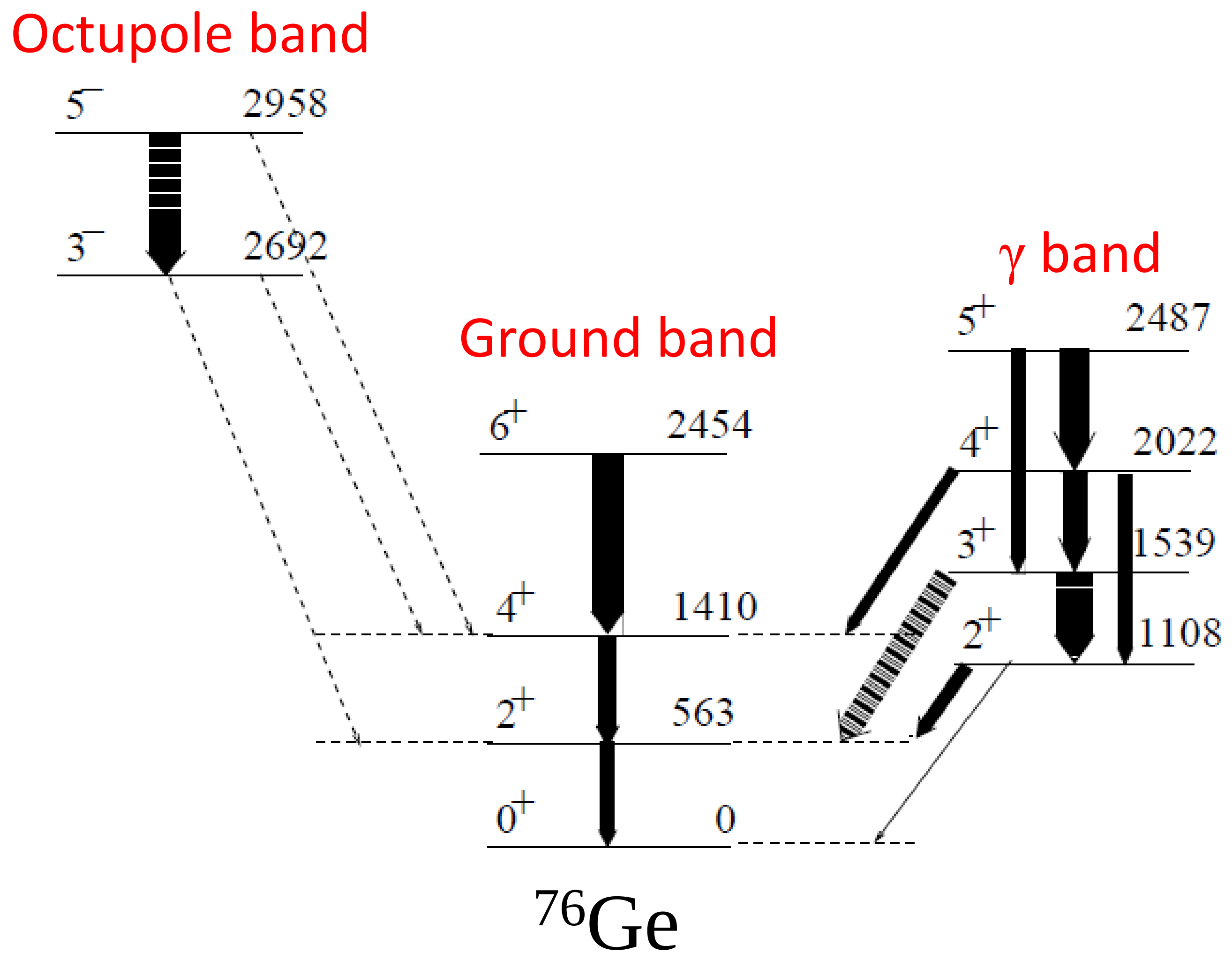


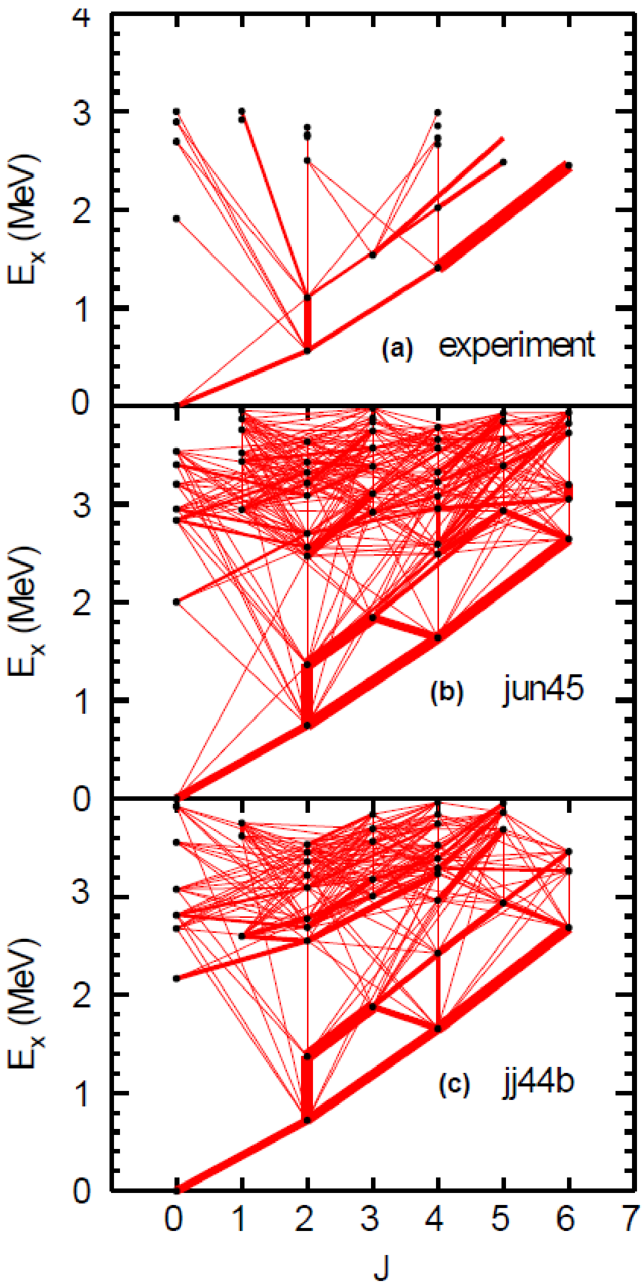
3.0
2.0
1.0
0
E_x (MeV)
Experiment (INS) + NDS
^{76}Ge
Shell Model (jun45)

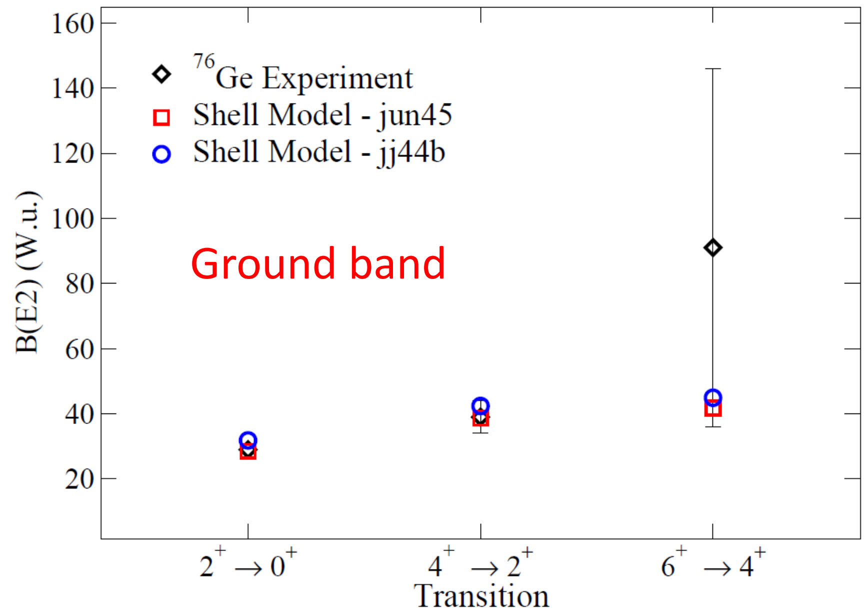

States Incorrectly Placed
3.0
2.0
1.0
0
E$_x$ (MeV)
Experiment (INS) + NDS
^{76}Ge
Shell Model (jun45)

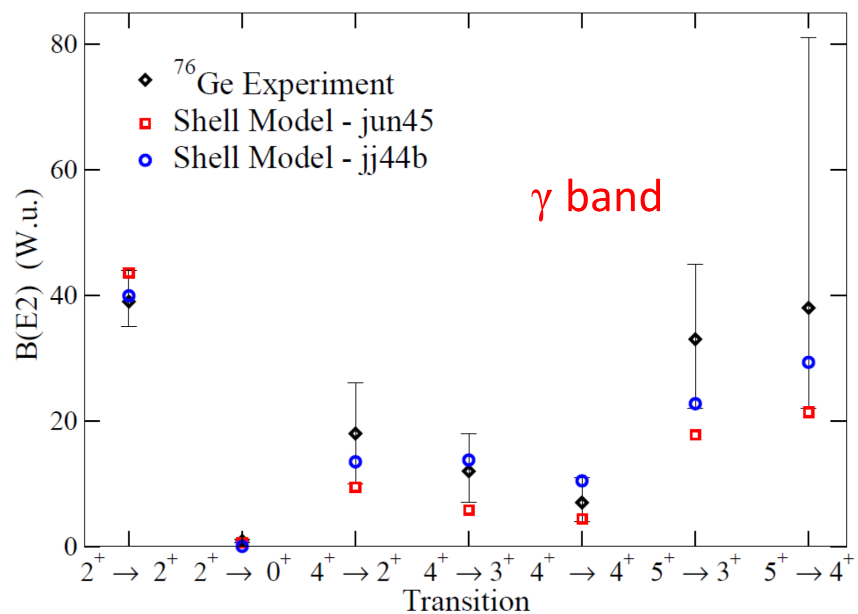


Ex (MeV)
3.0
2.0
1.0
0
0+
2+
5+
6+
4+
0+
3+
4+
2+
2+
0+
0+
6+
4+
2+
4+
2+
0+
3+
4+
2+
2+
0+
Experiment (INS)
76Ge
Shell Model (jun45)


Octupole band
5⁻ 2958
3⁻ 2692
Ground band
6+ 2454
4+ 1410
2+ 563
0+ 0
γ band
5+ 2487
4+ 2022
3+ 1539
2+ 1108
76Ge





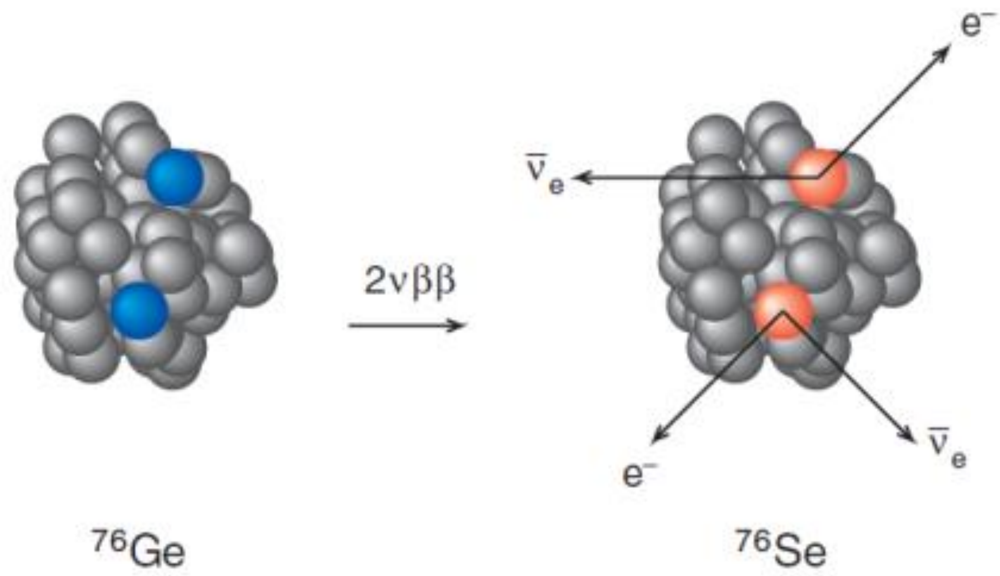


Calculations by B. A. Brown

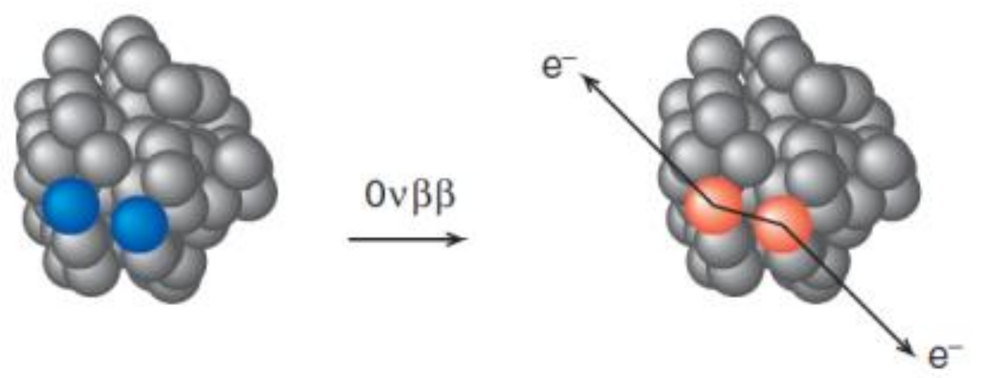
0νββ nuclei studied by INS at UKAL

^{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

Double-β Decay of ^{76}Ge



$Q_{\beta\beta}$ = 2039.06 keV



B. A. Brown, D. L. Fang, and M. Horoi, Phys. Rev. C **92**, 041301(R) (2015)

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

MAJORANA DEMONSTRATOR

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

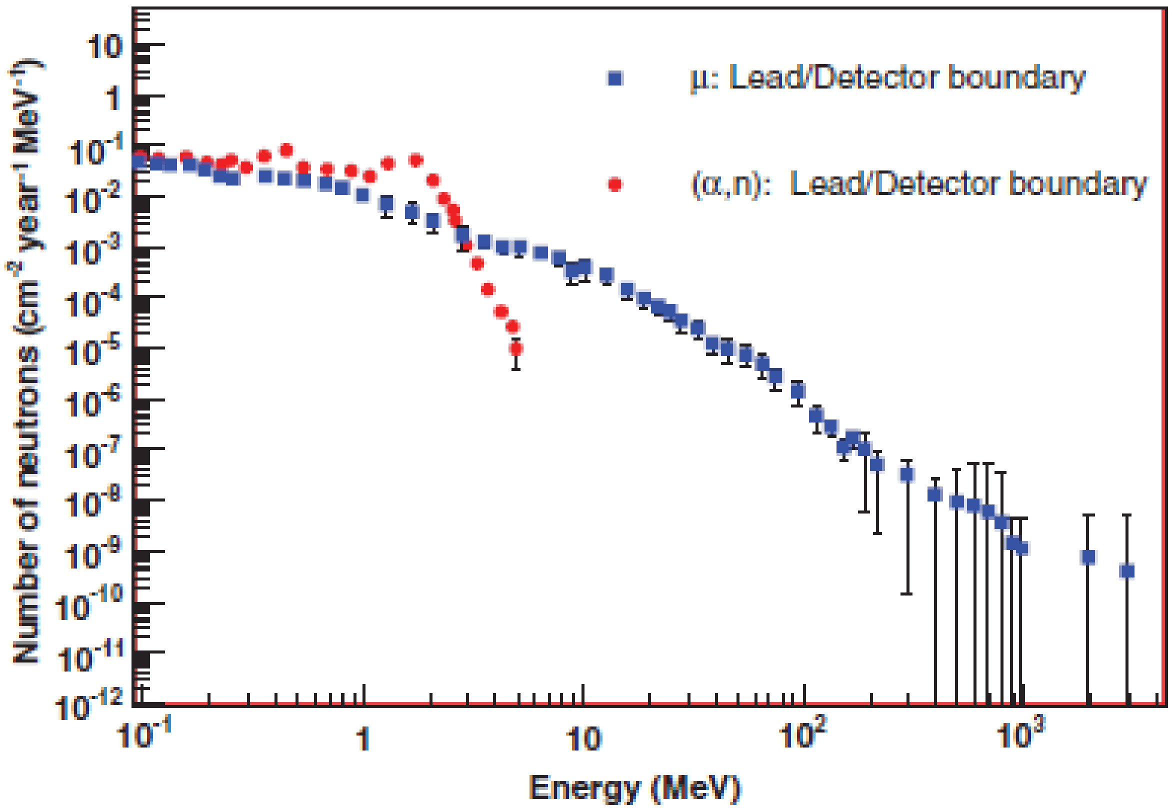
http://neutrino.lbl.gov/majorana.htm

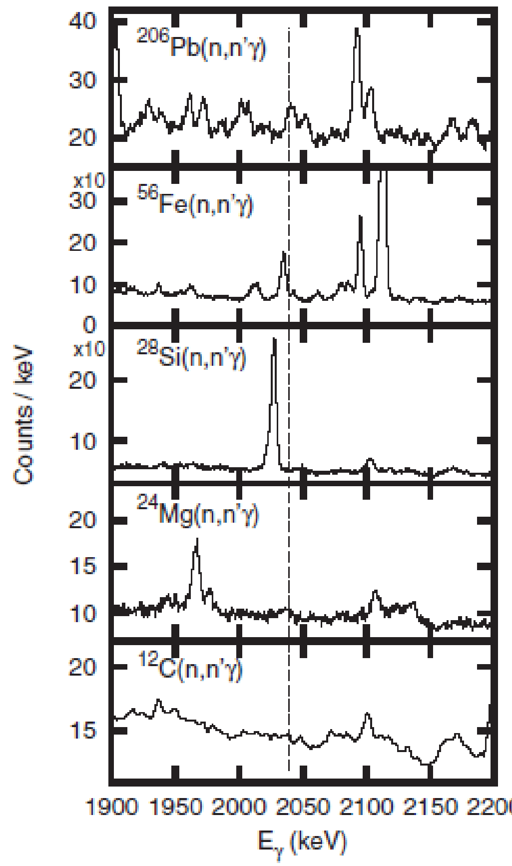
GERDA

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

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

(n,n′γ) reactions become important in assessing backgrounds for tonne-scale double-β decay experiments.

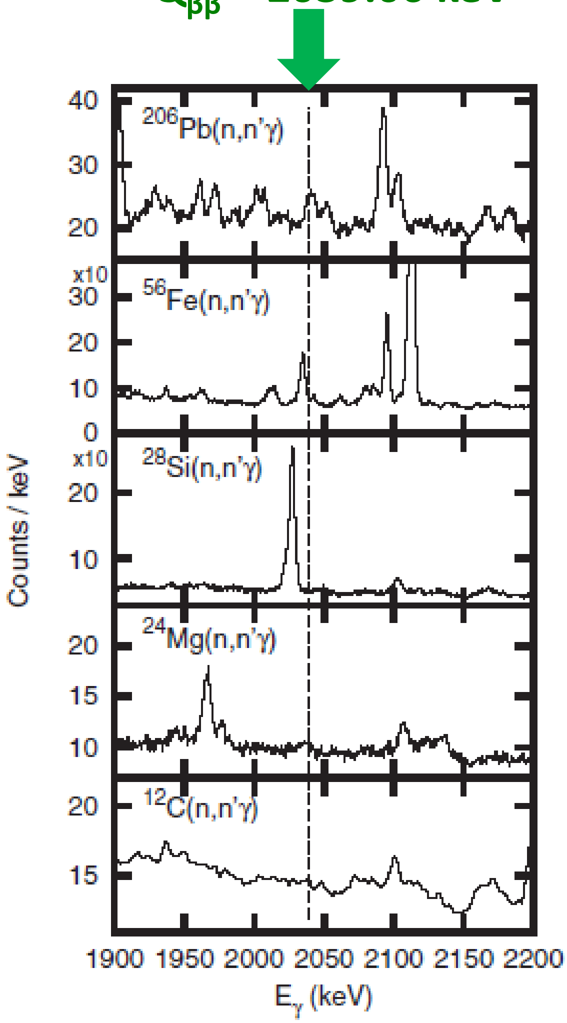




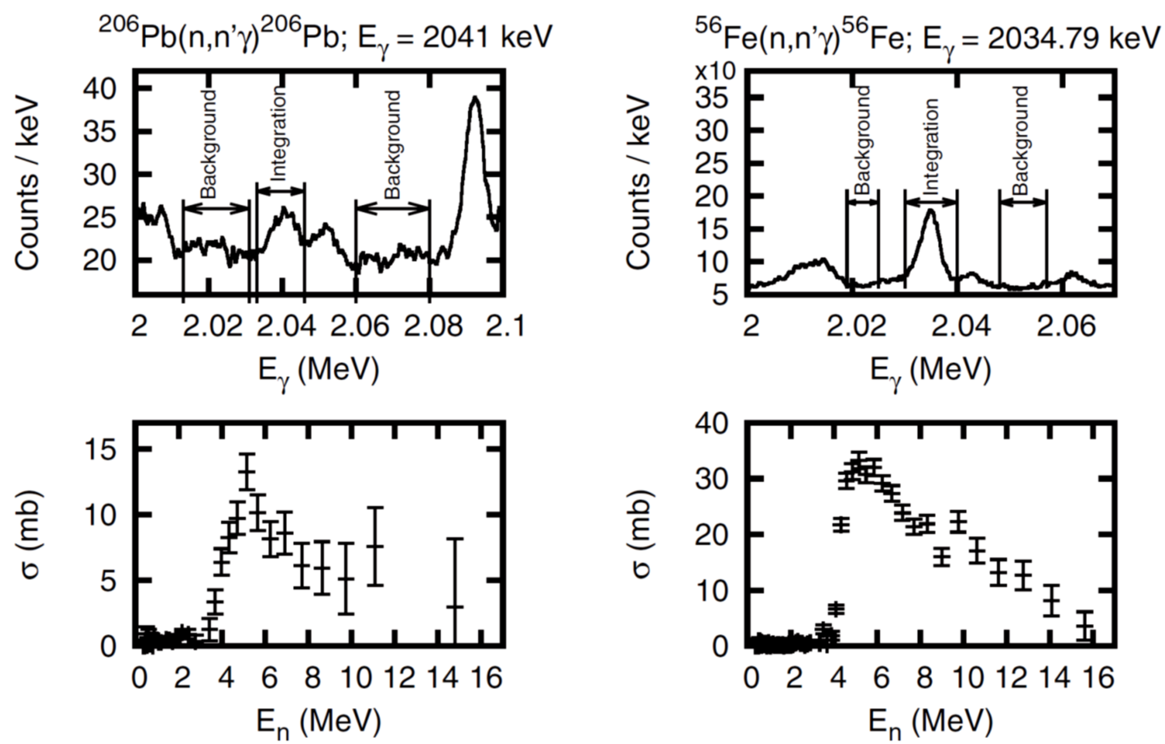
D.-M. Mei and A. Hime, Phys. Rev. D **73**, 053004 (2006)
D.-M. Mei *et al.*, Phys. Rev. C **77**, 054614 (2008)
A. Negret, C. Borcea, and A. J. M. Plompen, Phys. Rev. C **88**, 027601 (2013)

(n,n′γ) Backgrounds for Double-β Decay Experiments

$Q_{\beta\beta}$ = 2039.06 keV



GELINA (Geel Linear Accelerator) white neutron source



A. Negret, C. Borcea, and A. J. M. Plompen, Phys. Rev. C **88**, 027601 (2013)

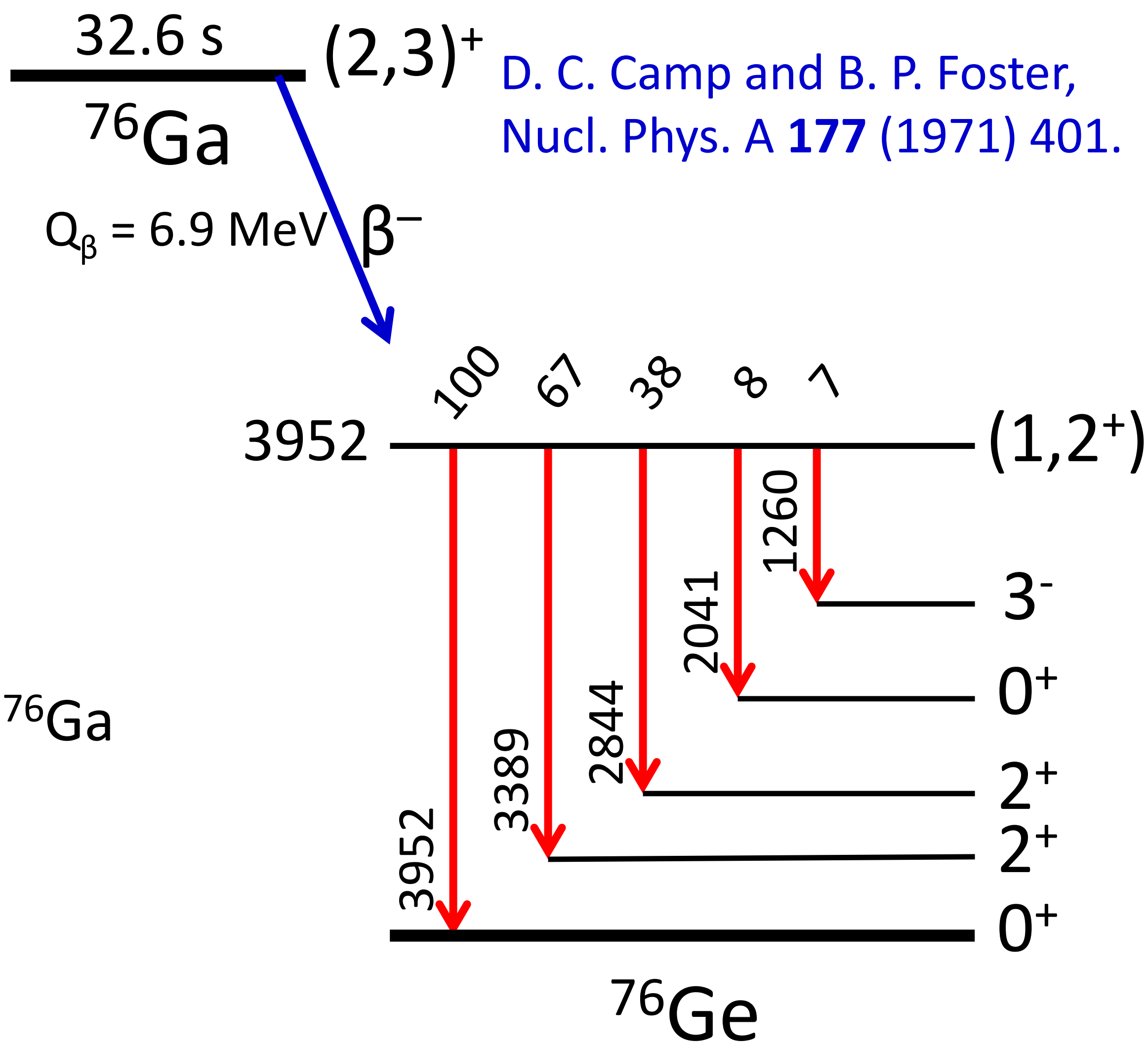
High sensitivity of 0νββ measurements means identification and characterization of the background is critical.

$Q_{\beta\beta}$ = 2039.06 keV

D. C. Camp and B. P. Foster, Nucl. Phys. A **177** (1971) 401.

69th level in ^{76}Ge

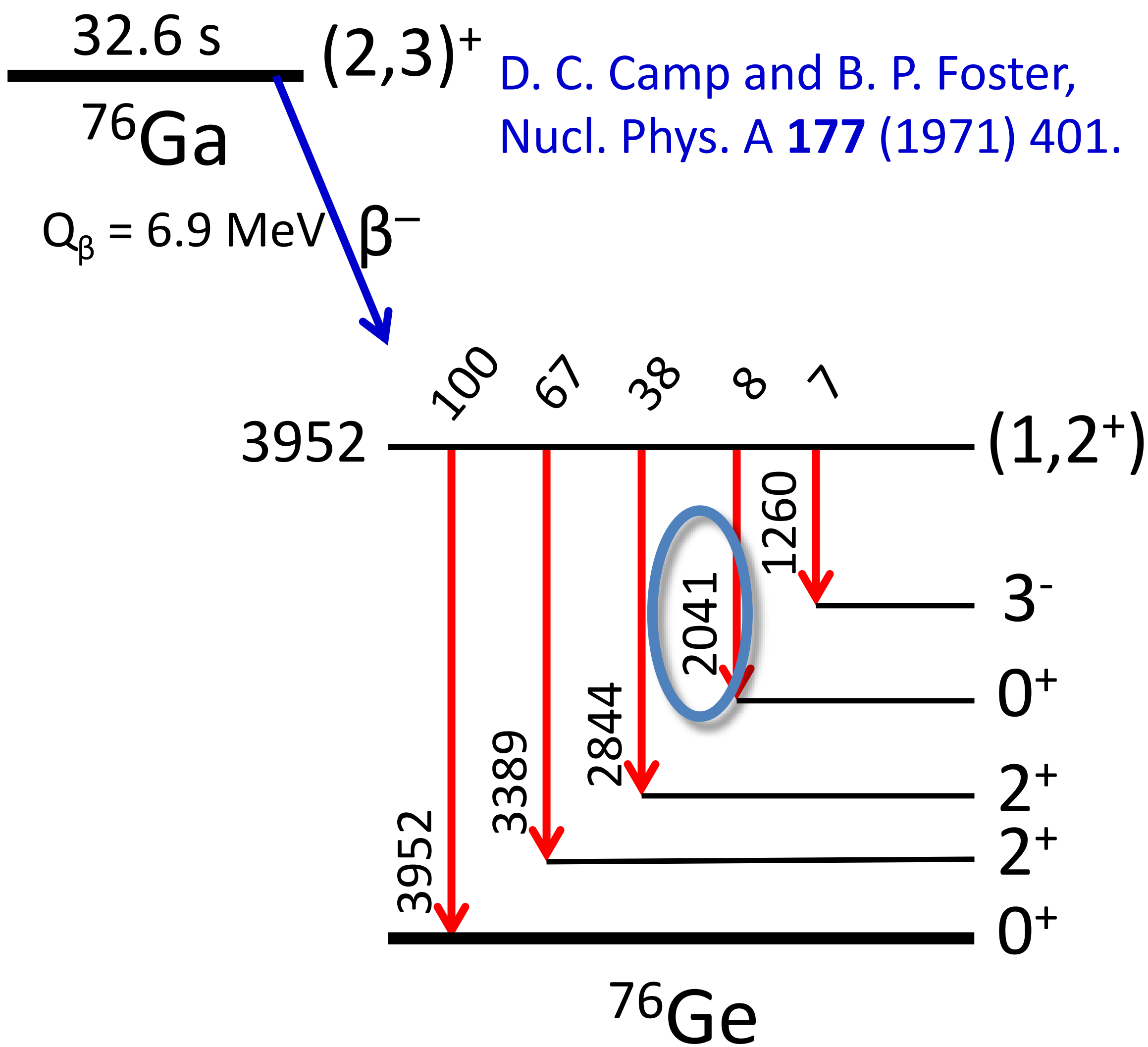
Produced by $^{76}Ge(n,p)^{76}Ga$



Possible Interferences from ^{76}Ga β Decay

$Q_{\beta\beta}$ = 2039.06 keV

D. C. Camp and B. P. Foster, Nucl. Phys. A **177** (1971) 401.



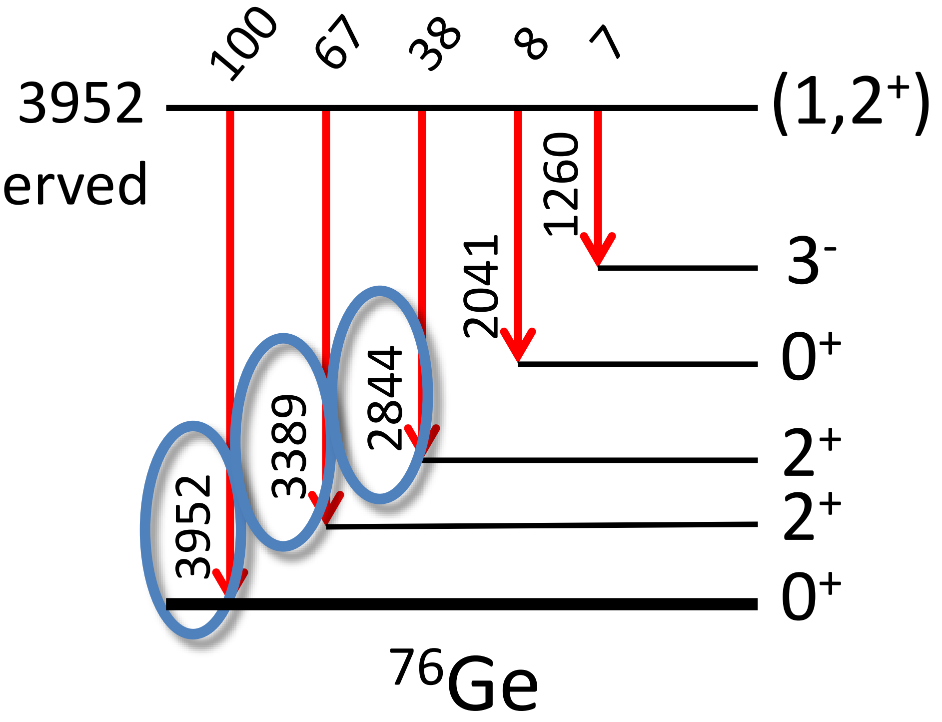
69th level in ^{76}Ge

Observed in ^{76}Ge(n,n'γ)

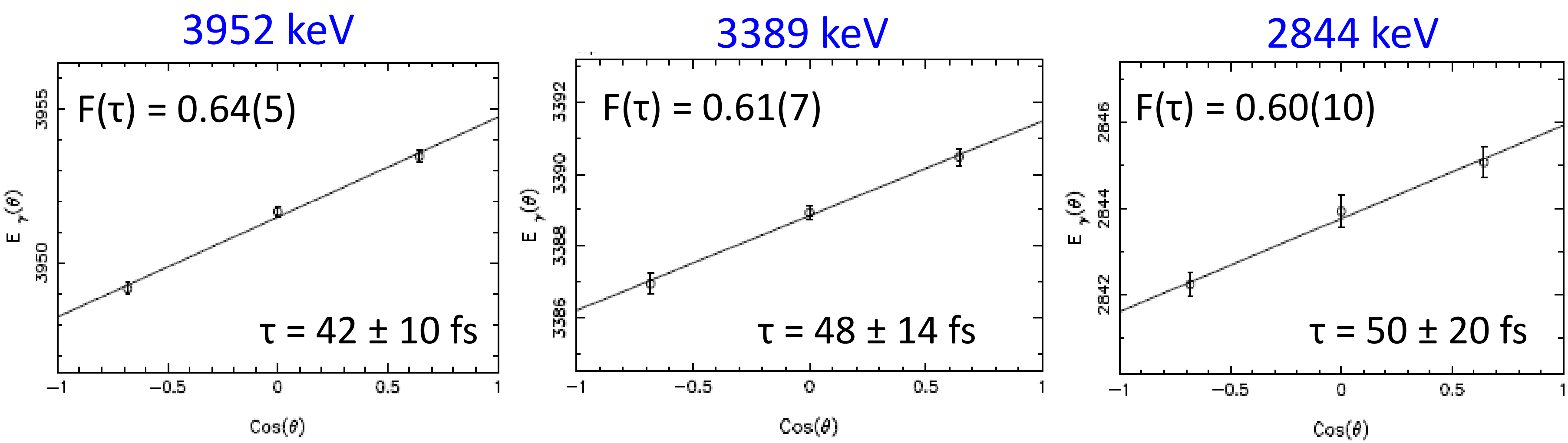
D. C. Camp and B. P. Foster,
Nucl. Phys. A **177** (1971) 401.

69th level in ^{76}Ge

3 most intense decay γ rays observed

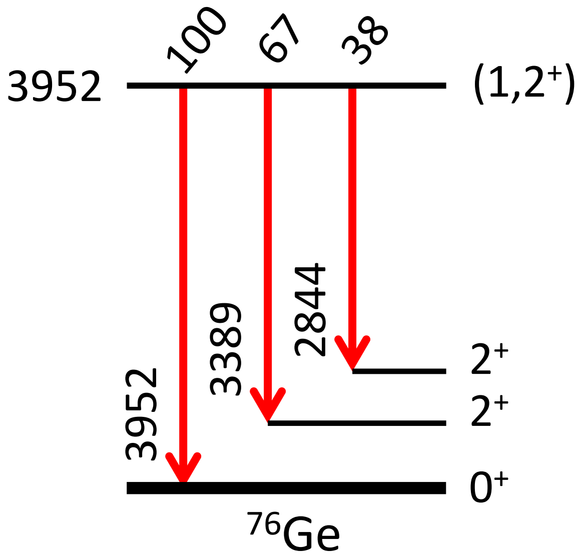


Investigating the 3952-keV Level



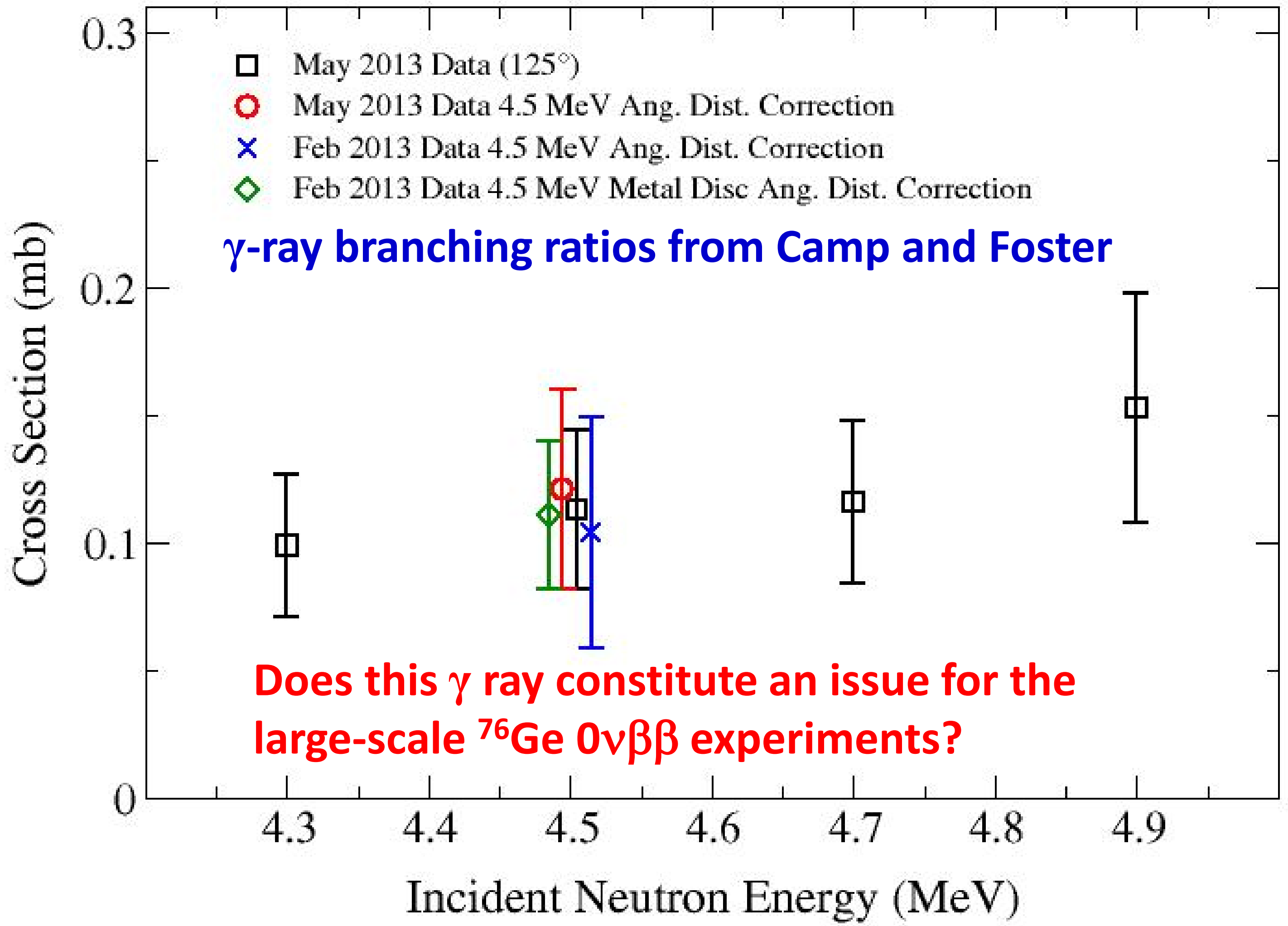
The three observed transitions yield the same lifetime.

$$\tau(3952\text{-keV Level}) = 46^{+14}_{-12}\ \text{fs}$$



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

Cross Section for Production of the 2041-keV γ ray



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

PHYSICAL REVIEW C **93**, 014614 (2016)

Fast-neutron-induced potential background near the Q value of neutrinoless double-β decay of ^{76}Ge

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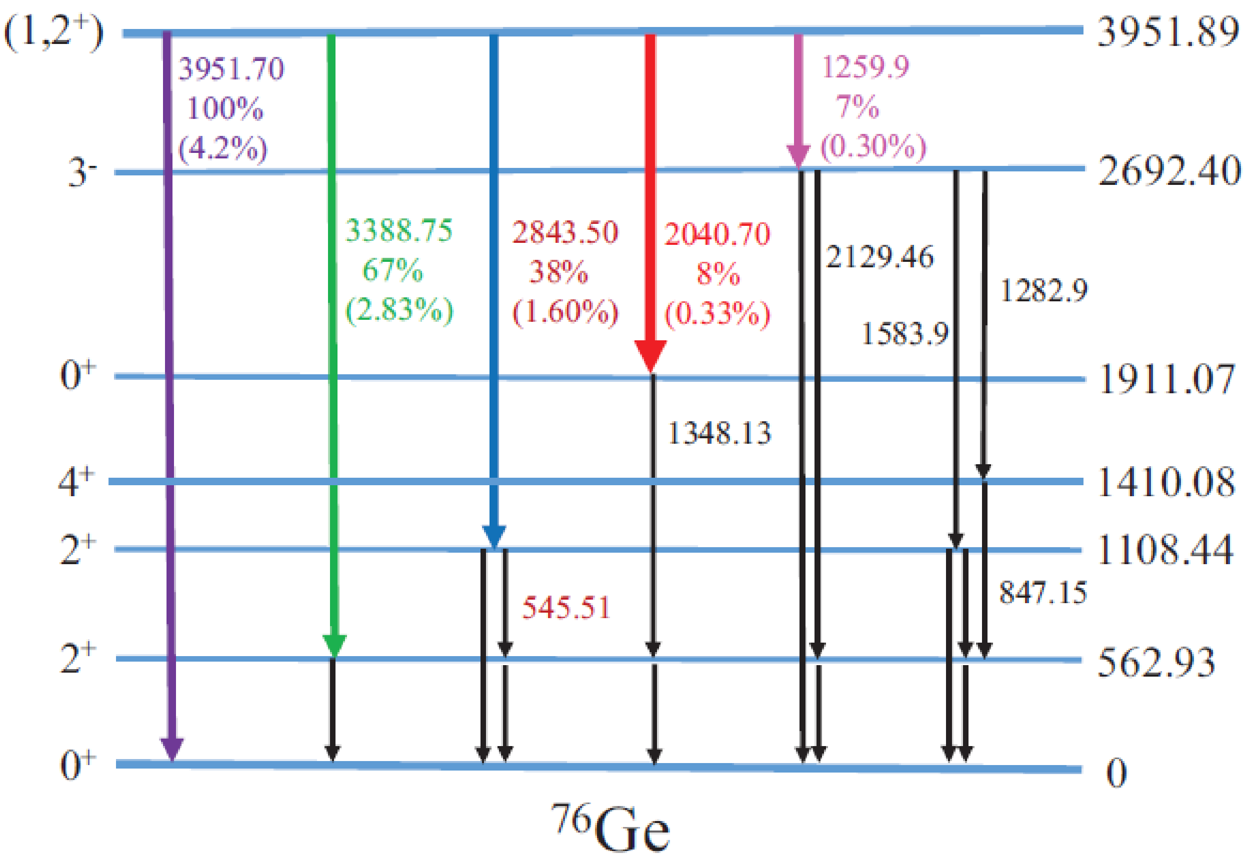
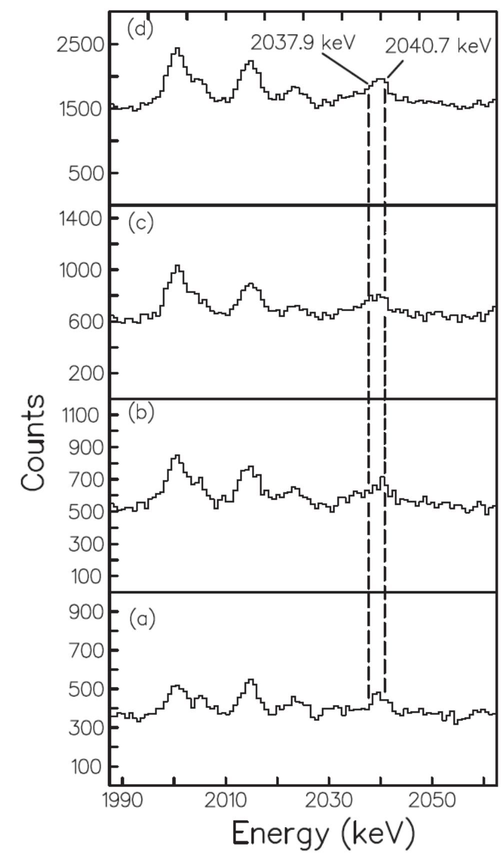
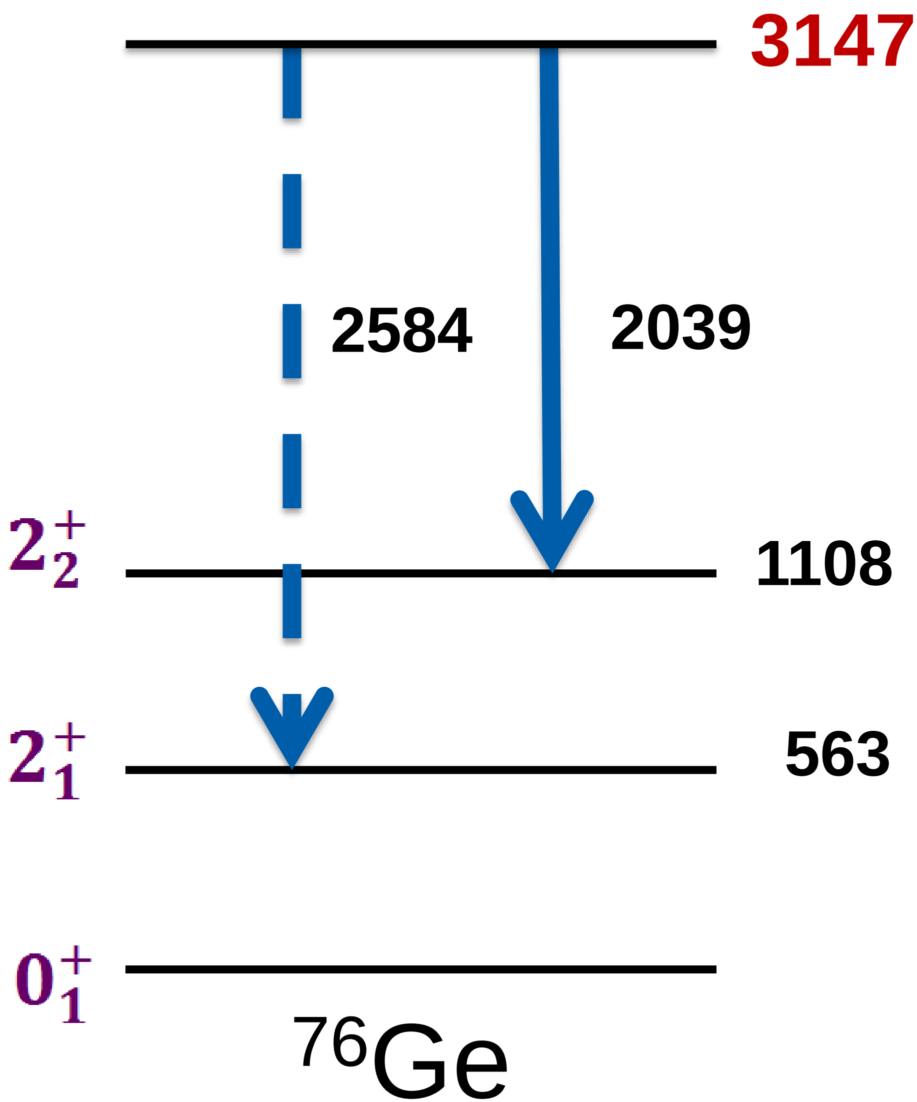
Department of Physics and Triangle Universities Nuclear Laboratory, Duke University, Durham, North Carolina 27708, USA

(Received 28 July 2015; published 20 January 2016)





New Level at 3147 keV

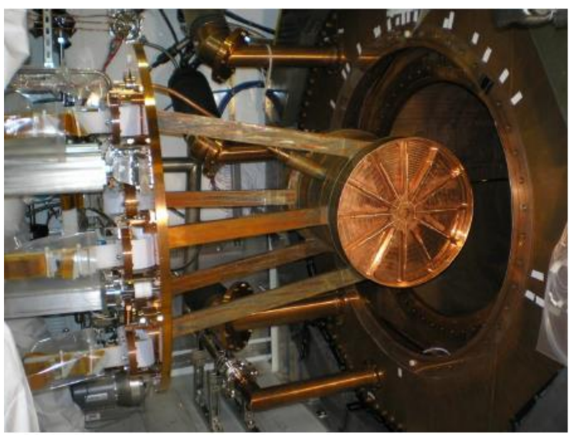


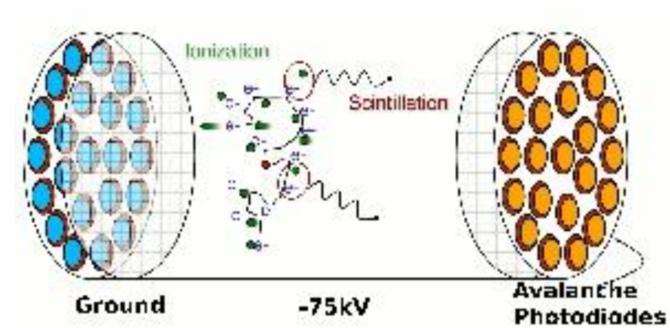
Do these γ rays constitute an issue for the tonne-scale ^{76}Ge $0\nu\beta\beta$ experiments?

- ❑ Other decays from excited states in ^{76}Ge
- ❑ New generation of Ge detectors (*e.g.*, P-type point contact detectors)
- ❑ Position resolution
- ❑ Single-site vs. multi-site events

EXO Enriched Xenon Observatory

- **EXO-200:**
  - 200 kg of Xe (*l*)
    - 80.6% enriched in ^{136}Xe (remaining 19.4% is ^{134}Xe)
  - Q-value: 2457.83 ± 0.37 keV

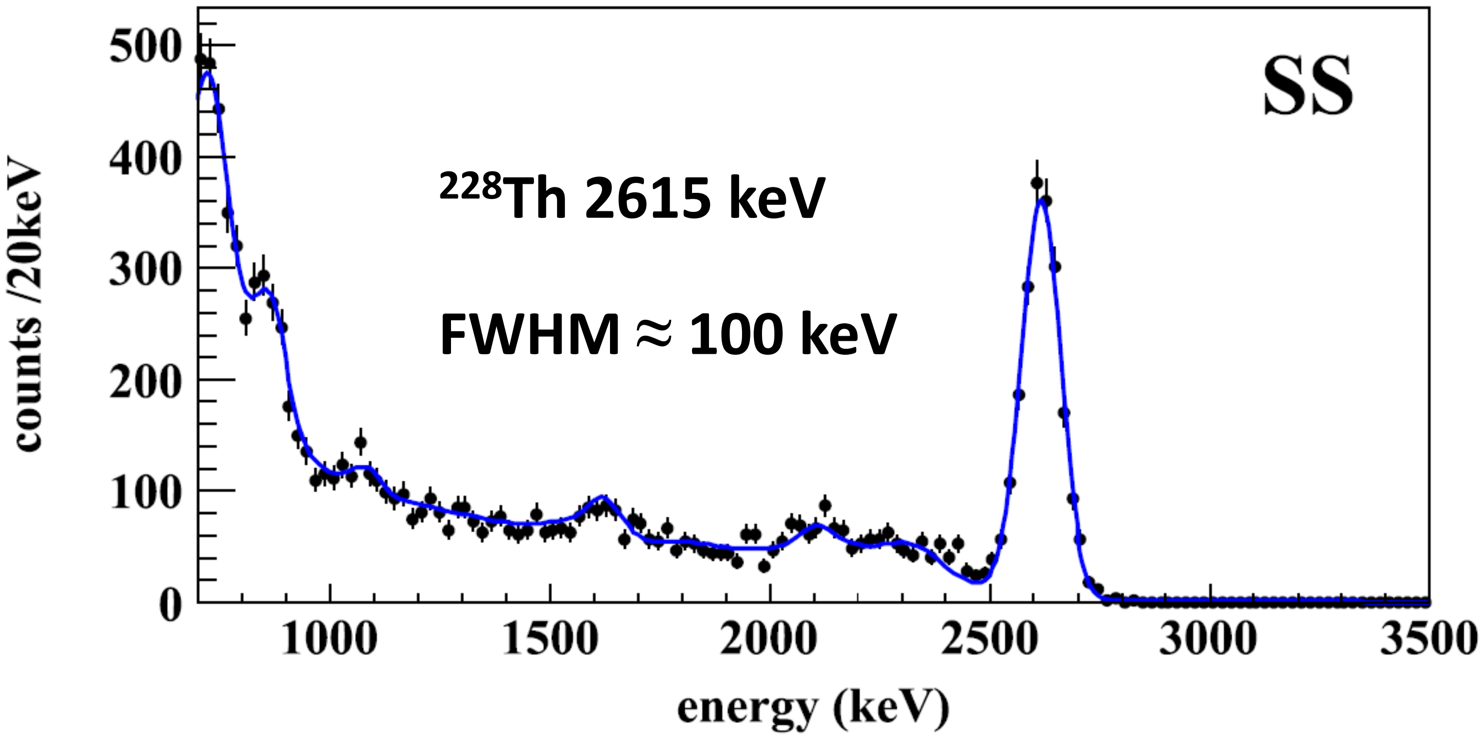




2012 JINST 7 P05010 PRL 109, 032505 (2012)

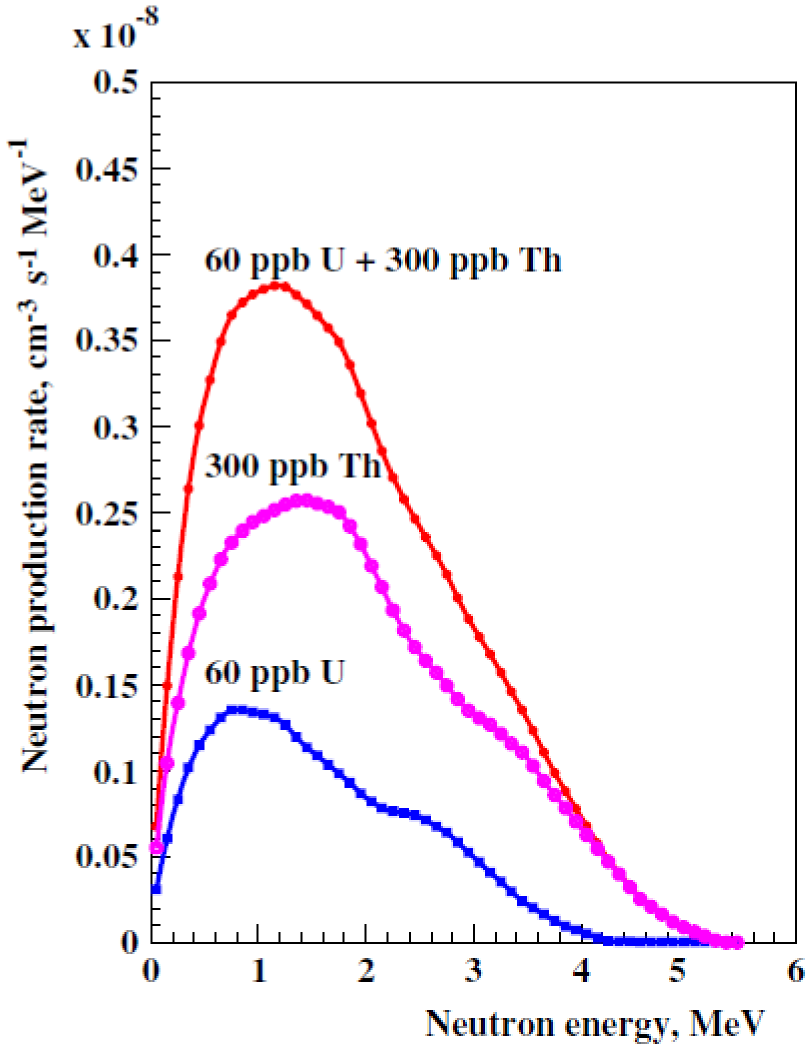
Pictures from R. Neilson TIPP 2011 and http://www-project.slac.stanford.edu/exo/

EXO Resolution



PRL 109, 032505 (2012)

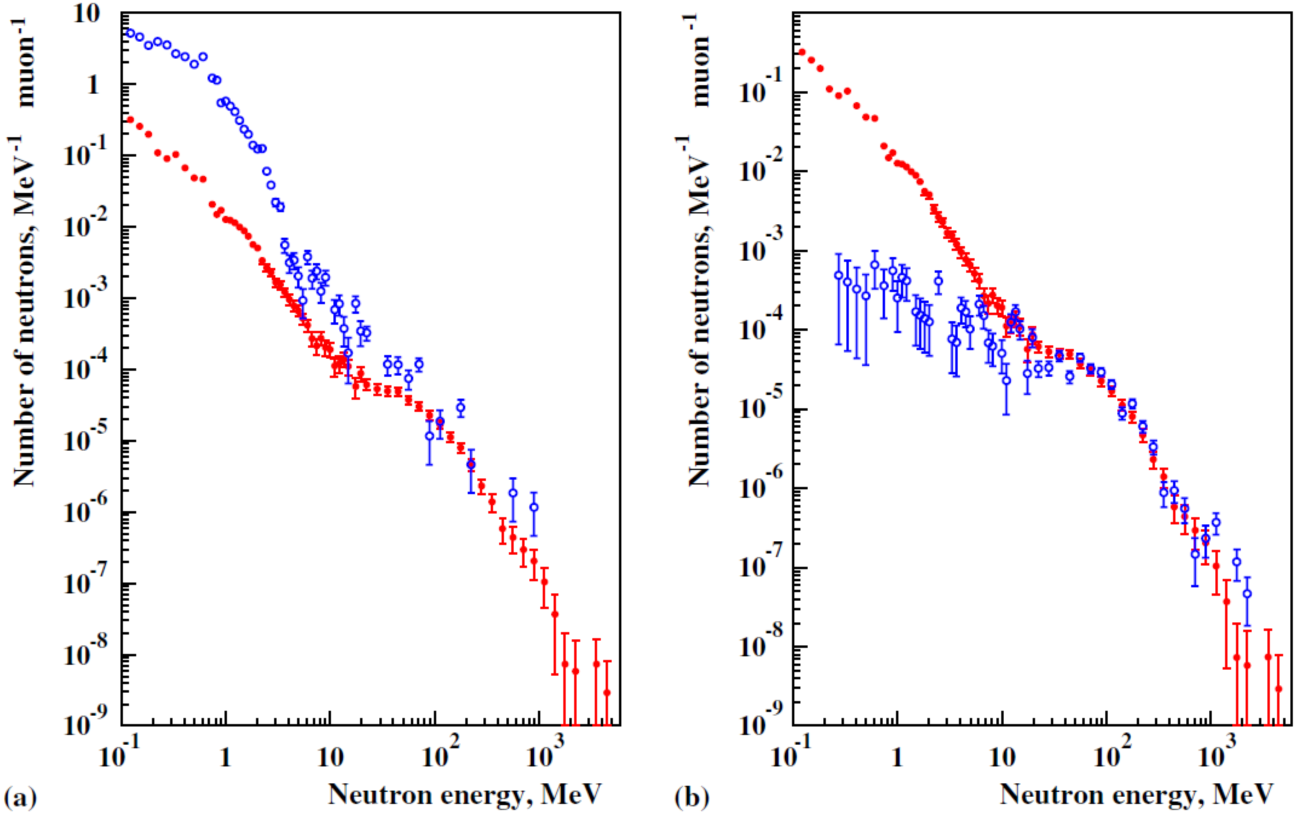
Neutron Backgrounds



Neutron energy spectrum from U and Th in rock

M.J. Carson et al. Astroparticle Physics 21 (2004) 667–687

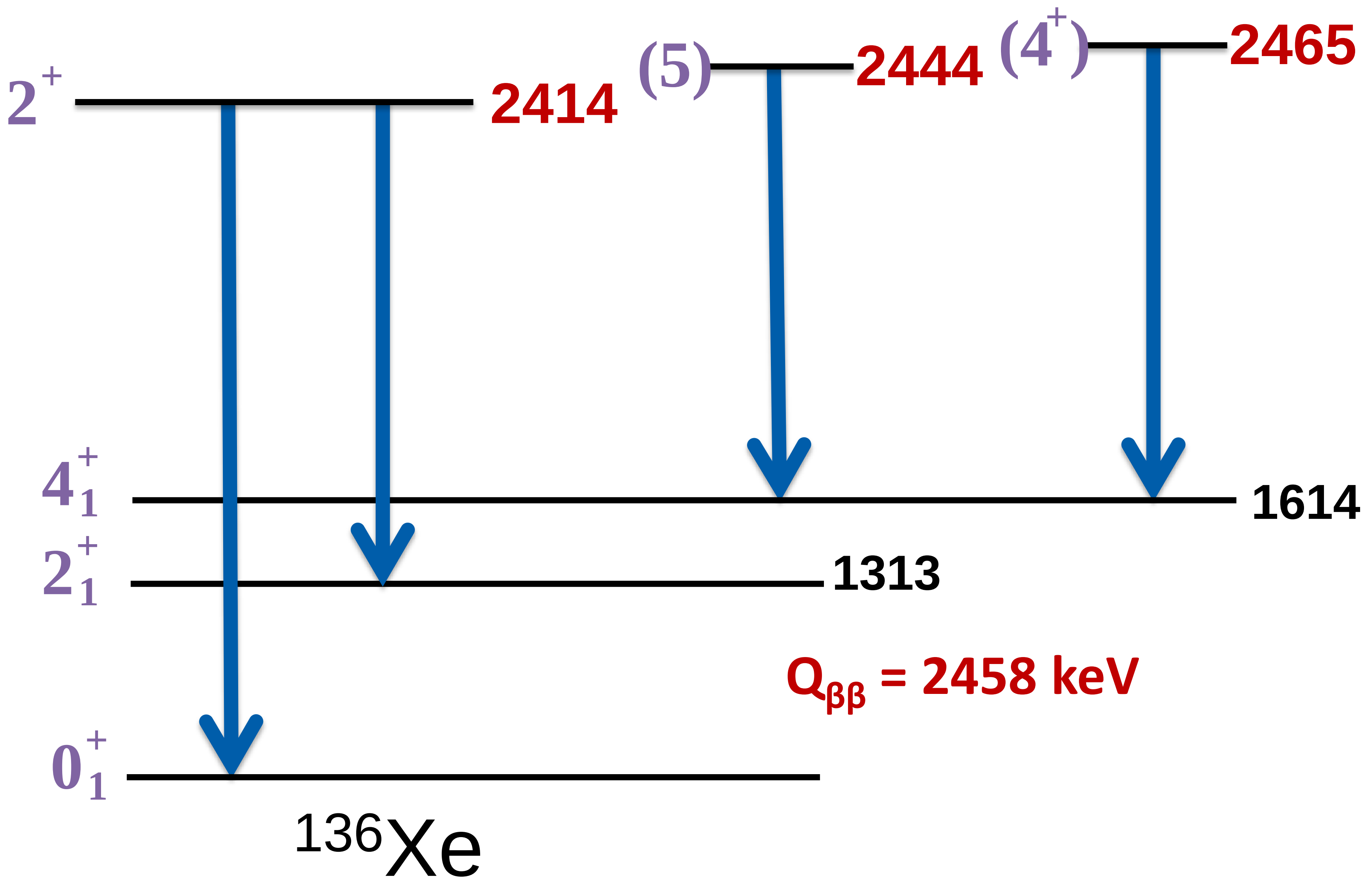
Neutron Backgrounds



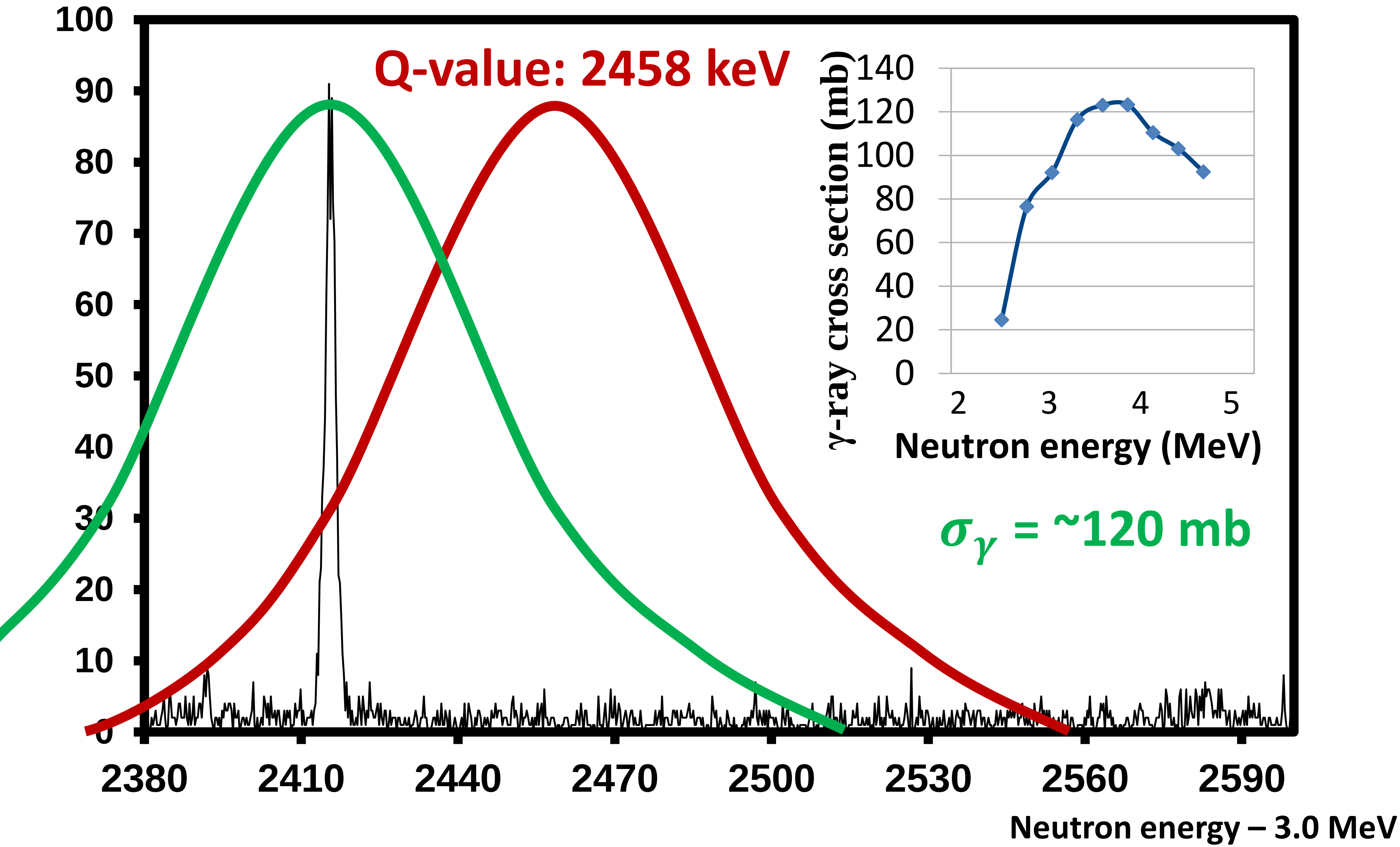
Energy spectra of muon-induced neutrons at various boundaries

M.J. Carson et al. Astroparticle Physics 21 (2004) 667–687

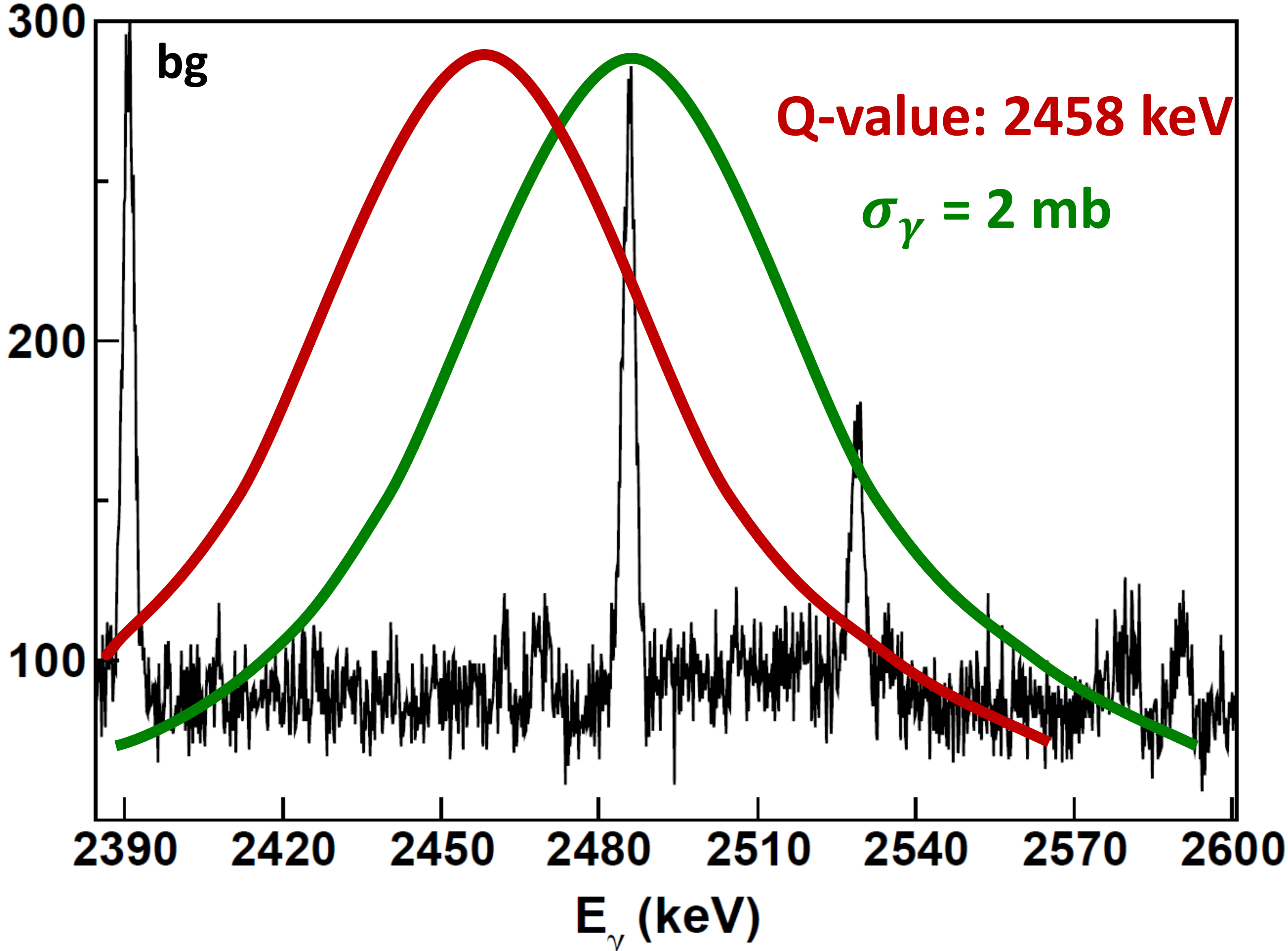
Three levels in the region



2414-keV γ ray in ^{136}Xe



2485-keV γ ray in ^{134}Xe



Acknowledgments

UKAL Collaborators:

M. T. McEllistrem
F. M. Prados-Estévez
T. J. Ross
B. P. Crider
S. Mukhopadhyay
E. E. Peters

Other Collaborators:

J. M. Allmond – ORNL
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