Probing Nuclear Structure with Neutrons

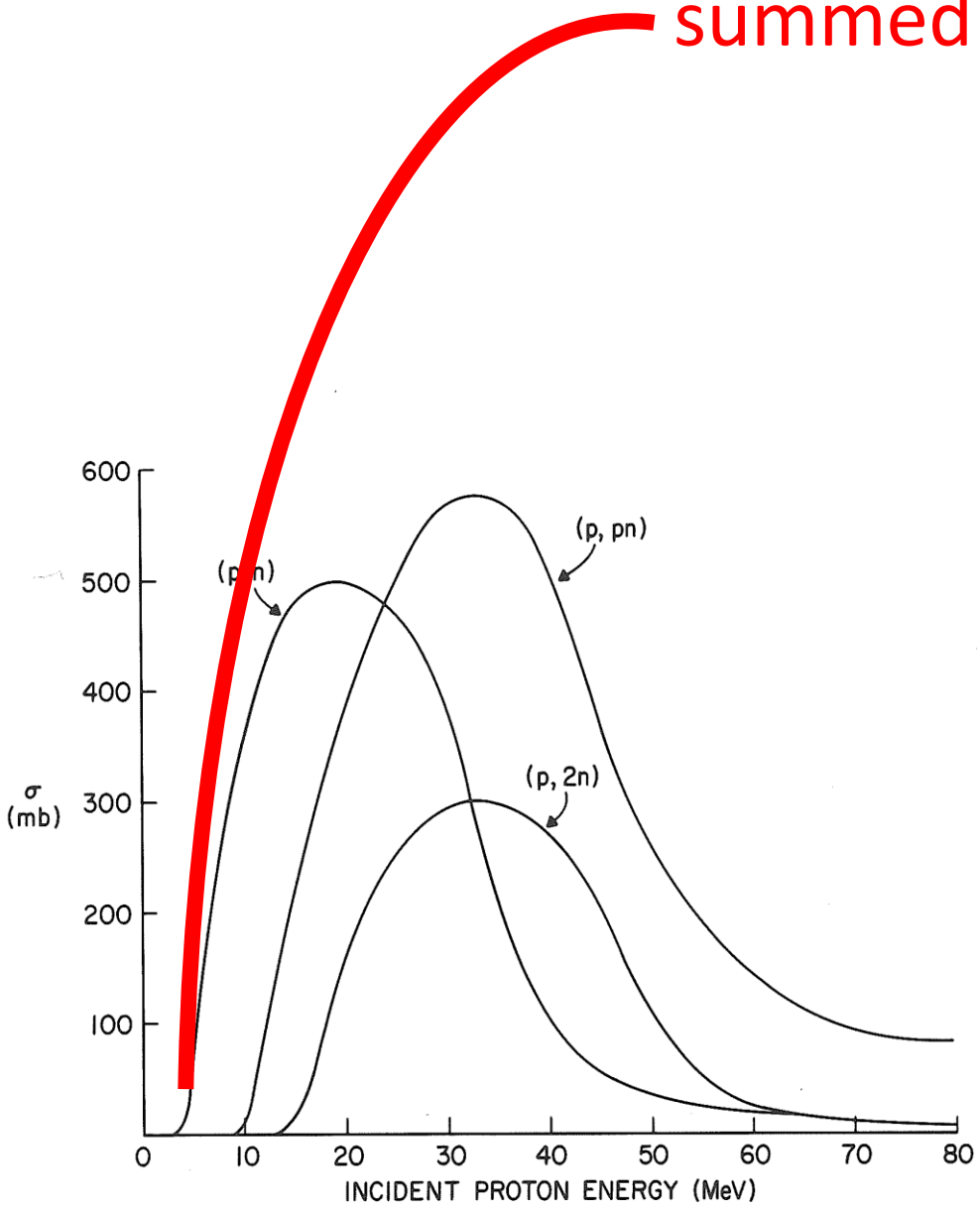
Steven W. Yates

University of Kentucky
Lexington, Kentucky

8th Tastes of Nuclear Physics
UWC, 9-12 October 2018

Association for Research at University Nuclear Accelerators

summed cross sections



summed cross sections

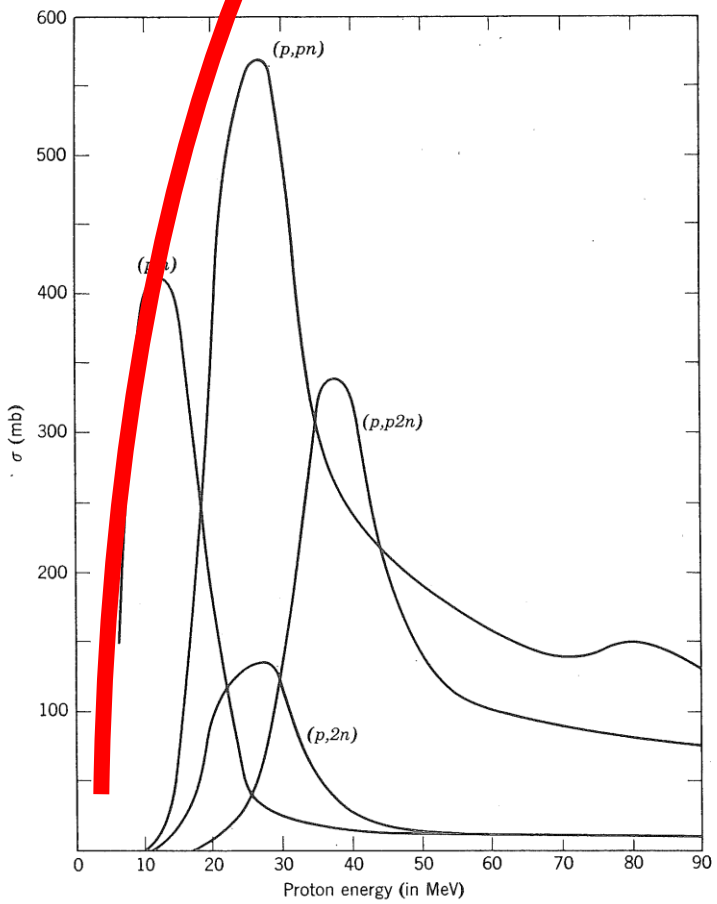
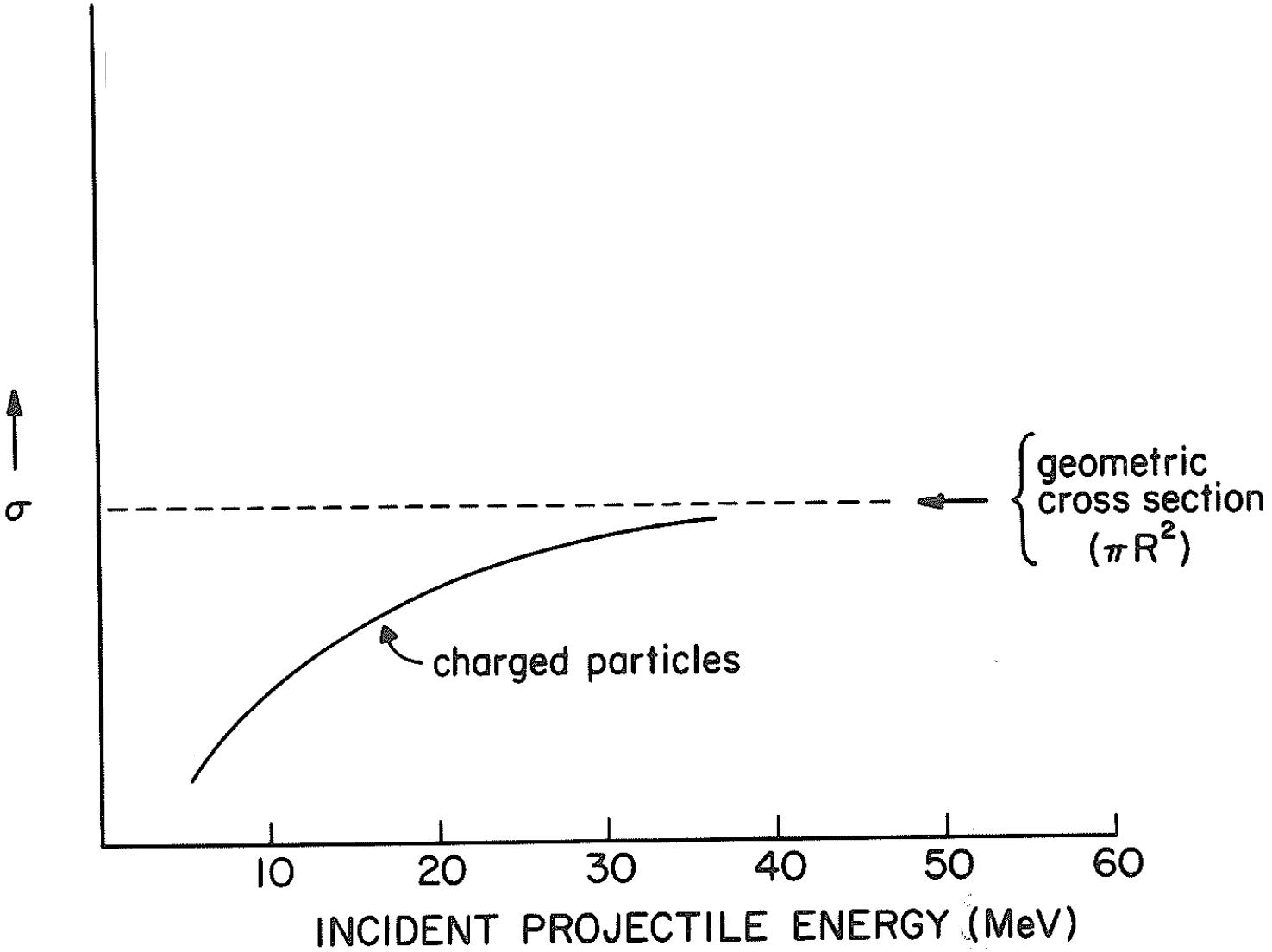
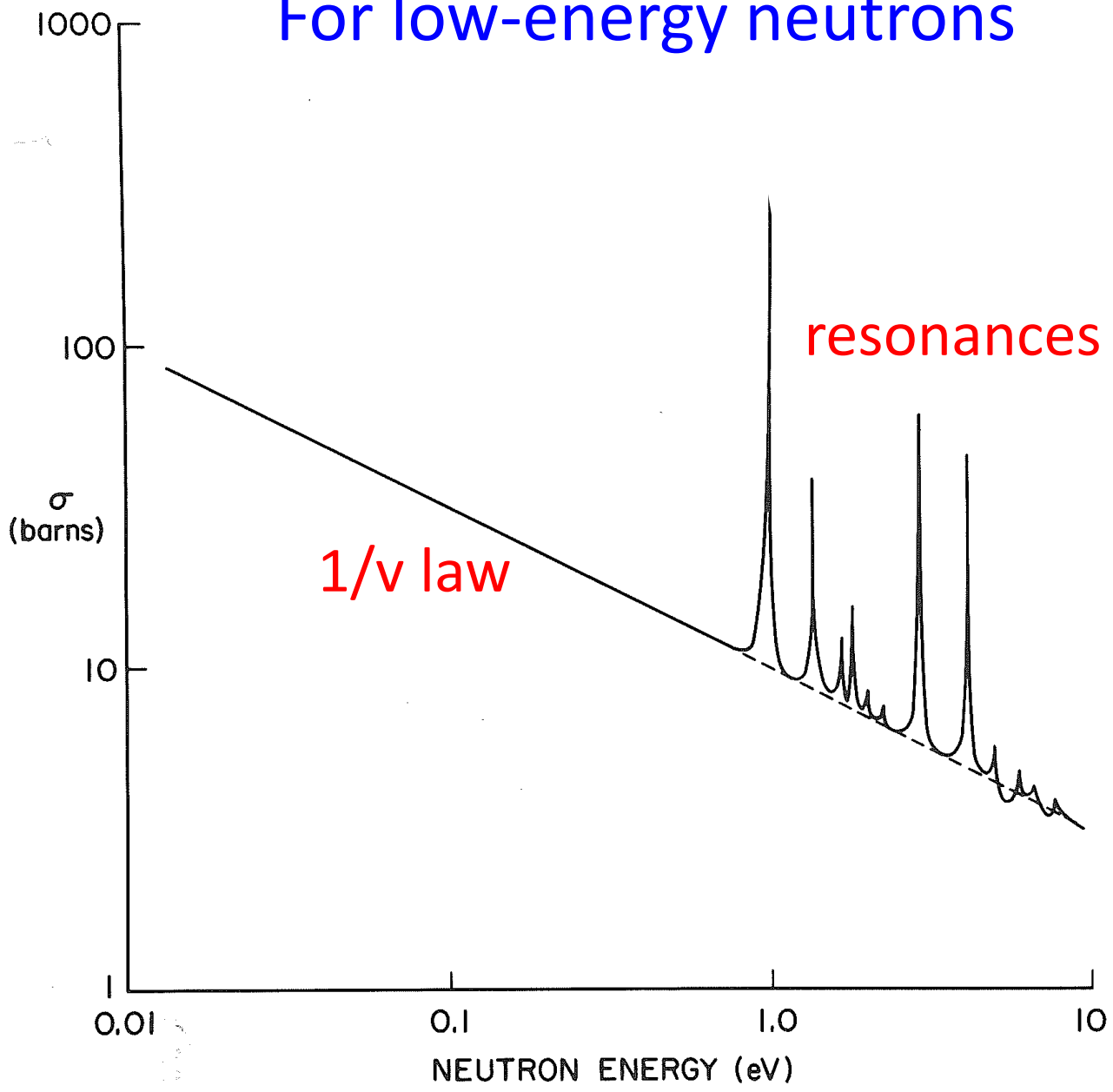


Fig. 4-5 Excitation functions for proton-induced reactions on ^{63}Cu. [From J. W. Meadows, *Phys. Rev.* **91**, 885 (1953).]


σ
geometric
cross section
(πR²)
charged particles
10
20
30
40
50
60
INCIDENT PROJECTILE ENERGY (MeV)

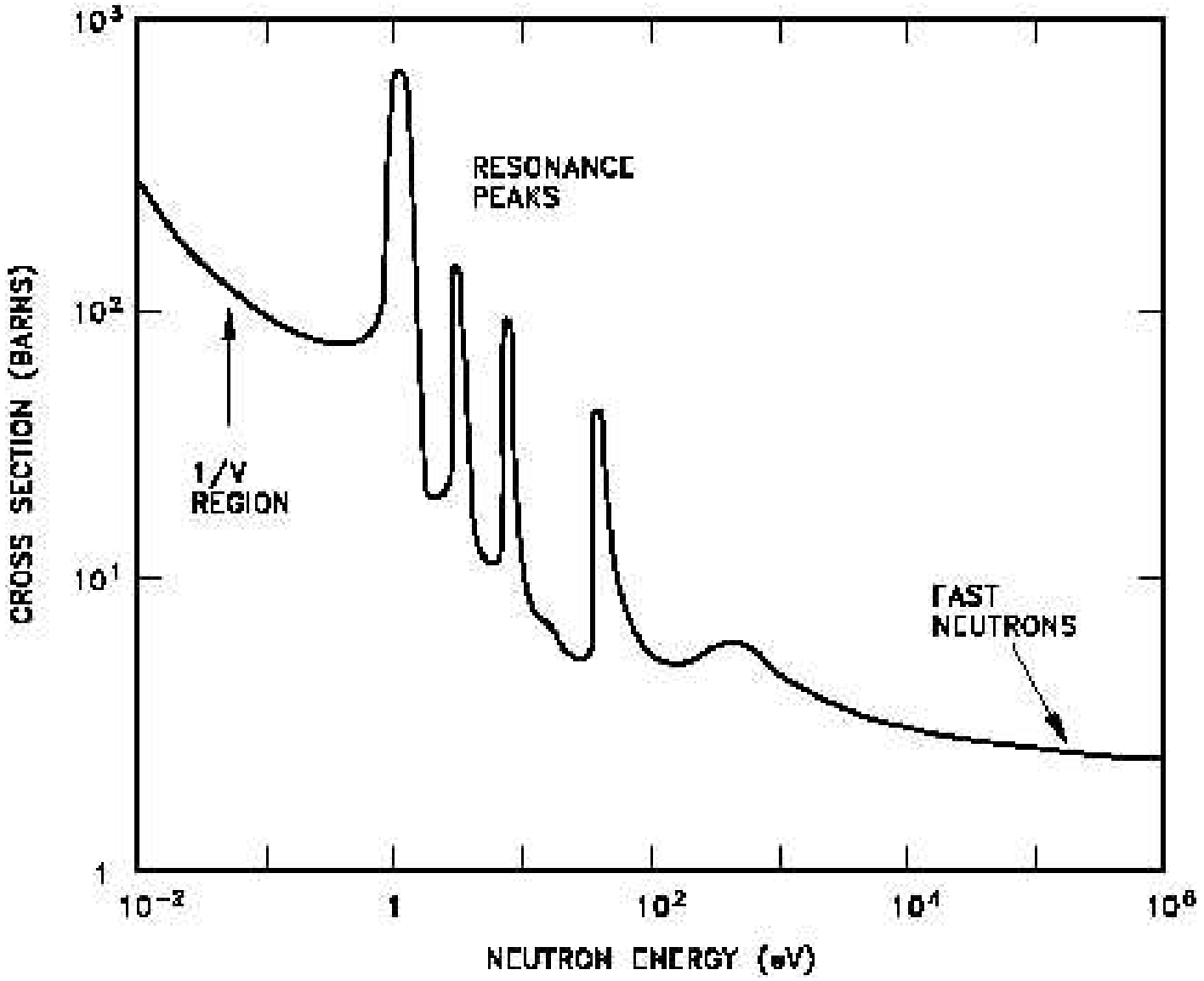
For low-energy neutrons



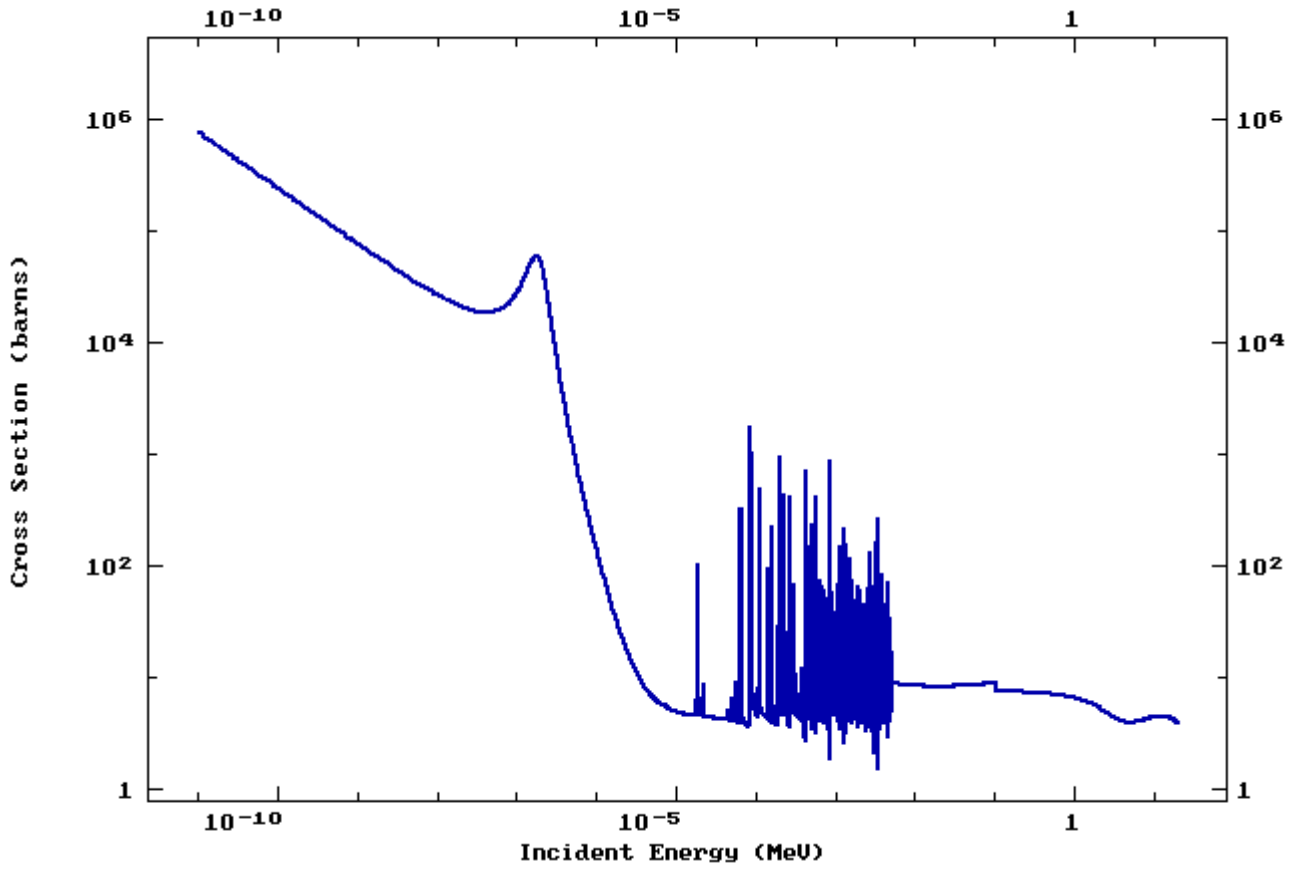
Neutrons

Neutron energy	Energy range
0.0–0.025 eV	Cold neutrons
0.025 eV	Thermal neutrons
0.025–0.4 eV	Epithermal neutrons
0.4–0.6 eV	Cadmium neutrons
0.6–1 eV	EpiCadmium neutrons
1–10 eV	Slow neutrons
10–300 eV	Resonance neutrons
300 eV–1 MeV	Intermediate neutrons
1–20 MeV	Fast neutrons
> 20 MeV	Ultrafast neutrons

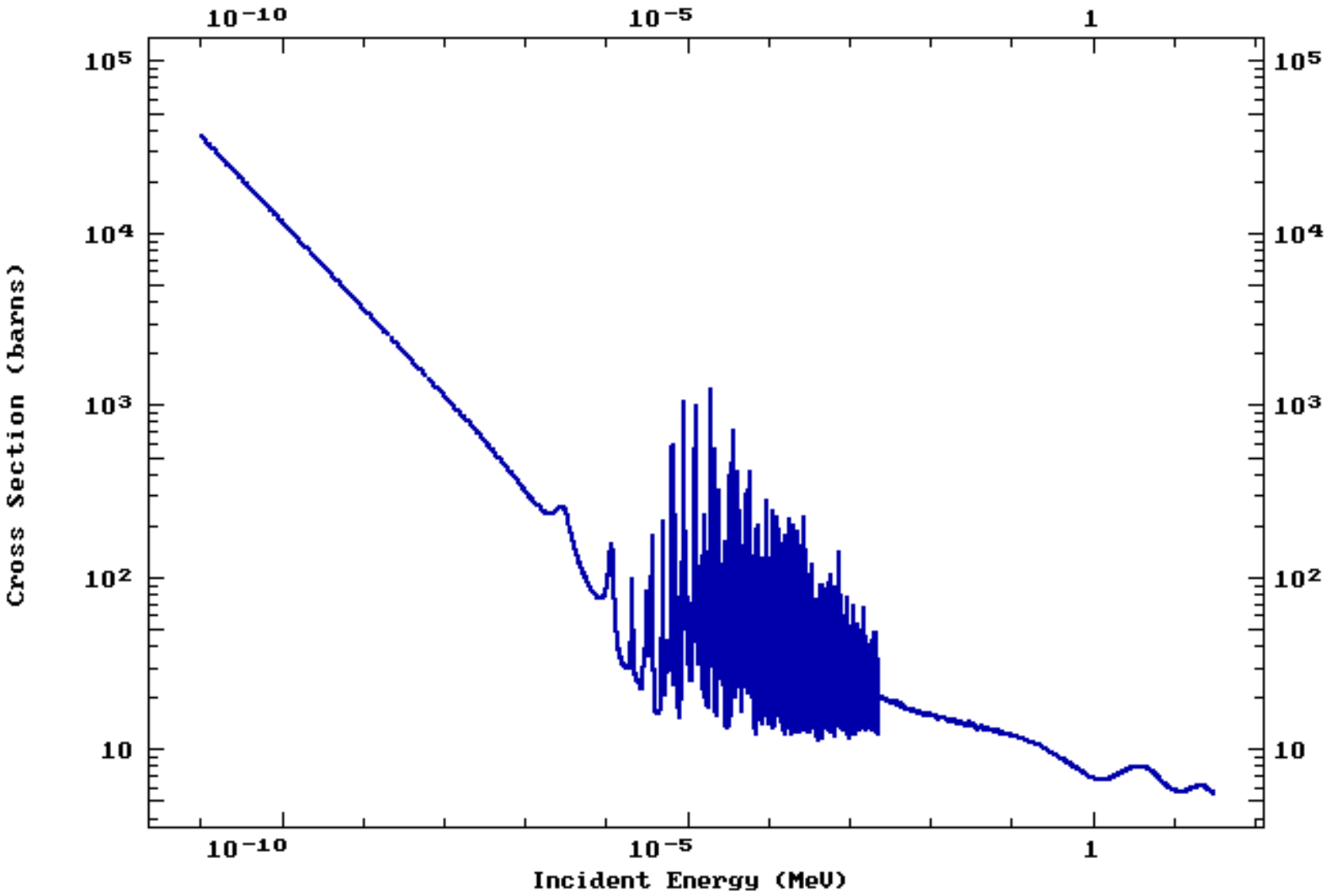
0.025 eV v = 2.2 km/s


CROSS SECTION (BARNS)
10^3
10^2
10^1
1
RESONANCE PEAKS
1/V REGION
FAST NEUTRONS
10^{-2}
1
10^2
10^4
10^6
NEUTRON ENERGY (eV)

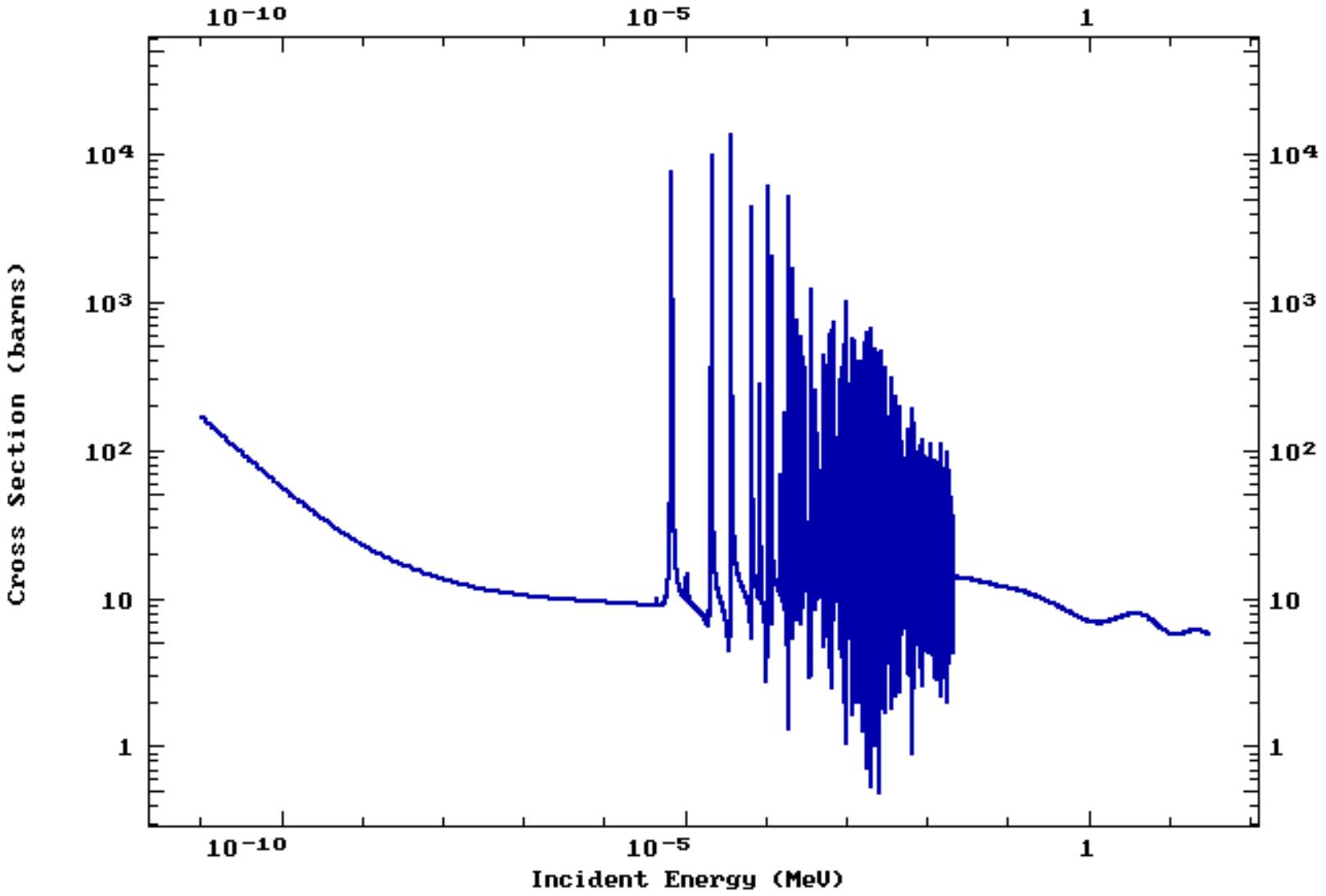
n + 113Cd


10⁻¹⁰
10⁻⁵
1
10⁶
10⁴
10²
1
Cross Section (barns)
Incident Energy (MeV)

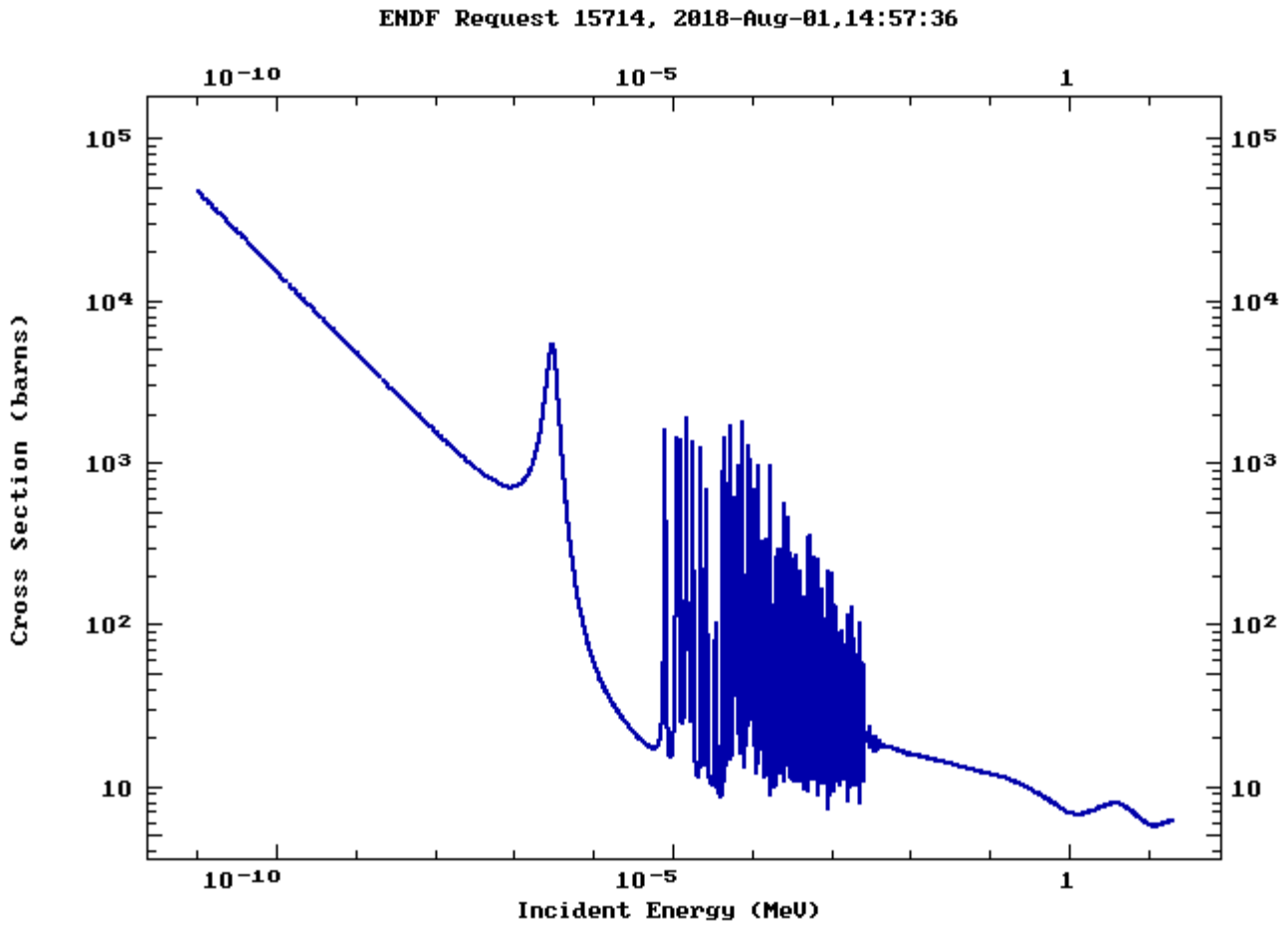
n + 235U


Cross Section (barns)
Incident Energy (MeV)
10^-10
10^-5
1
10^5
10^4
10^3
10^2
10

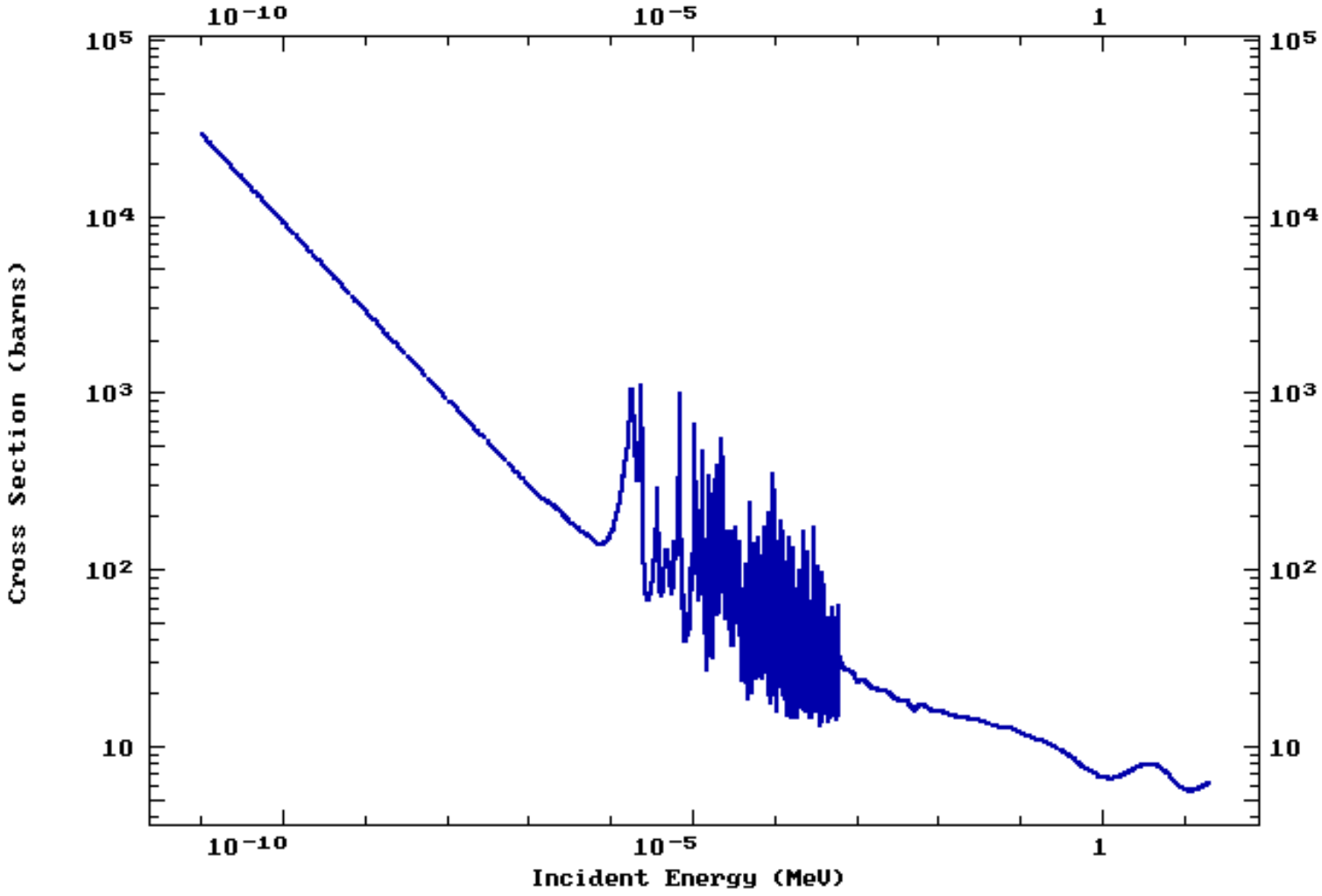
n + 238U

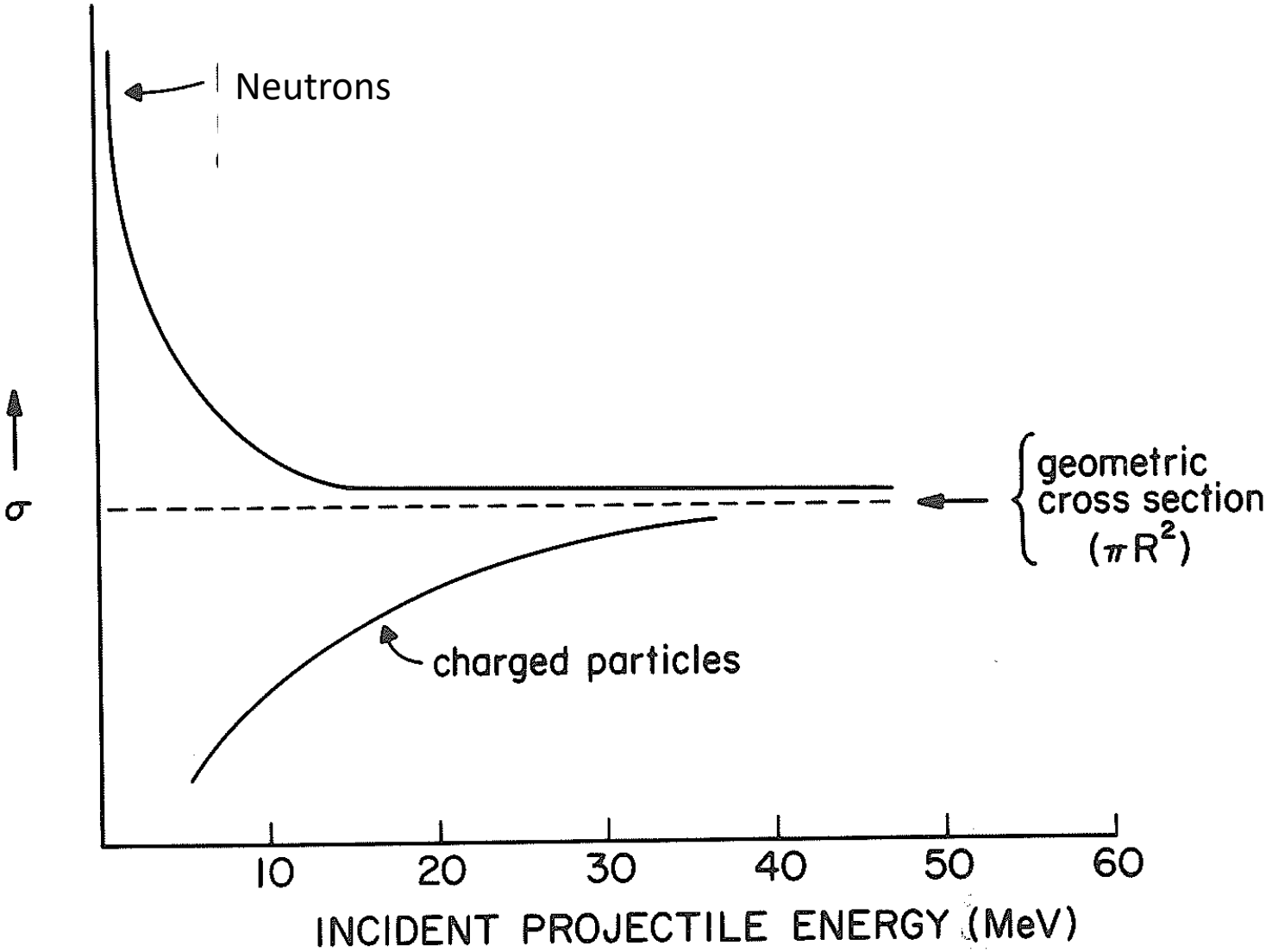

10⁻¹⁰
10⁻⁵
1
10⁴
10³
10²
10
1
Cross Section (barns)
Incident Energy (MeV)

n + 239Pu


ENDF Request 15714, 2018-Aug-01,14:57:36
Cross Section (barns)
Incident Energy (MeV)
10^-10
10^-5
1
10^5
10^4
10^3
10^2
10

n + 233U


Cross Section (barns)
Incident Energy (MeV)
10^5
10^4
10^3
10^2
10
10^-10
10^-5
1


Neutrons
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geometric
cross section
(πR²)
charged particles
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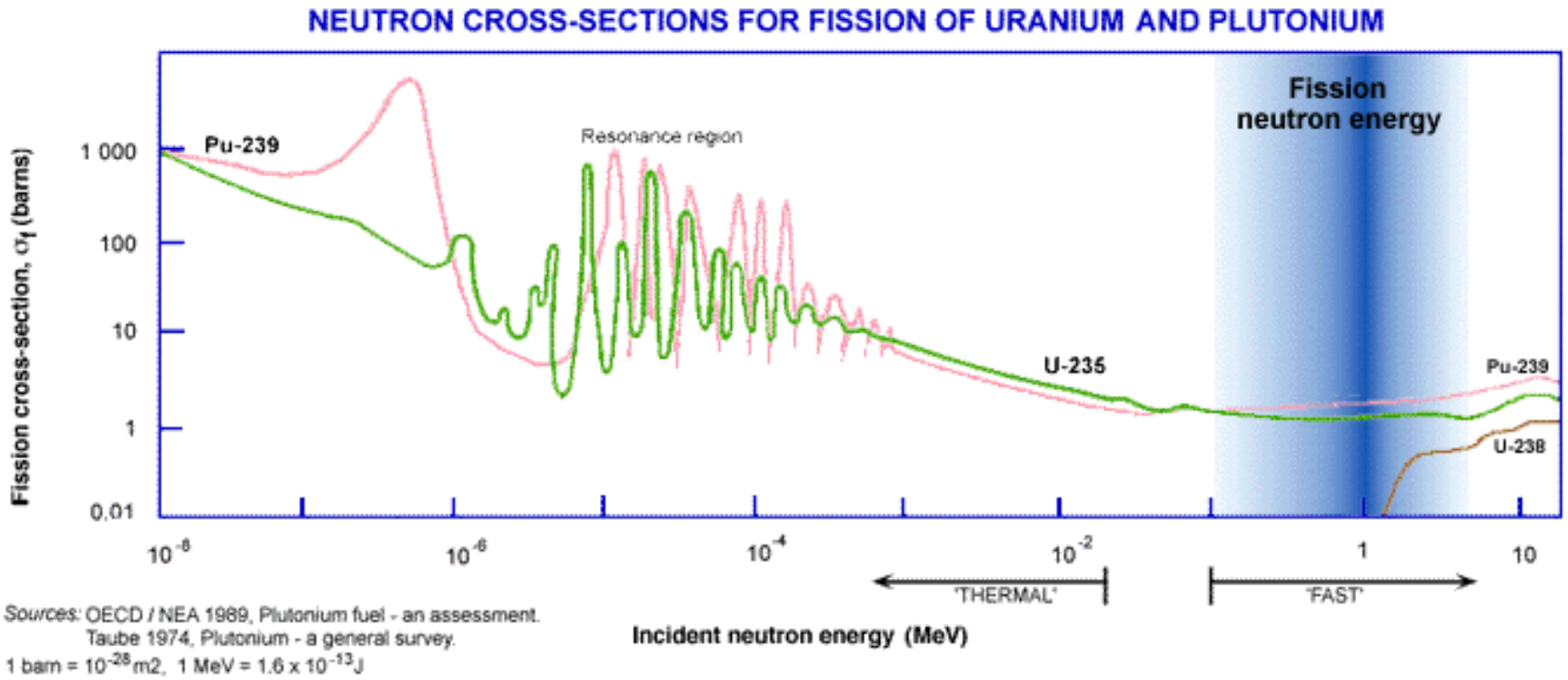
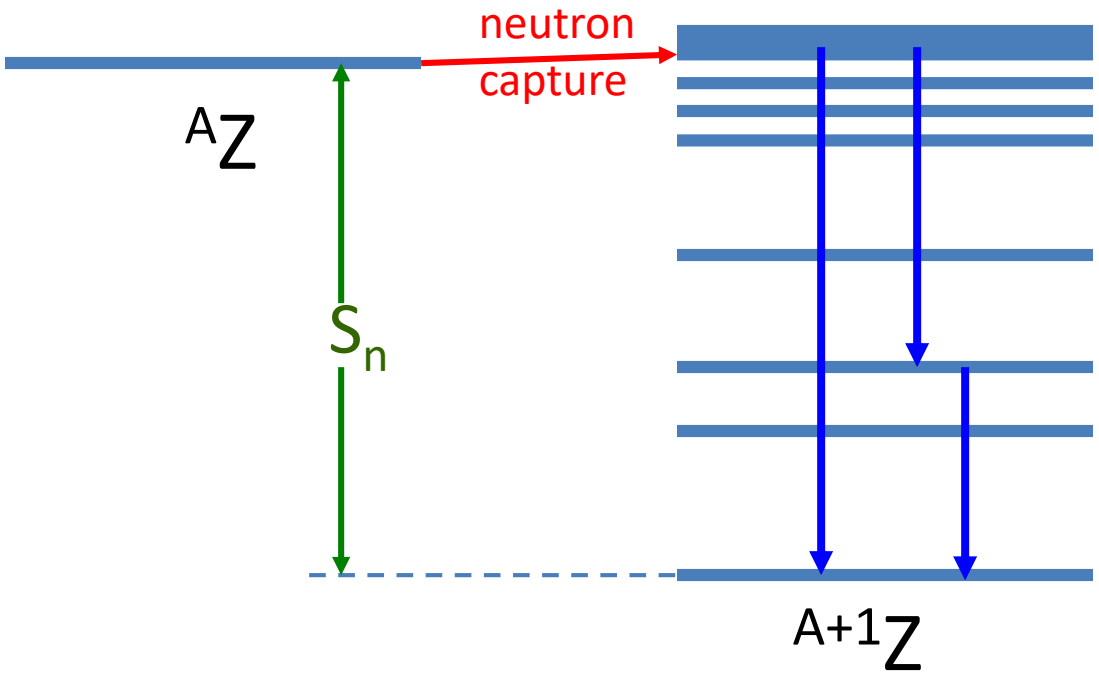
INCIDENT PROJECTILE ENERGY (MeV)



Sources: OECD / NEA 1989, Plutonium fuel - an assessment.
Taube 1974, Plutonium - a general survey.

1 barn = 10^{-28}m2, 1 MeV = 1.6 x 10^{-13}J

Neutron Reactions



$^{A-1}_{Z}X(n_{th},\gamma\gamma)$ reaction (in simple terms)

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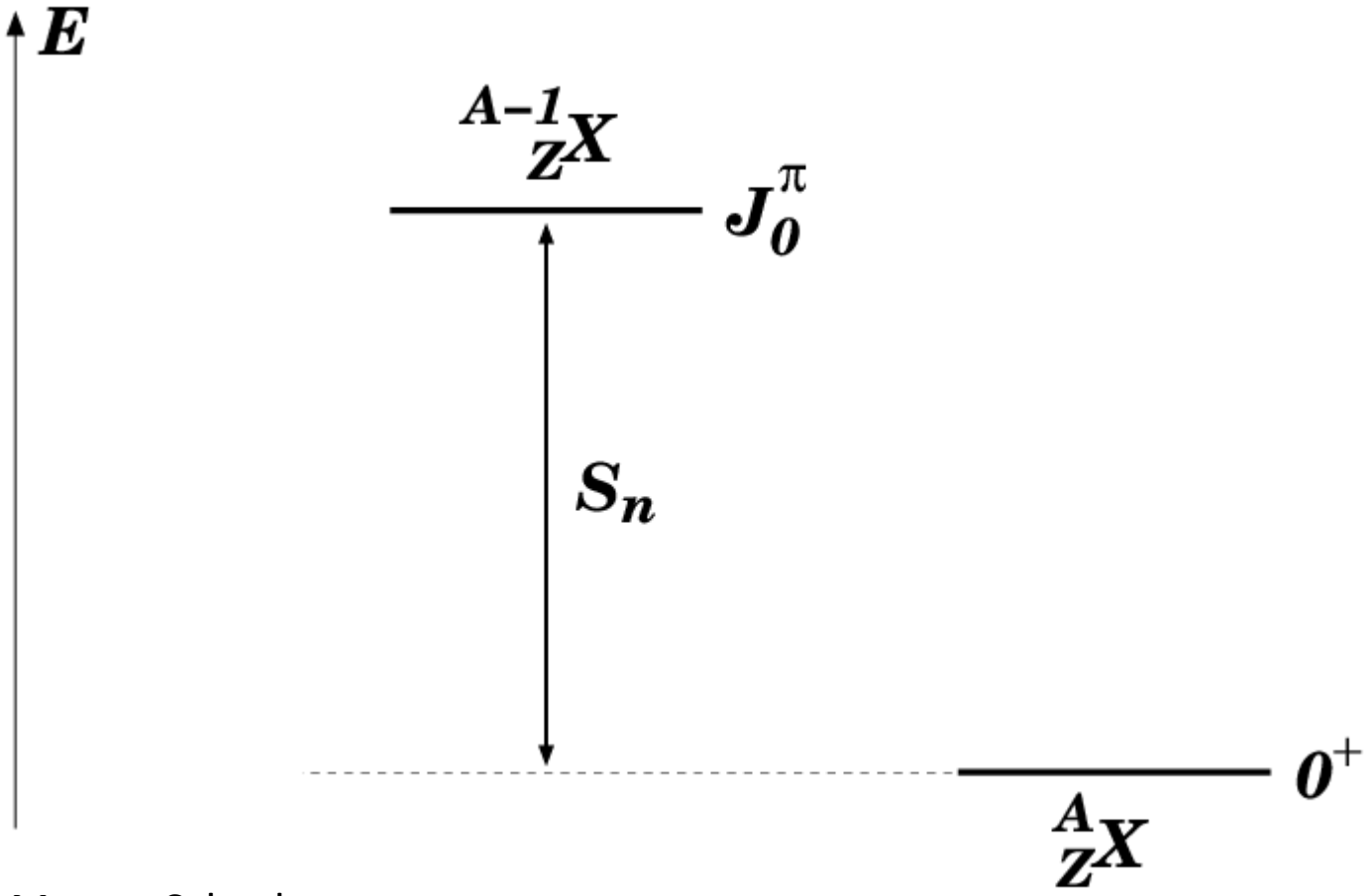
UWS



From Marcus Scheck

${}^{A-1}_{Z}X(n_{th},\gamma\gamma)$ reaction (in simple terms)

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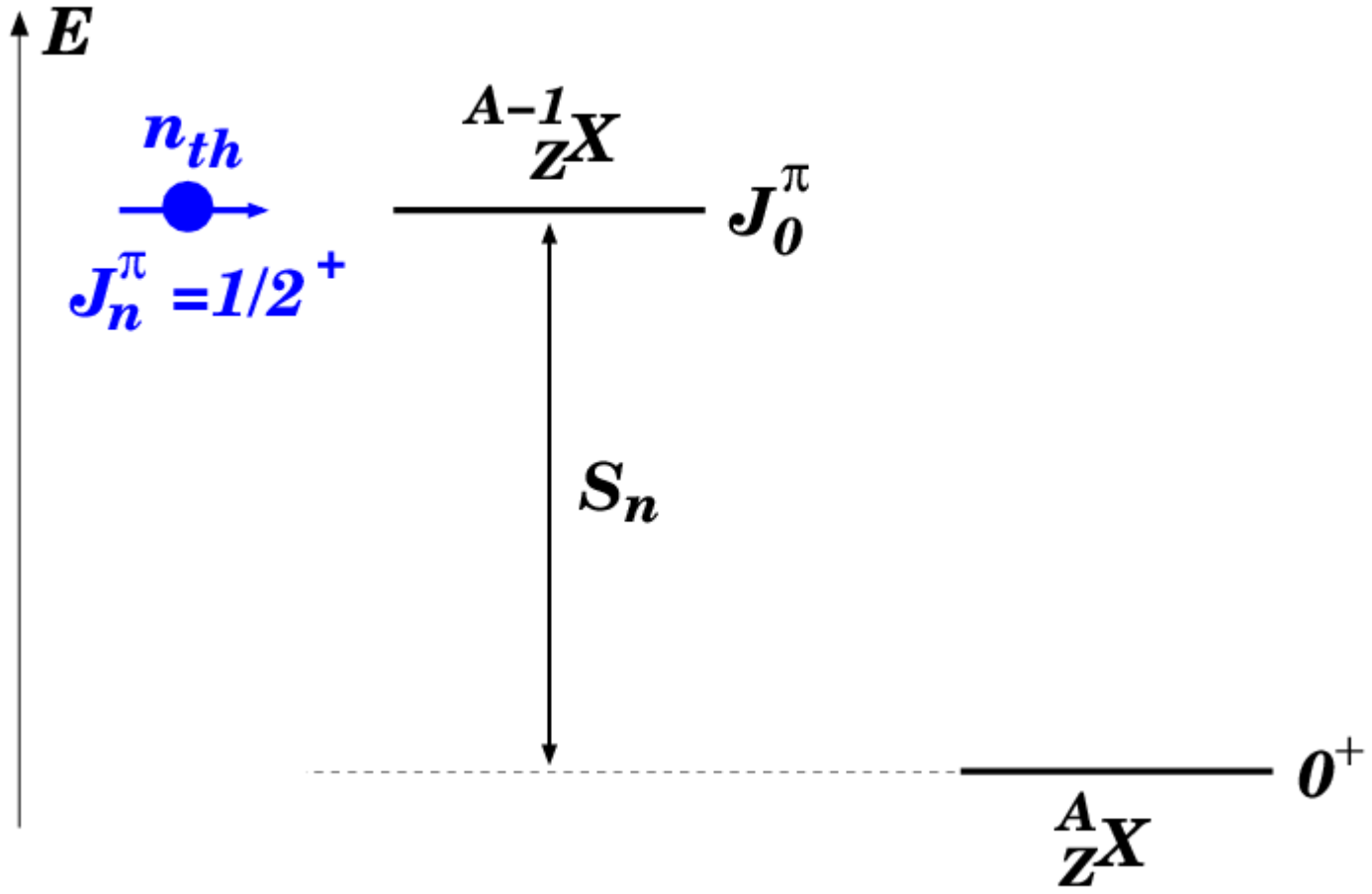

$^{A-1}_{Z}X(n_{th},\gamma\gamma)$ reaction (in simple terms)

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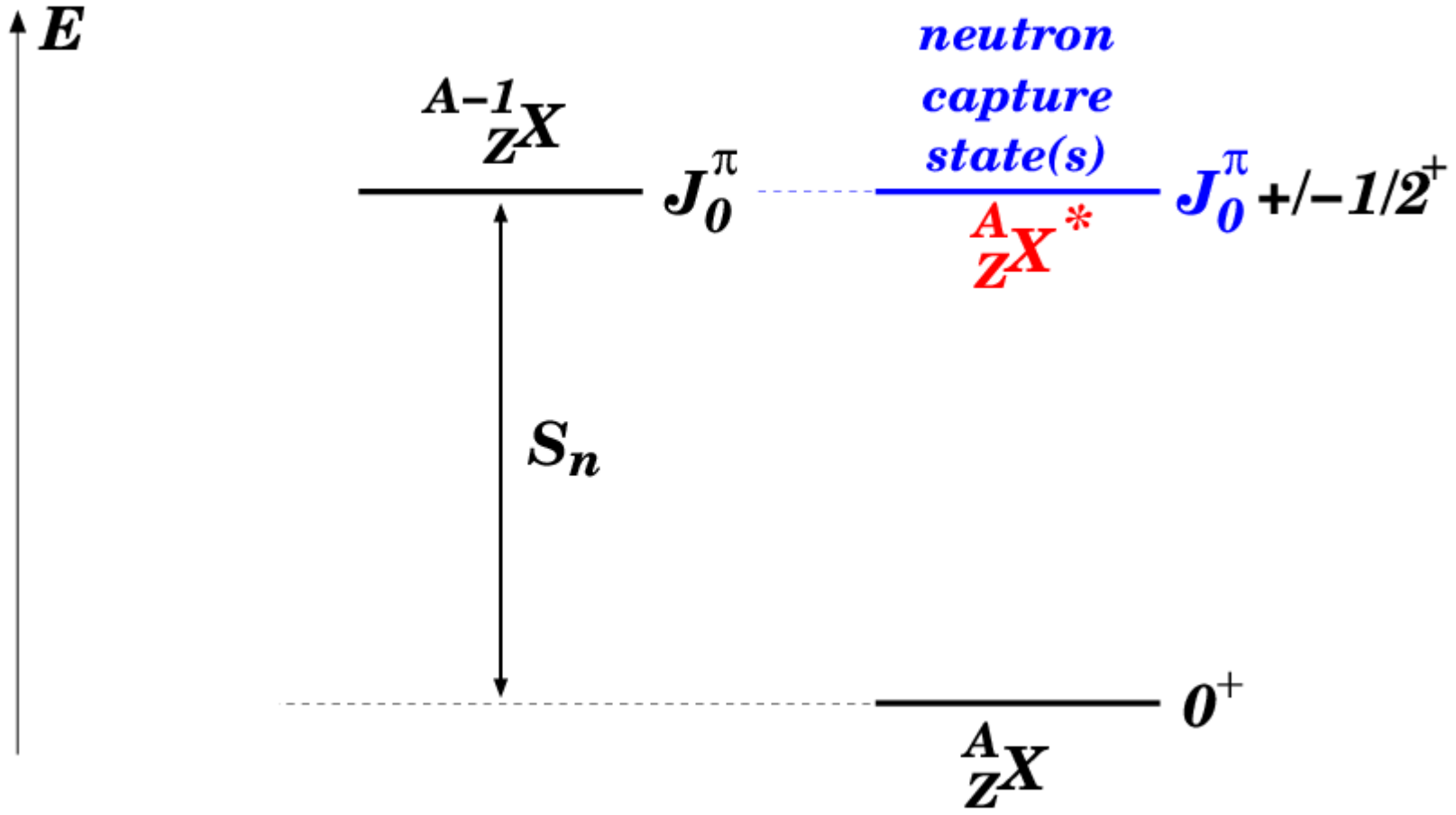

${}^{A-1}_{Z}X(n_{th},\gamma\gamma)$ reaction (in simple terms)

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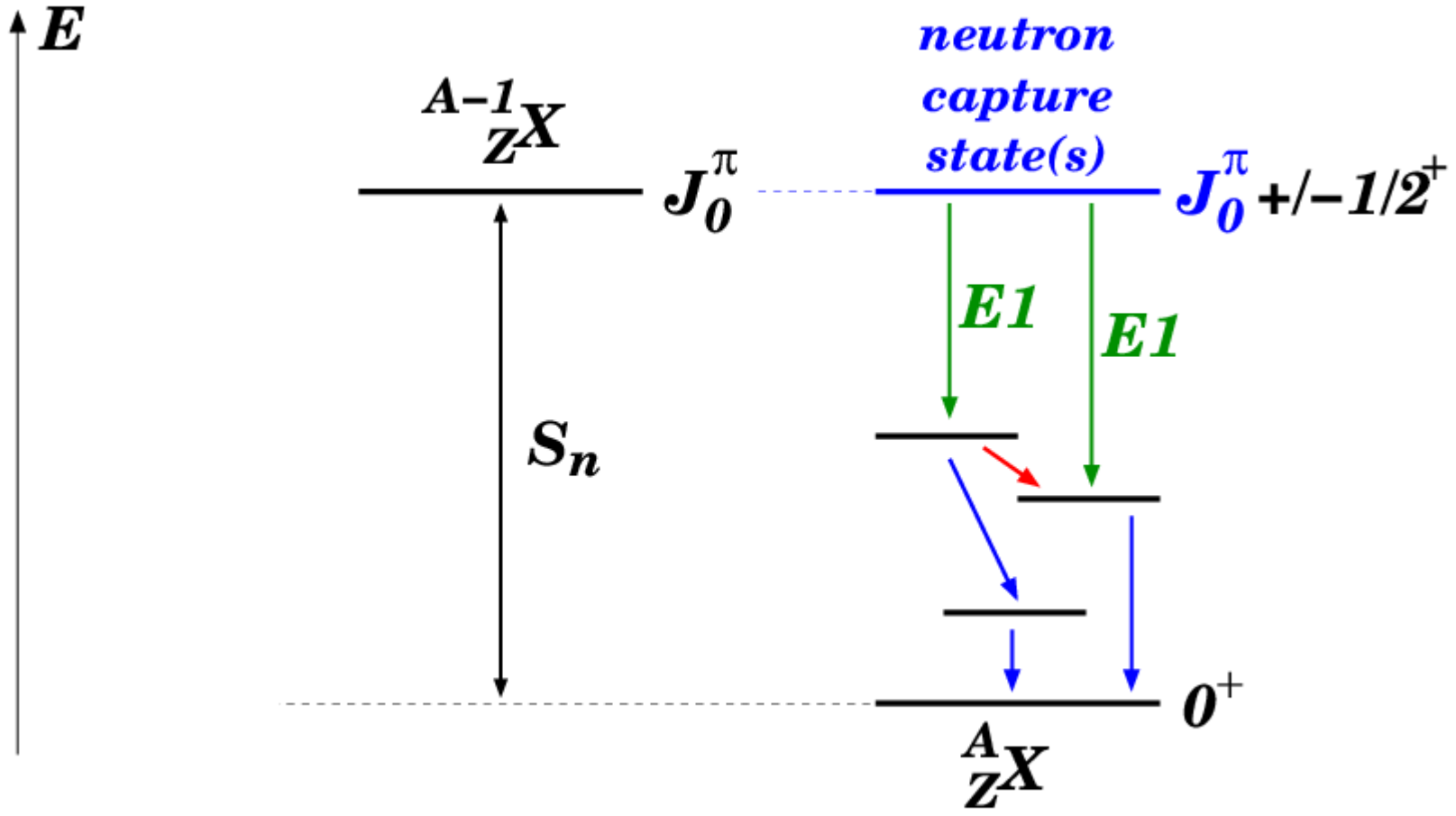

EXILL:
EX(ogam at) ILL
high statistics (n_{th},γγ)

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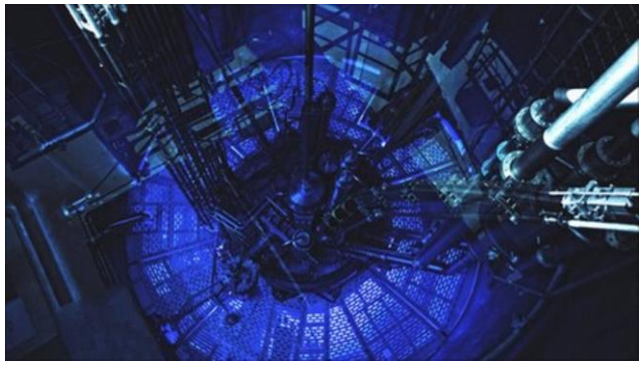
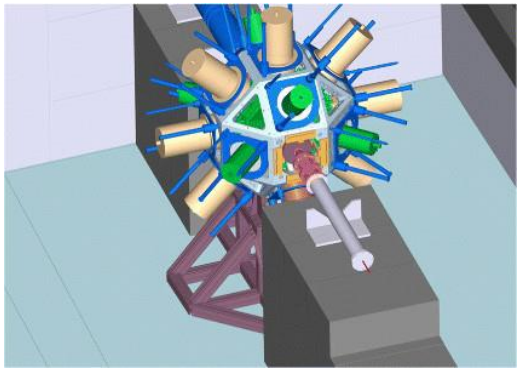


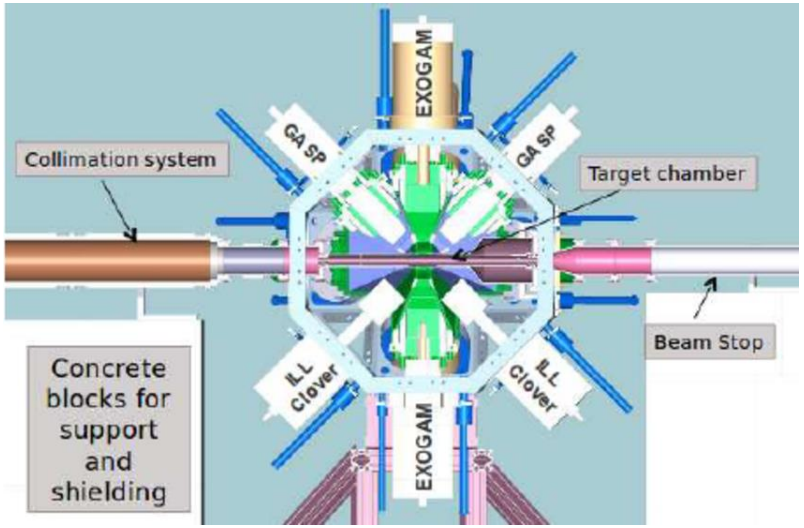
At target:

$$\phi_n \approx 5 \times 10^7 \frac{n}{s \cdot cm^2}$$

$$\sigma_{n_{th}} \cdot m_{target} \approx 250\, mg \cdot b$$

(good HPGe counts rates)





^{143}Nd(n_{th},γγ) and ^{95}Mo(n_{th},γγ) :
(only) 8 Clover detectors at $\Theta = 90^o$
octagonal symmetry ⇒ 4 angular groups
($45^o, 90^o, 135^o$, and 180^o)

Nucleus	m_{target} [mg]	t_{mess} [hours]
^{95}Mo	17	22
^{143}Nd	0.8	20

A.Blanc et al., Eur. Phys. Jour. Conf. **93** (2015) 01015

$^{95}Mo(n_{th},\gamma\gamma)^{96}Mo$ projection total $\gamma\gamma$ matrix

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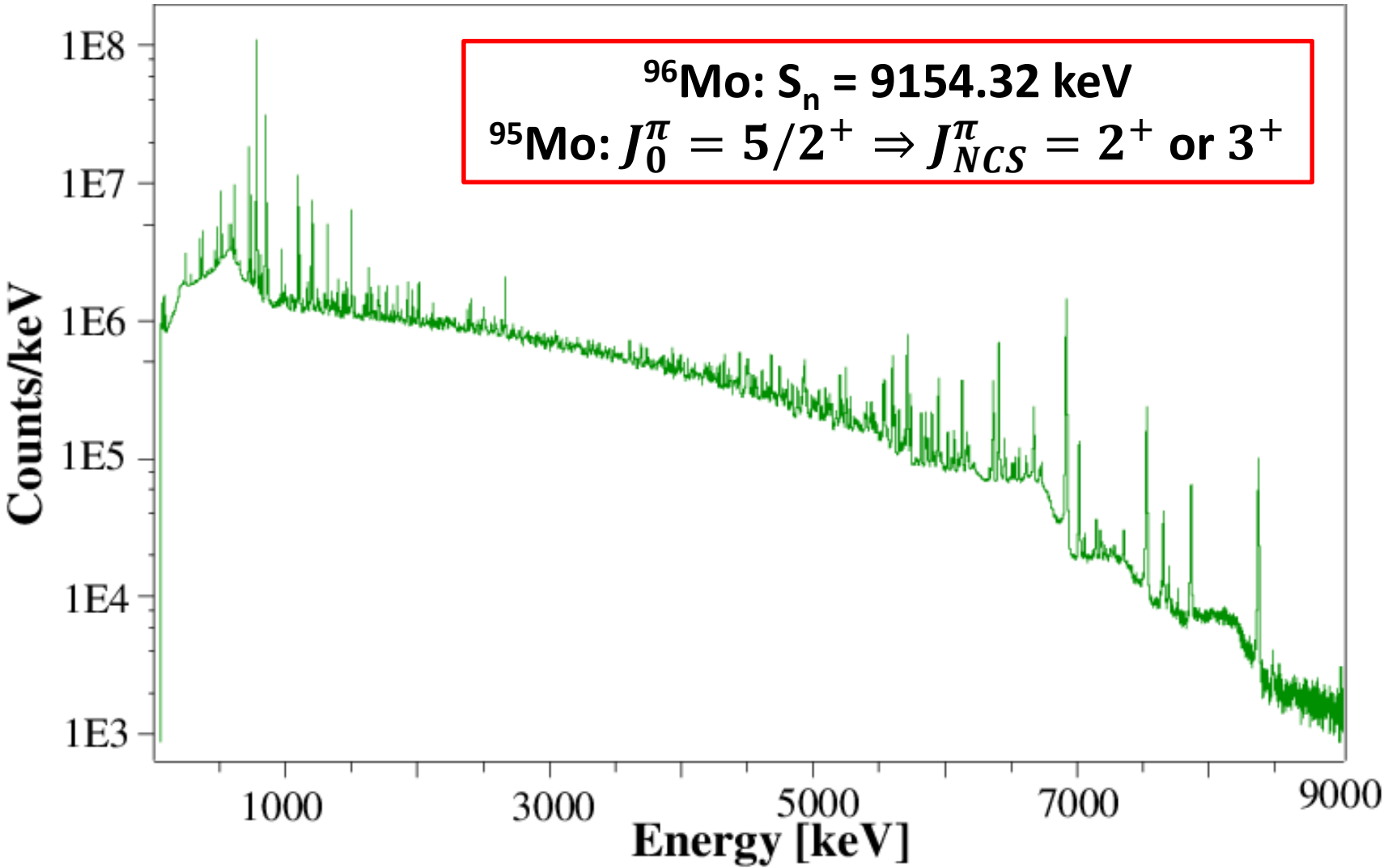

$^{95}Mo(n_{th},\gamma\gamma)^{96}Mo$ projection total $\gamma\gamma$ matrix

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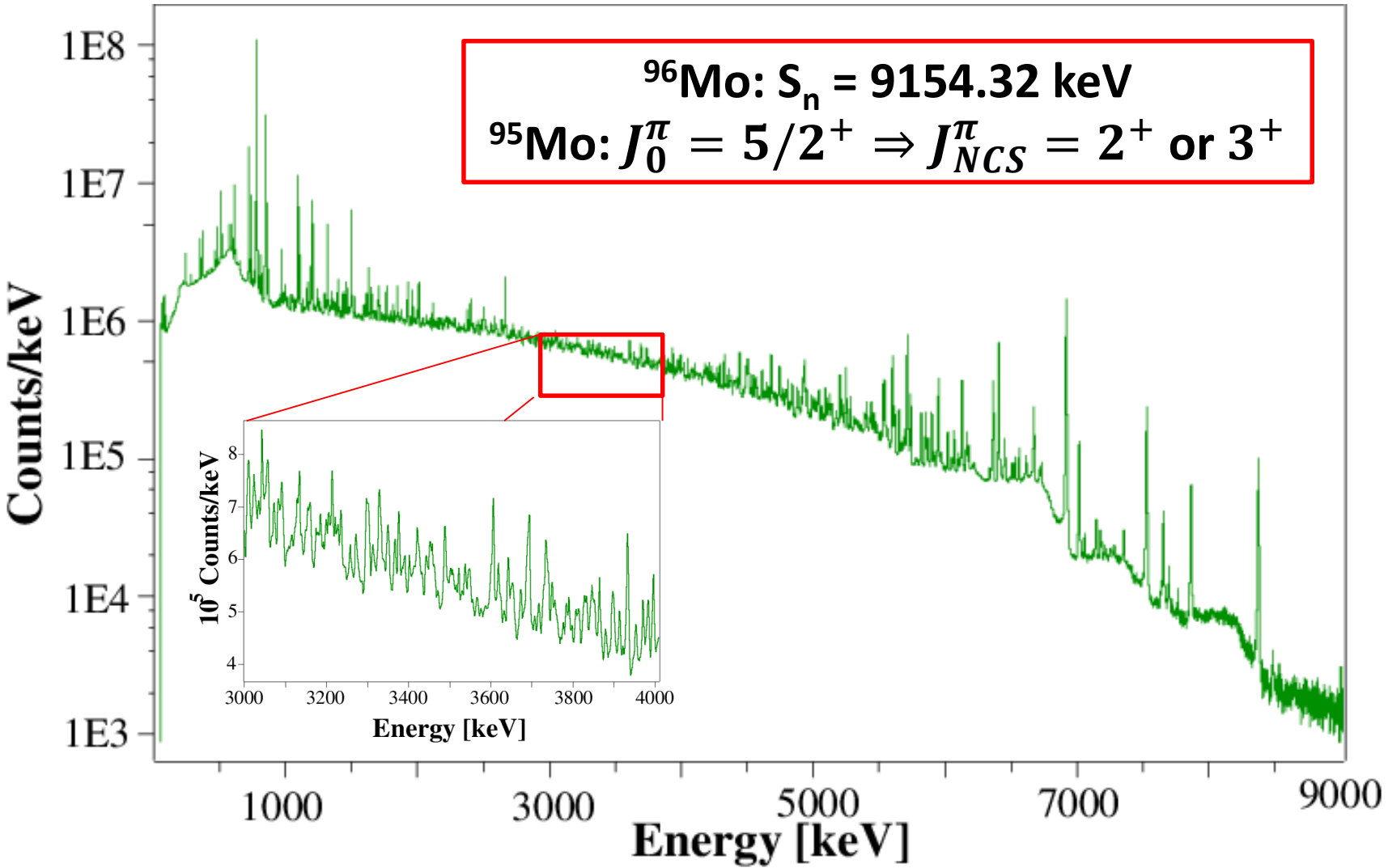
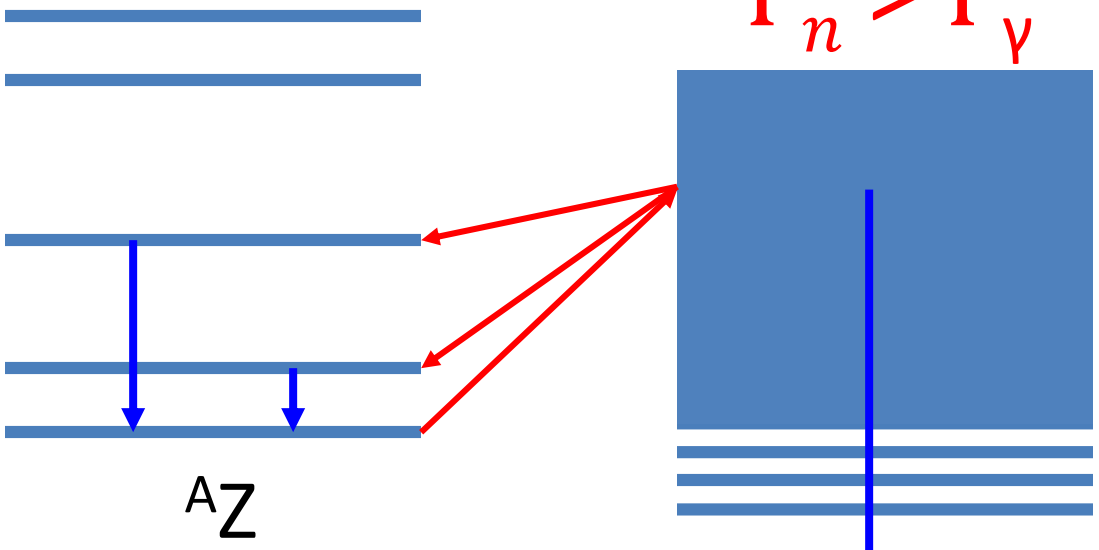


Neutron Reactions

(n,n'γ) reaction

neutron scattering



UK Accelerator Laboratory

- 7-MV single-ended Van de Graaff; rf ion source
- Gas targets: 0.5 to 10 MeV neutrons with $^{3}H(p,n)$ and $^{2}H(d,n)$; extended up to 25 MeV with $^{3}H(d,n)$; monoenergetic (ΔE_n < 100 keV) neutrons
- Nuclear spectroscopy with neutron time-of-flight and γ-ray (HPGe/BGO) detection
- Nuclear structure and reaction mechanisms
- Femtosecond nuclear level lifetimes
- Neutron detector development with collaborators
- Various applications of fast neutrons
- Research program supported by the NSF since accelerator installation in 1964; upgrade in 1990s
- A hands-on, student-run facility
- www.pa.uky.edu/accelerator/


Outside

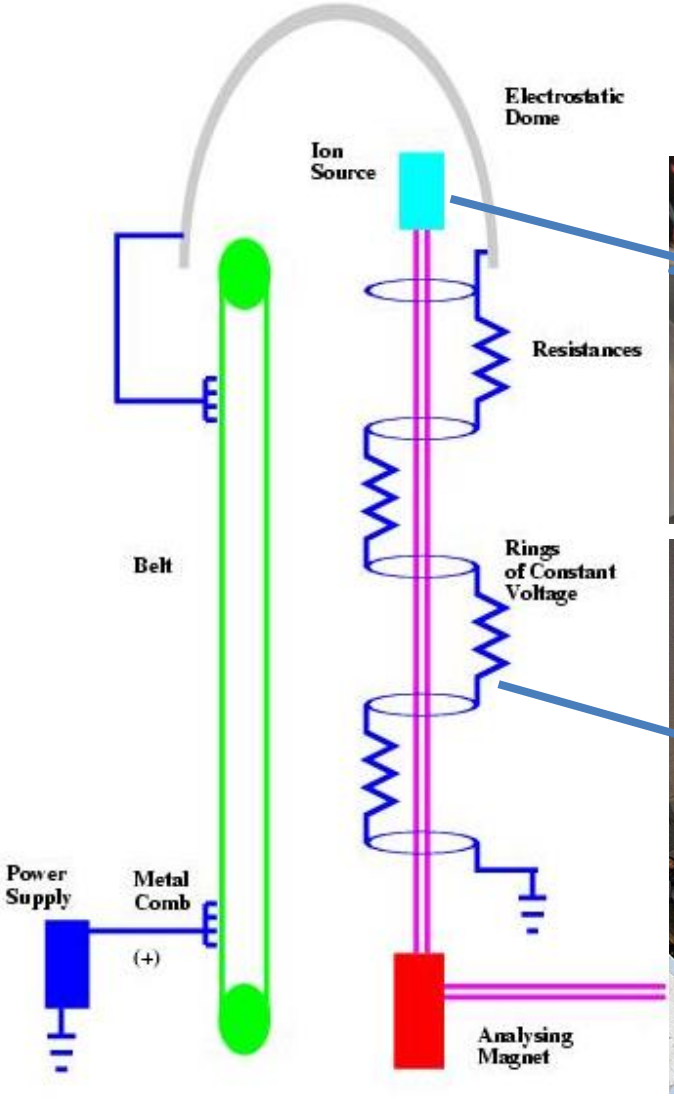

Inside

Miscellaneous Facts and Highlights

- Research program funded continuously by NSF for over 55 years!!
- About 10 publications per year result from work performed at the UK accelerator.
- In recent years, the accelerator has operated 24/7 for greater than half of the days of the year.
- For external (non-UK) non-collaborators, beam time is sold (at a bargain rate).
- For collaborations led by external users, beam time is considered an in-kind contribution.
- About half of a technician's time is in support of the accelerator facility.

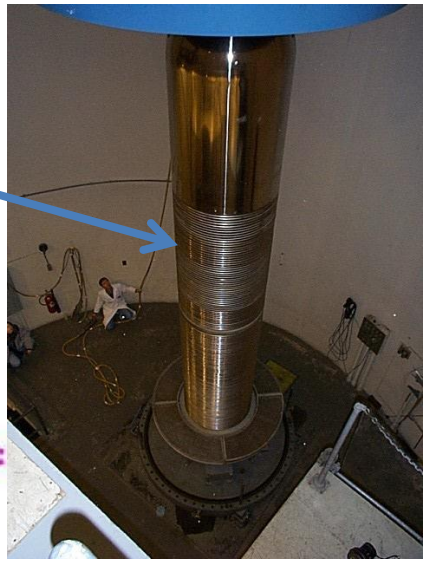
University of Kentucky Accelerator

www.pa.uky.edu/accelerator/

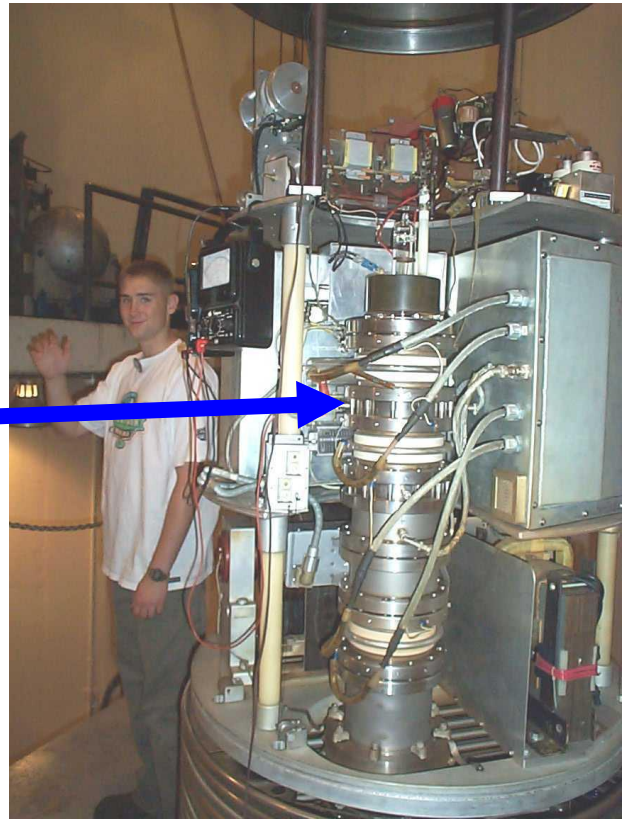


Properties of beams

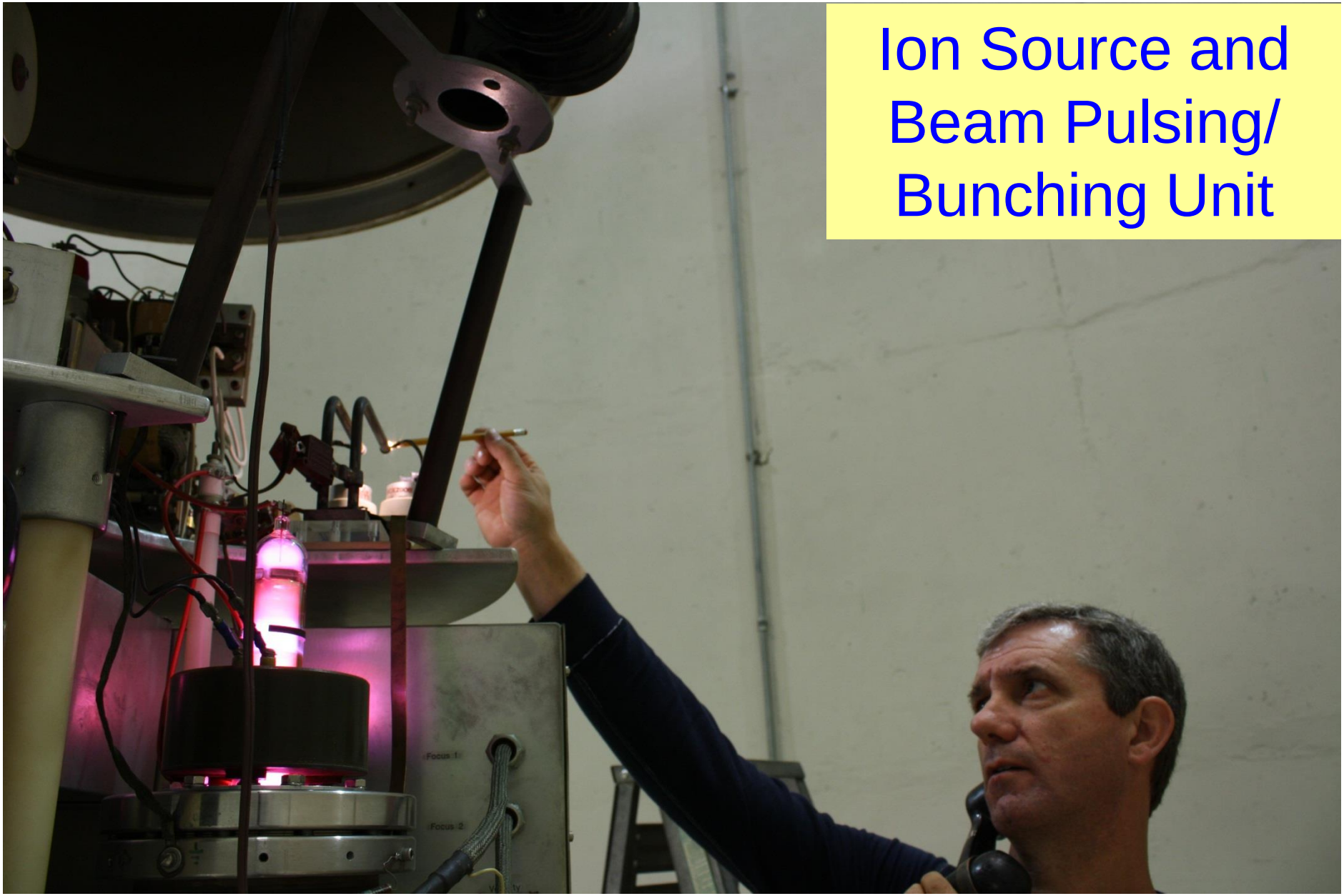
- ^{1}H, ^{2}H, ^{3}He, ^{4}He, Ne
- 0.5-7.0 MeV
- Bunched (< 1 ns) at 1.875 MHz



UK Accelerator



- HVEC 7-MV Model CN
- rf ion source
- pulsing and bunching to <1 ns pulse widths
- Terminal and post-acceleration bunching

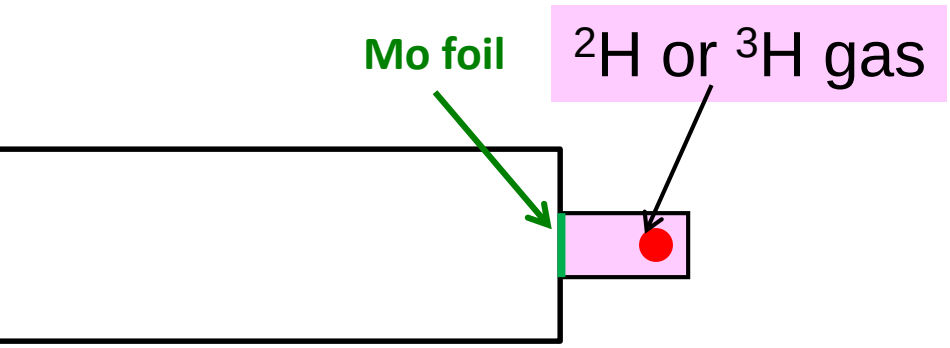

Ion Source and
Beam Pulsing/
Bunching Unit

Neutron Production

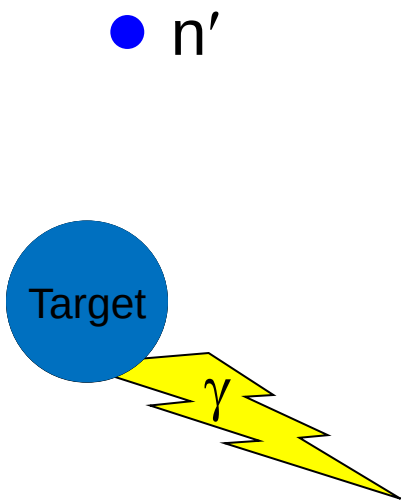
$^{3}H(p,n)^{3}He$ Q = -1 MeV $^{2}H(d,n)^{3}He$ Q = 3 MeV

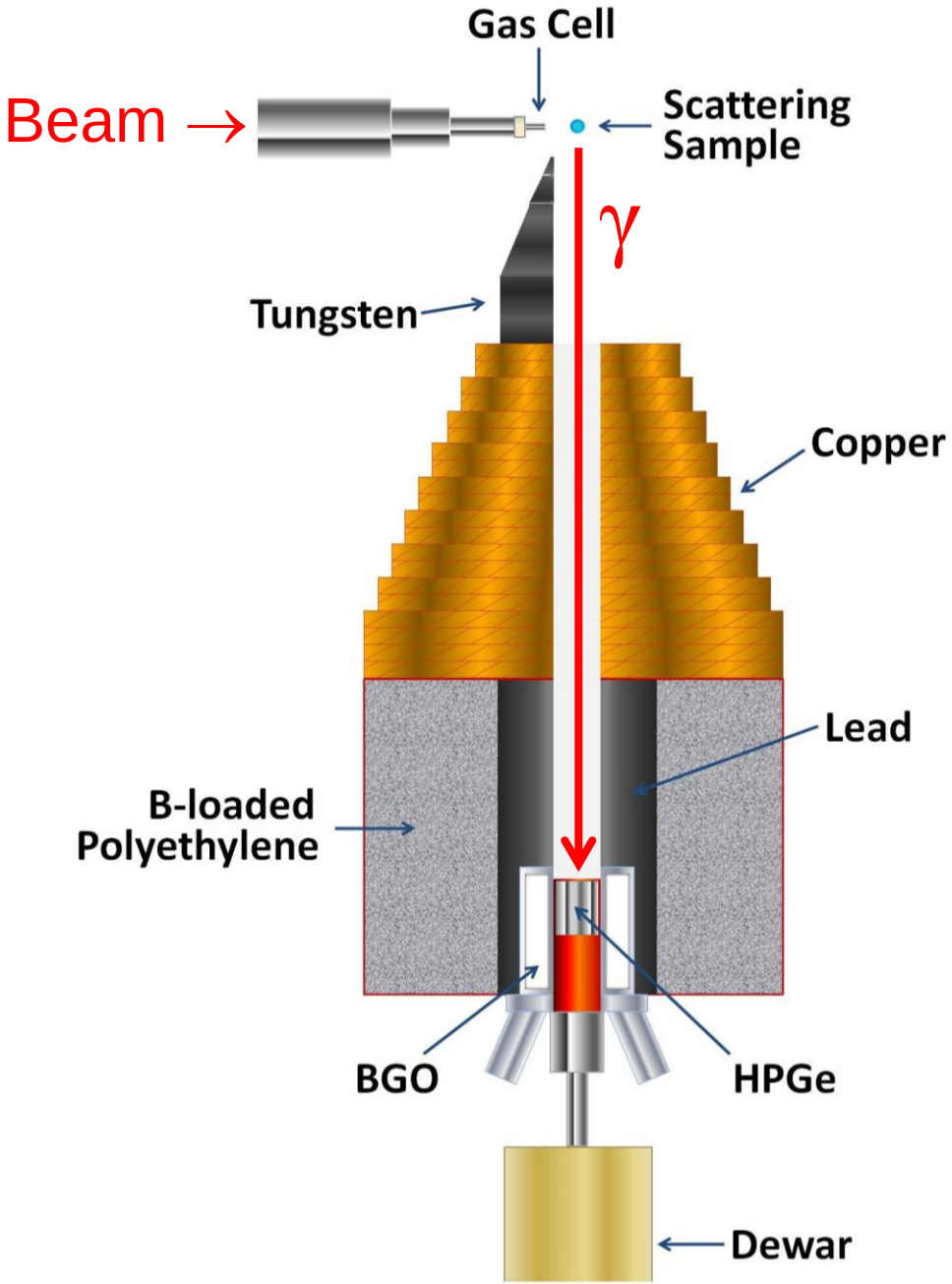
Neutron Energies (Accelerator Voltage: 1.5 – 7.0 MV)

$^{3}H(p,n)$ $0.5 < E_n < 6$ MeV $^{2}H(d,n)$ $4.5 < E_n < 10$ MeV



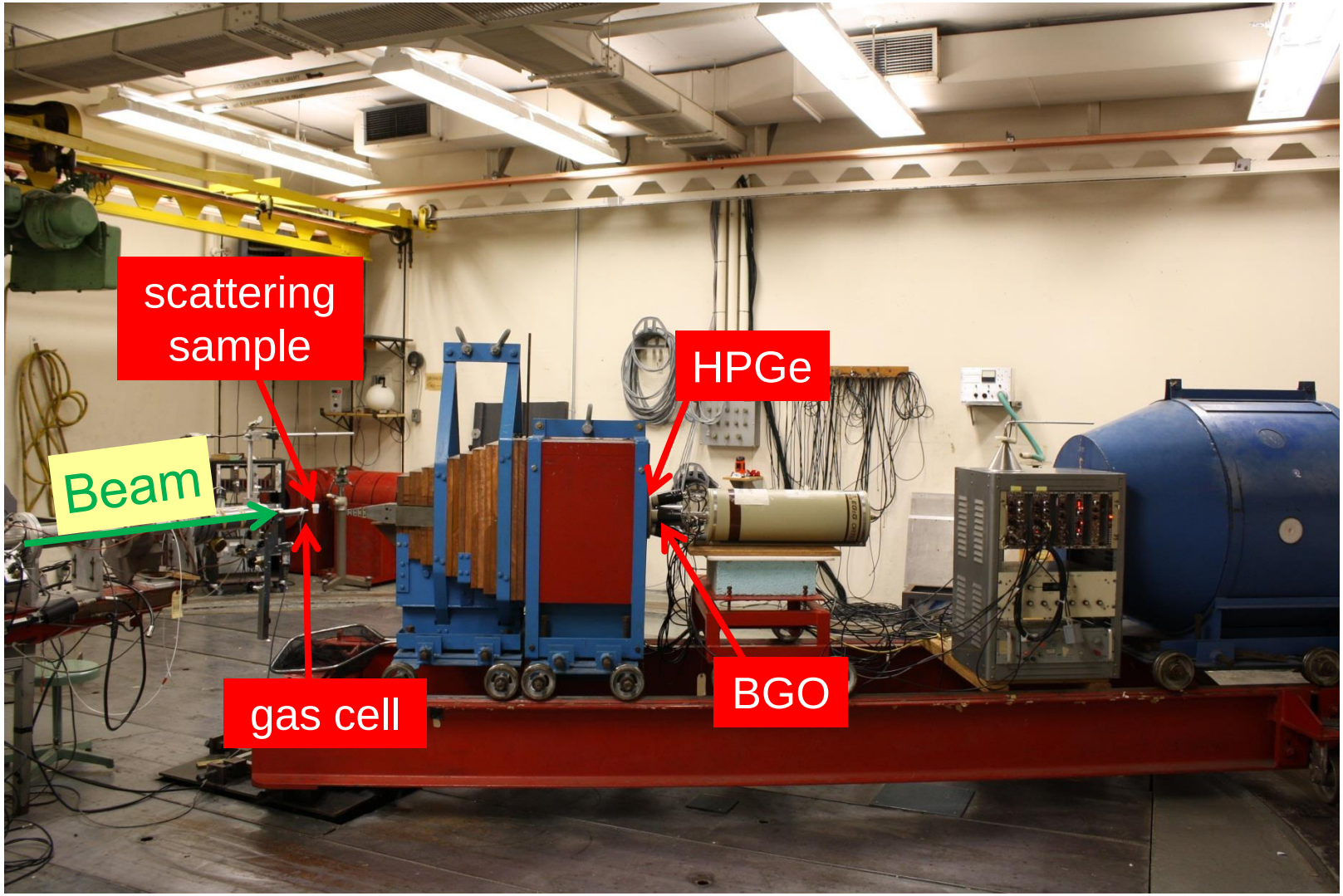
Pulsed p or d beam
from VdG accelerator



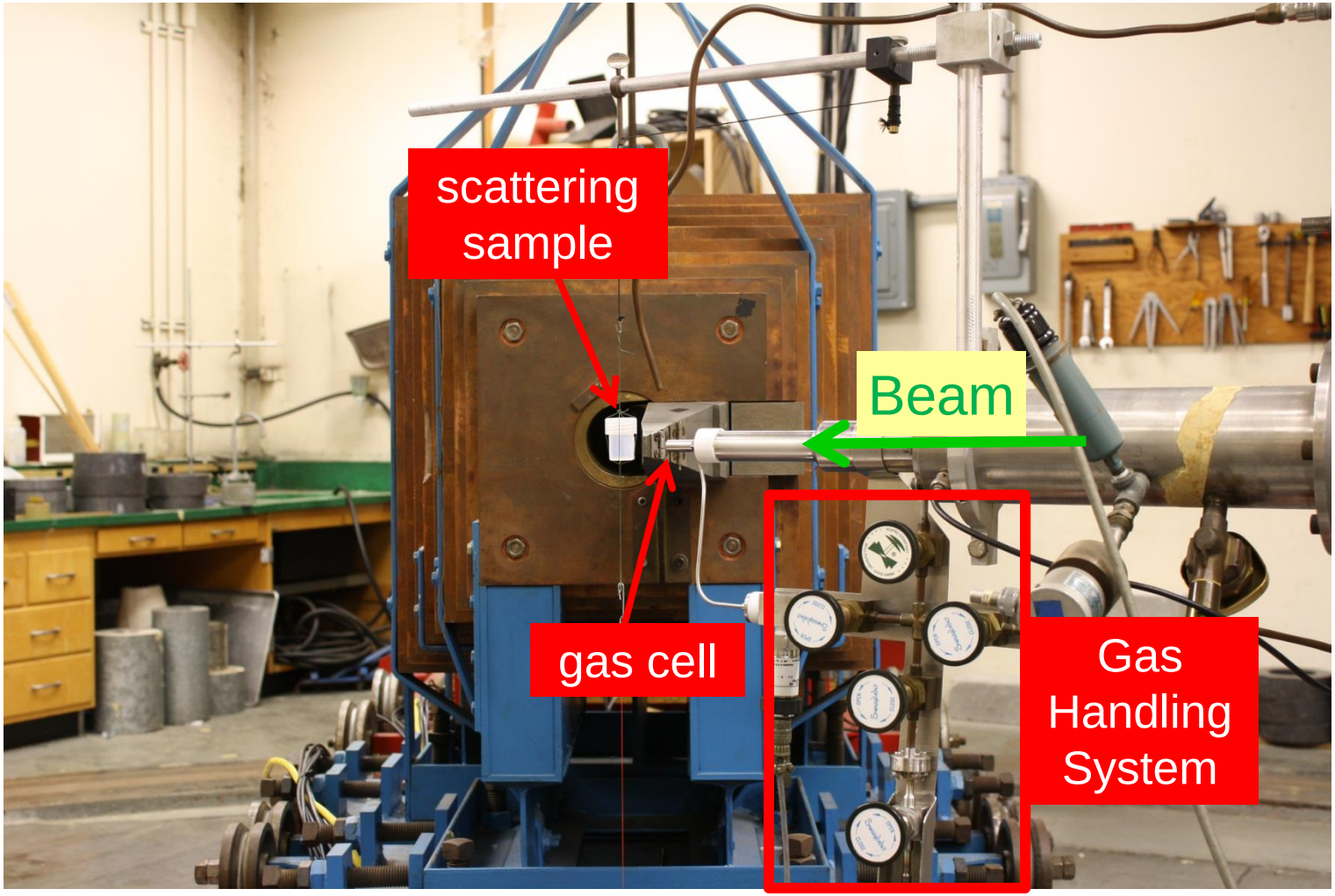

Gas Cell
Beam →
Scattering Sample
γ
Tungsten
Copper
Lead
B-loaded Polyethylene
BGO
HPGe
Dewar

(n,n'γ) singles

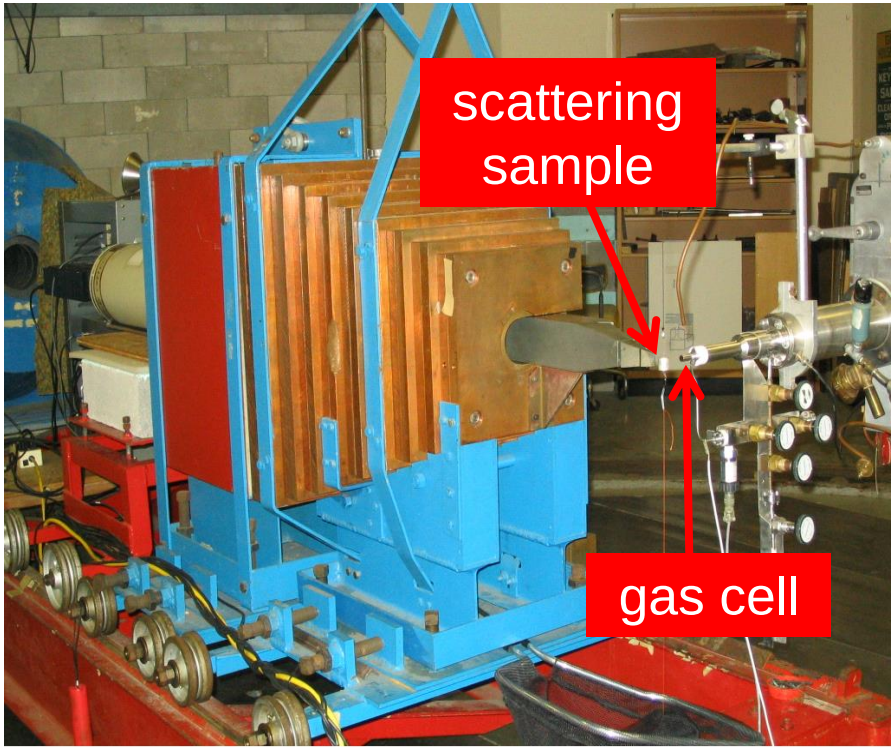
(n,n'γ) Singles Measurements

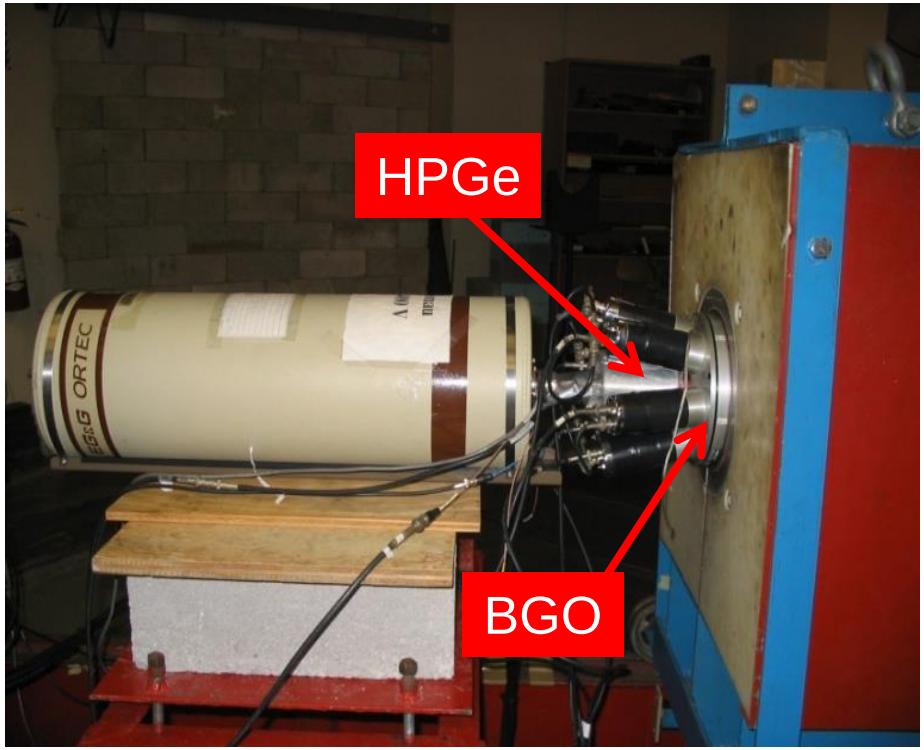


(n,n'γ) Singles Measurements

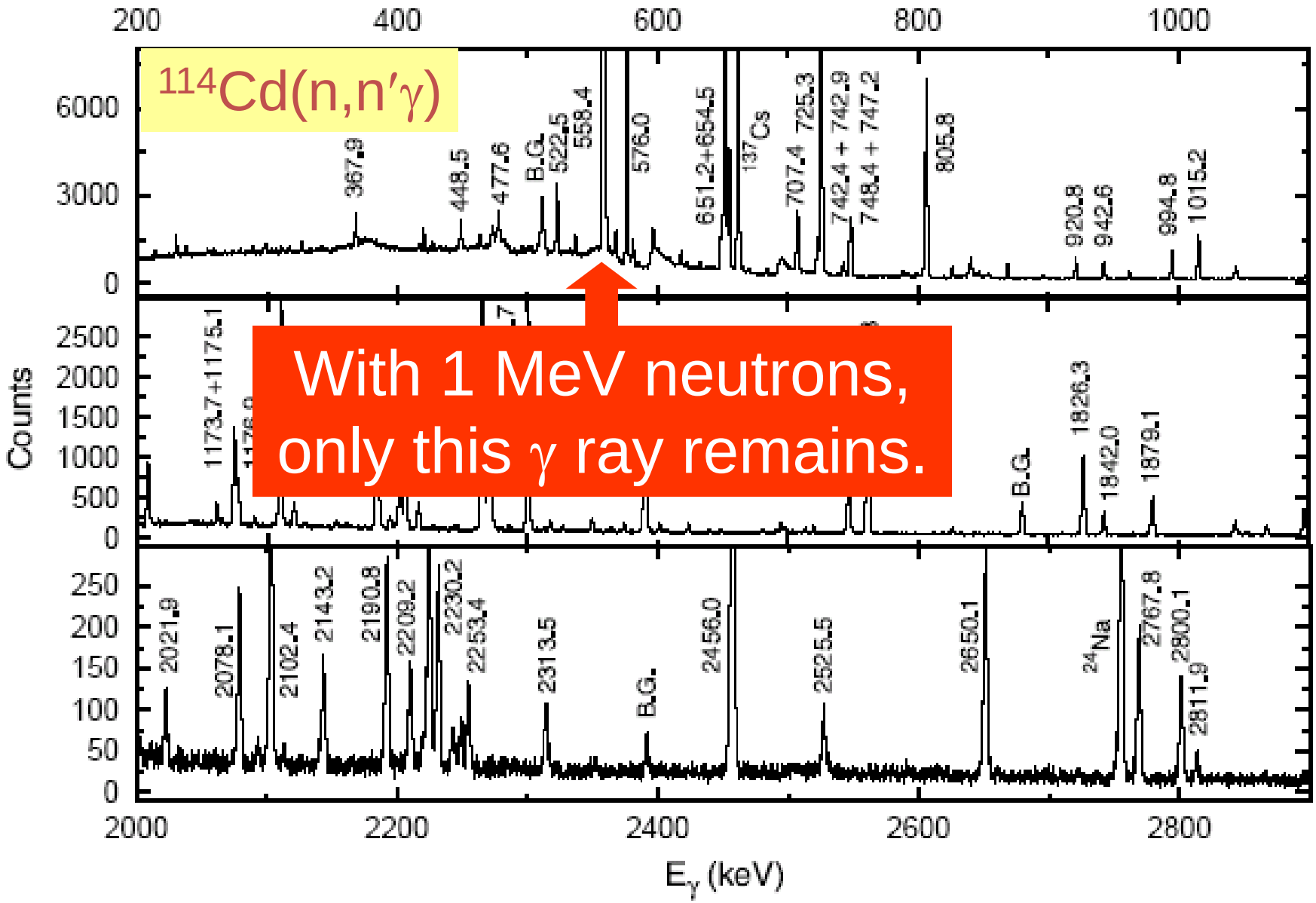


(n,n'γ) Singles Measurements

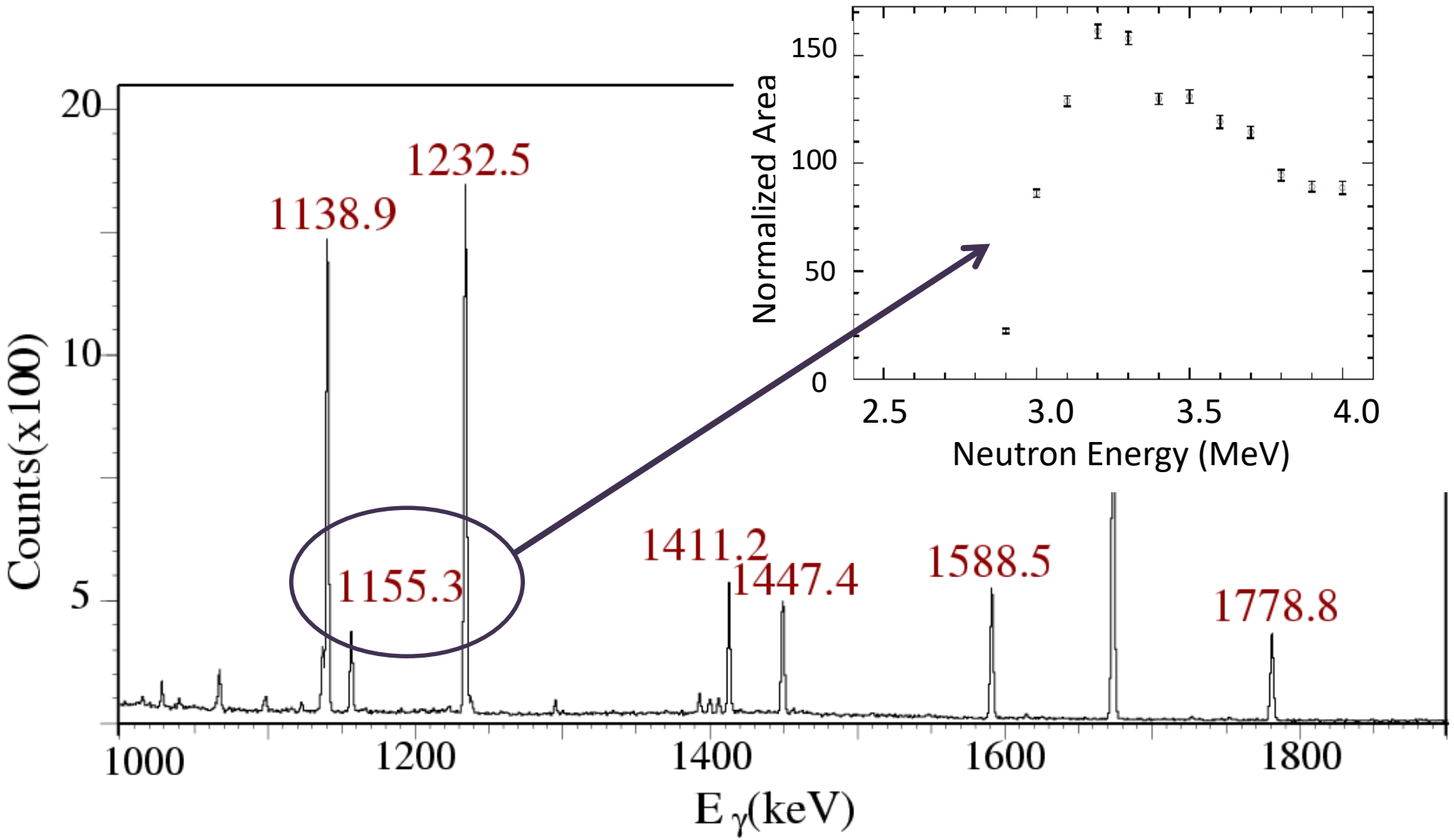


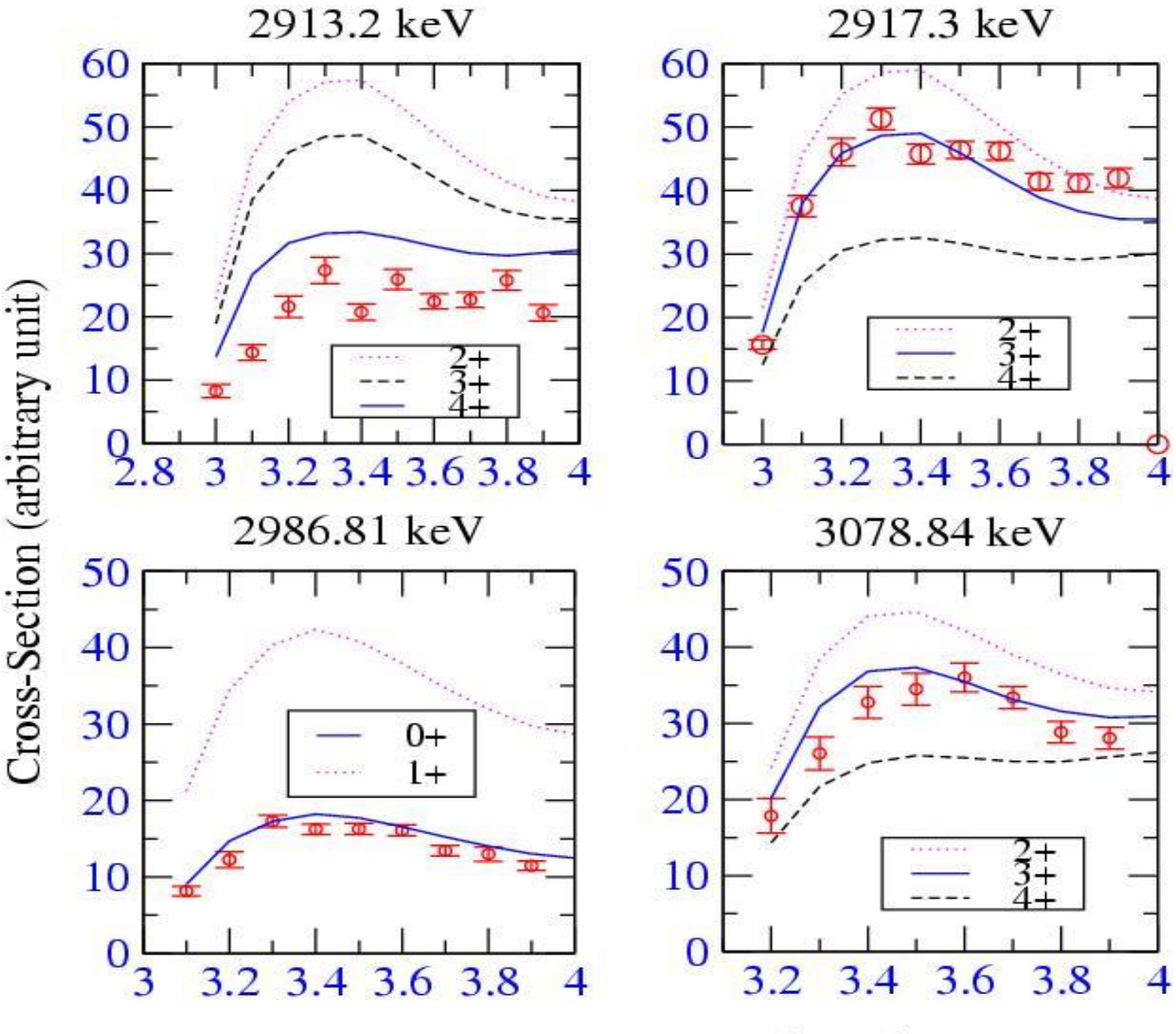


Compton suppression ~~3.0~~ MeV Neutrons TOF gating



^{94}Zr (n,n′γ) Compton suppressed TOF Gating



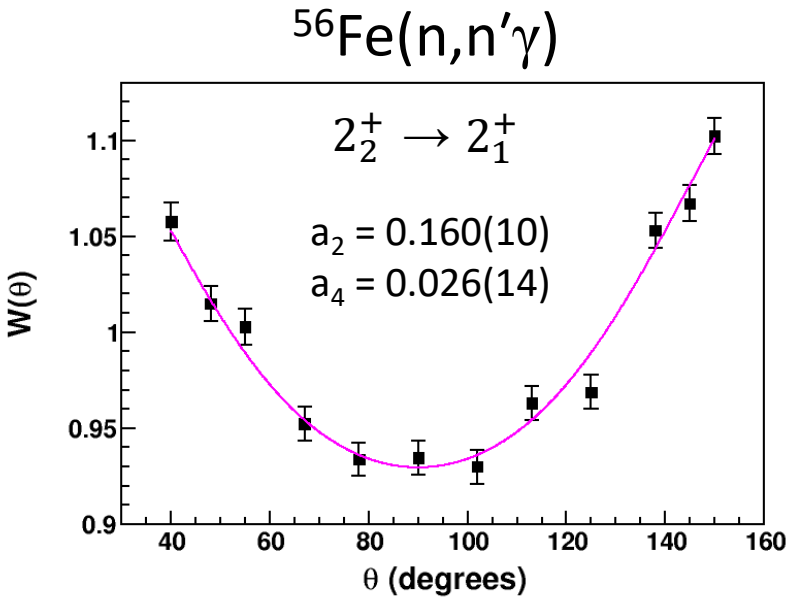

2913.2 keV
2917.3 keV
2986.81 keV
3078.84 keV
Cross-Section (arbitrary unit)
Neutron Energy (MeV)
2+
3+
4+
0+
1+

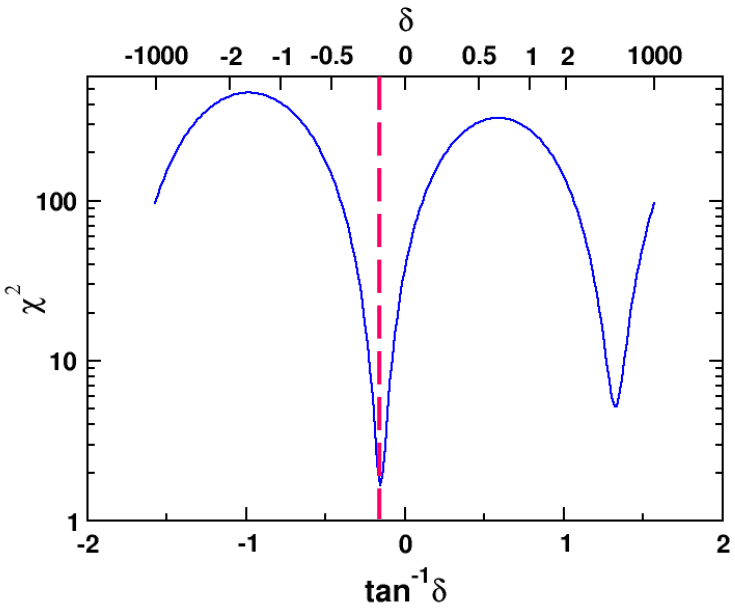
Angular Distribution

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

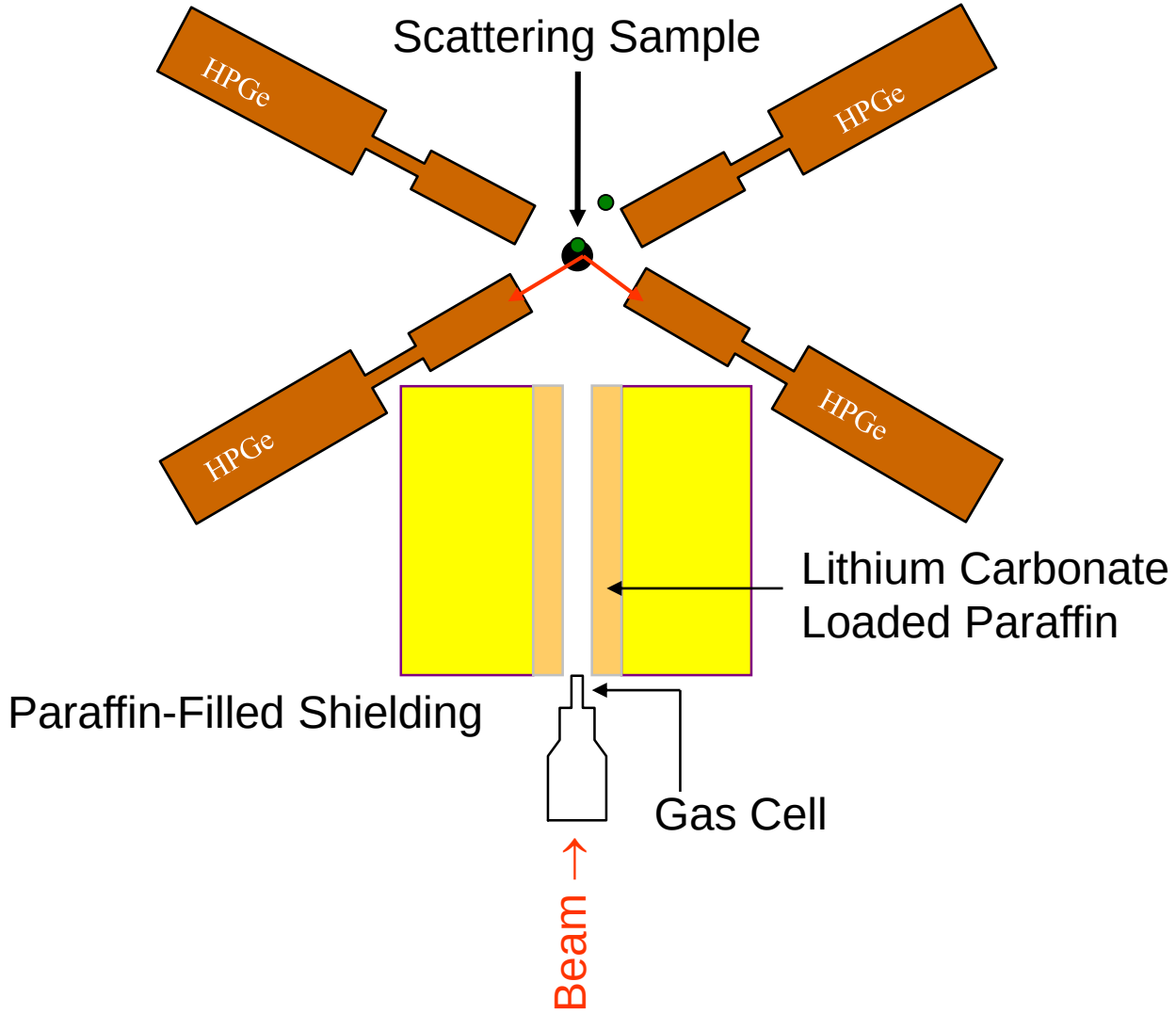
Comparison with statistical model calculations (CINDY)

→ multipole mixing ratio (δ) and spins





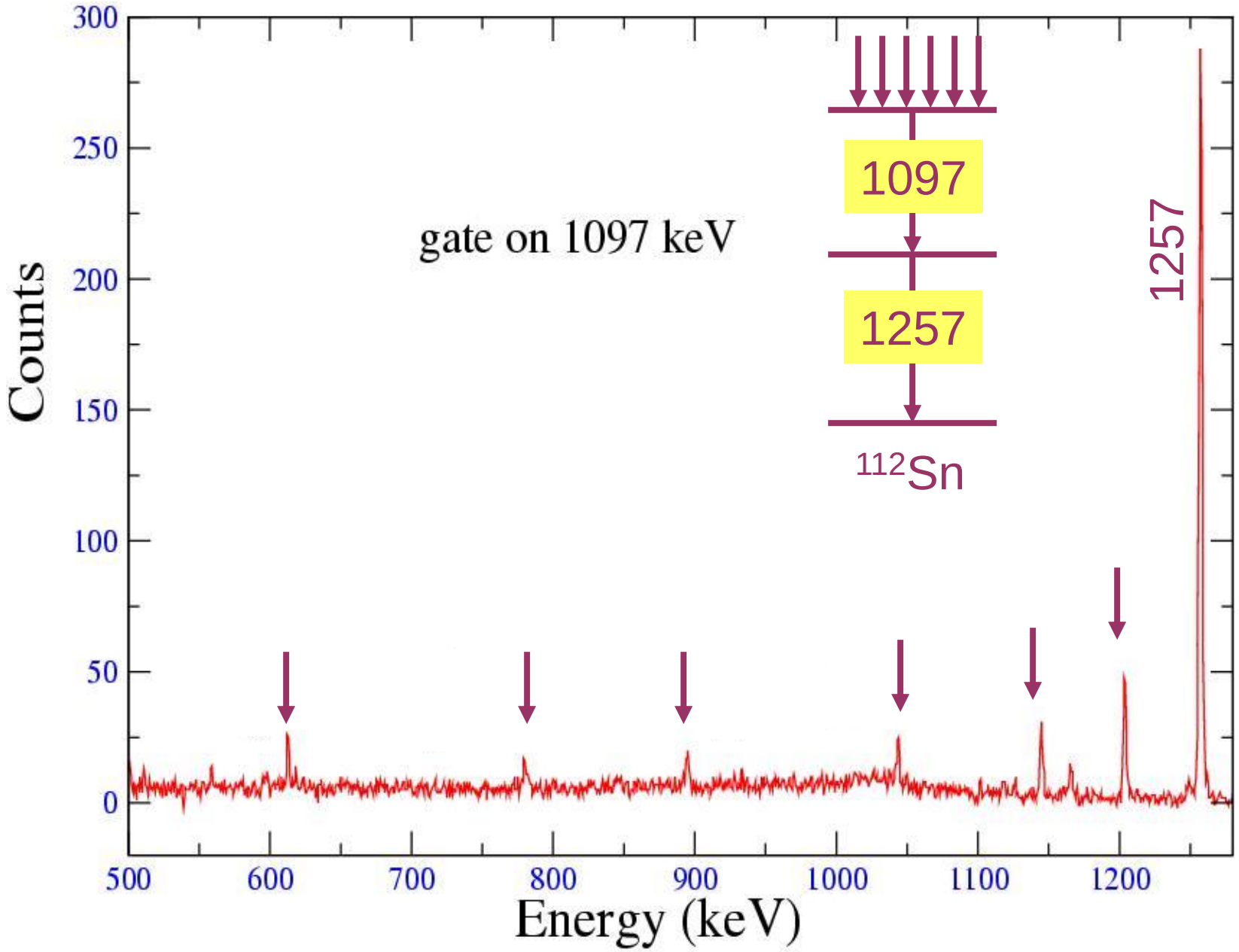
$\delta = -0.155^{+13}_{-20}$ $\delta(NNDC) = -0.18 \pm 0.01$



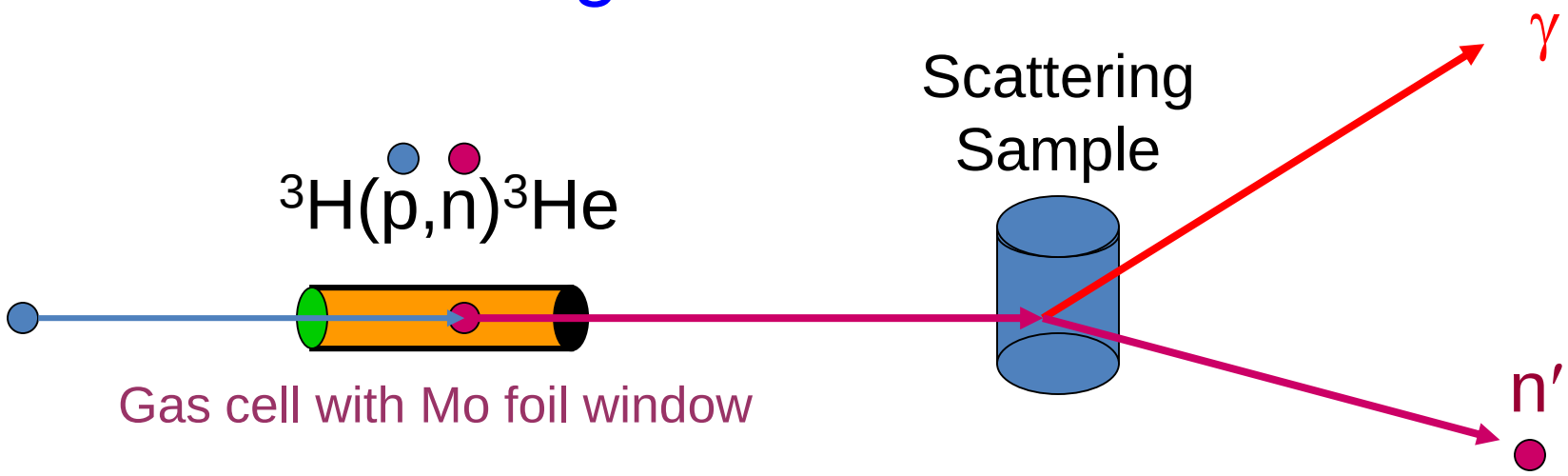
Kentucky Gamma-ray Spectrometer

KEGS

KEGS


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

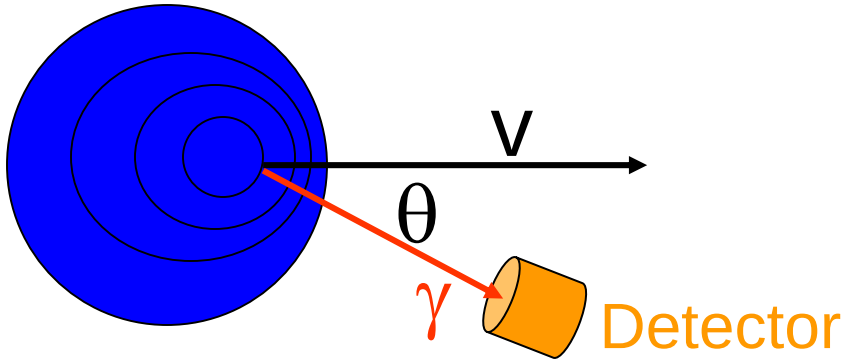
“Monoenergetic” Neutron Production



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

Doppler-Shift Attenuation Method



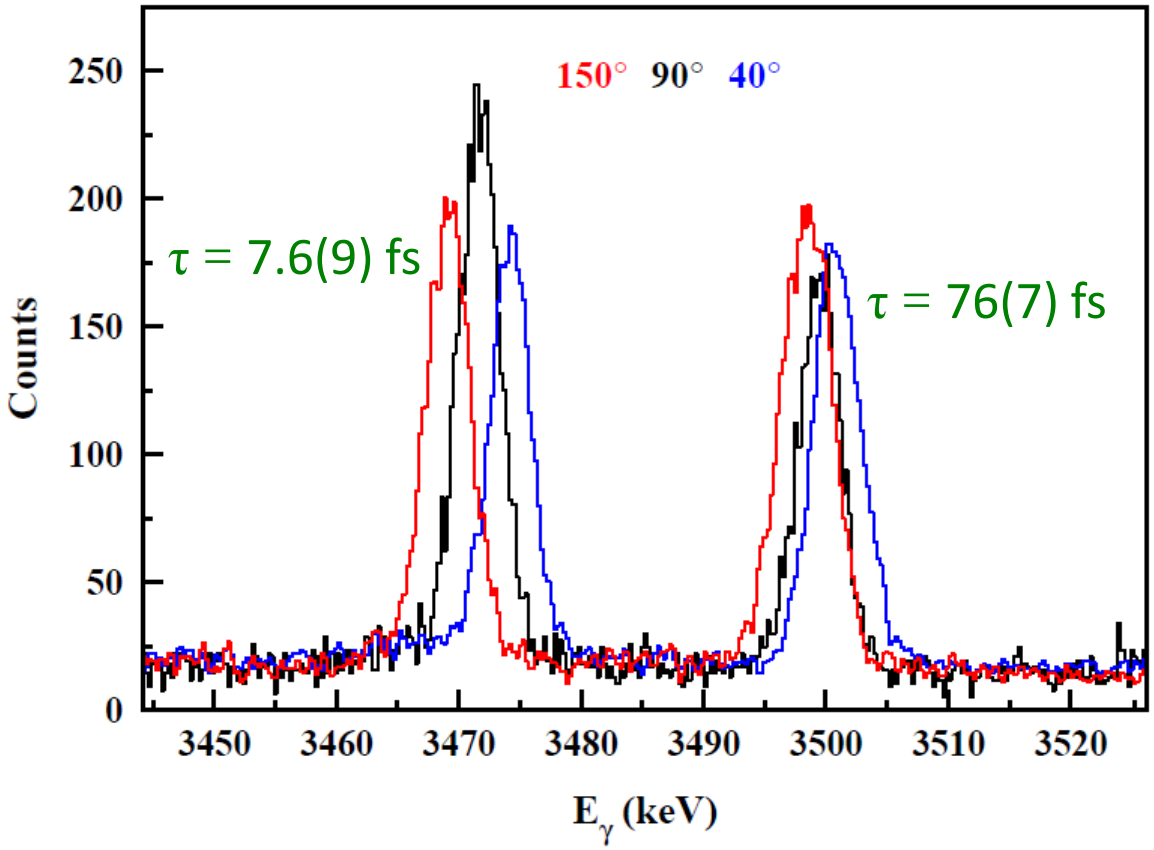
$$E(\theta) = E_\gamma (1 + v/c \cos\theta)$$

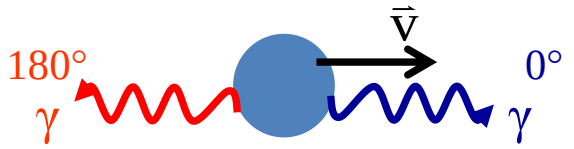
The nucleus is recoiling into a viscous medium.

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

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

Level Lifetimes: Doppler-Shift Attenuation Method (DSAM)





Scattered neutron causes the nucleus to recoil.

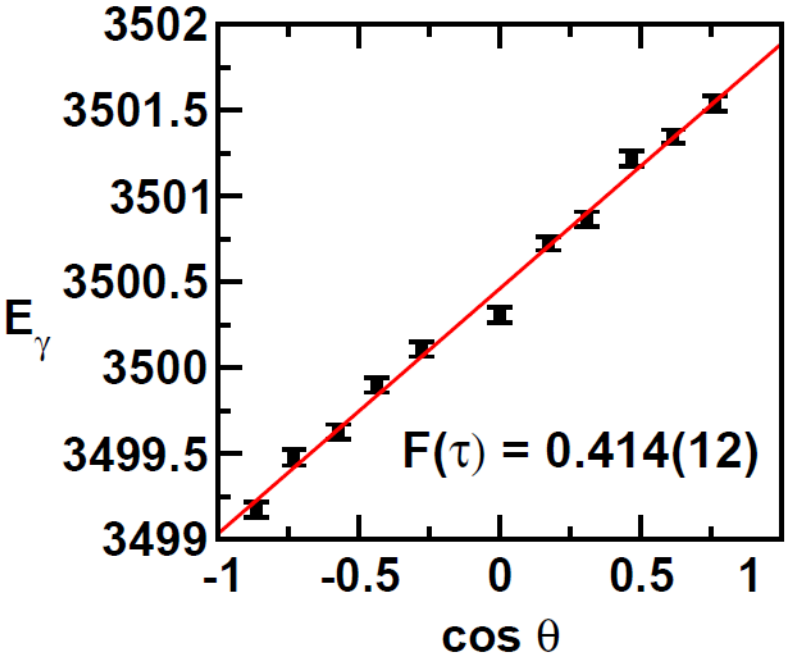
Emitted γ rays experience a Doppler shift.

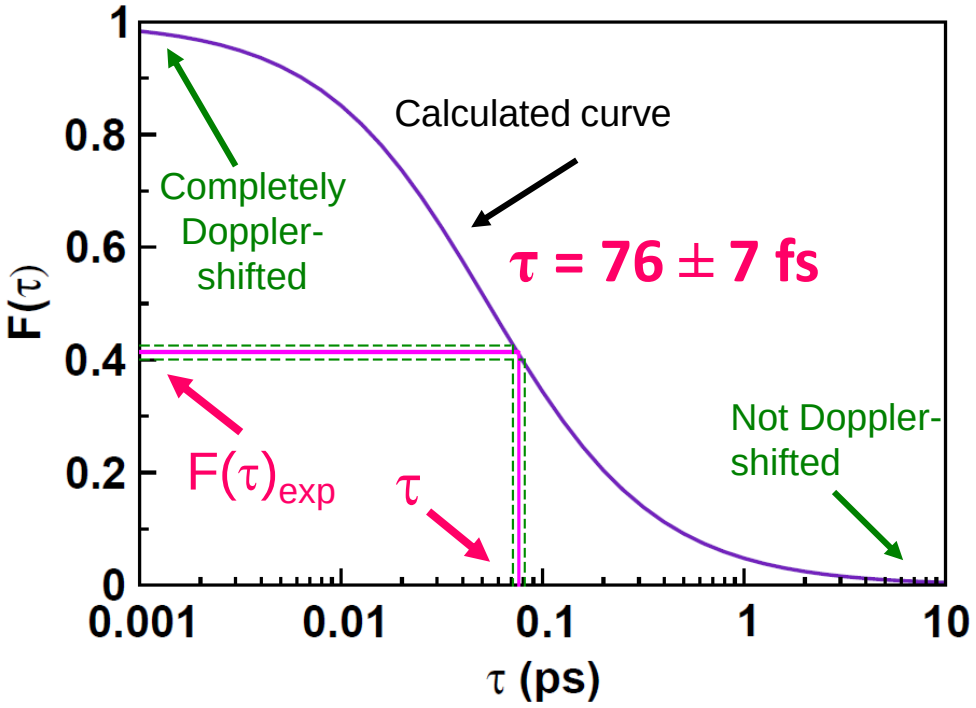
Level lifetimes in the femtosecond region can be determined.

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).

University of Kentucky Experiments

- Inelastic neutron scattering
  - Monoenergetic neutrons
  - Allows determination of :
    - Level scheme
    - Transition multipolarities
    - Multipole mixing ratios
    - Level lifetimes
    - Transition probabilities

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) (feeding-time problem minimized)

  E.E. Peters *et al*., Phys. Rev, C 88, 024317 (2013)
- Gamma-gamma coincidence measurements

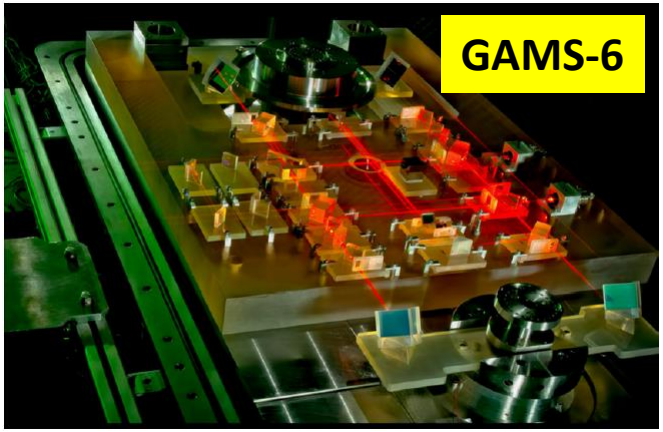
  C.A. McGrath *et al*., Nucl. Instrum. Meth. A421, 458 (1999)

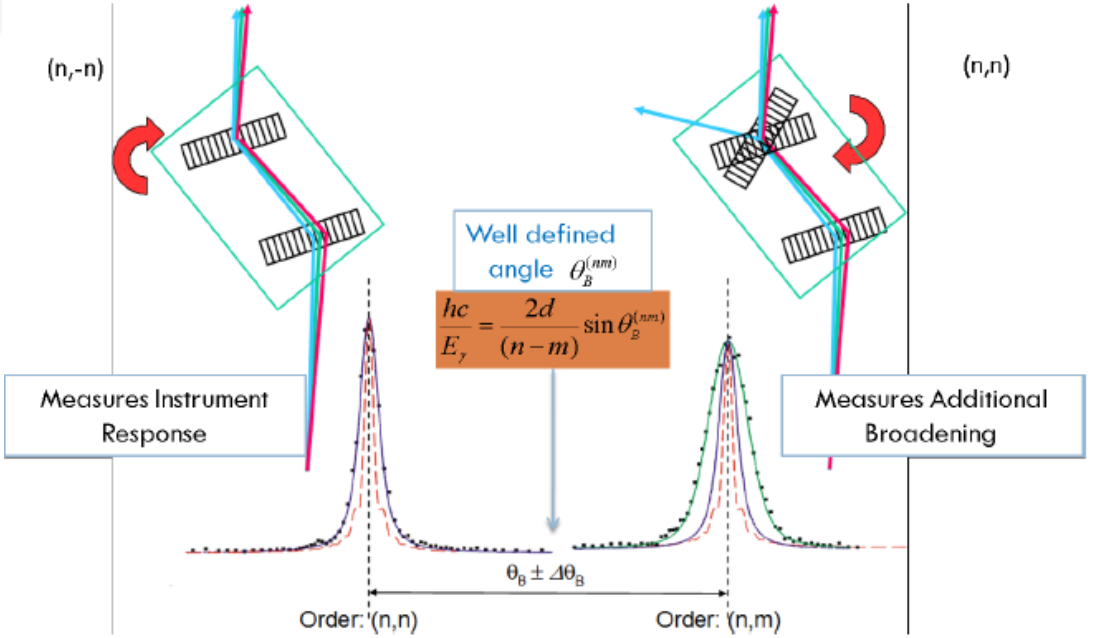
  E. Elhami *et al*., Phys. Rev. C 78, 064303 (2008)
- Limited to stable nuclei
- Large amounts of enriched isotopes required

^{144}Nd
3_3^- octupole isovector candidate

UNIVERSITY OF THE WEST of SCOTLAND
UWS

Lifetime measurement using Gamma-Ray induced Doppler (GRID) Broadening Method





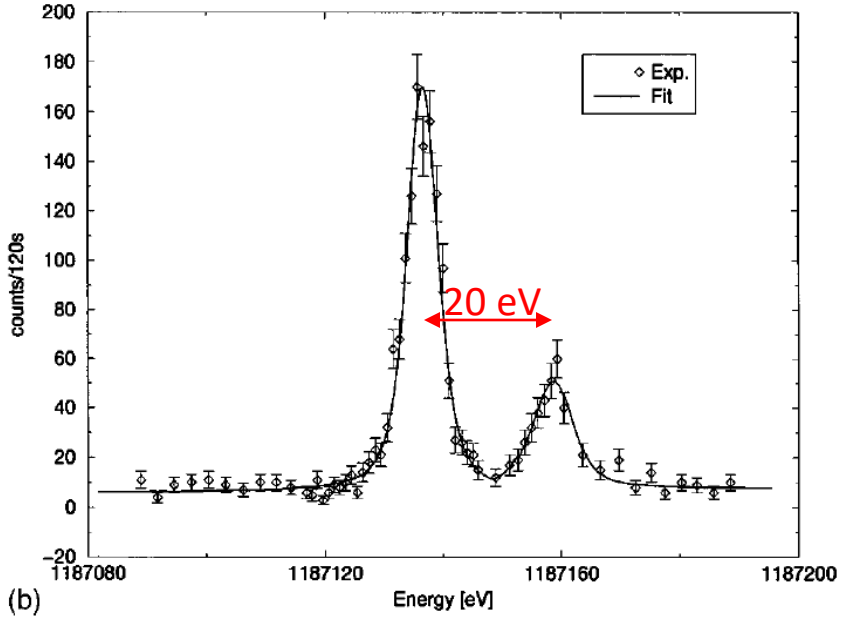
H.G.Boerner and J.Jolie, J.Phys.G. **19** (1993) 217

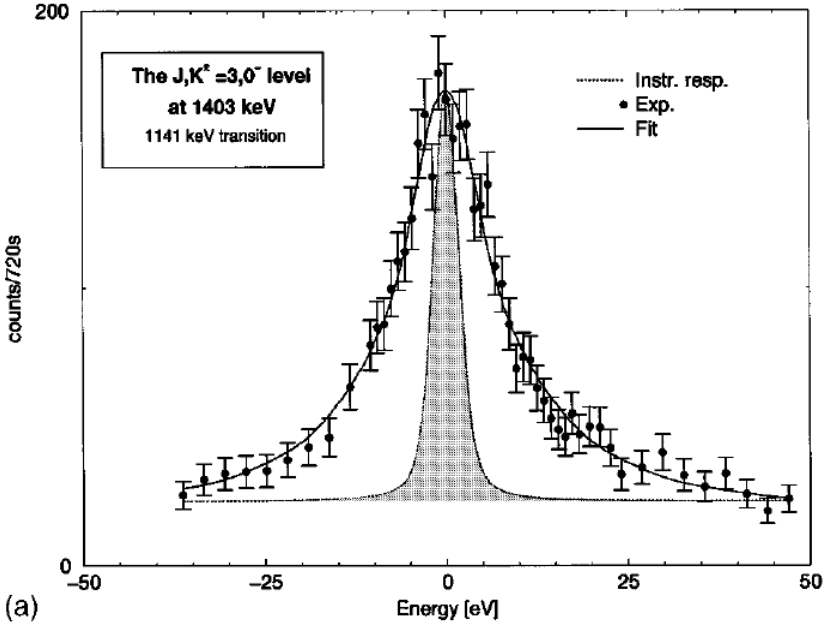
Literature:
$\tau(3_3^-) = 94^{+75}_{-34}$ **fs**

PHYSICAL REVIEW C VOLUME 59, NUMBER 5 MAY 1999

Ultrahigh resolution study of collective modes in ^{158}Gd

H. G. Börner,[1] M. Jentschel,[1] N. V. Zamfir,[2,3] R. F. Casten,[2] M. Krticka,[4] and W. Andrejtscheff[5]
[1]*Institut Laue-Langevin, F-38042 Grenoble, France*
[2]*Wright Nuclear Structure Laboratory (WNSL), Yale University, New Haven, Connecticut 06520*
[3]*Clark University, Worcester, Massachusetts 01610*
[4]*Charles University, CZ-18000 Prague, Czech Republic*
[5]*Bulgarian Academy of Sciences, Institute for Nuclear Research and Nuclear Energy, 1784 Sofia, Bulgaria*
(Received 13 November 1998)





PHYSICAL REVIEW C VOLUME 47, NUMBER 3 MARCH 1993

Absolute $B(E1)$ values in the shape transitional $^{148-152}$Sm isotopes

A. Jungclaus
Institut Laue-Langevin, F-38042 Grenoble, France
and II. Physikalisches Institut, Universität Göttingen, D-3400 Göttingen, Germany

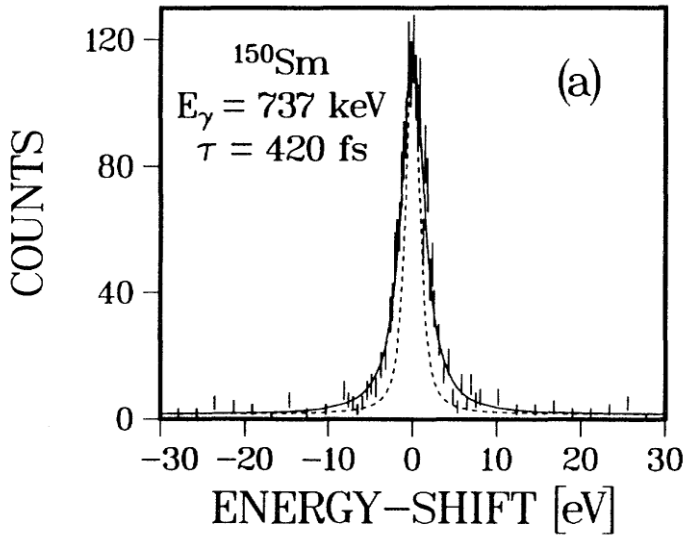
H. G. Börner, J. Jolie,* and S. Ulbig
Institut Laue-Langevin, F-38042 Grenoble, France

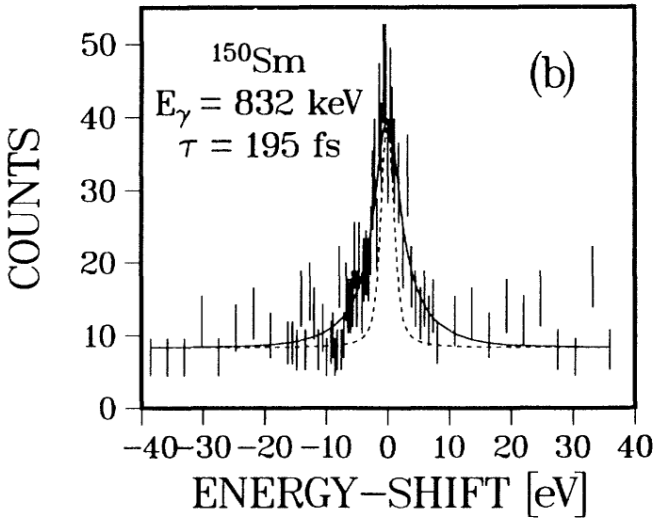
R. F. Casten
Brookhaven National Laboratory, Upton, New York 11973

N. V. Zamfir
Brookhaven National Laboratory, Upton, New York 11973;
Institute of Atomic Physics, Bucharest-Magurele, Romania;
and Clark University, Worcester, Massachusetts 01610

P. von Brentano
Institut für Kernphysik, Universität Köln, D-5000 Köln 41, Germany

K. P. Lieb
II. Physikalisches Institut, Universität Göttingen, D-3400 Göttingen, Germany
(Received 21 September 1992)





Nuclear Instruments and Methods in Physics Research A 794 (2015) 171–176

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Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Lifetime measurement of excited low-spin states via the $(p, p'\gamma)$ reaction

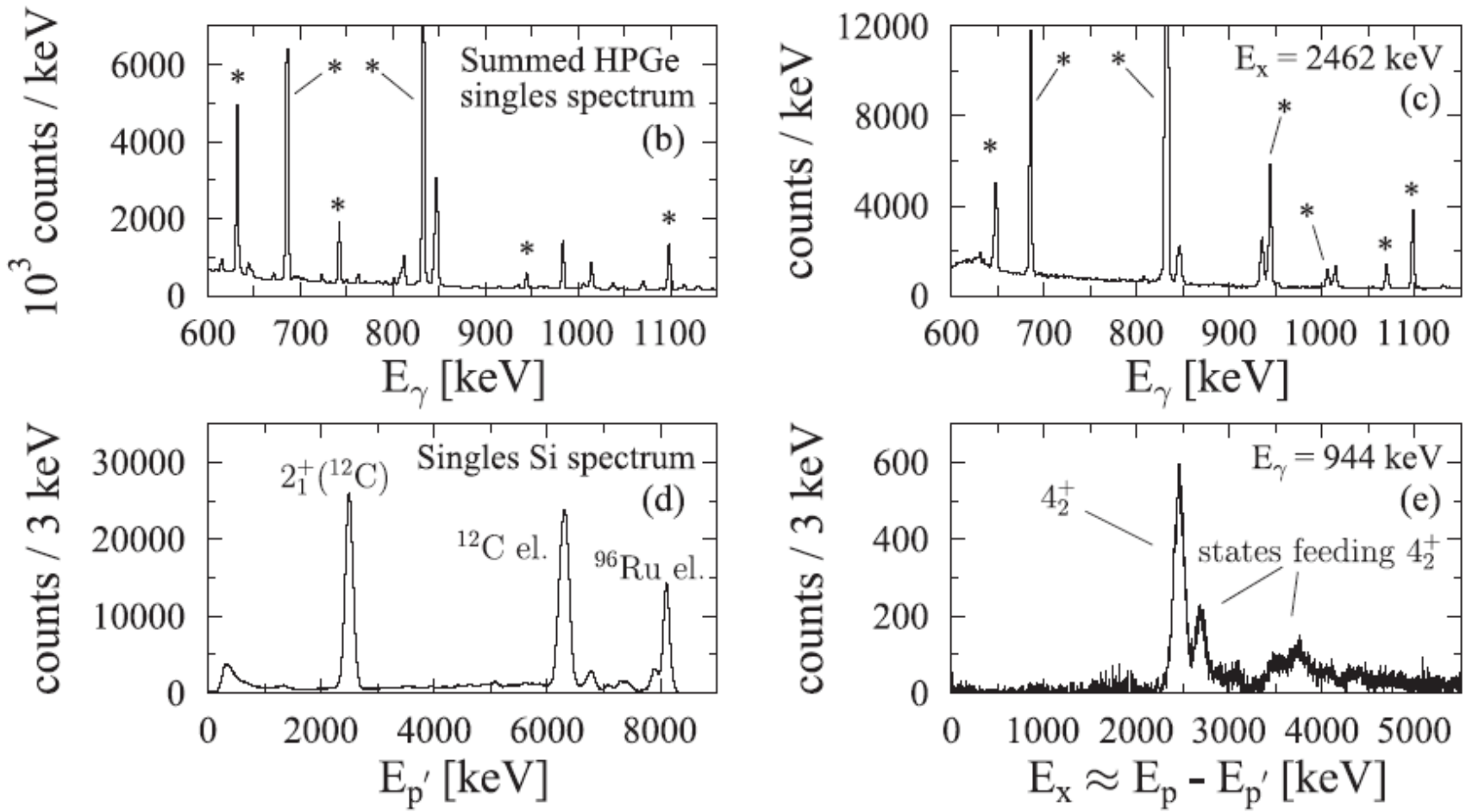
A. Hennig [a,*], V. Derya [a], M.N. Mineva [b,c], P. Petkov [a,c], S.G. Pickstone [a], M. Spieker [a], A. Zilges [a]

[a] Institute for Nuclear Physics, University of Cologne, Zülpicher Straße 77, D-50937 Cologne, Germany
[b] Faculty of Physics, University of Sofia, BG-1164 Sofia, Bulgaria
[c] Institute for Nuclear Research and Nuclear Energy INRNE, Bulgarian Academy of Sciences, BG-1784 Sofia, Bulgaria

PHYSICAL REVIEW C **92**, 064317 (2015)

Collective excitations of ^{96}Ru by means of $(p, p'\gamma)$ experiments

A. Hennig,[1,*] T. Ahn,[2,†] V. Anagnostatou,[2,3] A. Blazhev,[1] N. Cooper,[2] V. Derya,[1] M. Elvers,[1,2] J. Endres,[1] P. Goddard,[2,3] A. Heinz,[2,4] R. O. Hughes,[2,5] G. Ilie,[2,6] M. N. Mineva,[7,8] P. Petkov,[1,6,7] S. G. Pickstone,[1] N. Pietralla,[9,10] D. Radeck,[1,2] T. J. Ross,[3,5] D. Savran,[11,12] M. Spieker,[1] V. Werner,[2,9] and A. Zilges[1]



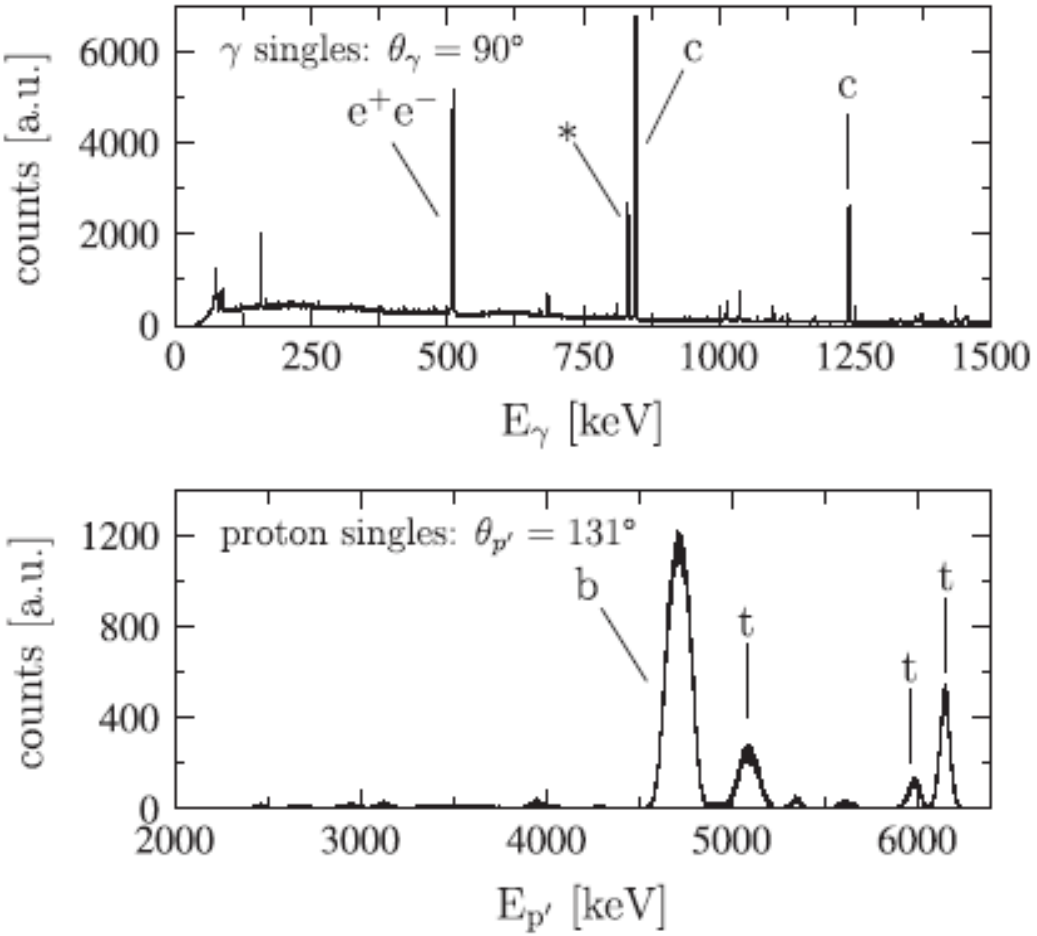


Fig. 1. Typical γ-ray singles spectrum (upper panel) and proton singles spectrum (lower panel) obtained in the ^{96}Ru(p, p′γ) experiment at angles of $\theta_\gamma = 90°$ and $\theta_{p'} = 131°$, respectively. The former is dominated by the $2_1^+ \rightarrow 0_{g.s.}^+$ γ-ray transition of ^{96}Ru (indicated with *) and transitions stemming from the ^{56}Co calibration source (c). The proton spectrum is dominated by protons scattered in the target and backing material, indicated with (t) and (b), respectively.

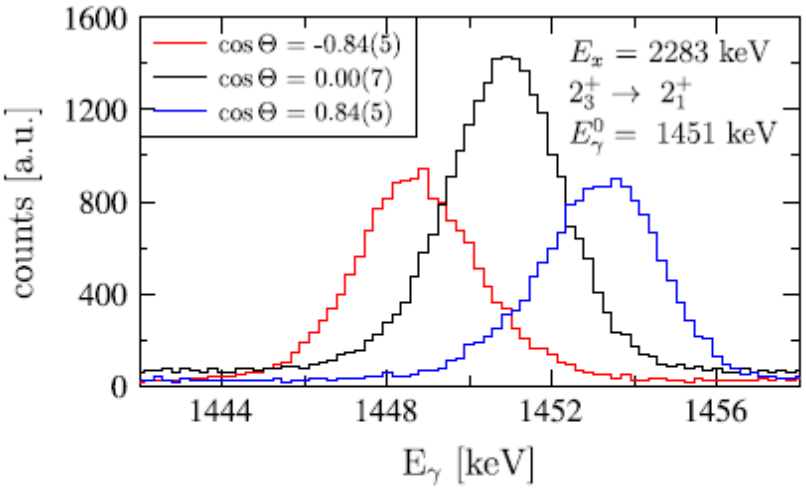


Fig. 3. (Color online) γ-ray spectra gated on the excitation energy of the 2_3^+ state at $E_x = 2283$ keV obtained for three different groups which are characterized by three different values of $\cos\Theta$. An unshifted peak is observed for $\cos\Theta = 0.00(7)$, while the peaks for $\cos\Theta = -0.84(5)$ and $\cos\Theta = +0.84(5)$ are shifted to lower and higher energies, respectively.

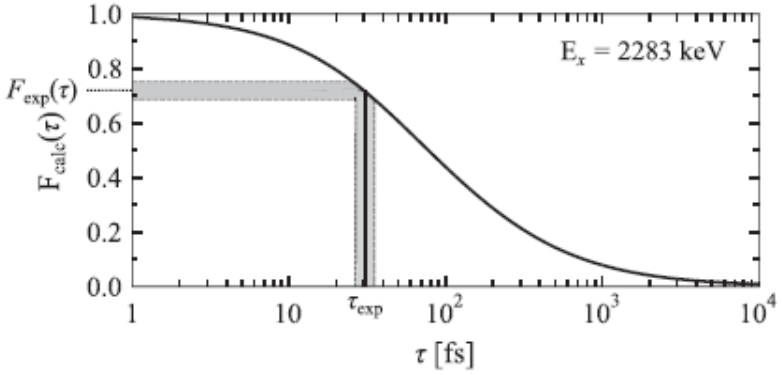


Fig. 6. Calculated Doppler-shift attenuation factor $F_{calc}(\tau)$ for the 2_3^+ state at $E_x = 2283$ keV as a function of the level lifetime τ. The experimental lifetime value τ_{exp} is obtained by projecting the experimental Doppler-shift attenuation factor $F_{exp}(\tau)$ to the x-axis. The gray-shaded area corresponds to the statistical uncertainties.

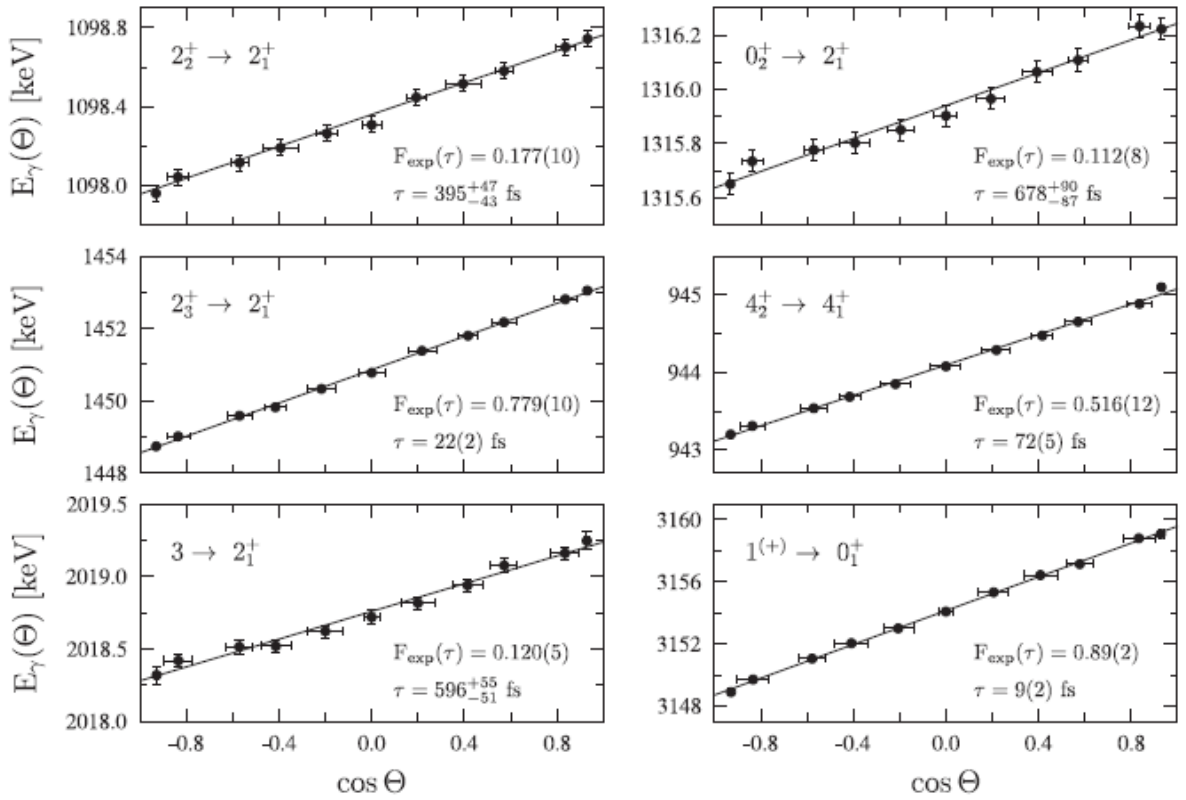
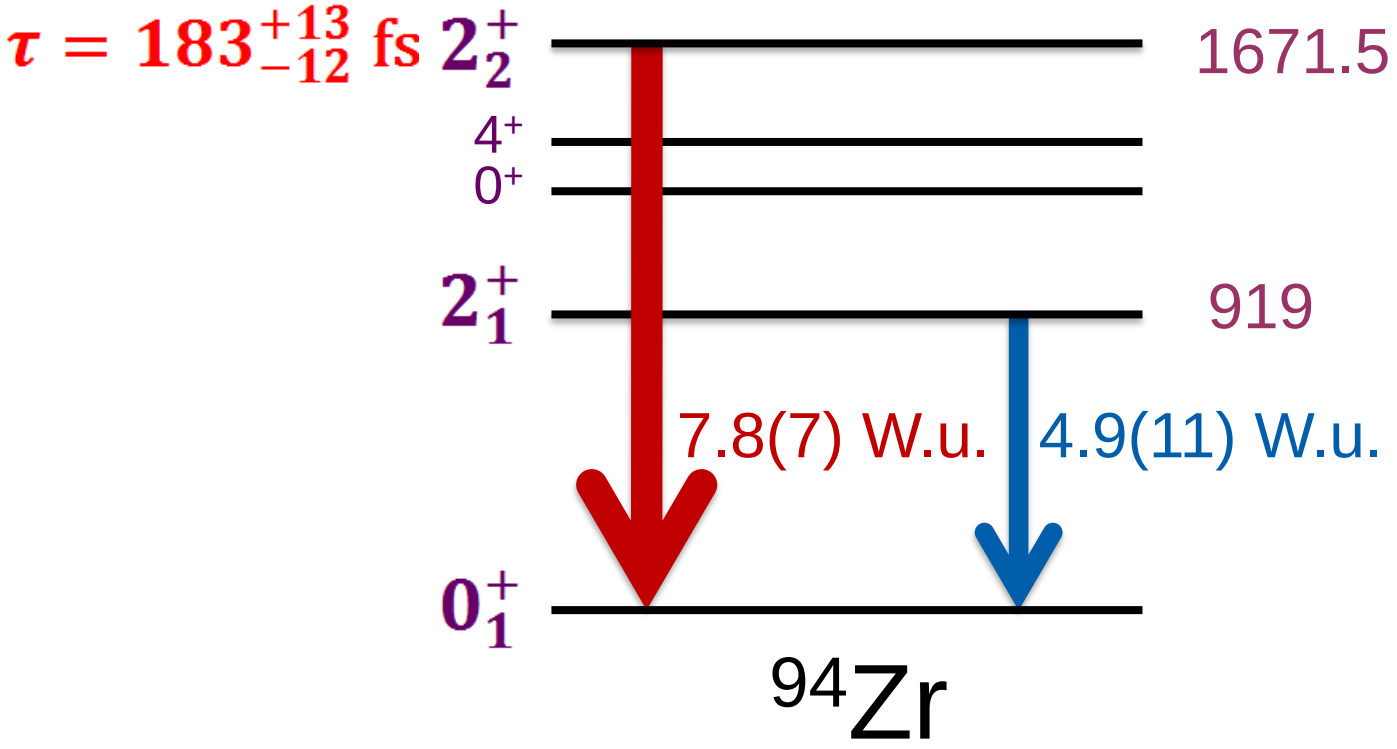


Fig. 4. Centroid shifts of the peaks observed in the proton-gated γ-ray spectra as a function of the $\cos\Theta$ value characterizing the groups. The linear trend of the peak centroids is clearly visible. The error bars in horizontal direction include the standard deviation to the mean value of $\cos\Theta$ for each group as well as the uncertainty introduced by the opening angles of the particle detectors. The uncertainties of the peak centroids are dominated by the uncertainty in the energy calibration with the ^{56}Co source.

The ^{94}Zr Story: In the beginning…

Our studies of ^{94}Zr with the (n,n'γ) reaction and an enriched $^{94}ZrO_2$ scattering sample revealed an interesting and unique result — *i.e.*,

$$B(E2; 2_2^+ \rightarrow 0_1^+) > B(E2; 2_1^+ \rightarrow 0_1^+)$$



E. Elhami *et al.*, Phys. Rev. C **78**, 064303 (2008).

"Anomalous behavior"

Measurements at TU Darmstadt

Studies of ^{94}Zr with electron scattering indicated a conflict with our results.

M. Scheck, N. Pietralla *et al.*, Technical Univ. Darmstadt

$$B(E2; 2_2^+ \rightarrow 0_1^+) \not\geq B(E2; 2_1^+ \rightarrow 0_1^+)$$

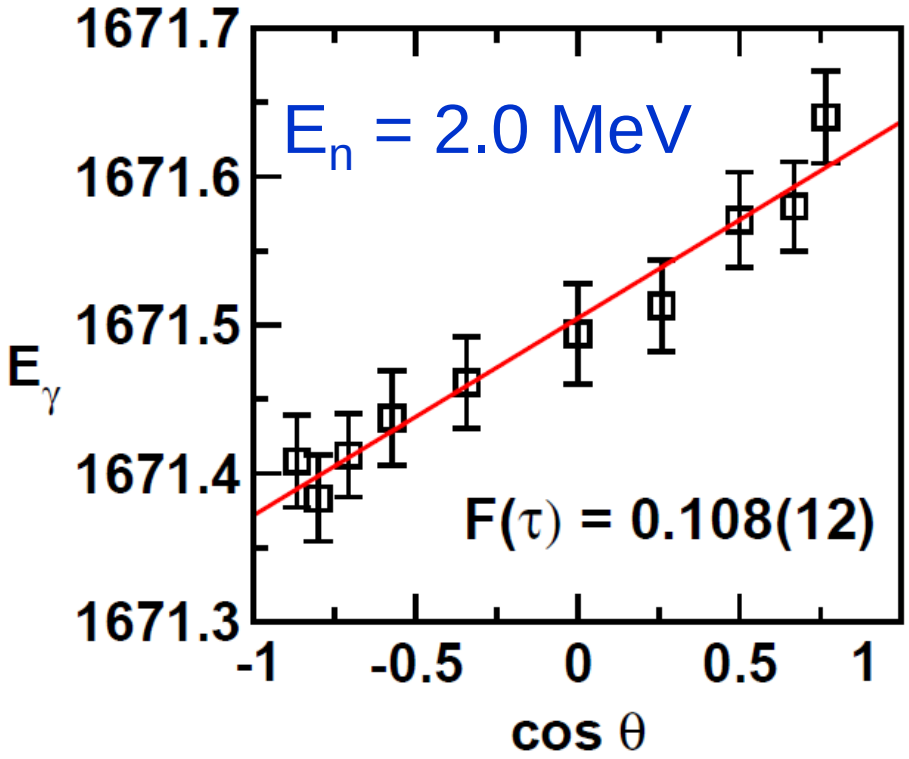
$$B(E2; 2_2^+ \rightarrow 0_1^+) = 0.9 \times B(E2; 2_1^+ \rightarrow 0_1^+)$$

$$\left(\tau = 183^{+13}_{-12}\ \text{fs}\right) \times \sim 2$$

Is there a problem with our measurement of the 2_2^+ lifetime?

- Return to the analysis of Elhami's data: $\tau = 183^{+13}_{-12}$ fs
  - Revealed an error in the density used
  - Corrected result: $\tau = 202^{+16}_{-13}$ fs
- Re-analyze the data, starting from the spectra:
  - Result: $\tau = 215^{+21}_{-19}$ fs
- Re-measure with a metallic Zr scattering sample of natural abundance:
  - Elhami *et al.* used an enriched (98.6%) $^{94}ZrO_2$ sample.
  - Any problems which may arise due to sample composition should be eliminated.
  - Stopping powers are better understood for metals.
    - Validity of Bragg's Rule – additivity of stopping powers
  - Natural sample allows comparison with other isotopes.

$^{nat}Zr_{metal}(n,n'\gamma)$



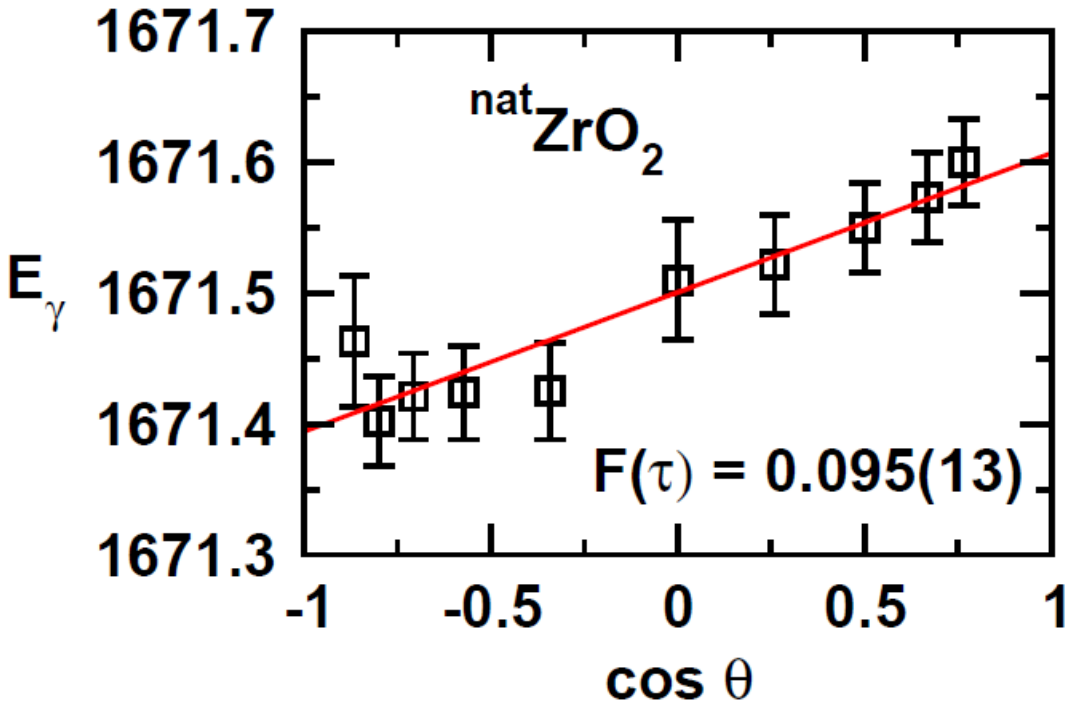
$\tau = 388^{+42}_{-33}$ fs

Previous result:

$\tau = 215^{+21}_{-19}$ fs

Is this difference due to the use of an oxide scattering sample by Elhami *et al*.?

$^{nat}ZrO_2(n,n'\gamma)$



E_n = 2.0 MeV

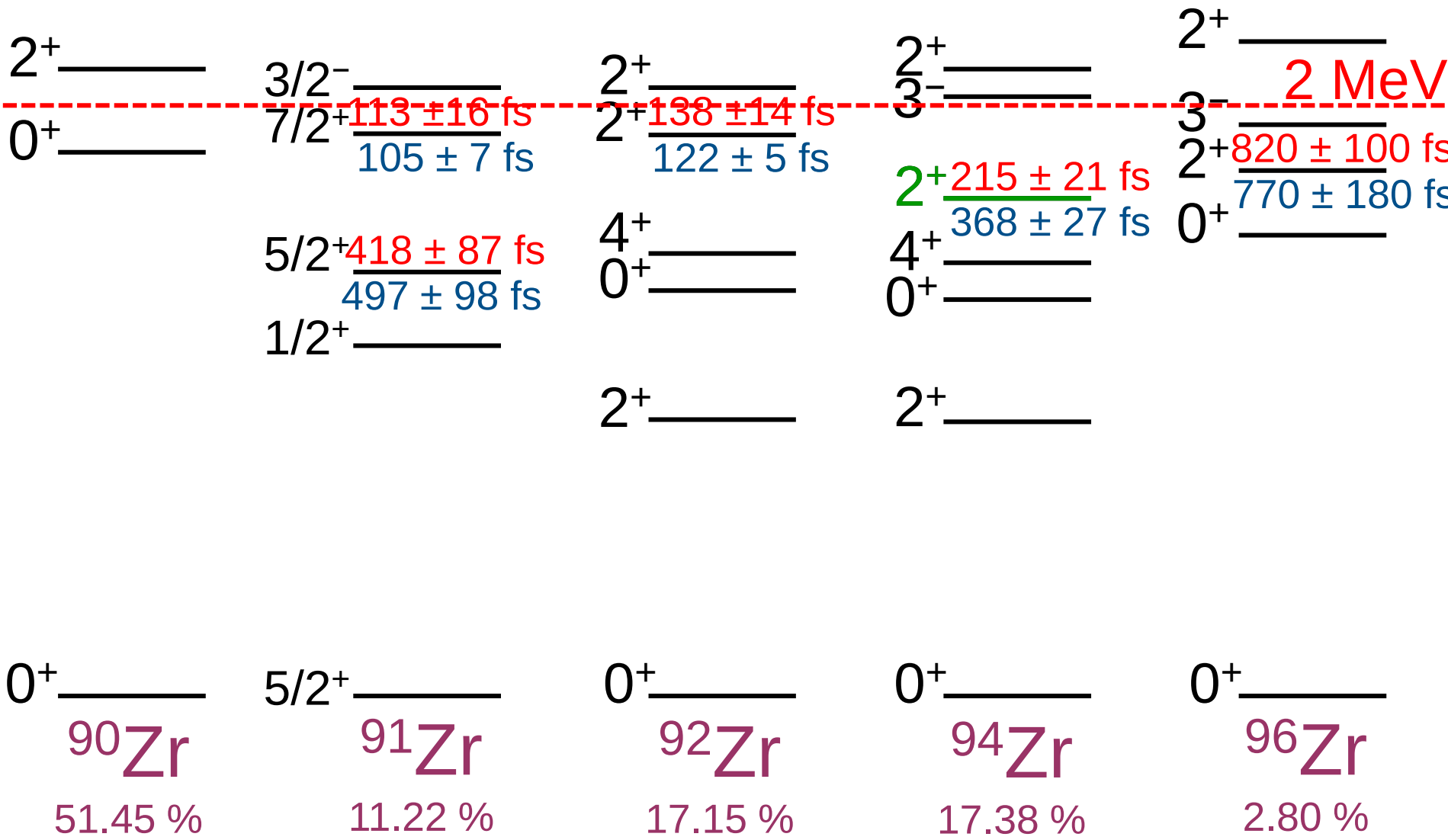
$\tau = 343^{+38}_{-33}$ fs

^{nat}Zr metal:

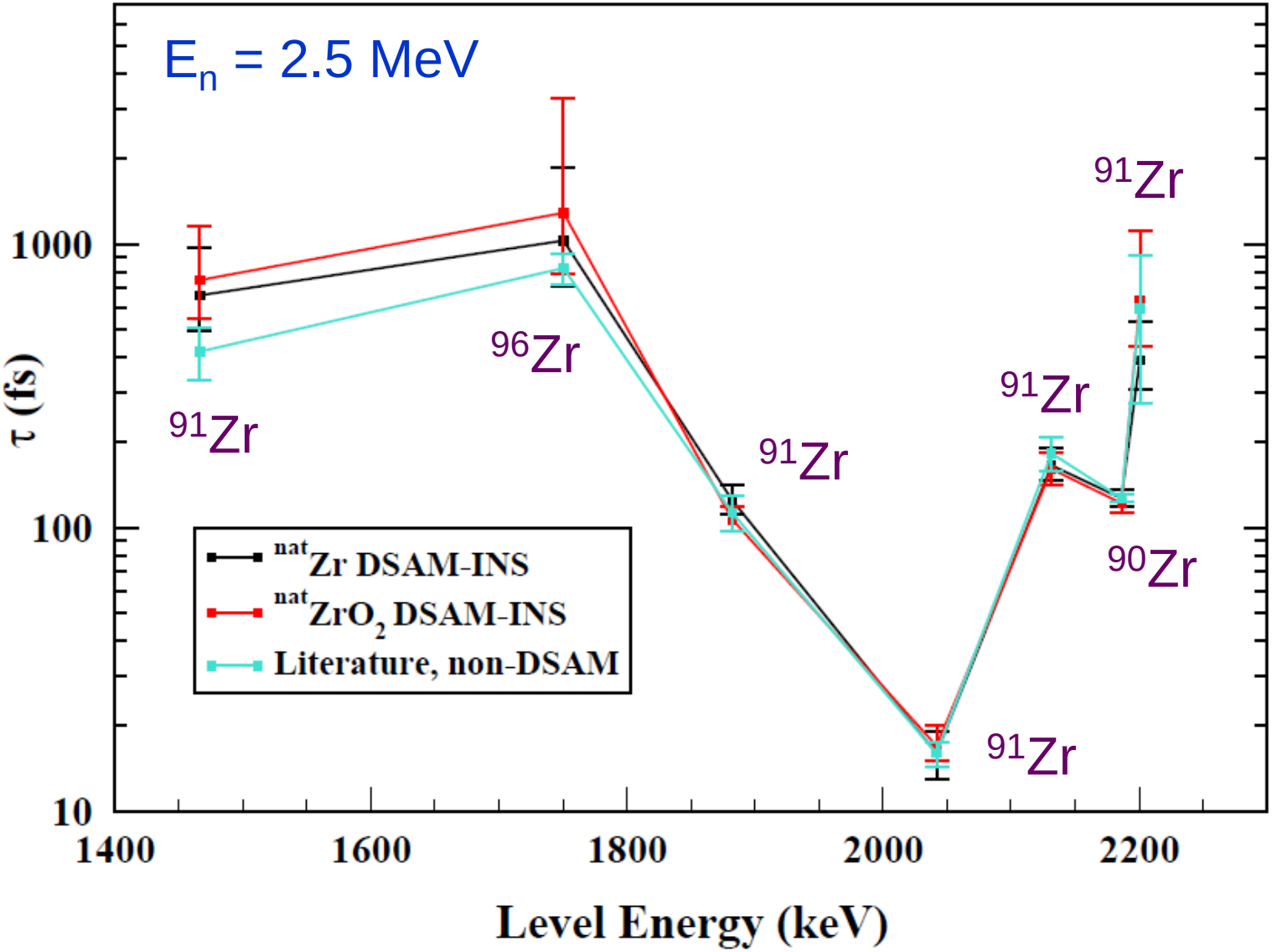
$\tau = 388^{+42}_{-33}$ fs

Within the uncertainties, they agree.

NNDC New


2+
0+
3/2−
7/2+
113 ±16 fs
105 ± 7 fs
5/2+
418 ± 87 fs
497 ± 98 fs
1/2+
2+
2+
138 ±14 fs
122 ± 5 fs
4+
0+
2+
2+
3−
2+
215 ± 21 fs
368 ± 27 fs
4+
0+
2+
2+
3−
3−
2+
820 ± 100 fs
770 ± 180 fs
0+
2 MeV
0+
90Zr
51.45 %
5/2+
91Zr
11.22 %
0+
92Zr
17.15 %
0+
94Zr
17.38 %
0+
96Zr
2.80 %

Literature/Metal/Oxide Comparison



What is the source of the discrepancy?

- Stopping powers?
  - **No!** The lifetimes from the metallic and oxide samples of natural abundance agree well.

- Enriched $^{94}ZrO_2$ sample composition?
  - Is it really ZrO_2?
  - Is it crystalline material?

ZrO_2 exhibits polymorphism.

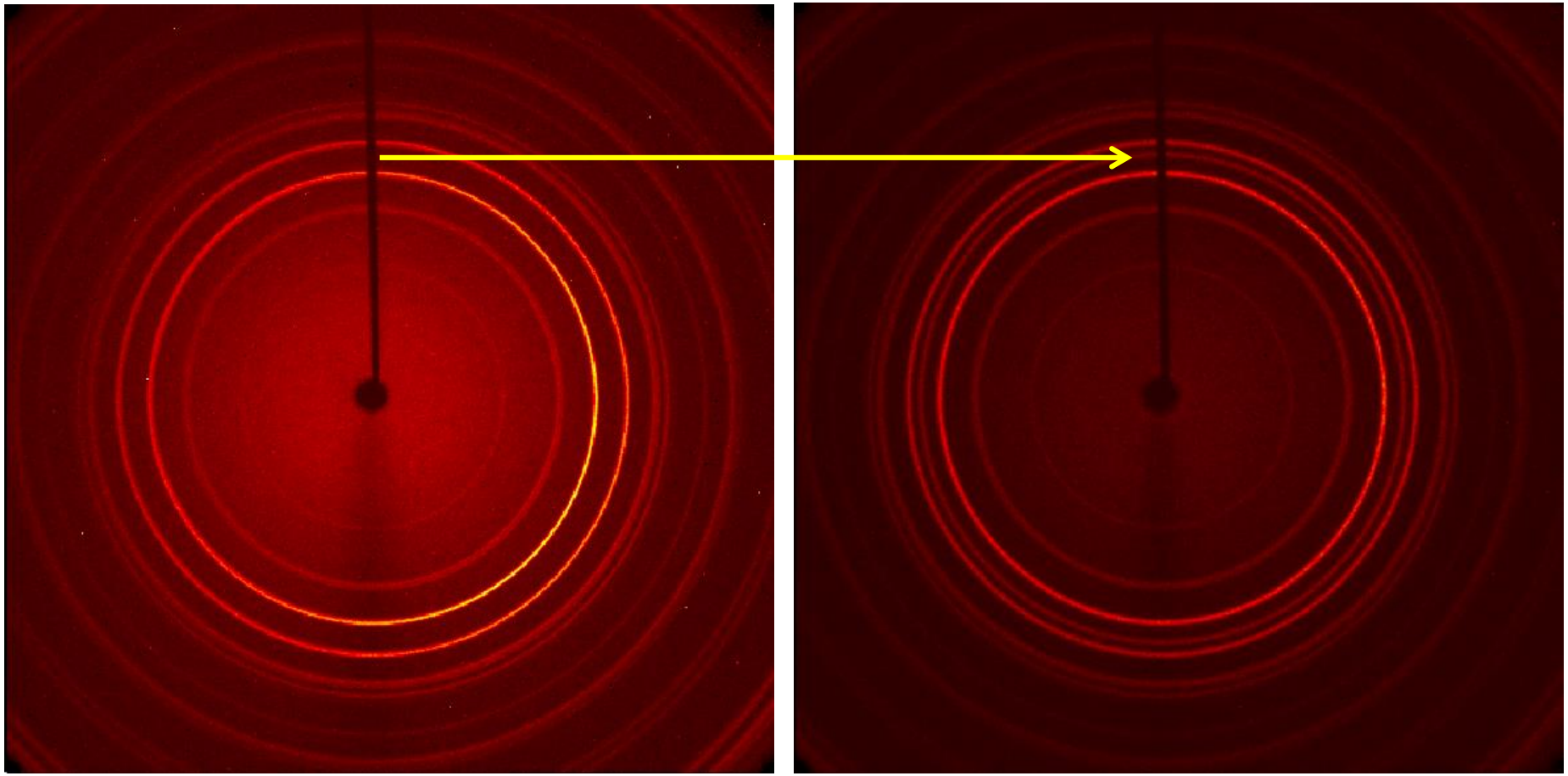
- Monoclinic phase – 5.850 g/cm^3
- Tetragonal phase – 6.045 g/cm^3
- Cubic zirconia – 5.500 g/cm^3

$^{94}ZrO_2$ Sample

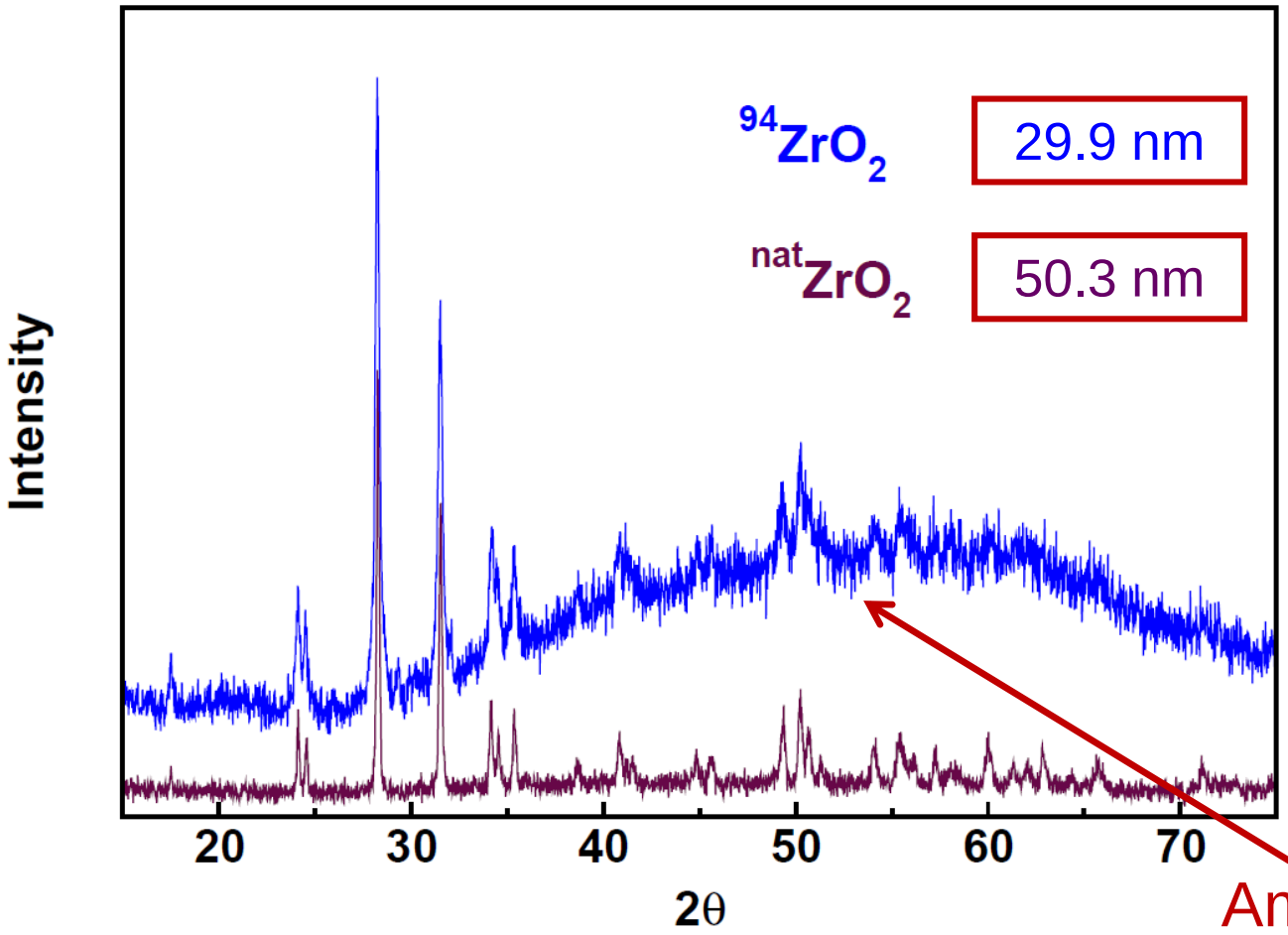
- 98.57% enriched, leased from ORNL
- 20 g in 2.6 cm x 3.9 cm container; compressed to 0.988 g/cm^3
- "This is much less dense than other ZrO_2 samples. The material was very grainy and did not compress well." — SWY 3/5/06

From X-ray Diffraction

$^{nat}ZrO_2$ $^{94}ZrO_2$



Powder X-ray Diffraction



Scherrer Equation

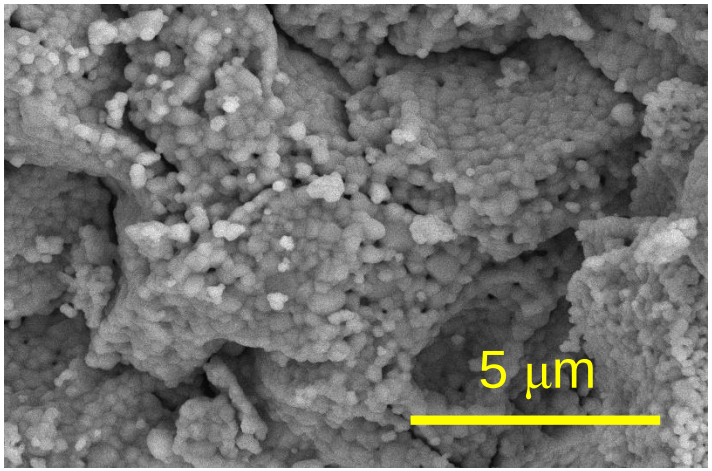
$$D = \frac{K\lambda}{\beta \cos\theta}$$

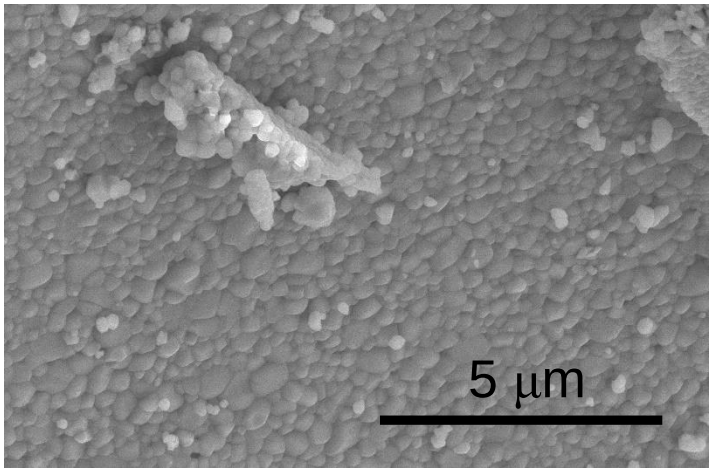
gives size of crystalline domains.

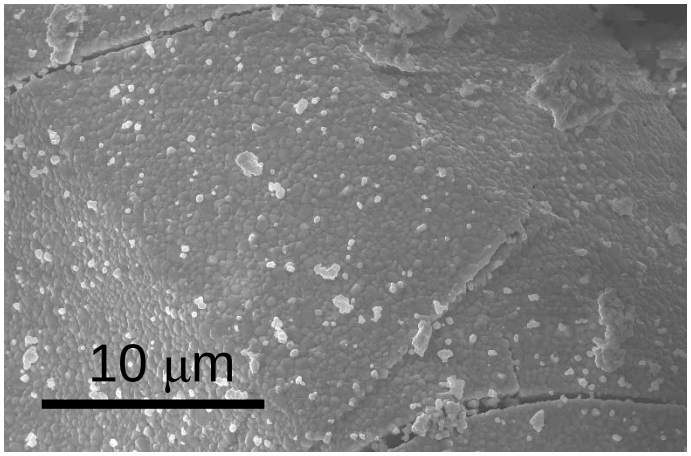
Monoclinic ZrO_2

Amorphous component?

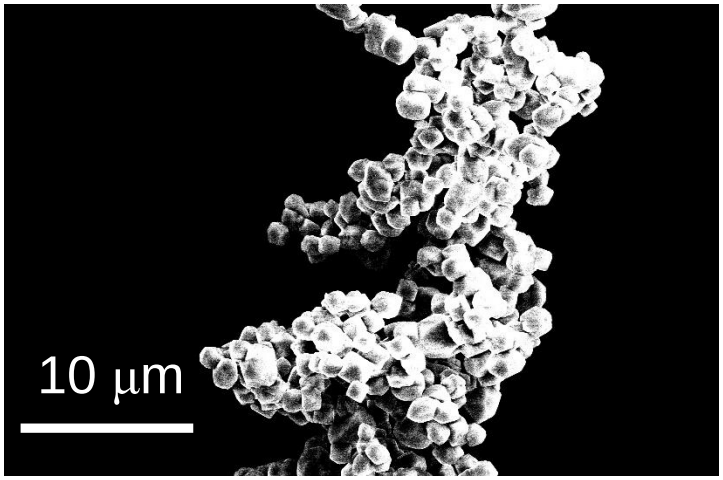
SEM $^{nat}ZrO_2$

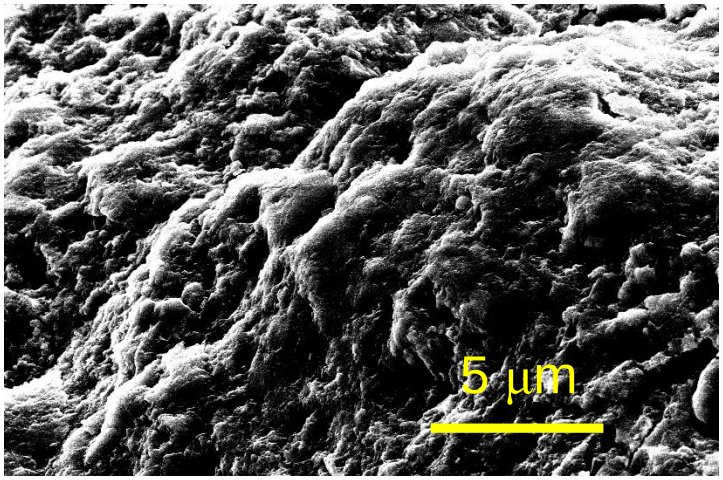


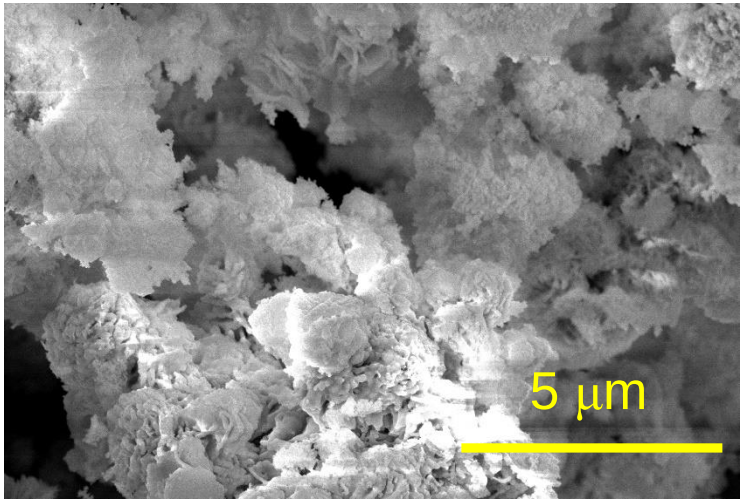




SEM $^{94}ZrO_2$



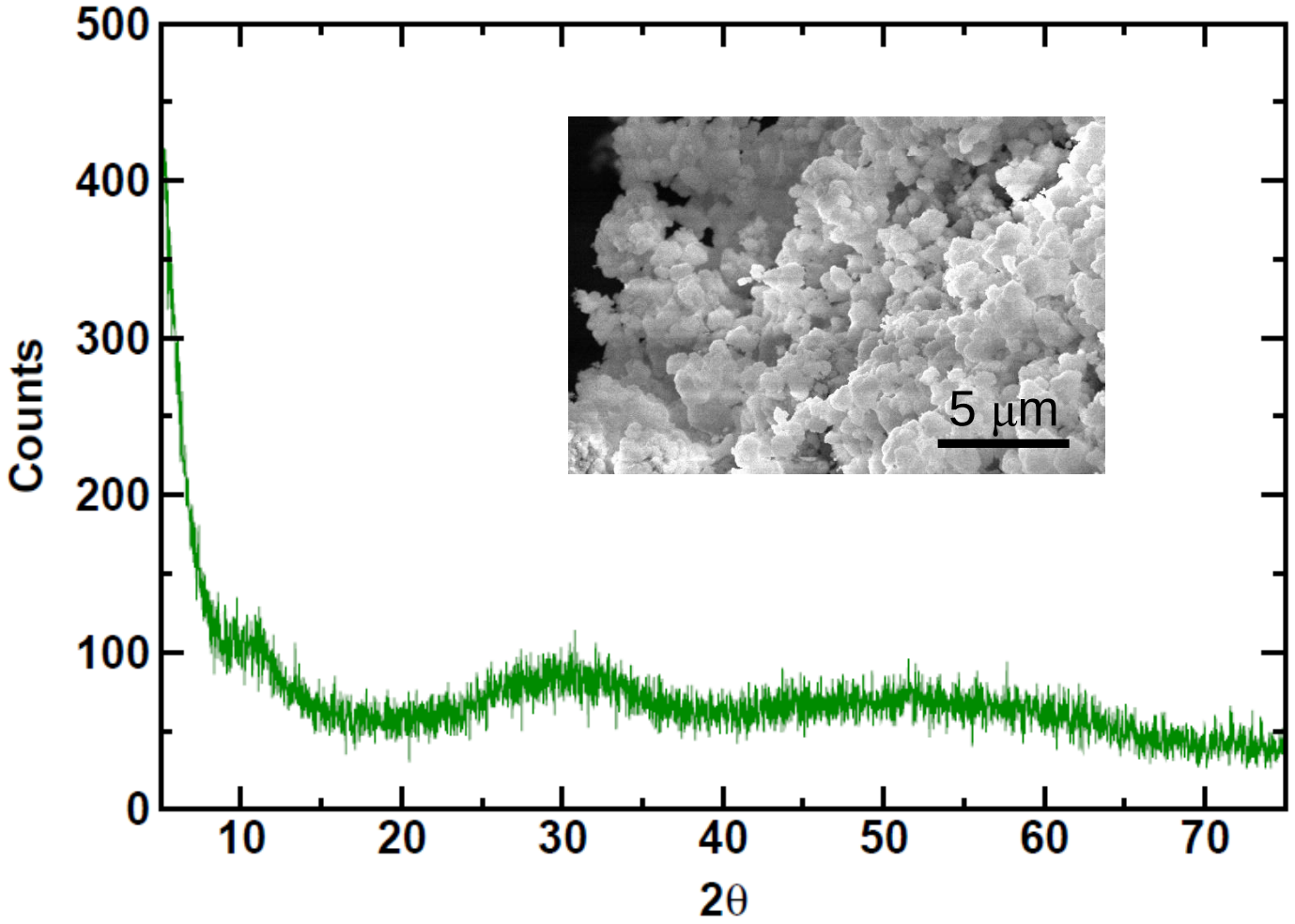




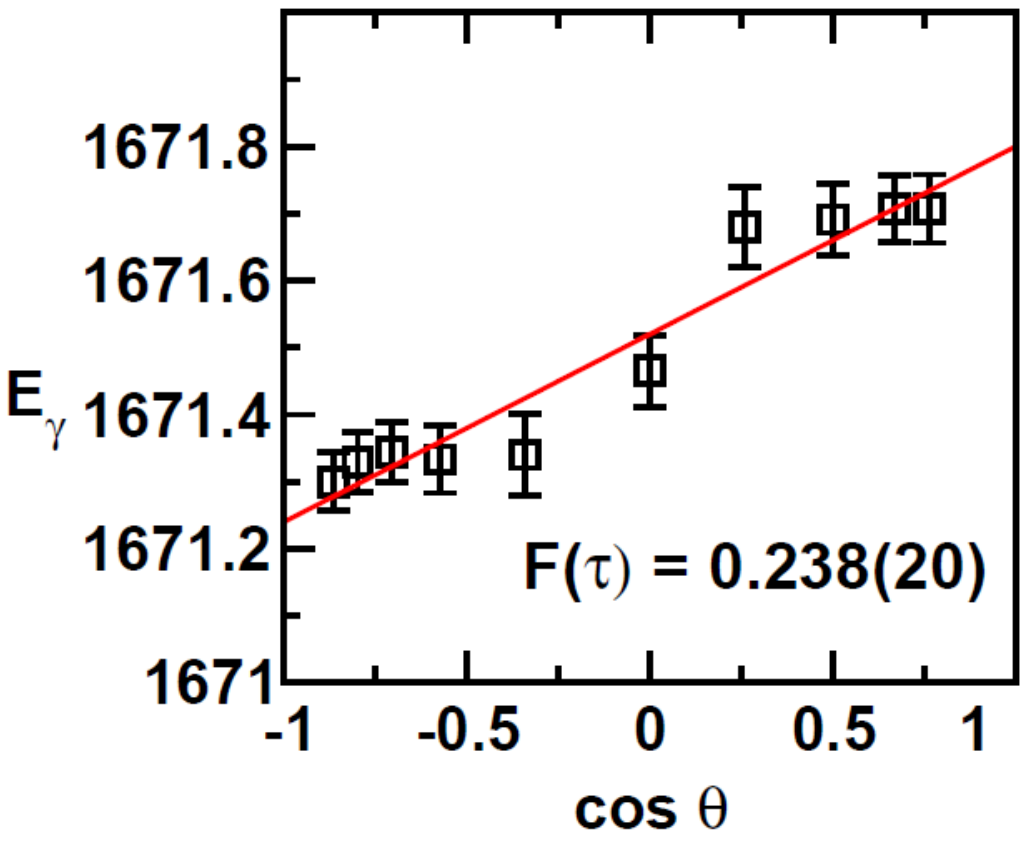
Is the difference in lifetimes due to the amorphous component?

Effect of Amorphous Material: $^{nat}Zr(OH)_4$

Powder X-ray Diffraction Spectrum



Effect of Amorphous Material: $^{nat}Zr(OH)_4$



E_n = 2.0 MeV

$\tau = 198^{+24}_{-19}$ fs

Previous result:

$\tau = 215^{+21}_{-19}$ fs

^{nat}Zr metal:

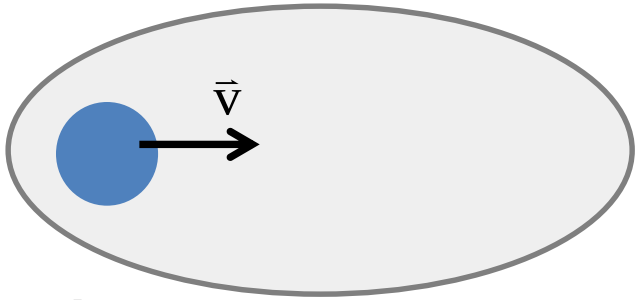
$\tau = 388^{+42}_{-33}$ fs

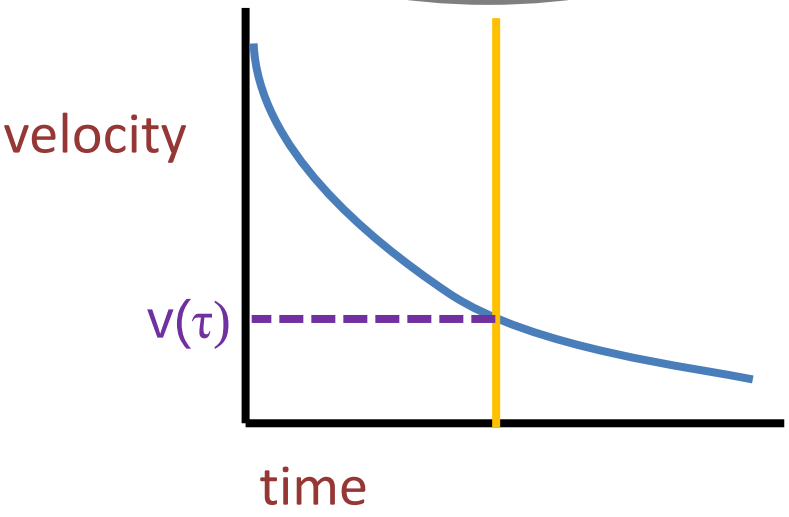
$^{nat}ZrO_2$:

$\tau = 343^{+38}_{-33}$ fs

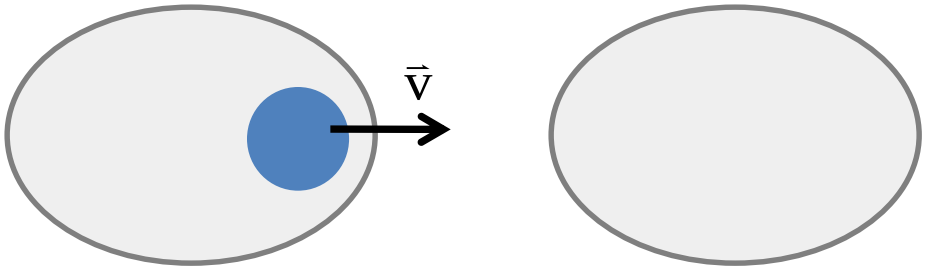
Why???

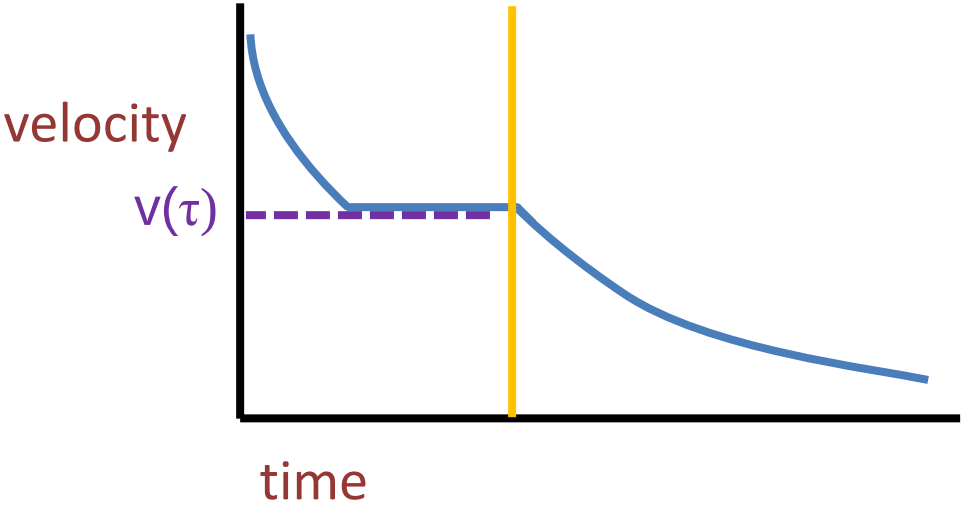
Effect of Particle Size





Large Particle Size
- Recoil within a single particle
- Uniform stopping



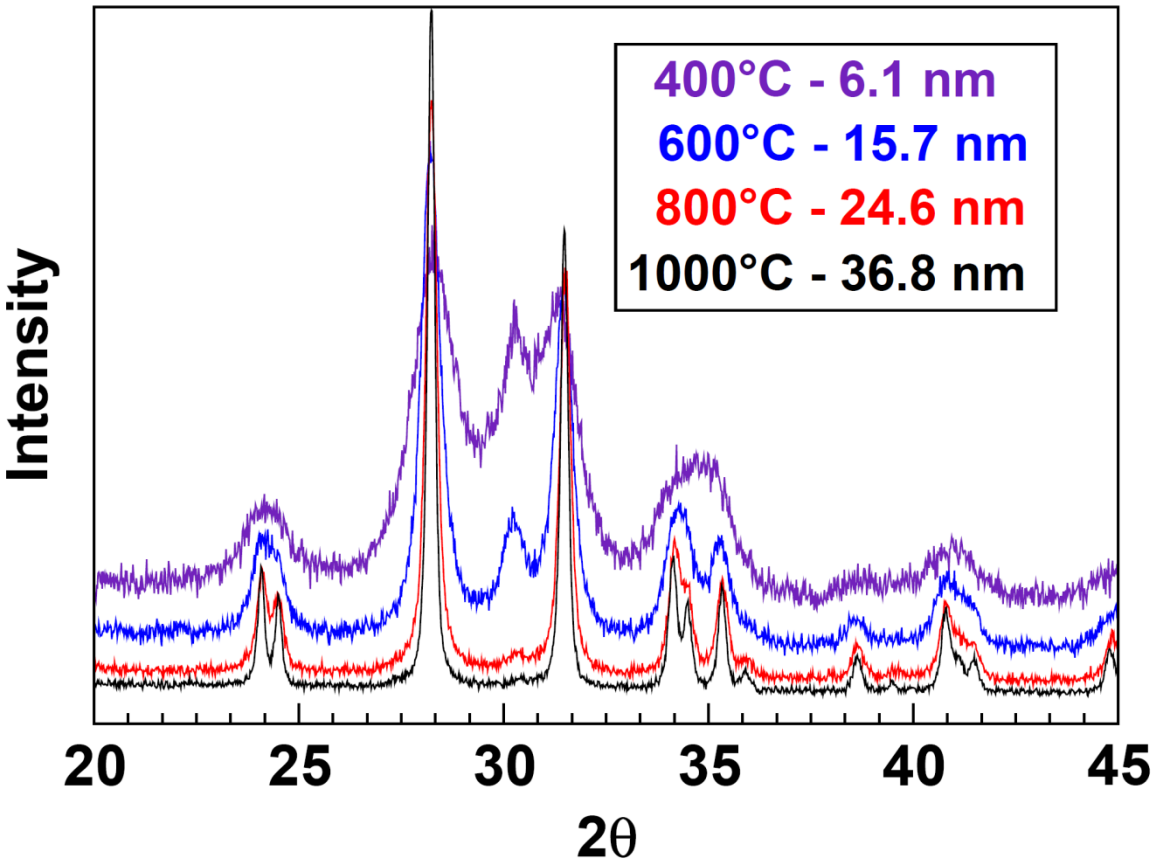


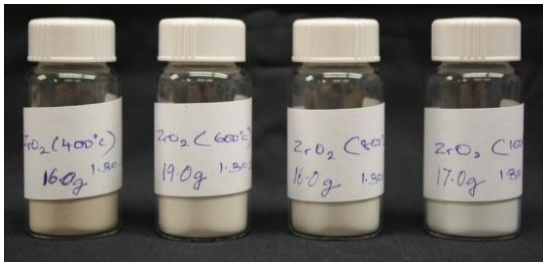
Small Particle Size
- Recoiling through multiple particles
- Non-uniform stopping

$^{nat}ZrO_2$ Particles of Different Sizes

$$ZrO(NO_3)_2 \cdot nH_2O(s) + H_2O(l) + 2NH_4OH(aq) \rightarrow Zr(OH)_4(s) + 2NH_4^+(aq) + 2NO_3^-(aq)$$

$$Zr(OH)_4(s) \xrightarrow[\text{Heat}]{calcination} ZrO_2(s) + 2H_2O(g)$$

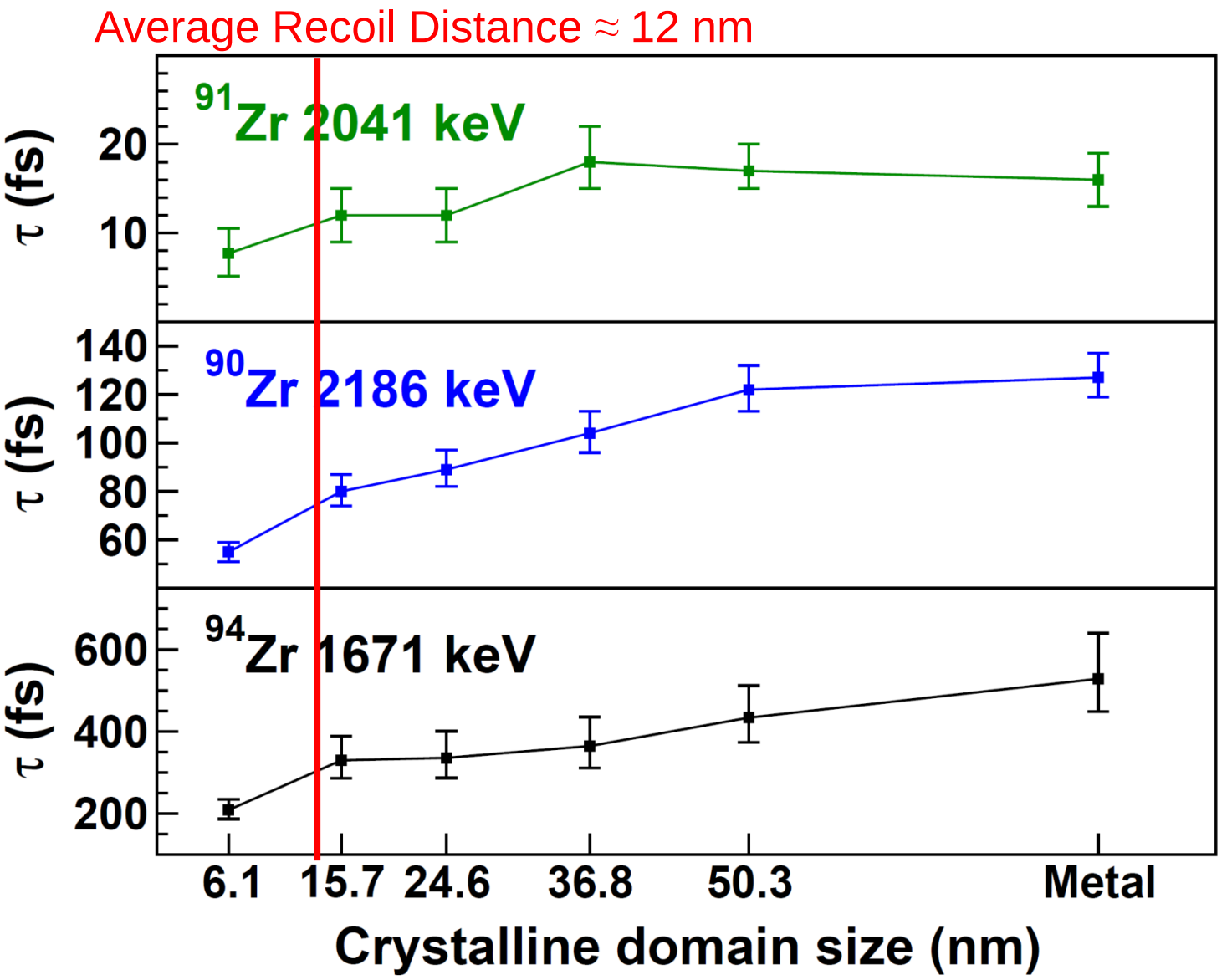




with B.H. Davis

University of Kentucky Center for Applied Energy Research

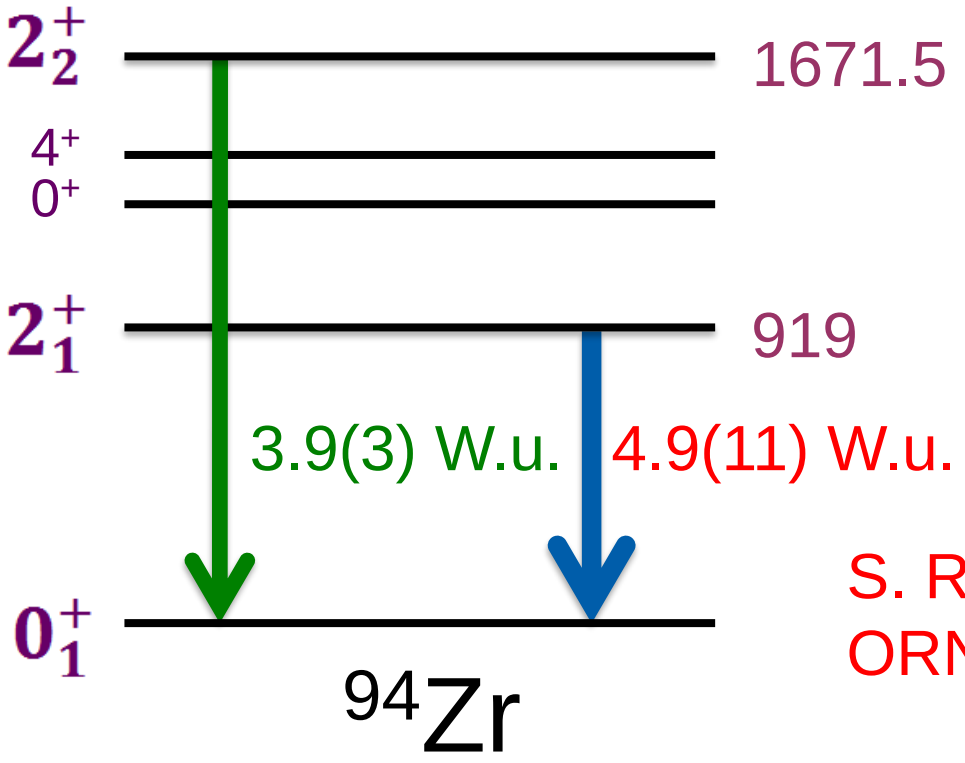
Lifetime as a Function of Domain Size



Final Results

(Metal/Oxide Average)

$\tau = 368^{+27}_{-23}$ fs



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$B(E2; 2_2^+ \rightarrow 0_1^+) \gtrless B(E2; 2_1^+ \rightarrow 0_1^+)$?

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Level lifetimes in the stable Zr nuclei: Effects of chemical properties in Doppler-shift measurements

E. E. Peters,[1] A. Chakraborty,[1,2,*] B. P. Crider,[2] B. H. Davis,[3] M. K. Gnanamani,[3] M. T. McEllistrem,[2] F. M. Prados-Estévez,[1,2] J. R. Vanhoy,[4] and S. W. Yates[1,2]

[1]*Department of Chemistry, University of Kentucky, Lexington, Kentucky 40506-0055, USA*
[2]*Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40506-0055, USA*
[3]*Center for Applied Energy Research, University of Kentucky, Lexington, Kentucky 40511-8479, USA*
[4]*Department of Physics, United States Naval Academy, Annapolis, Maryland 21402, USA*

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Collective Structure in ^{94}Zr and Subshell Effects in Shape Coexistence

A. Chakraborty,[1,2,*] E. E. Peters,[2] B. P. Crider,[1] C. Andreoiu,[3] P. C. Bender,[4] D. S. Cross,[3] G. A. Demand,[5] A. B. Garnsworthy,[4] P. E. Garrett,[5] G. Hackman,[4] B. Hadinia,[5] S. Ketelhut,[4] Ajay Kumar,[1,2,†] K. G. Leach,[5] M. T. McEllistrem,[1] J. Pore,[3] F. M. Prados-Estévez,[1,2] E. T. Rand,[5] B. Singh,[6] E. R. Tardiff,[4] Z.-M. Wang,[3,4] J. L. Wood,[7] and S. W. Yates[1,2]

[1]*Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40506-0055, USA*
[2]*Department of Chemistry, University of Kentucky, Lexington, Kentucky 40506-0055, USA*
[3]*Department of Chemistry, Simon Fraser University, Burnaby, British Columbia V5A 1S6, Canada*
[4]*TRIUMF, University of British Columbia, Vancouver, British Columbia V6T 2A3, Canada*
[5]*Department of Physics, University of Guelph, Guelph, Ontario N1G 2W1, Canada*
[6]*Department of Physics and Astronomy, McMaster University, Hamilton, Ontario L8S 4L8, Canada*
[7]*School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332-0430, USA*

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