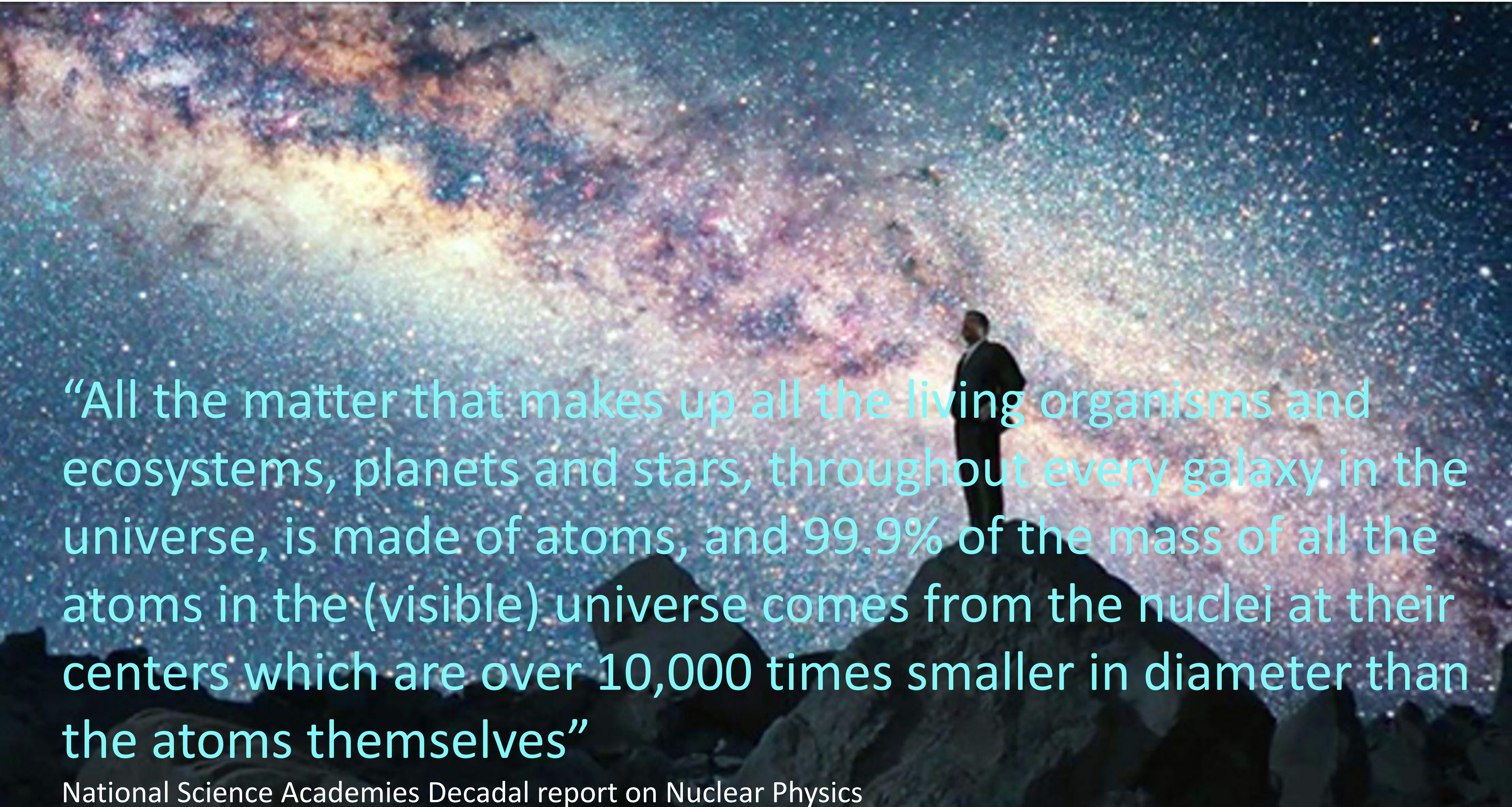
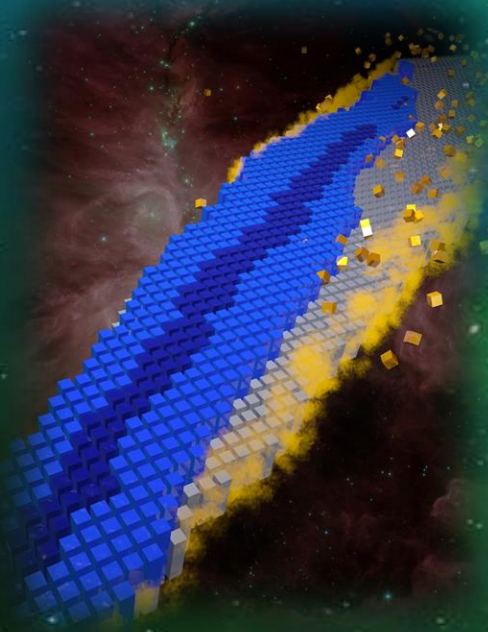

"All the matter that makes up all the living organisms and ecosystems, planets and stars, throughout every galaxy in the universe, is made of atoms, and 99.9% of the mass of all the atoms in the (visible) universe comes from the nuclei at their centers which are over 10,000 times smaller in diameter than the atoms themselves"
National Science Academies Decadal report on Nuclear Physics

Nuclear Structure Experiment I



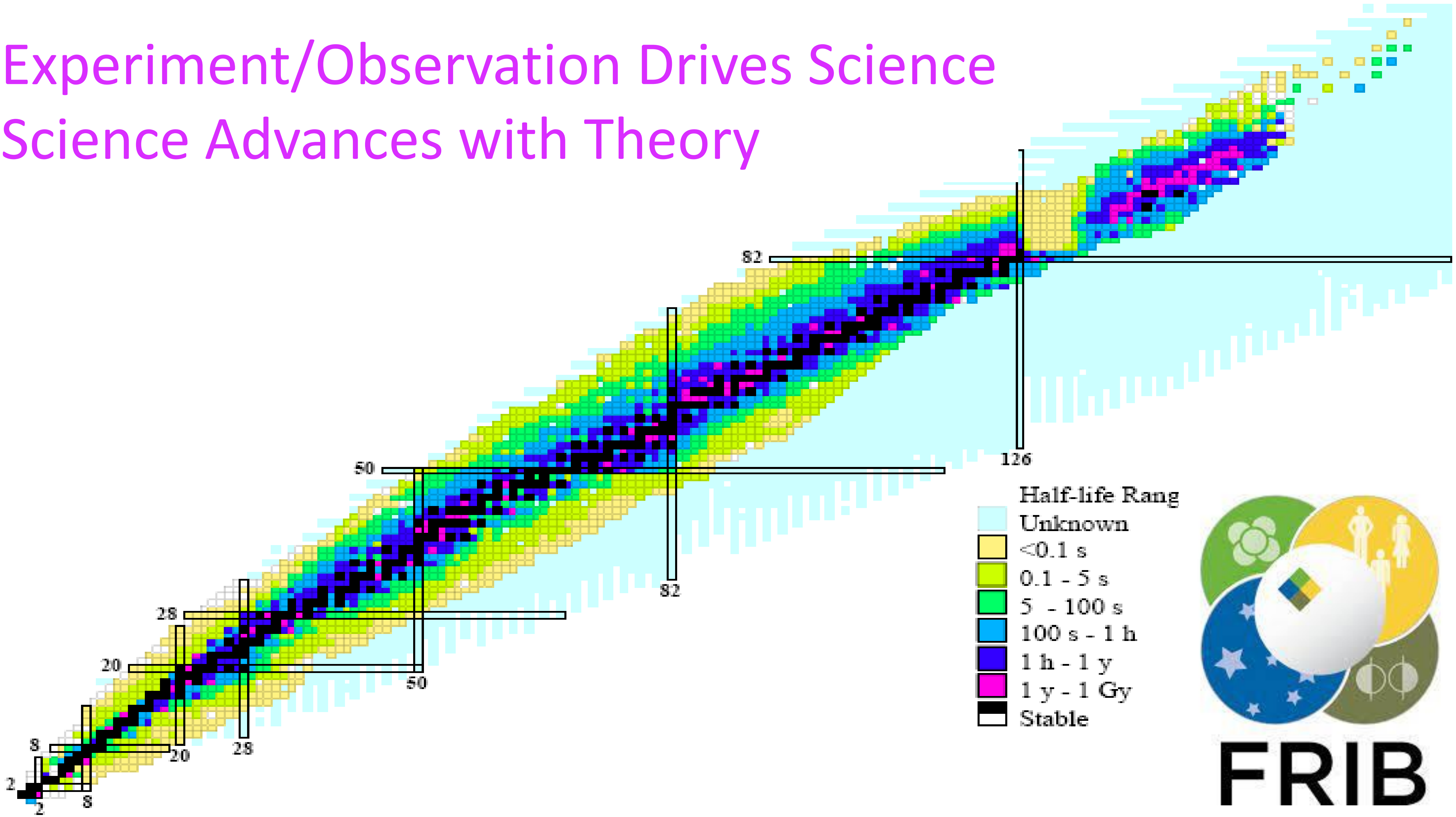
Ani Aprahamian

University of Notre Dame

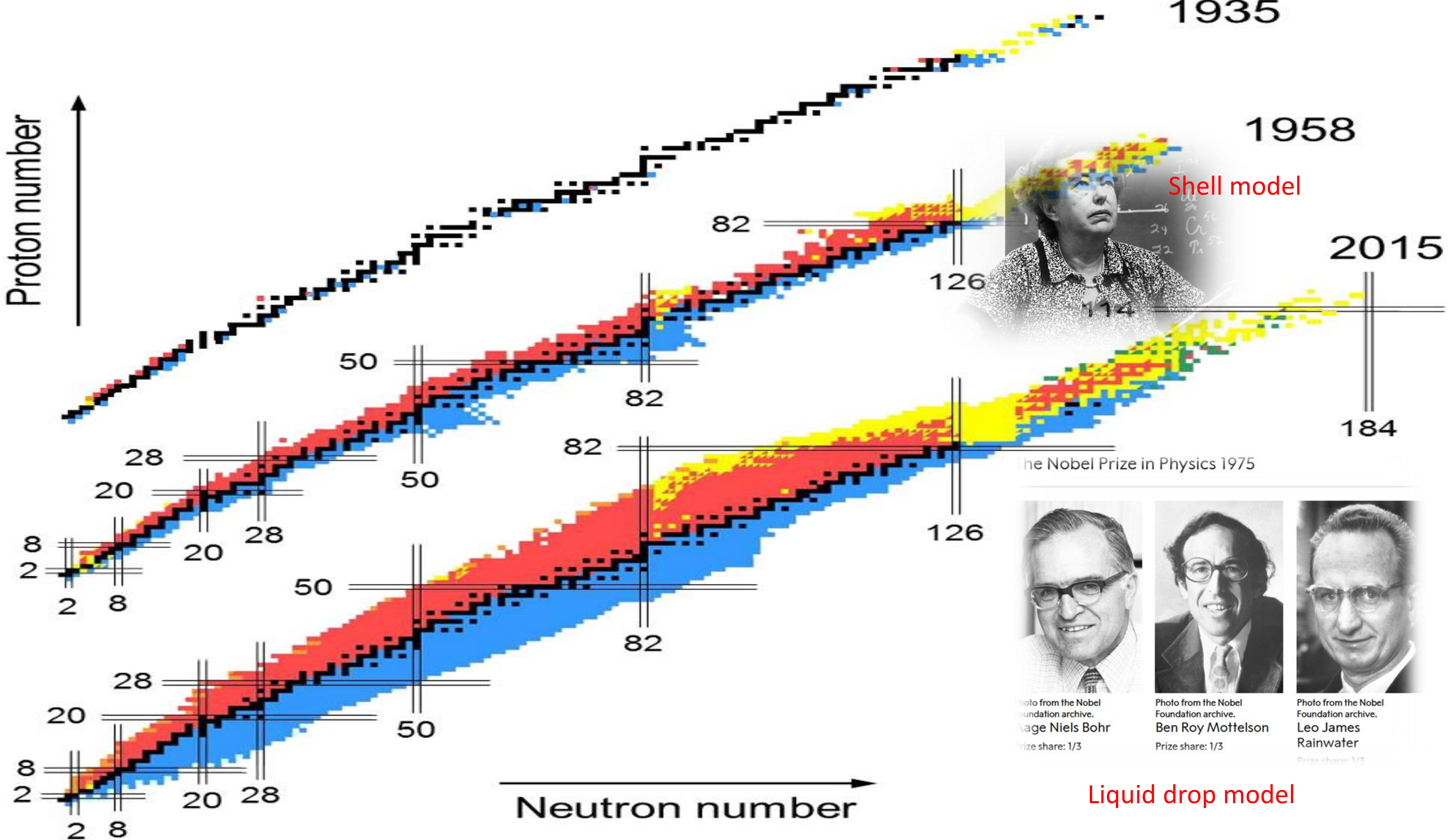
&

A. Alikhanyan National Science Laboratory of Armenia

Experiment/Observation Drives Science
Science Advances with Theory



FRIB



Shell model

Liquid drop model

LIQUID DROP MODEL

(George Gamow in 1929)

⇒ TREATED nucleus as 'DROP OF LIQUID'.

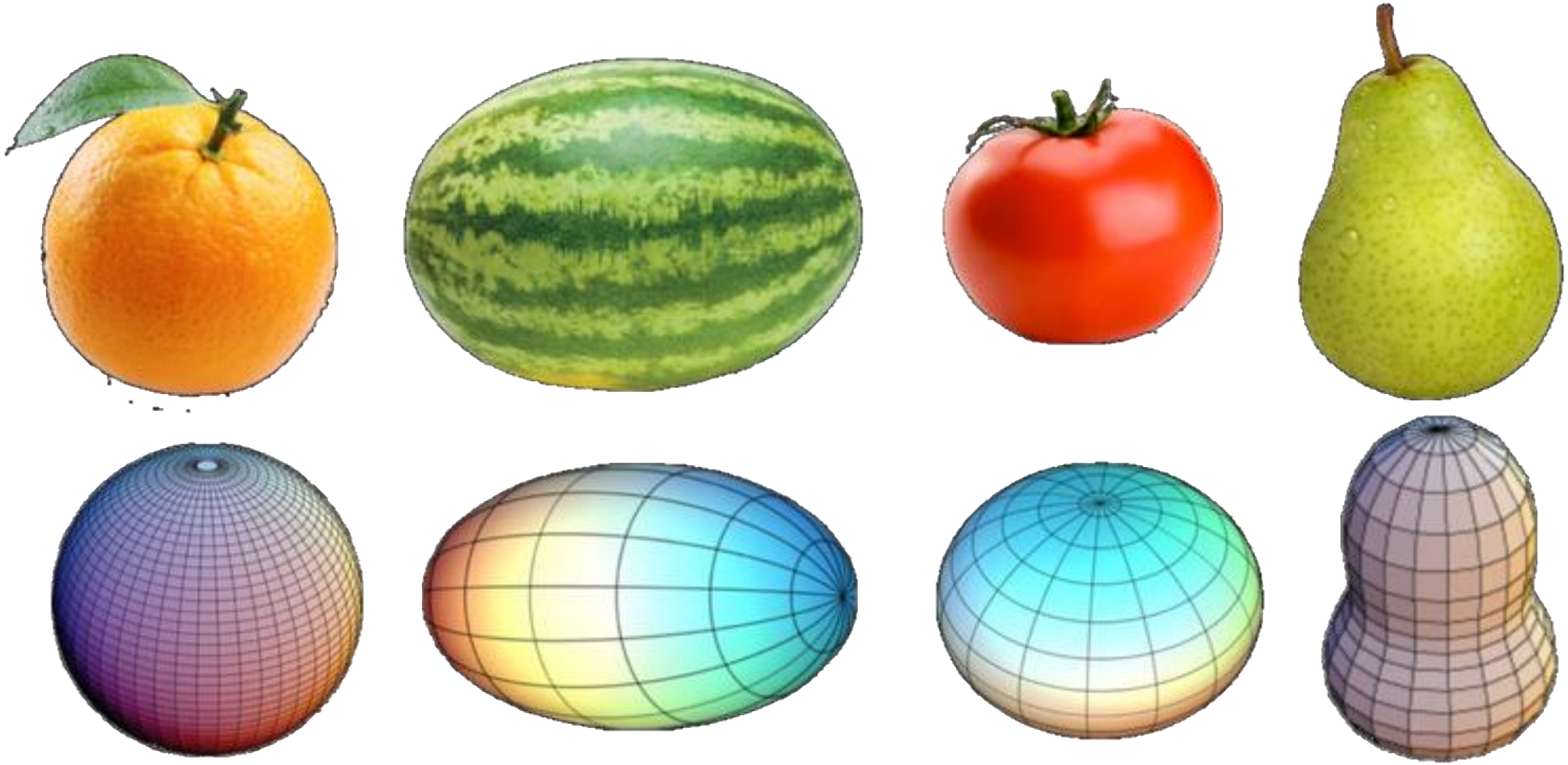
⇒ Liquid drop Model suggests that the BE of nucleus is sum of three different energies

(i) Volume. E_v

(ii) Surface. E_s

(iii) Coulomb. E_c

$$E_b = E_v + E_s + E_c$$

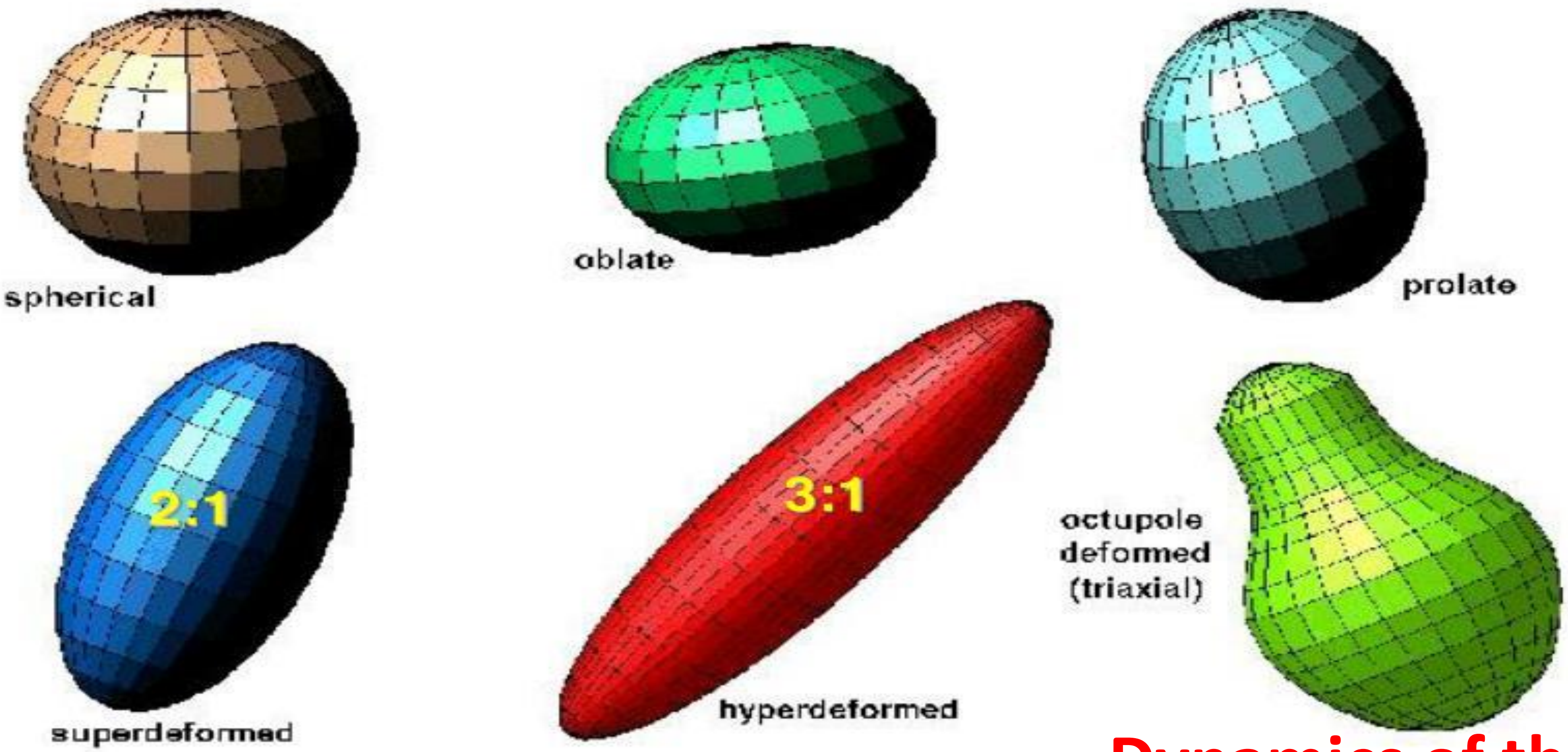


^{186}Pb ^{186}Po ^{186}Hg ^{224}Ra

Nuclear Shapes

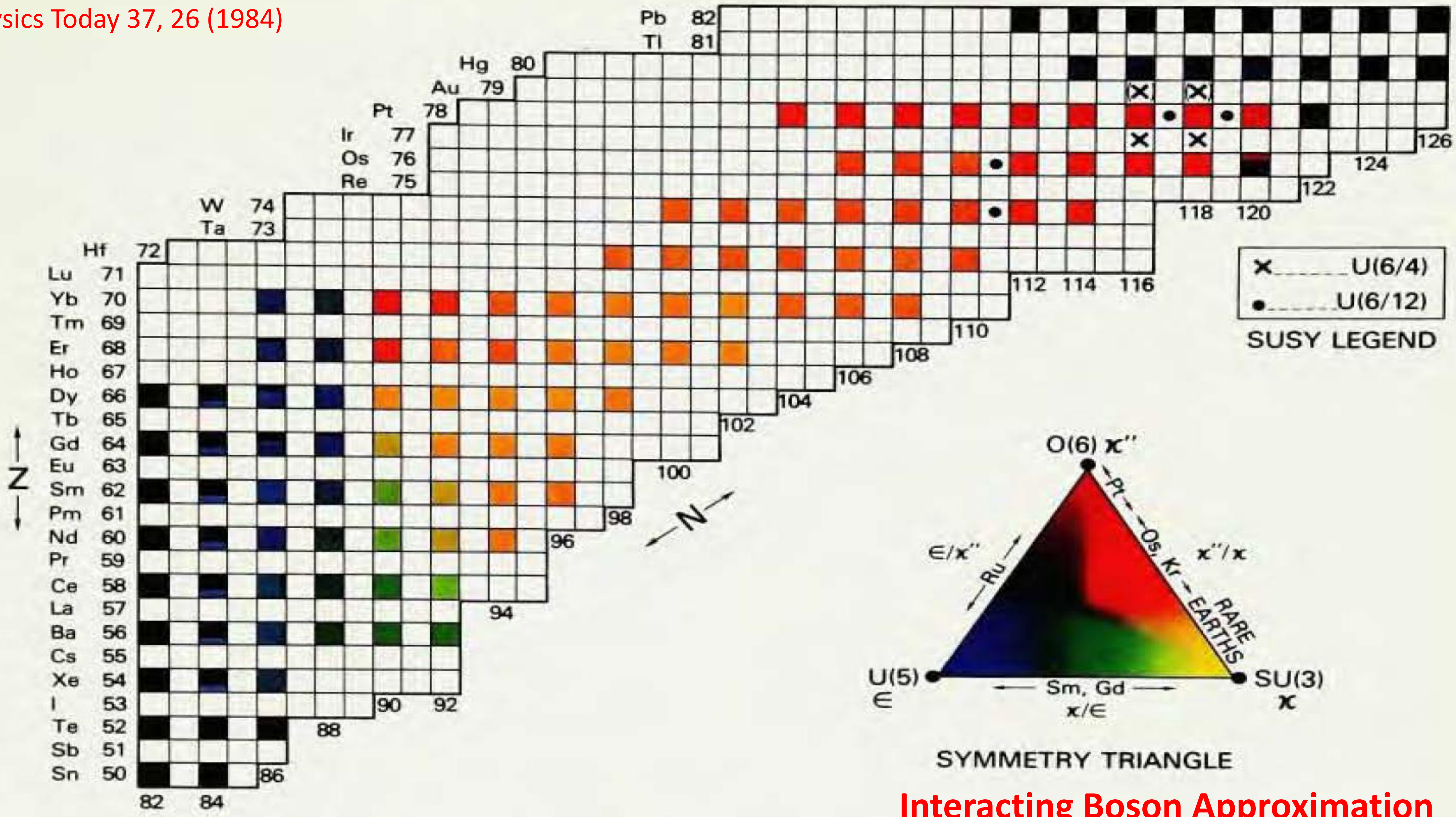
$$R(\theta,\varphi) = R_0(1 + \beta Y_{\lambda\mu}(\theta,\varphi))$$

$\lambda=2$; $\beta = 0$ spherical; $\beta < 0$ oblate (disk-like) ; $\beta > 0$ prolate (football-like)
$\lambda=3$; triaxial, octupole deformed

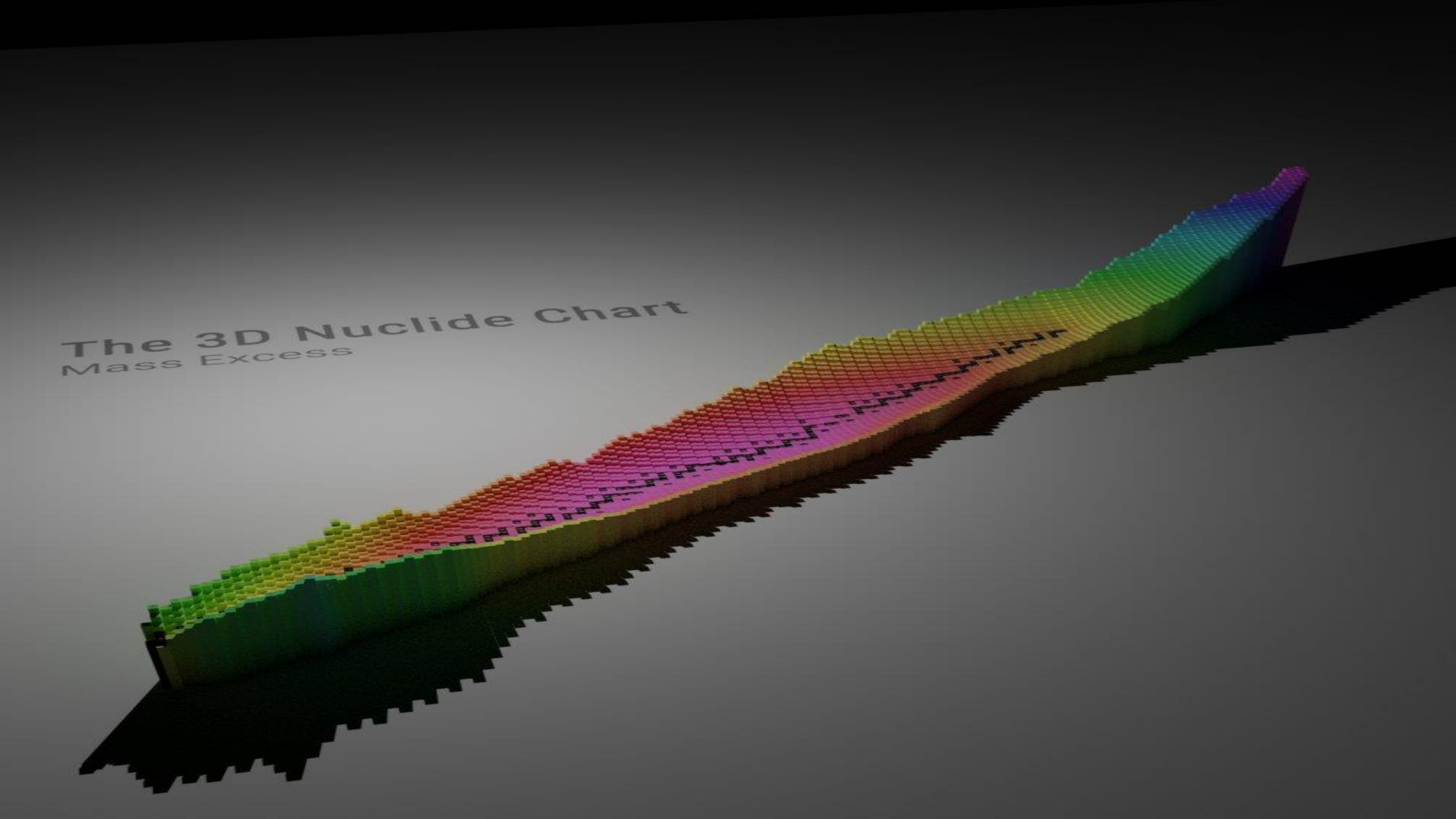


Dynamics of the Shapes

Casten & Feng
Physics Today 37, 26 (1984)



Interacting Boson Approximation


The 3D Nuclide Chart
Mass Excess

VOLUME 59, NUMBER 5 PHYSICAL REVIEW LETTERS 3 AUGUST 1987

First Observation of a Near-Harmonic Vibrational Nucleus

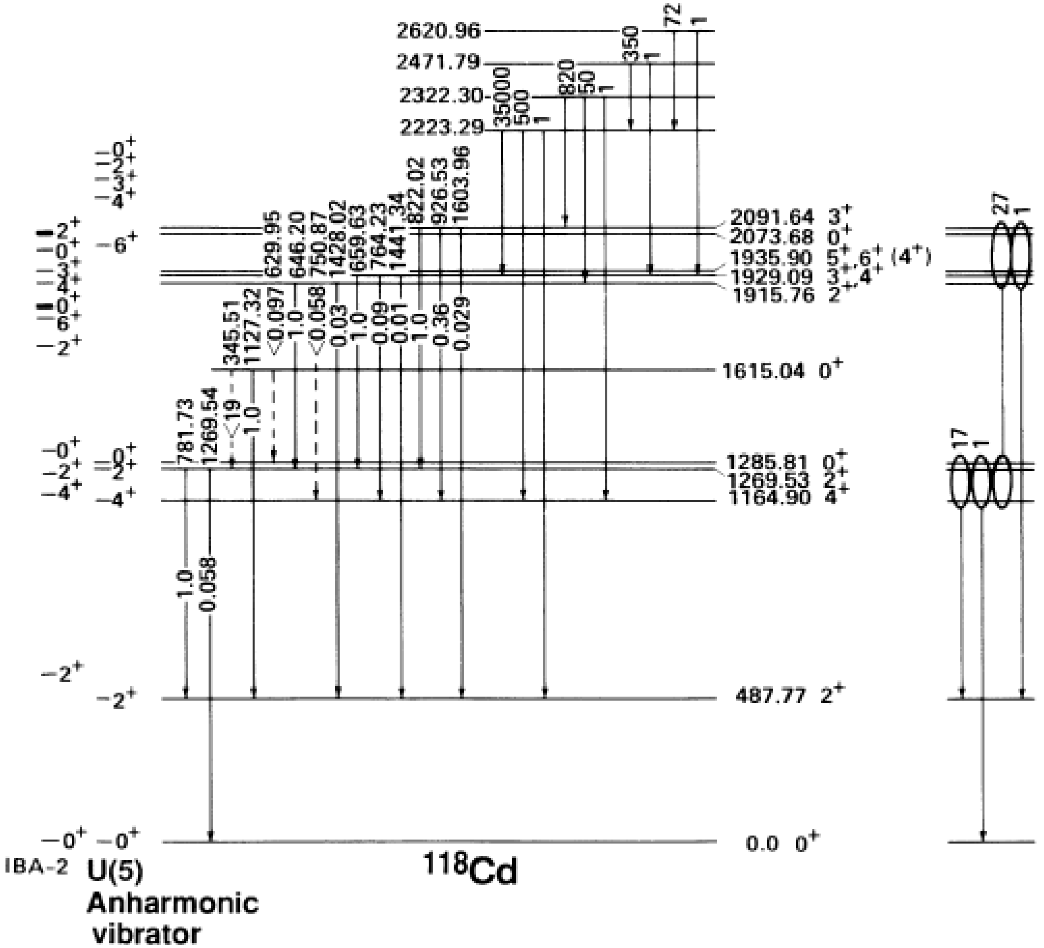
A. Aprahamian
Clark University, Worcester, Massachusetts 01610, and
Lawrence Livermore National Laboratory, Livermore, California 94550

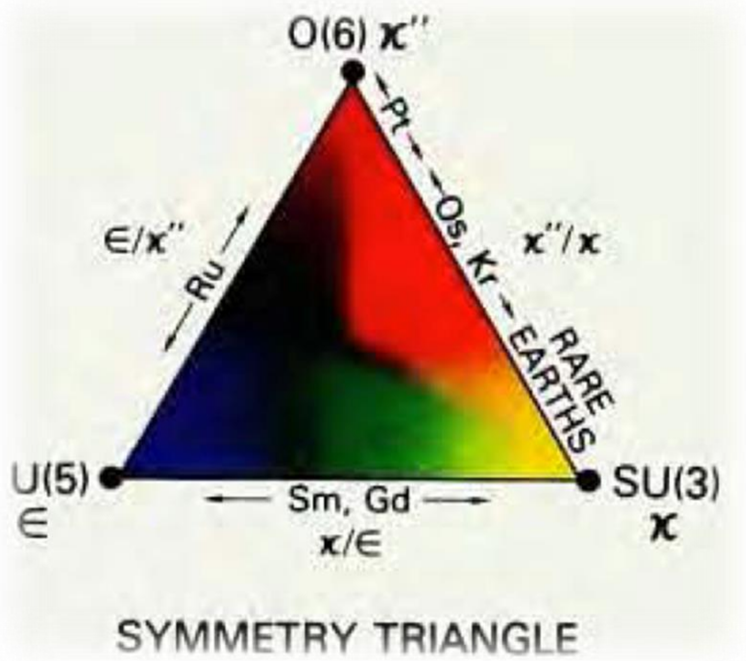
D. S. Brenner
Clark University, Worcester, Massachusetts 01610

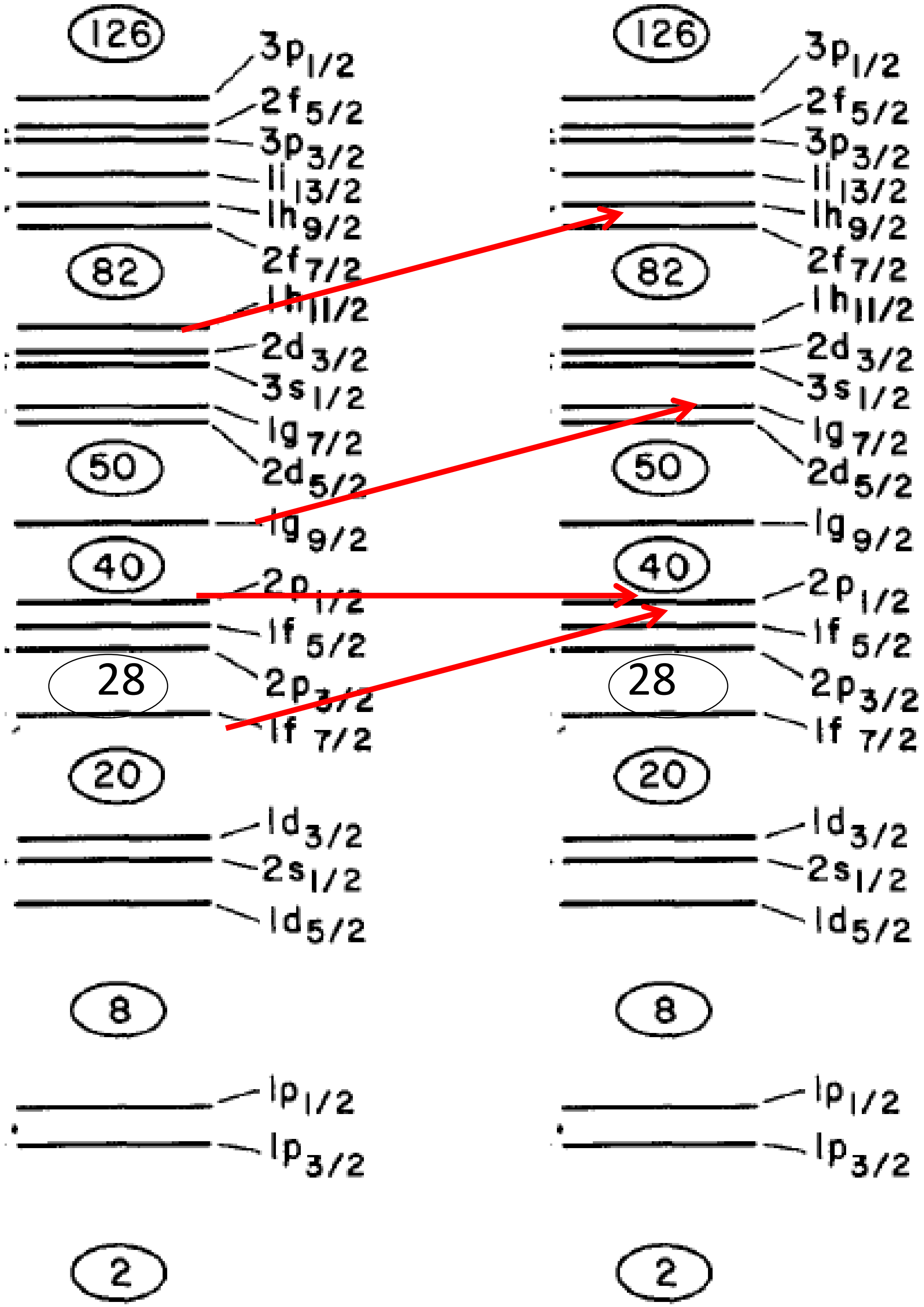
and

R. F. Casten, R. L. Gill, and A. Piotrowski[(a)]
Brookhaven National Laboratory, Upton, New York 11973

(Received 4 May 1987)

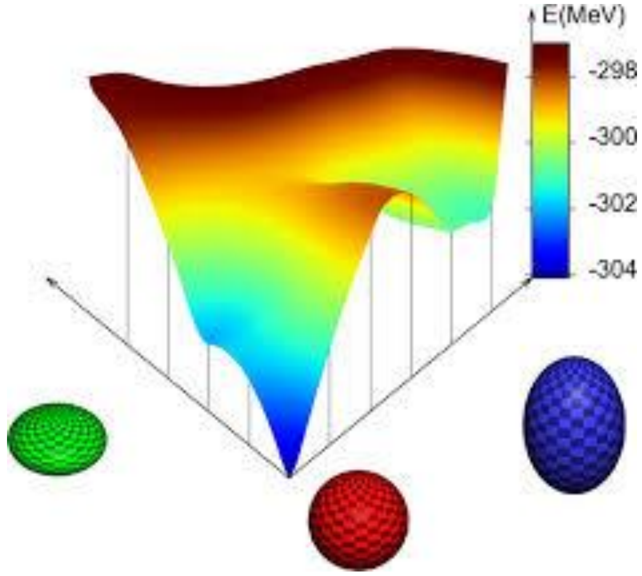


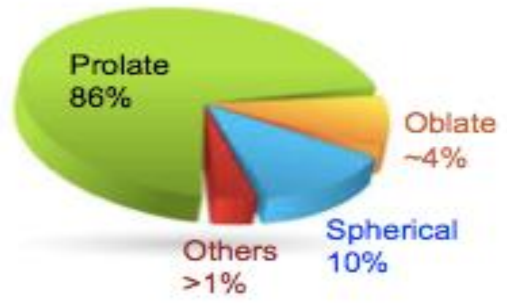


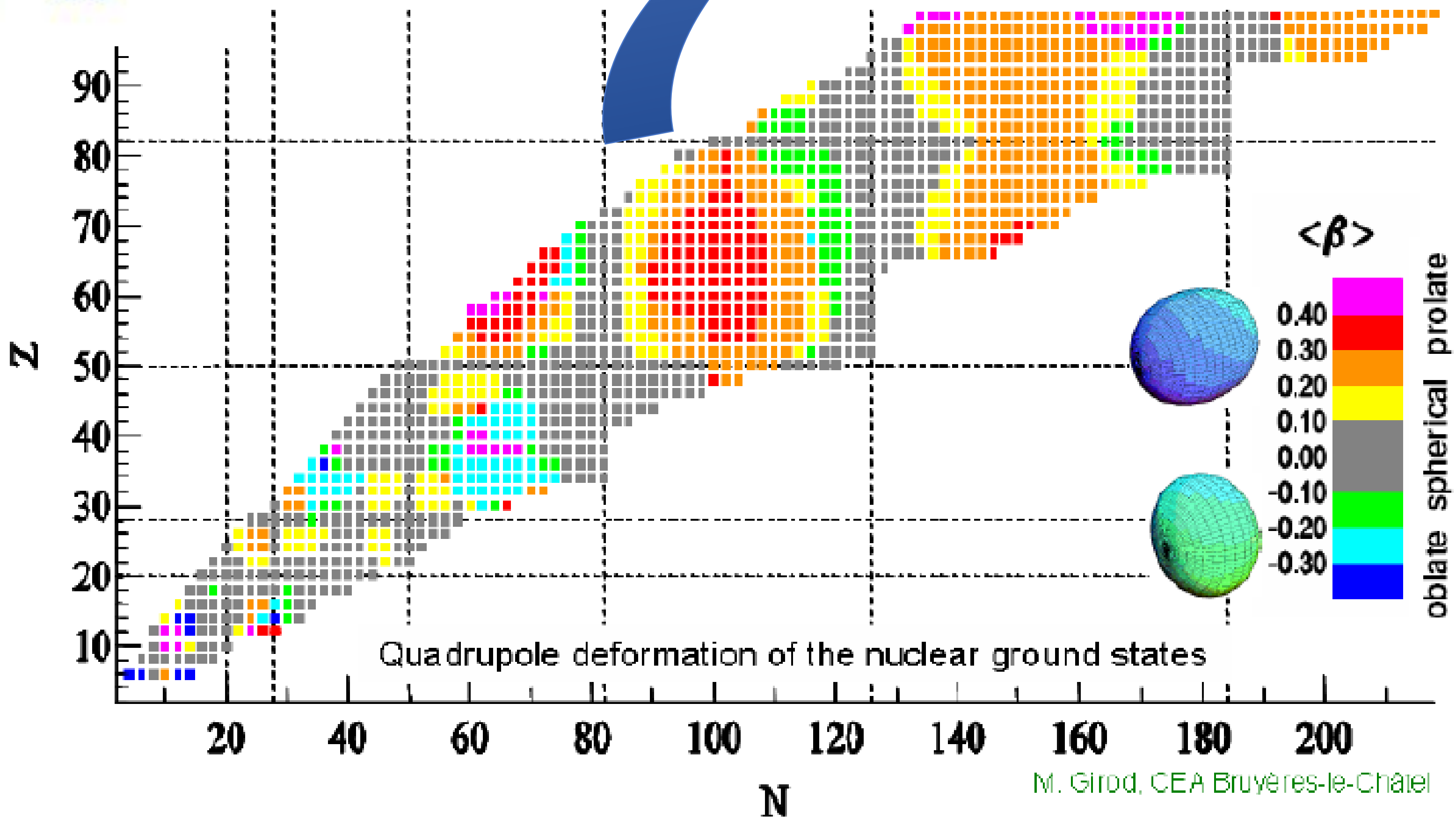


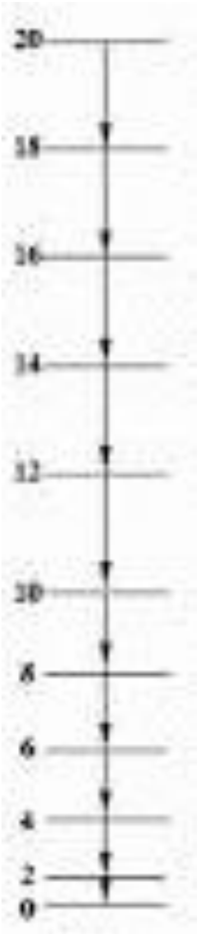
Shape Coexistence:
Near closed shells

O, Ca, Ni,
Zr, Mo
Cd, Sn
Hg,Pb




Prolate
86%
Oblate
~4%
Spherical
10%
Others
>1%


Quadrupole deformation of the nuclear ground states
Z
N
10
20
30
40
50
60
70
80
90
20
40
60
80
100
120
140
160
180
200
<β>
0.40
0.30
0.20
0.10
0.00
-0.10
-0.20
-0.30
oblate spherical prolate
M. Girod, CEA Bruyères-le-Châtel


20
18
16
14
12
10
8
6
4
2
0

Institute for Structure And Nuclear Astrophysics

Nuclear Structure Plan

Experiment & Theory

Nuclear Vibrations

Types of vibrations

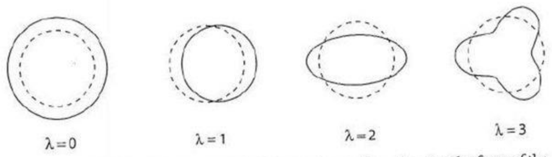
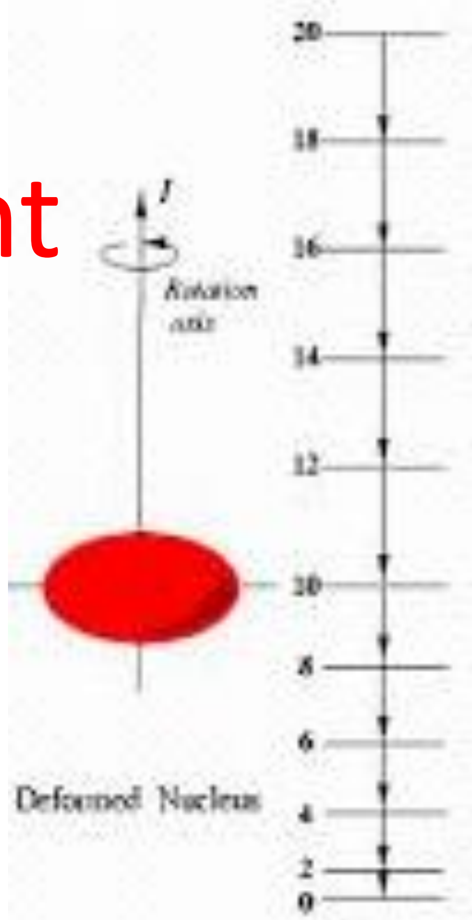
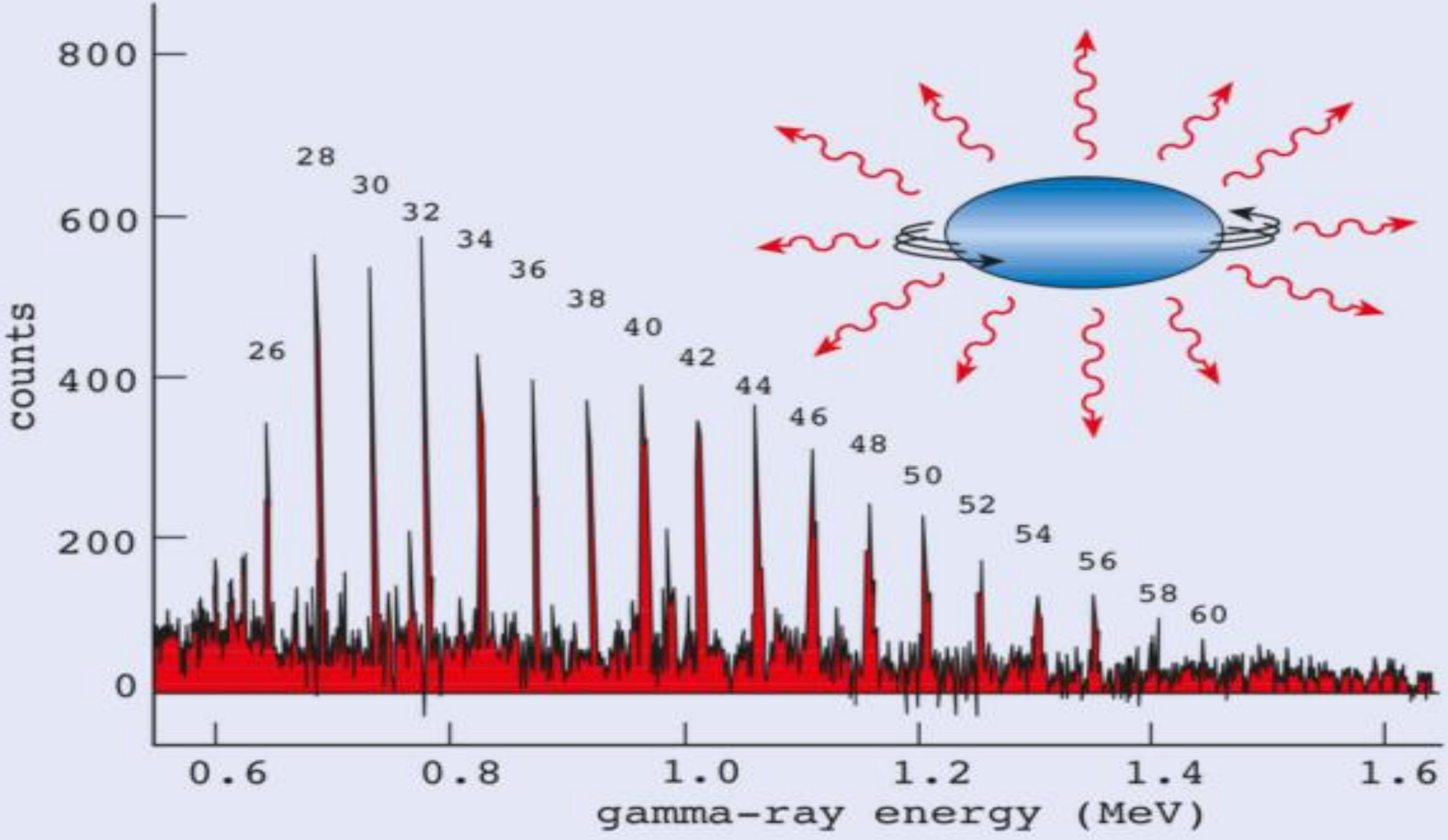


Figure 5.13 The first vibration modes of the nuclear surface, showing the form of the nucleus for each mode (solid line) in comparison to the original spherical nucleus. The dotted line represents the original "fixed volume" sphere.



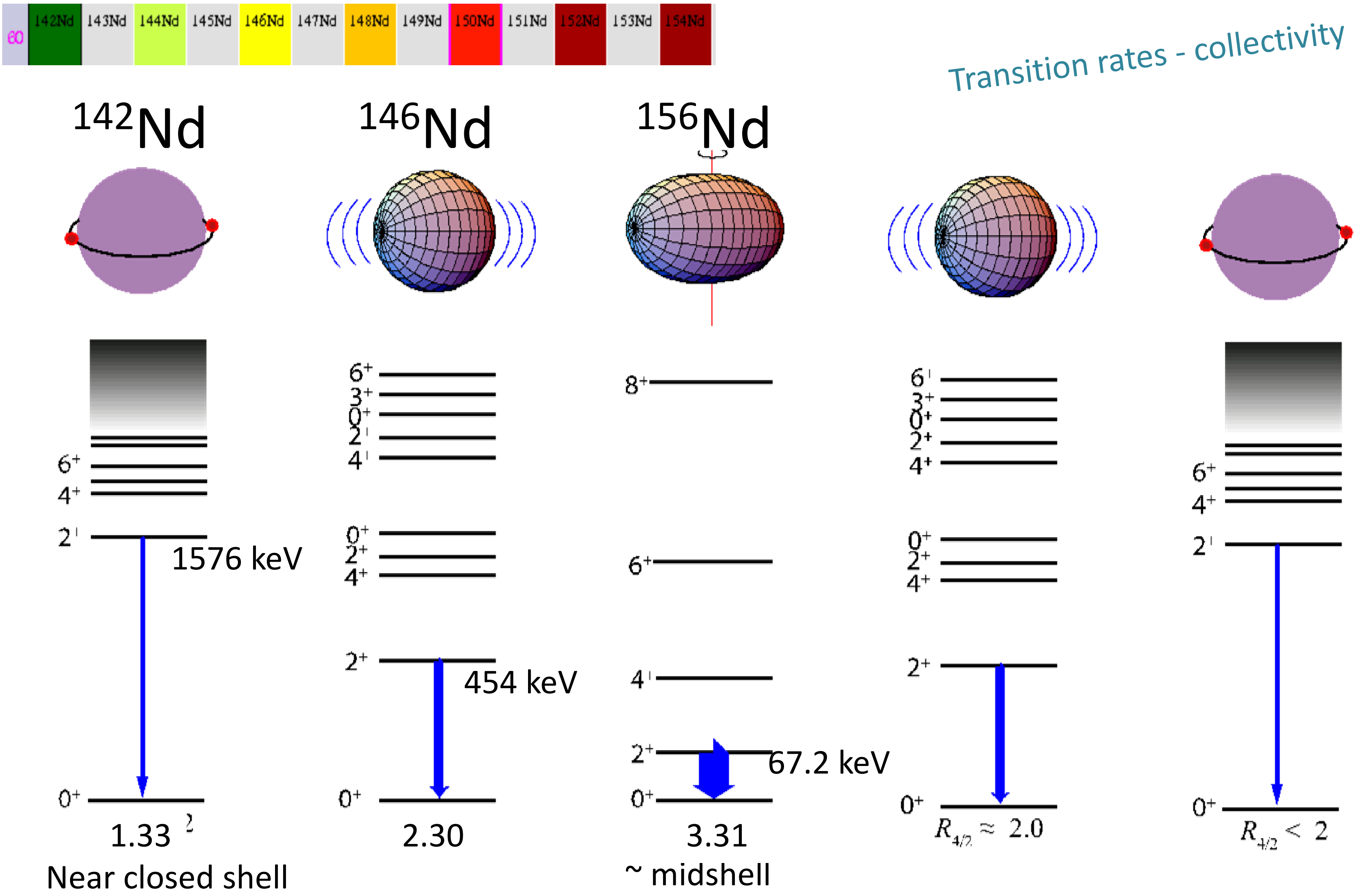
J(J+1)

UNIVERSITY OF NOTRE DAME



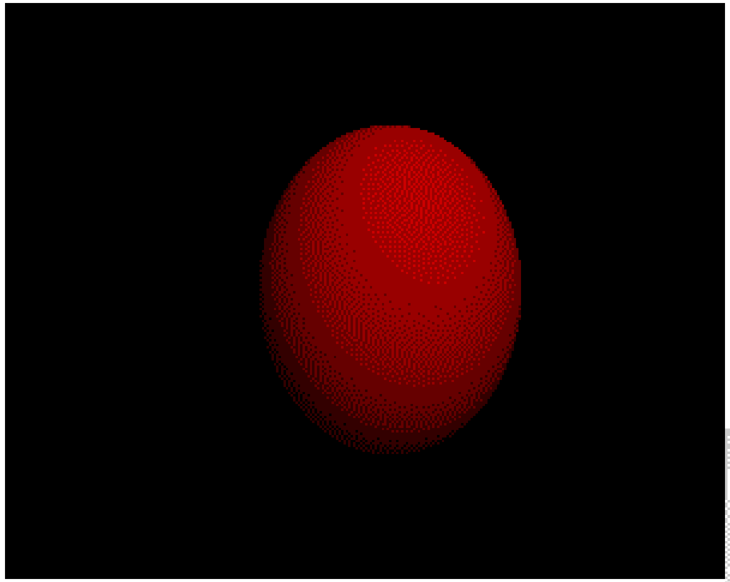
800
600
400
200
0
counts
26
28
30
32
34
36
38
40
42
44
46
48
50
52
54
56
58
60
0.6
0.8
1.0
1.2
1.4
1.6
gamma-ray energy (MeV)

Evolution of Nuclear Structure

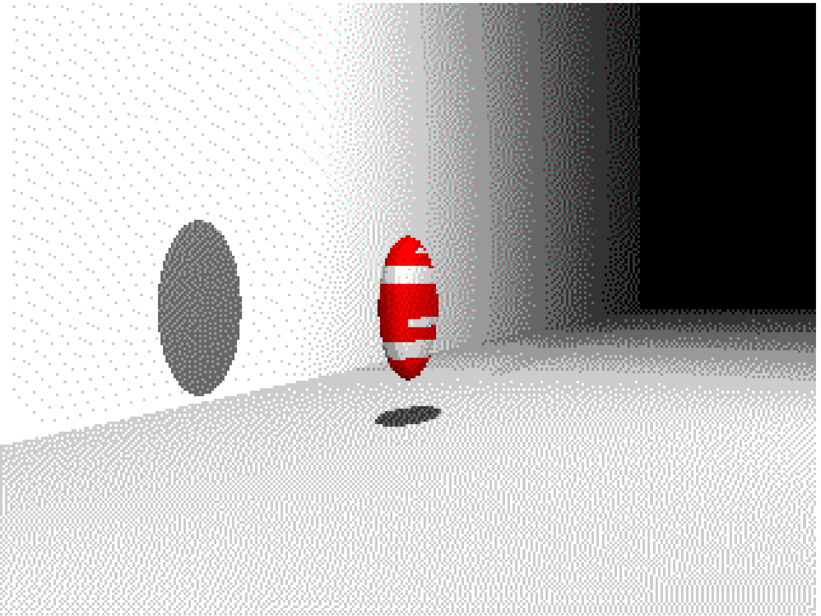


Quadrupole oscillations of a deformed nucleus: β and γ

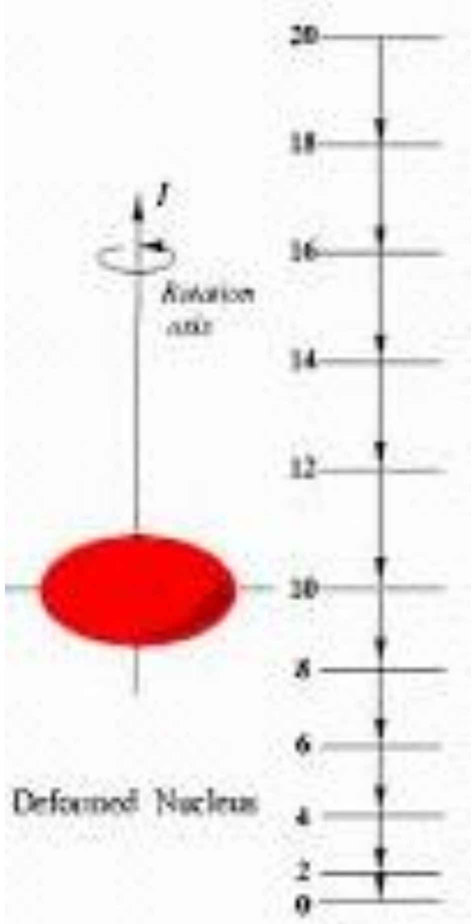
$K=0^+$



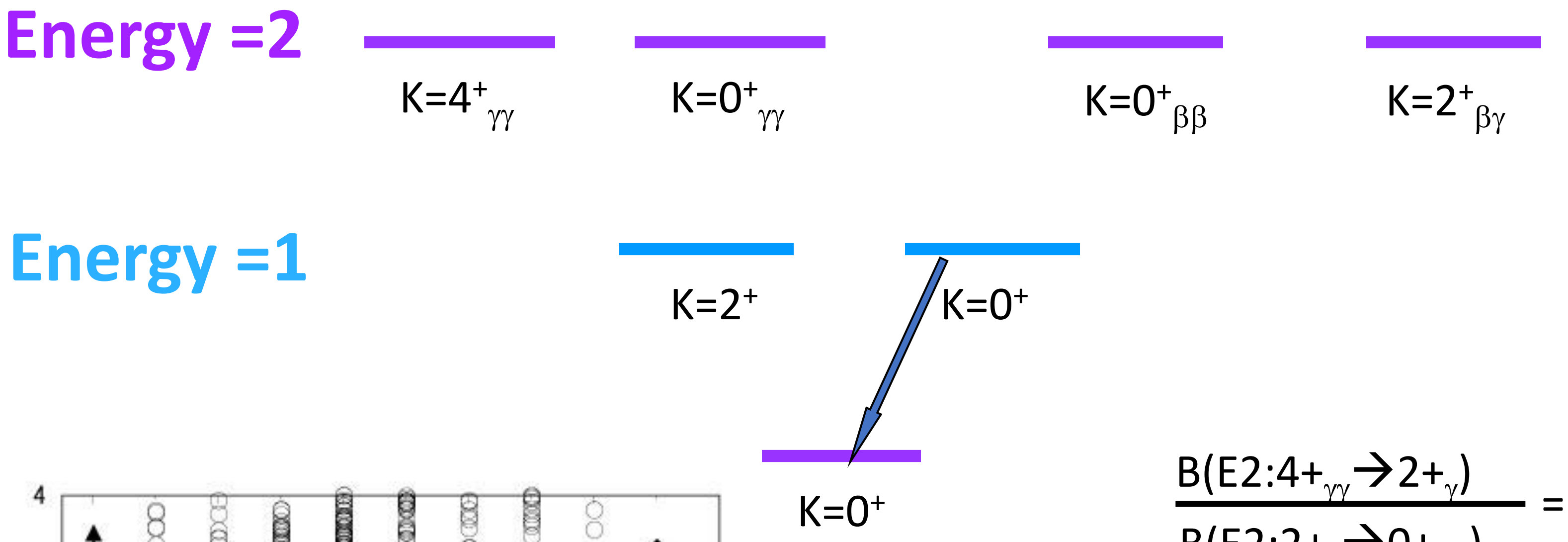
$K=2^+$

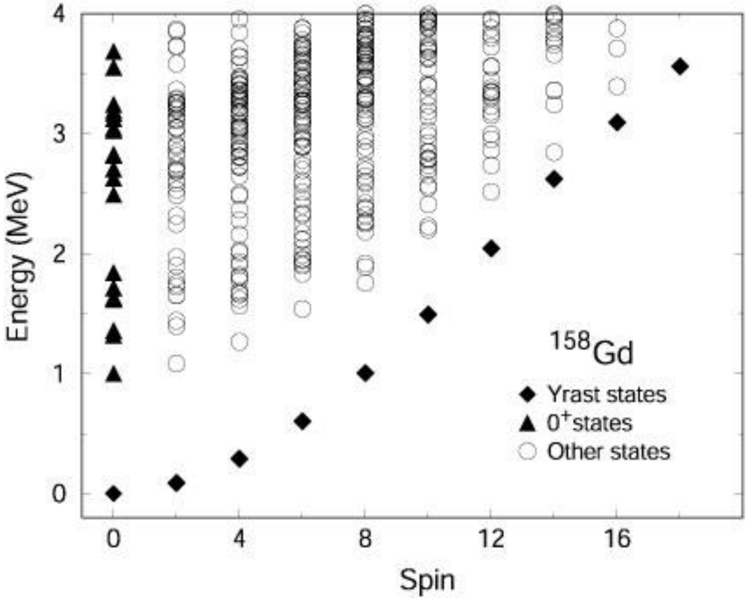


University of Lund



What can we expect to see? Transition Probabilities





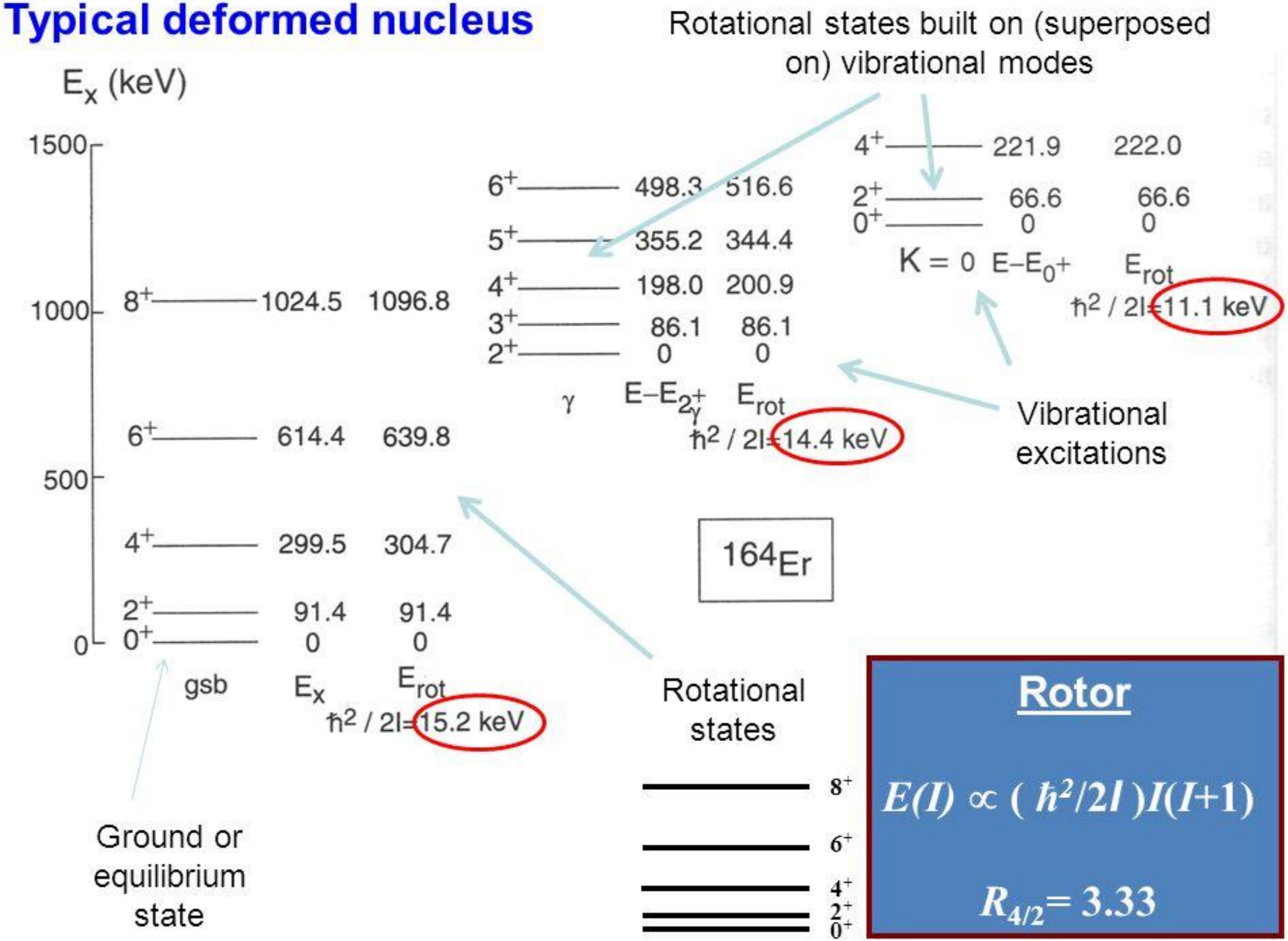
Y.Sun, 2003

$$\frac{B(E2:4+_{\gamma\gamma}\rightarrow 2+_{\gamma})}{B(E2:2+_{\gamma}\rightarrow 0+_{gs})} = 2.78$$

$$\frac{B(E2:0+_{\gamma\gamma}\rightarrow 2+_{\gamma})}{B(E2:2+_{\gamma}\rightarrow 0+_{gs})} = 5.0$$

$$\frac{B(E2:2+_{\beta\beta}\rightarrow 0+_{gs})}{B(E2:2+_{\beta}\rightarrow 0+_{gs})} = 2.0$$

Typical deformed nucleus



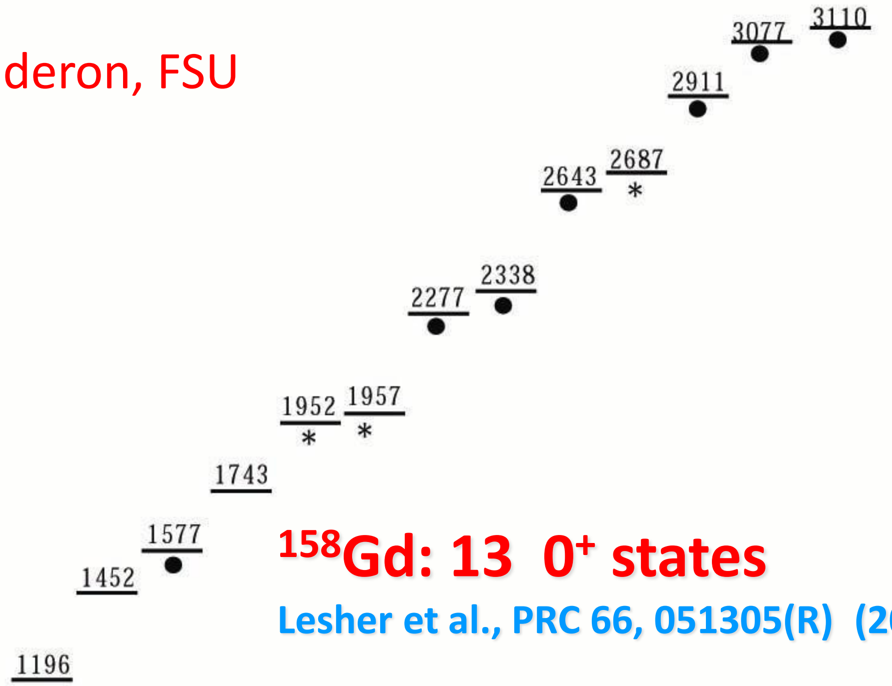
Pairing gaps: Nuclear Masses

	$2\Delta n$	$2\Delta p$	$E_{K=0+}$
^{154}Gd	2468 keV	2234 keV	680 keV
^{156}Gd	1996	1914	1168
^{158}Gd	1768	1738	1196
^{162}Dy	1720	1914	1400
^{164}Dy	1692	1792	1656
^{166}Er	1824	1814	1460
^{168}Er	1540	1787	1217
^{178}Hf	1360	1660	1199

Institute for Structure And Nuclear Astrophysics

p,t reaction on the Q3D spectrograph in Munich

Reactions: Sergio Almaraz-Calderon, FSU



^{158}Gd: 13 0^+ states

Lesher et al., PRC 66, 051305(R) (2002)

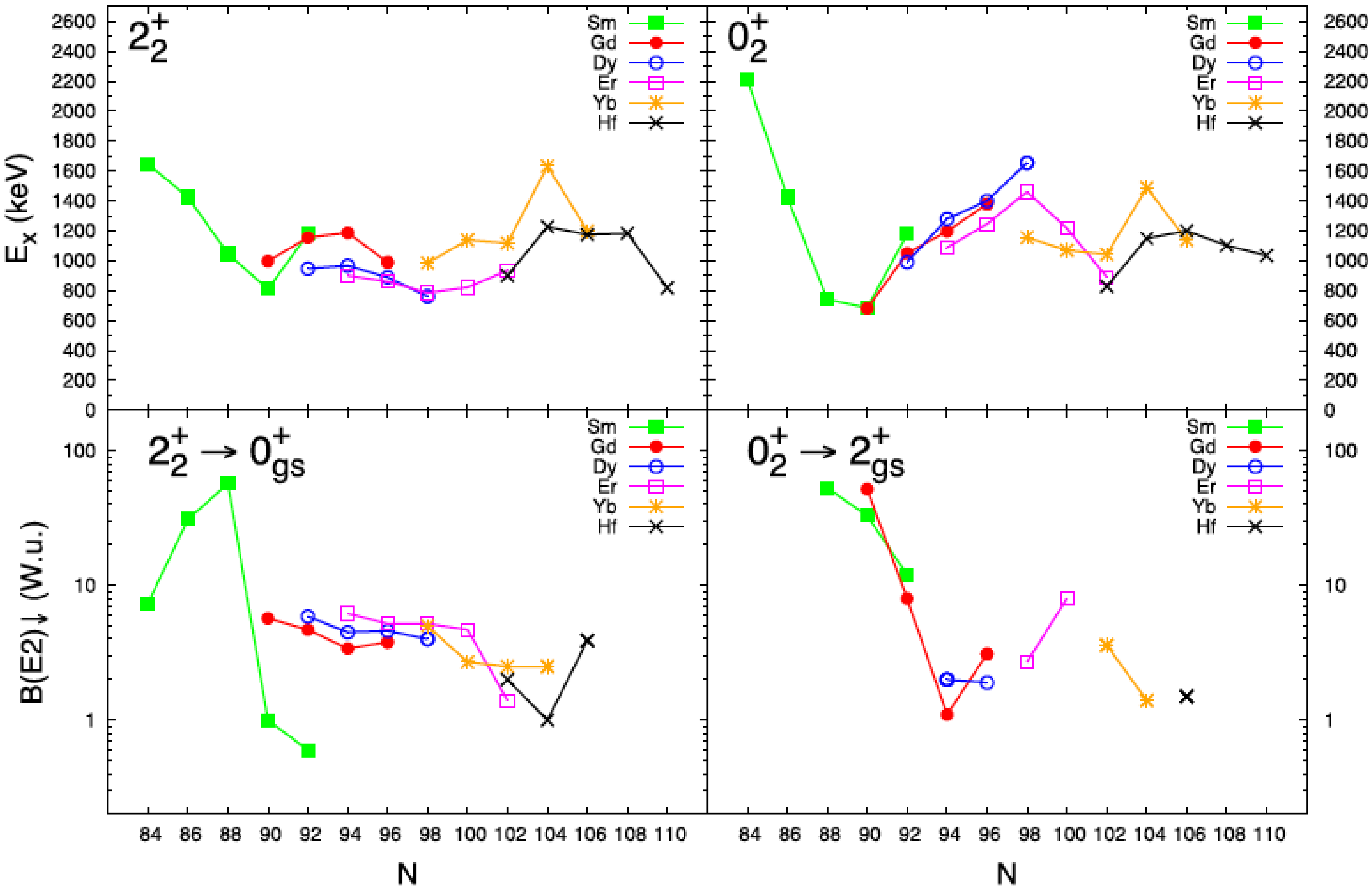
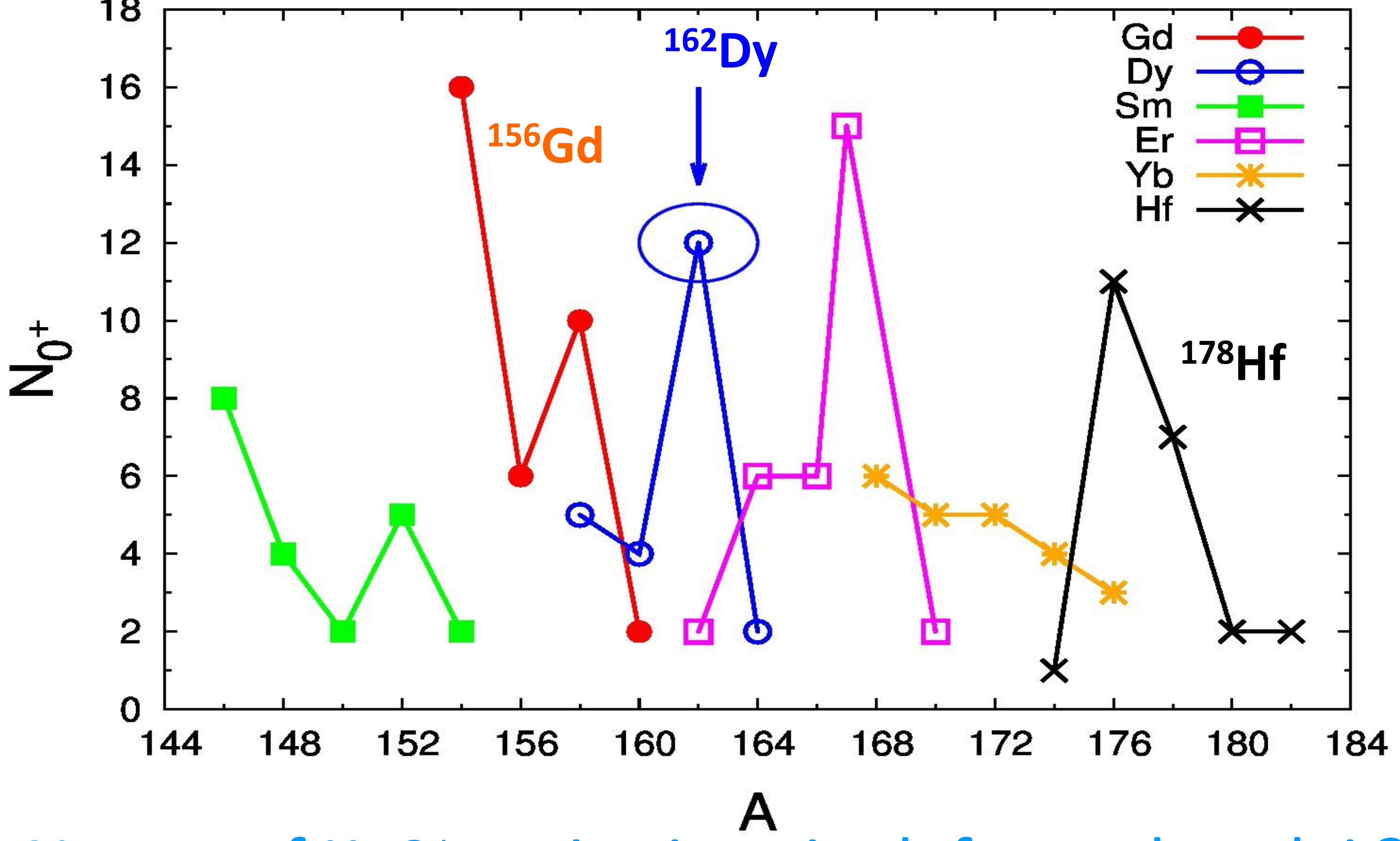


FIG. 1. Systematics of the first excited $K^\pi = 2^+$ "γ" and $K^\pi = 0^+$ bands in several isotopes of Sm, Gd, Dy, Er, Yb, and Hf as a function of neutron number "N" along with the observed $B(E2; 2^+_{K=2+} \rightarrow 0^+)$ values for the γ bands and the $B(E2; 0^+_2 \rightarrow 2^+_{\mathrm{g.s.}})$ values for the first excited $K^\pi = 0^+$ bands.

Figure from C. Casarella



Nature of K=0$^+$ excitations in deformed nuclei ?

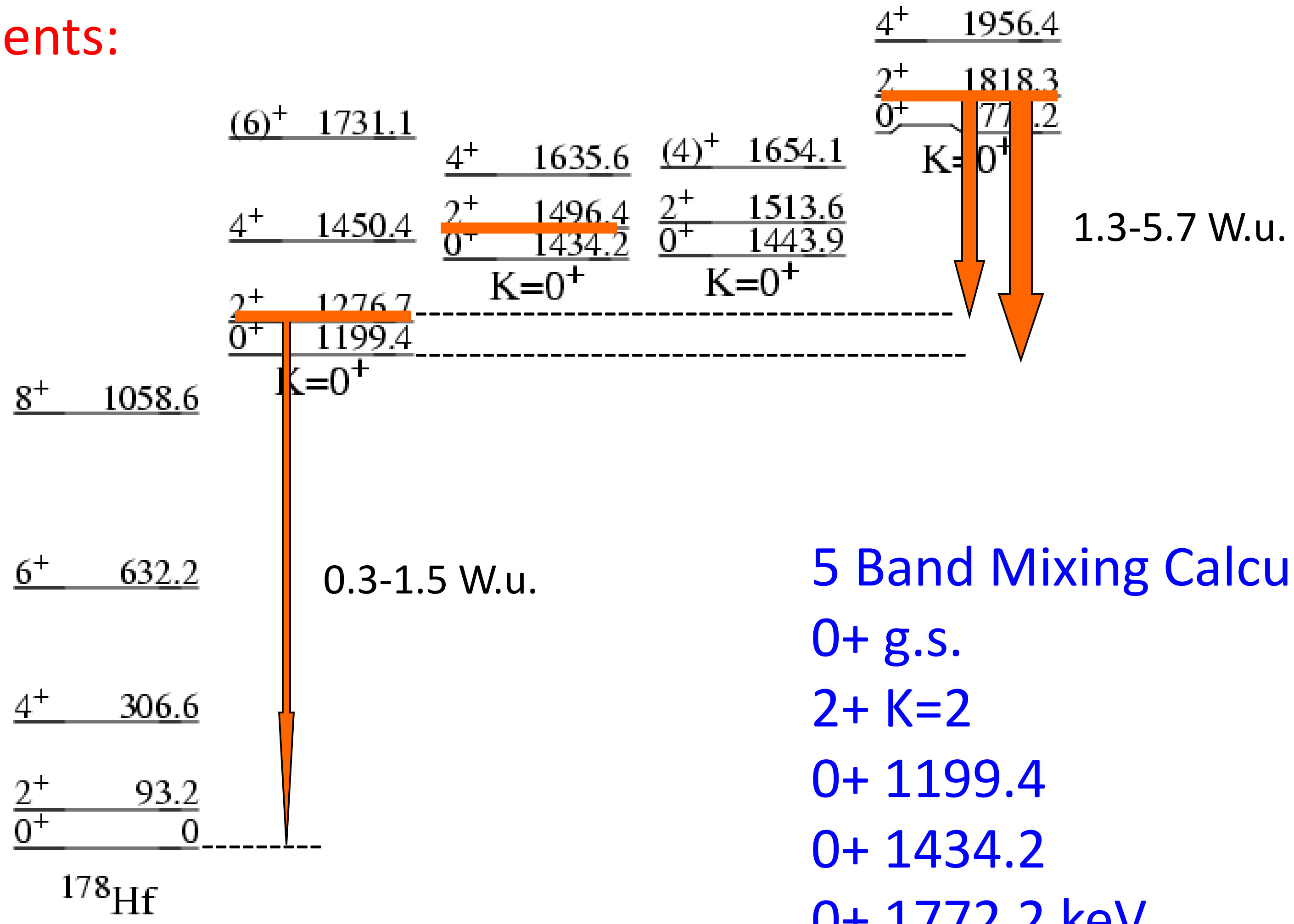
Quasi-particle excitations

Pairing vibrations

Collective excitations

GRID Measurements: E_{1772}/E_{1199}= 1.5

Lifetime Measurements:



5 Band Mixing Calculation

0+ g.s.

2+ K=2

0+ 1199.4

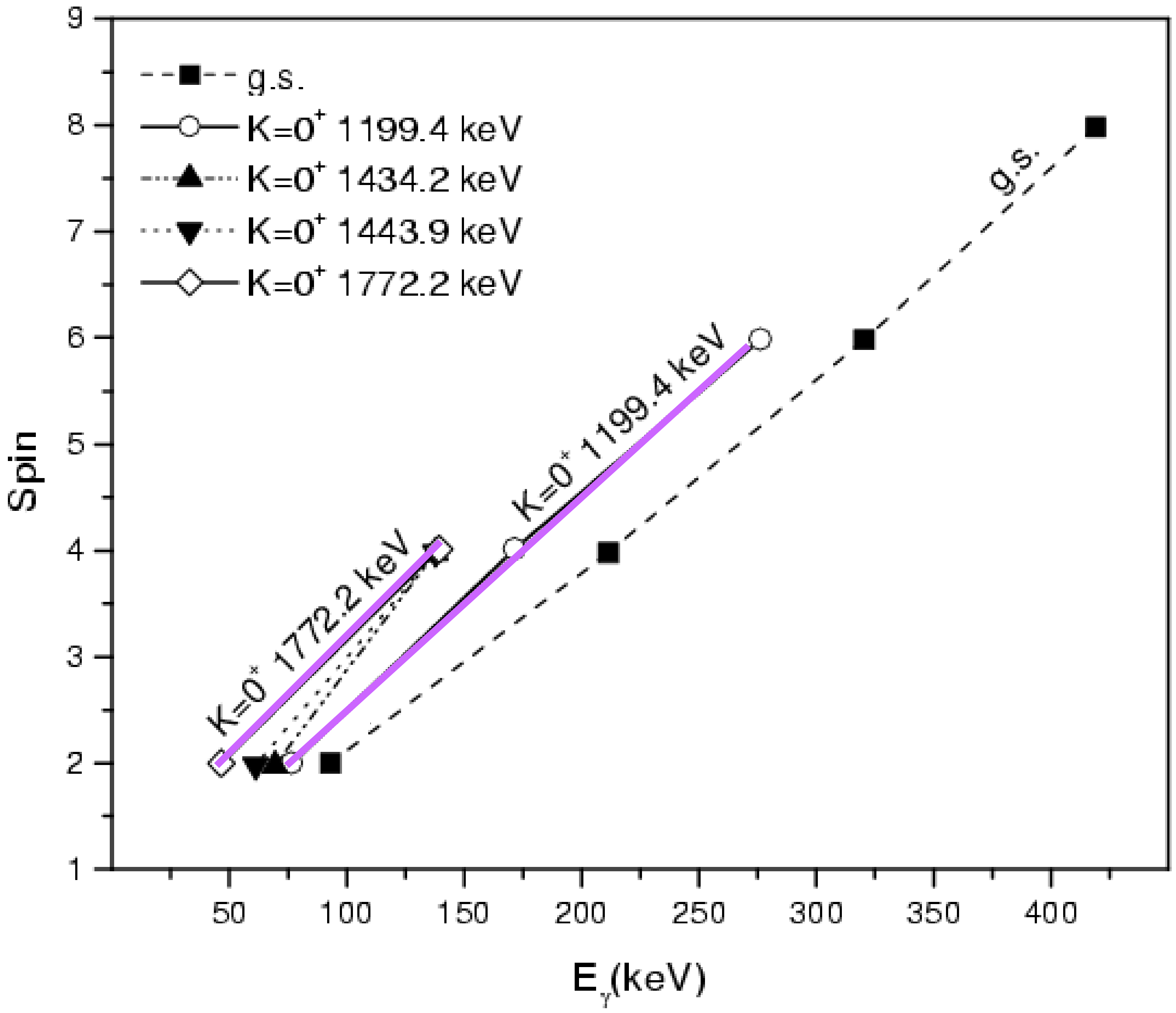
0+ 1434.2

0+ 1772.2 keV

Aprahamian, Phys. Rev. C65, 031301R (2002)

Gamma-ray Spectroscopy

Dynamic moments of Inertia



Aprahamian, Phys.Rev. C65, 031301R (2002)

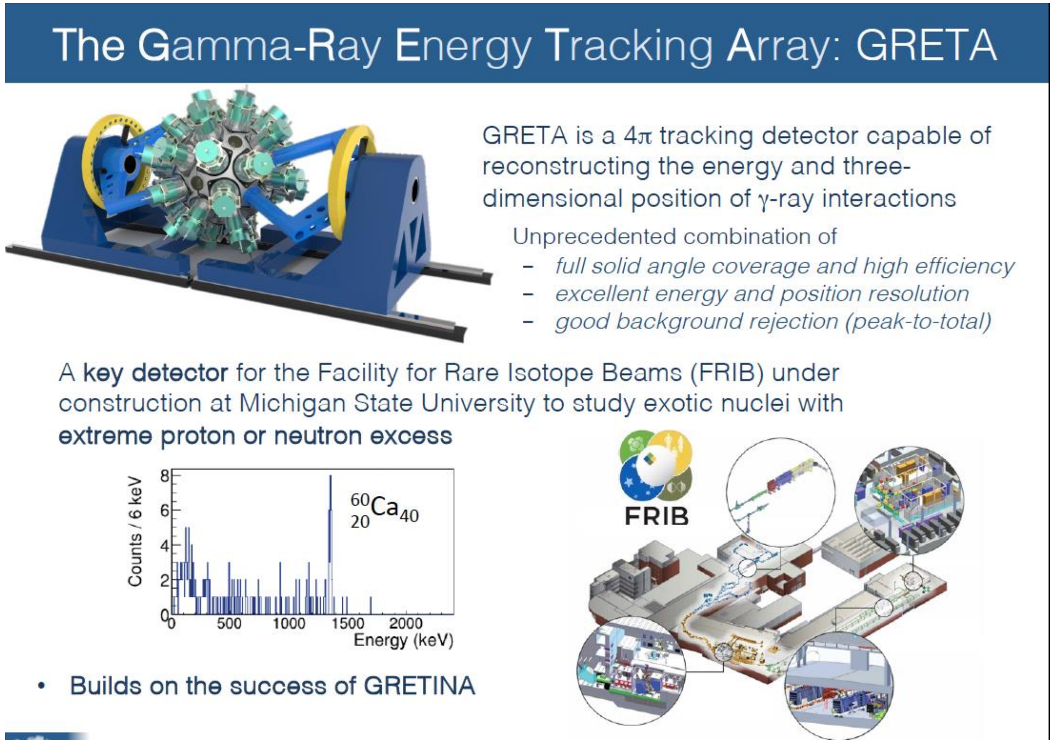
Observables for nuclear structure studies:

Energy Levels from gamma-ray spectroscopy: Level energy ratios

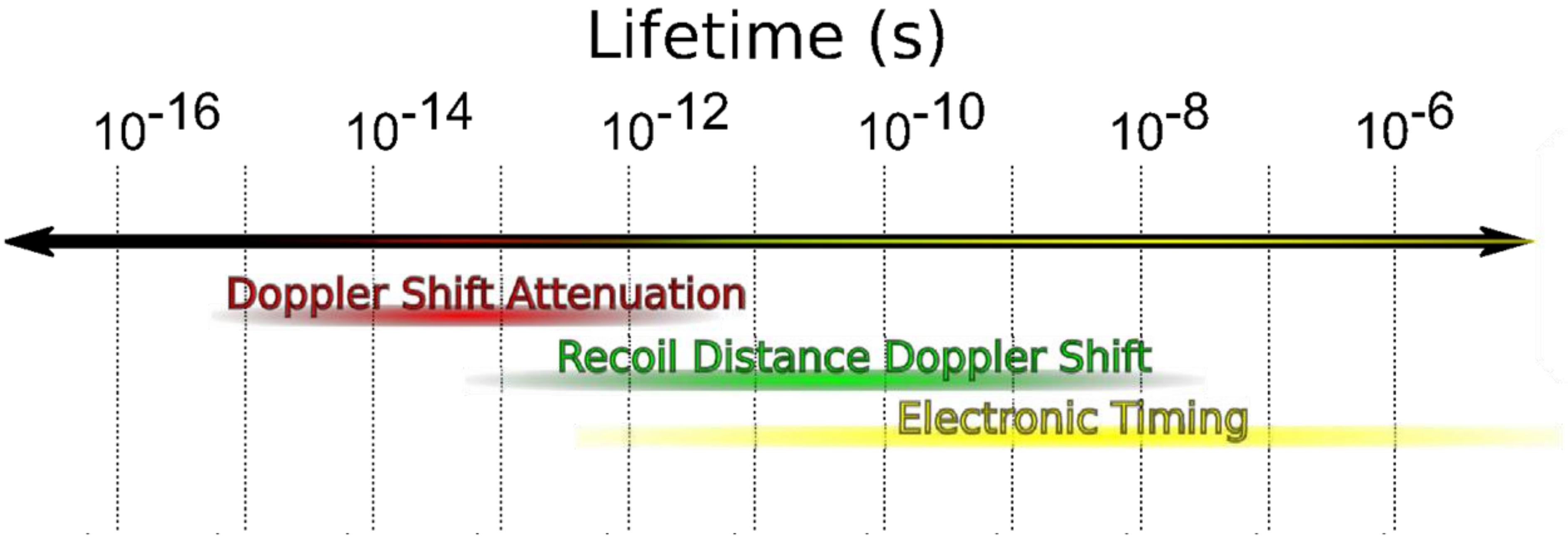
Masses of Nuclei from traps: proton and neutron separation energies

Reaction cross sections by spectrometers

Lifetimes of excited states: Transition Rates



Lifetime Techniques



adapted from
Klaus-Peter Lieb, "The Measurement of Nuclear Lifetimes"
Experimental Techniques in Nuclear Physics
ed. D. N. Poenaru, W. Greiner. 1997

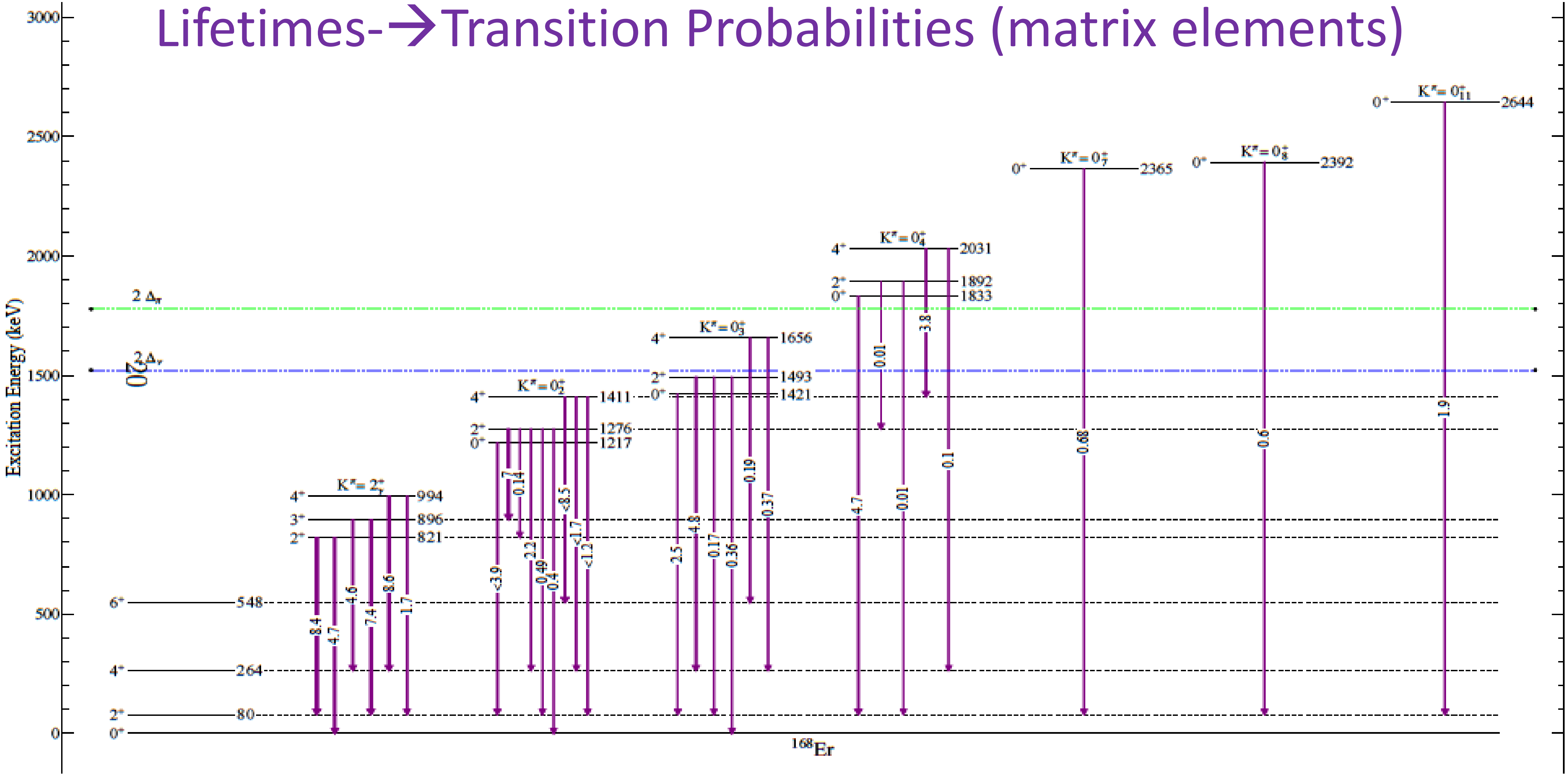
DSAM: Inelastic neutron scattering (n,n'γ)

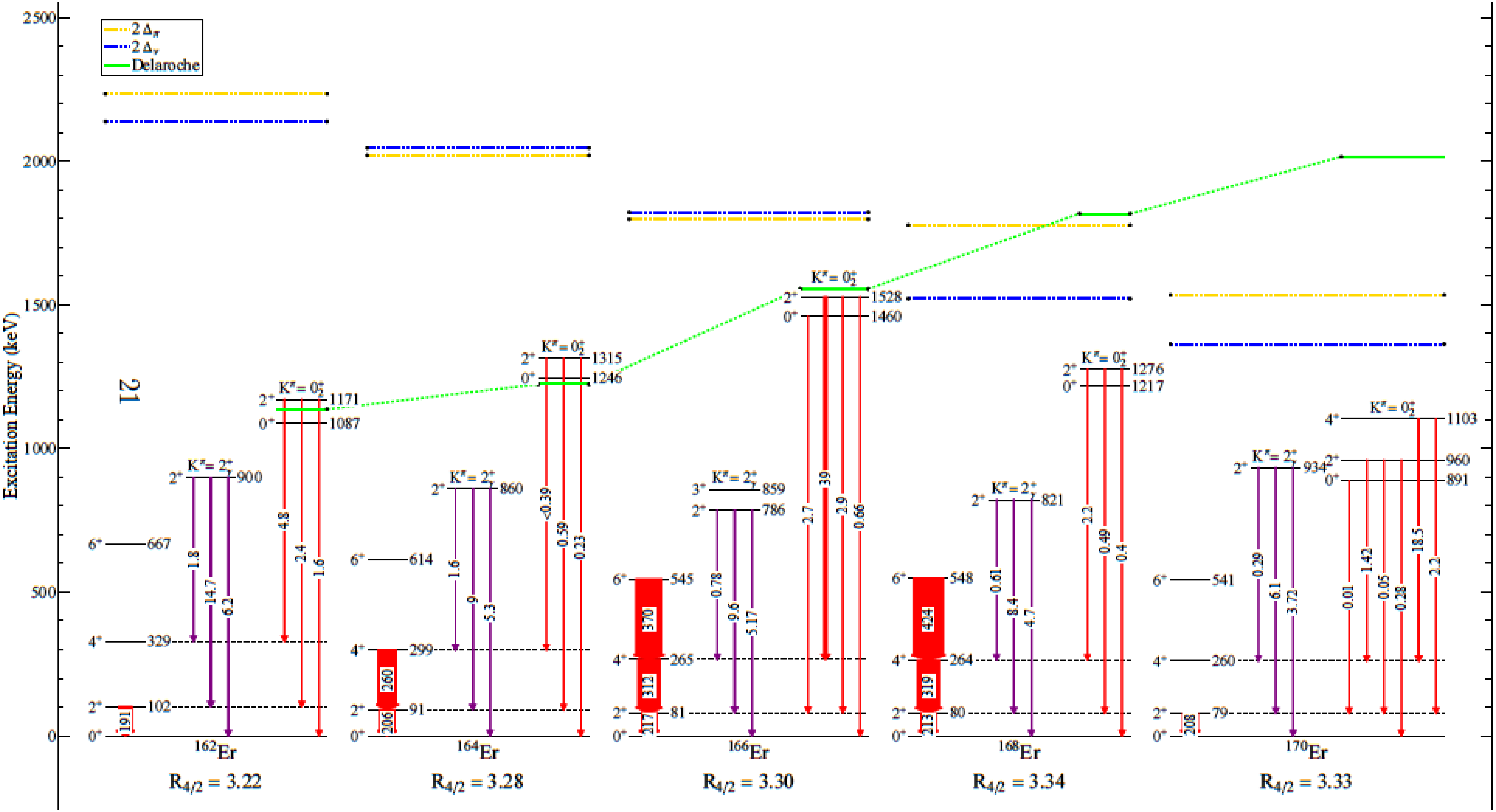
fs to ps range of lifetimes
Stable target/beam combinations

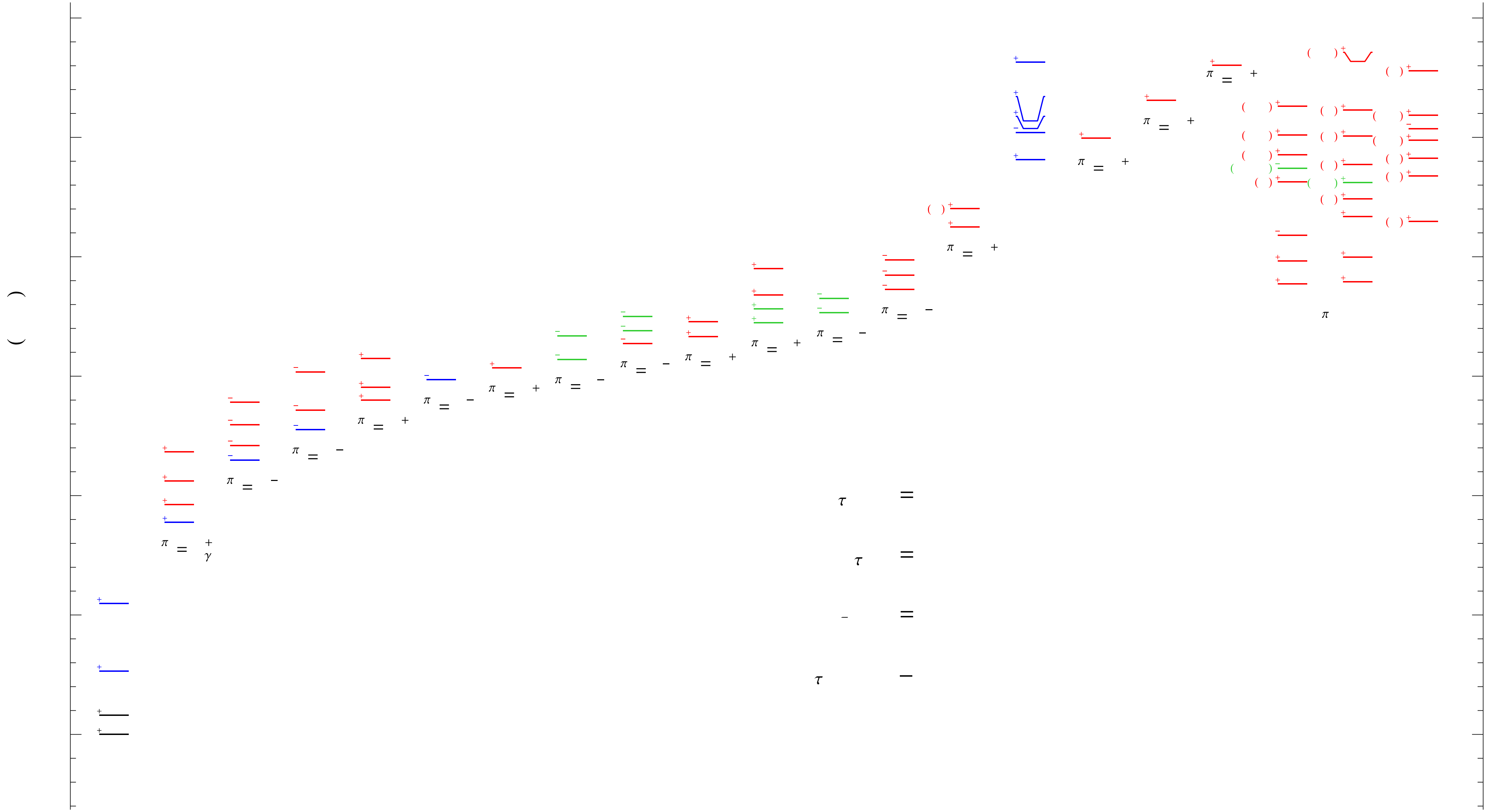
$$E_\gamma(\theta_\gamma) = E_0[1 + F_{\mathrm{exp}}(\tau)\frac{v_{\mathrm{cm}}}{c}\cos\theta_\gamma]$$

$F_{\mathrm{exp}}(\tau)$ Is the experimental attenuation factor determined from the measured Doppler shift and compared to calculated Ones to determine the lifetime of the state.

Lifetimes→Transition Probabilities (matrix elements)




Excitation Energy (keV)
2500
2000
1500
1000
500
0
2 Δπ
2 Δν
Delaroche
^{162}Er
$R_{4/2}$ = 3.22
^{164}Er
$R_{4/2}$ = 3.28
^{166}Er
$R_{4/2}$ = 3.30
^{168}Er
$R_{4/2}$ = 3.34
^{170}Er
$R_{4/2}$ = 3.33
$K^\pi = 2^+_\gamma$
$K^\pi = 0^+_2$
0+ 2+ 102 4+ 329 6+ 667 2+ 900 0+ 1087 2+ 1171
0+ 2+ 91 4+ 299 6+ 614 2+ 860 0+ 1246 2+ 1315
0+ 2+ 81 4+ 265 6+ 545 2+ 786 3+ 859 0+ 1460 2+ 1528
0+ 2+ 80 4+ 264 6+ 548 2+ 821 0+ 1217 2+ 1276
0+ 2+ 79 4+ 260 6+ 541 2+ 934 0+ 891 2+ 960 4+ 1103
191 1.8 14.7 6.2 4.8 2.4 1.6
206 260 1.6 9 5.3 <0.39 0.59 0.23
217 312 370 0.78 9.6 5.17 2.7 39 2.9 0.66
213 319 424 0.61 8.4 4.7 2.2 0.49 0.4
208 0.29 6.1 3.72 0.01 1.42 0.05 0.28 18.5 2.2

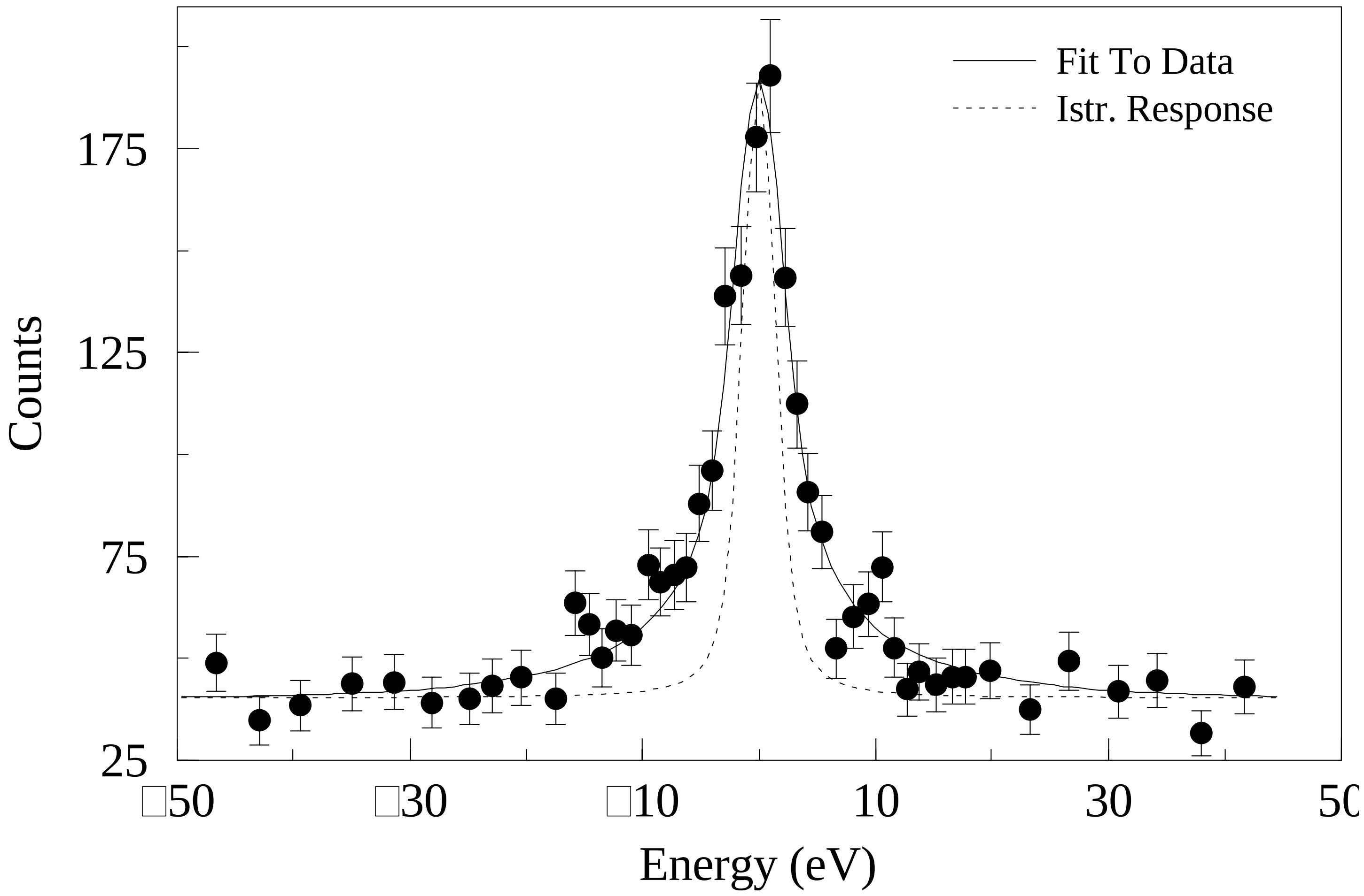


GRID: Sub-picosecond lifetime measurements by gamma ray induced Doppler broadening

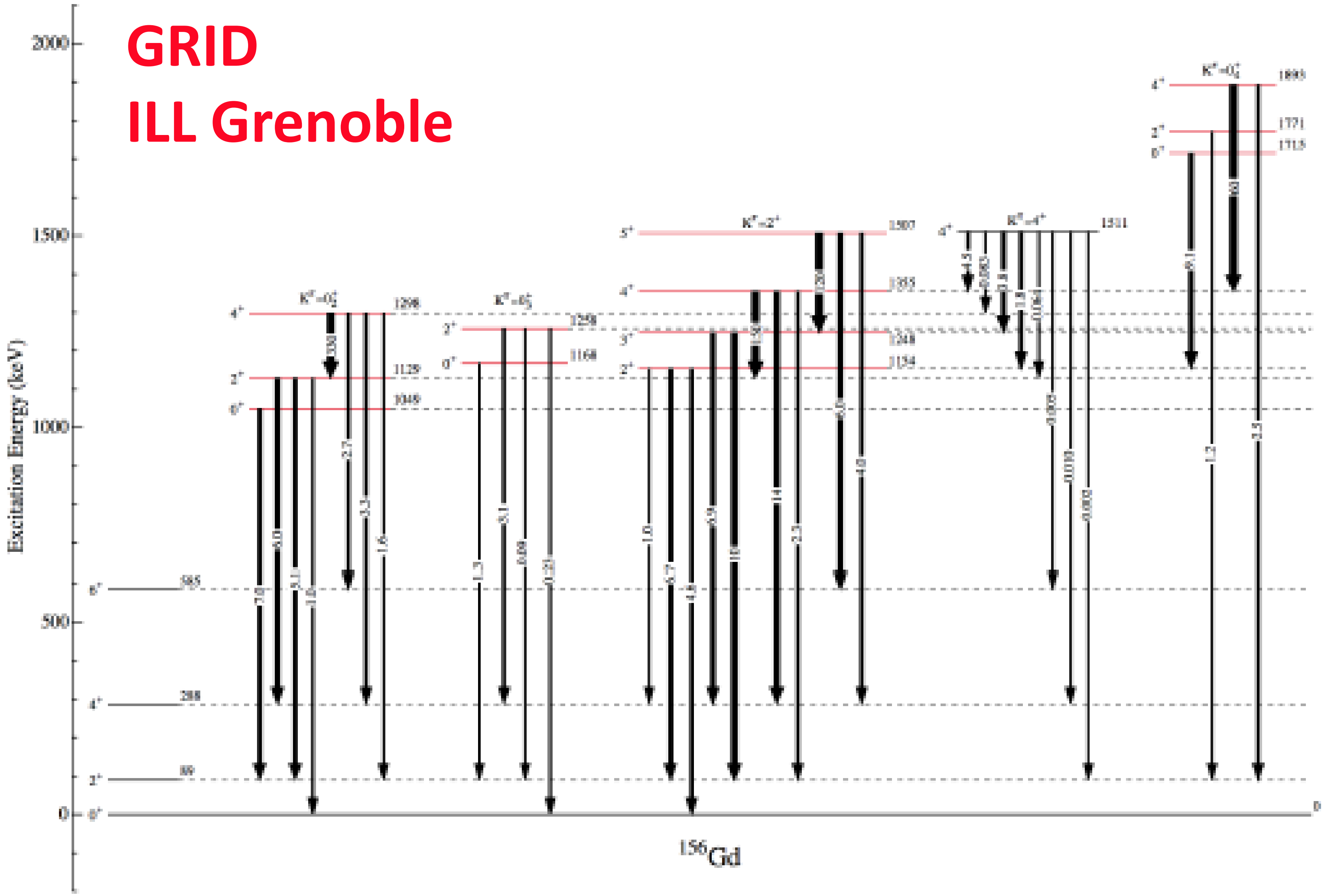
Thermal neutron capture……excited by the neutron binding energy (~ 8-10 MeV)
Thermal neutron energies ~25 meV not significant

Excited nucleus de-excites by emission of gamma-rays

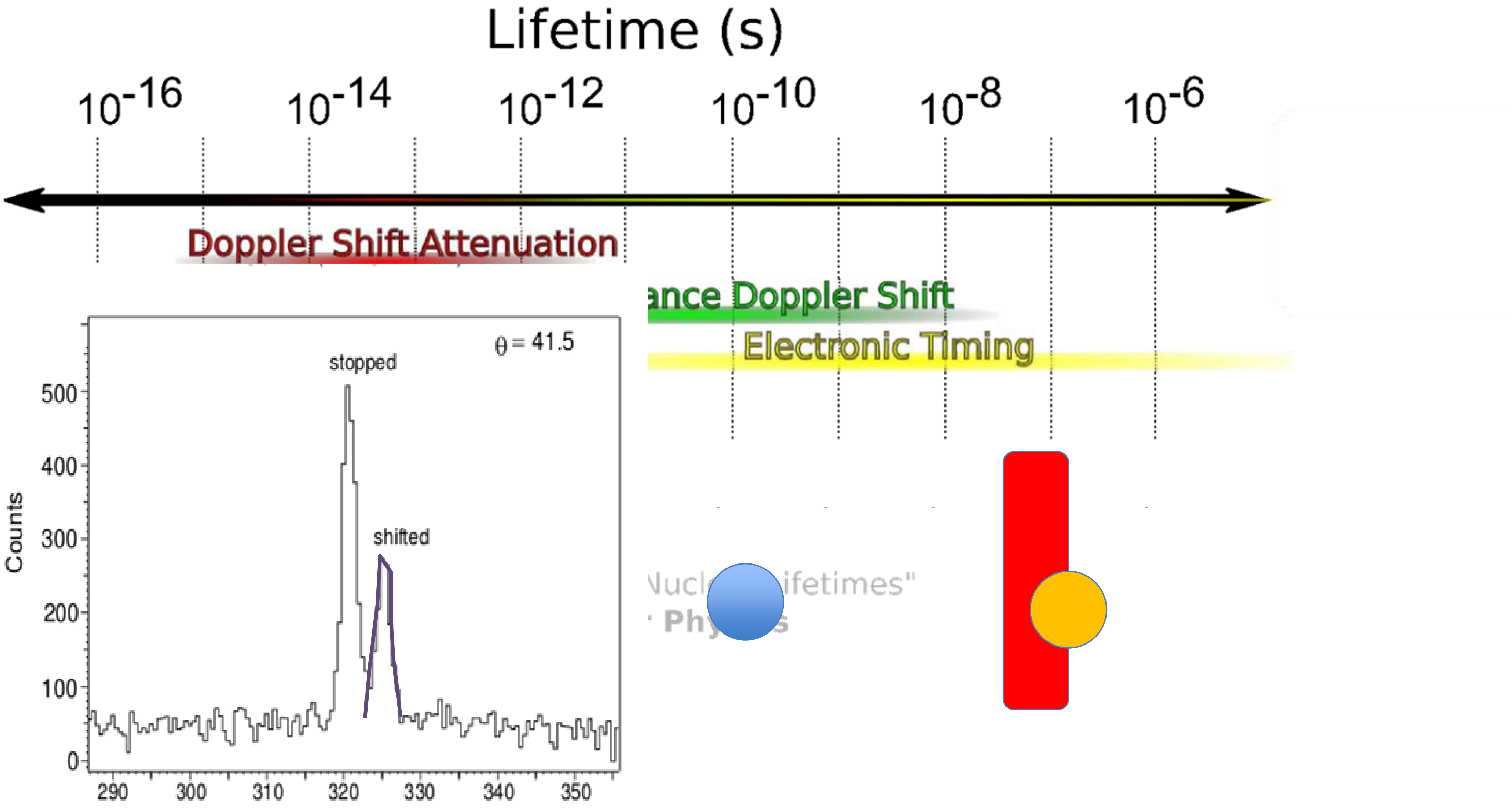
GAMS 4 Spectrometer @ILL
Gamma Ray Induced Doppler Broadening



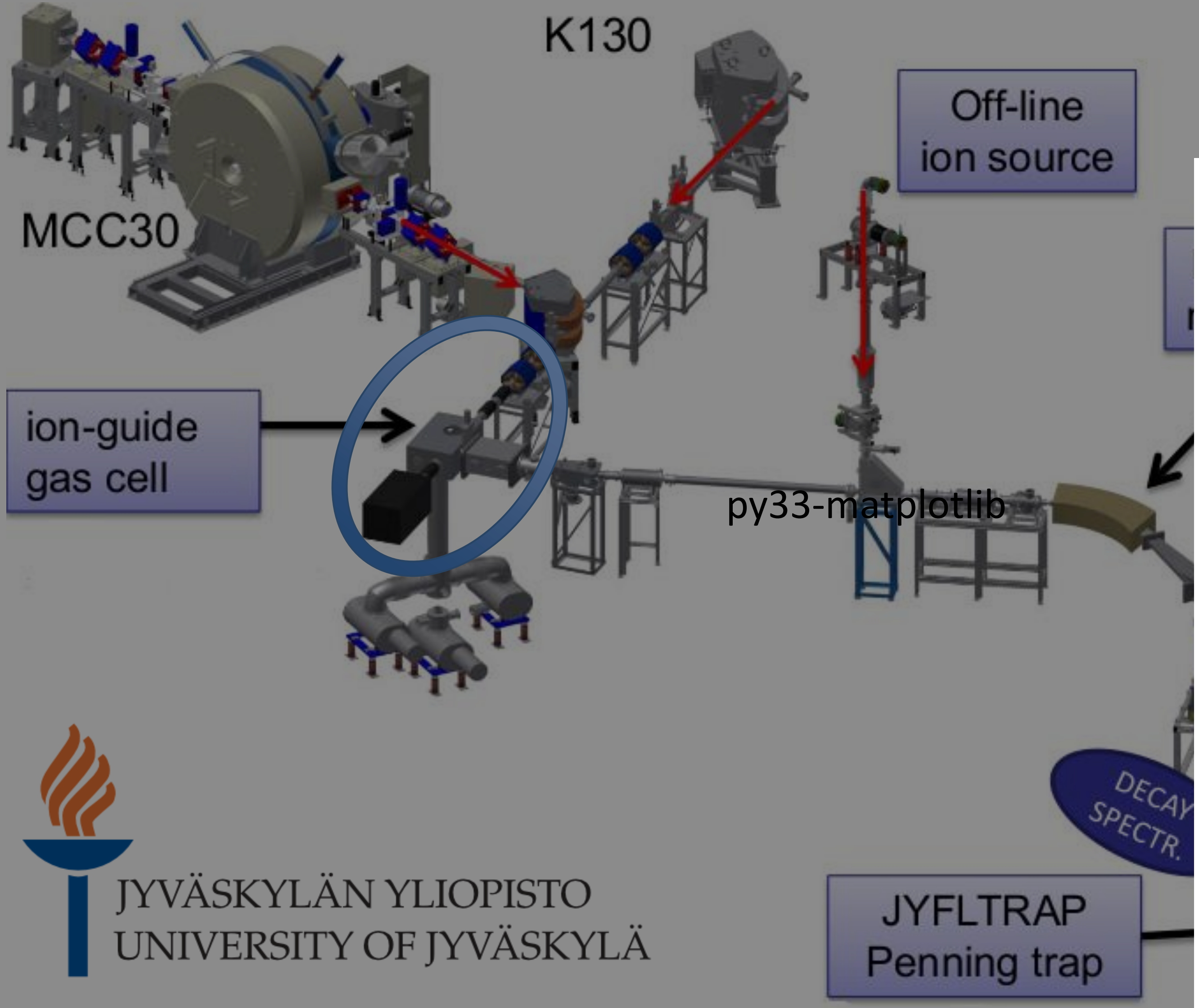
GRID
ILL Grenoble

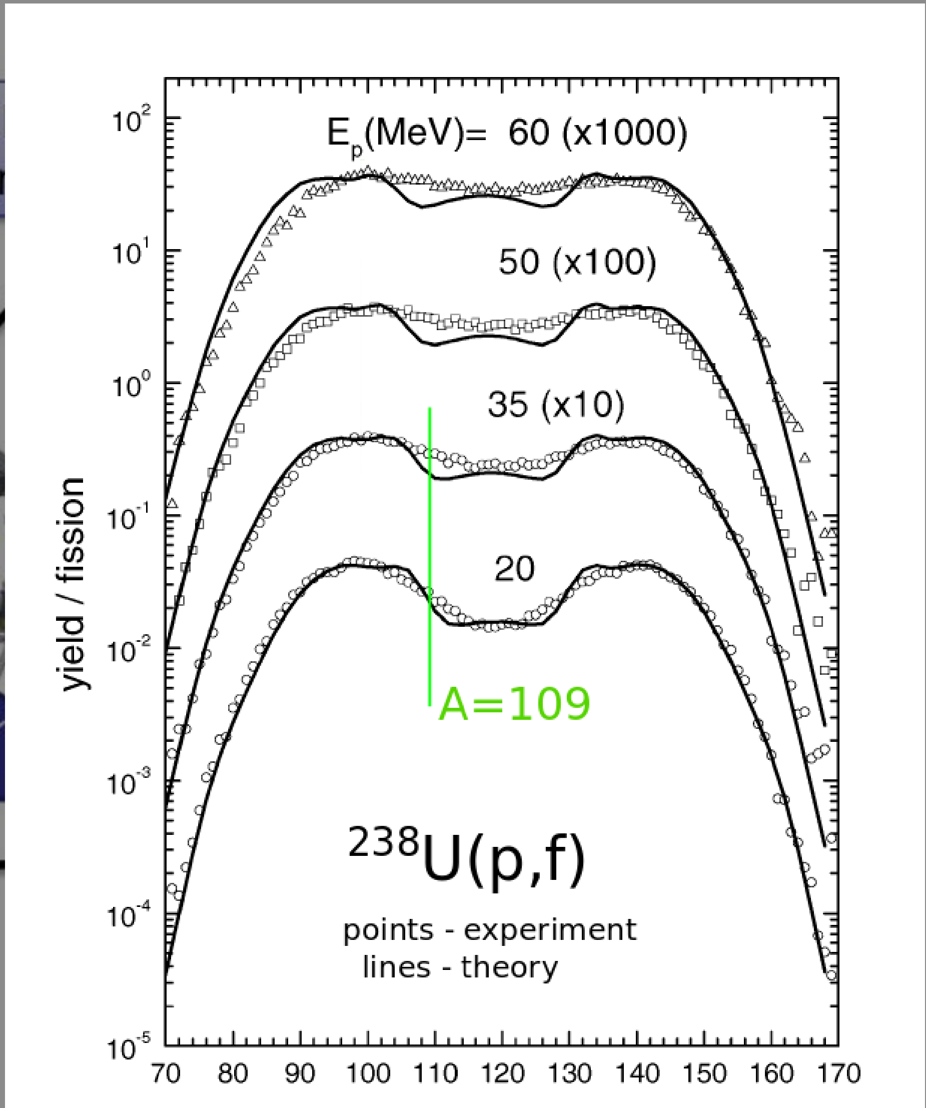


Lifetime Techniques



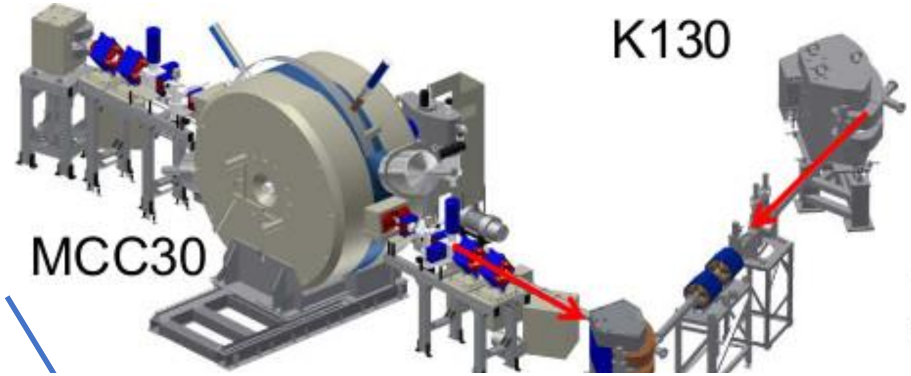
IGISOL – Current Layout

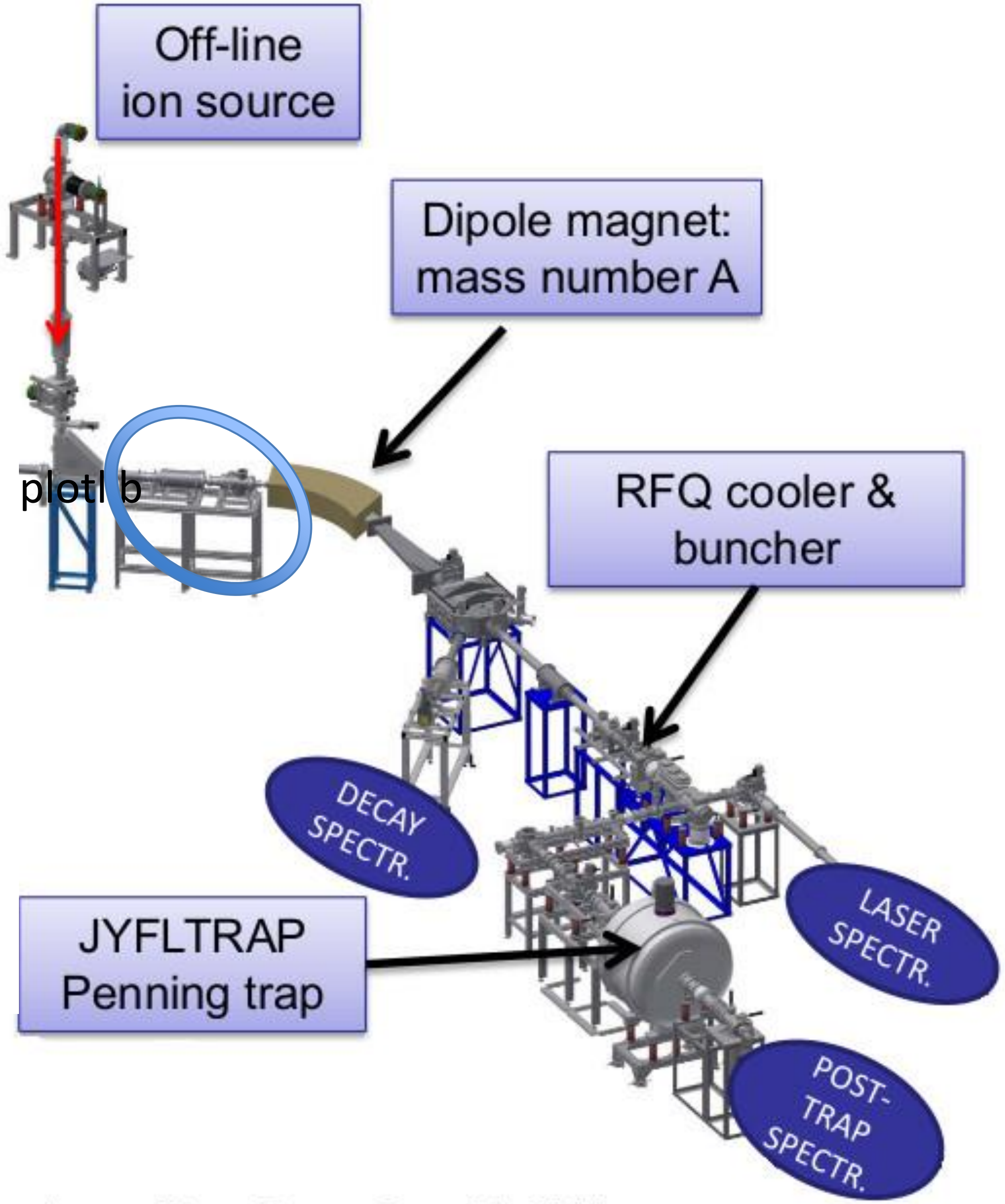


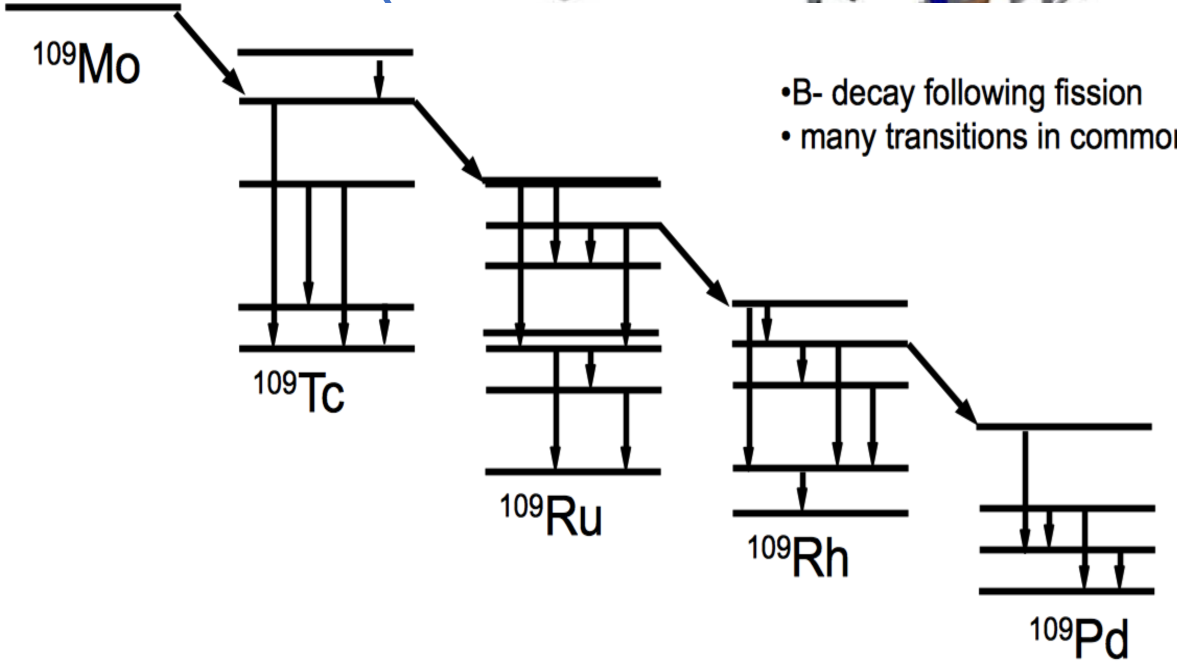


Courtesy of A. Kankainen

IGISOL – Current Layout

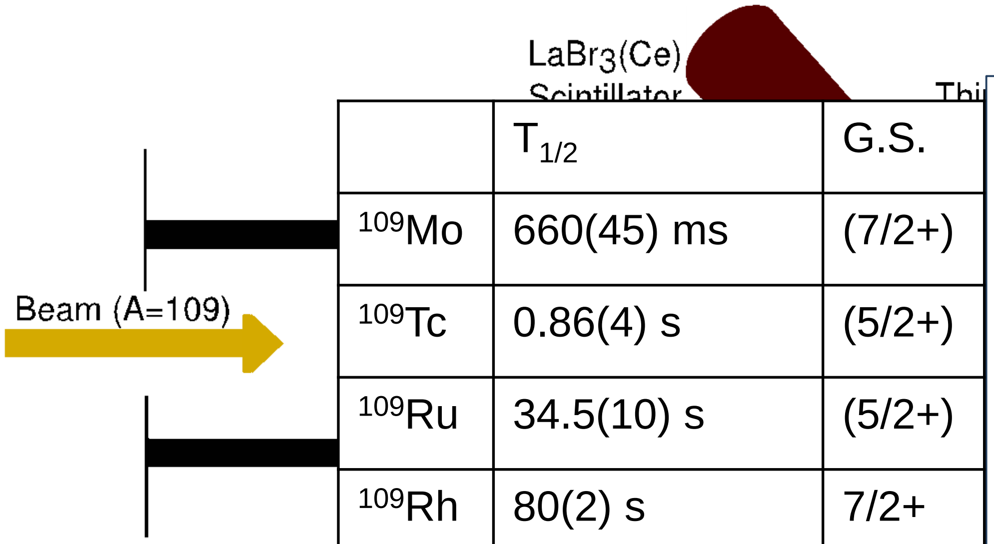




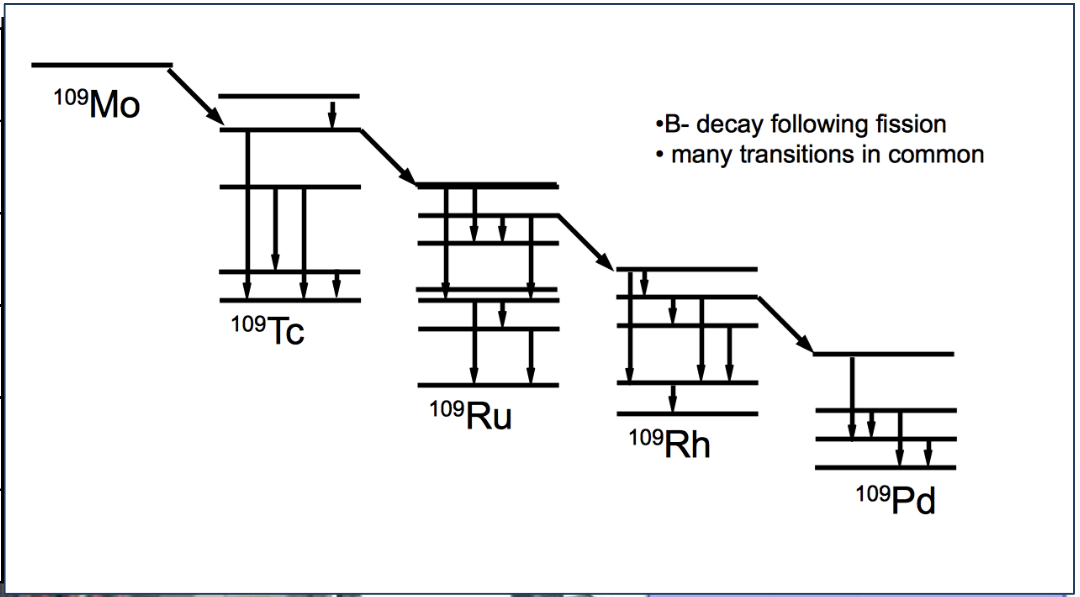


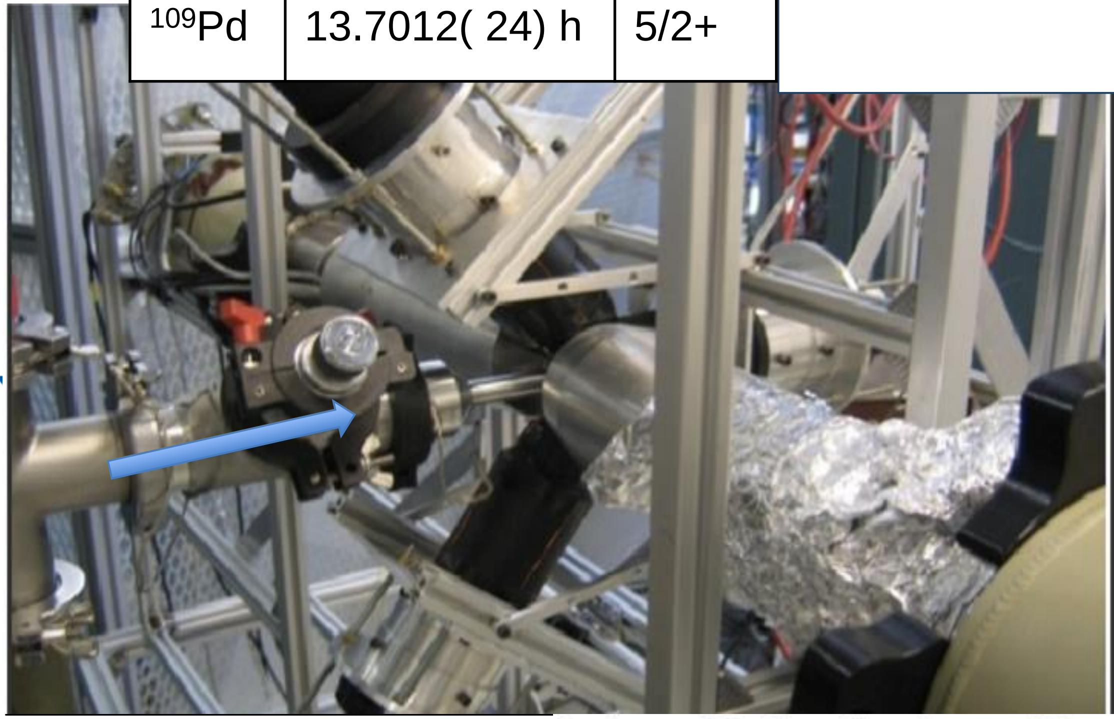
- B- decay following fission
- many transitions in common

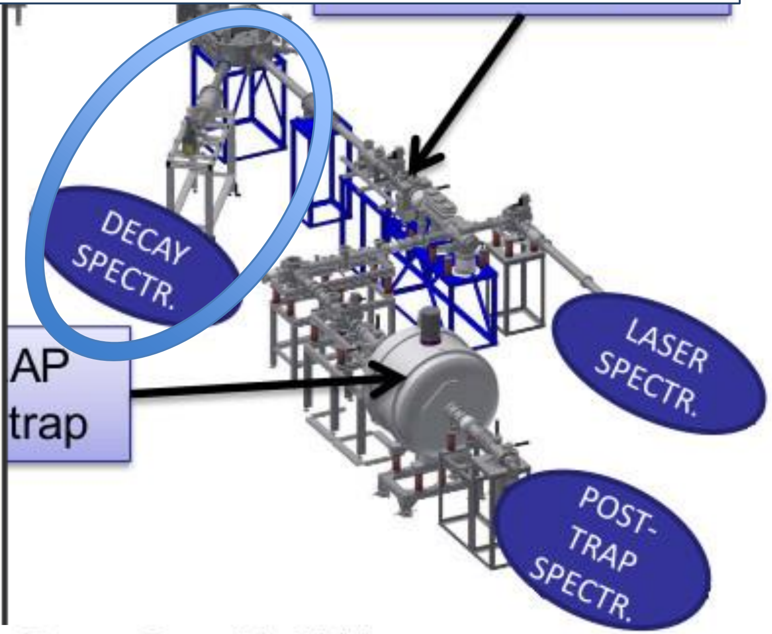
IGISOL – Current Layout



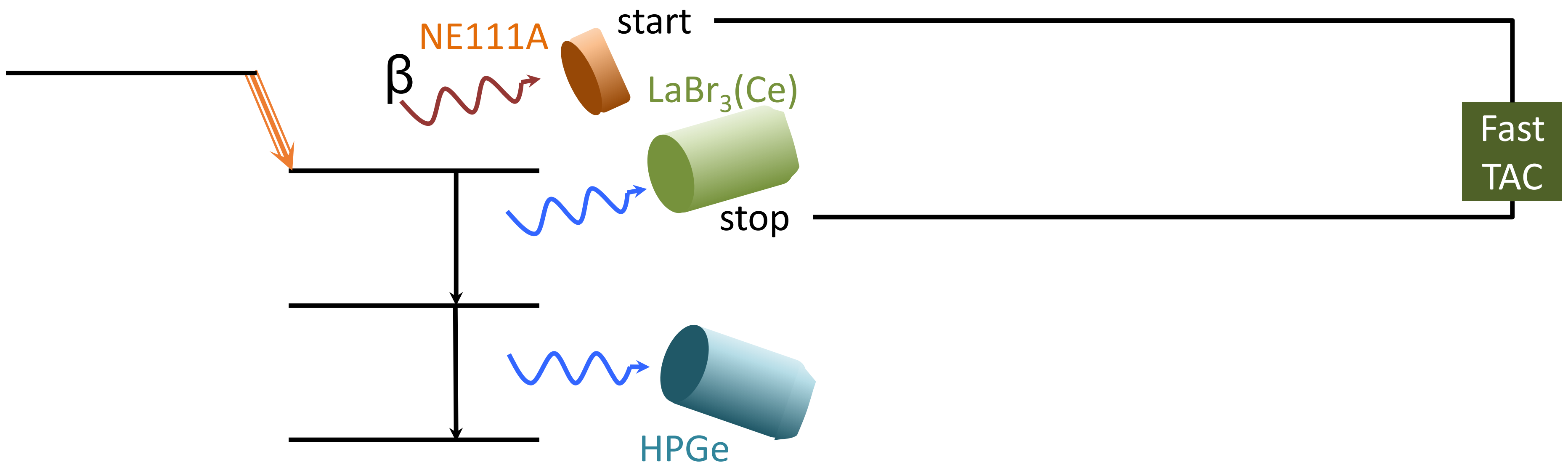
	$T_{1/2}$	G.S.
^{109}Mo	660(45) ms	(7/2+)
^{109}Tc	0.86(4) s	(5/2+)
^{109}Ru	34.5(10) s	(5/2+)
^{109}Rh	80(2) s	7/2+
^{109}Pd	13.7012(24) h	5/2+







Advanced Time Delay Technique

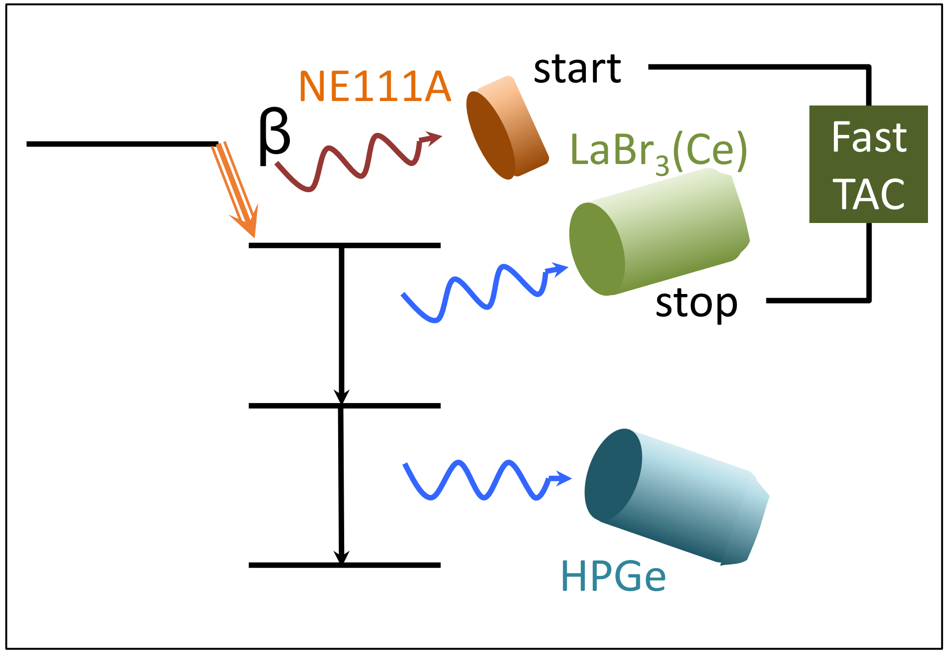


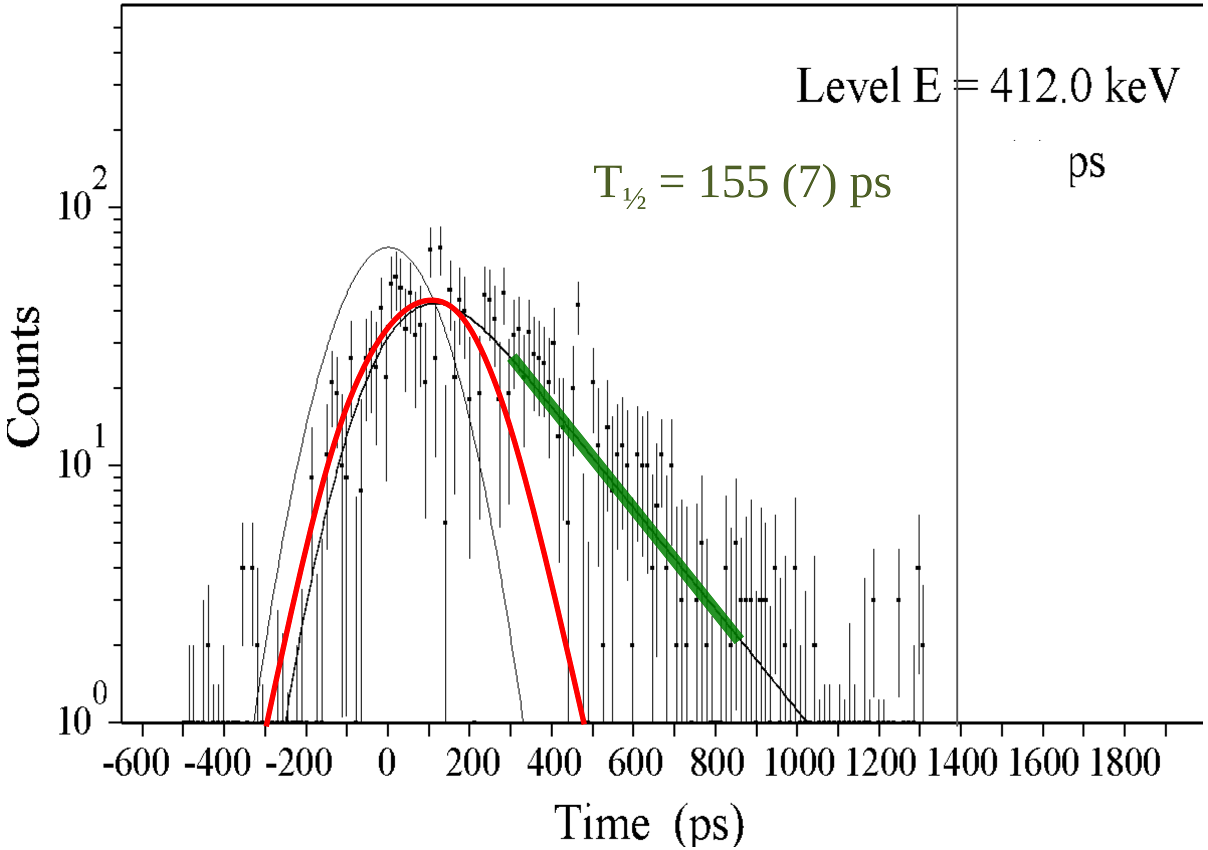
Advanced Time Delay Technique

- Developed by Henryk Mach

Slope Fitting Method

$$F(t_j) = \gamma \int_A^{+\infty} e^{-\delta(t_j - t)^2} e^{-\lambda(t-A)} dt$$

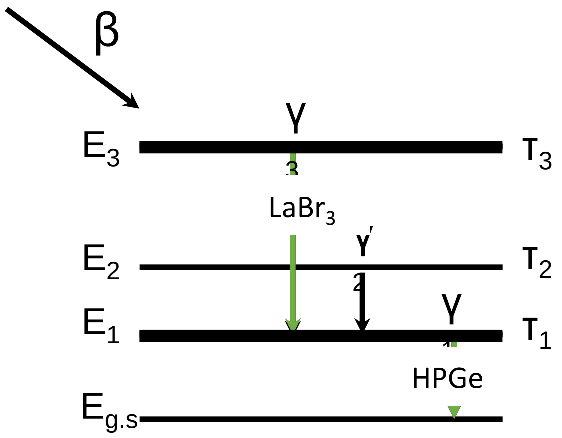




Centroid Shift Method

- In some cases, the level lifetime is too short to leave a measurable slope in the TAC spectrum
- 2 methods to get lifetime from relative comparisons

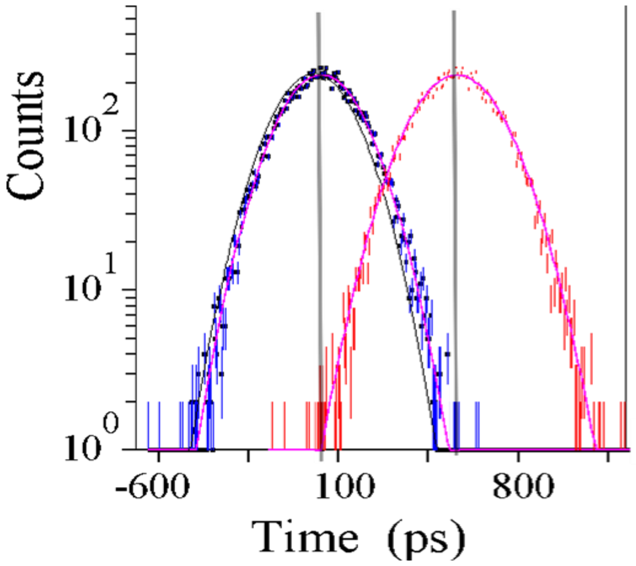
- **Sequential Transitions**



$t_3 = \tau_0 + \tau_3 + \tau_1$ ⟶ β−HPGe(γ_3)-LaBr$_3$(γ_1)

$-\quad t_1 = \tau_0 + \tau_3$ ⟶ β−HPGe(γ_1)-LaBr$_3$(γ_3)

$t_3 - t_1 = \tau_1$

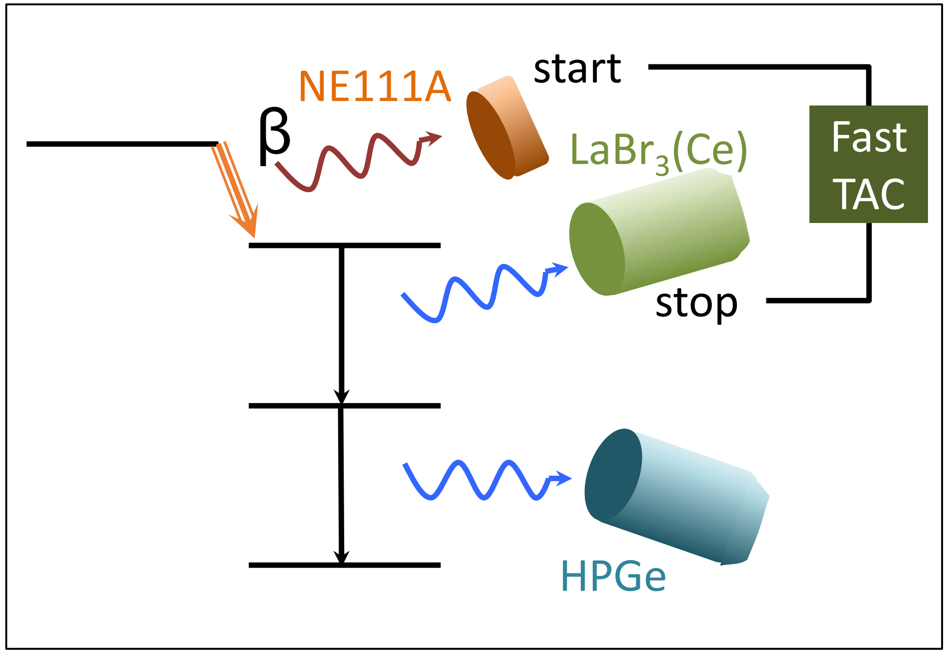


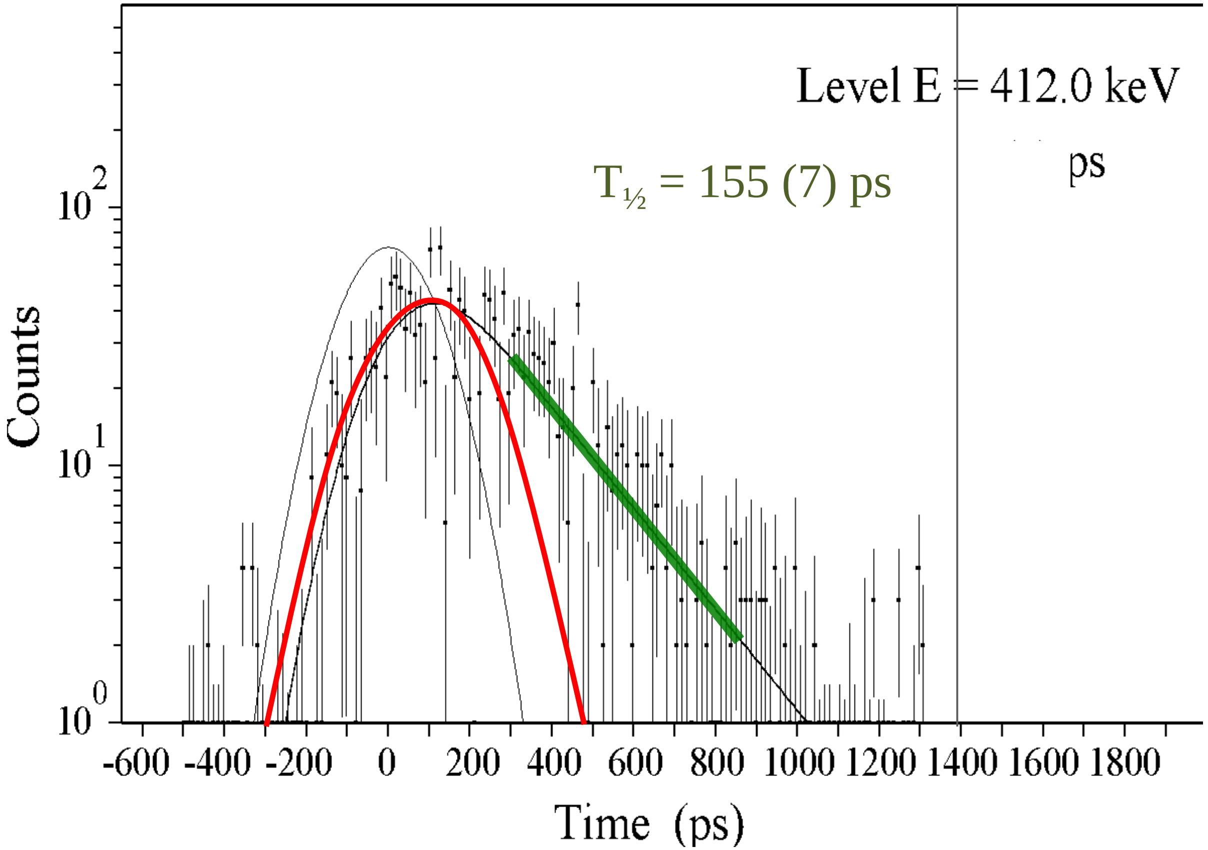
Advanced Time Delay Technique

- Developed by Henryk Mach

Slope Fitting Method

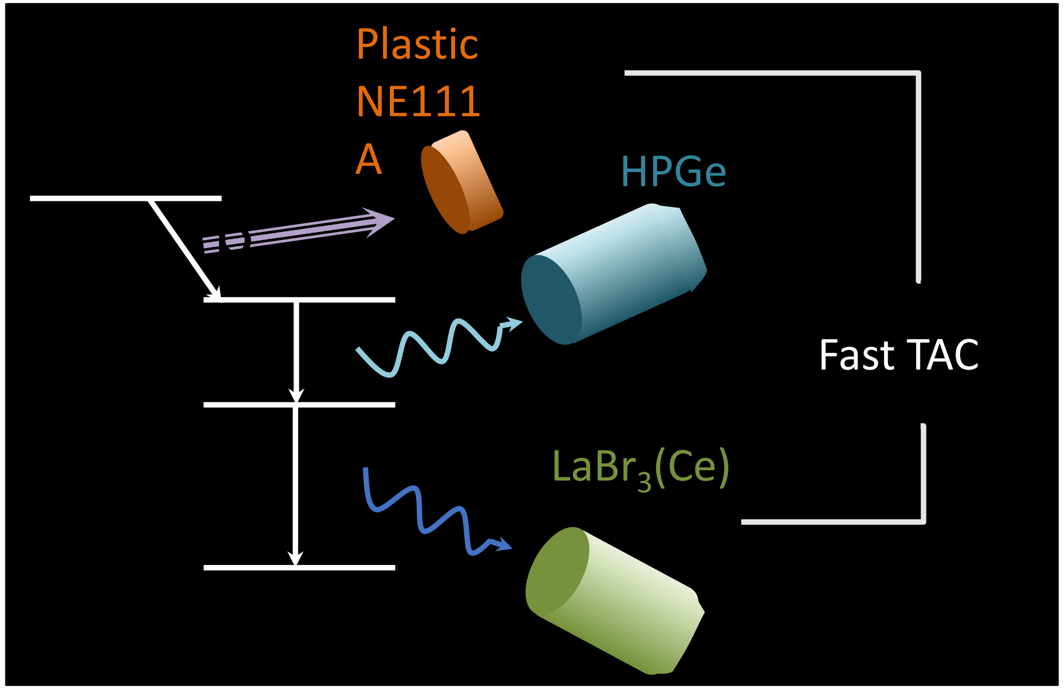
$$F(t_j) = \gamma \int_A^{+\infty} e^{-\delta(t_j - t)^2} e^{-\lambda(t-A)} dt$$





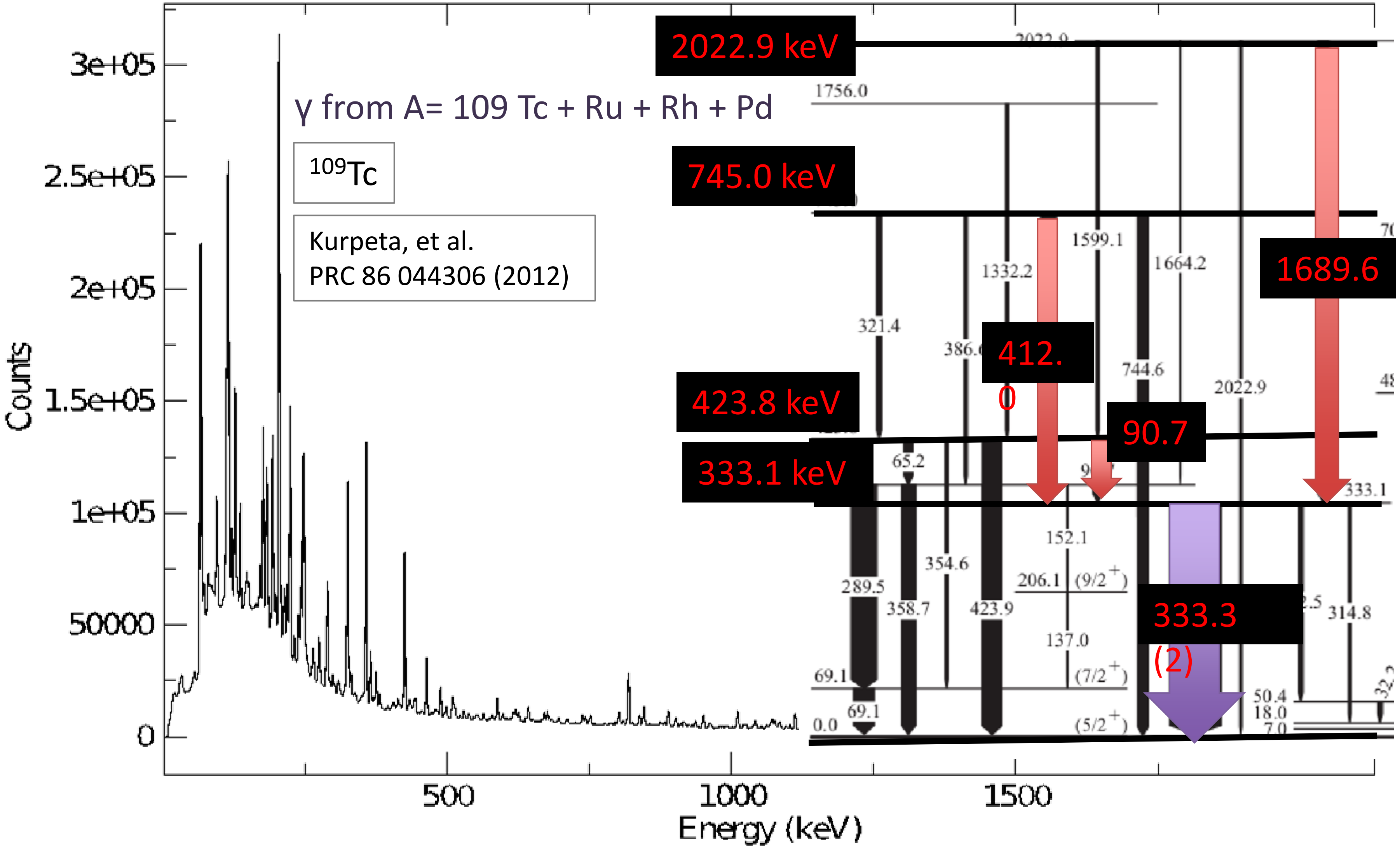
β−γ−γ Triple Coincidences

- β−γ−γ Required
- Timing = β-LaBr$_3$-Ge
- Trigger window open for 500ns in HPGe detectors, 50ns in LaBr$_3$(Ce)

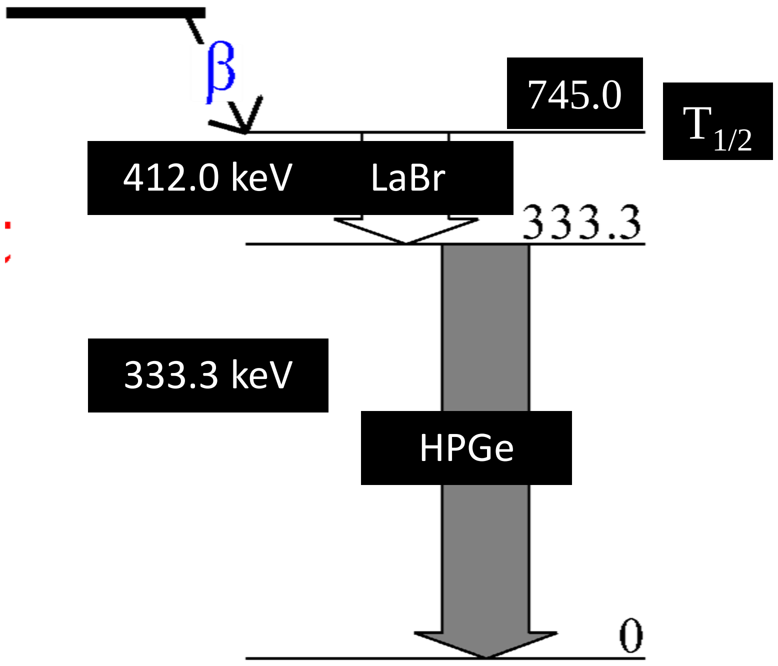


- Energy calibration:
  For both HPGe & LaBr$_3$ detectors using well known peaks in ^{109}Rh
- Timing calibration (walk curve): Time signal is energy dependent
  - NE111A calibrated with known β−γ−γ cascade
  - LaBr$_3$(Ce) calibrated using A=138 (^{138}Ba)

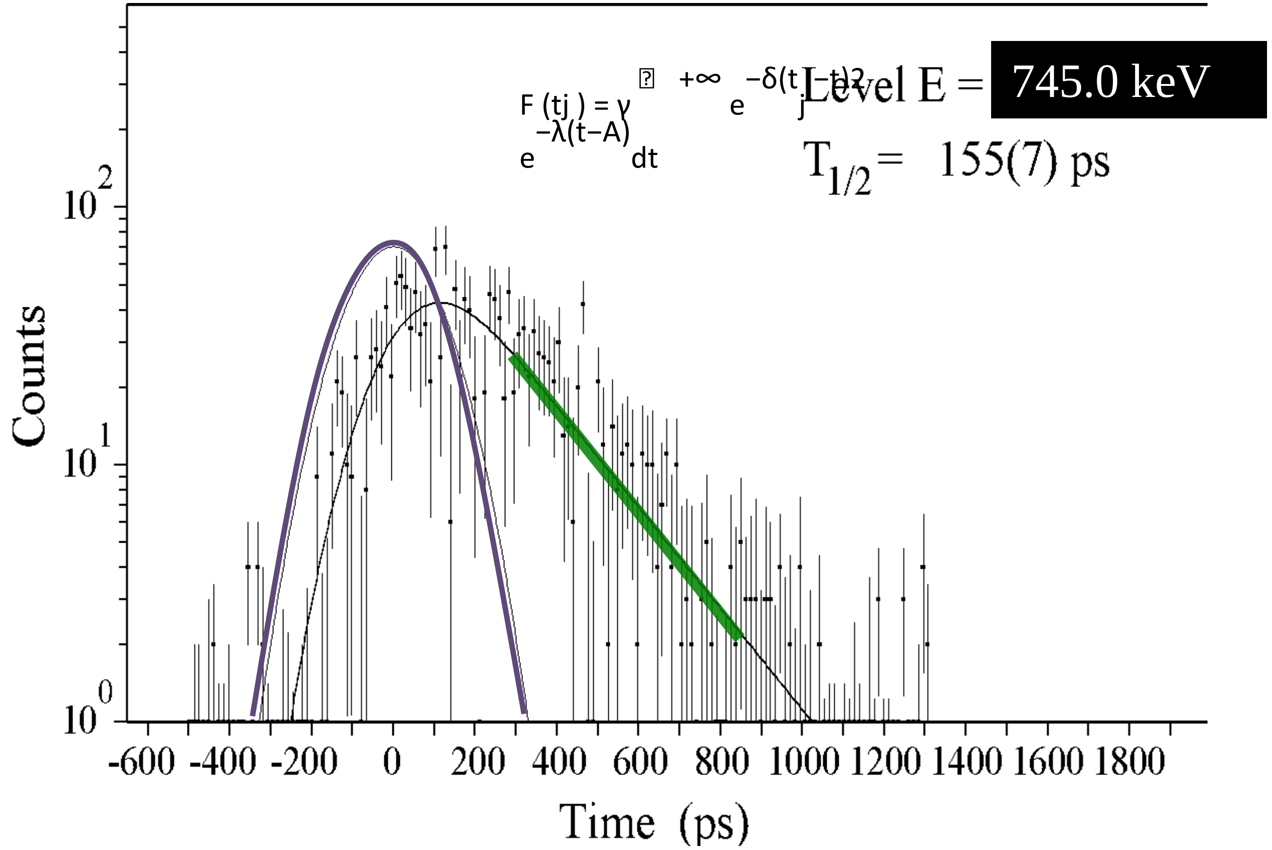
Example: β−γ−γ Coincidences for ^{109}Tc



Slope Fitting Method



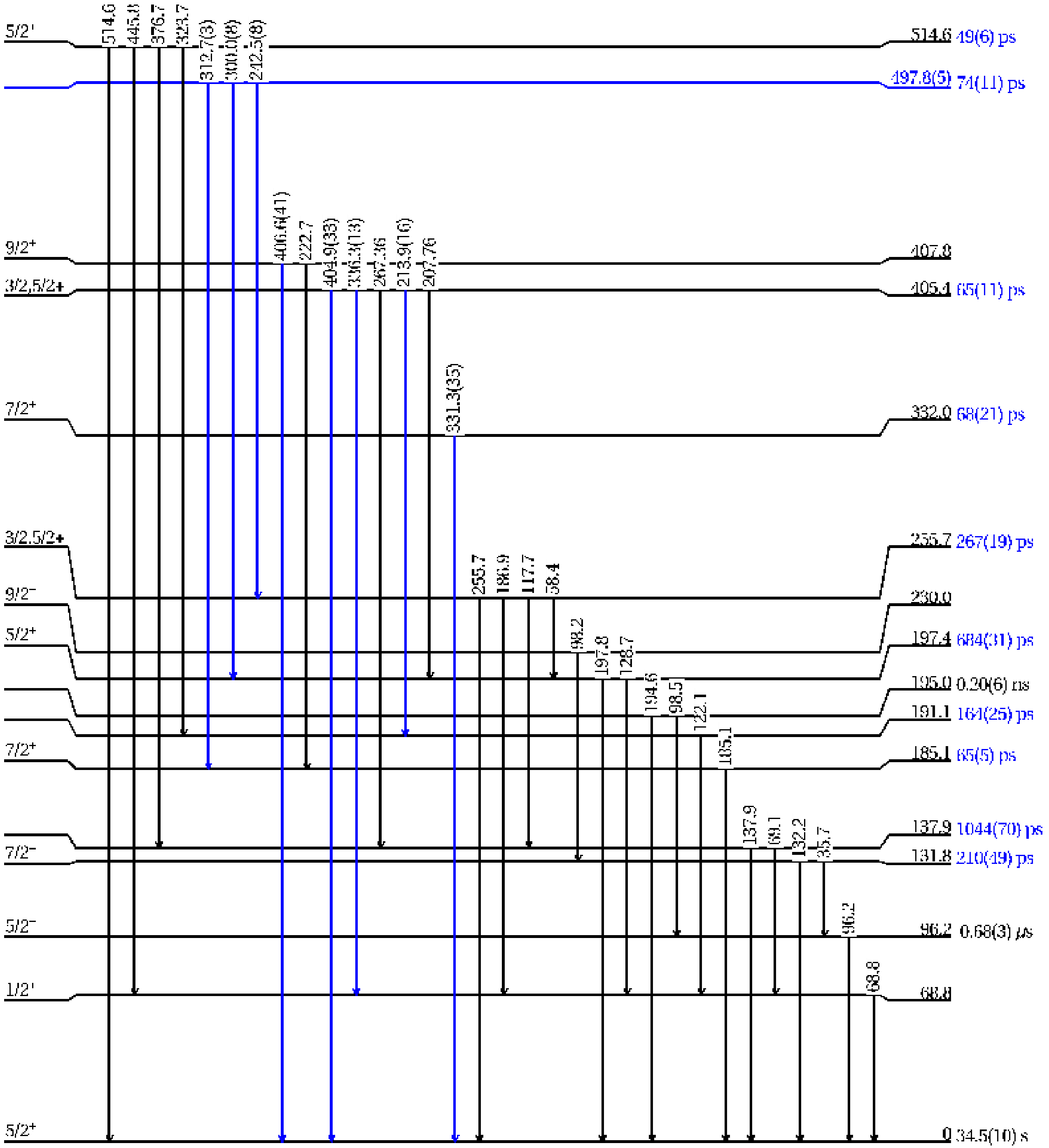
$$F(t_j) = \gamma \int_A^{+\infty} e^{-\delta(t_j - t)^2} e^{-\lambda(t-A)} dt$$



β – $LaBr_3$(412) – 333.3)

TAC Projection

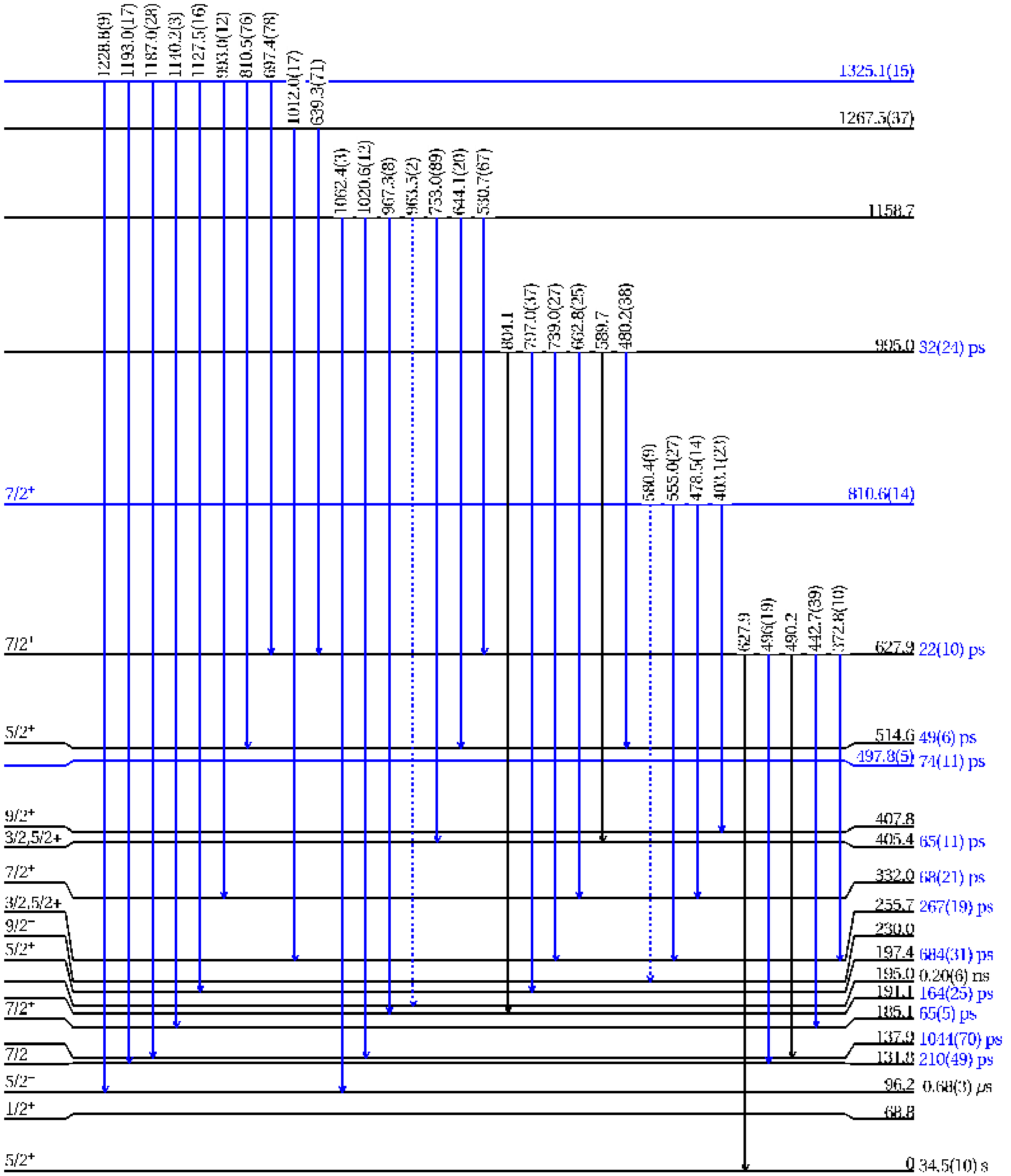
^{109}Ru Low Energy Decay Scheme



Blue = new results from this work

^{109}Ru High Energy Decay Scheme

Blue = new results from this work

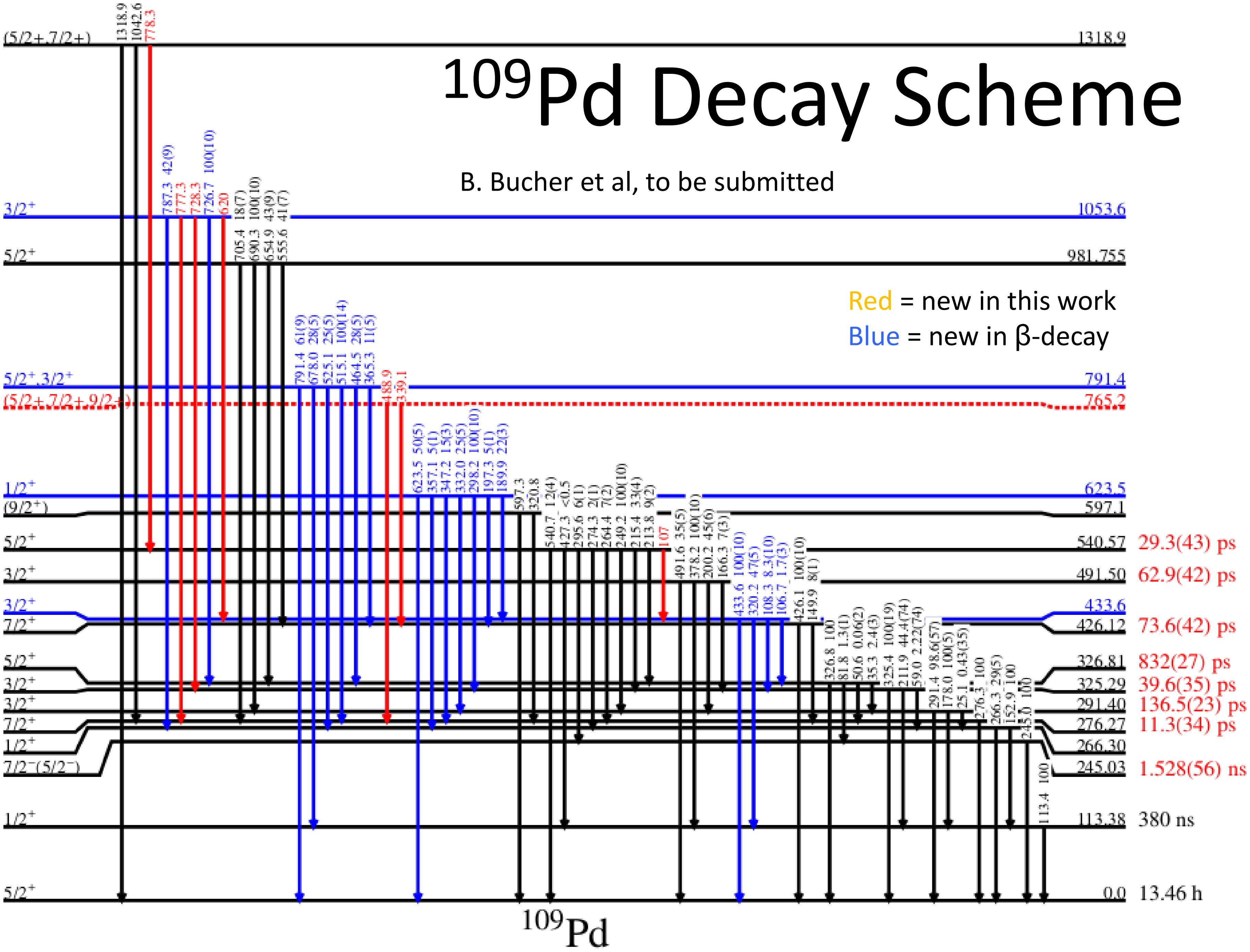


^{109}Pd Decay Scheme

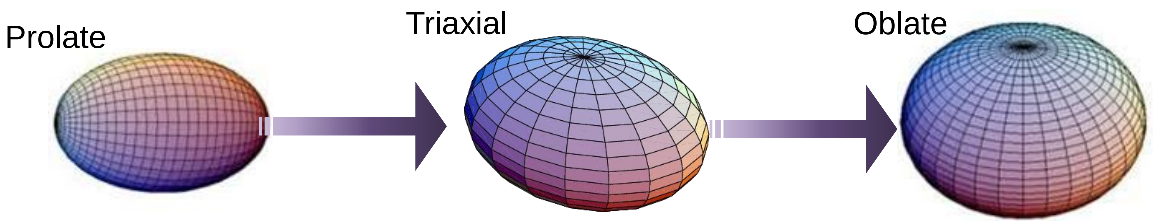
B. Bucher et al, to be submitted

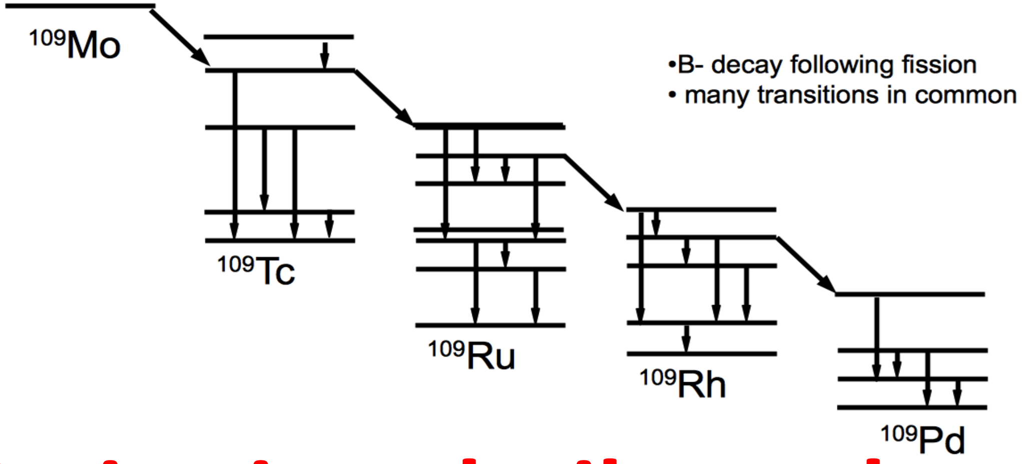
Red = new in this work

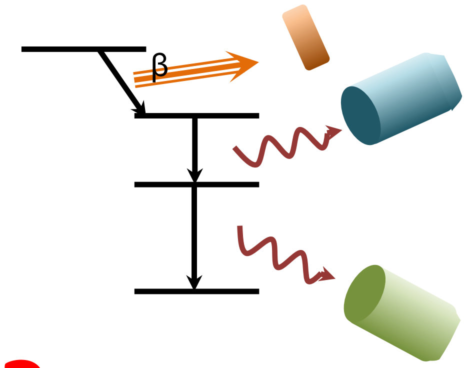
Blue = new in β-decay



Lifetime measurements of exotic nuclei







Collective Excitations built on the g.s.?

Energies of excitations

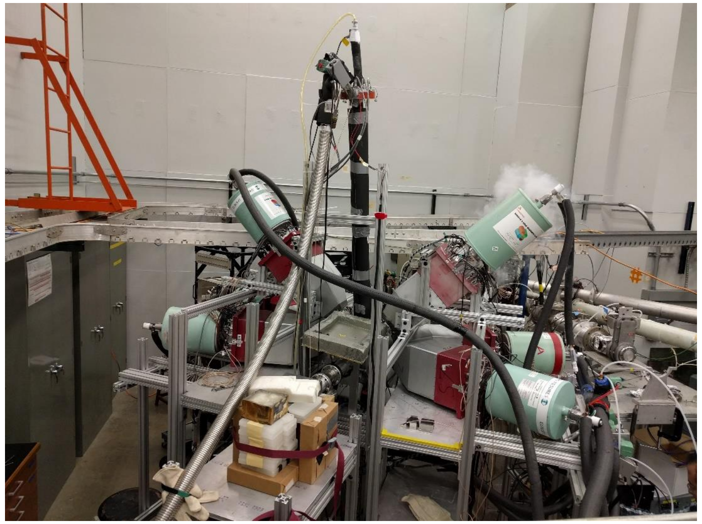
Matrix elements

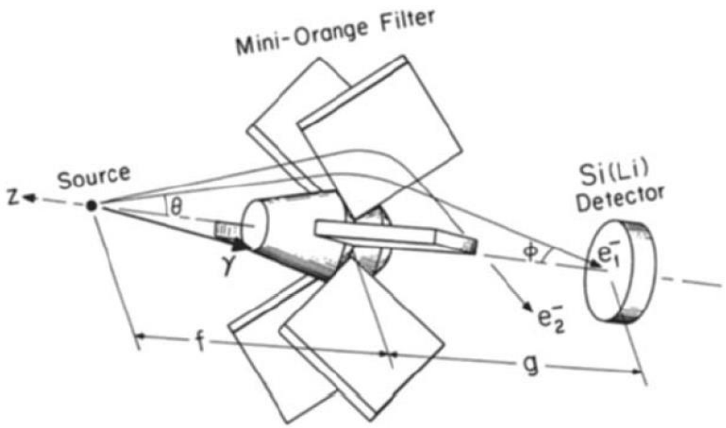
Rx cross sections

….last piece of the puzzle…..**stay tuned!**

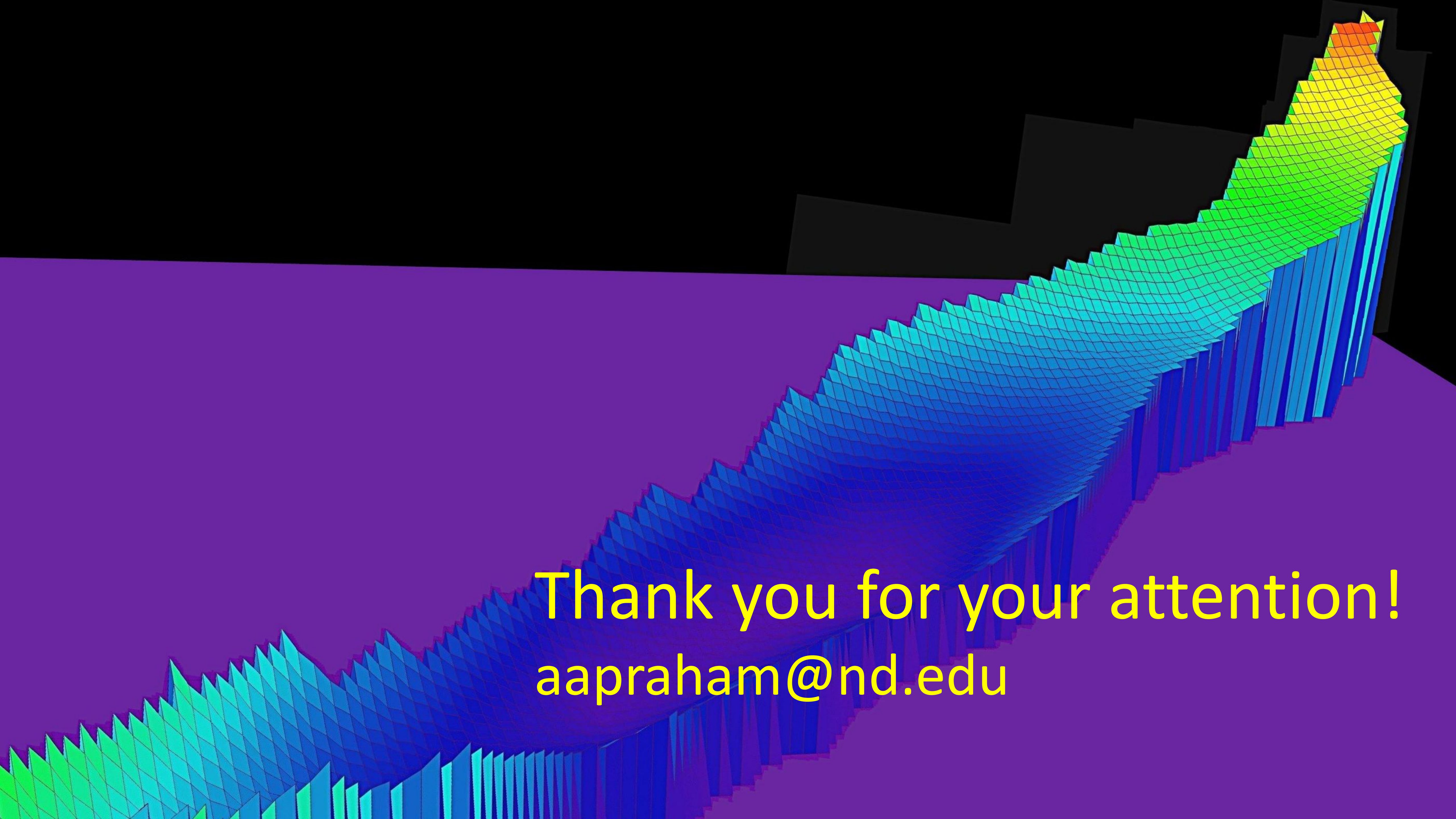
Last piece of the puzzle: E0 Transitions in coincidence with γ–rays

- fIreBallI consists of 6 Mini-Orange Spectrometers for detecting conversion electrons





Conversion Electrons in ^{154}Gd and ^{156}Gd



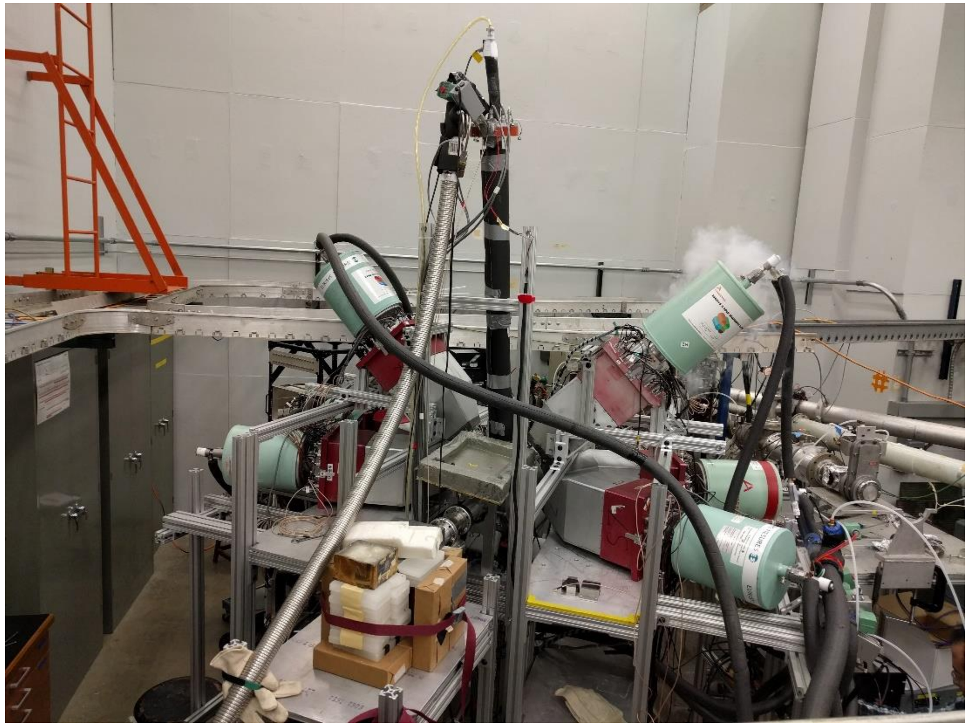
Thank you for your attention!

aapraham@nd.edu

fIreBall: Search for E0 Transitions

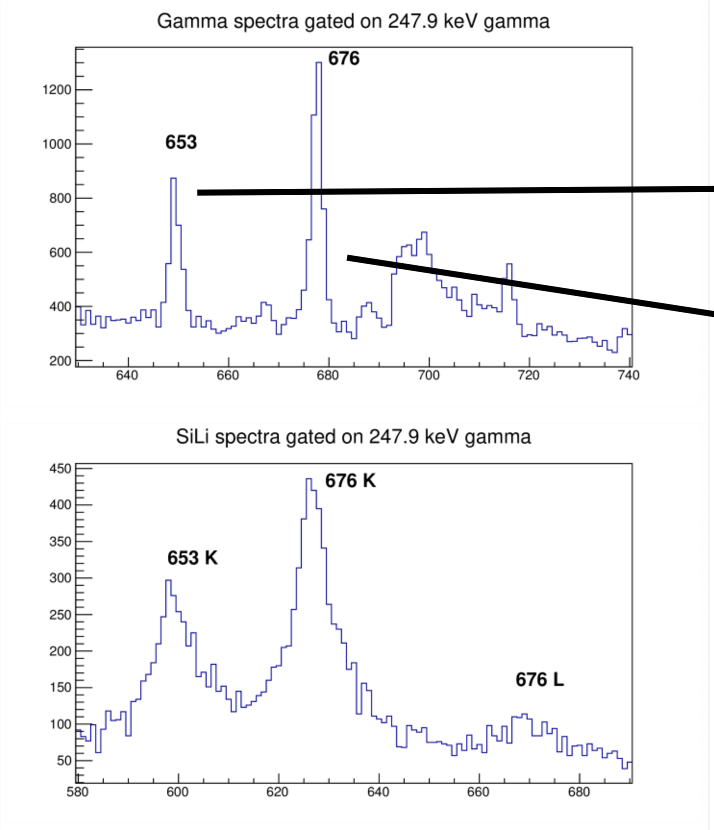
Clovershare was paired with ICEBall (Internal Conversion Electron Ball)

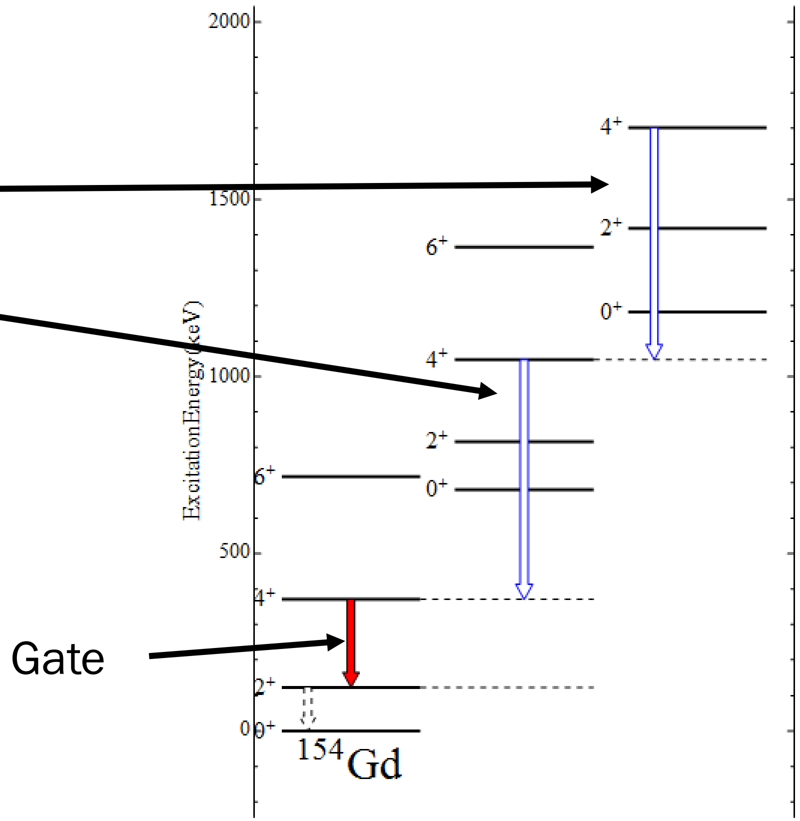
- ICEBall consists of 6 Mini-Orange Spectrometers for detecting conversion electrons
- ^{152}Sm(α,2n) reaction was used
- ^{154}Gd has 16 known 0^+ states. 10 of these were only found in 2006 by Meyer et al.
- The nature of excited 0^+ states is not well understood, E0 transitions are critical for understanding.



^{154}Gd: Search for E0 Transitions

Proof of populating the first two excited 0^+ bands using 247.9 keV gate





Plots show γ-spectrum with corresponding SiLi spectrum beneath, shifted for the K-electrons to align with the corresponding γ-lines

Search for E0 Transitions in ^{154}Gd

Proof of populating the excited 0^+ bands using 123.1 keV gate