Inelastic Neutron Scattering Studies of ^{76}Ge and ^{76}Se: Relevance to Neutrinoless Double-β Decay

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50 years 1964-2014

UK

ARUNA

NSF

Why study these nuclei?

They are structurally interesting.

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

They are the parent and daughter for double-β decay, a rare process.

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

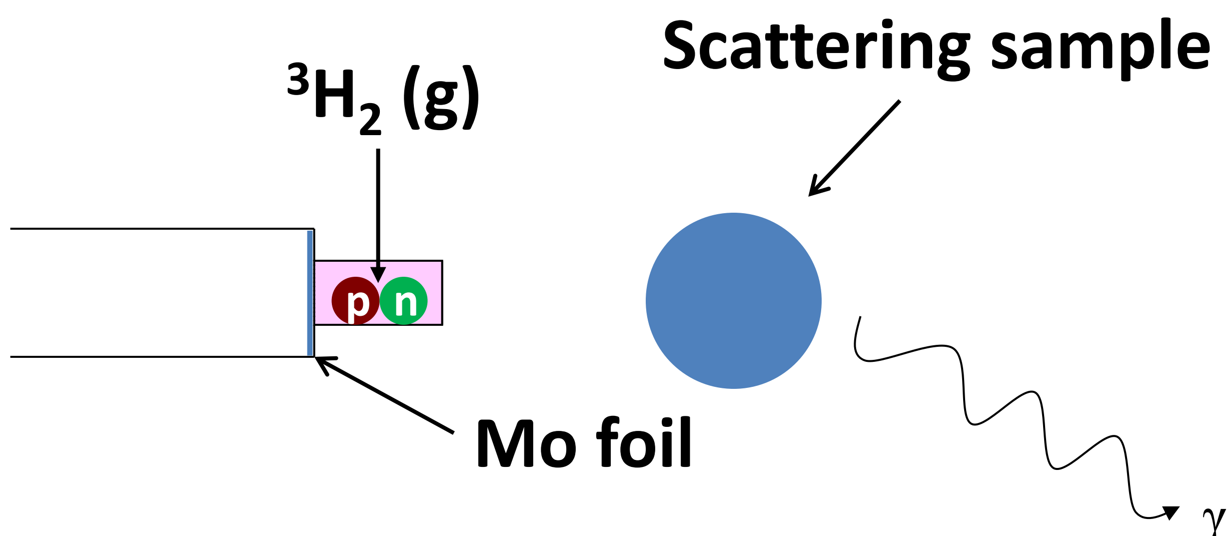
$$^{76}\mathrm{Ge} \longrightarrow {}^{76}\mathrm{Se} + 2\beta^{-} \quad ?$$

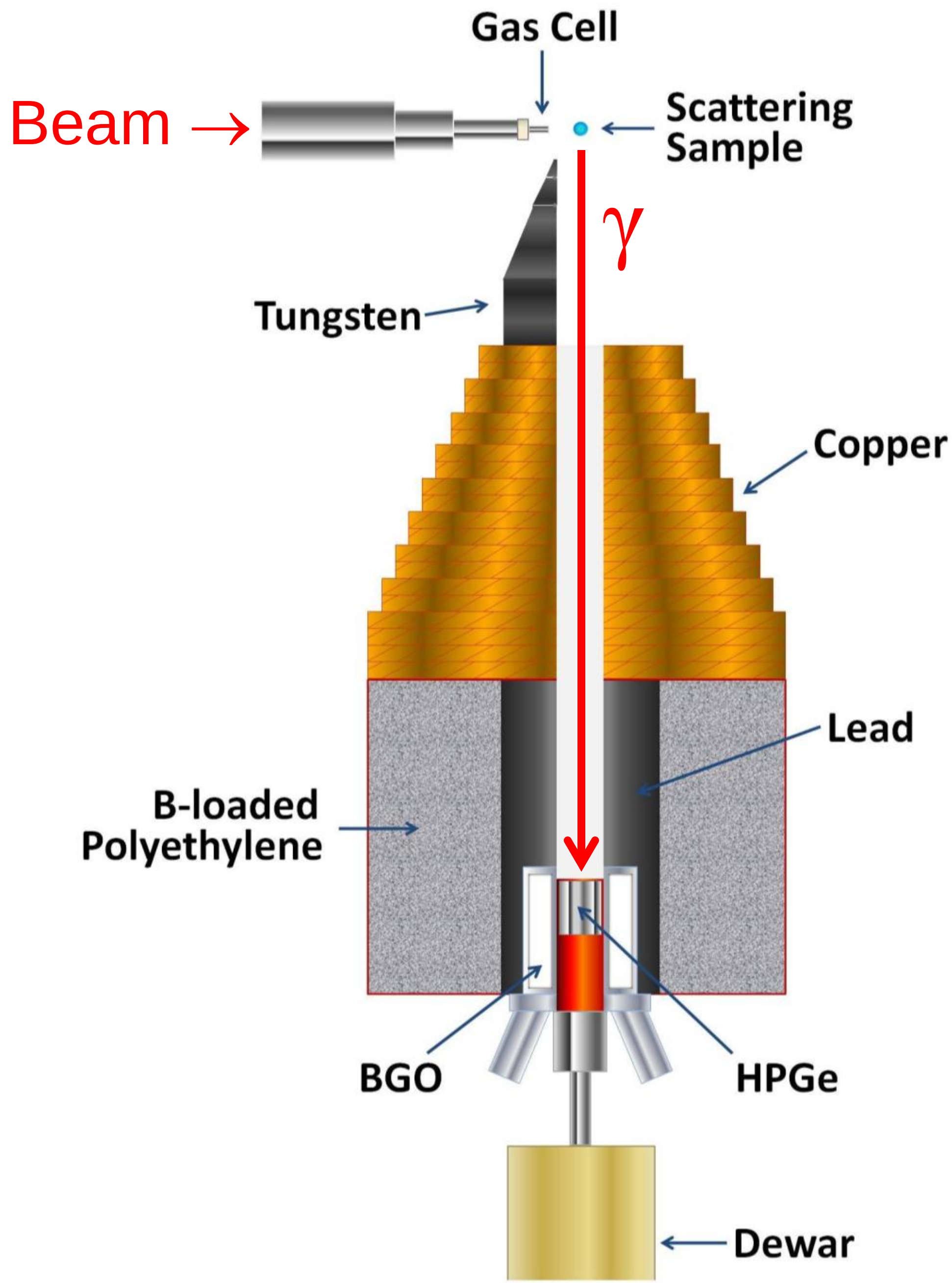
Inelastic Neutron Scattering (INS)

- (n,n'γ) reaction
- Monoenergetic neutrons created by:

$$^{3}H + p \rightarrow \ ^{3}He + n \qquad \text{Q = -0.764 MeV}$$

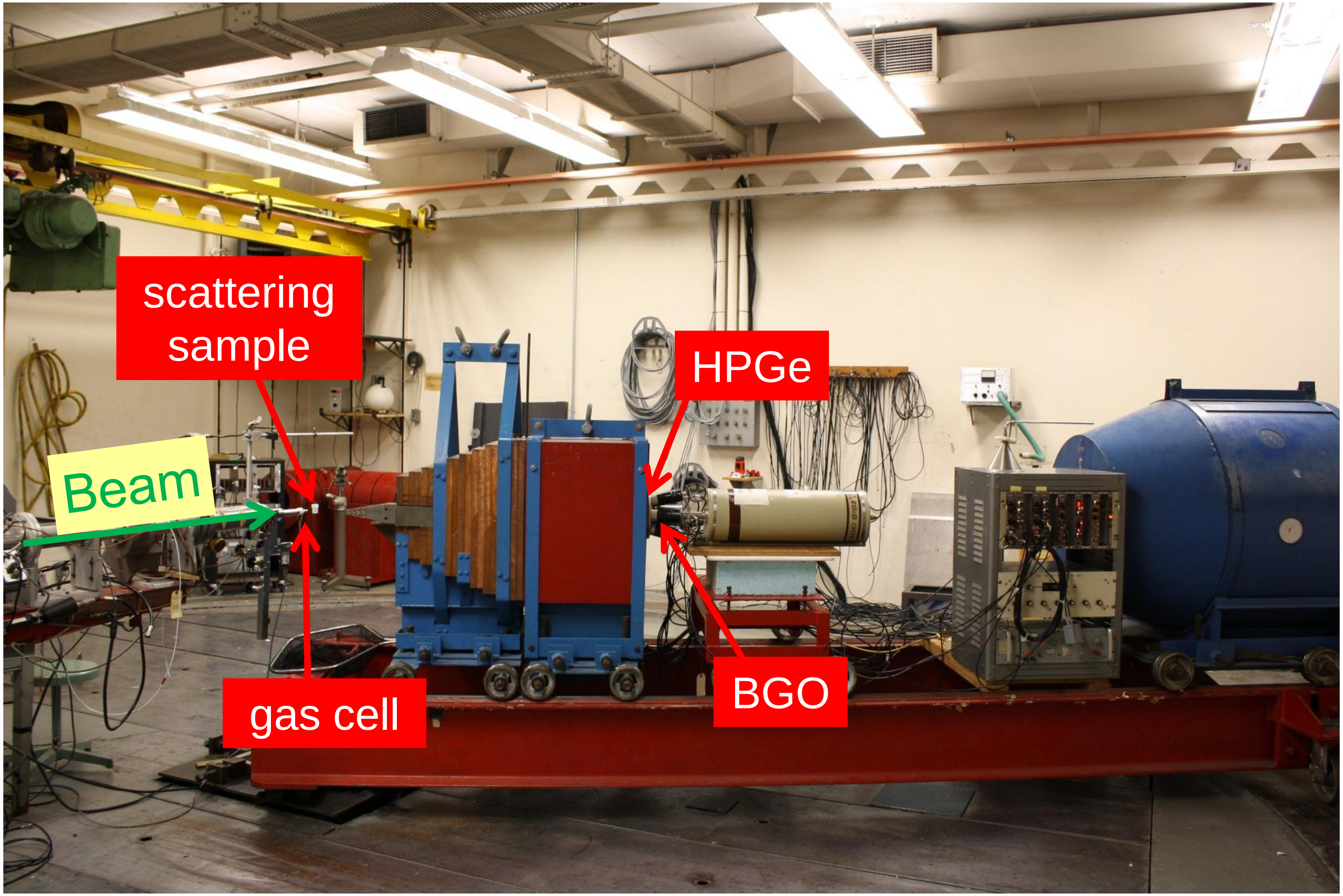
  - Target cell of $^{3}H_2$ gas and accelerator produced protons from the UK 7-MV Van de Graaff accelerator



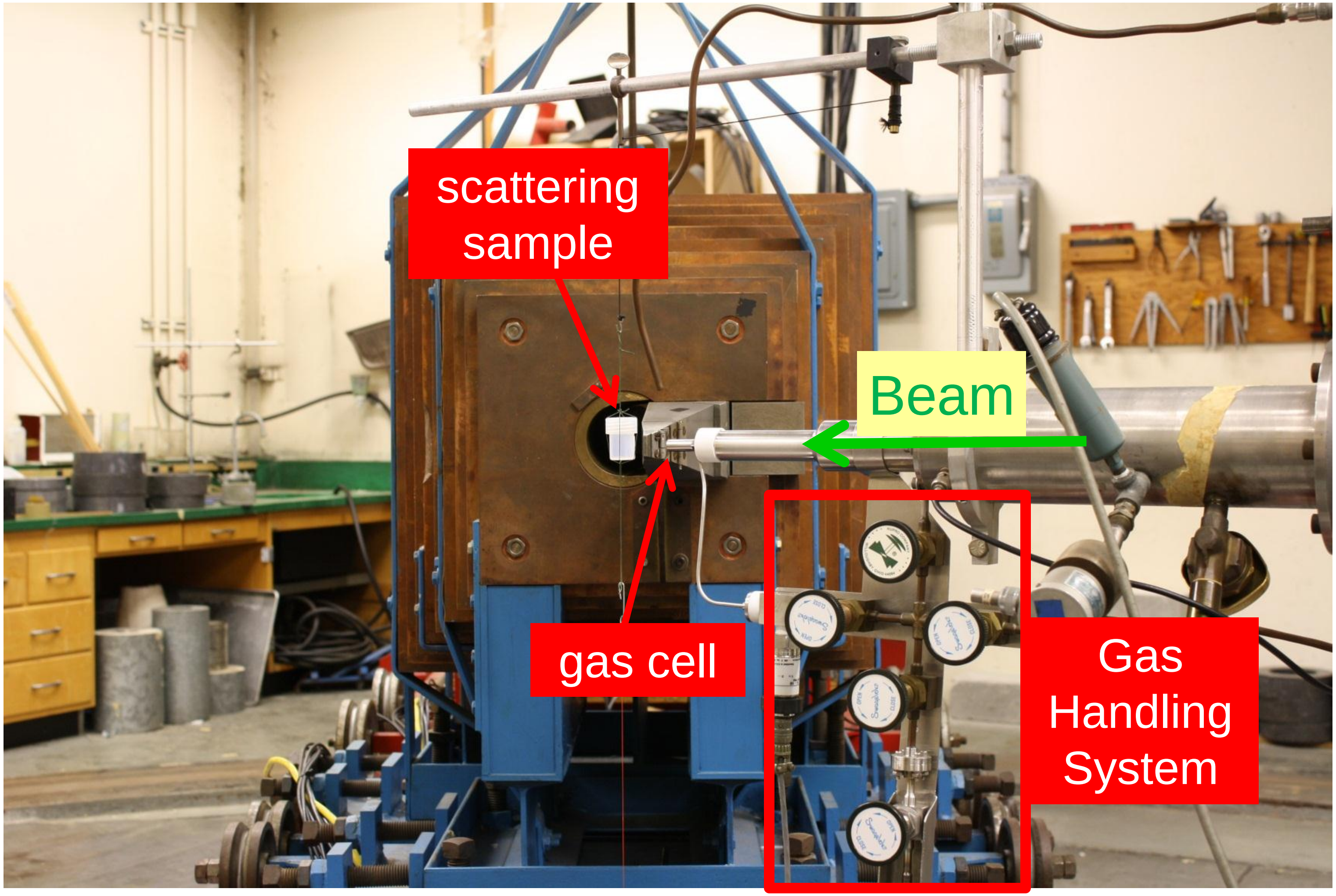

Beam →
Gas Cell
Scattering Sample
γ
Tungsten
Copper
Lead
B-loaded Polyethylene
BGO
HPGe
Dewar

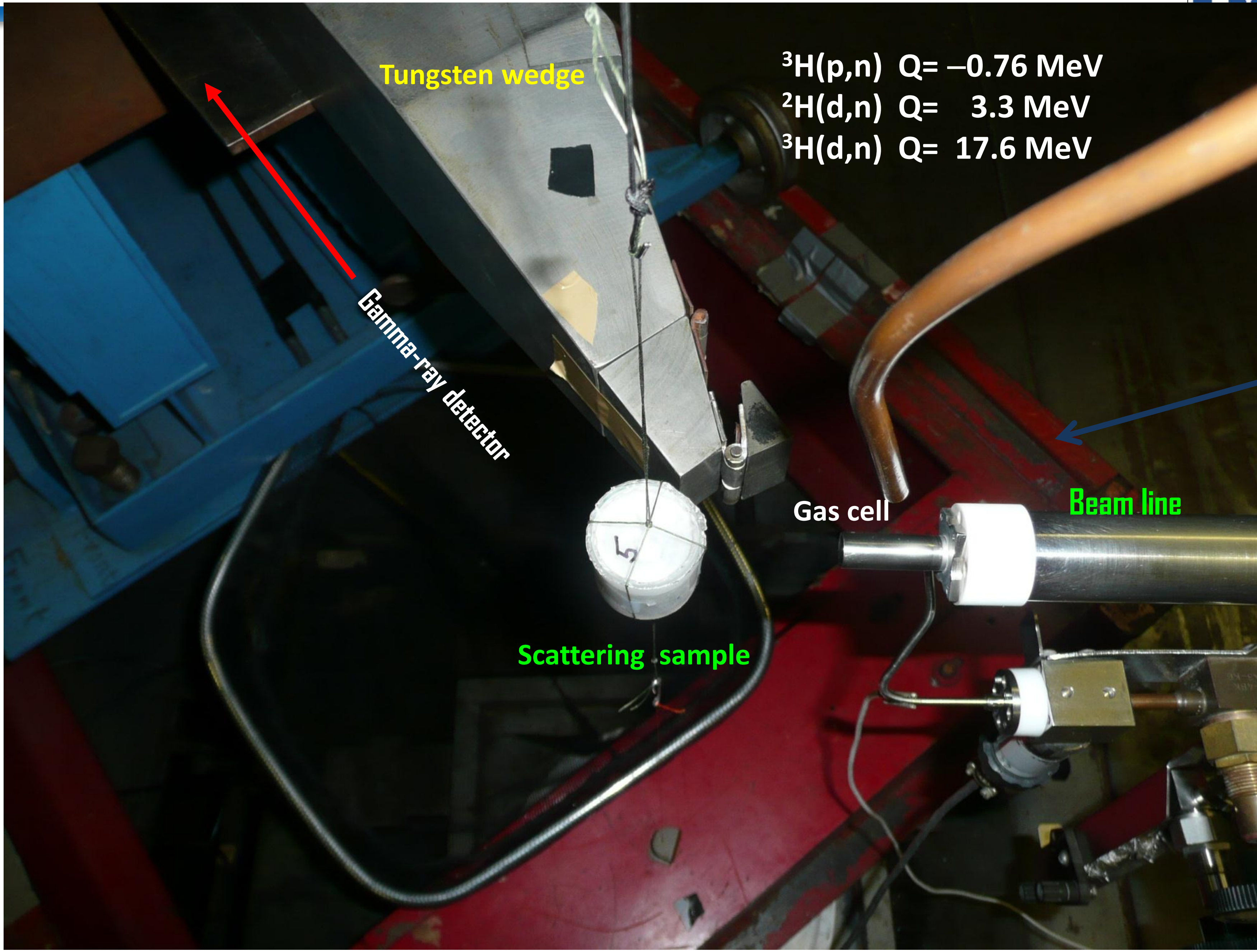
(n,n'γ) singles

(n,n'γ) Singles Measurements



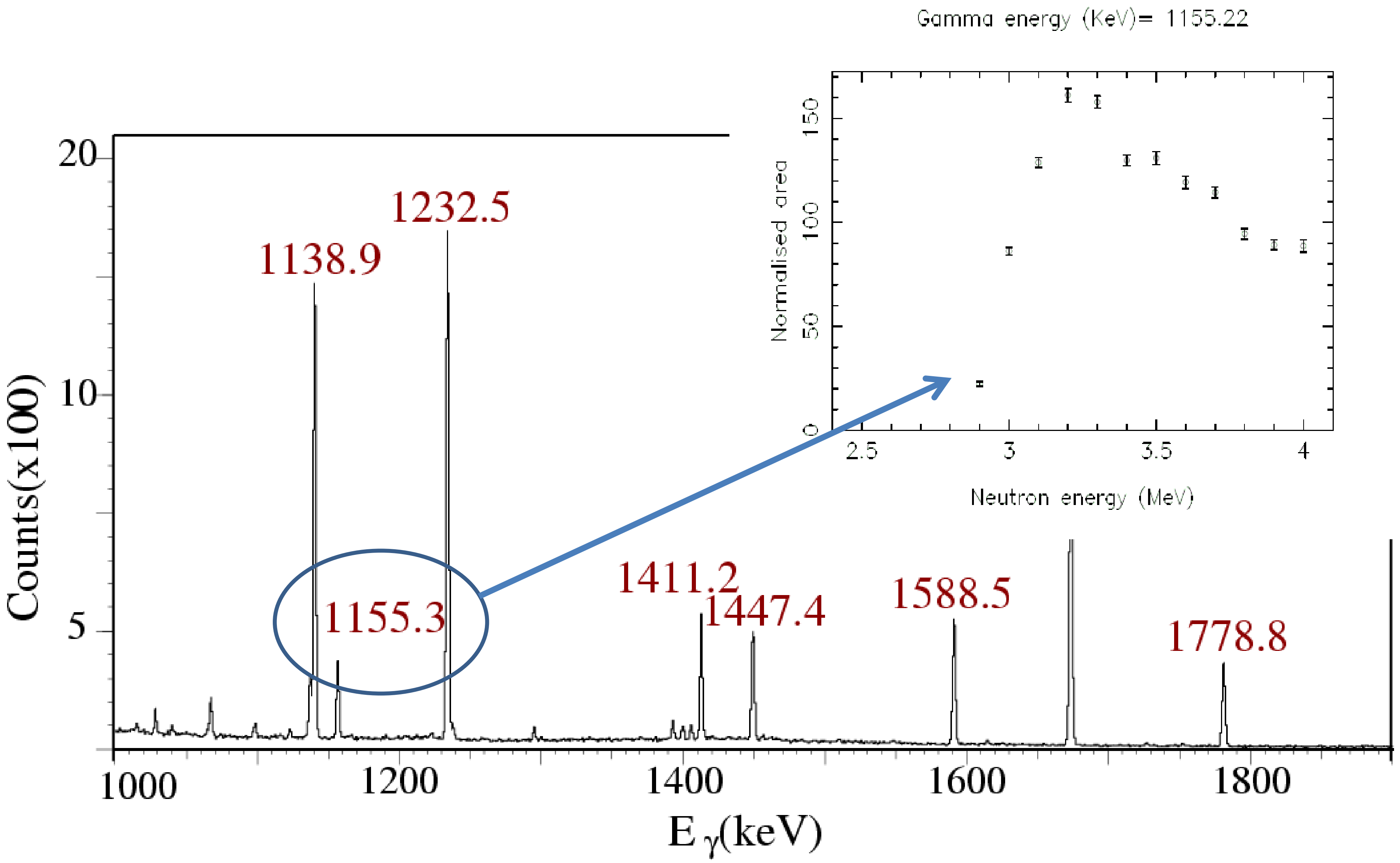
(n,n'γ) Singles Measurements

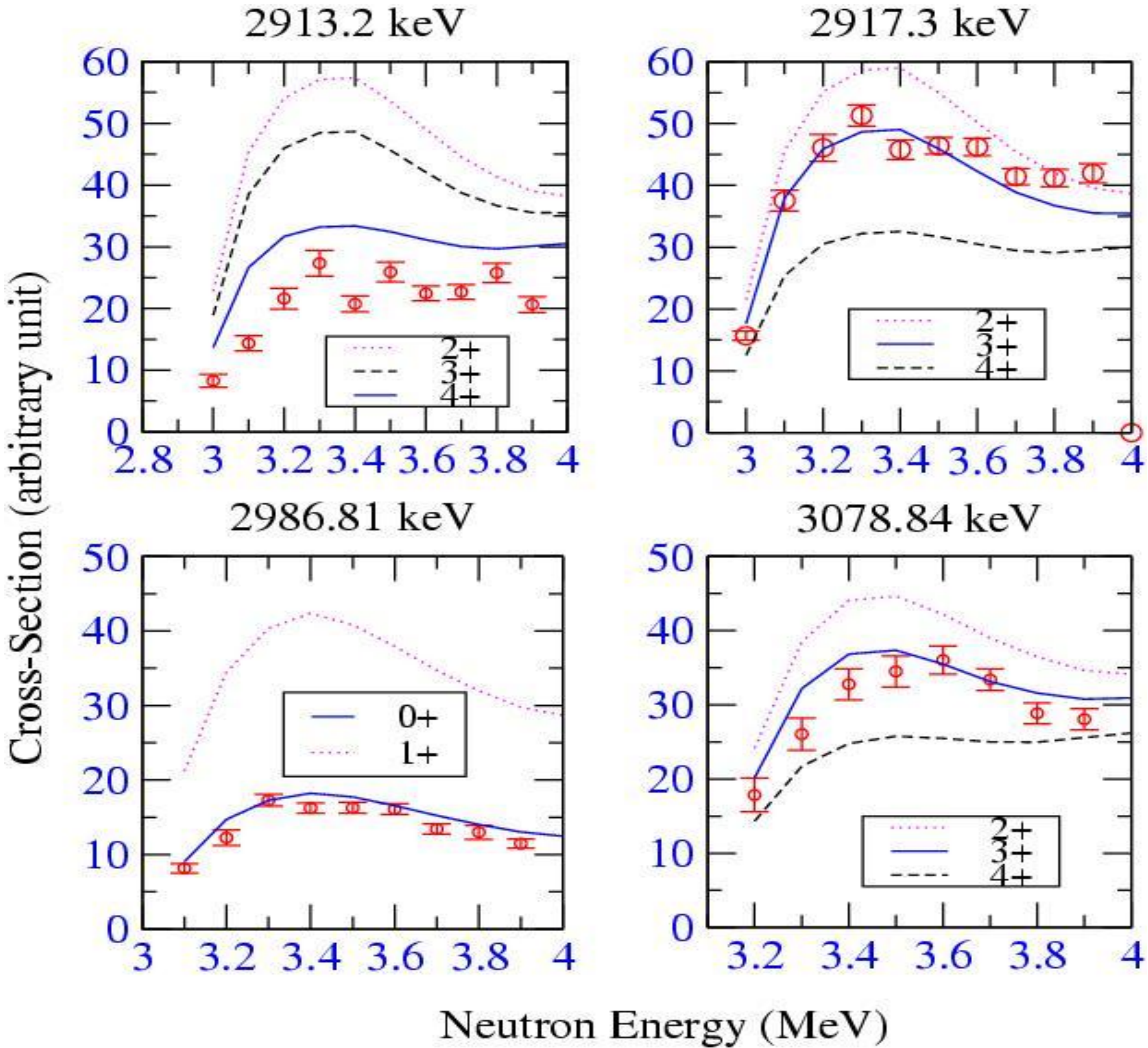




Tungsten wedge
$^3H(p,n)$ Q= –0.76 MeV
$^2H(d,n)$ Q= 3.3 MeV
$^3H(d,n)$ Q= 17.6 MeV
Gamma-ray detector
Gas cell
Beam line
Scattering sample

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



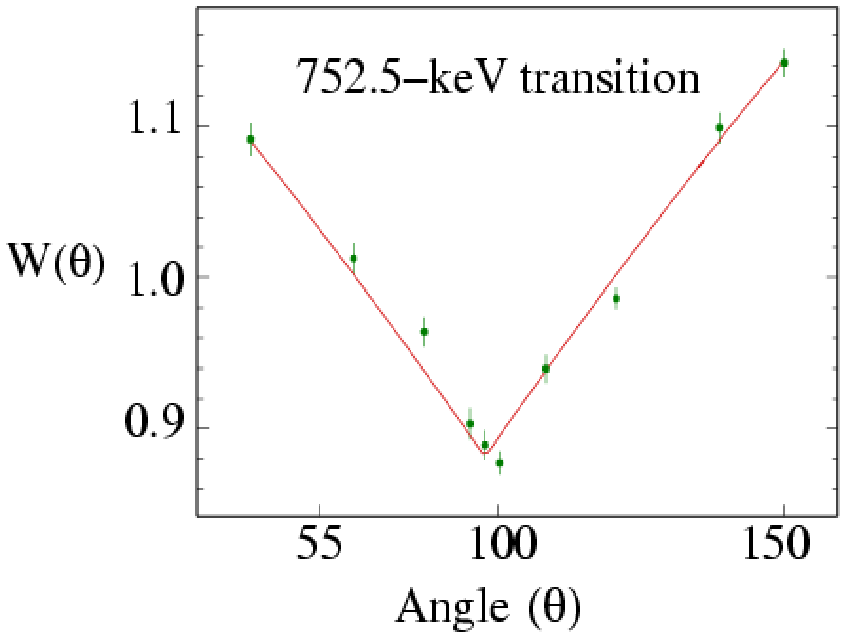

2913.2 keV
2917.3 keV
2986.81 keV
3078.84 keV
Cross-Section (arbitrary unit)
Neutron Energy (MeV)
2+
3+
4+
0+
1+

Angular Distribution

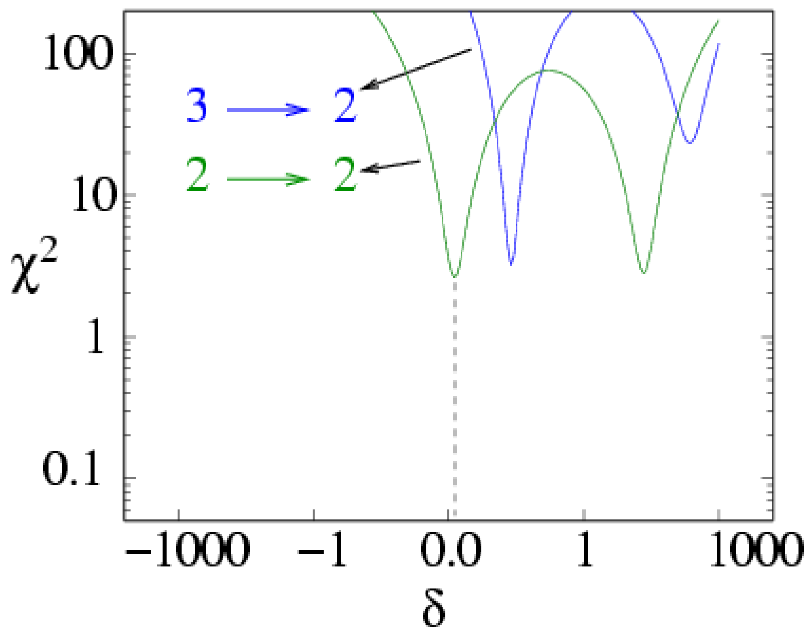
$$W(\theta) = 1 + a_2 P_2(\cos\theta) + a_4 P_4(\cos\theta)$$

Comparison with statistical model calculations (CINDY)

→ multipole mixing ratio (δ) and spins

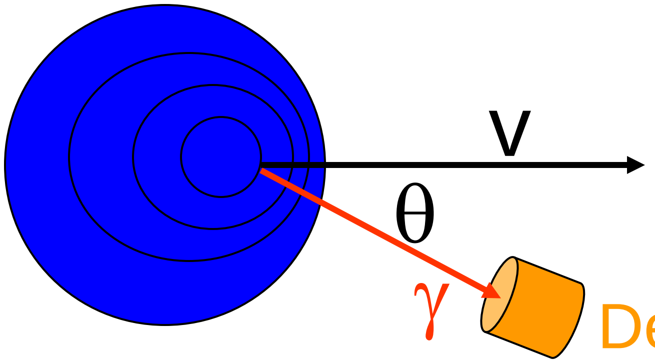


a_2: 0.23(15) a_4: −0.09(2)



δ (2 → 2) = 0.02(2)

Doppler-Shift Attenuation Method



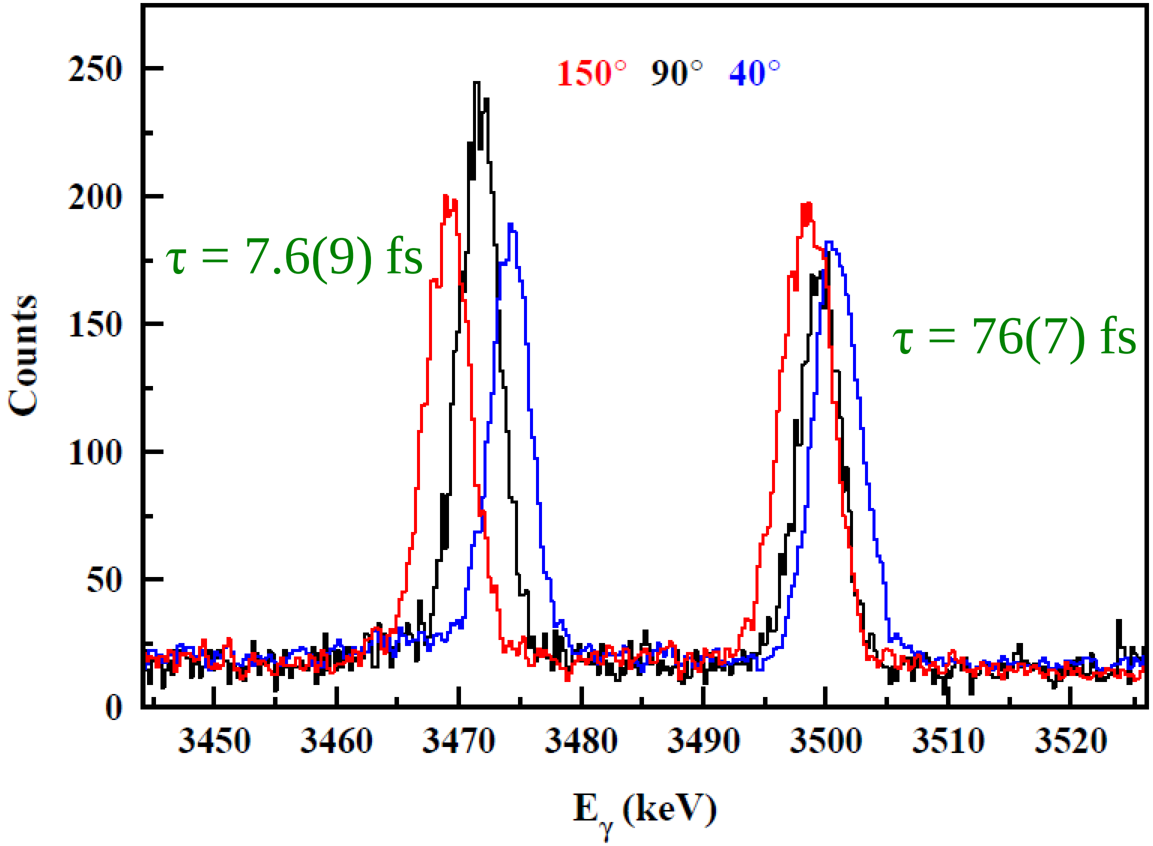
$$E(\theta) = E_\gamma\,(1 + v/c \cos\theta)$$

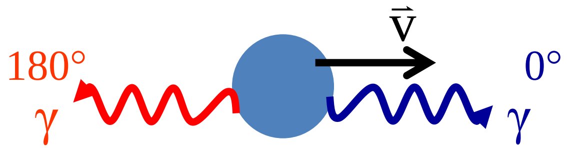
The nucleus is recoiling into a viscous medium.

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

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

Level Lifetimes: Doppler-Shift Attenuation Method (DSAM)





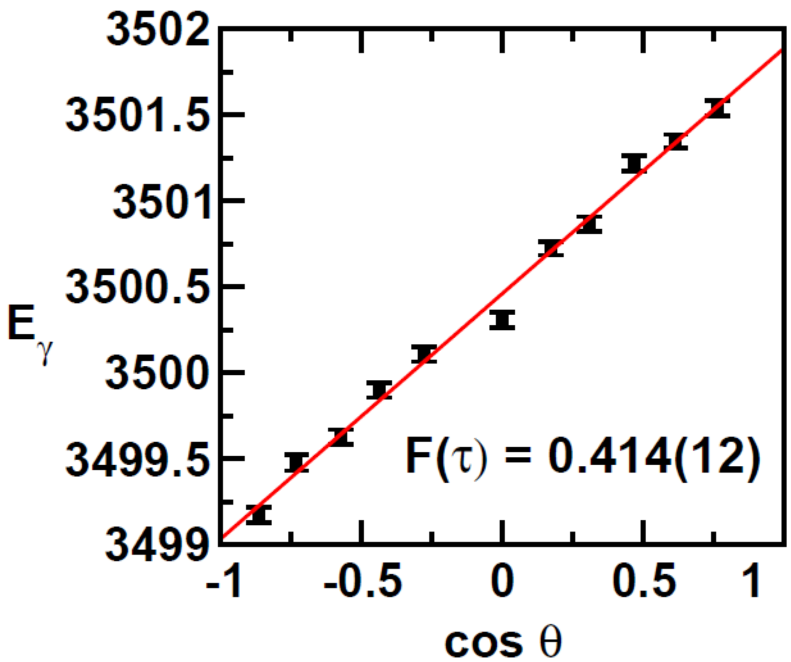
Scattered neutron causes the nucleus to recoil.

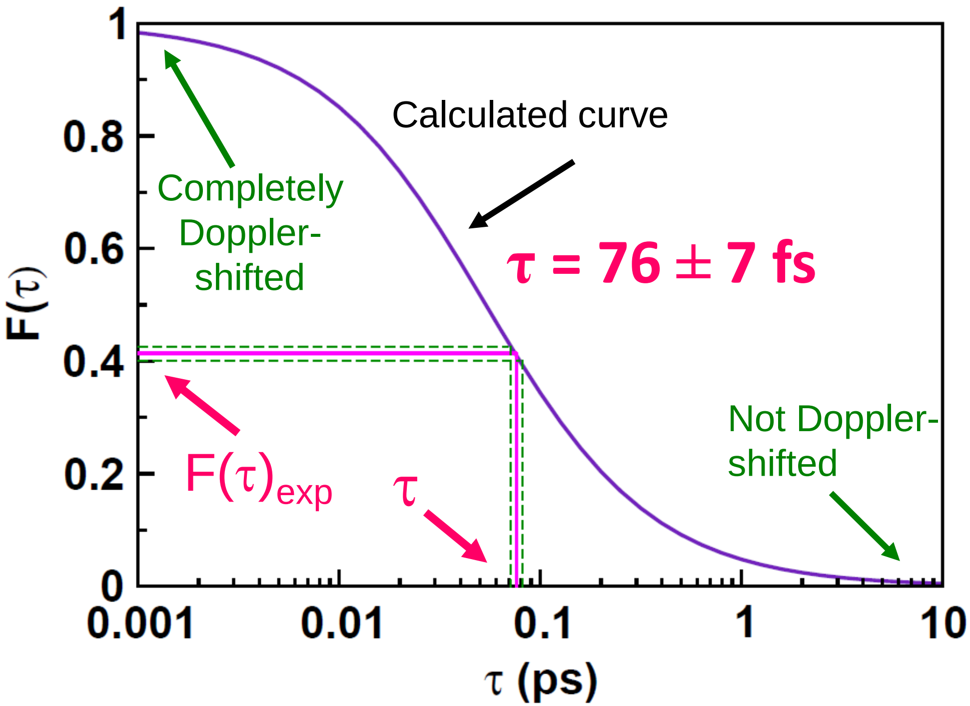
Emitted γ rays experience a Doppler shift.

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

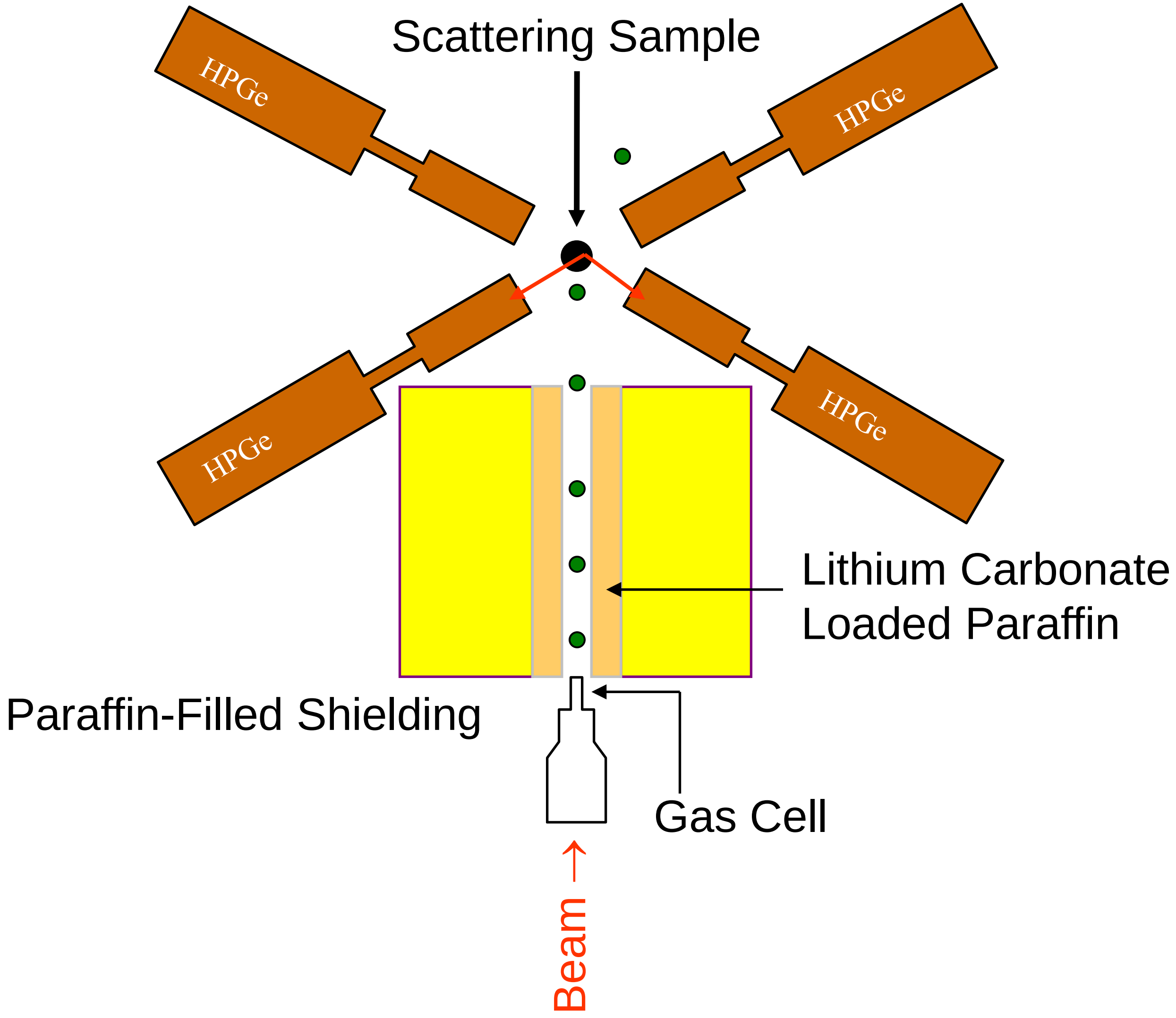




$$E_\gamma(\theta) = E_\gamma\left[1 + F_{exp}(\tau)\frac{v_{cm}}{c}\cos\theta\right]$$

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

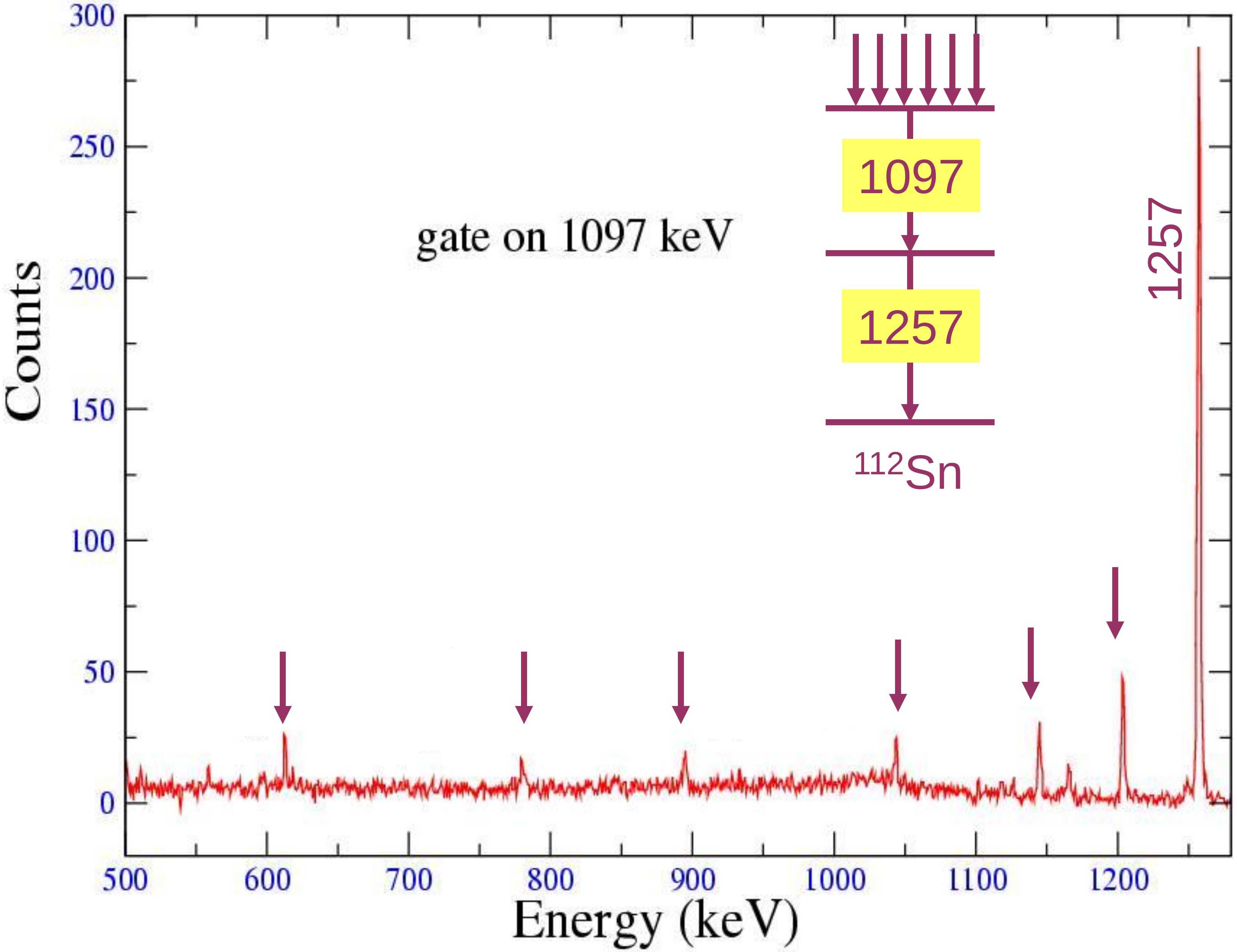
T. Belgya, G. Molnár, and S. W. Yates, Nucl. Phys. **A607**, 43 (1996).



Kentucky Gamma-ray Spectrometer

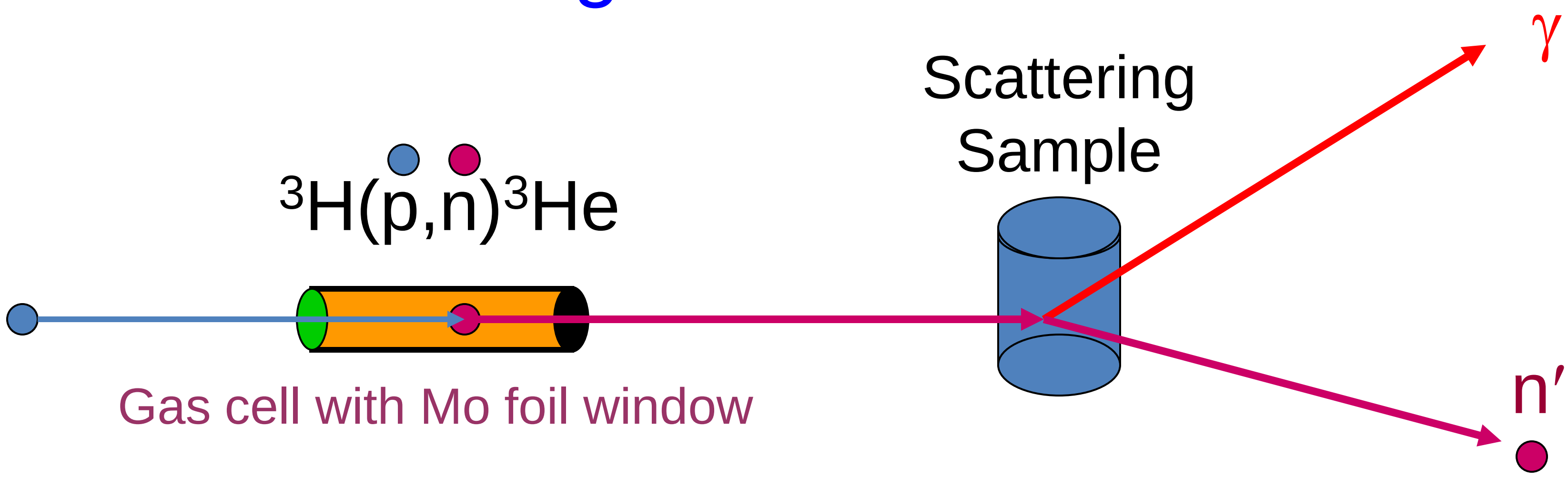
KEGS

KEGS



gate on 1097 keV
1097
1257
^{112}Sn
1257
Counts
Energy (keV)
0
50
100
150
200
250
300
500
600
700
800
900
1000
1100
1200

"Monoenergetic" Neutron Production



Neutron energy at center of the gas cell	1.75 MeV	3.19 MeV
Straggling in 3.3-µm Mo entrance foil (keV)	32	31
dE/dgas, 3-cm tritium cell at 1 atm (keV)	81	55
dE/dθ, outgoing neutron energy deviation over the sample (keV)	23	40

Diagnostic MCNPX calculations of neutron production in gas cell

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

(n,n'γ) Experiments

Isotopically enriched $^{76}GeO_2$ and ^{76}Se

Monoenergetic neutrons via $^{3}H(p,n)^{3}He$

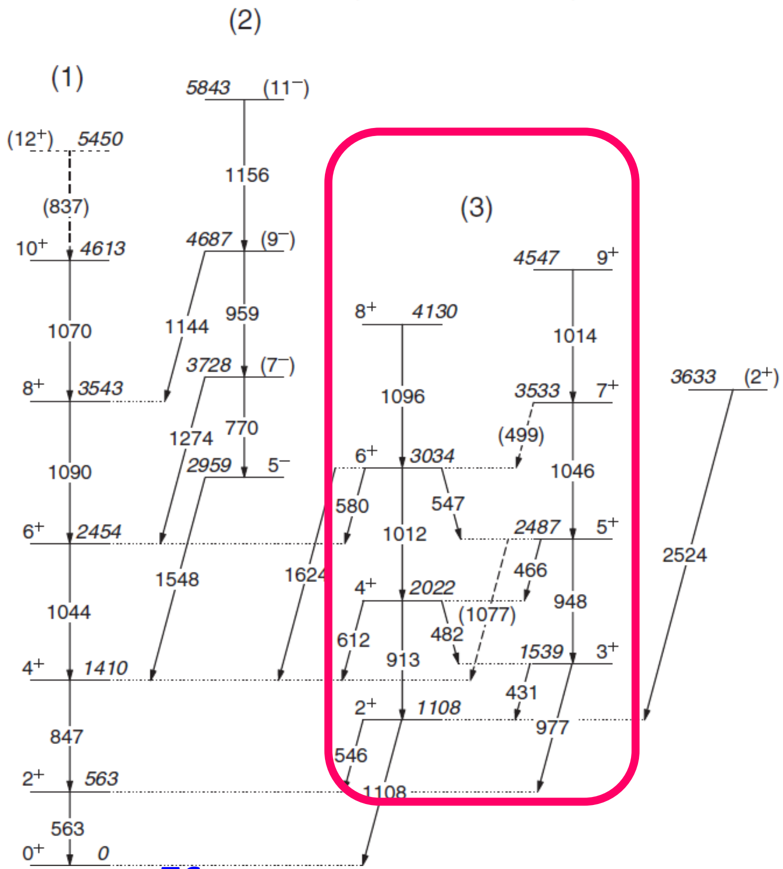
Determination of :

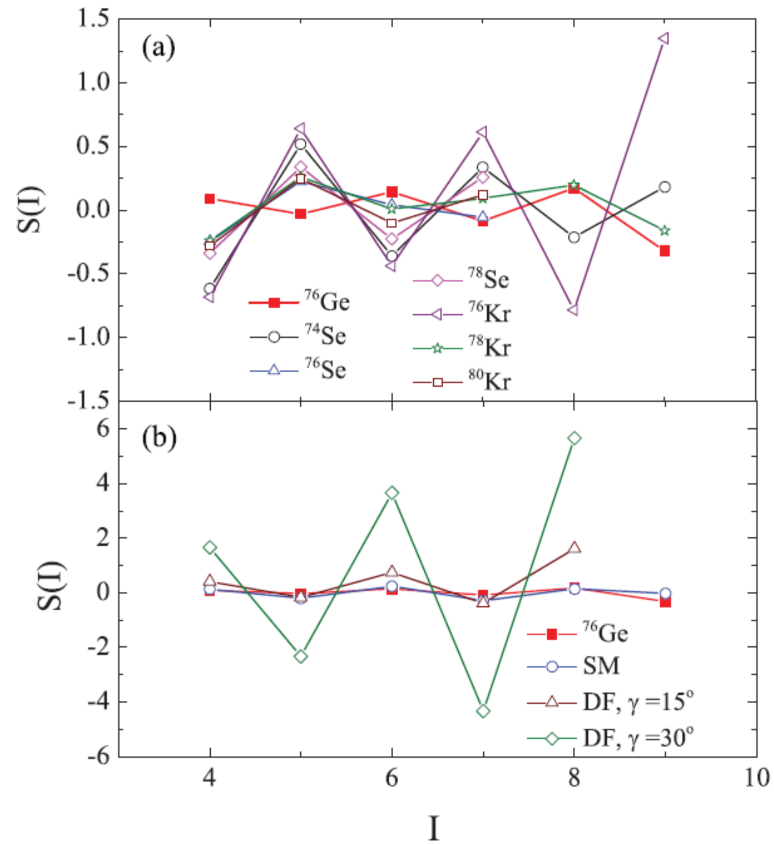
- Level scheme
- Transition multipolarities
- Multipole mixing ratios
- Level lifetimes
- Transition probabilities
- Cross sections

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

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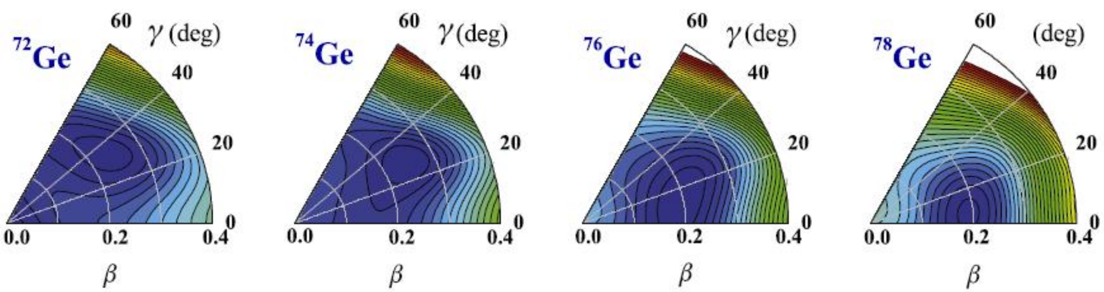
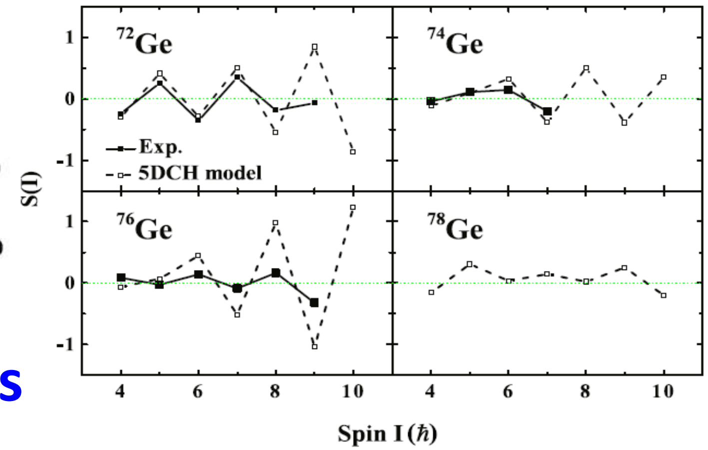
Spectroscopy of ^{74}Ge: From soft to rigid triaxiality

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."

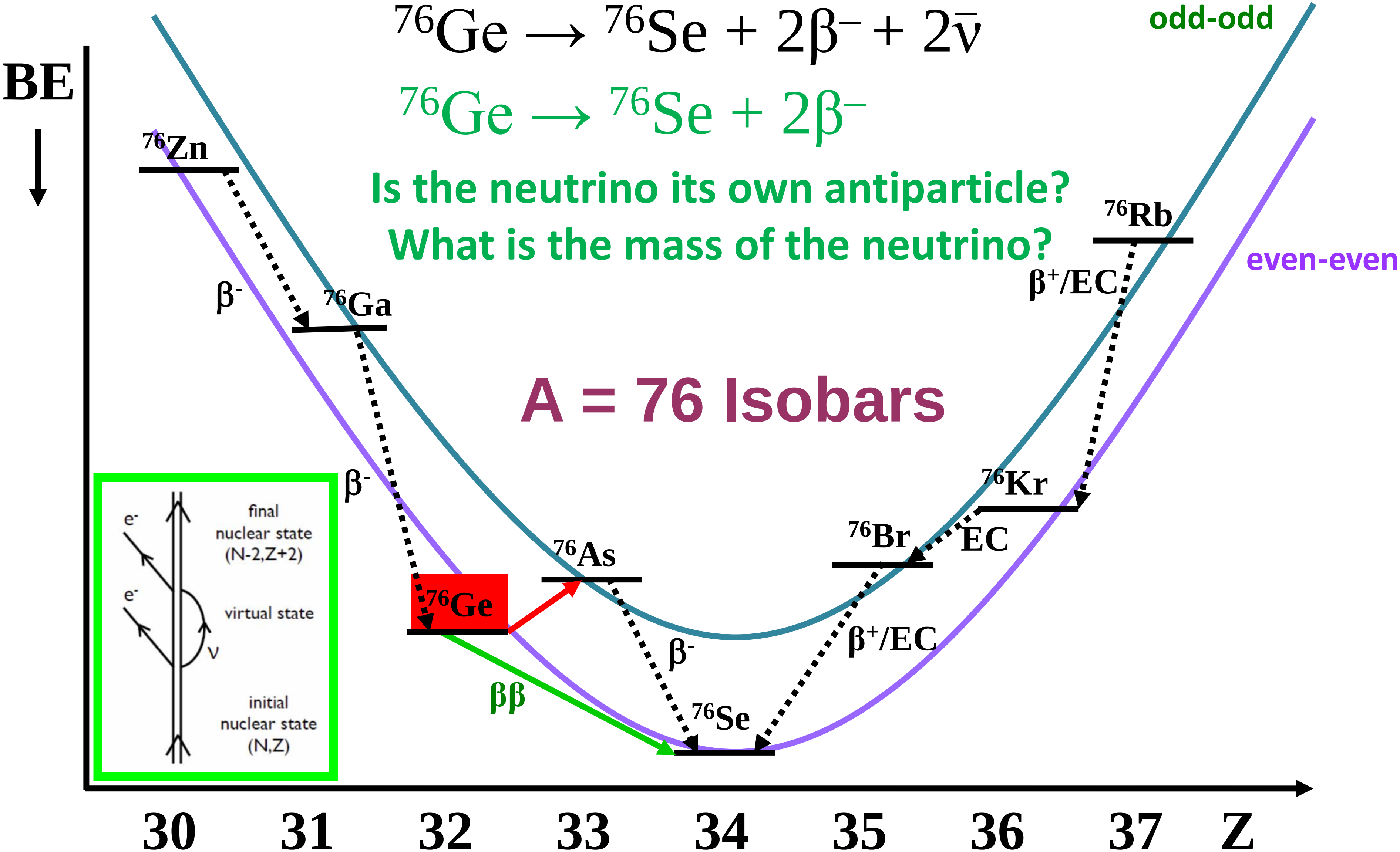
Double-β Decay

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

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

Is the neutrino its own antiparticle?

What is the mass of the neutrino?



Decay Rates of 2νββ and 0νββ

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

Phase space factor

Nuclear Matrix Element

Effective Majorana neutrino mass

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

$$T_{1/2}^{2\nu}({}^{76}Ge) = 1.84\times10^{21}\ yr$$

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

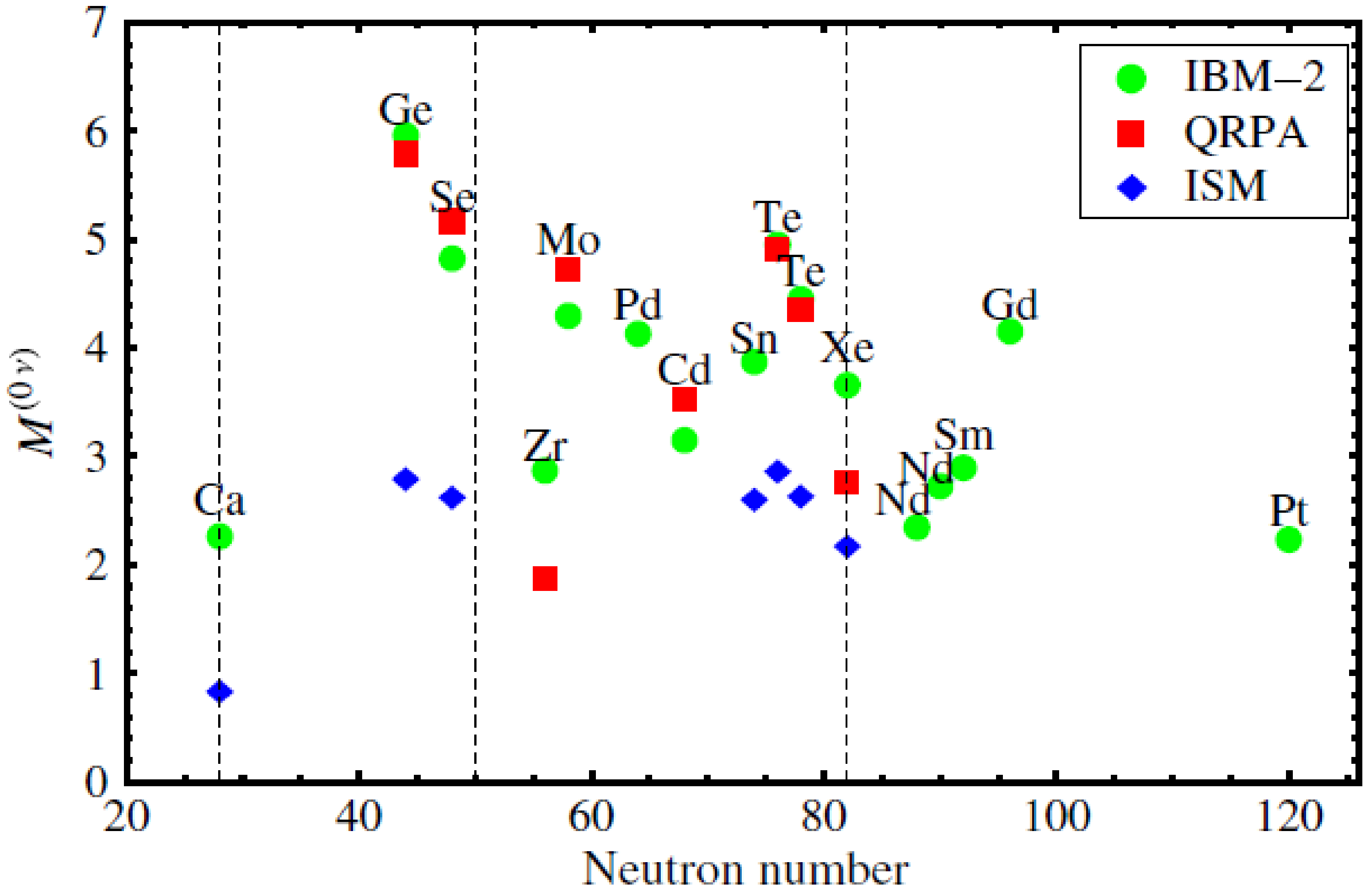
$$T_{1/2}^{0\nu}({}^{76}Ge) = 1.19\times10^{25}\ yr$$

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

$$T_{1/2}^{0\nu}({}^{76}Ge) > 2.1\times10^{25}\ yr$$

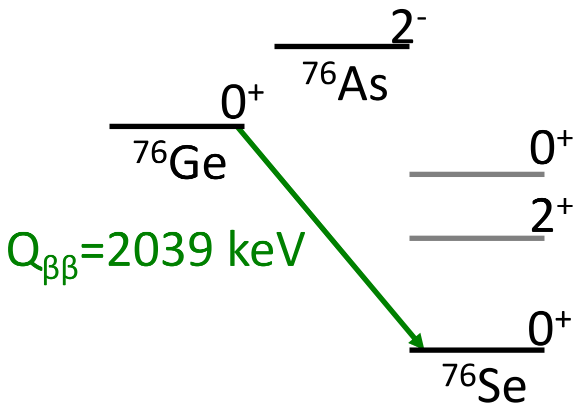
M. Agostini et al. (GERDA), PRL **111**, 122503 (2013)

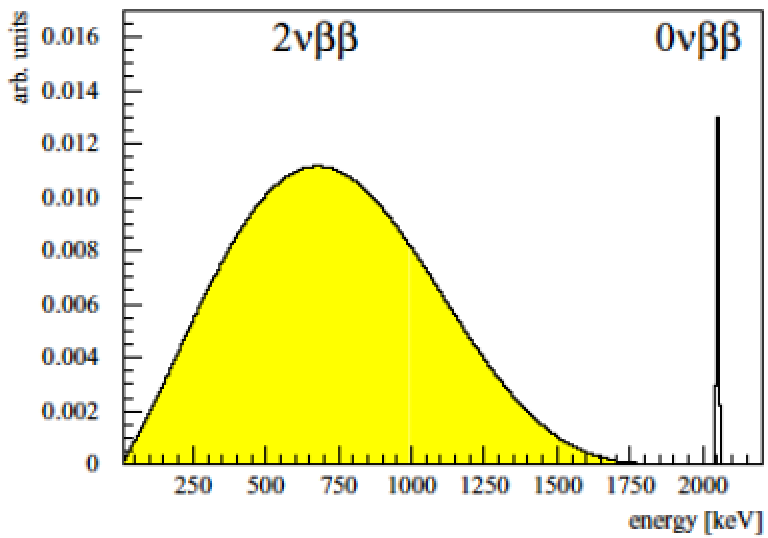
Comparison of calculated nuclear matrix elements for 0νββ candidates

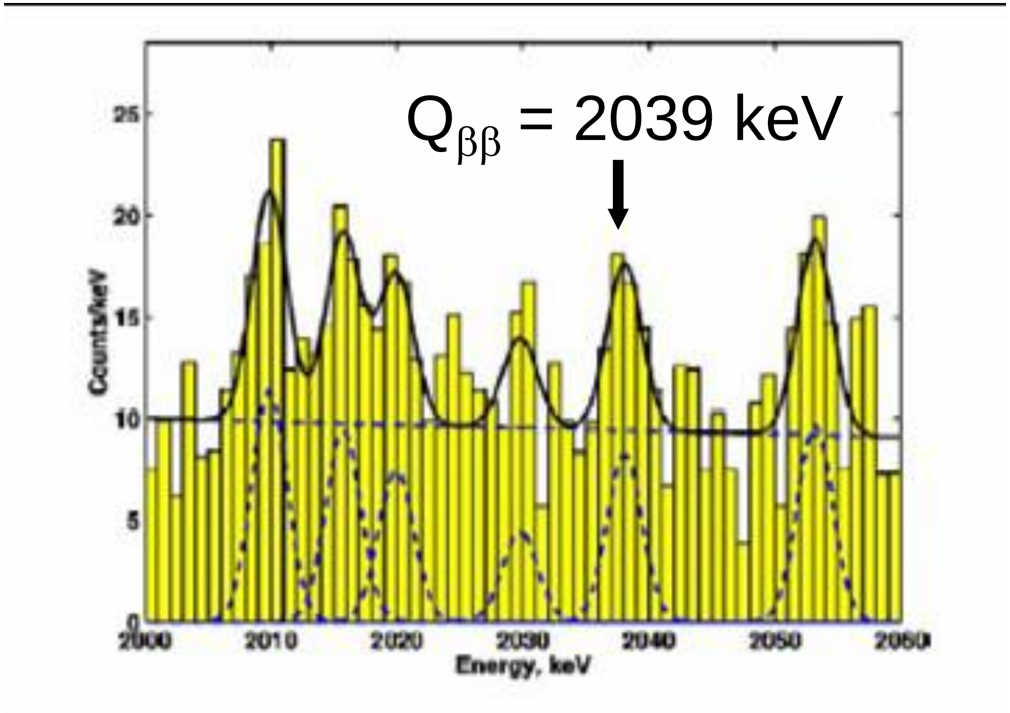


J. Barea, J. Kotila, and F. Iachello, Phys. Rev. Lett. **109**, 042501 (2012).

Experimental Signature of 0νββ







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

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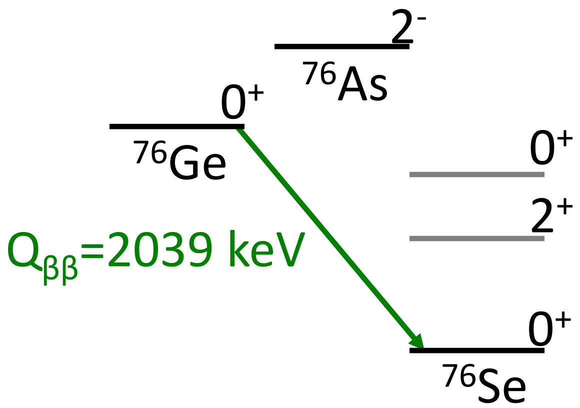
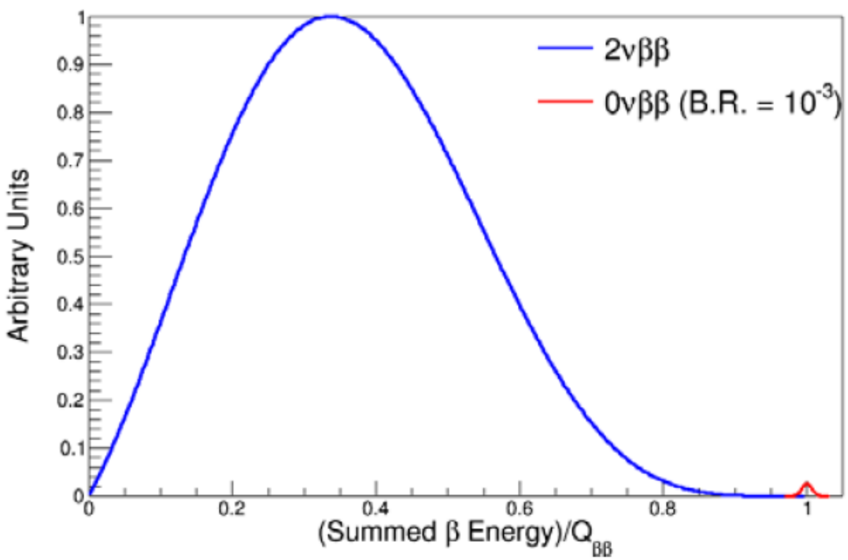
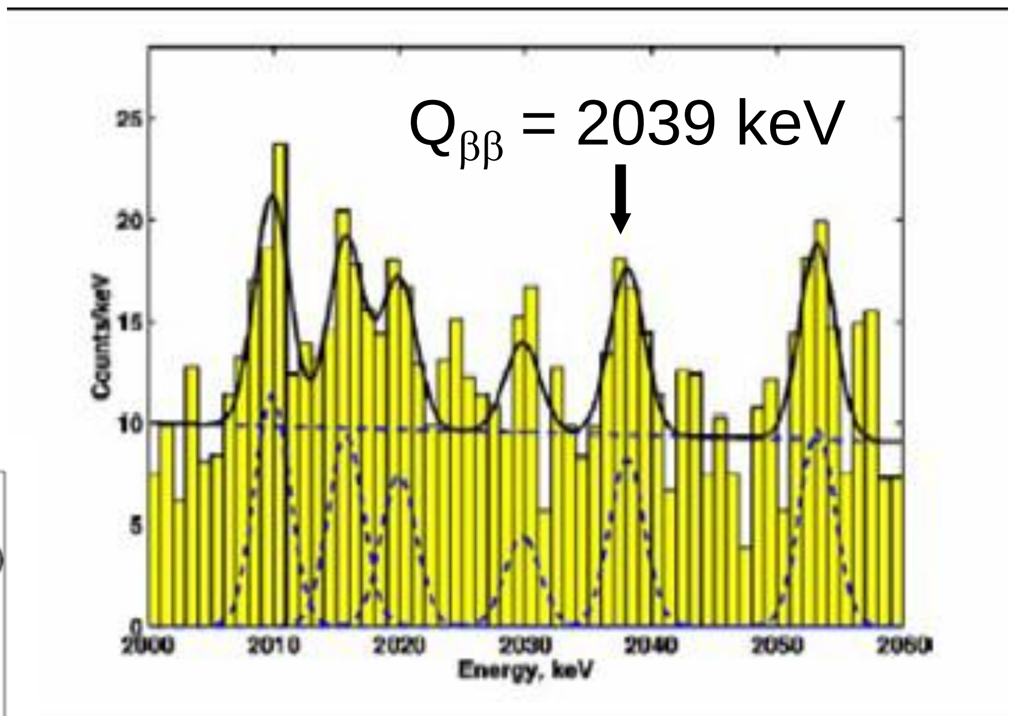






H.V. Klapdor-Kleingrothaus, I.V. Krivoshina, A. Dietz, and O. Chkvorets, Phys. Lett. **B586**, 198 (2004)

Current Searches for ^{76}Ge 0νββ

MAJORANA

GERDA

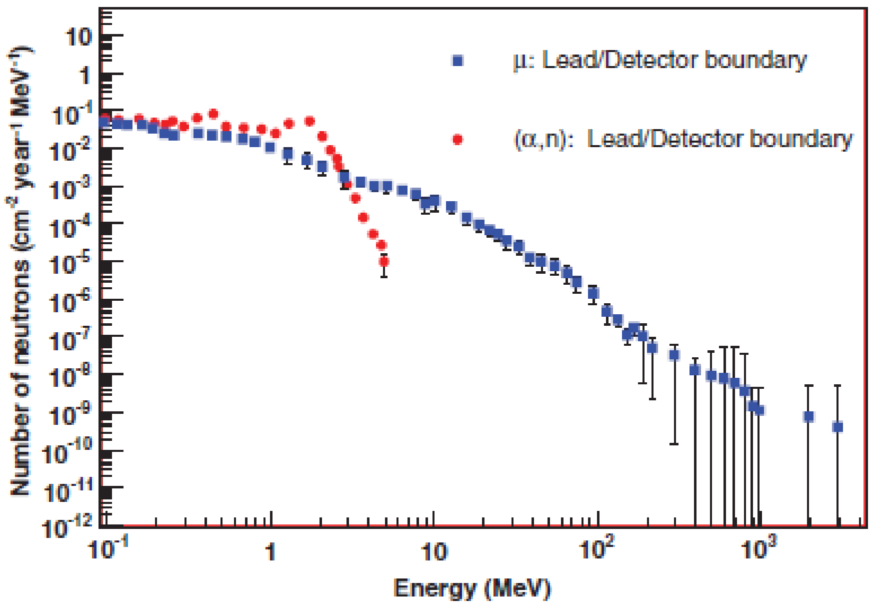
30 kg 86% ^{76}Ge + 10 kg ^{nat}Ge
SURF, SD, USA

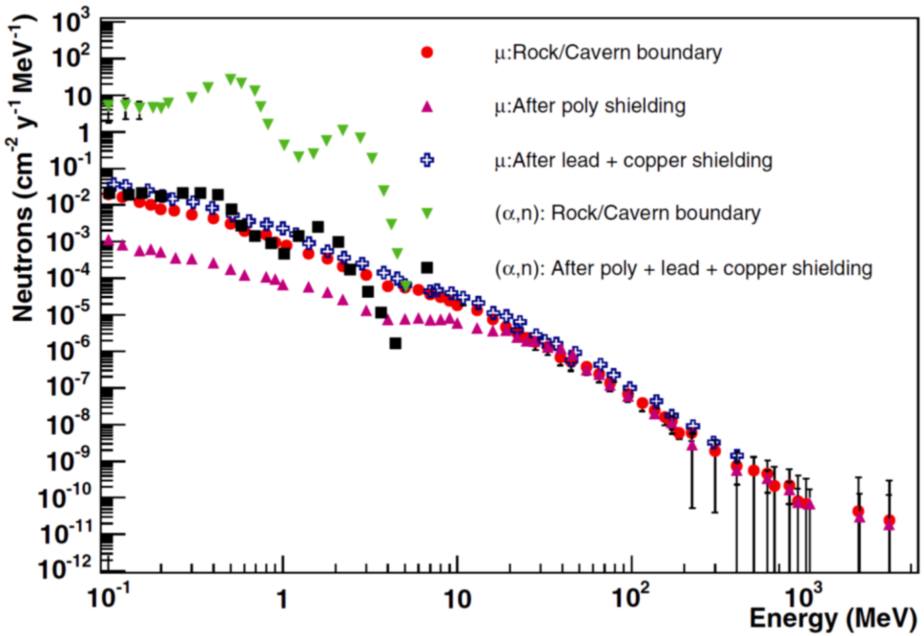
40 kg 86% ^{76}Ge
Gran Sasso, Italy

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

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

Neutron Flux for Double-β Decay Experiments

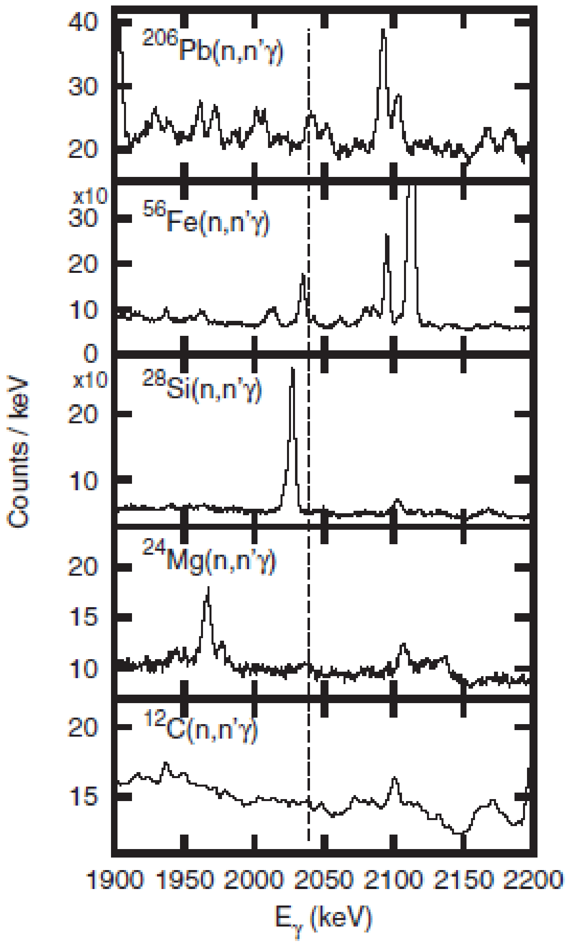




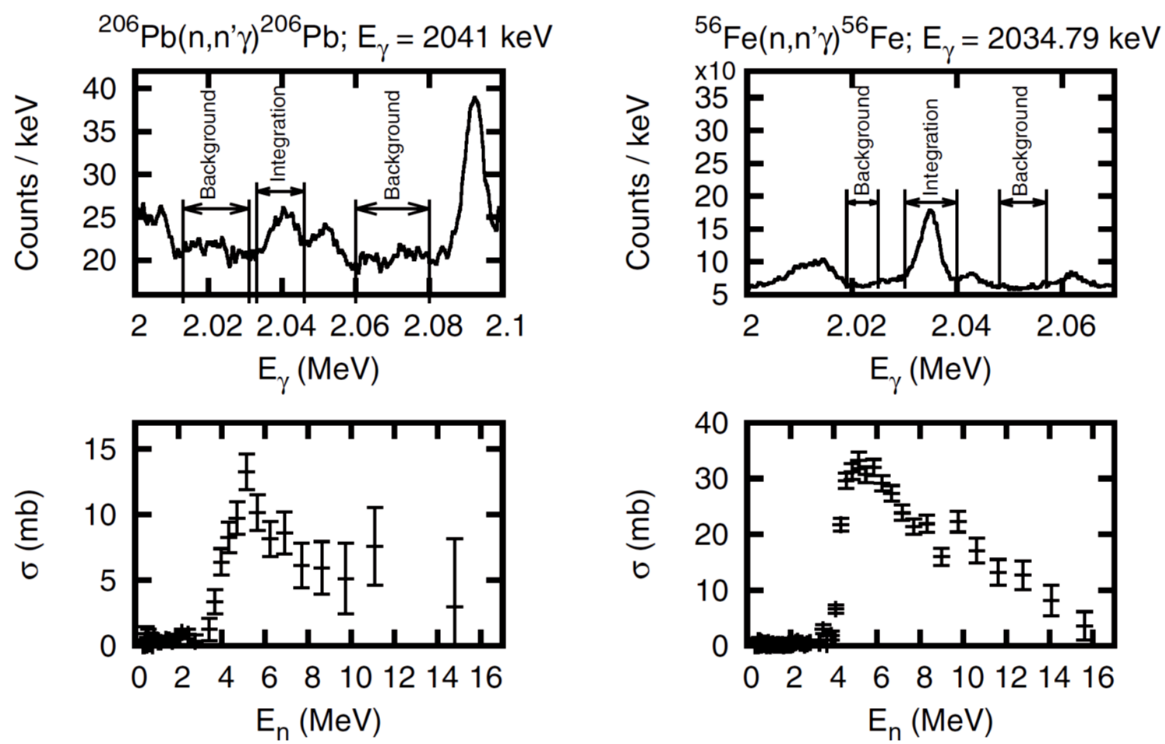
FLUKA simulations

D.-M. Mei and A. Hime, Phys. Rev. D **73**, 053004 (2006)
D.-M. Mei *et al.*, Phys. Rev. C **77**, 054614 (2008)

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

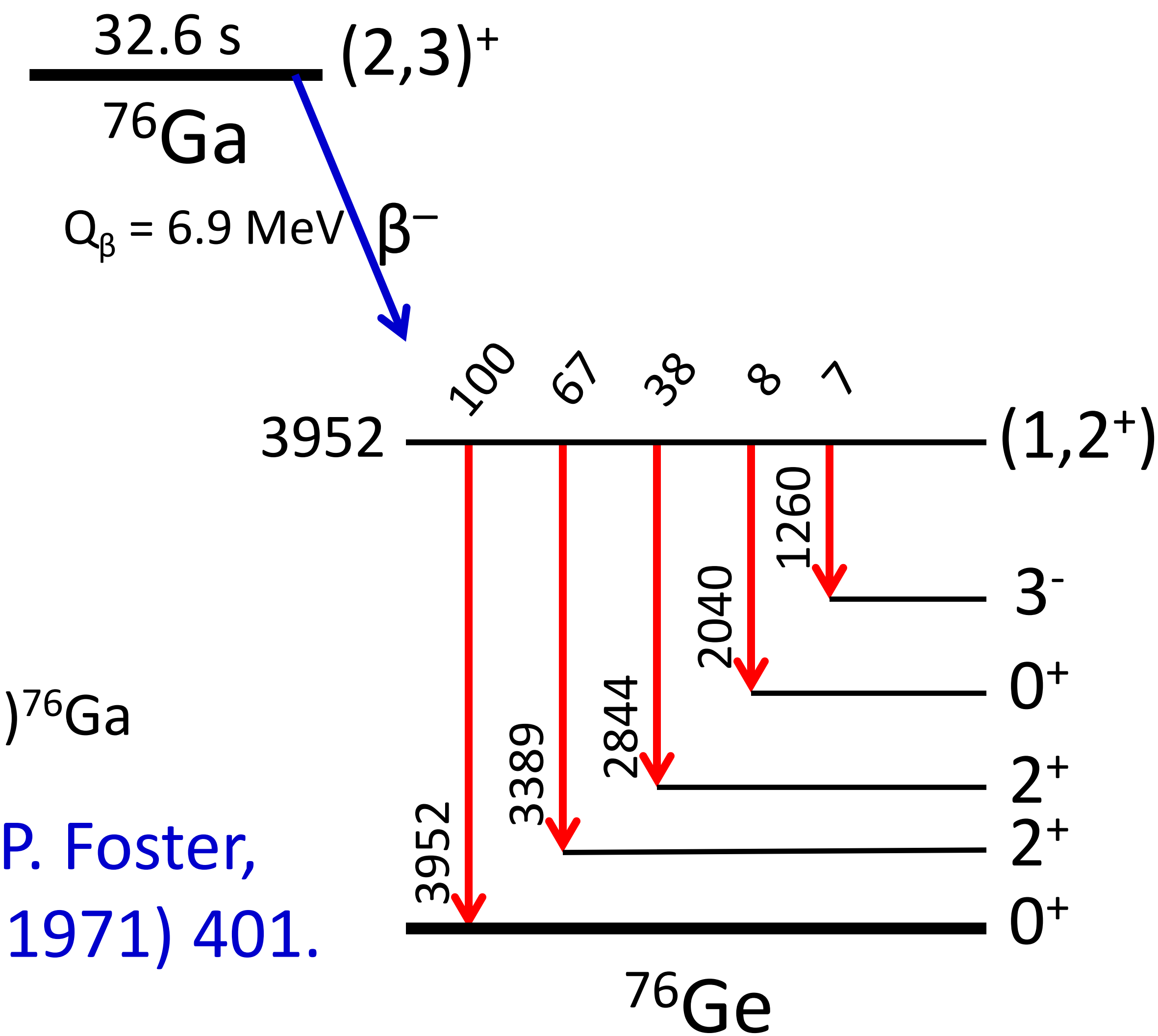


GELINA (Geel Linear Accelerator) white neutron source



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.



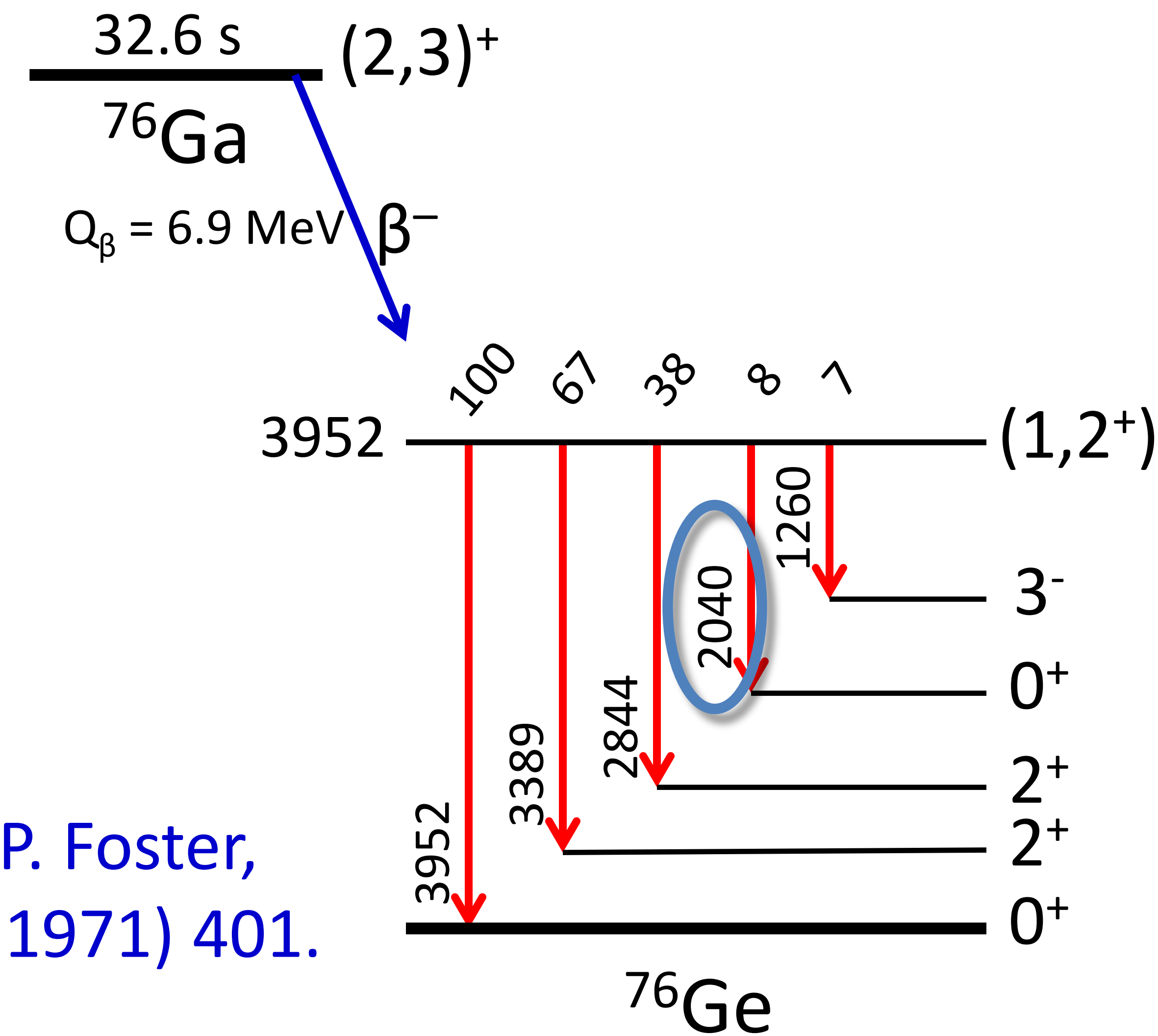
69th level in ^{76}Ge

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

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

Possible Interferences from ^{76}Ga β Decay

69th level in ^{76}Ge

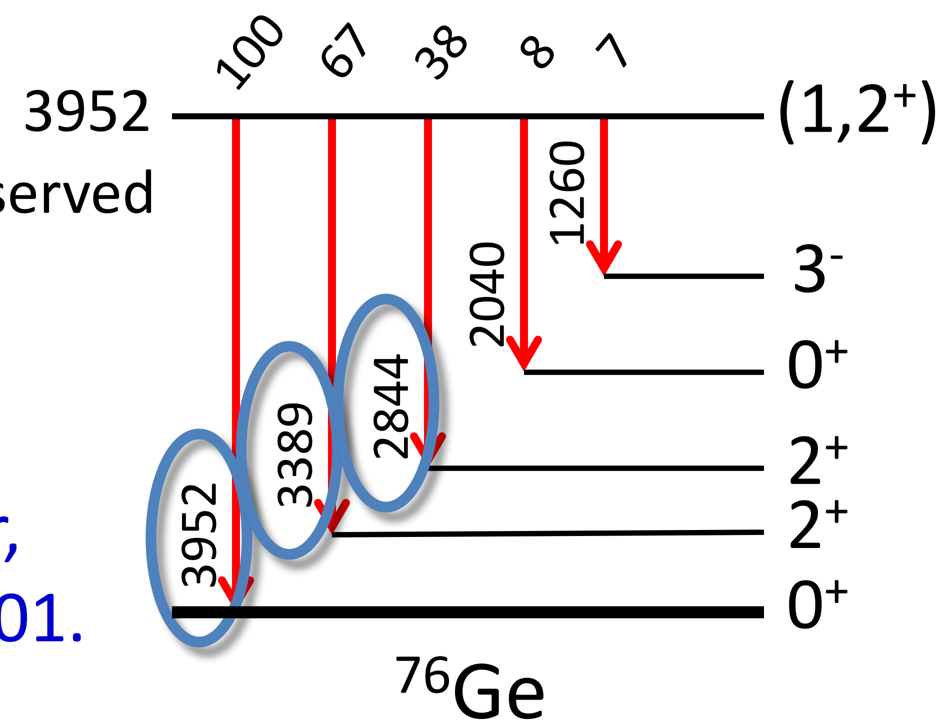


D. C. Camp and B. P. Foster, Nucl. Phys. A **177** (1971) 401.

Observed in ^{76}Ge(n,n′γ)

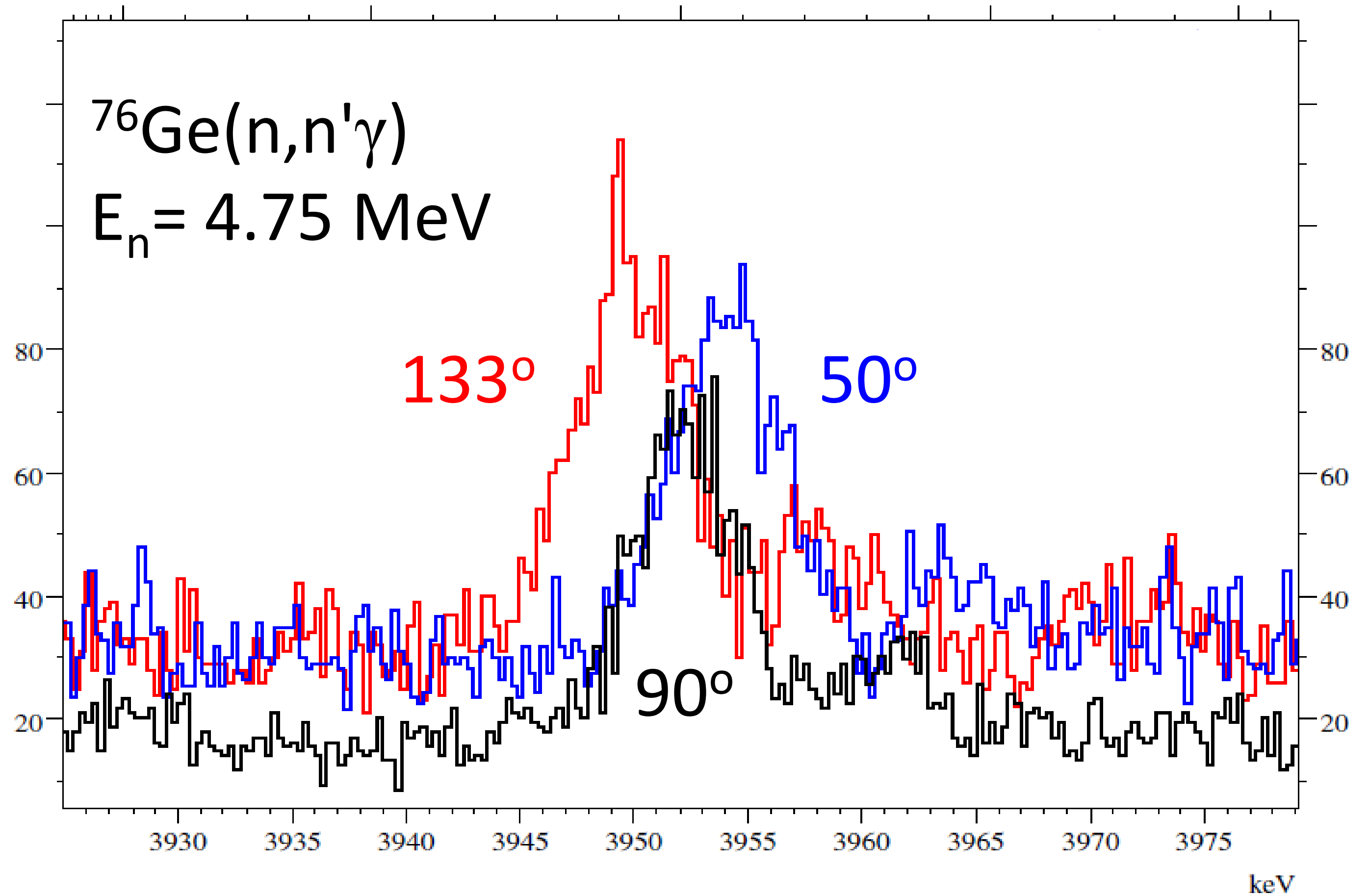
69th level in ^{76}Ge

3 most intense decay γ rays observed



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

Investigating the 3952-keV Level

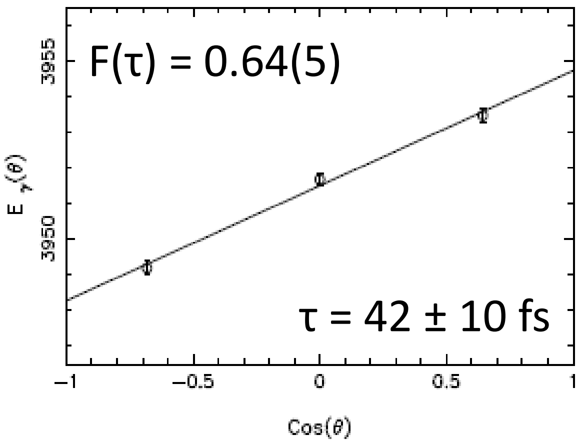


The 3952-keV transition to the ground state:

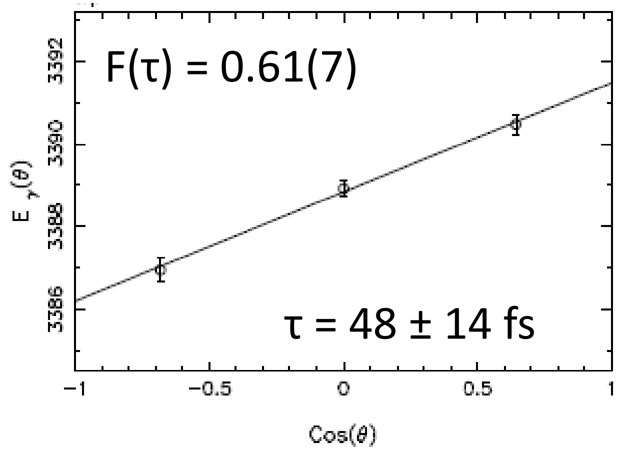
- **confirms the $(1,2^+)$ assignment from NNDC.**
- **appears to be of quadrupole character.**

Investigating the 3952-keV Level

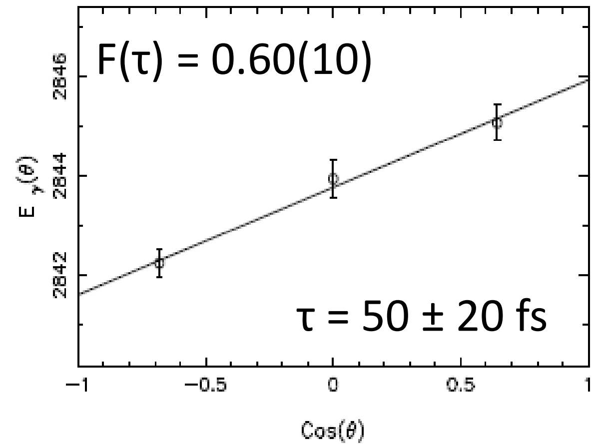
3952 keV



3389 keV

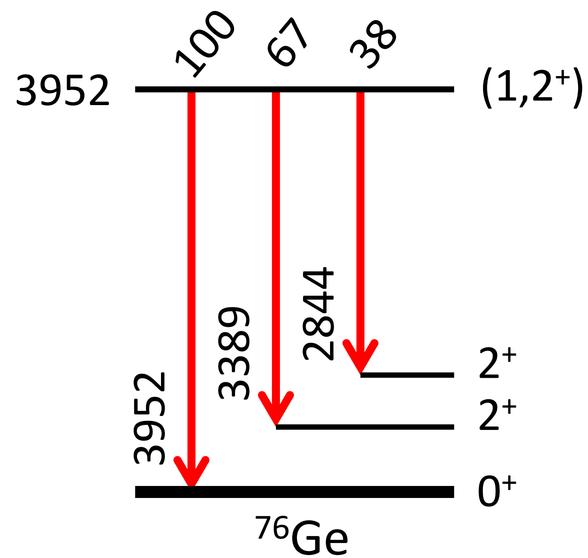


2844 keV

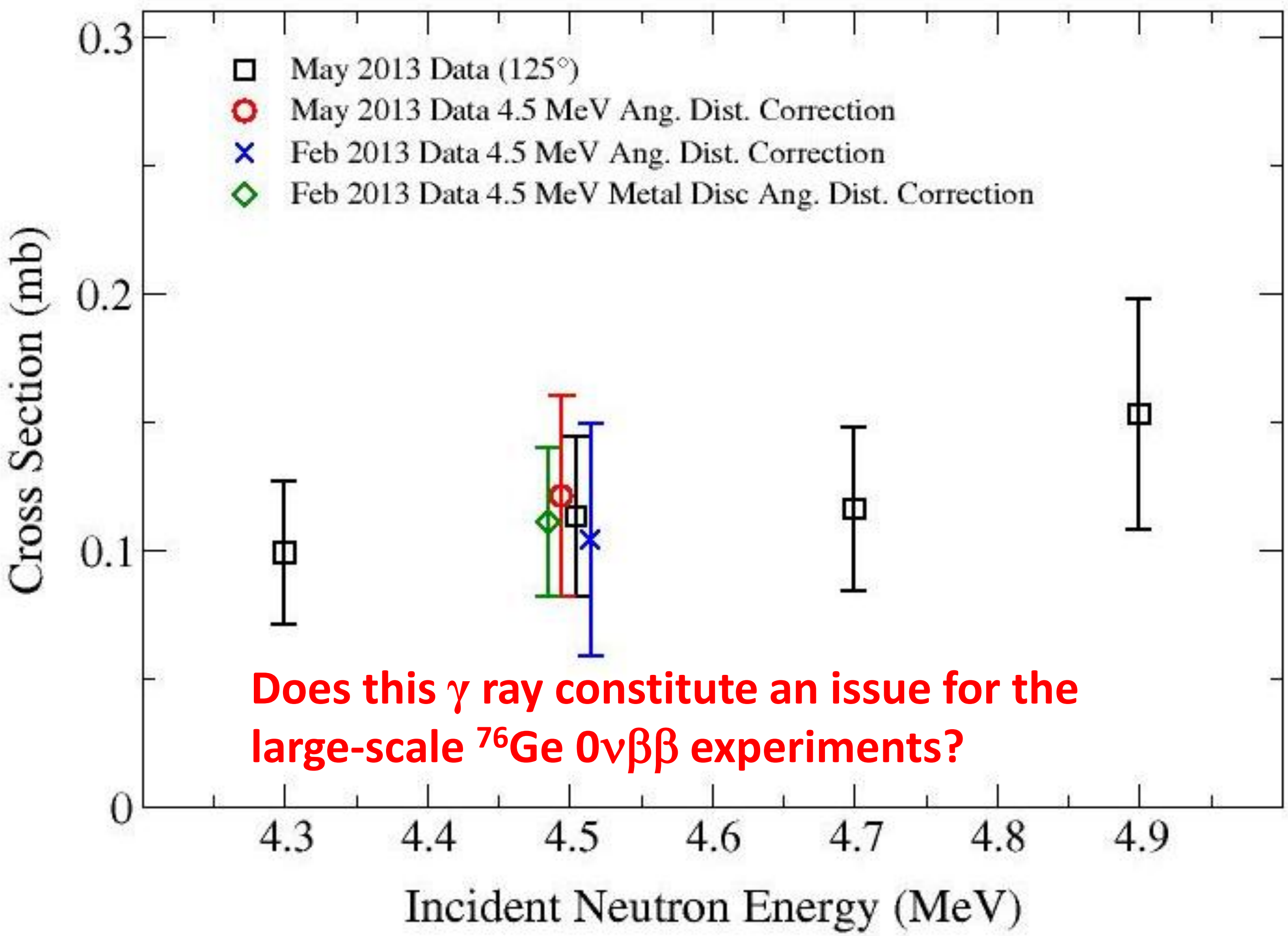


The three observed transitions yield the same lifetime (within uncertainties).

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



Cross Section for Production of the 2040-keV γ ray

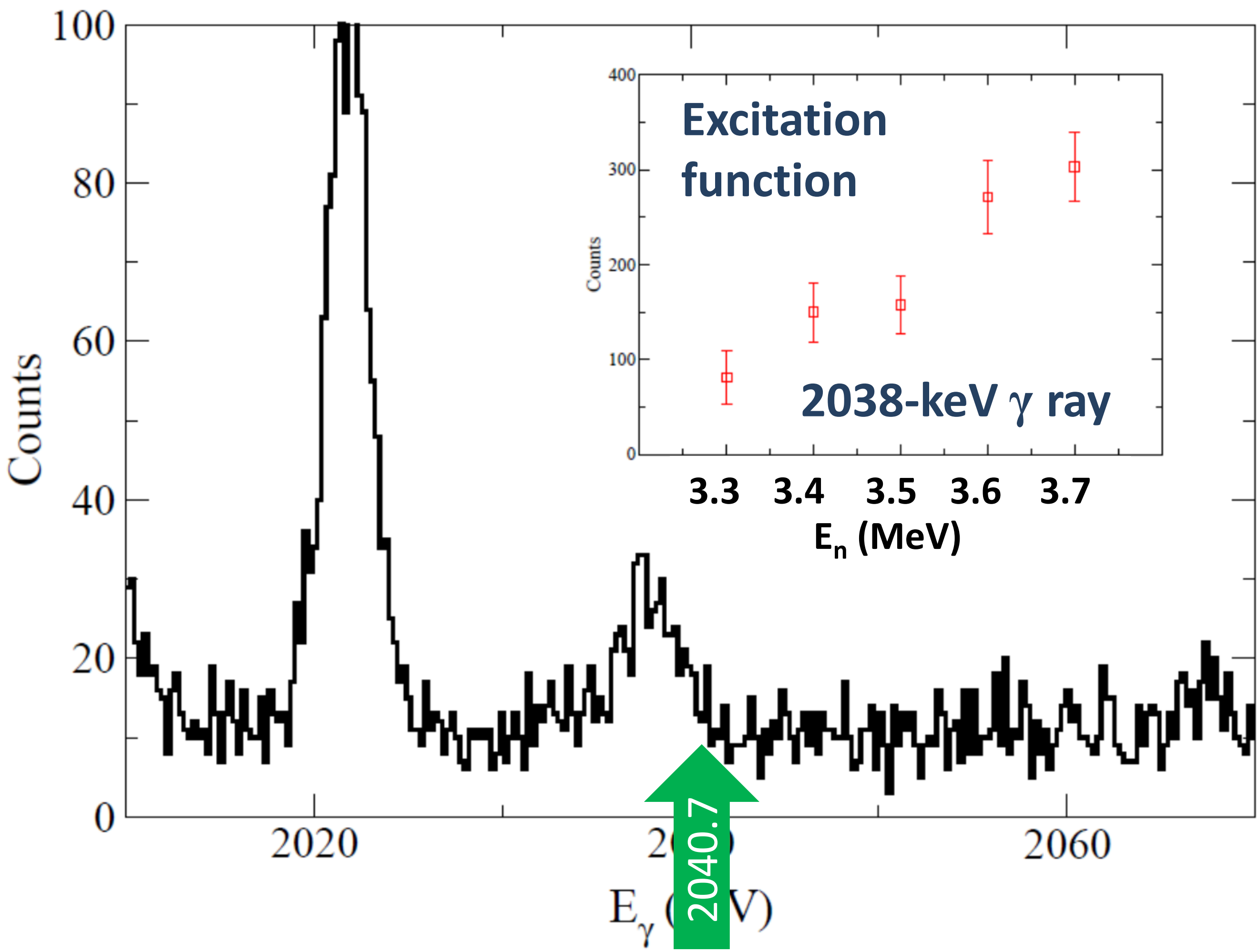


Does this γ ray constitute an issue for the large-scale ^{76}Ge 0νββ experiments?

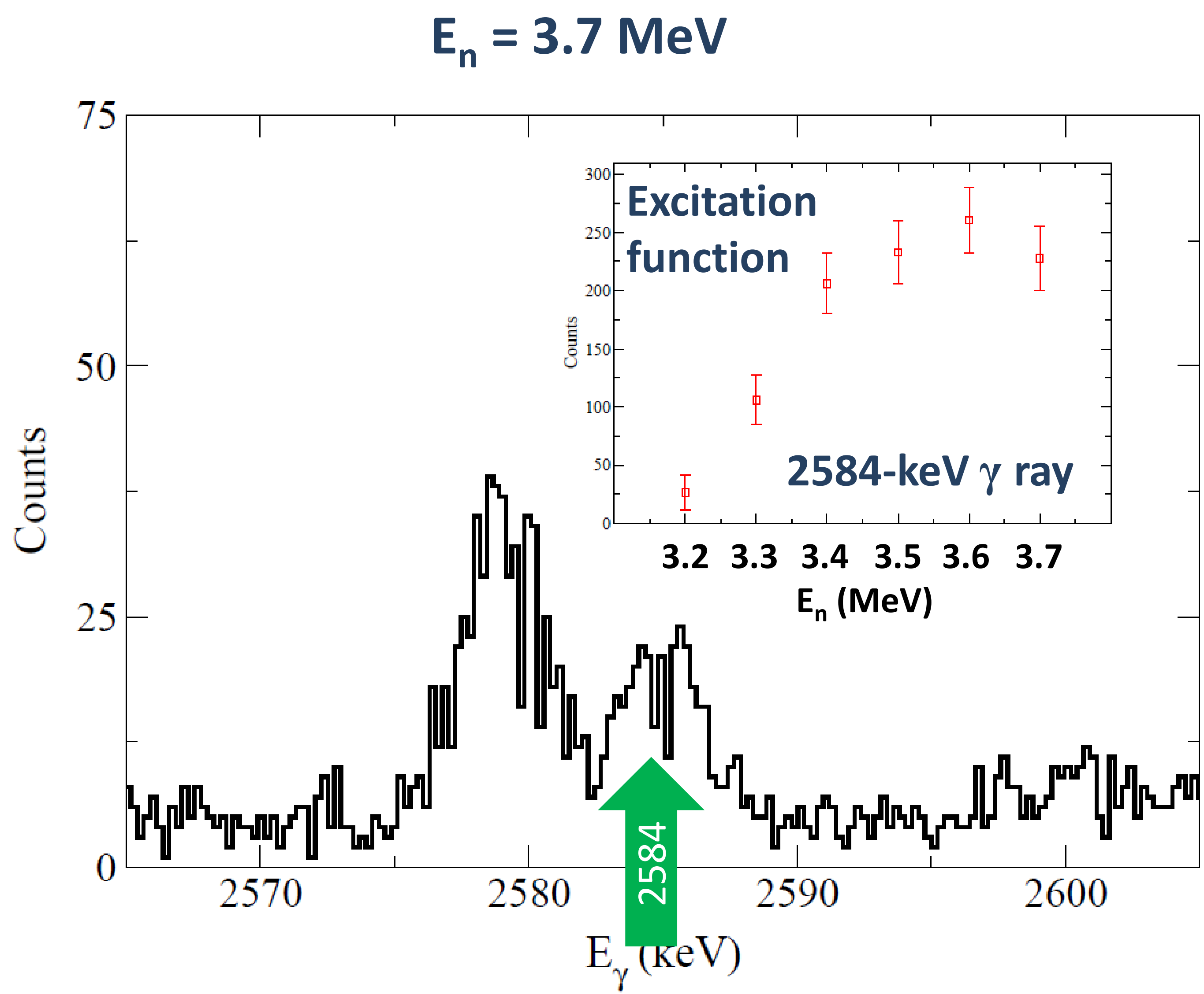
γ-ray branching ratios from Camp and Foster

2040-keV Region in the ^{76}Ge(n,n′γ) Spectrum

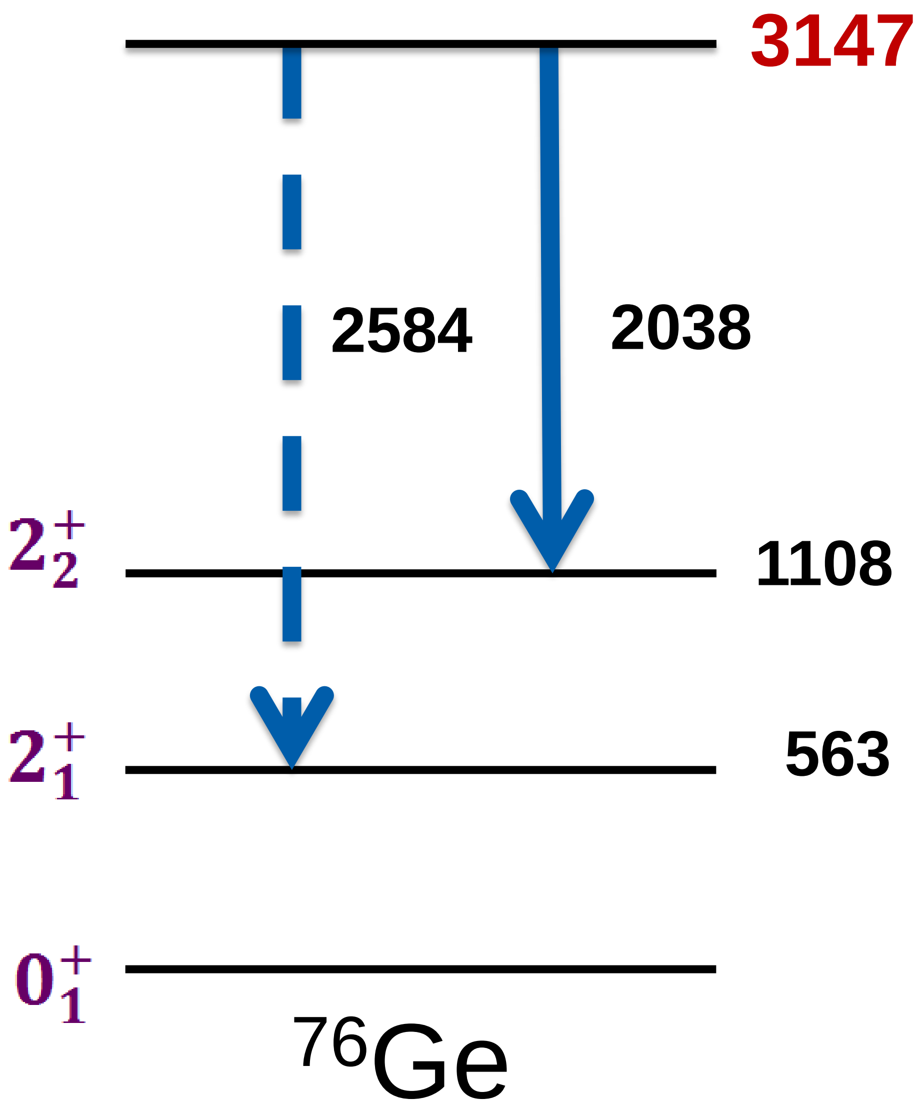
E_n = 3.7 MeV



2584-keV Region in the $^{76}Ge(n,n'\gamma)$ Spectrum

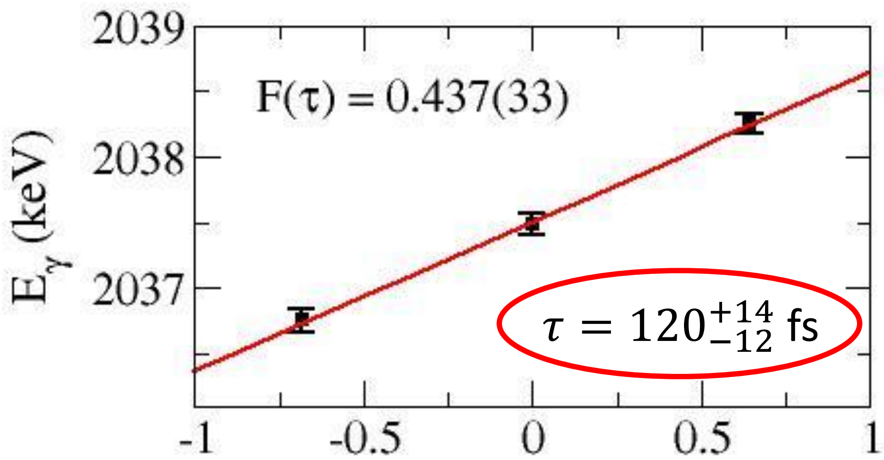


New Level at 3147 keV ?

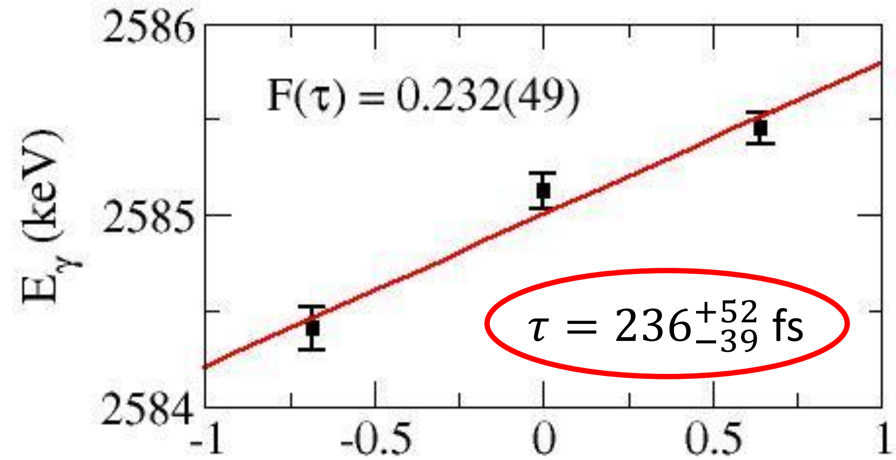


Another wrinkle…

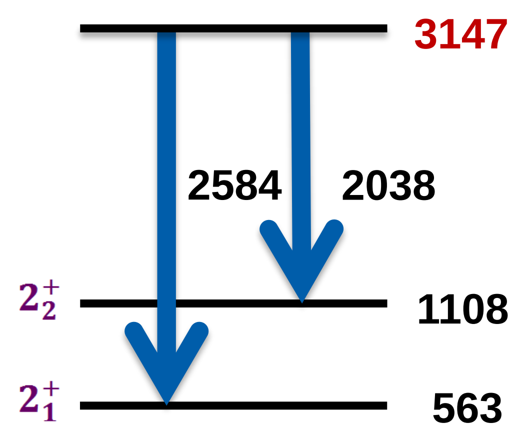
2038 keV



2584 keV



Potentially another interference?

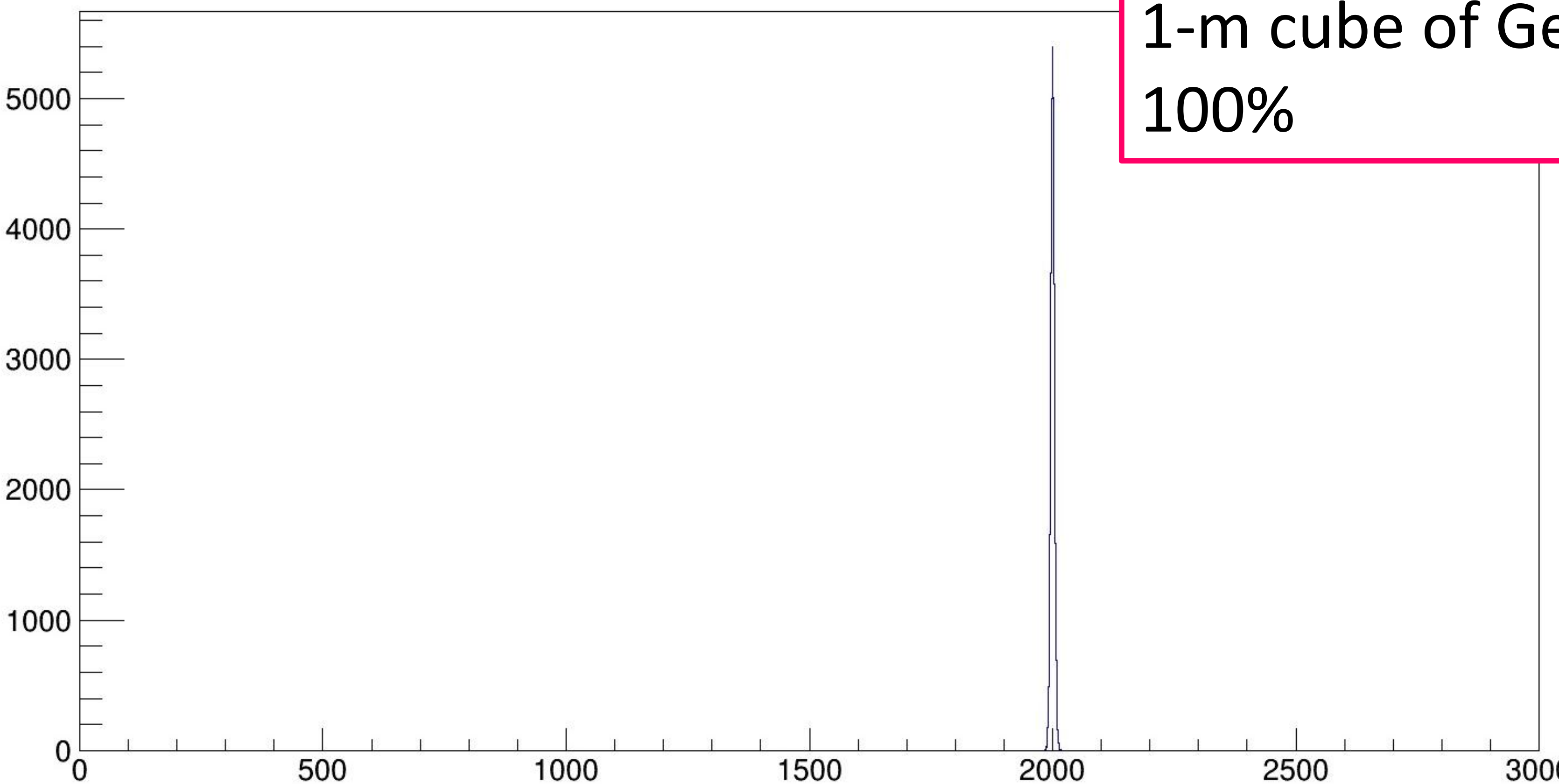


Do these γ rays constitute an issue for the large-scale ^{76}Ge 0νββ experiments?

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

Single-Site Events

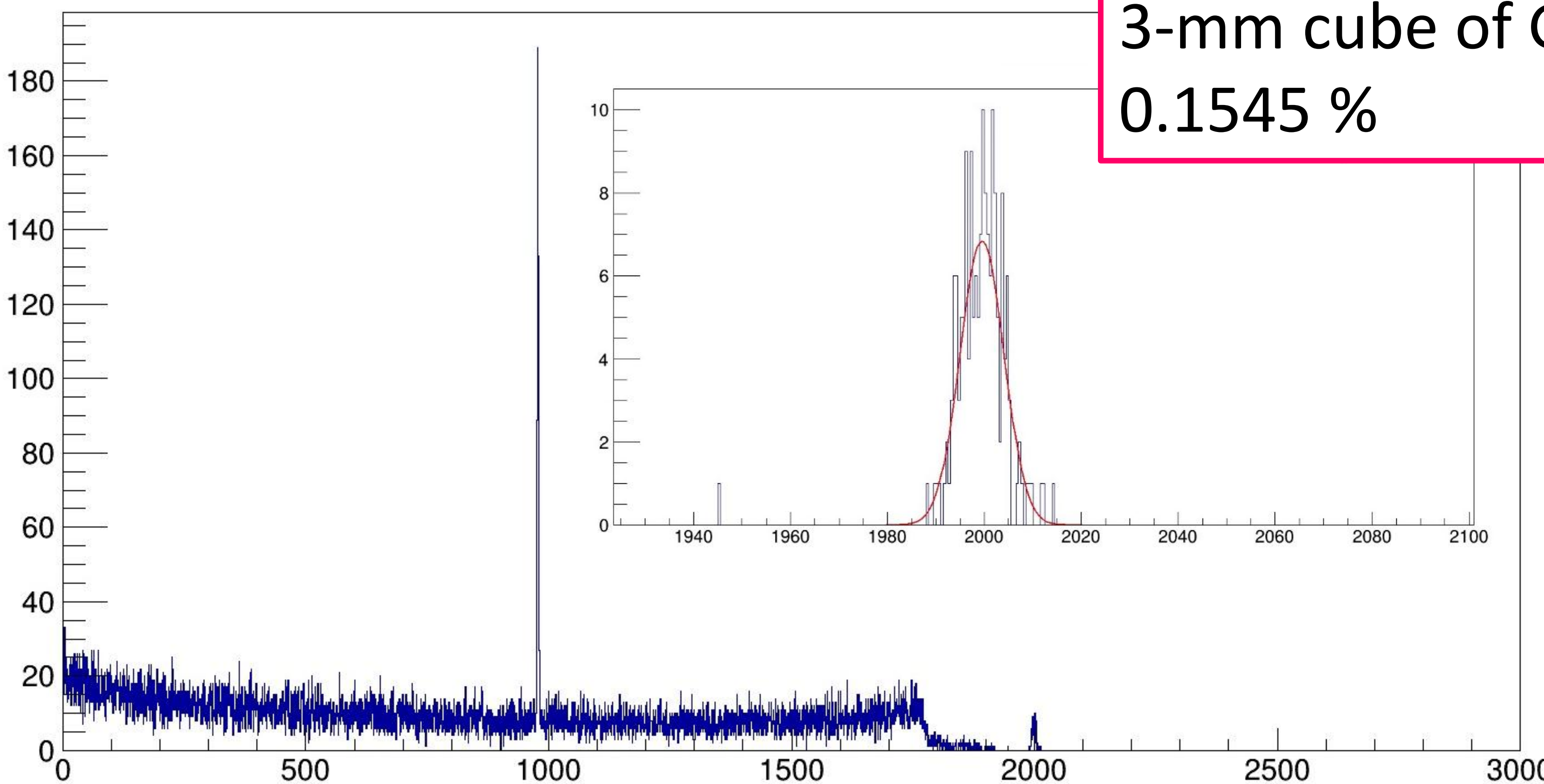
1-m cube of Ge
100%



E_γ (keV)

Single-Site Events

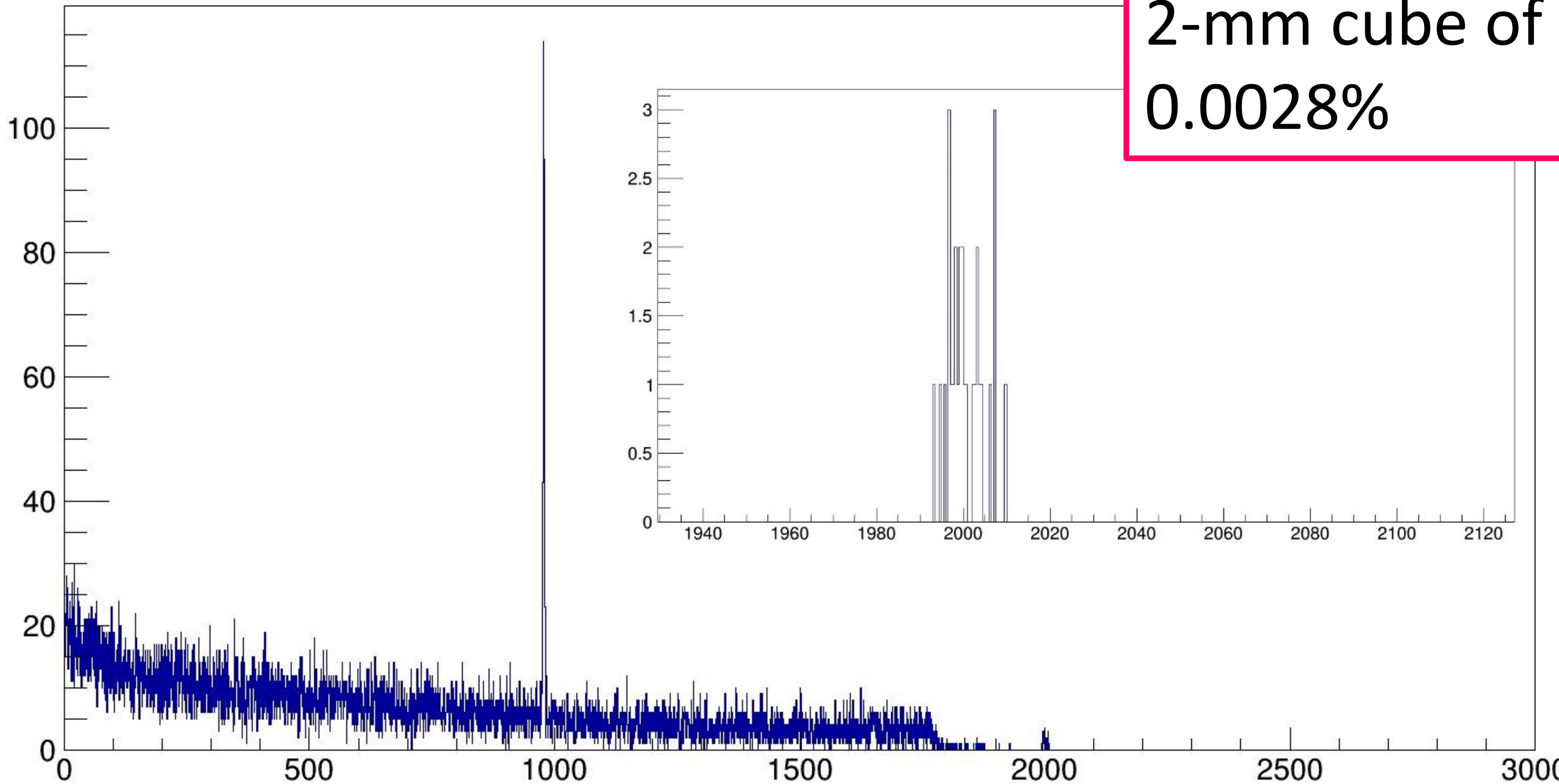
3-mm cube of Ge
0.1545 %



E_γ (keV)

Single-Site Events

2-mm cube of Ge
0.0028%



E_γ (keV)

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Vielen Dank!