Probing Nuclear Structure with Fast Neutrons

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UNIVERSITY OF KENTUCKY
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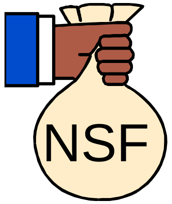
TRIUMF

Warsaw 10 March 2010



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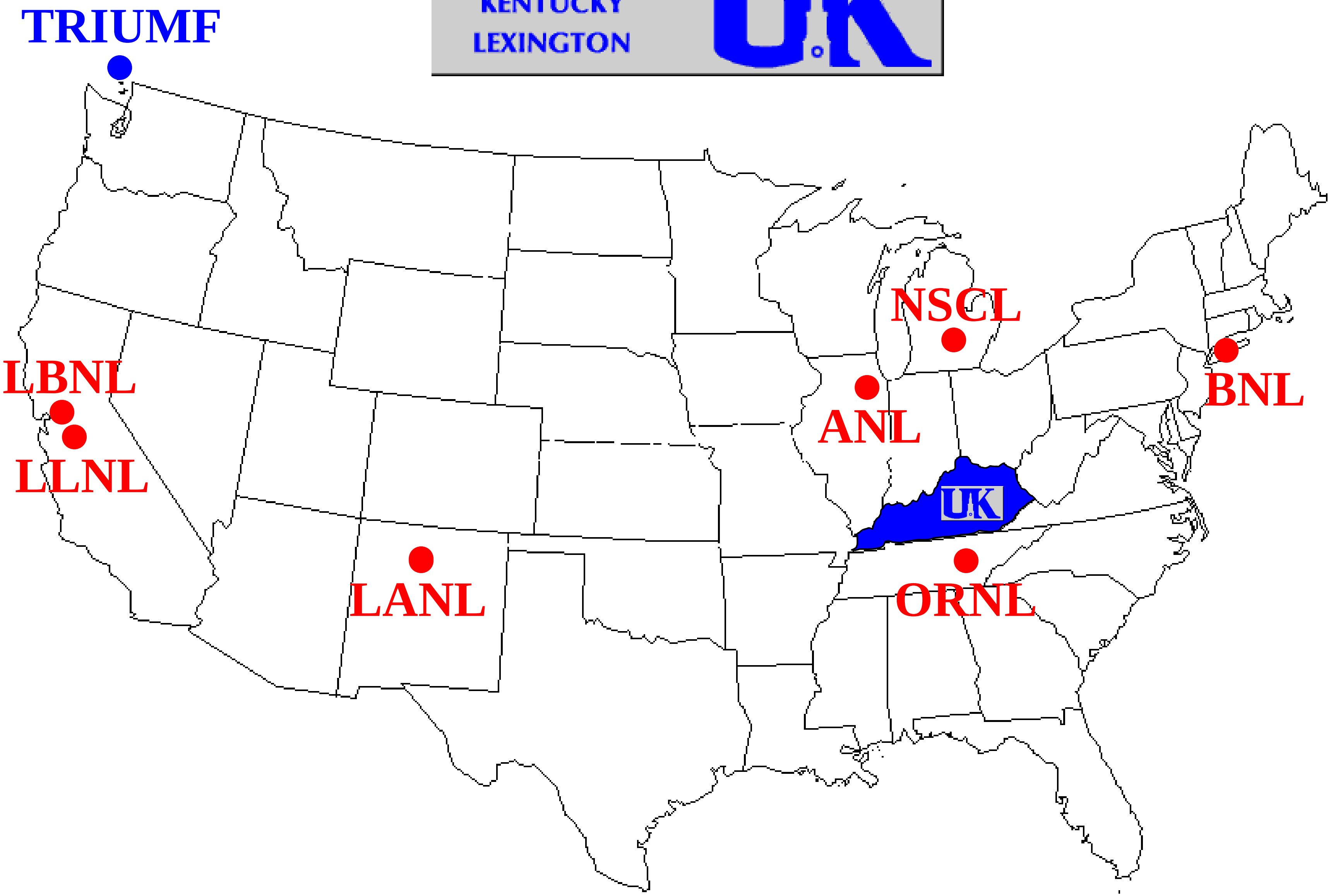
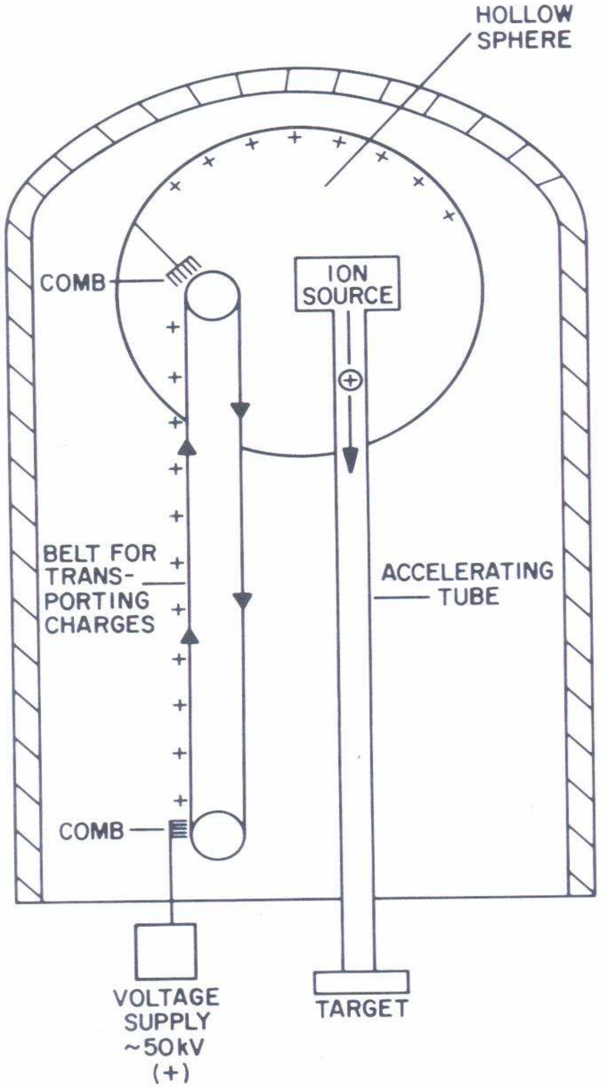


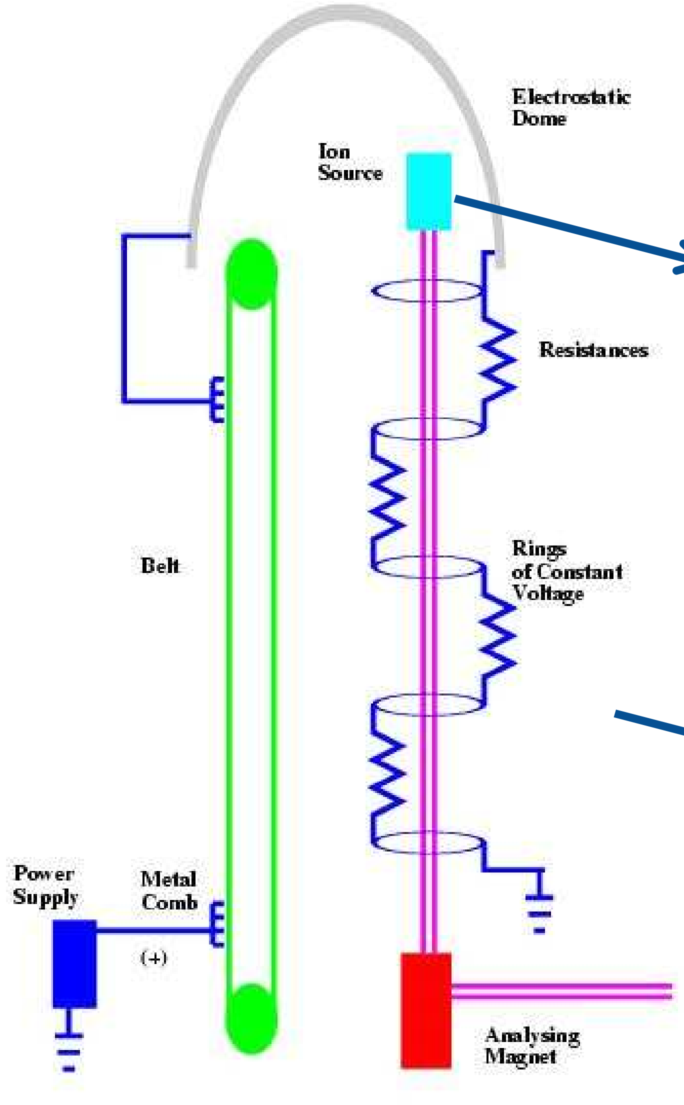

Bornholm
(DEN.)
Baltic Sea
15
18
21
24
LITH.
RUS.
Ustka
Kołobrzeg
Gdynia
Gdańsk
near Rad
Elbląsk
54
Świnoujście
Szczecin
Bydgoszcz
Lexington
BELA.
GER.
Lublin
51
Częstochwa
Gliwice
Katowice
Kraków
Rzeszów
CZECH REP.
UKR.
0 50 100 km
0 50 100 mi
Rysy
15 AUS.
18
SLOVAKIA
21

7 MV
Van de Graaff Accelerator



an

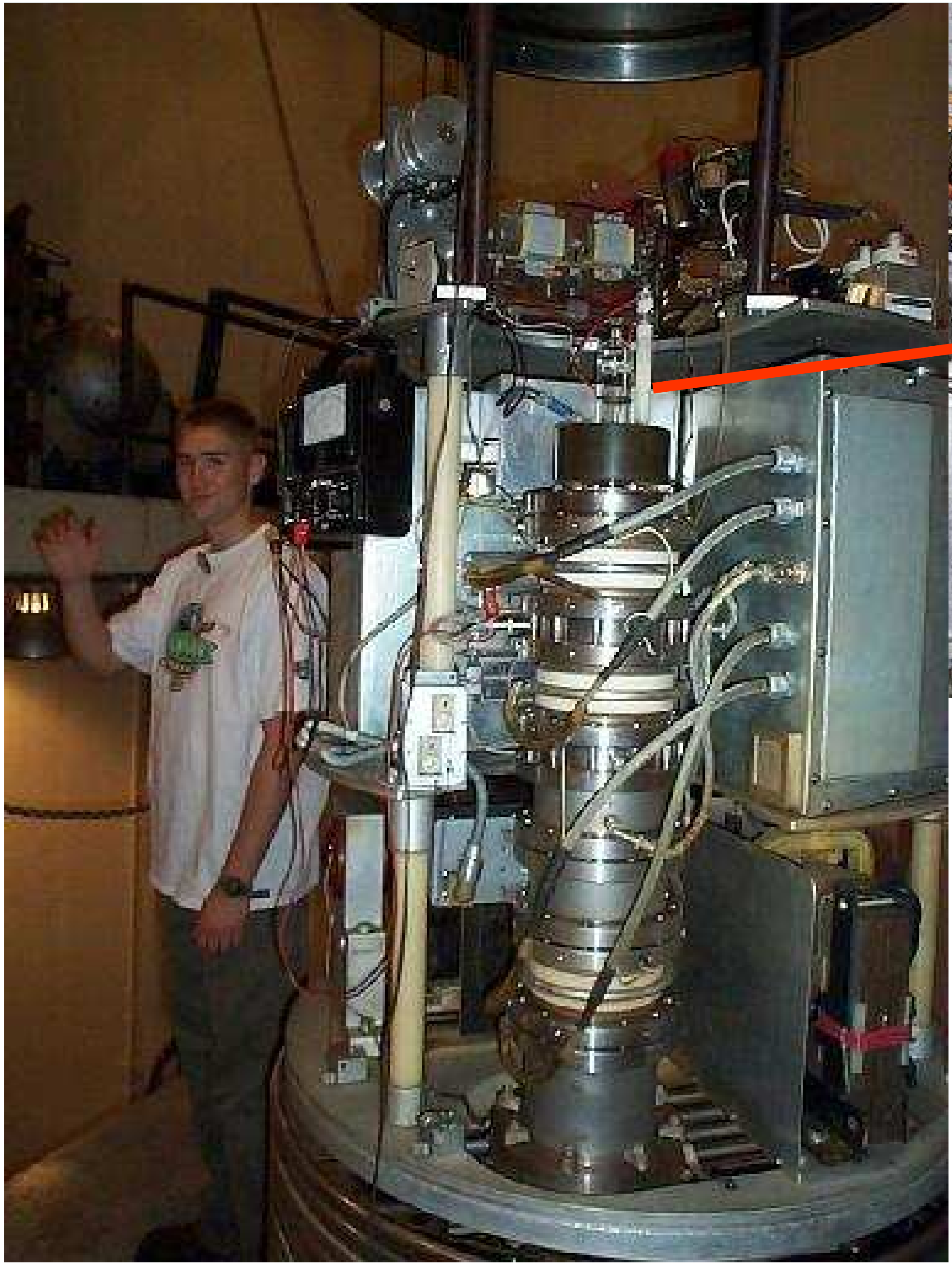
7 MV Van de Graaff Accelerator

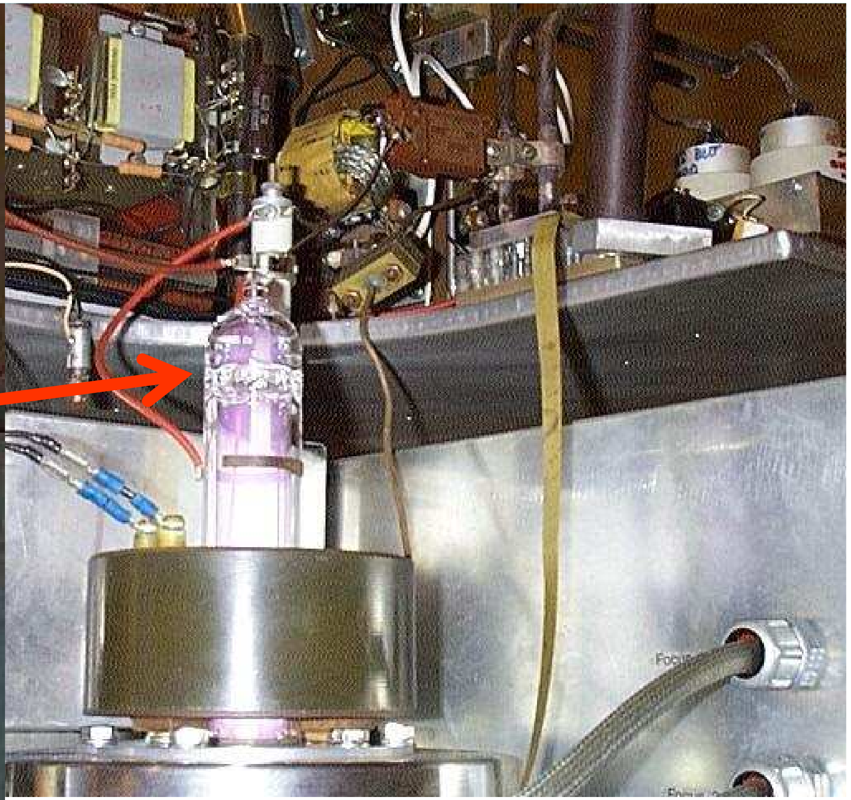


Properties of beams

- ^{1}H, ^{2}H, ^{3}He, and ^{4}He
- 0.5-7.0 MeV
- Pulsed at 1.875 MHz

7 MV Van de Graaff Accelerator





Ion Source

As Feynman said, the hadron-hadron work [in the Stanford Linear Accelerator Center, SLAC] was like trying to figure out a pocket watch by smashing two of them together and watching the pieces fly out.

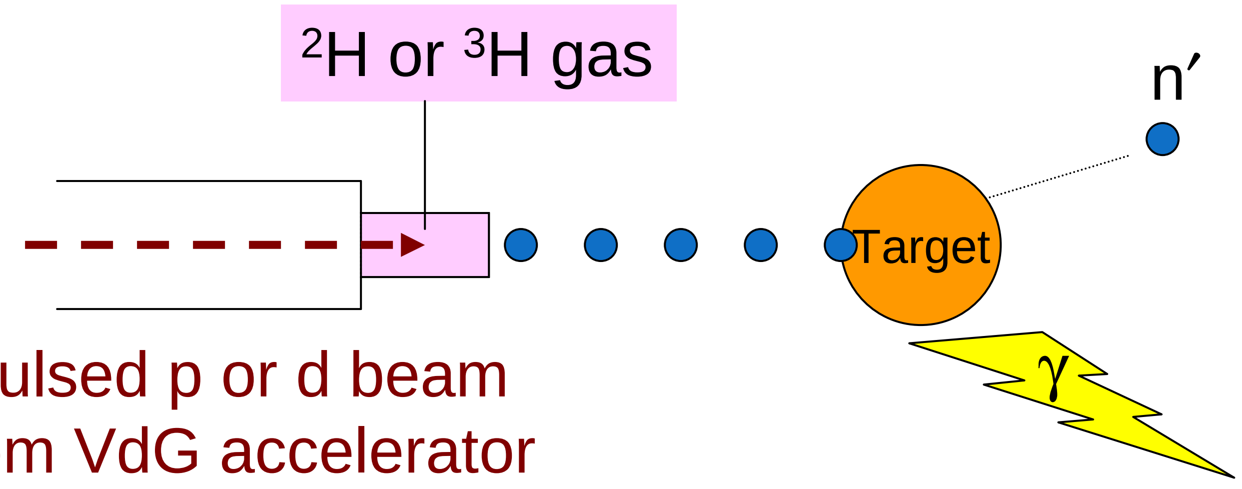
James Gleick, *Genius: The Life and Science of Richard Feynman*

Neutron Production

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

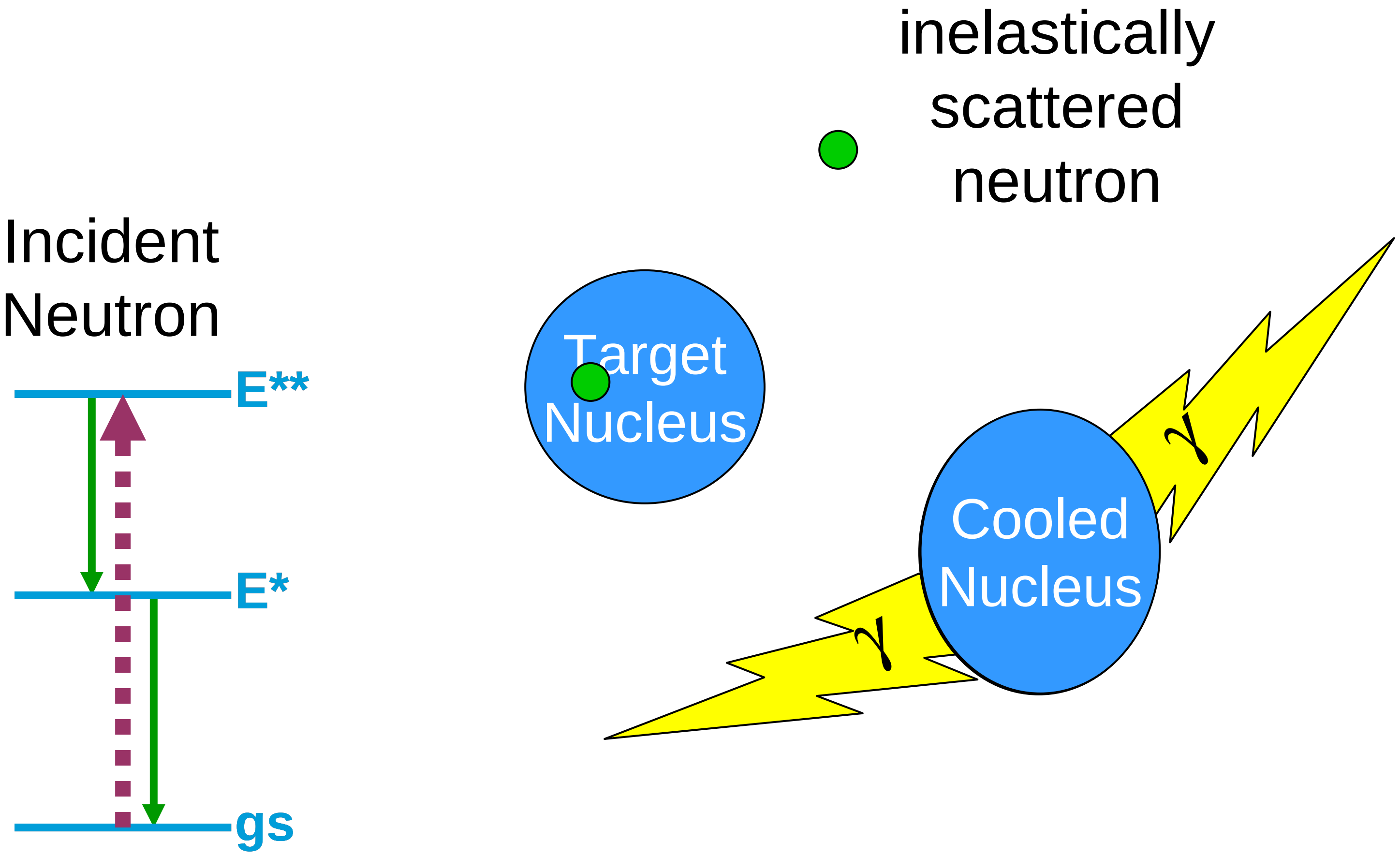
Neutron Energies (Accelerator Voltage: 1.5 – 7.0 MV)

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



Pulsed p or d beam
from VdG accelerator

Inelastic Neutron Scattering



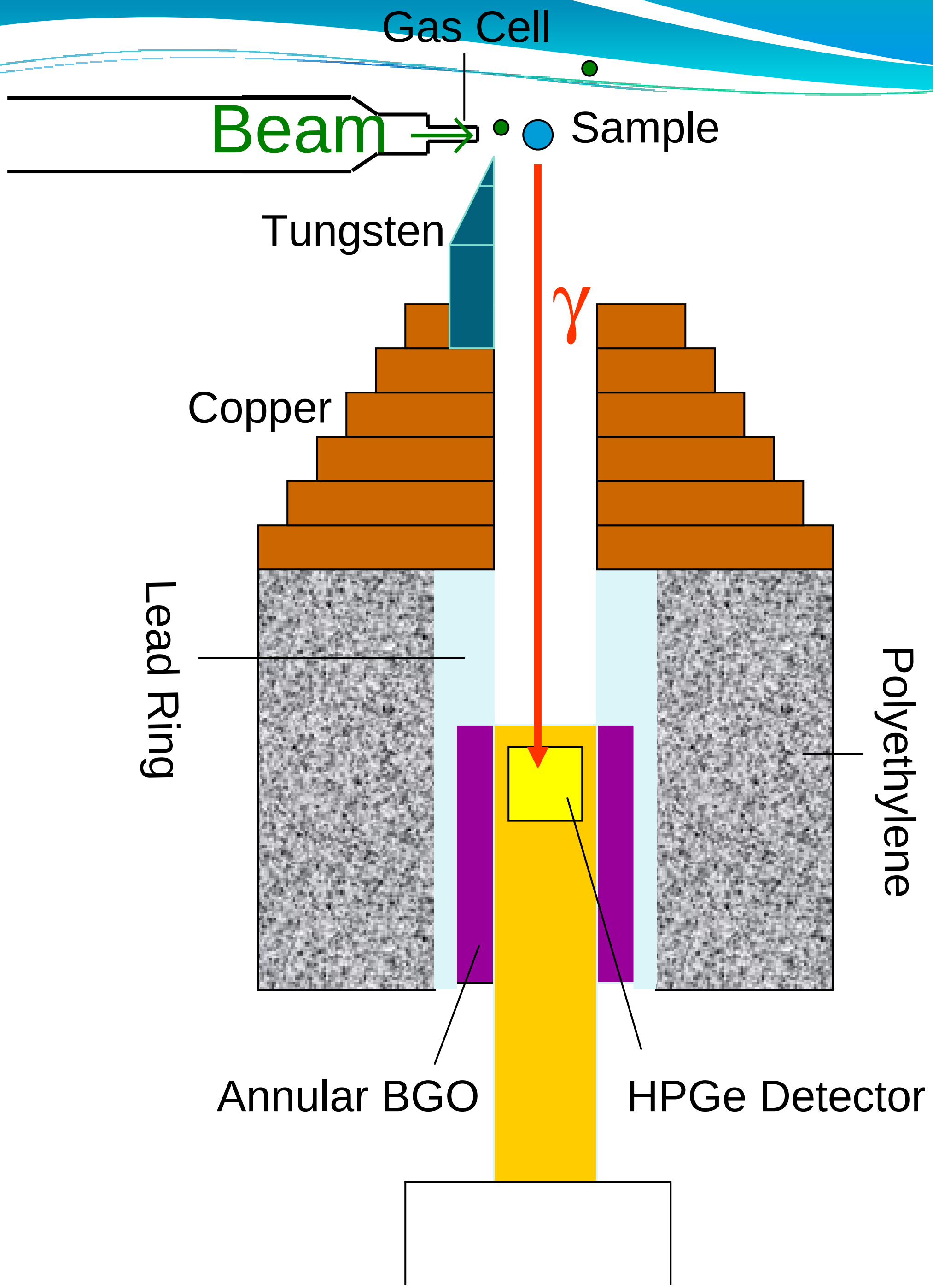
Incident
Neutron

inelastically
scattered
neutron

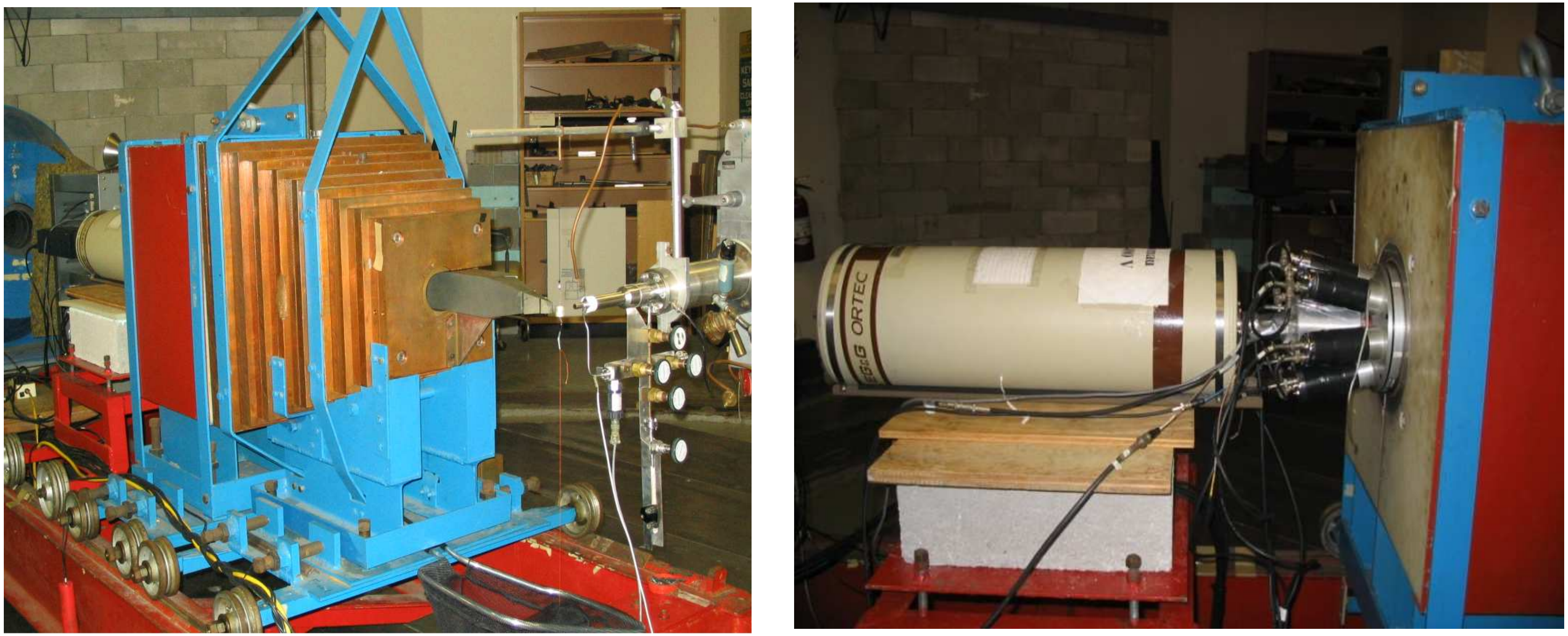
Target
Nucleus

Cooled
Nucleus

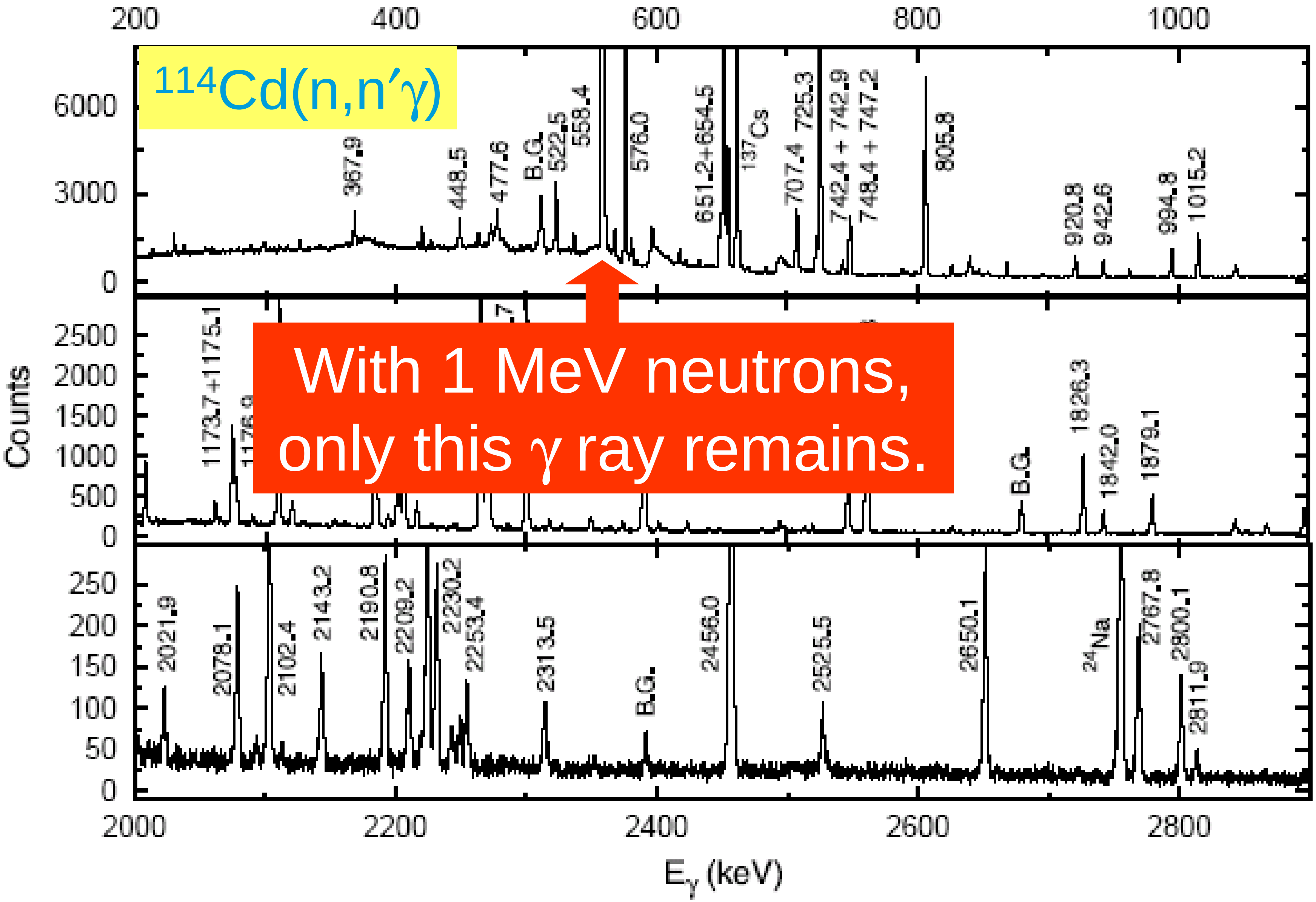
(n,n'γ) reaction


Gas Cell
Beam
Sample
Tungsten
γ
Copper
Lead Ring
Polyethylene
Annular BGO
HPGe Detector

Singles Measurements



Compton suppression ~~3.0~~ MeV Neutrons TOF gating

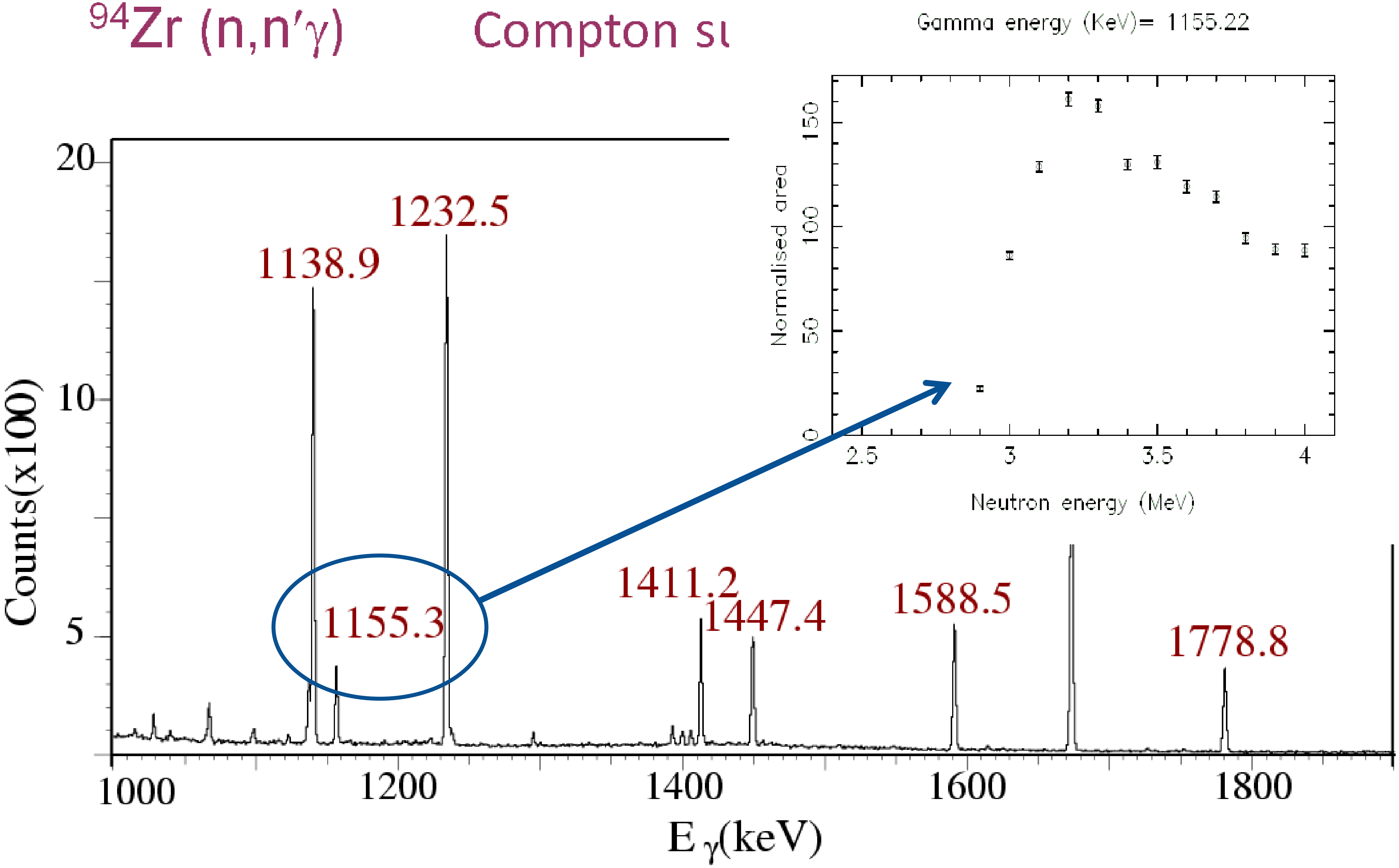


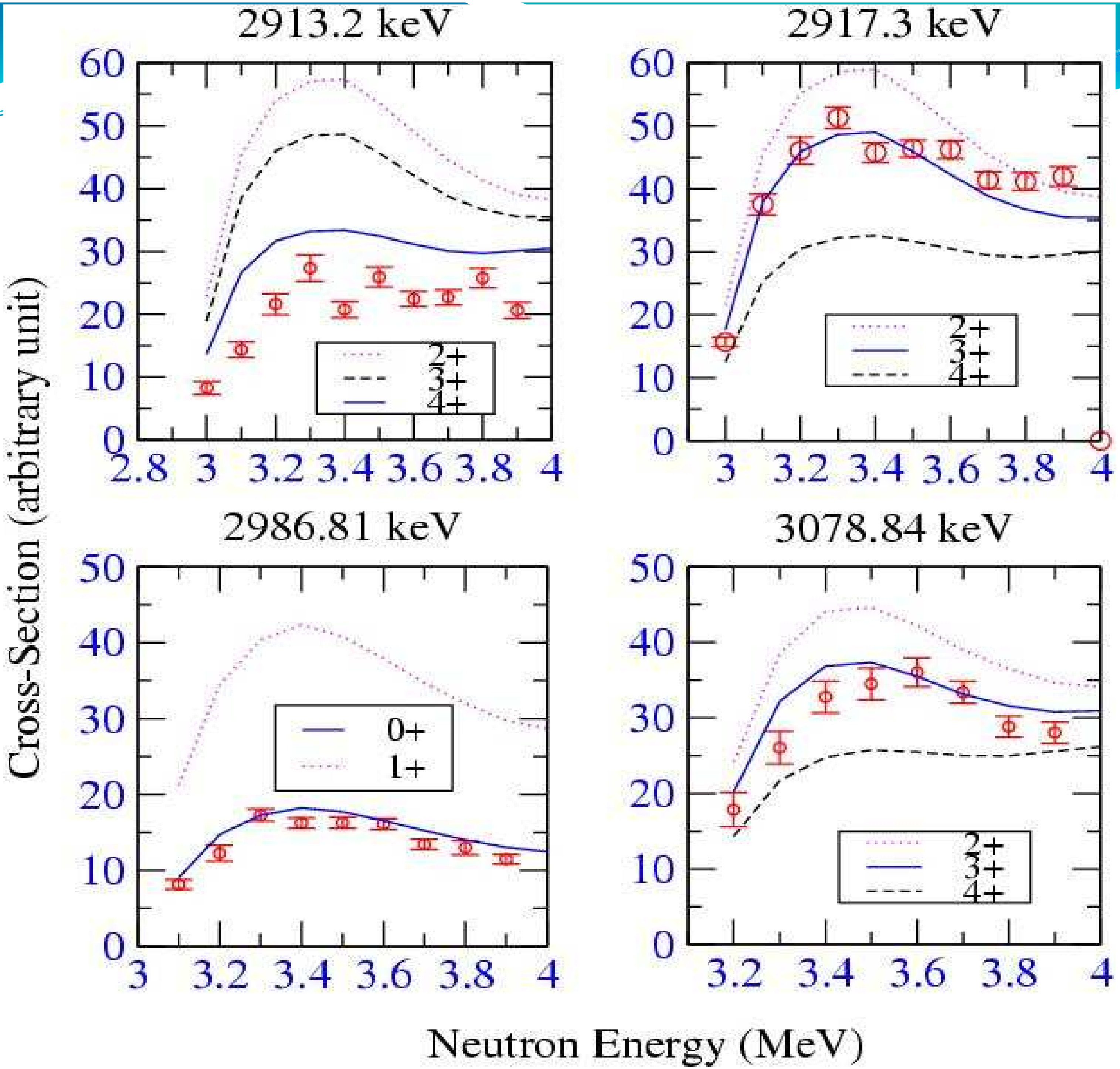
^{114}Cd(n,n′γ)

With 1 MeV neutrons, only this γ ray remains.

D. Bandyopadhyay *et al*., Phys. Rev. C **68**, 014324 (2003).

^{94}Zr (n,n′γ)   Compton s



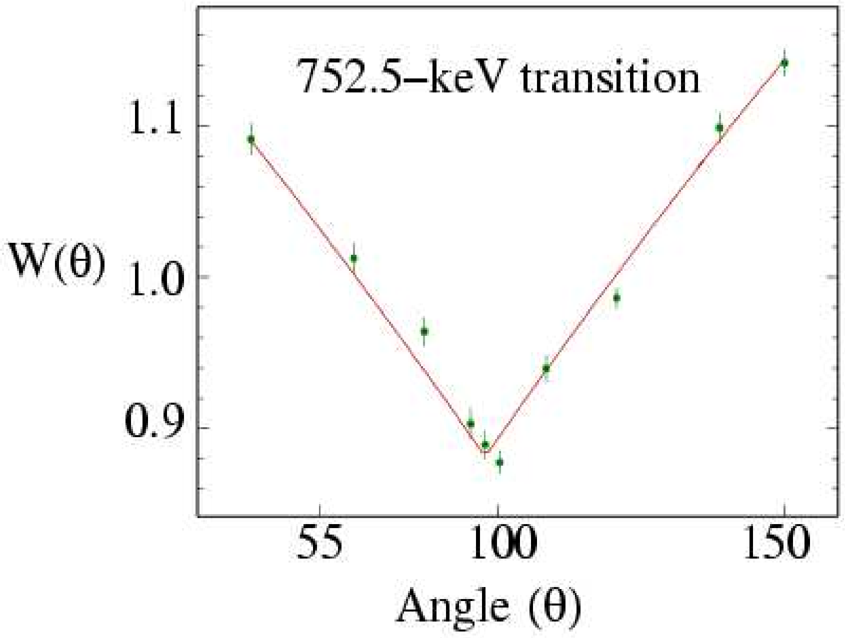

2913.2 keV
2917.3 keV
2986.81 keV
3078.84 keV
Cross-Section (arbitrary unit)
Neutron Energy (MeV)
2+
3+
4+
0+
1+
0
10
20
30
40
50
60
2.8
3
3.2
3.4
3.6
3.8
4

^{94}Zr(n,n′γ) Angular Distribution

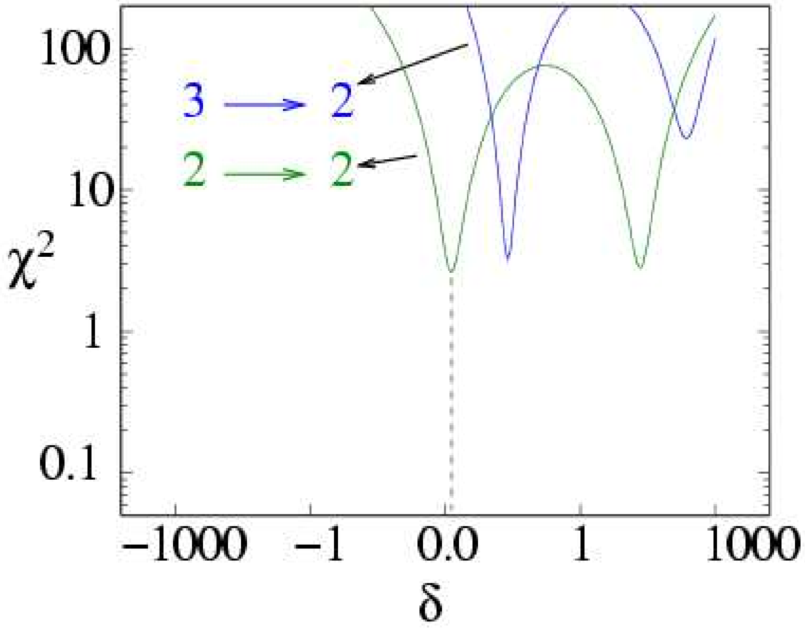
$$W(\theta) = 1 + a_2 P_2(\cos\theta) + a_4 P_4(\cos\theta)$$

Comparison with statistical model calculations (CINDY)

⇒ multipole mixing ratio (δ) and spins

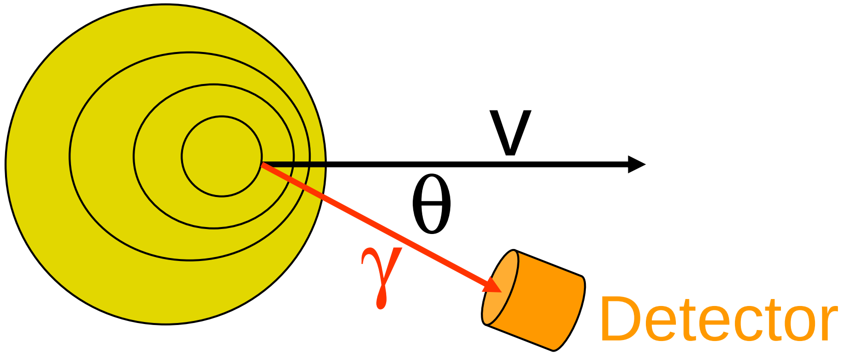


a_2: 0.23(15) a_4: −0.09(2)



$\delta\ (2 \rightarrow 2) = 0.02(2)$

Doppler-Shift Attenuation Method

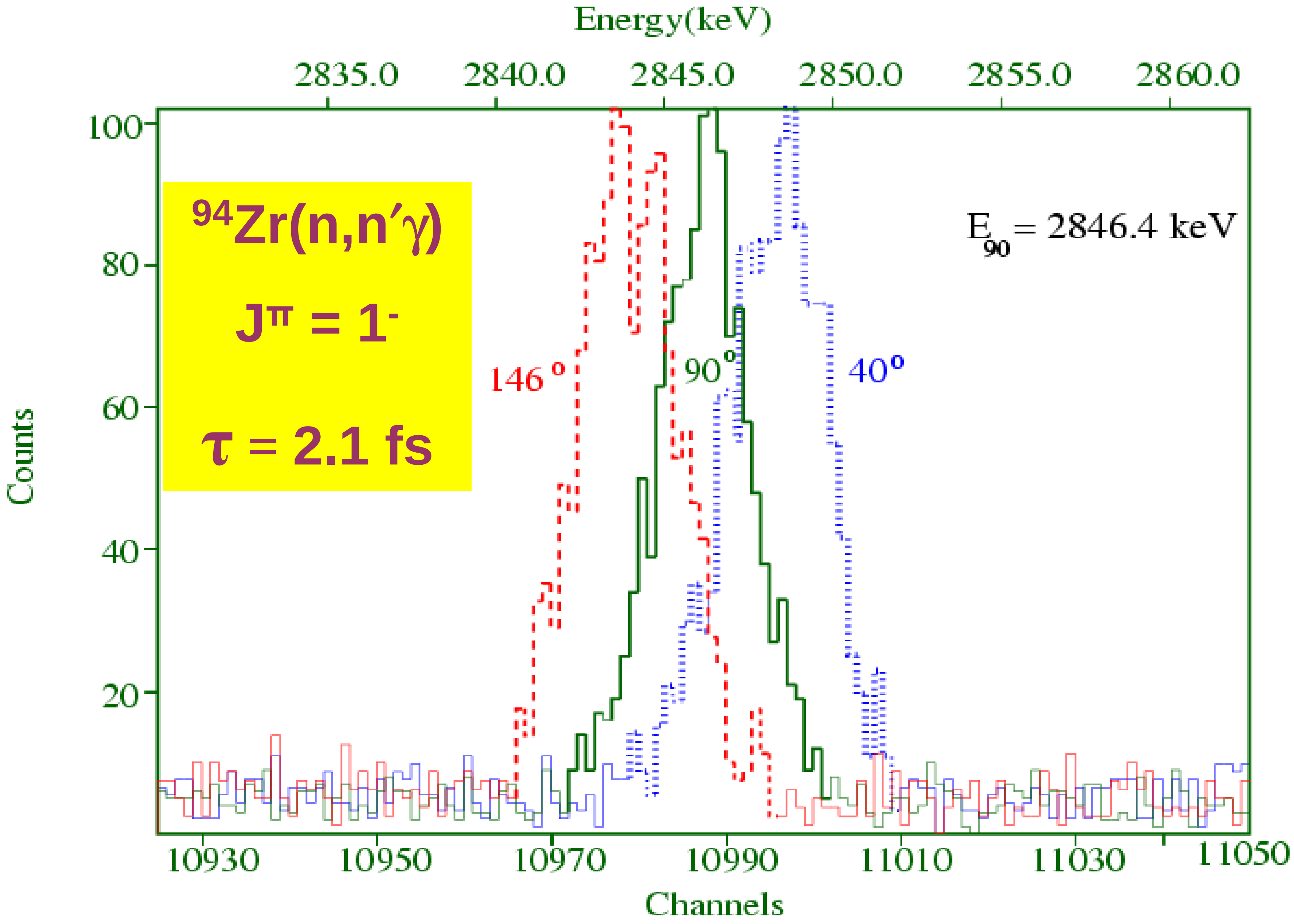


$$E(\theta) = E_\gamma (1 + v/c \cos \theta)$$

The nucleus is recoiling into a viscous medium.

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

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

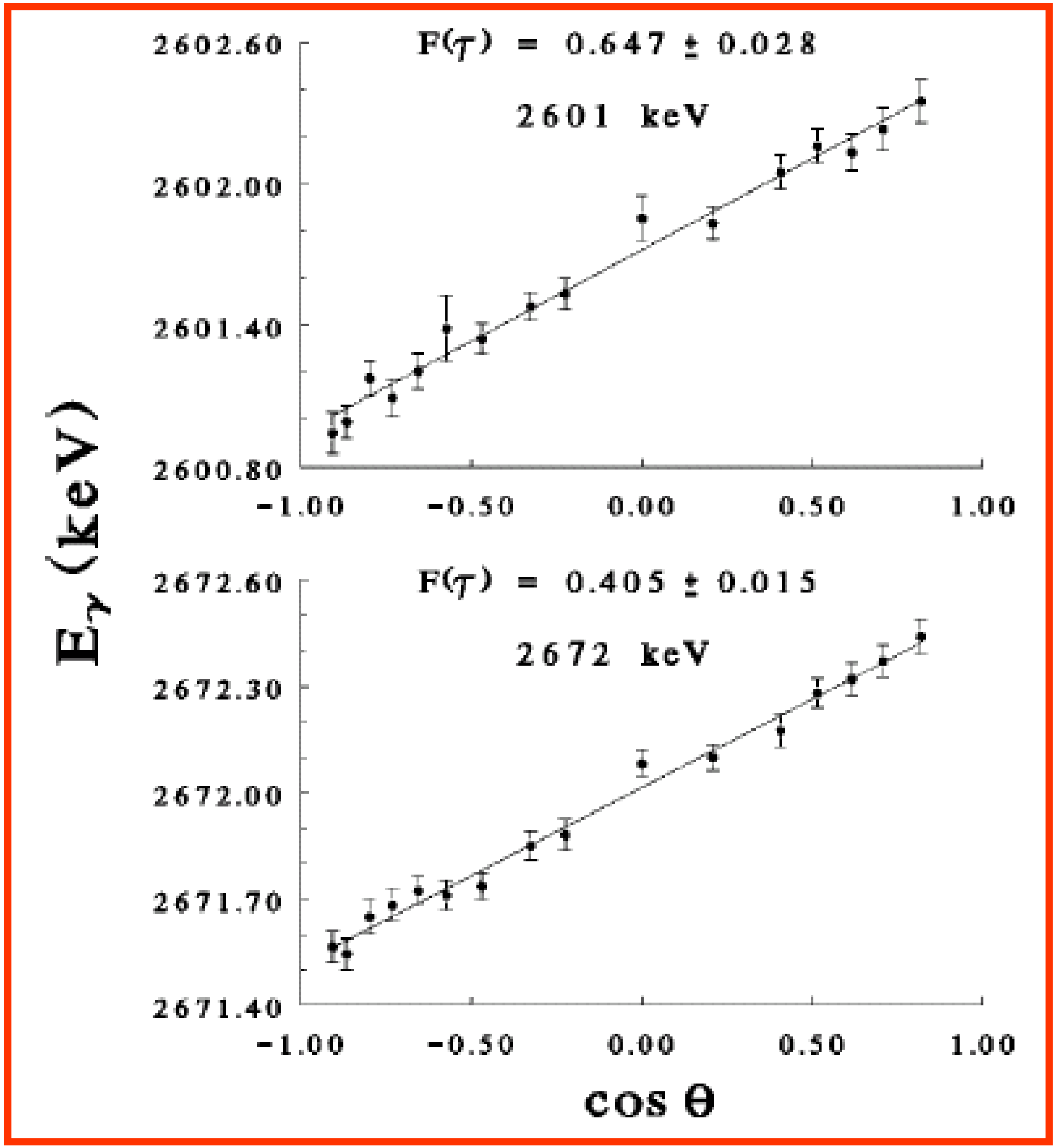


^{94}Zr(n,n′γ)

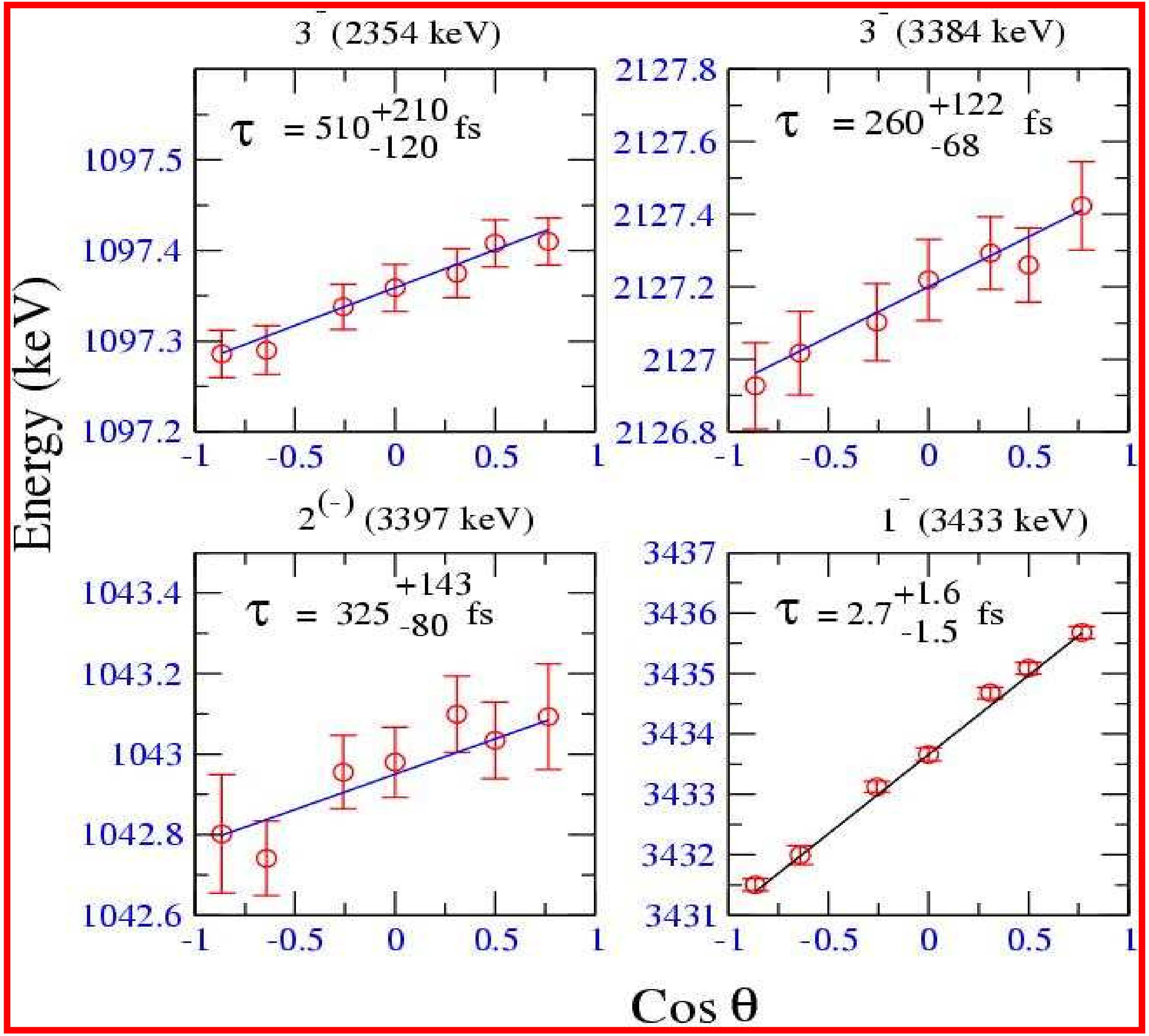
$J^{\pi} = 1^{-}$

$\tau = 2.1$ fs

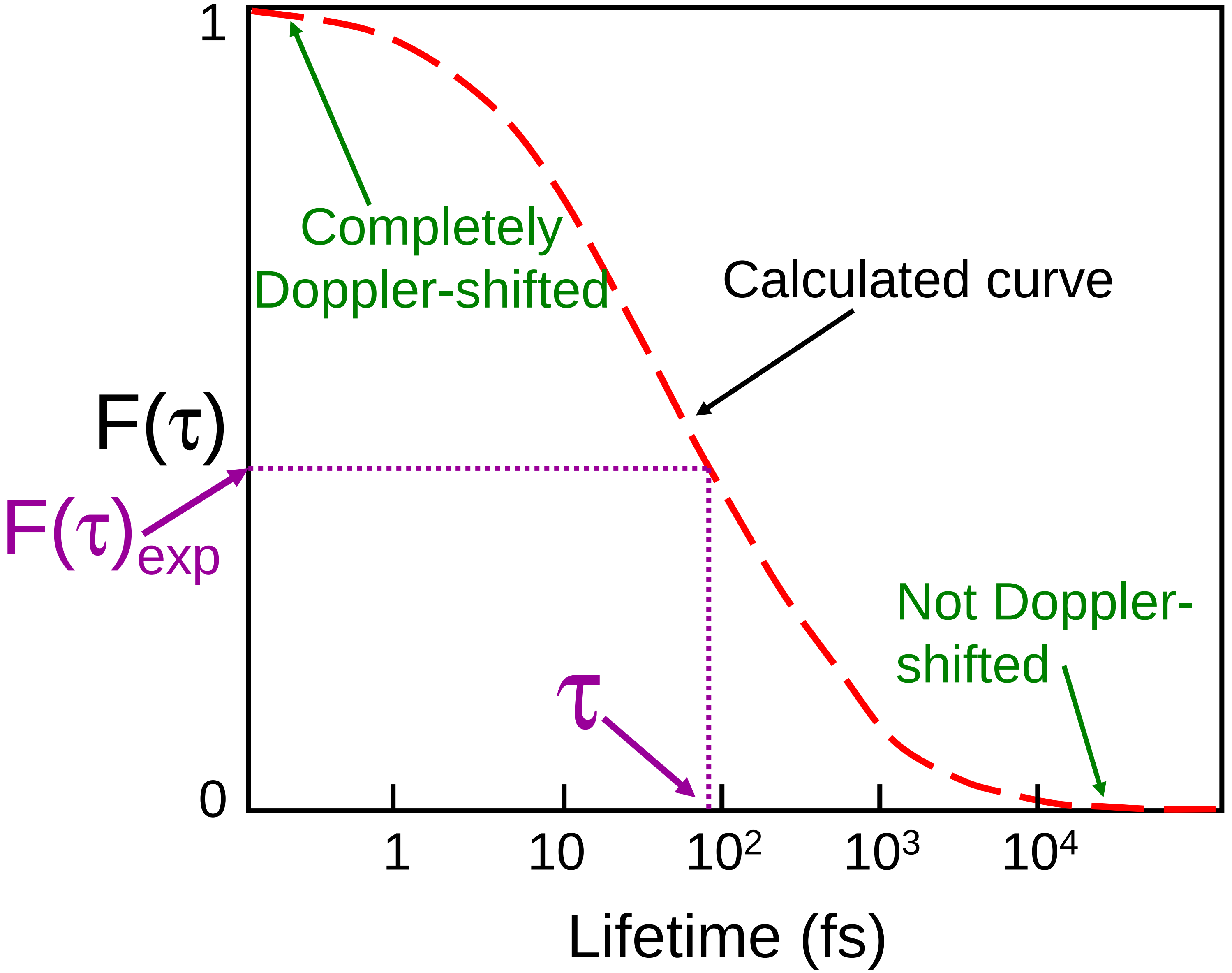
M. Yeh *et al.*, Phys. Rev. C **57**, R2085 (1998)



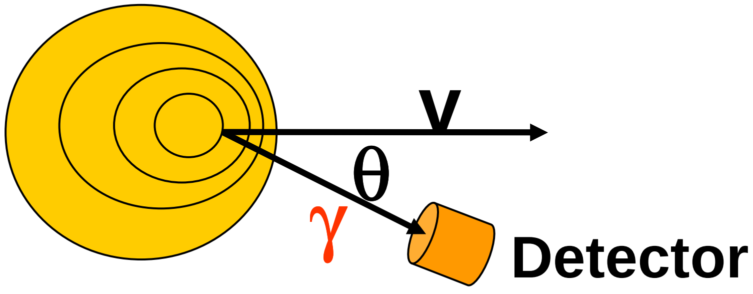
$E(\theta) = E\gamma\,(1 + F(\tau)\, v/c \cos\theta)$



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



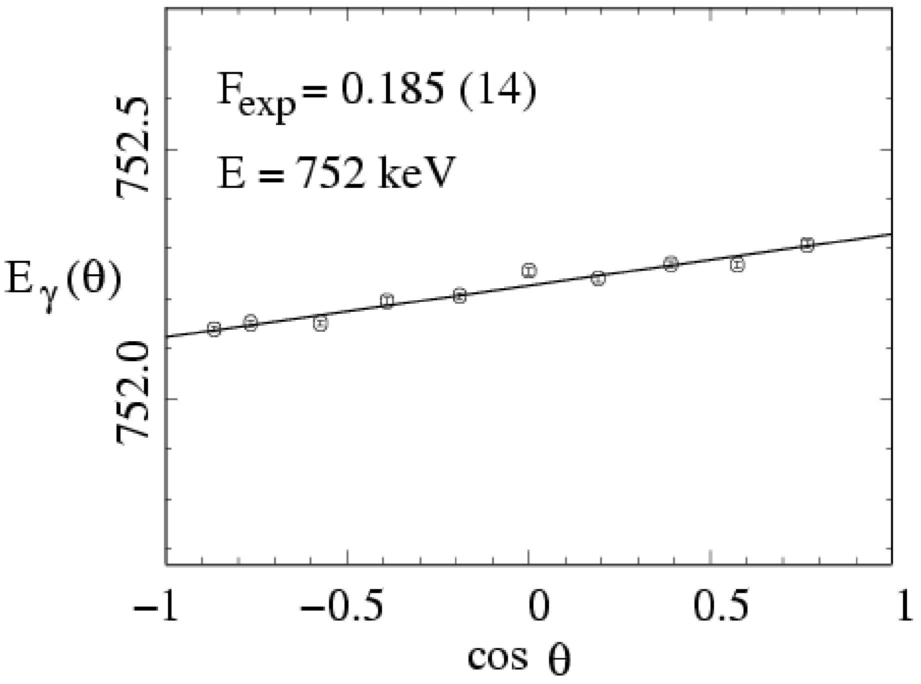
DSAM Lifetimes

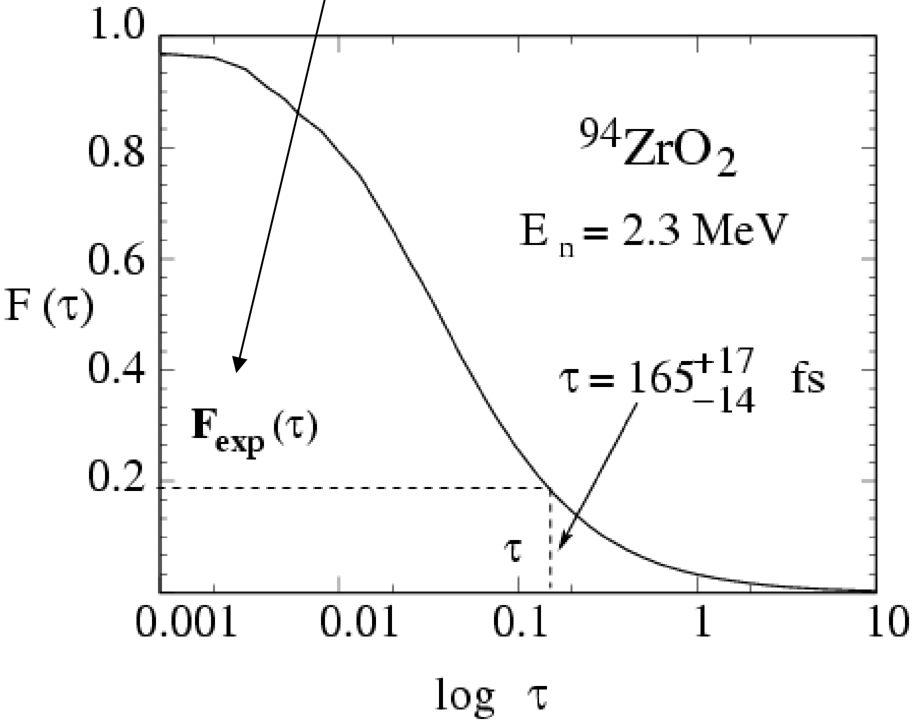


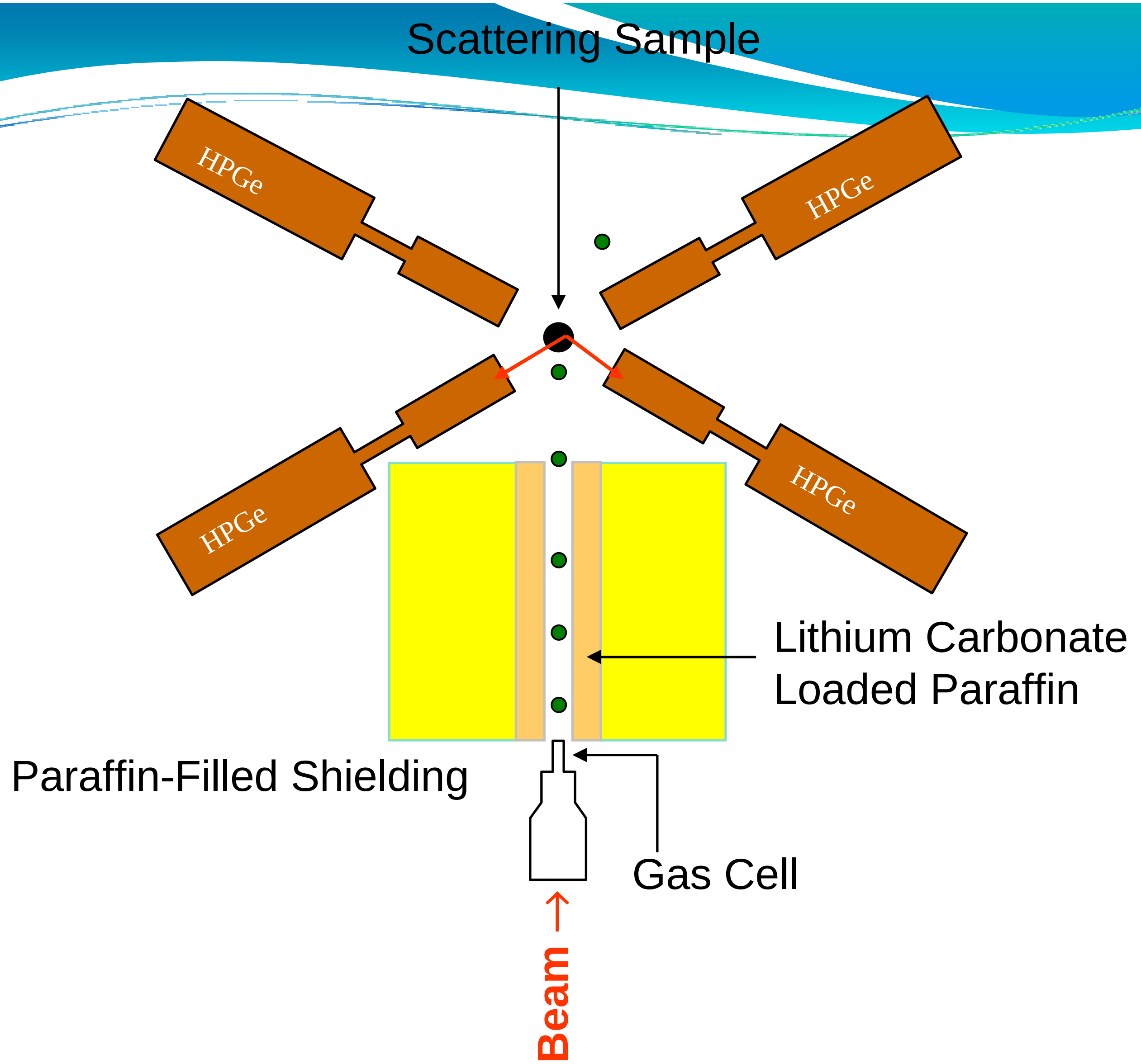
$$E_\gamma(\theta) = E_\gamma\,(1 + v/c \cos\theta)$$

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

$$E_\gamma(\theta) = E_\gamma\,(1 + F(\tau)\, v_{cm}/c \cos\theta)$$

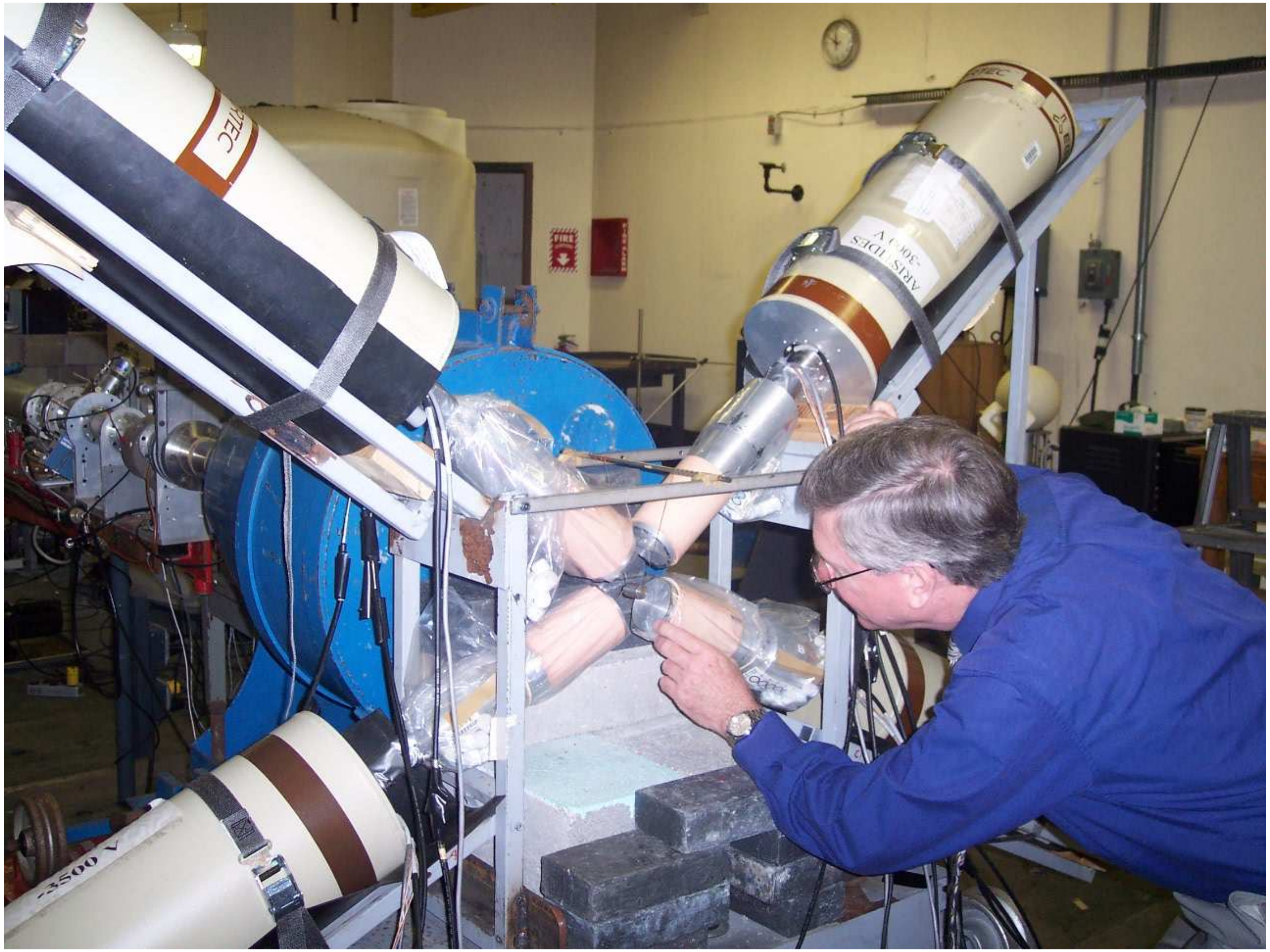






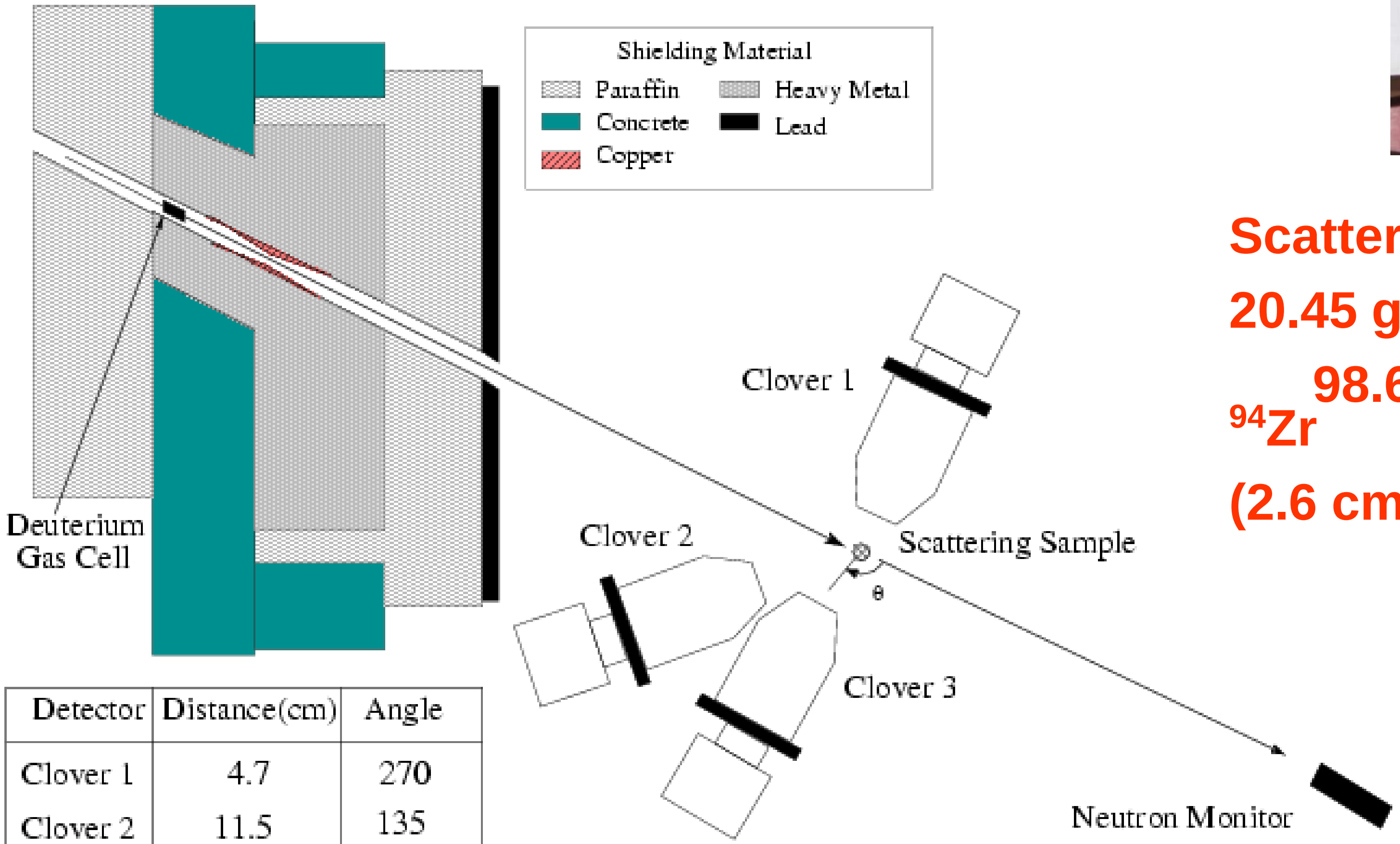
Kentucky Gamma-ray Spectrometer
KEGS

KEGS

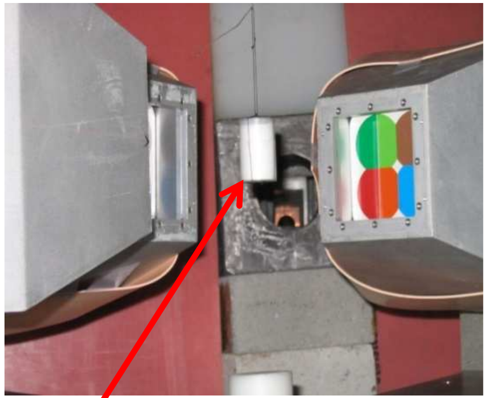


Coincidence Measurements at TUNL

3 Compton-suppressed clover detectors



Detector	Distance(cm)	Angle
Clover 1	4.7	270
Clover 2	11.5	135
Clover 3	5.8	118



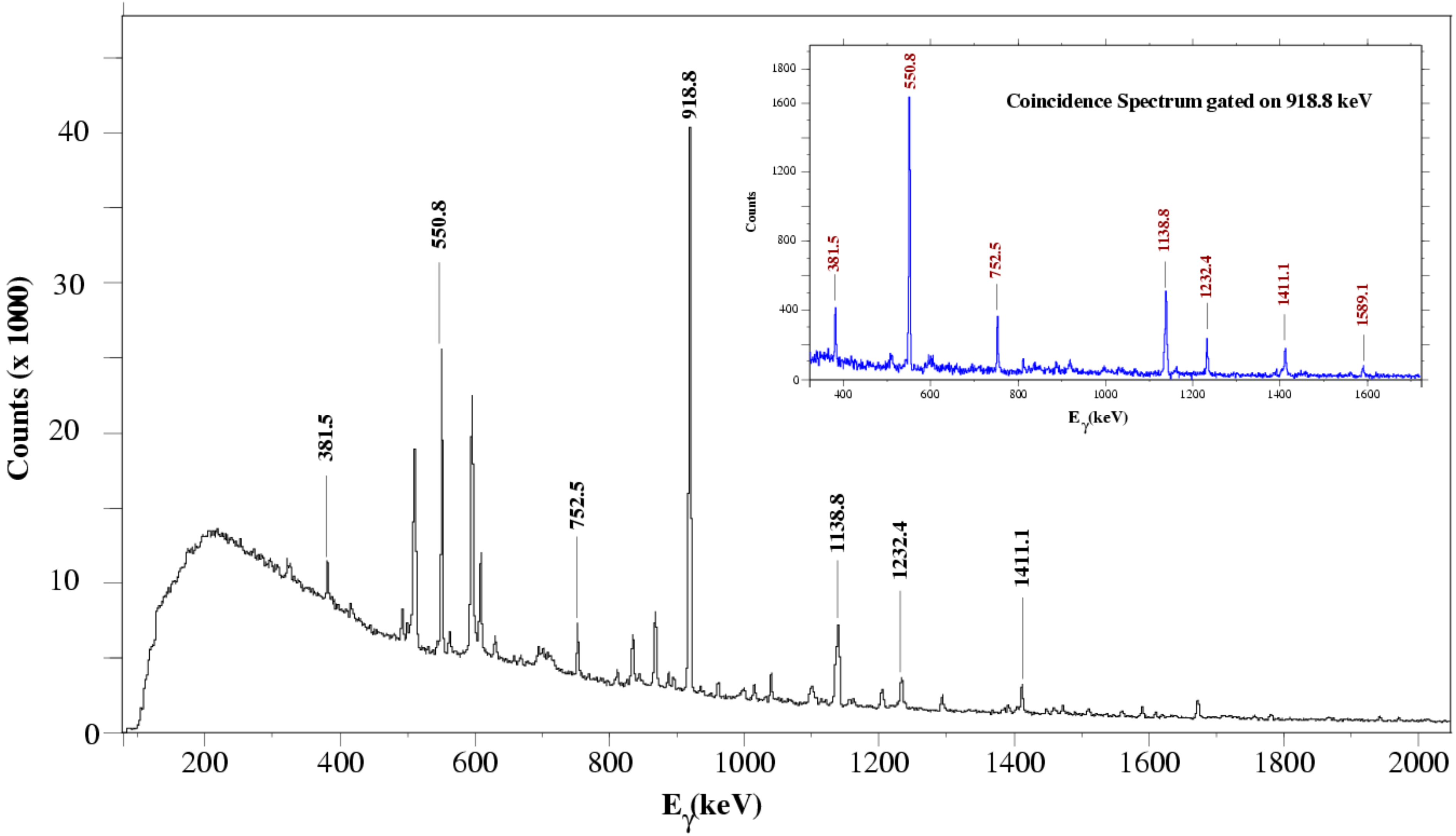
Scattering Sample:

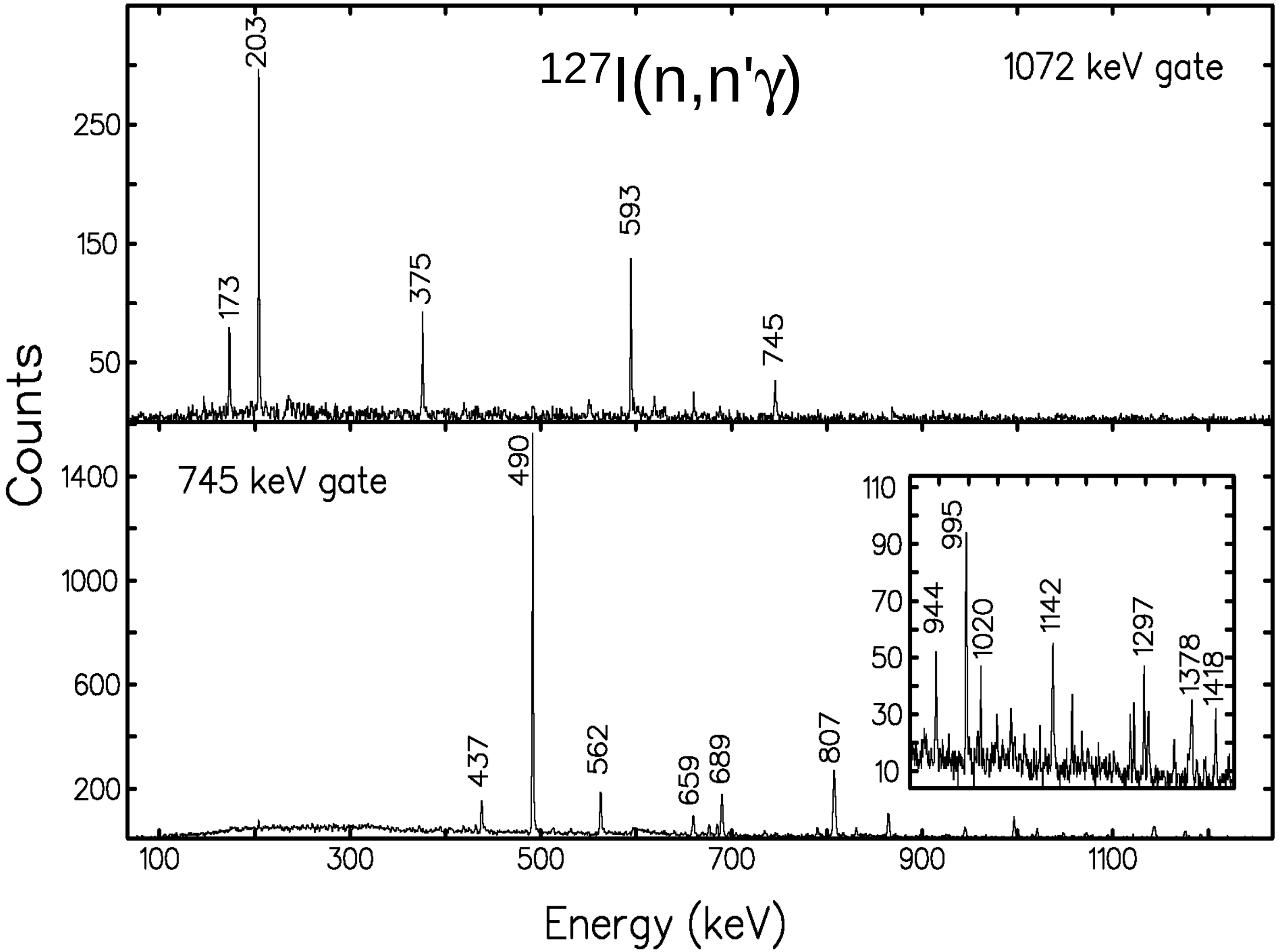
20.45 g of ZrO_2 powder

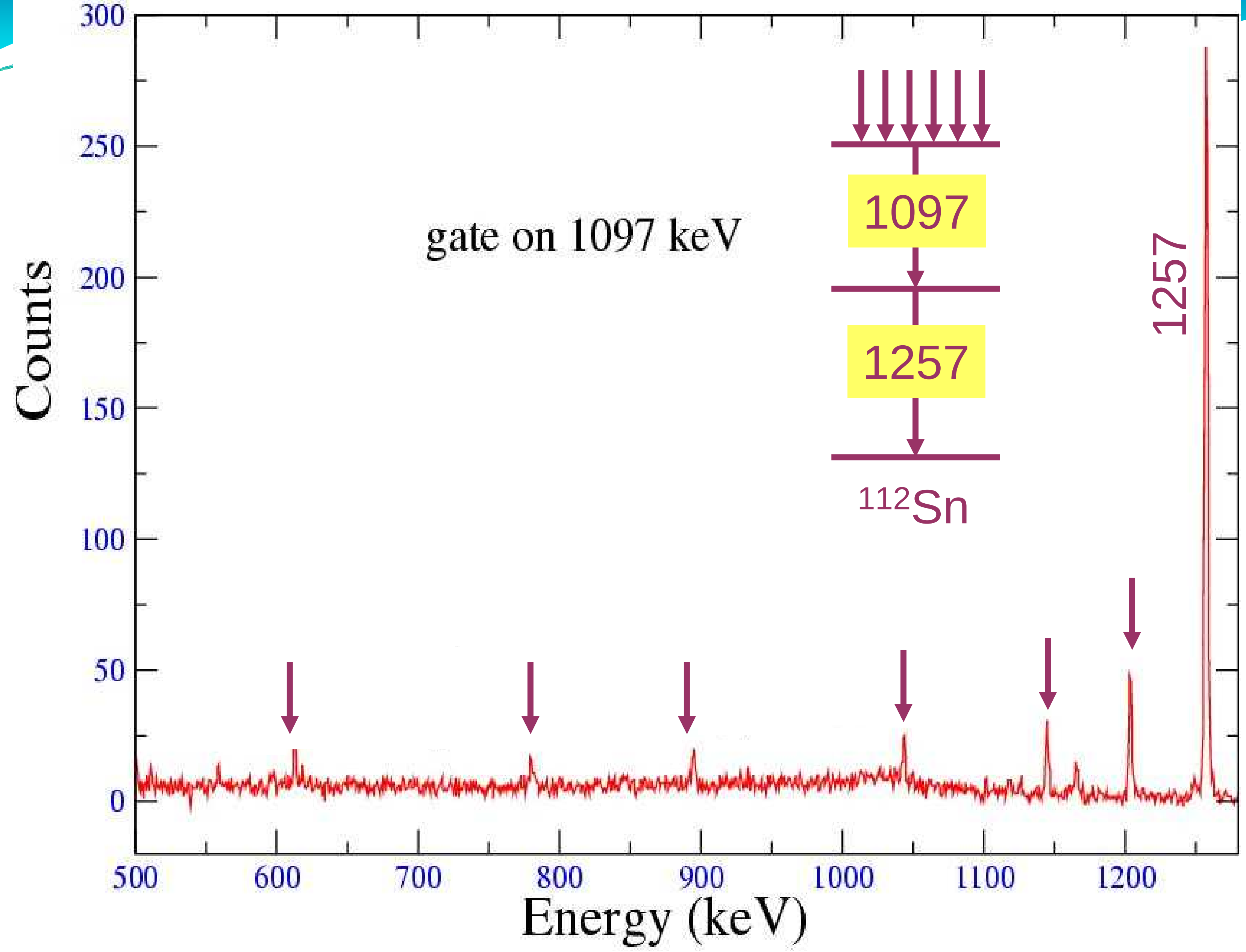
98.6% enriched in ^{94}Zr

(2.6 cm x 3.9 cm)

^{94}Zr(n,n'γγ) Spectra



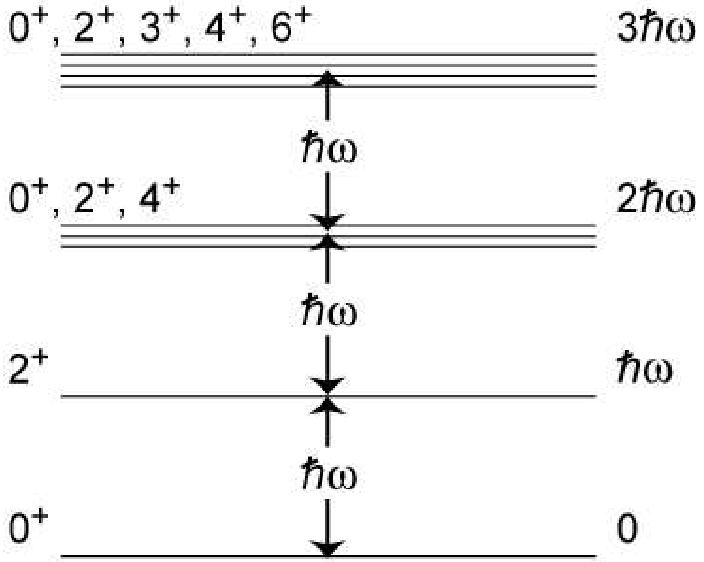

^{127}I(n,n'γ)
1072 keV gate
745 keV gate
Counts
Energy (keV)
250
150
50
1400
1000
600
200
100
300
500
700
900
1100
203
173
375
593
745
490
437
562
659
689
807
110
90
70
50
30
10
995
944
1020
1142
1297
1378
1418

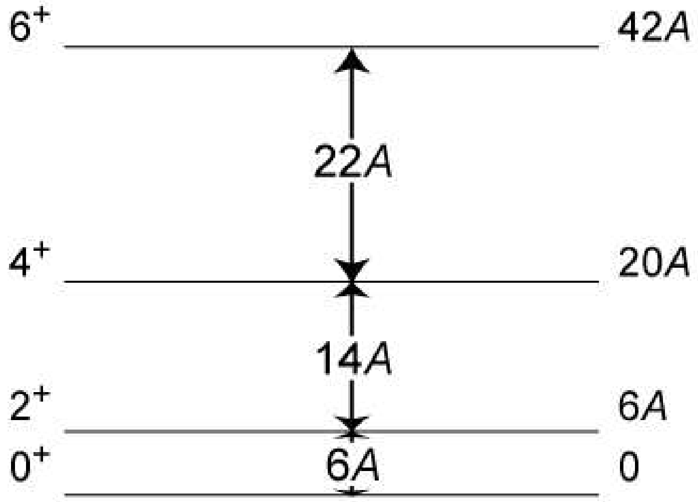

gate on 1097 keV
1097
1257
^{112}Sn
1257
Counts
Energy (keV)
300
250
200
150
100
50
0
500
600
700
800
900
1000
1100
1200

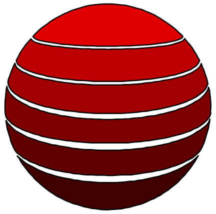
Inelastic Neutron Scattering

- ☞ No Coulomb barrier/variable neutron energies
- ☞ Good energy resolution (γ rays detected)
- ☞ Nonselective, but limited by angular momentum
- ☞ Lifetimes by Doppler-shift attenuation method
  Belgya, Molnár, and Yates, Nucl. Phys. **A607**, 43 (1996)
  (feeding-time problem minimized)
- ☞ Gamma-gamma coincidence measurements
  McGrath *et al*., Nucl. Instrum. Meth. **A421**, 458 (1999)
  Elhami *et al*., Phys. Rev. C **78**, 064303 (2008).
- 👎 Limited to stable nuclei
- 👎 Large amounts of enriched isotopes required

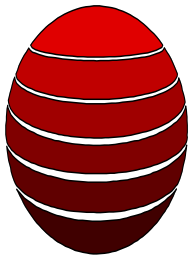
Collective Structures







$$\frac{E(4^+)}{E(2^+)} = 2.0$$



$$\frac{E(4^+)}{E(2^+)} = 3.333$$

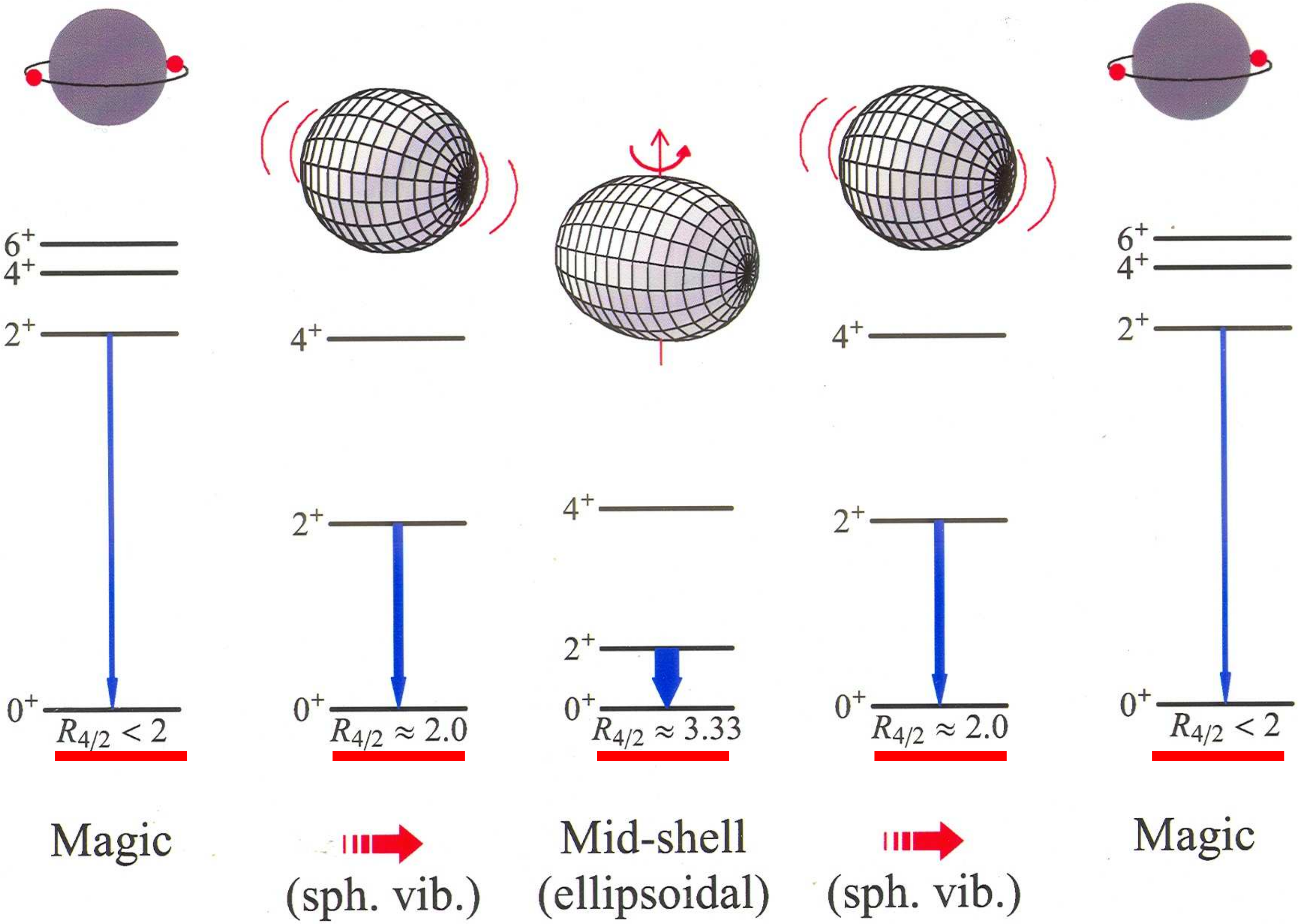
Spherical (Vibrational)

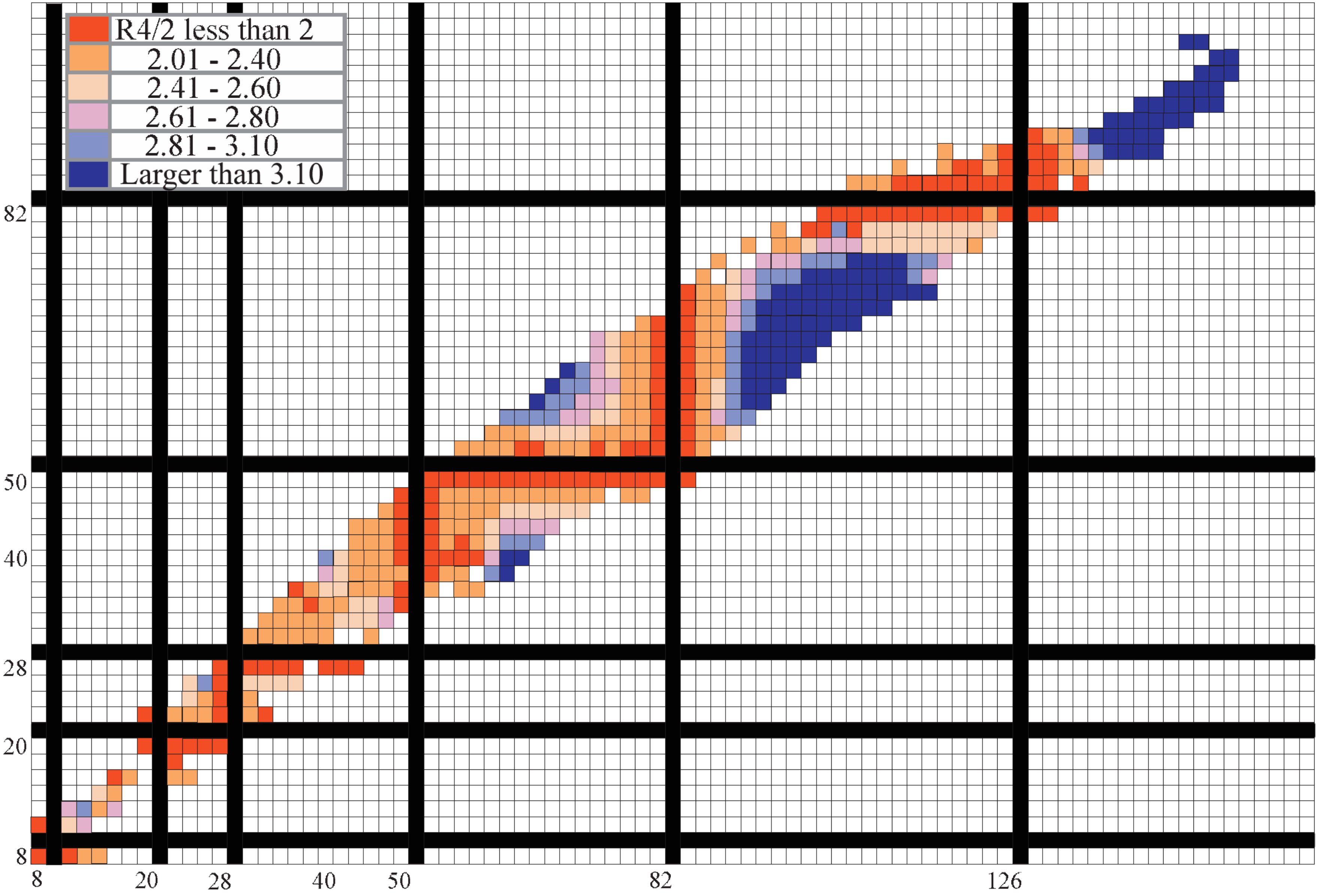
$E = n\hbar\omega$

Deformed (Rotational)

$E = I(I+1)\hbar^2/2\mathcal{I}$

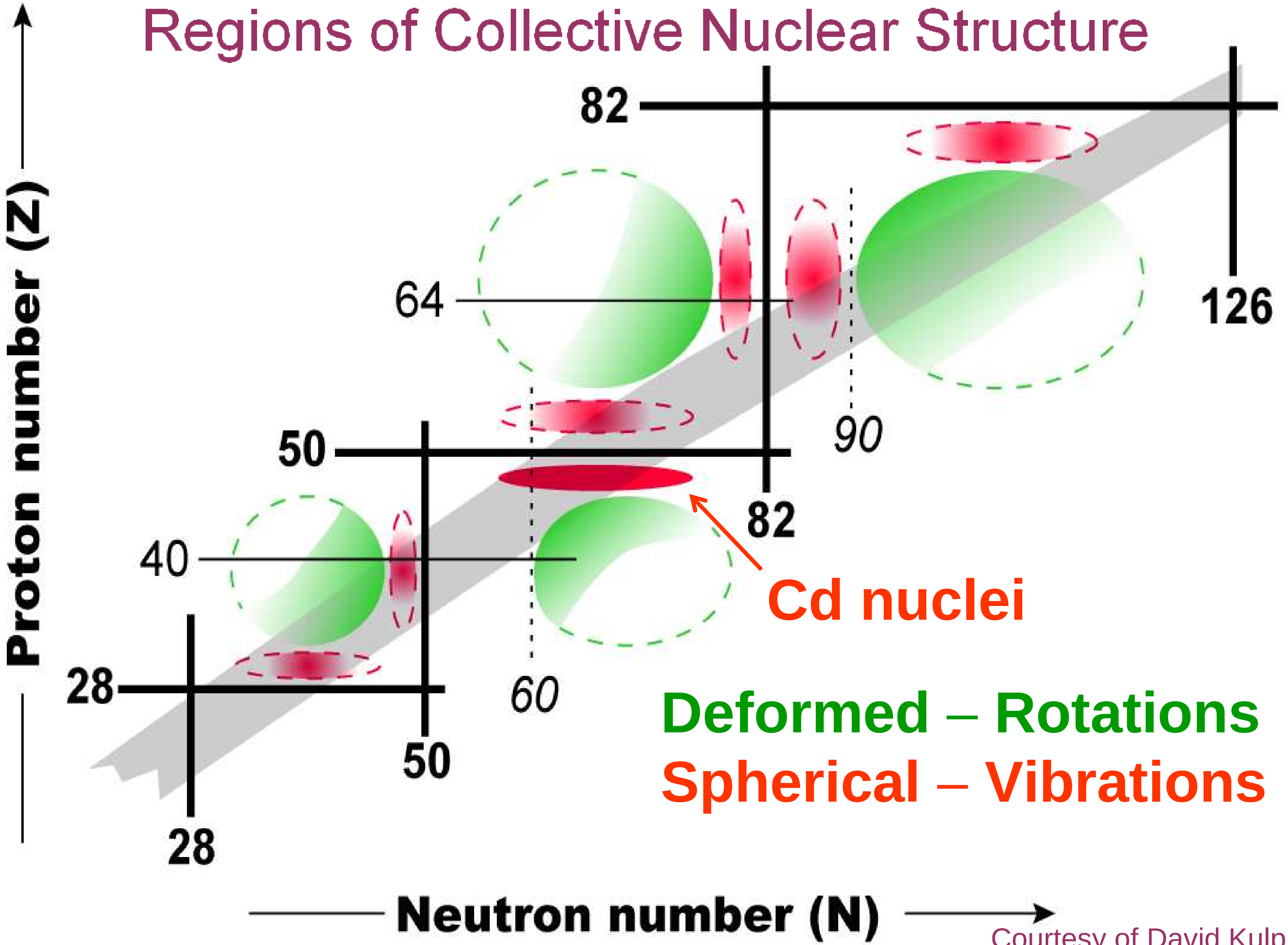
Evolution of nuclear structure
(as a function of nucleon number)





R(E(4$^+$) / E(2$^+$)) Systematics plot from Burcu Cakirli

Regions of Collective Nuclear Structure

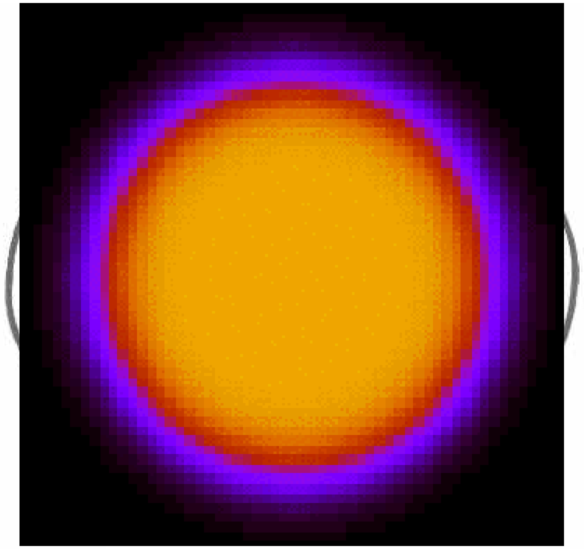


Cd nuclei

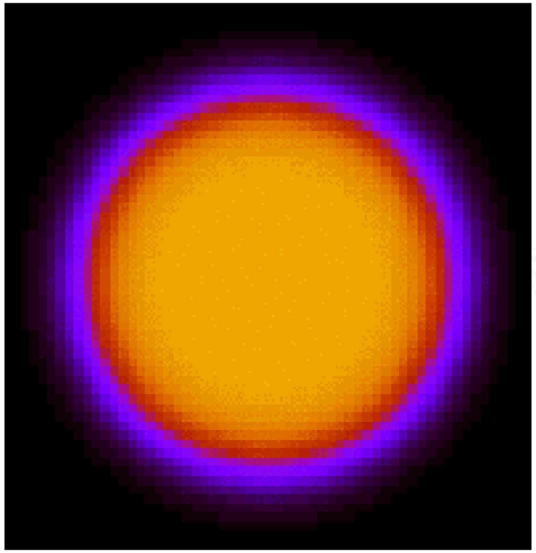
Deformed – Rotations

Spherical – Vibrations

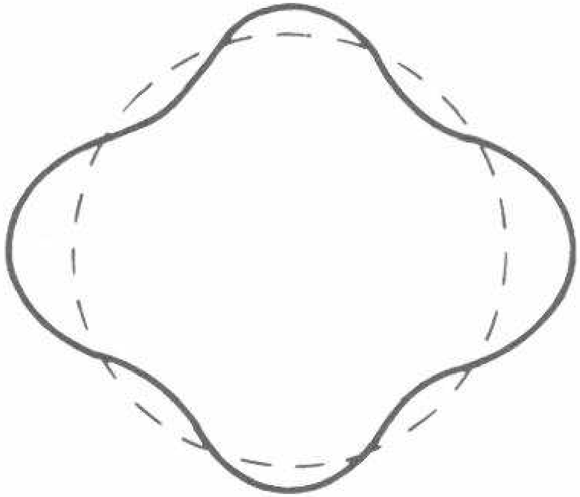
Courtesy of David Kulp



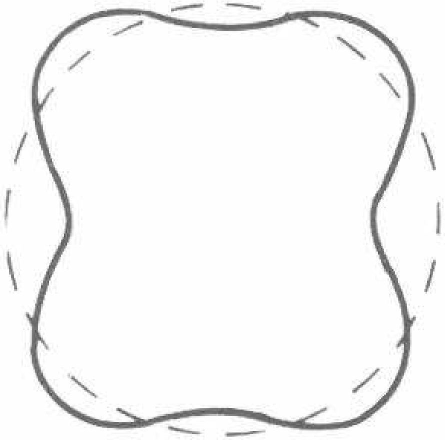
Quadrupole



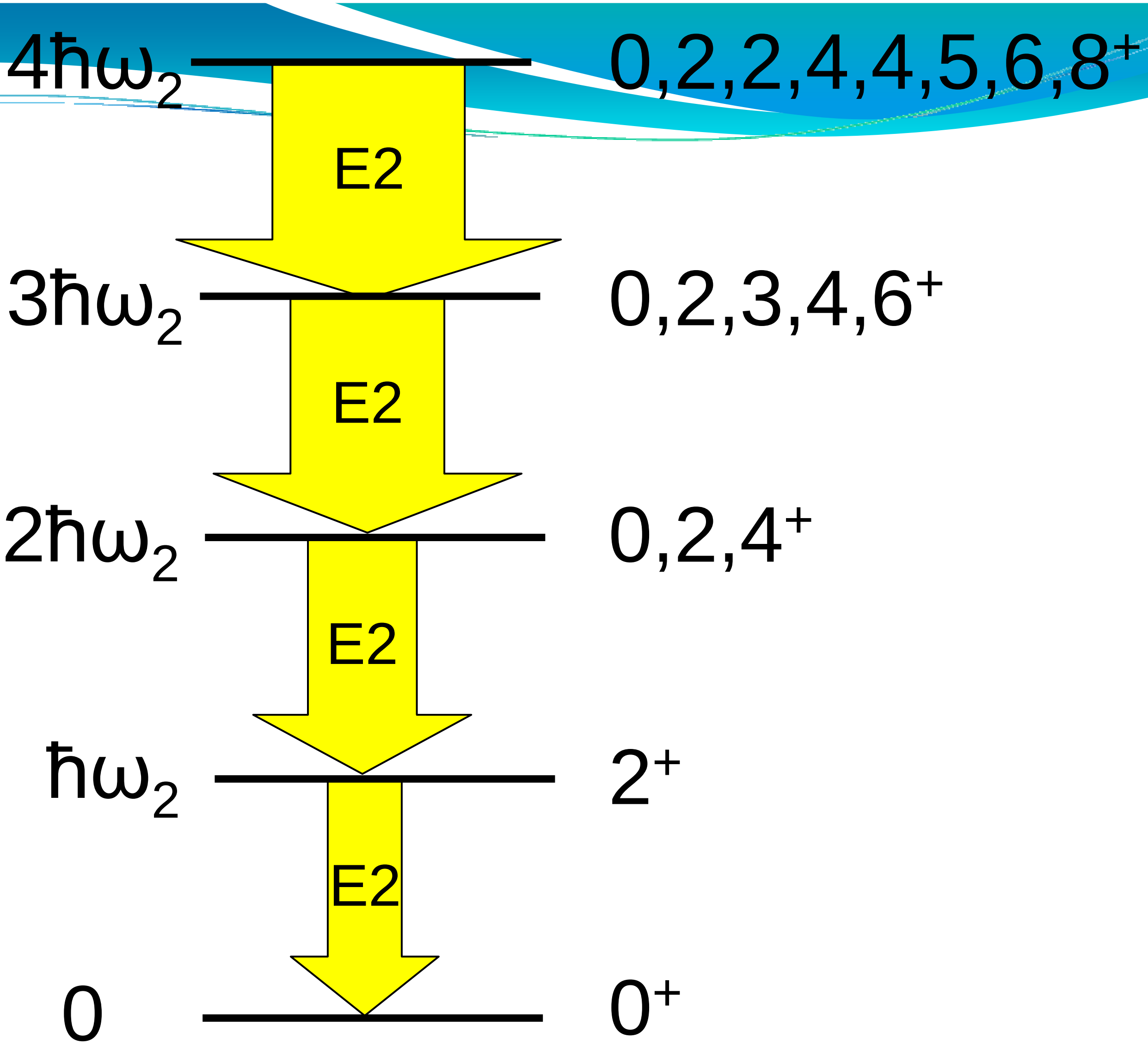
Octupole



Hexadecapole



Hexadecapole



$4\hbar\omega_2$ $0,2,2,4,4,5,6,8^+$

E2

$3\hbar\omega_2$ $0,2,3,4,6^+$

E2

$2\hbar\omega_2$ $0,2,4^+$

E2

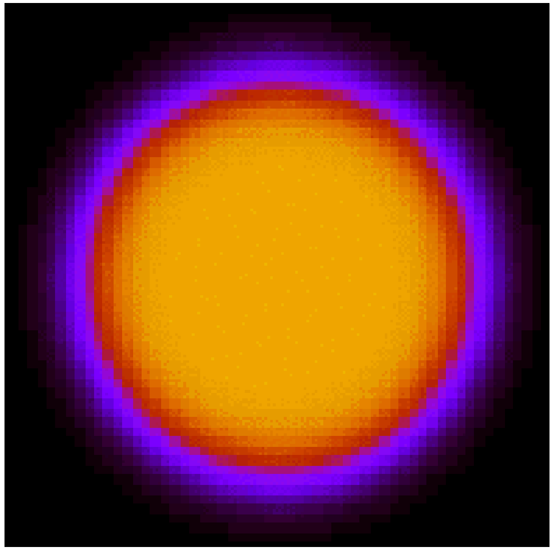
$\hbar\omega_2$ 2^+

E2

0 0^+

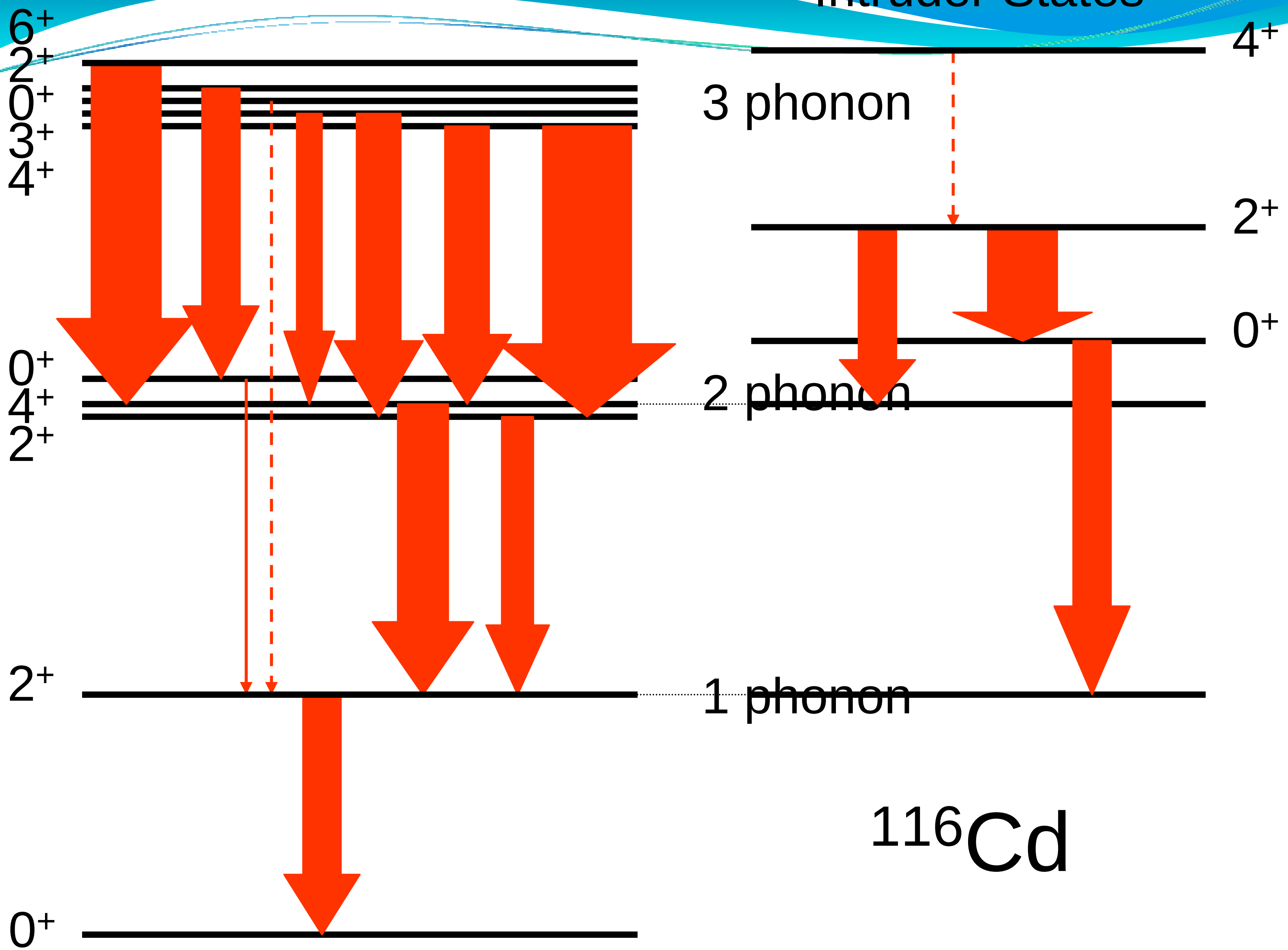
Quadrupole
Vibrations

$\Delta n = \pm 1$



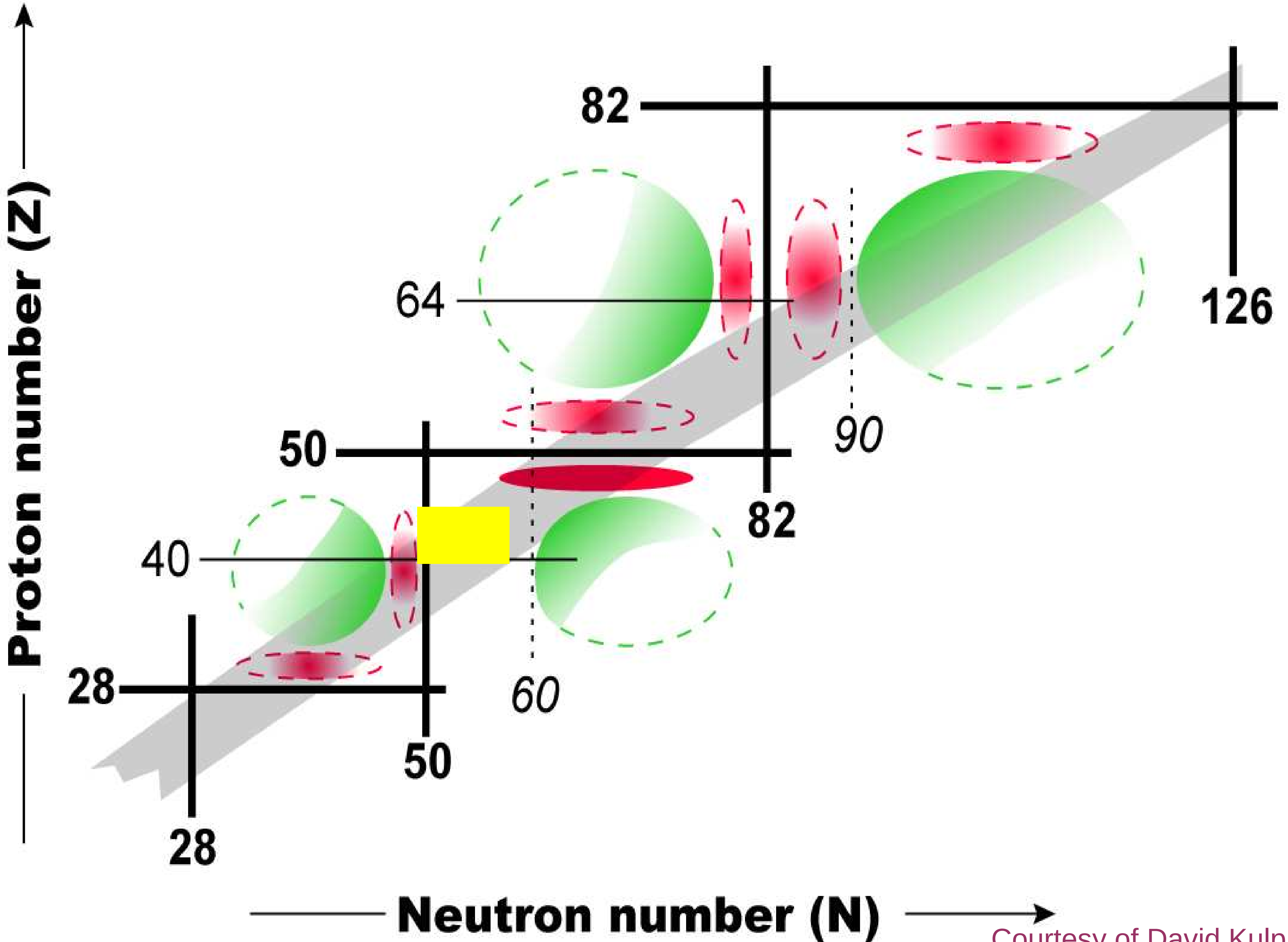
Courtesy of M. Itoh and Y. Fujita

Intruder States



^{116}Cd

M. Kadi *et al*., Phys. Rev. C **68**, 031306(R), 2003



Courtesy of David Kulp

↑ Z

44			^{96}Ru		^{98}Ru	^{99}Ru	^{100}Ru
42	^{92}Mo		^{94}Mo	^{95}Mo	^{96}Mo	^{97}Mo	^{98}Mo
			^{93}Nb				
40	^{90}Zr	^{91}Zr	^{92}Zr		^{94}Zr		^{96}Zr
	50		52		54		56

N →

$B(E2;2_1^+ \rightarrow 0_1^+)$ in W.u.

↑ Z							
44			^{96}Ru 18.1		^{98}Ru 32.5	^{99}Ru	^{100}Ru 35.6
42	^{92}Mo 8.4		^{94}Mo 15.4	^{95}Mo	^{96}Mo 20.7	^{97}Mo	^{98}Mo 19.8
			^{93}Nb				
40	^{90}Zr 5.4	^{91}Zr	^{92}Zr 6.4		^{94}Zr 4.9		^{96}Zr 4
	50		52		54		56

N →

Mixed-Symmetry States

Predicted by IBM-2

Symmetric States: Q_S

Mixed-Symmetry (MS) States: Q_m

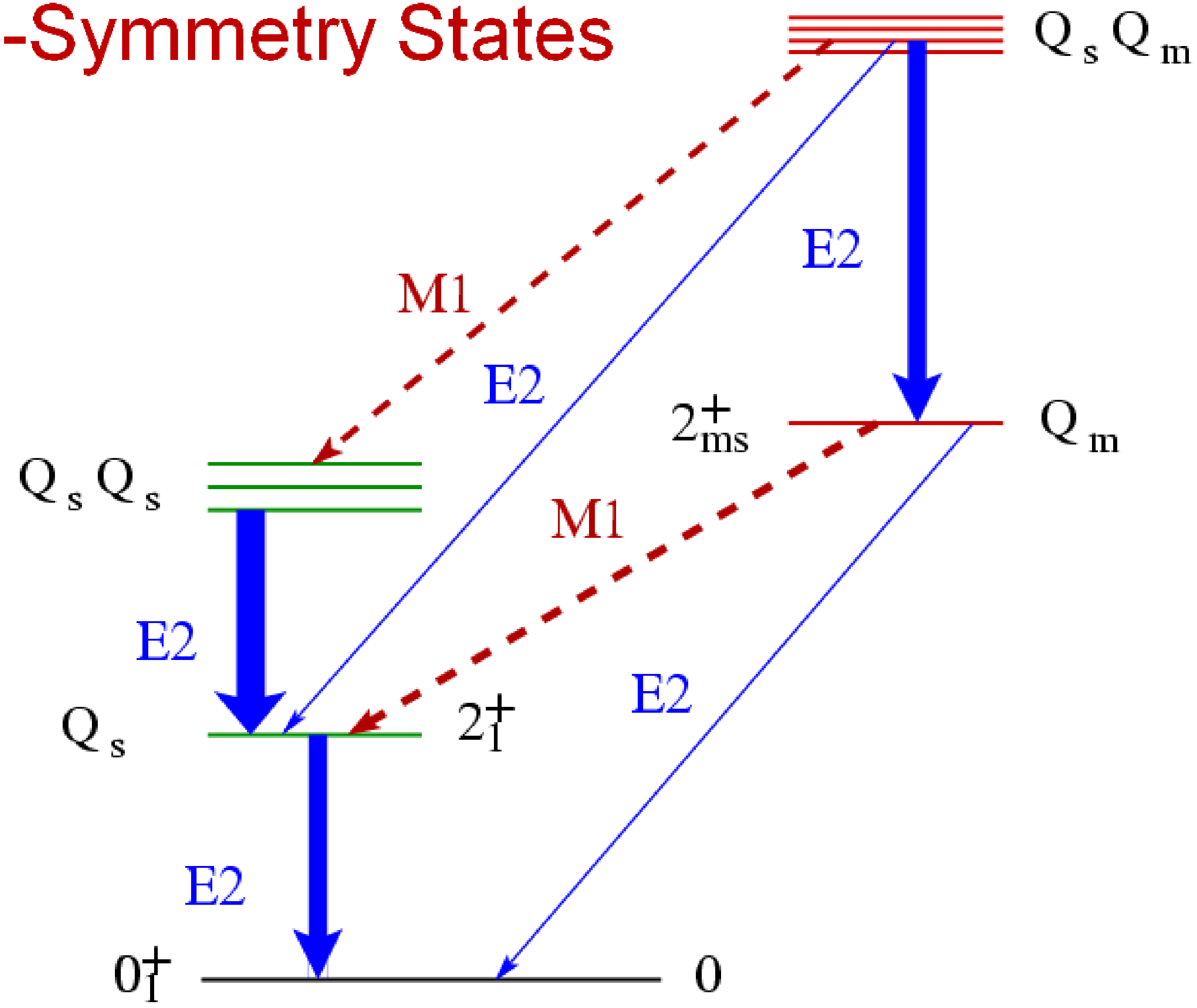
Experimental Observables for MS States

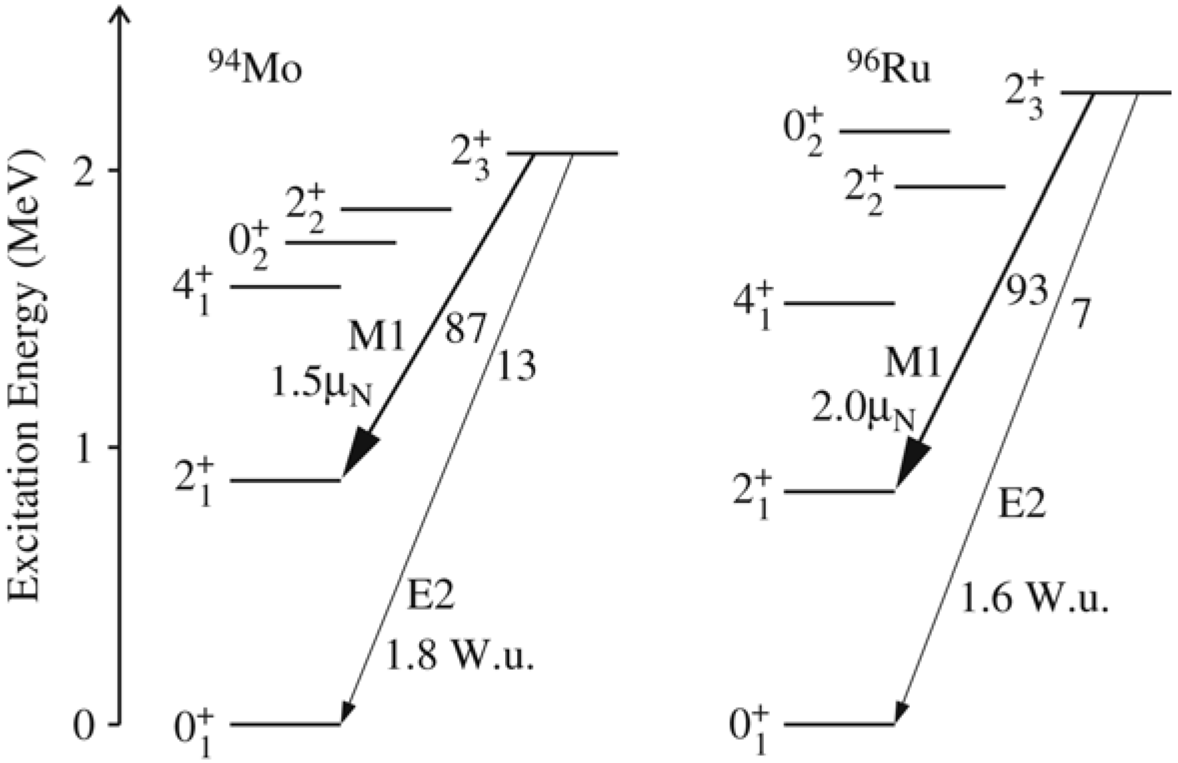
Low-lying 2^+ state in weakly deformed nucleus

Strong M1 transition to the symmetric state of the same phonon order, $B(M1) \sim 1\mu_N^2$

Weakly collective E2 transitions to the symmetric state of lower phonon order

Mixed-Symmetry States





N. Pietralla, P. von Brentano, and A. F. Lisetskiy,
Prog. Part. Nucl. Phys., 60 (2008) 225

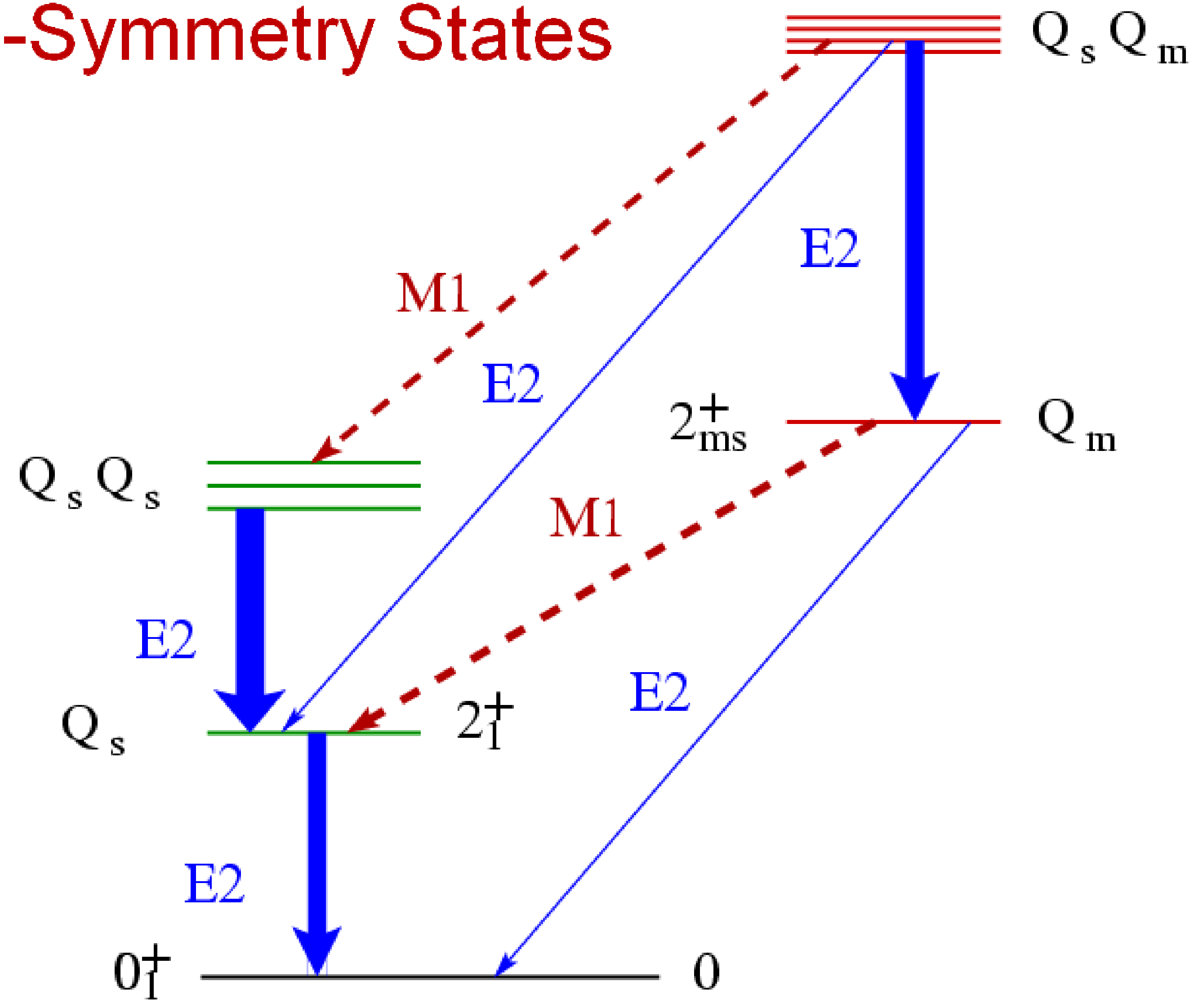
↑ Z

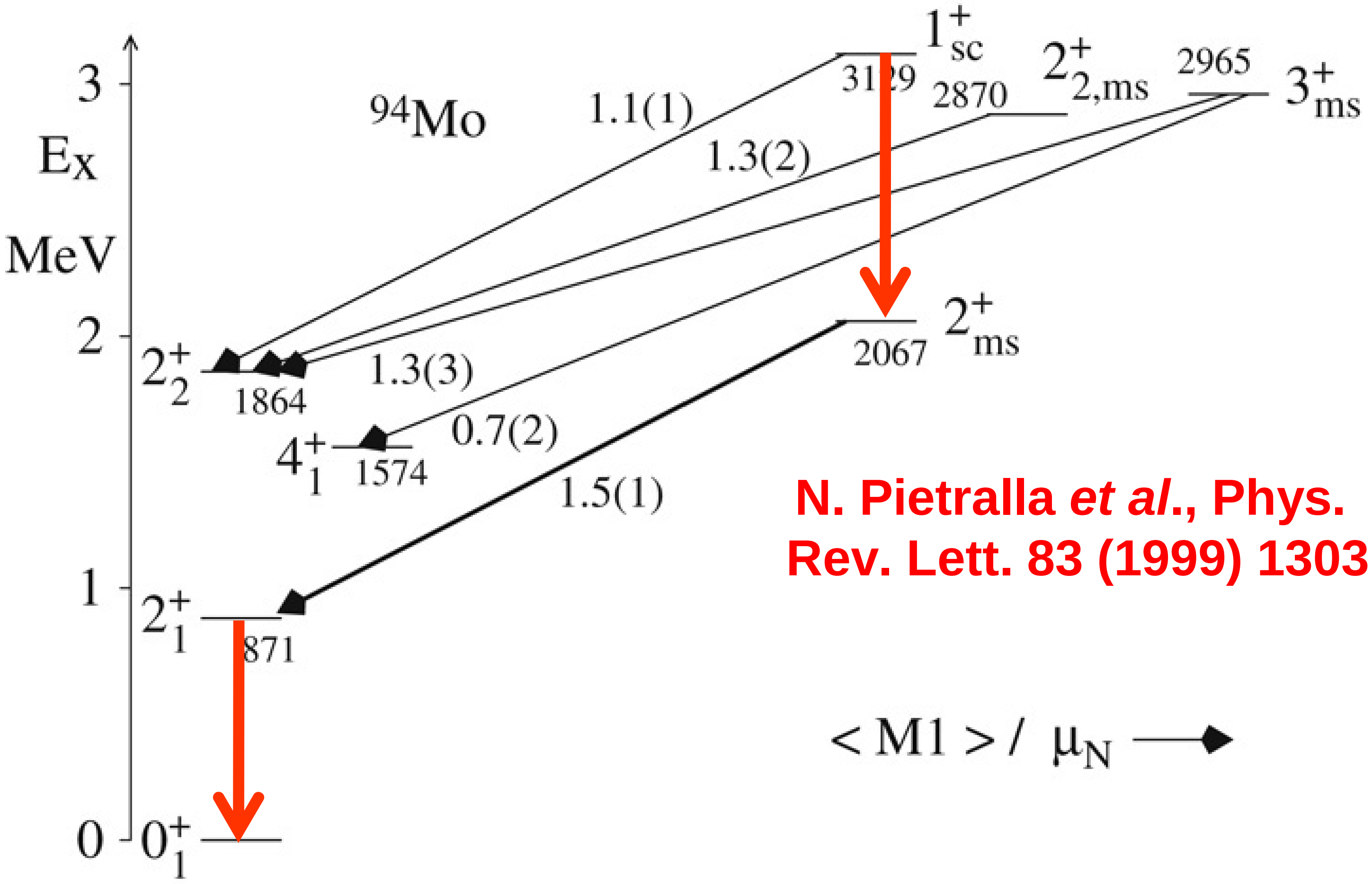
$B(M1;2_{ms}^{+} \rightarrow 2_{1}^{+})$ in μ_N^2

	50		52		54		56
44			^{96}Ru 0.78		^{98}Ru	^{99}Ru	^{100}Ru
42	^{92}Mo		^{94}Mo 0.56	^{95}Mo	^{96}Mo 0.17	^{97}Mo	^{98}Mo
			^{93}Nb				
40	^{90}Zr	^{91}Zr	^{92}Zr 0.37		^{94}Zr 0.31		^{96}Zr

N →

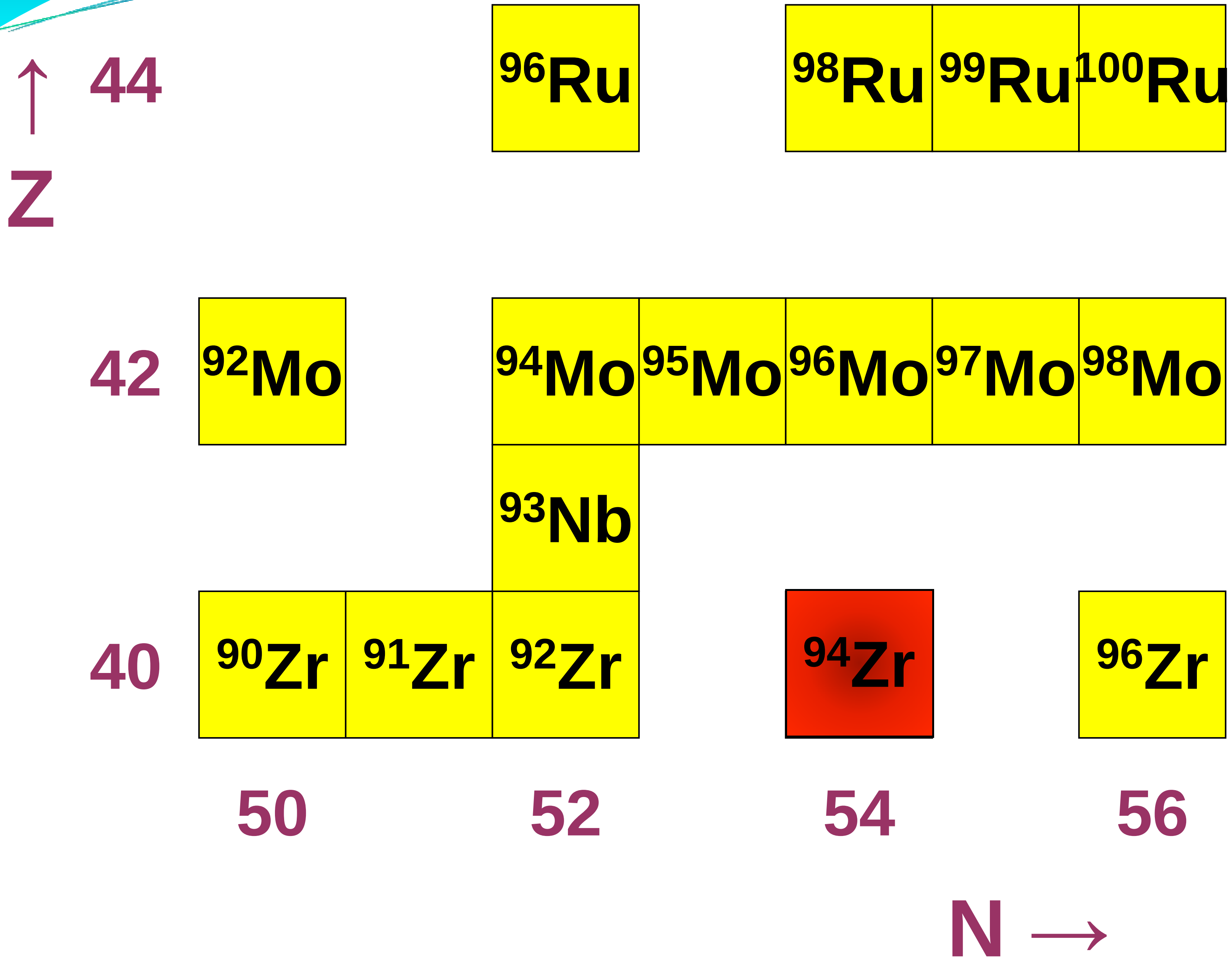
Mixed-Symmetry States





N. Pietralla *et al.*, Phys. Rev. Lett. 83 (1999) 1303

N. Pietralla, P. von Brentano, and A. F. Lisetskiy, Prog. Part. Nucl. Phys., 60 (2008) 225



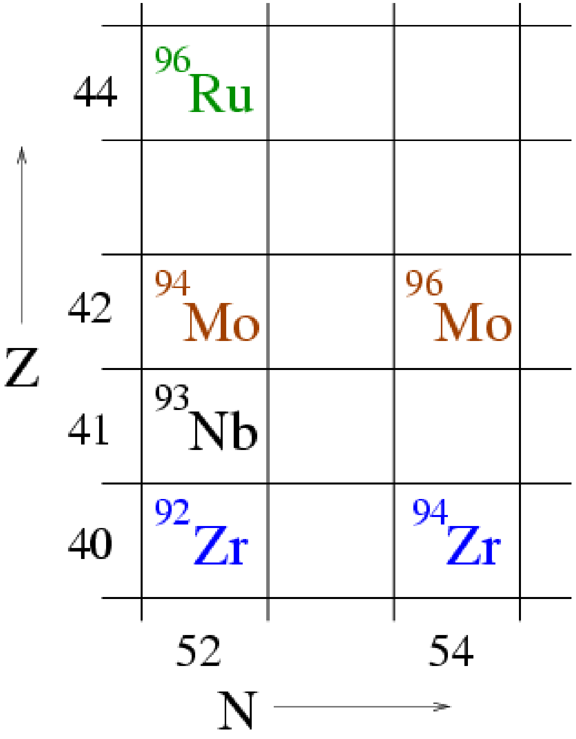
↑ Z

	50		52		54		56
44			^{96}Ru		^{98}Ru	^{99}Ru	^{100}Ru
42	^{92}Mo		^{94}Mo	^{95}Mo	^{96}Mo	^{97}Mo	^{98}Mo
			^{93}Nb				
40	^{90}Zr	^{91}Zr	^{92}Zr		🟥 ^{94}Zr		^{96}Zr

N →

Why study ^{94}Zr?

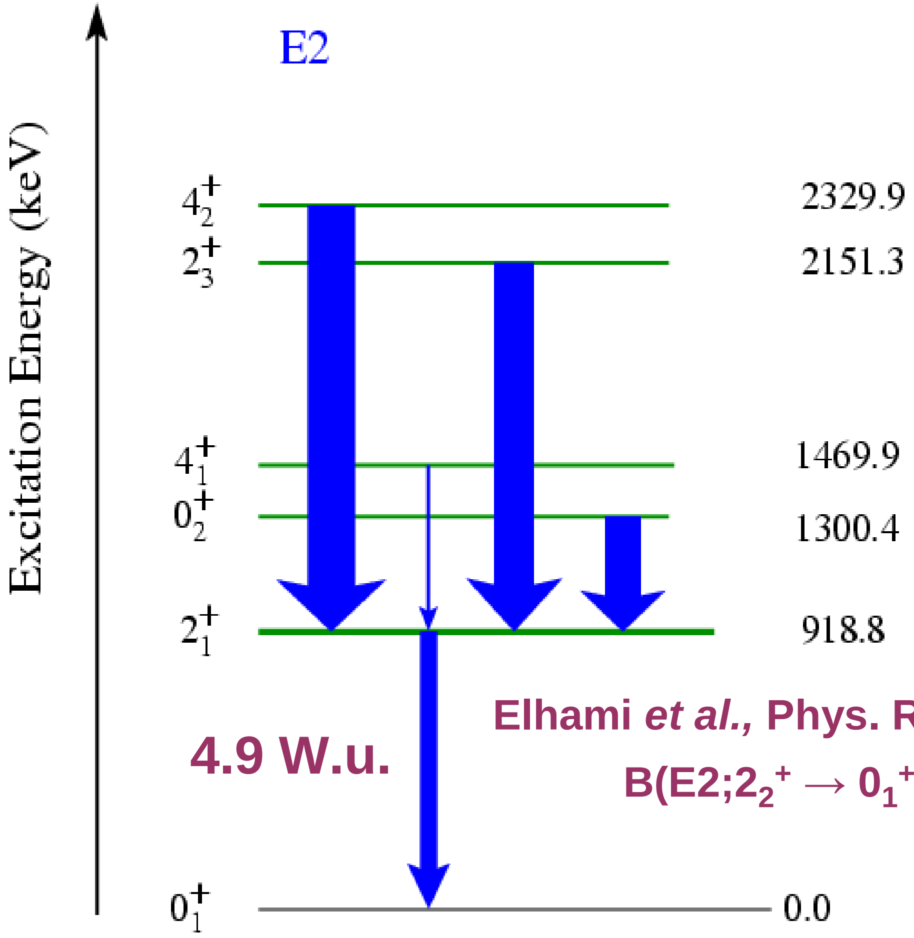
- ❖ **MS states have been observed in neighboring nuclei (N=52). How do they evolve in this region, *e.g.*, in N=54 nuclei?**
- ❖ **The (n,n'γ) reaction is effective in obtaining information on low-lying, low-spin states, *i.e.*, MS states and other collective excitations.**
- ❖ **With lifetimes and other spectroscopic information (δ, BR), absolute transition rates can be obtained.**



Z	52		54
44	^{96}Ru		
42	^{94}Mo		^{96}Mo
41	^{93}Nb		
40	^{92}Zr		^{94}Zr

Symmetric and MS States in ^{94}Zr?

Symmetric States?



$0.31 \pm 0.03\ \mu_N^2$

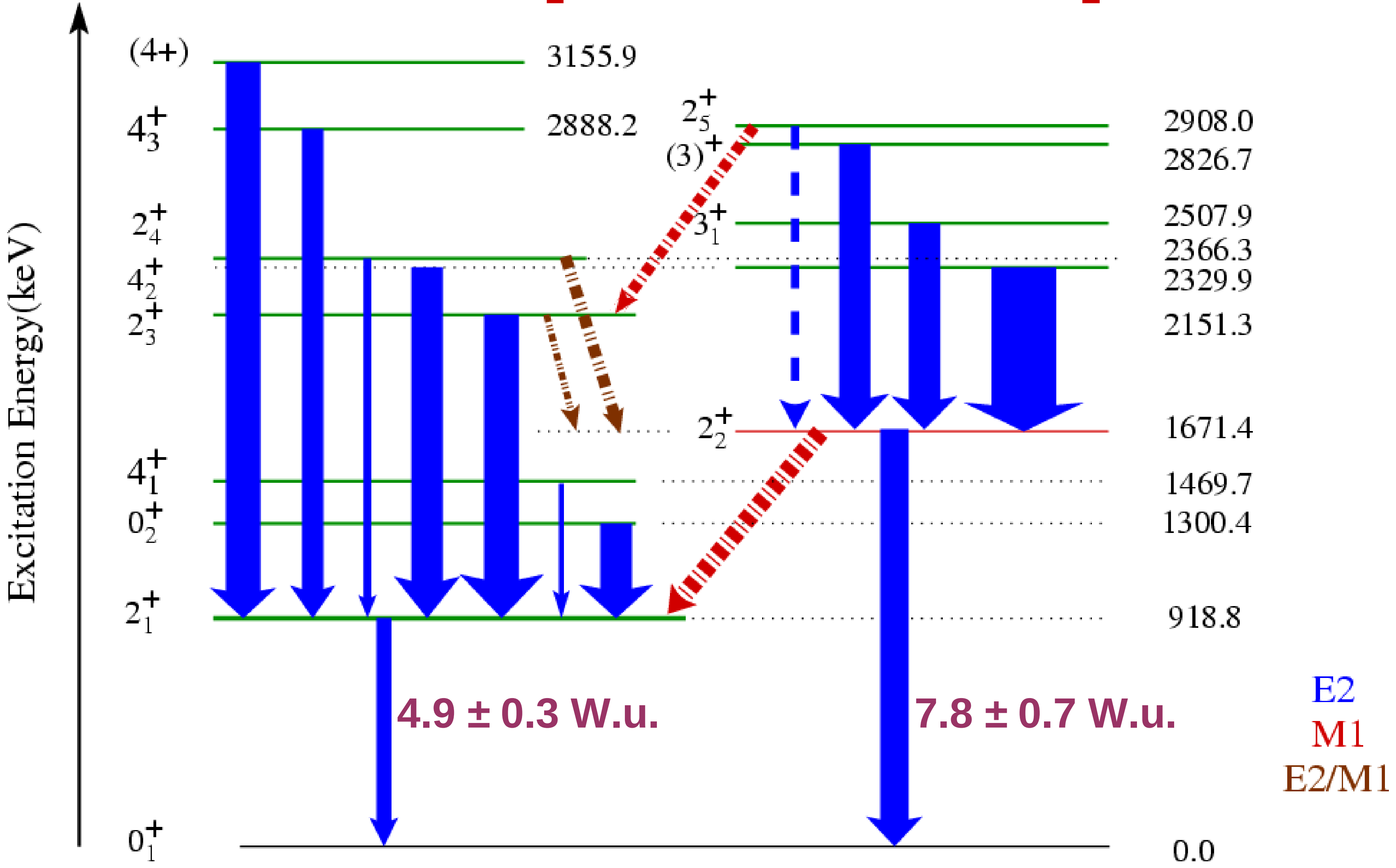
4.9 W.u.

Elhami *et al.*, Phys. Rev. C 75, 011301(R) 2007

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

7.8 W.u.

Transitions to 2_1^+ vs. Transitions to 2_2^+ state



Two Configurations?

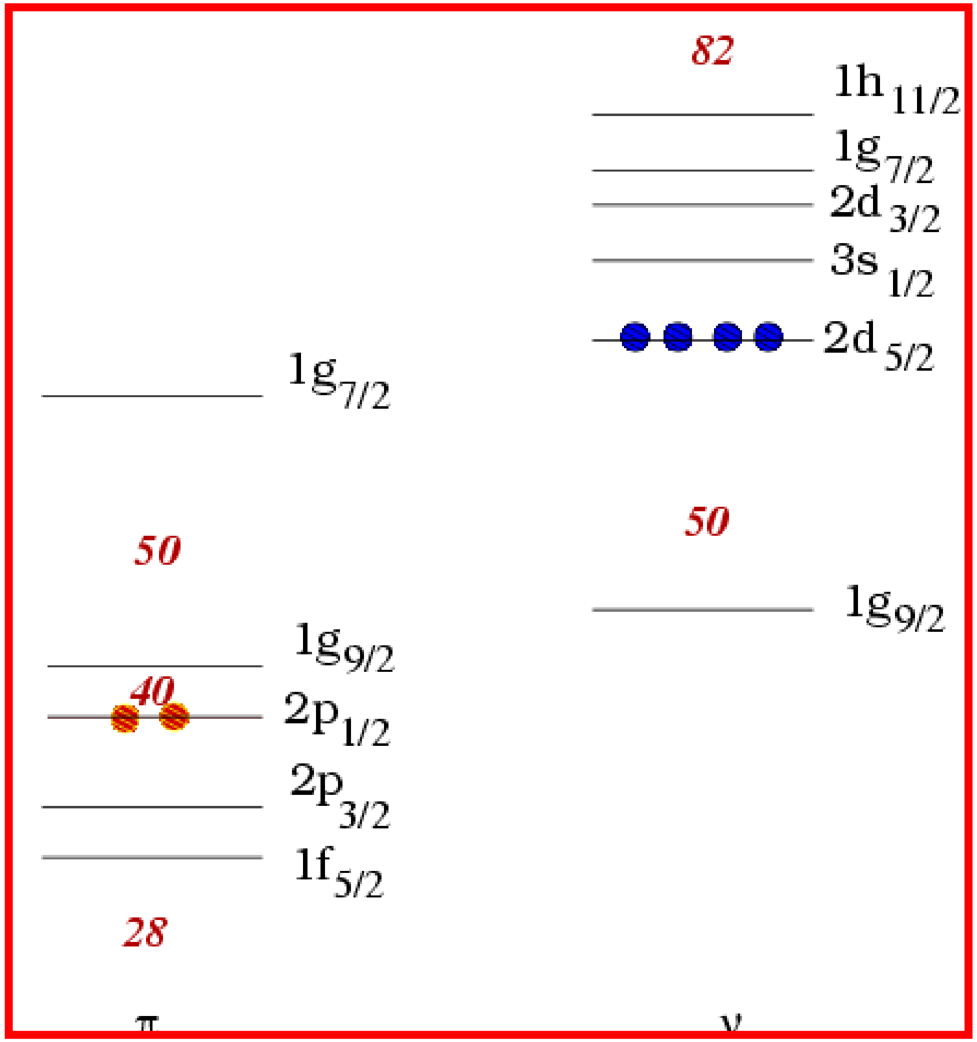
- 2_1^+ state: neutron dominant, negative g-factor
- 2_2^+ state: proton dominant, positive g-factor (Werner *et al*., Phys. Rev. C **78**, 031301(R), 2008)
- Excitations decay to 2_1^+ and 2_2^+ states via enhanced E2 transitions.
- M1 transitions connect different configurations.

Valence Nucleons in ^{94}Zr

$\pi(p_{1/2})^2\ \nu\ (d_{5/2})^4$

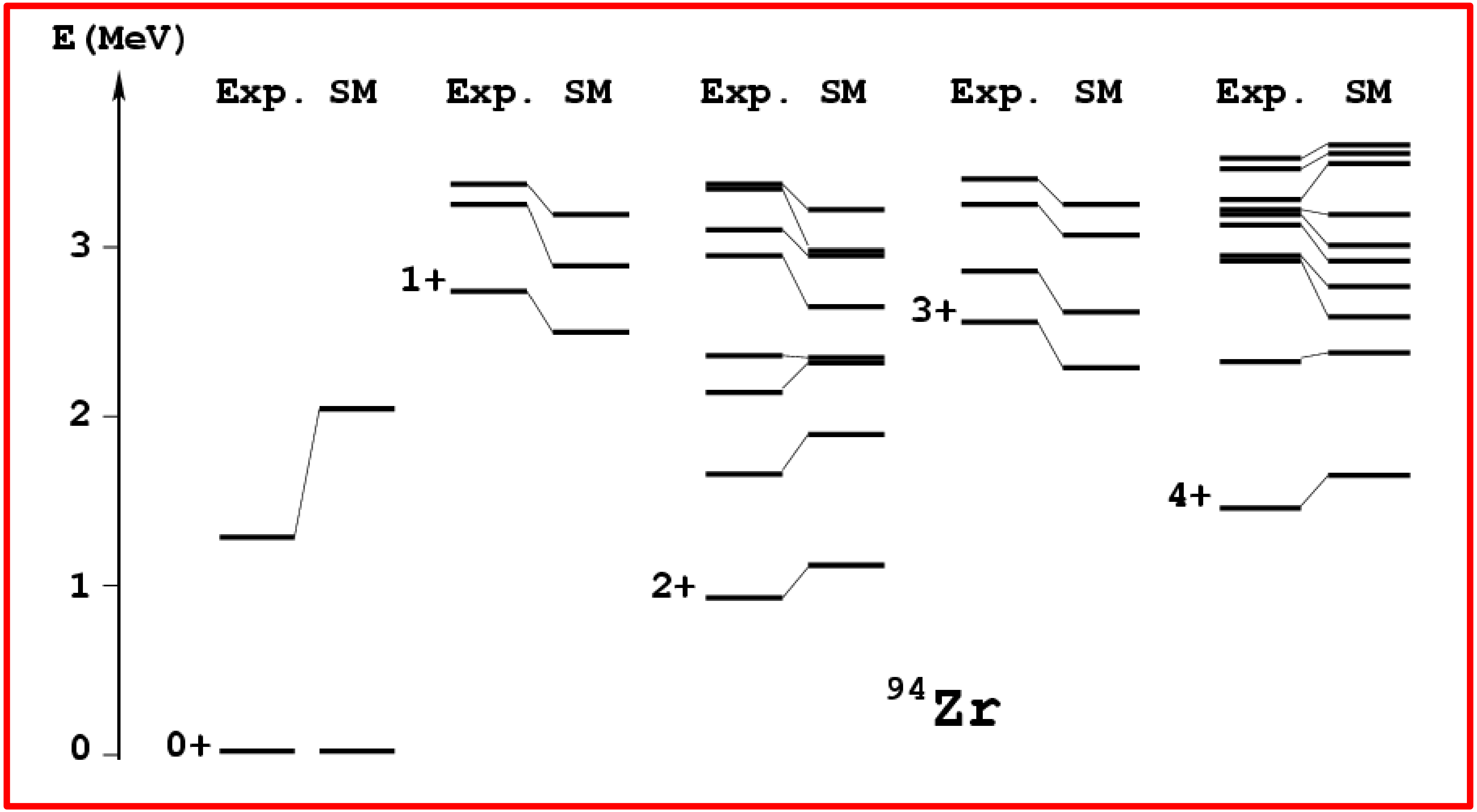
Subshell closure at Z=40

Subshell closure at N=56



Shell Model Calculations:

$V_{low\text{-}k}$ Interaction and ^{88}Sr core



Shell Model and IBM-2 Results

J_i	J_f	$B(M1)_{Exp}$ (μ_N^2)	$B(E2)_{Exp}$ (W.u.)	$B(M1)_{SM}$ (μ_N^2)	$B(E2)_{SM}$ (W.u.)	$B(M1)_{IBM2}$ (μ_N^2)	$B(E2)_{IBM2}$ (W.u.)
2_1^+	0_1^+		4.9(11)		5.5		4.7
2_2^+	0_1^+		7.8(7)		2.8		2.6
	2_1^+	0.31(3)		0.08		0.32	
2_3^+	2_1^+	$0.05^{+0.02}_{-0.01}$	11(3)	0.16	0.3		
	2_2^+	$0.07^{+0.04}_{-0.03}$	7^{+4}_{-3}	0.16	1.1		

?

Also, K. Sieja *et al.*, Phys. Rev. C **79**, 064310 (2009), almost reproduces $B(E2;2_2^+ \rightarrow 0_1^+)/B(E2;2_1^+ \rightarrow 0_1^+)$ by increasing the effective charges to $e^\nu = 0.8$ and $e^\pi = 1.8$.

Conclusions and Outlook

- Inelastic neutron scattering continues to provide new insights into nuclear structure.
- Studies of ^{94}Zr reveal an interesting and unique result — *i.e.*, $B(E2;2_2^+ \rightarrow 0_1^+) > B(E2;2_1^+ \rightarrow 0_1^+)$.
- A unexpectedly large number of collective excitations are observed in ^{94}Zr.
- These levels can be classified into sets of states according to their E2 decays to the 2_1^+ (neutron dominant) and 2_2^+ (proton dominant) states.
- M1 decays occur between these sets of states.
- The quadrupole moments should be measured.
  (M. Scheck *et al*.)

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“Art is I; science is we.” – Claude Bernard

Thank you