

Experimental Nuclear Structure with Gamma-ray Spectroscopy & EM Transition Rates

International Graduate School (IRTG) 2891
Nuclear Photonics -

IRTG Lecture Week 2026

IFIN-HH / ELI-NP, Magurele, Romania

12 - 15 October 2026

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4 hours of lectures:

Lects 1 & 2: Nuclear Structure and Gamma Spec.

Lects 3 & 4: EM Transition Rates & Nuclear Lifetimes.

Lectures 1 & 2: Some nuclear basics.

- Decay modes and stability, the Segre chart, production and measurement of nuclei and excited nuclear states, selection rules.
- Why gamma rays? Types of gamma detectors. HpGe vs Scintillators.
- How do you measure nuclear observables including spins, parities and excitation energies?
- Reactions around Coulomb barrier energies - Coulomb Excitation, Fusion-Evaporation Reactions, High-Spin vs low Spin ? neutron rich spectroscopy; Channel selection; In-beam vs decay spectroscopy.

Lectures 3 & 4: Measurements of EM transition rates and excited state nuclear lifetimes.

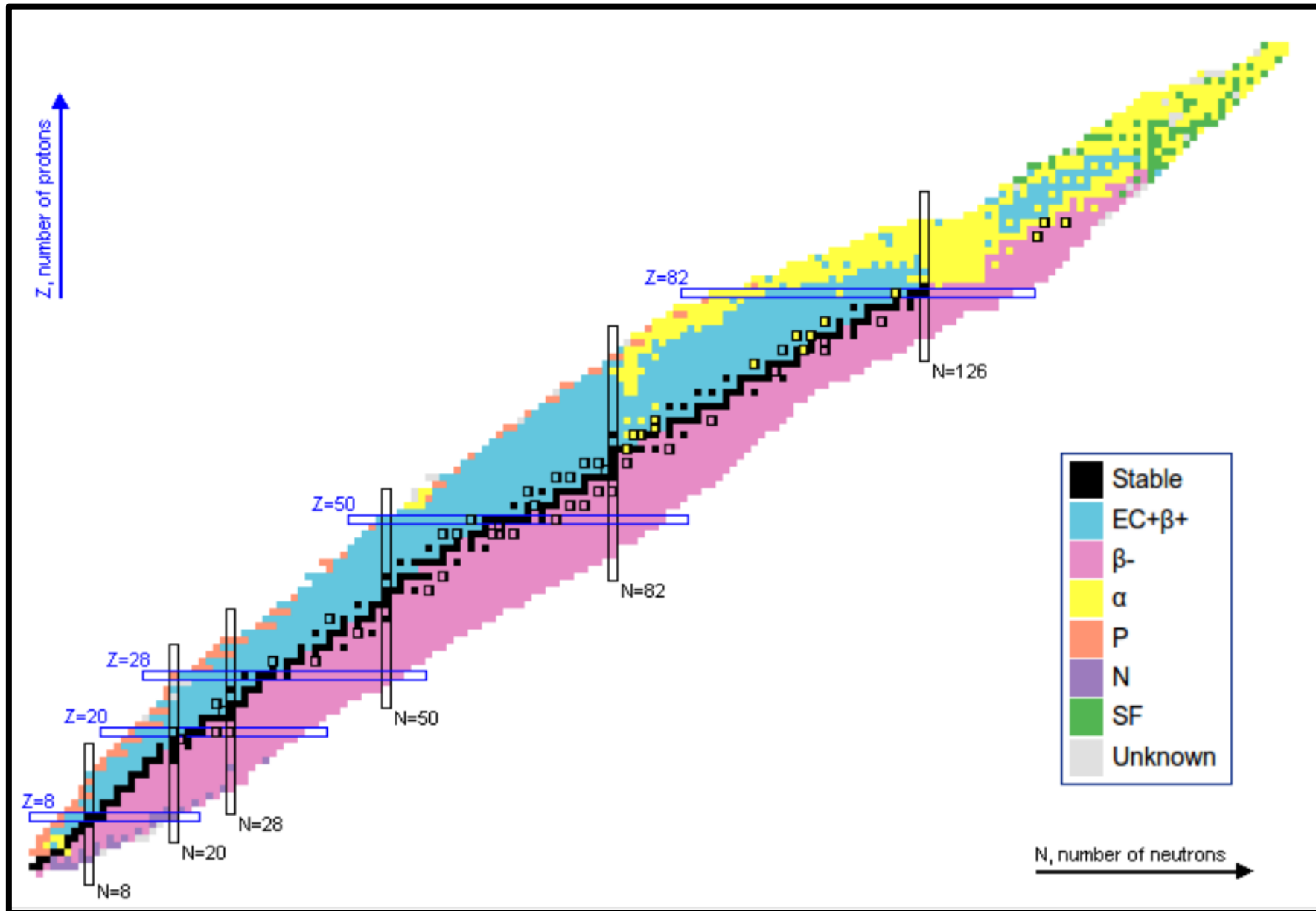
- What do they tell you ?
- Doppler methods in-beam;
- isomer and decay spectroscopy using e.g. fast-timing co-incidence spectroscopy.

TIMETABLE · 12–15 October 2026

Time	MONDAY 12 Oct 2026	TUESDAY 13 Oct 2026	WEDNESDAY 14 Oct 2026	THURSDAY 15 Oct 2026
09:30	Welcome and introduction			
09:45		Welcome and introduction	Welcome and introduction	Welcome and introduction
10:00	Laser technology I: Basics of ultrashort pulses and propagation (Jolly)	Laser technology II: Complex pulse shaping and metrology (Jolly)	Nuclear structure and gamma spectroscopy I (Regan)	EM transition rates and nuclear lifetimes II (Regan)
10:30			Advances in theoretical studies of electron capture (Sevestrean)	Nuclear transitions assisted by high-power lasers (Yang)
11:00				
11:30	Coffee break	Coffee break	Coffee break	Coffee break
12:00	Laser-plasma applications I: Radioisotope production for medical applications (Alejo)	Laser-plasma applications II: Experiments on neutron generation (Alejo)	Nuclear structure and gamma spectroscopy II (Regan)	Laser-plasma applications III: Nuclear activation beyond the Giant Dipole Resonance (Alejo)
12:30				
13:00	Lunch	Lunch	Lunch	Lunch
13:30				
14:00	The Particle-in-Cell (PIC) method for laser-plasma interactions I (Perez)	The Particle-in-Cell (PIC) method for laser-plasma interactions II (Perez)	Discussion sessions with students	Scientific career advice discussion with Prof. Regan
14:30				
15:00	Electron acceleration and photon production in near-critical density and double-layer targets (Dreghici)	Plasma-based inverse Compton gamma sources at multi-PW laser intensities (Horný)	EM transition rates and nuclear lifetimes I (Regan)	Laser-plasma experiments relevant to kinetic modeling (Perez)
15:30	Coffee and poster session	Coffee break and free time		
16:00			Closing remarks and farewell	
16:30				
17:00				

'Big' Questions in Nuclear Structure Science?

- How do protons and neutrons interact?
 - Can we write down a nuclear 'force' equation?
- Evolution of nuclear single-particle structure.
 - Why/where/how do nuclear excitations change from 'single particle' to 'collective' ?
- Why do some nuclei exhibit 'deformation' ?
 - How do we measure nuclear 'deformation' ?

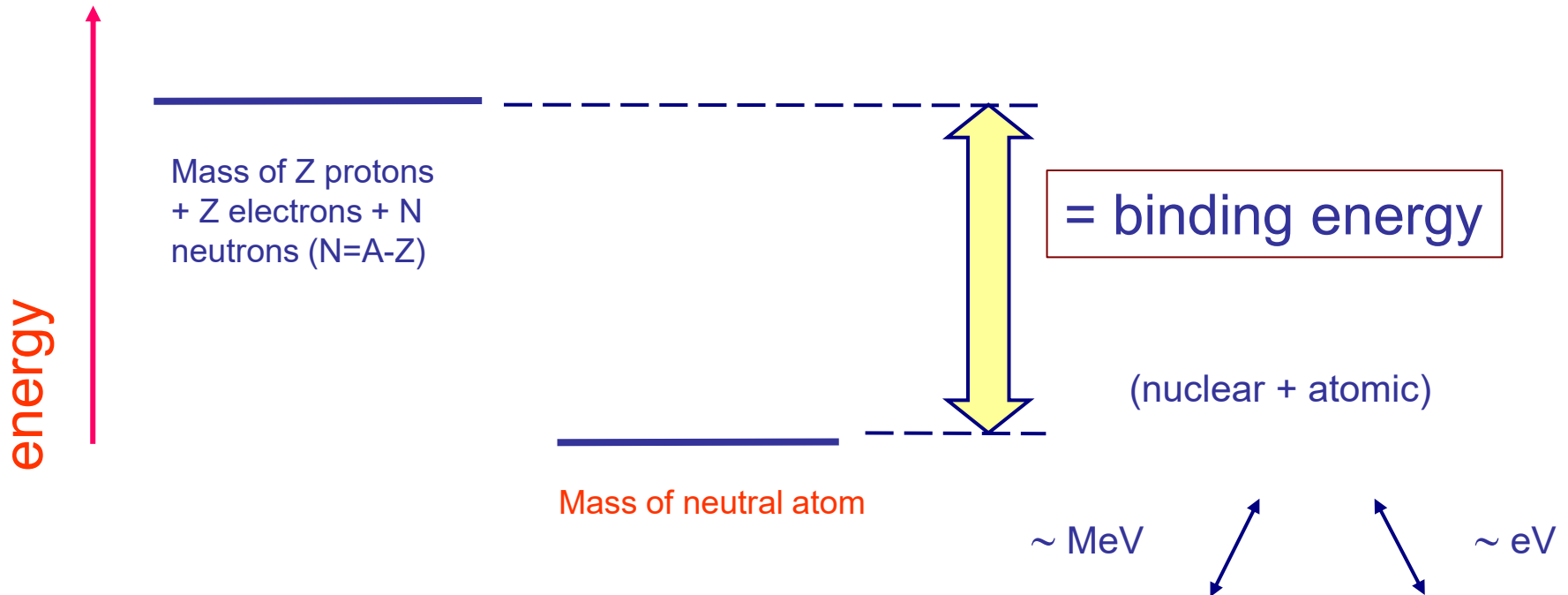


Atomic Masses and Nuclear Binding Energies

$M(Z,A)$ = mass of *neutral atom* of element Z as isotope A

$$M(Z,A) = Z \cdot m({}_1^1\text{H}) + N \cdot m_n - BE_{\text{nuclear}}$$

The binding energy is the energy needed to take a nucleus of Z protons and N neutrons apart into A separate nucleons



Ground (or meta-stable) State Decay: Radioactivity

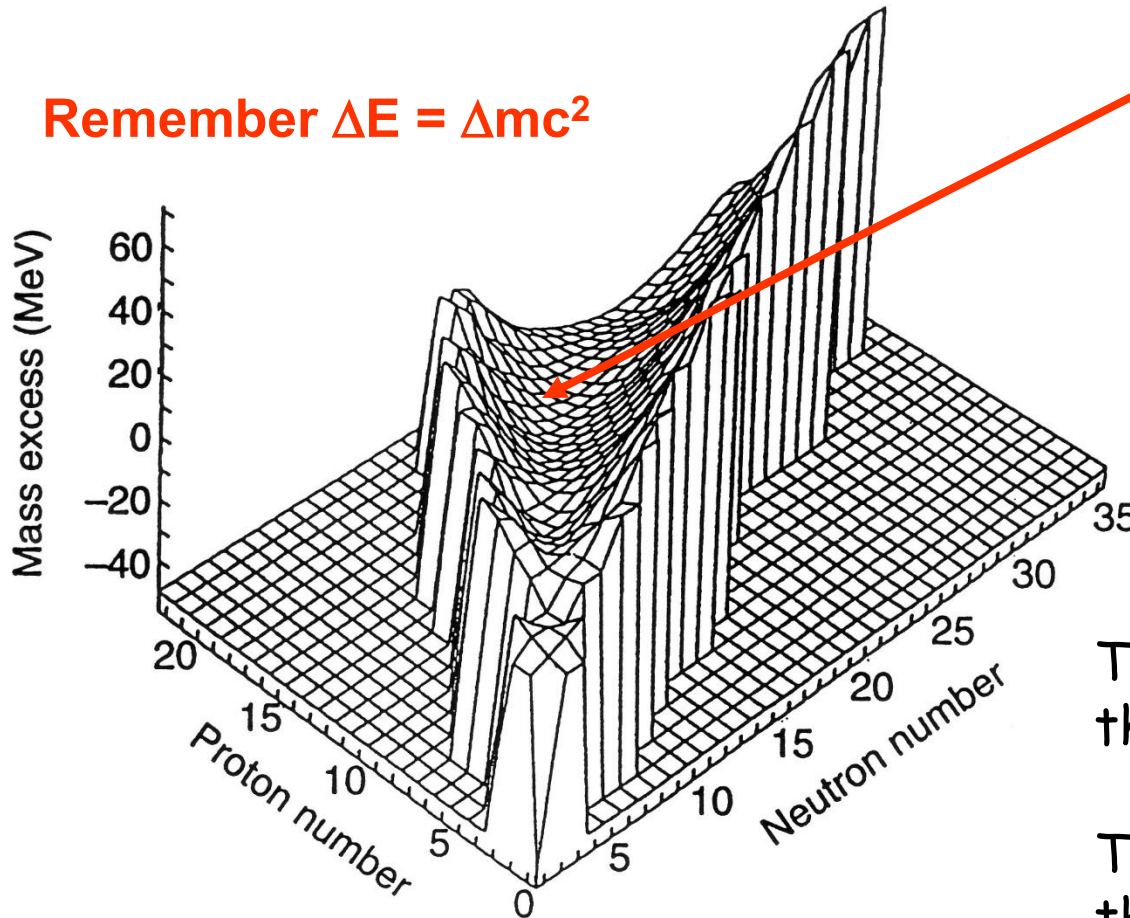
- Beta or alpha decay (i.e. Q_β or $Q_\alpha > 0$).
- Proton emission (if $S_p < 0$).

These 'decay' modes populate excited states in the daughter nucleus which are defined by the selection rules in the excitation energy vs, spin plane (E_x, I^π)

The selection rules are based on conservation of total mass-energy, linear and angular momentum conservation

Binding Energies/ Ground State Masses

Remember $\Delta E = \Delta mc^2$



The valley represents the nuclei with the lowest total energy for a constant $A(=N+Z)$

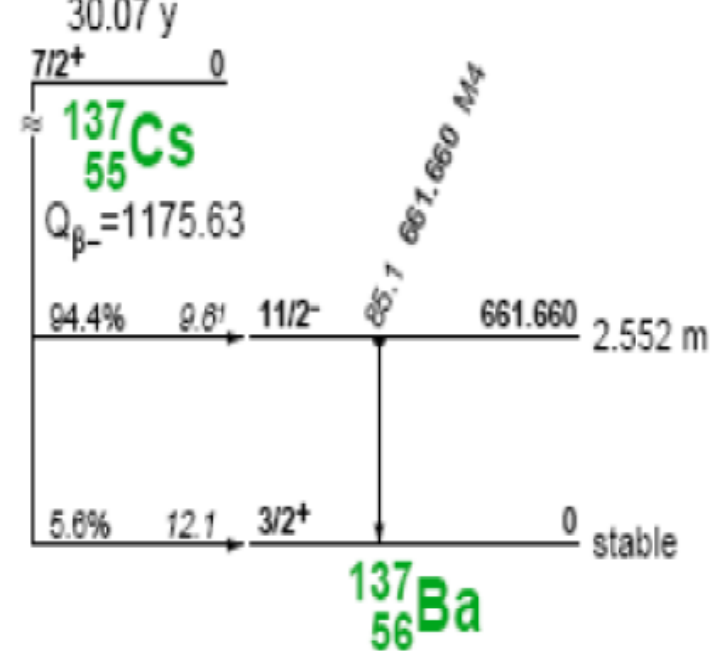
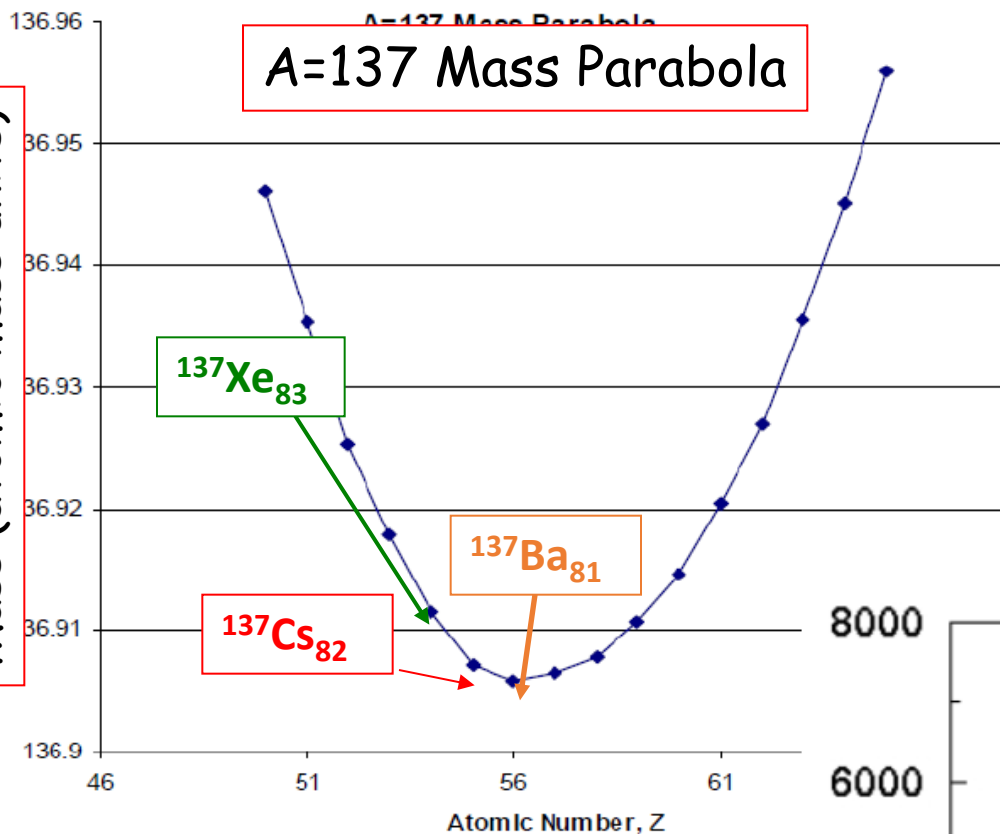
The nuclei up on the sides of the valley are unstable.

They decay successively until they reach **stability**.

$$M(Z, A) = Z \cdot m({}^1_1\text{H}) + N \cdot m_n - BE_{\text{nuclear}}$$

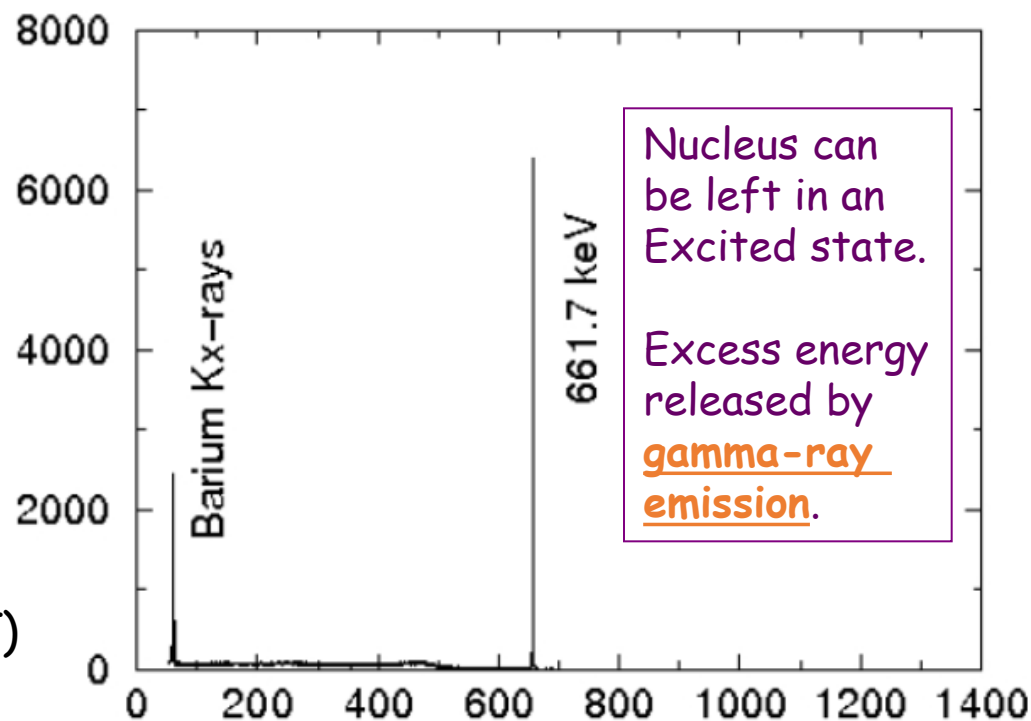
Mass (atomic mass units)

A=137 Mass Parabola

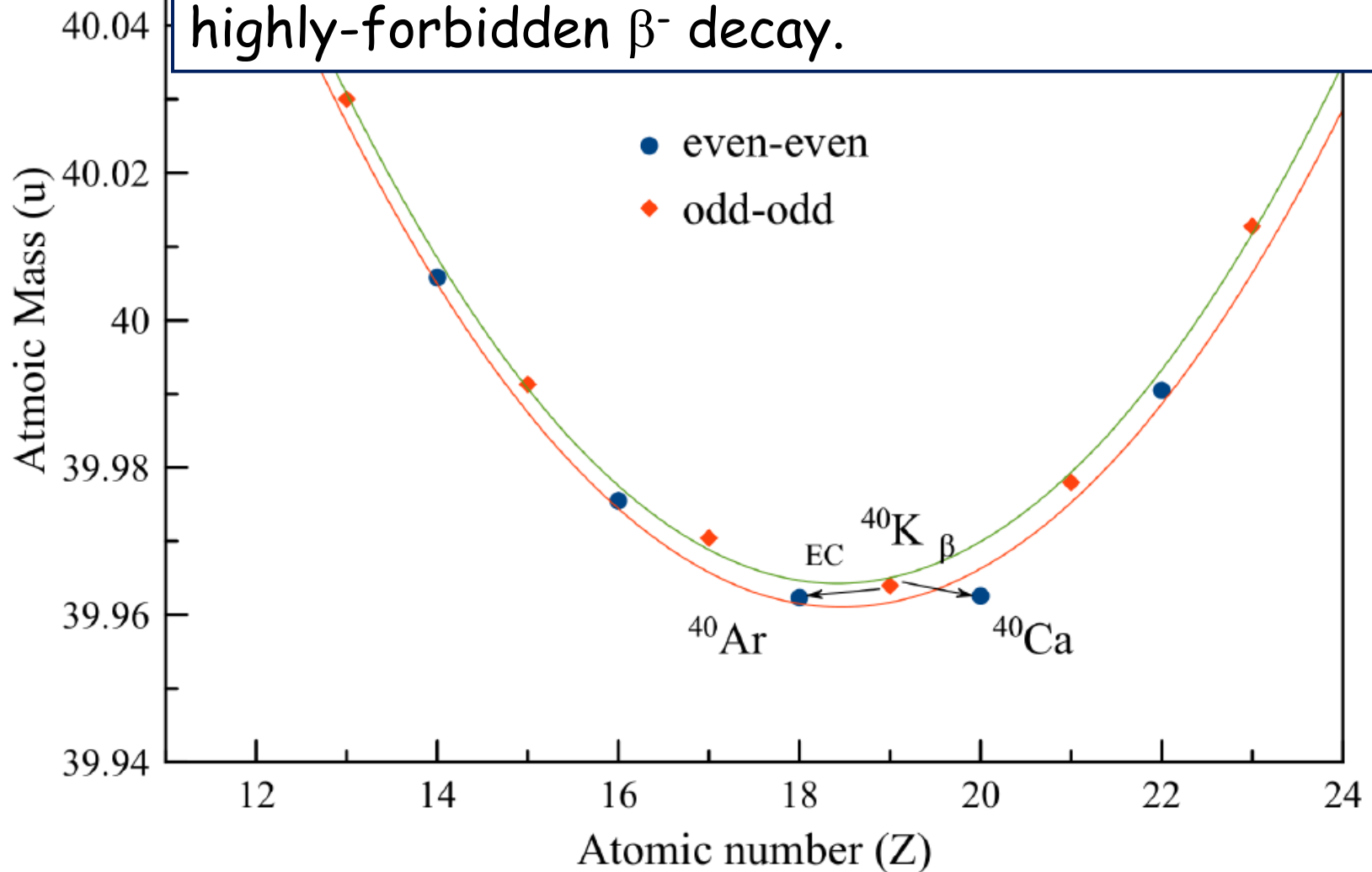


β^- - decay: $\Delta I=0,1$, selection):

- 1) **Neutron-rich nuclei** (fission)
 $n \rightarrow p + \beta^- + n$
- 2) **Neutron-deficient nuclei** (^{18}F PET)
 $p \rightarrow n + \beta^+ + n$



Mass parabolas very useful for understanding NORMS and radioactivity in general....
e.g., Doubly magic nature of $^{40}\text{Ca}_{20}$ is responsible for the long half-life of ^{40}K due to highly-forbidden β^- decay.



Excitation Energy (MeV)

4

2

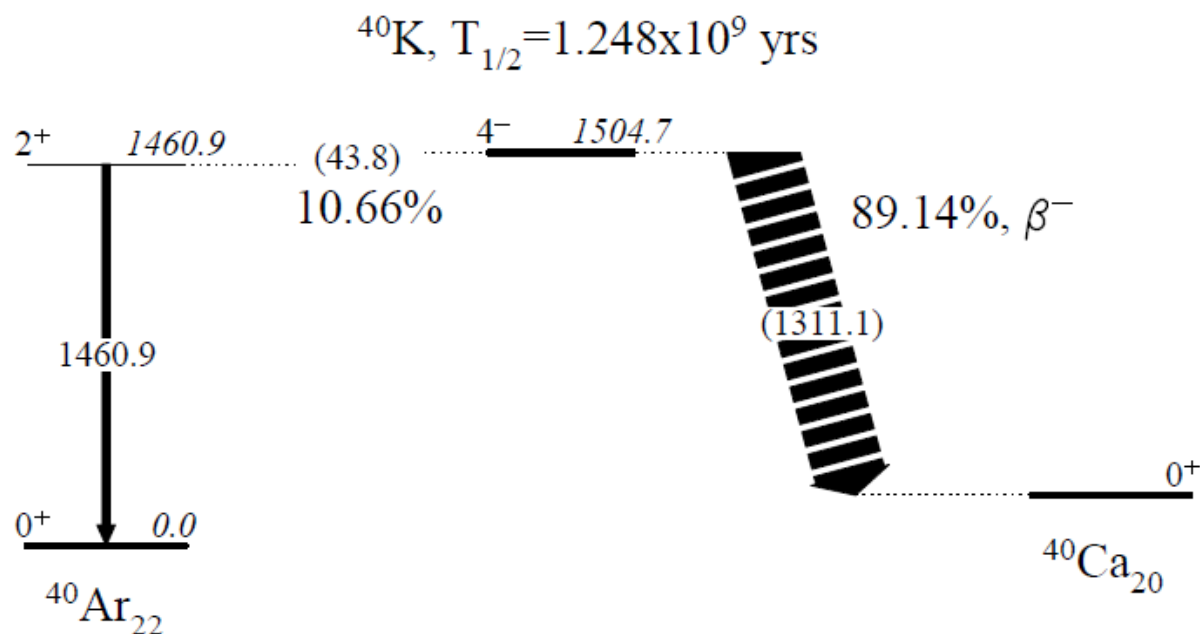
0

Understanding level schemes underpins metrology:
e.g. The number of primordial ^{40}K decays equals the
number of 1461 keV γ rays emitted, divided by the
'branching ratio' (0.1067).

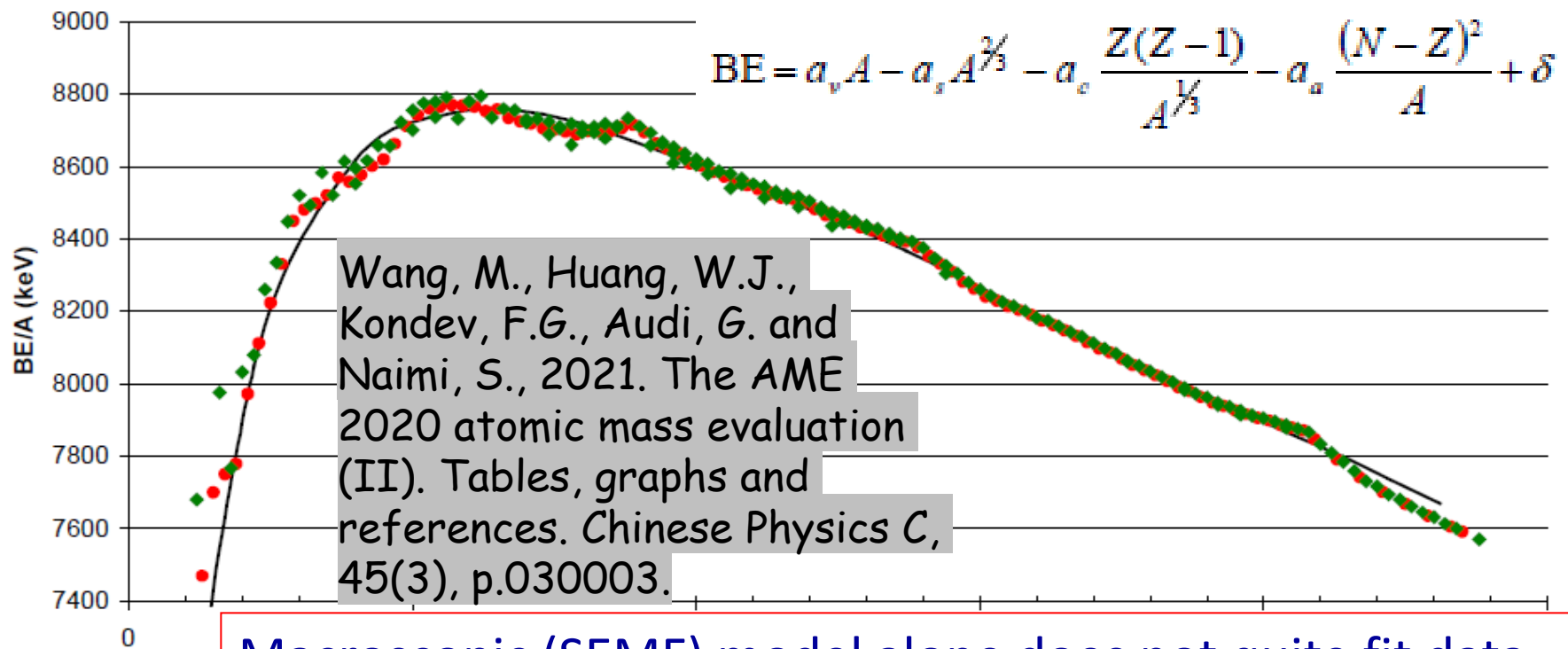
Nuclear structure matters!

Q. Why no decay to an excited state in ^{40}Ca ?

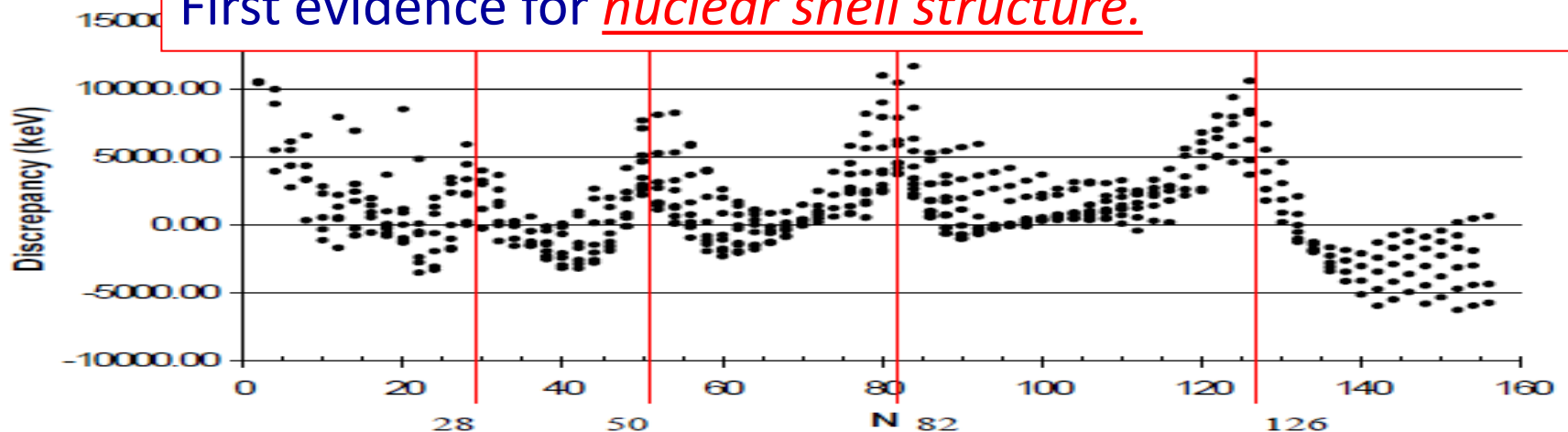
A. $I^\pi=2^+$ in Doubly Magic ^{40}Ca @3904 keV



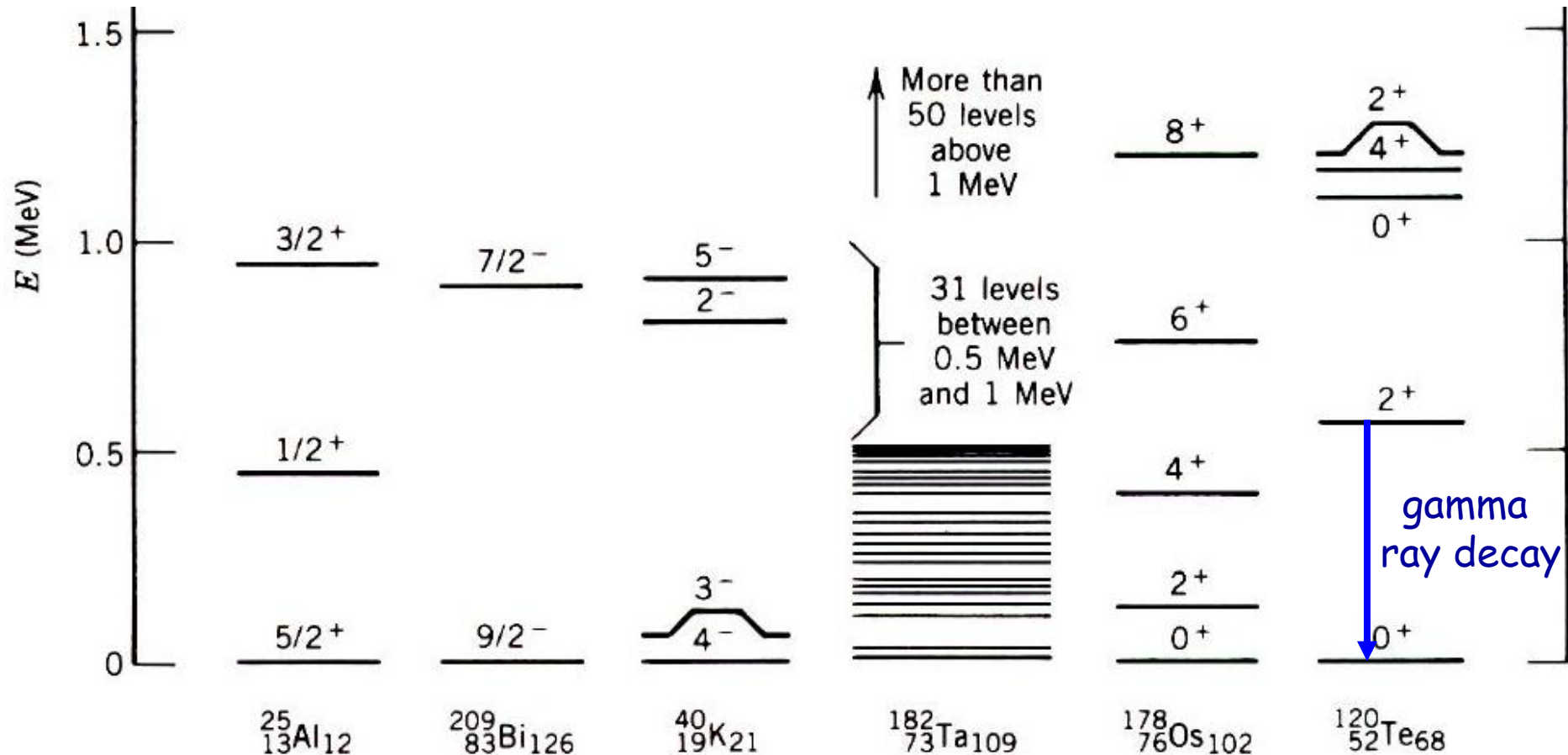
2^+
 3^-
 0^+



Macroscopic (SEMF) model alone does not quite fit data....
 Need to also account for microscopic nuclear effects.
 First evidence for nuclear shell structure.



Measuring Excited States - Nuclear Spectroscopy & Nuclear (Shell) Structure



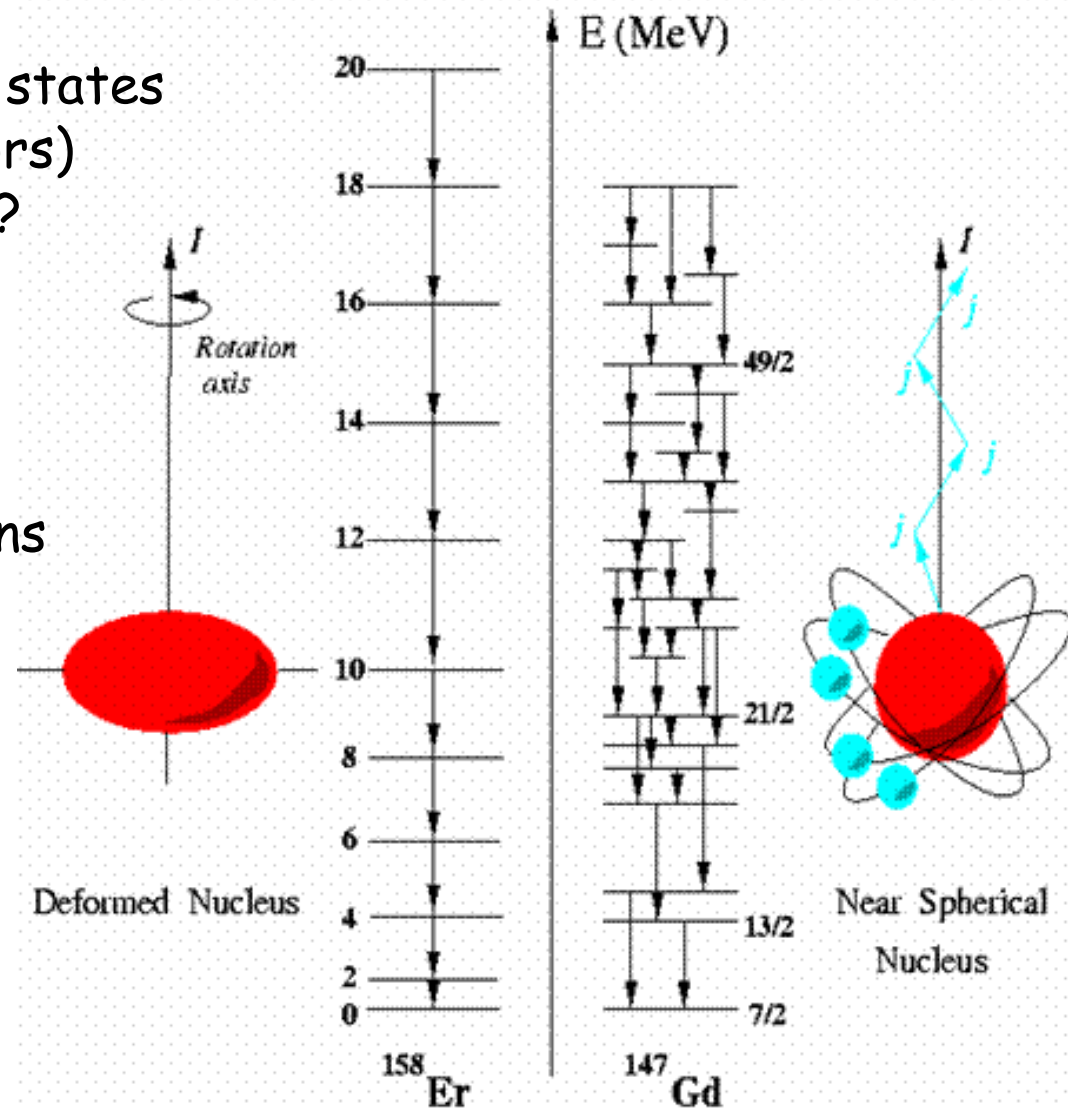
- Nuclear states labelled by spin and parity quantum numbers and energy.
- Excited states (usually) decay by gamma rays (non-visible, high energy light).
- Measuring gamma rays gives the energy differences between quantum states.

Some nuclear observables.

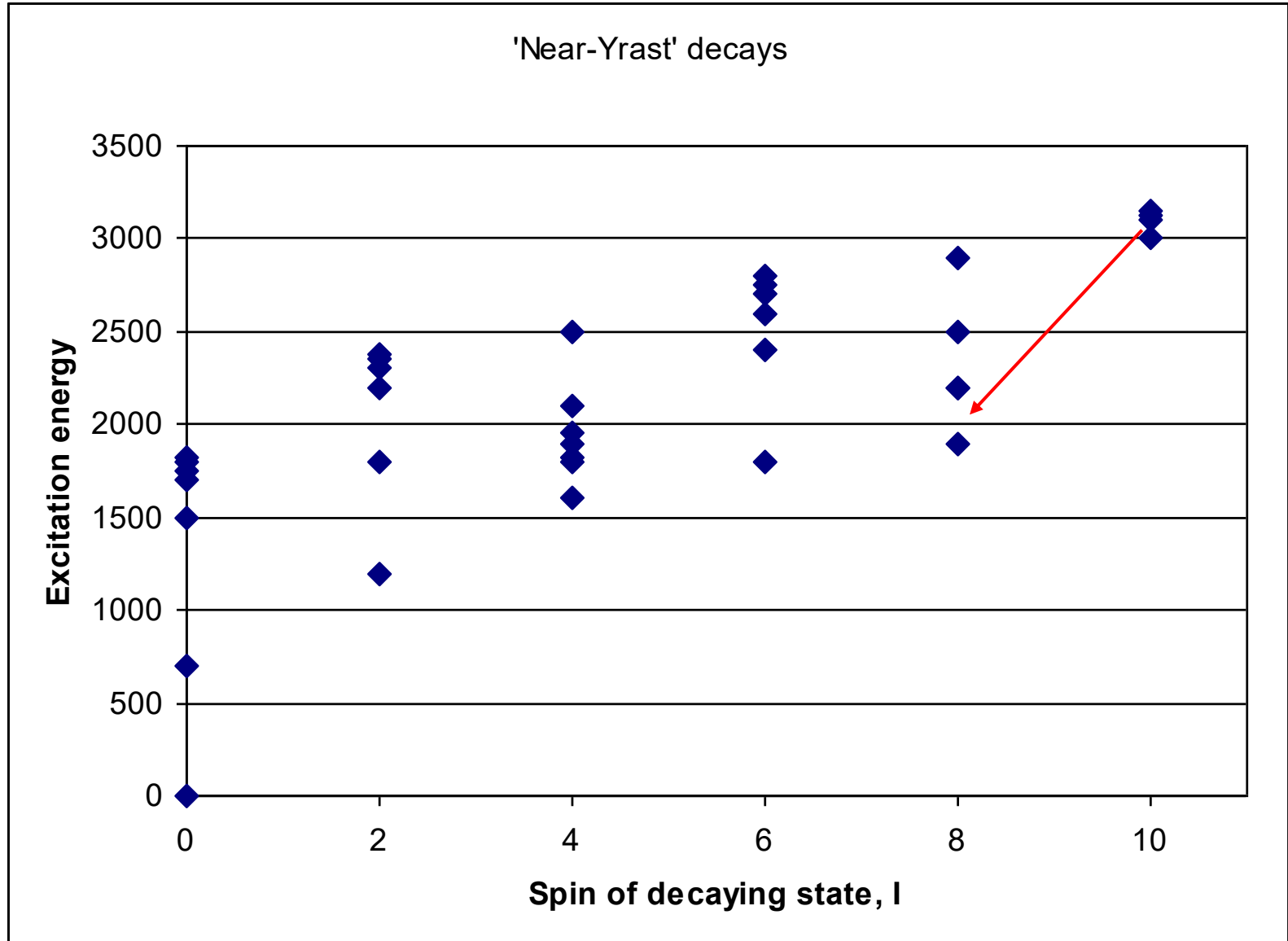
- 1) Masses and energy differences
- 2) Energy levels
- 3) Level spins and parities
- 4) EM transition rates between states
- 5) Magnetic properties (g-factors)
- 6) Electric quadrupole moments?

This is the essence of nuclear structure physics.

How do these change as functions of N , Z , I , E_x ?



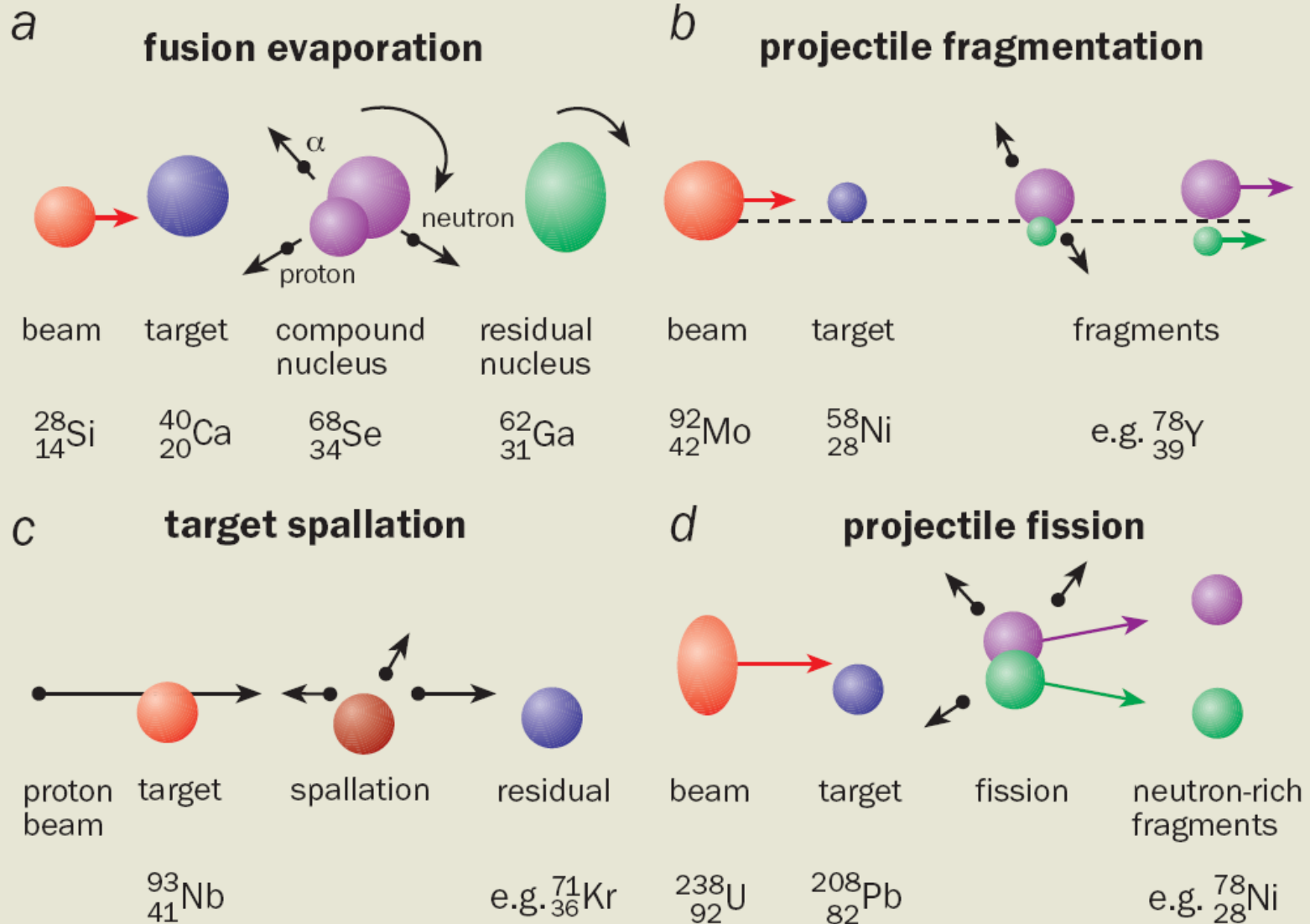
The EM transition rate depends on $E_\gamma^{2\lambda+1}$; the highest energy transitions for the lowest λ are (usually) favoured.
This results in the preferential population of yrast and near-yrast states.



Nuclear Structure Physics with Gamma Spectroscopy.

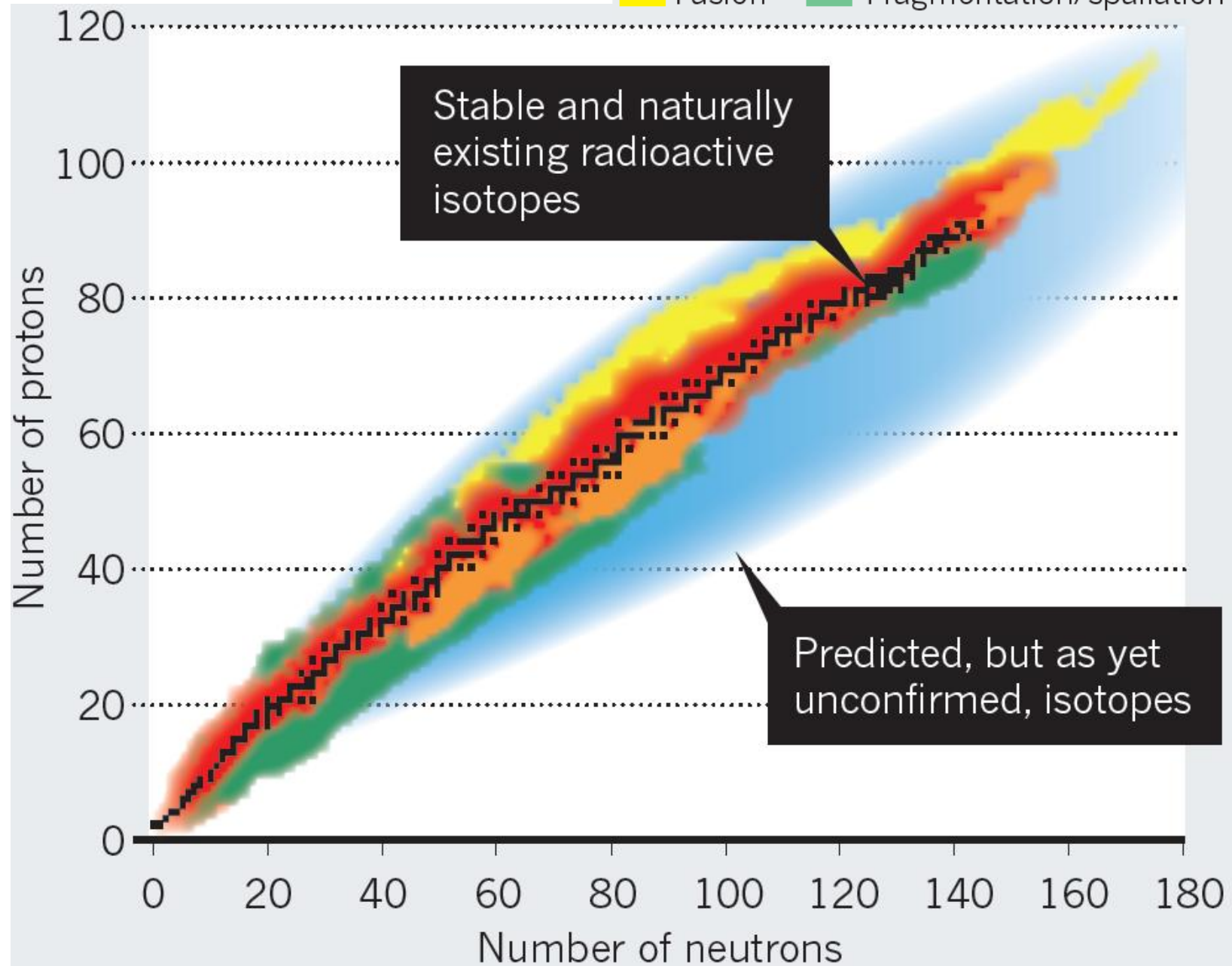
- Measurement and properties of excited states and their internal energy levels.
- More than 3,000 nucleus species now created experimentally.
- Internal (nuclear) structure can be measured / observed by:
 - Radioactive decay INTO the nucleus of interest (limited information depending on Q-values and selection rules).
 - Create the nucleus of interest in an excited state and measure the decay sequence to the ground state via γ rays (or ICE e^- s).
 - Large range of (Ex,I), depending on the population method.
 - Different (Ex,I) ranges can be populated / probed using inelastic (neutron, γ , e^- , ...) scattering, Coulomb Excitation, fusion evaporation, projectile fragmentation and/or fission....

2 How to make exotic nuclei



Isotope-discovery technique

- Light particle reactions
- Neutron reactions
- Fusion
- Fragmentation/spallation



Fundamental Rules in Nuclear Structure Research

- The nuclei and final excited states populated depend on the reaction / decay mechanism used.
- All of these are **SELECTIVE** in one way or another.
 - **Fusion-evaporation**: higher spins; near yrast states; usually neutron deficient nuclei.
 - **(Prompt) Fission**: Medium spins ($\sim 8-16 \hbar$ per fragment; near yrast(ish) states; wide spread of neutron-rich nuclei centred around $A \sim 95$ & ~ 135 .
 - **Radioactive decay (α, β)** usually lower-spin states due to selection rules; $\Delta I = 0, 1$ 'allowed'.
 - **Populated excited states below particle separation energies decay via EM selection rules and transition rates dependency.**

EM decay selection rules reminder.

Suppose we are concerned with a transition between the states i and f of characters (spin, parity) (J_i, π_i) and (J_f, π_f) respectively; defining a quantity p , which is 0 for even parity and $+1$ for odd parity, we see that the multipoles that can contribute are delimited by

$$J_i + J_f \geq L \geq |J_i - J_f|,$$

and by the further conditions:

$$p_i + p_f + L = \text{odd for magnetic multipoles}$$

$$p_i + p_f + L = \text{even for electric multipoles.}$$

TABLE I

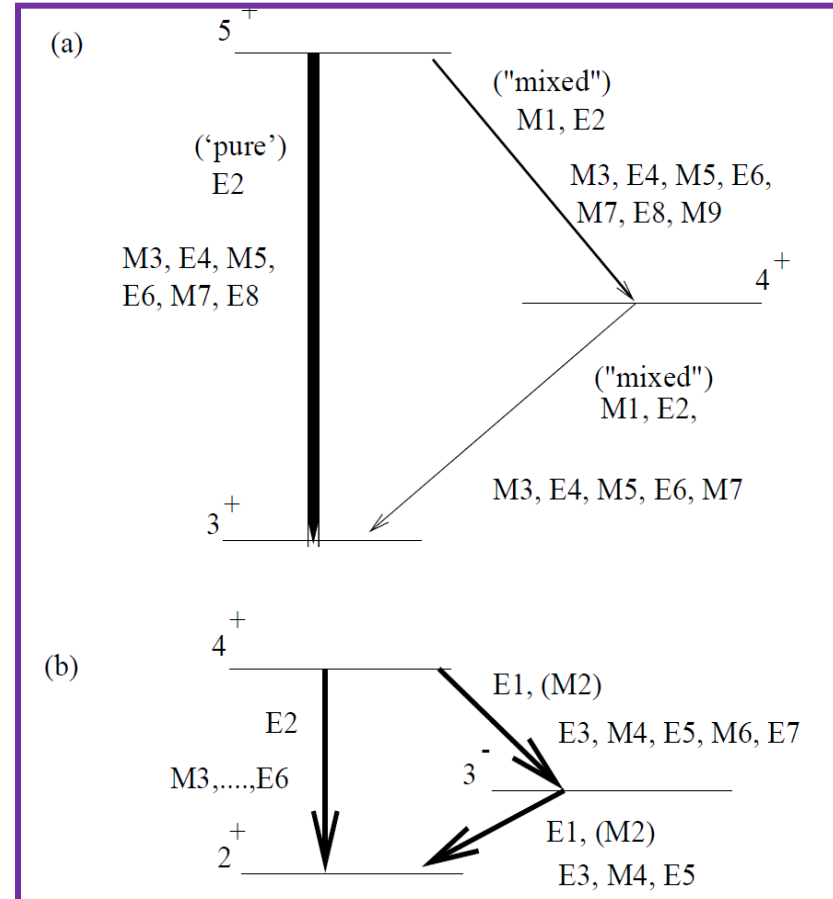
OBSERVED MULTIPOLE TRANSITIONS

Multipole L	1	2	3	4	5
Parity change $\left\{ \begin{array}{l} \text{Yes} \\ \text{No} \end{array} \right.$	$E1 \longleftrightarrow M2$	$E3$	$M4$	$E5$	
	$M1 \longleftrightarrow E2$	$M3$	$E4$		

Since the quantity that enters in the vector potential of the L -multipole is:

$$j_L(kr) \cong \frac{(kr)^L}{(2L+1)!}, \quad 9.$$

we see that the lowest possible multipole transition is greatly favored for $kr \ll 1$. The range of energies for which $(kr) \ll 1$ is frequently called the "long wave-length" region. In fact, usually only the lowest possible multipole contributes, but sometimes also the next order will appear. It is this fact that makes the measurement of multipole order so useful a tool in the assignment of characters to levels. The most important examples of mixed multipoles are found for $M1+E2$ and $E1+M2$ transitions; these are indicated in the above table by connecting lines.



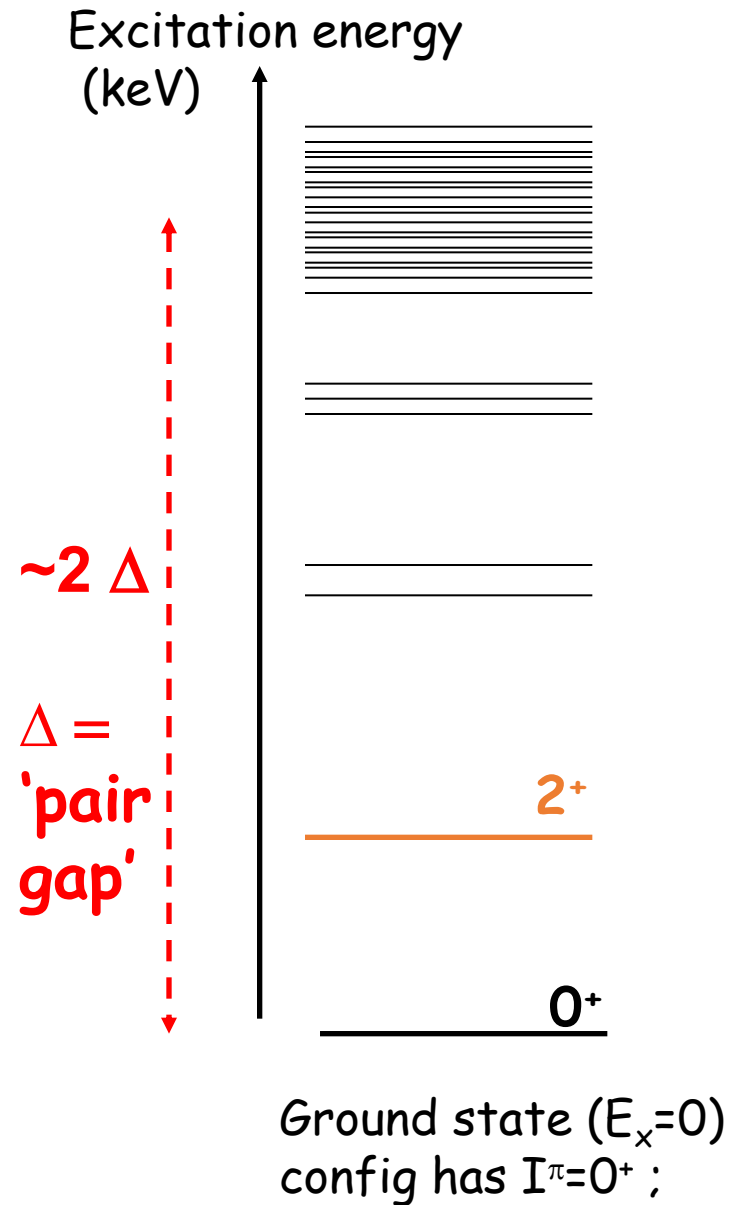
Even-Even Nuclei

Excited state properties such as spin and parity depend on the nucleon configurations.

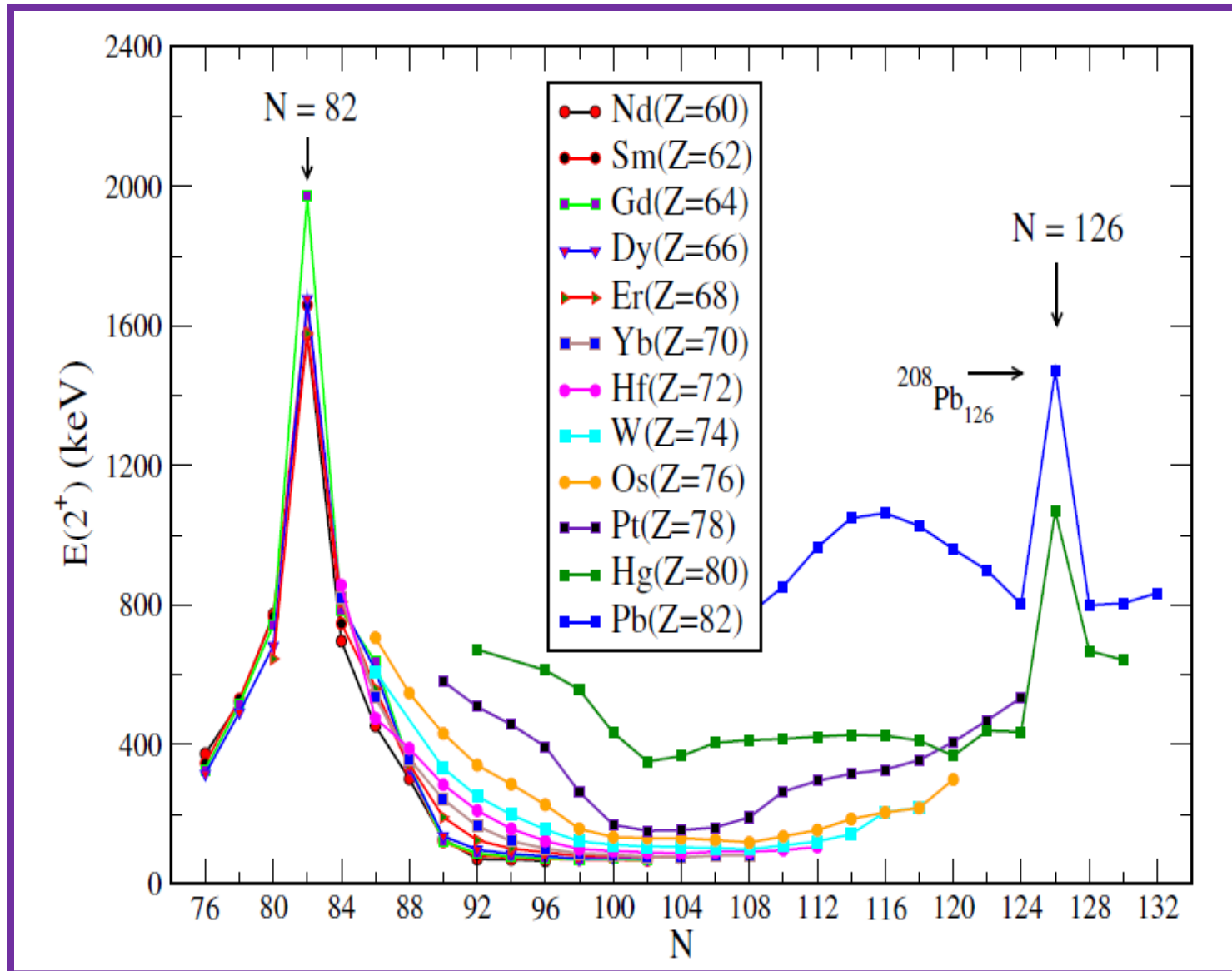
i.e., which specific orbits the protons and neutrons occupy.

Different orbits costs different amounts of energy
→ The result can be a complex energy 'level scheme'.

First excited state in (most) even-N AND even-Z has $I^\pi=2^+$



'Simplest' signature (of nuclear 'shape' and deformation) is the Excitation energy of the first spin/parity 2^+ state, i.e. $E(2^+)$.

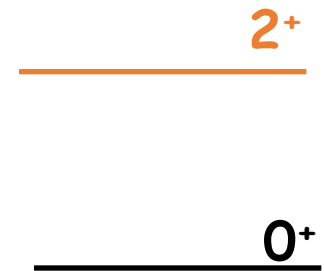
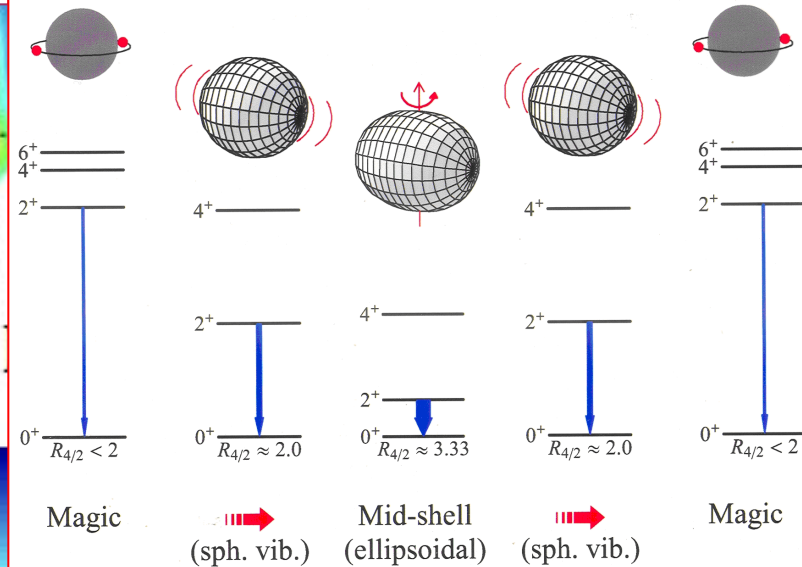


Proton Number

PHR, Physics World, Nov. 2011, p37

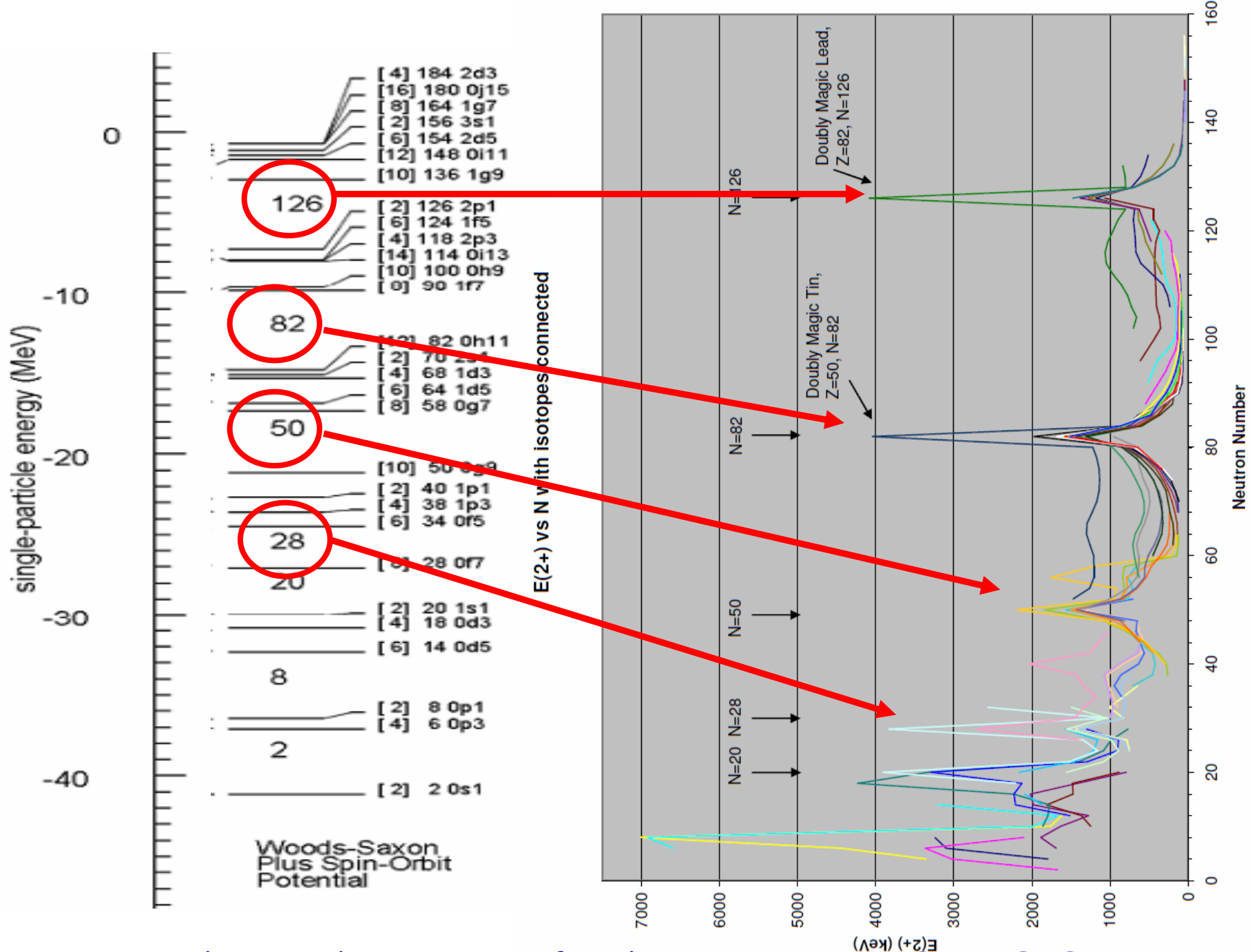
Excitation energy (keV)

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



Ground state
Configuration.
Spin/parity $I^\pi=0^+$;
 $E_x = 0$ keV

Neutron Number



large gaps in single-particle structure of nuclei...MAGIC NUMBERS = ENERGY GAPS

Nuclear Rotations: - the opposite of shell structure

Extreme theoretical limits for perfect rotor and vibrator in even-even nuclei are:

$$E_J = \frac{\hbar^2}{2\mathcal{I}} J(J+1), \quad \frac{E(4^+)}{E(2^+)} = \frac{4(5) = 20}{2(3) = 6} = 3.33$$

$$E_N = \hbar\omega N \quad \frac{E(4^+)}{E(2^+)} = \frac{2}{1} = 2.00$$

Interpretation of Isomeric Transitions of Electric Quadrupole Type

AAGE BOHR AND BEN R. MOTTELSON*
Institute for Theoretical Physics, Copenhagen, Denmark
(Received November 10, 1952)

IN the recent classification of nuclear isomers,¹ the transitions of electric quadrupole type are unique in possessing several examples of lifetimes appreciably shorter than predicted on the basis of the shell model. In some cases, the predicted lifetimes are more than a factor of a hundred too long. It appears evident that we have here the effect of some type of cooperative nuclear motion.¹

In regions of high surface deformability, one obtains very low-lying states of collective excitation, which may be considered as rotational levels of the deformed nucleus. In the case of even-even nuclei, these states yield a spectrum with $I=0, 2, 4$, etc., even parity, and with energy values

$$E_I = (\hbar^2/2\mathcal{J})I(I+1), \quad (1)$$

neglecting the influence of rotation-vibration interaction. The effective moment of inertia $\mathcal{J}$ is related to the deformation of the nucleus and is given by

$$\mathcal{J} = 3B\beta^2 \quad (2)$$

in terms of β the deformation parameter, and B , the mass parameter of the surface oscillators.⁵ The wave functions for these states are obtained from the strong coupling solutions $\Omega=K=0$.

These states possess the spins, parities, low energies, and very short lifetimes of the observed levels. The transition from the first excited state to the ground state is of electric quadrupole type, with a probability per unit time given by

$$T = (\kappa^5/300\hbar)e^2Q_0^2, \quad (3)$$

where κ is the wave number of the emitted photon, and Q_0 the intrinsic quadrupole moment of the nucleus, measured with respect to the symmetry axis. For a uniformly charged incompressible nucleus, we have

$$Q_0 = [3/(5\pi)^{1/2}] \cdot ZR_0^2\beta, \quad (4)$$

with Z and R_0 , the nuclear charge and radius.

Rotational States in Even-Even Nuclei

AAGE BOHR AND BEN R. MOTTELSON*
Institute for Theoretical Physics, Copenhagen, Denmark
(Received March 24, 1953)

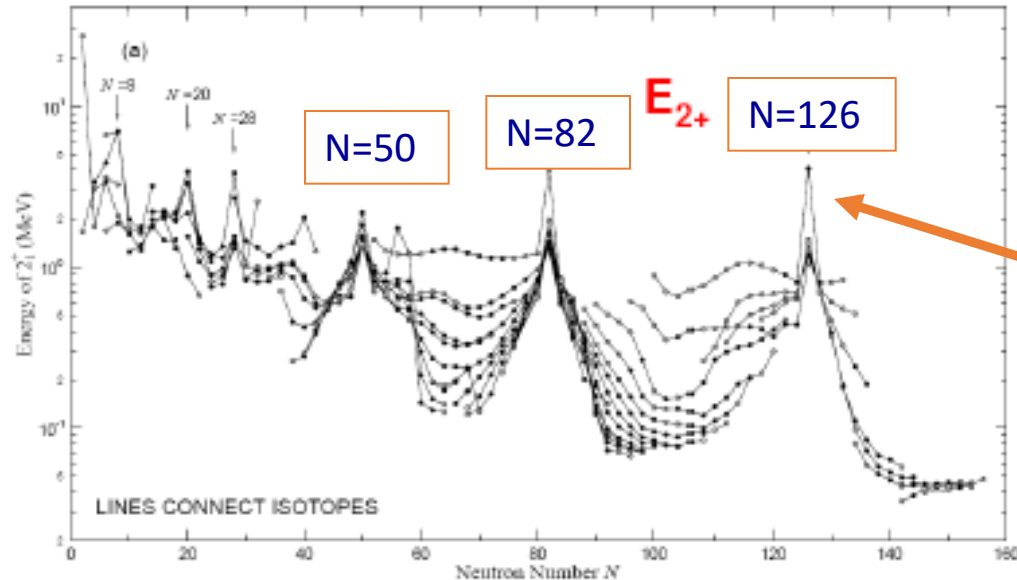
IN a recent note,¹ an interpretation of the short-lived $E2$ isomers has been suggested in terms of rotational states of the deformed nucleus. Empirical evidence is rapidly accumulating on the low energy spectra of even-even nuclei;²⁻⁴ the purpose of the present note is to call attention to the extensive support which exists in these data for the above interpretation, and to suggest its usefulness in the analysis of decay schemes.

In the model describing the nucleus in terms of the coupled particle motion and surface oscillations, low-lying rotational states are associated with the large deformations expected in regions with many particles outside of closed shells. In such regions, the rotational spectrum is expected to be given rather accurately by the simple expression¹

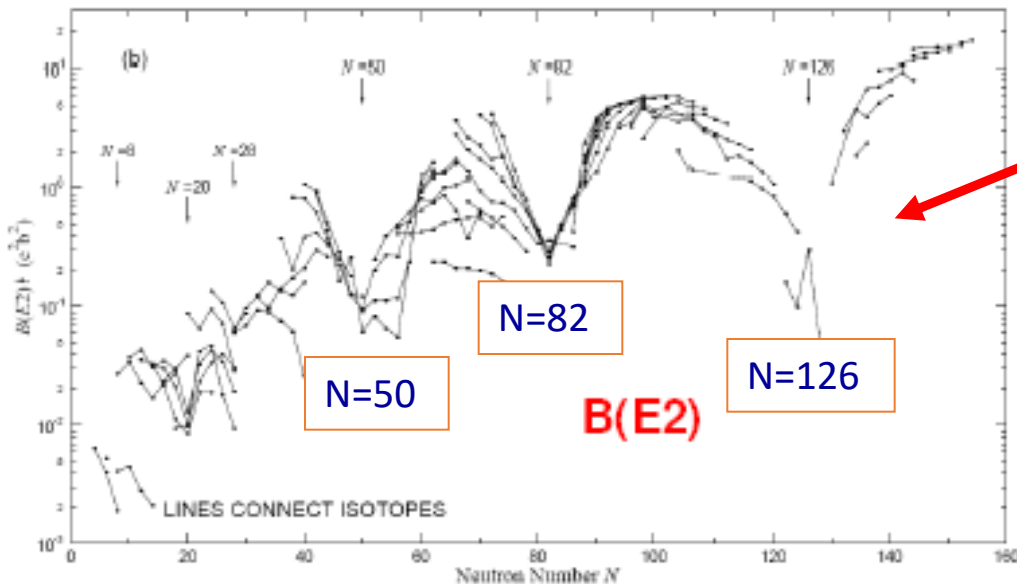
$$E_I = \frac{\hbar^2}{2\mathcal{J}}I(I+1), \quad I=0, 2, 4, 6, \quad \text{even parity} \quad (1)$$

II. Lifetimes.—The transition probabilities, more than a hundred times larger than single particle estimates,¹ which are observed for the levels in the rare earth region, furnish direct evidence for the collective nature of the excitation. The interpretation of the states as rotational levels permits one to calculate from the lifetimes the intrinsic quadrupole moments of the deformed surface, which are found to be just of the magnitude of those deduced from spectroscopic data.¹

More Evidence for Nuclear Shell Structure?



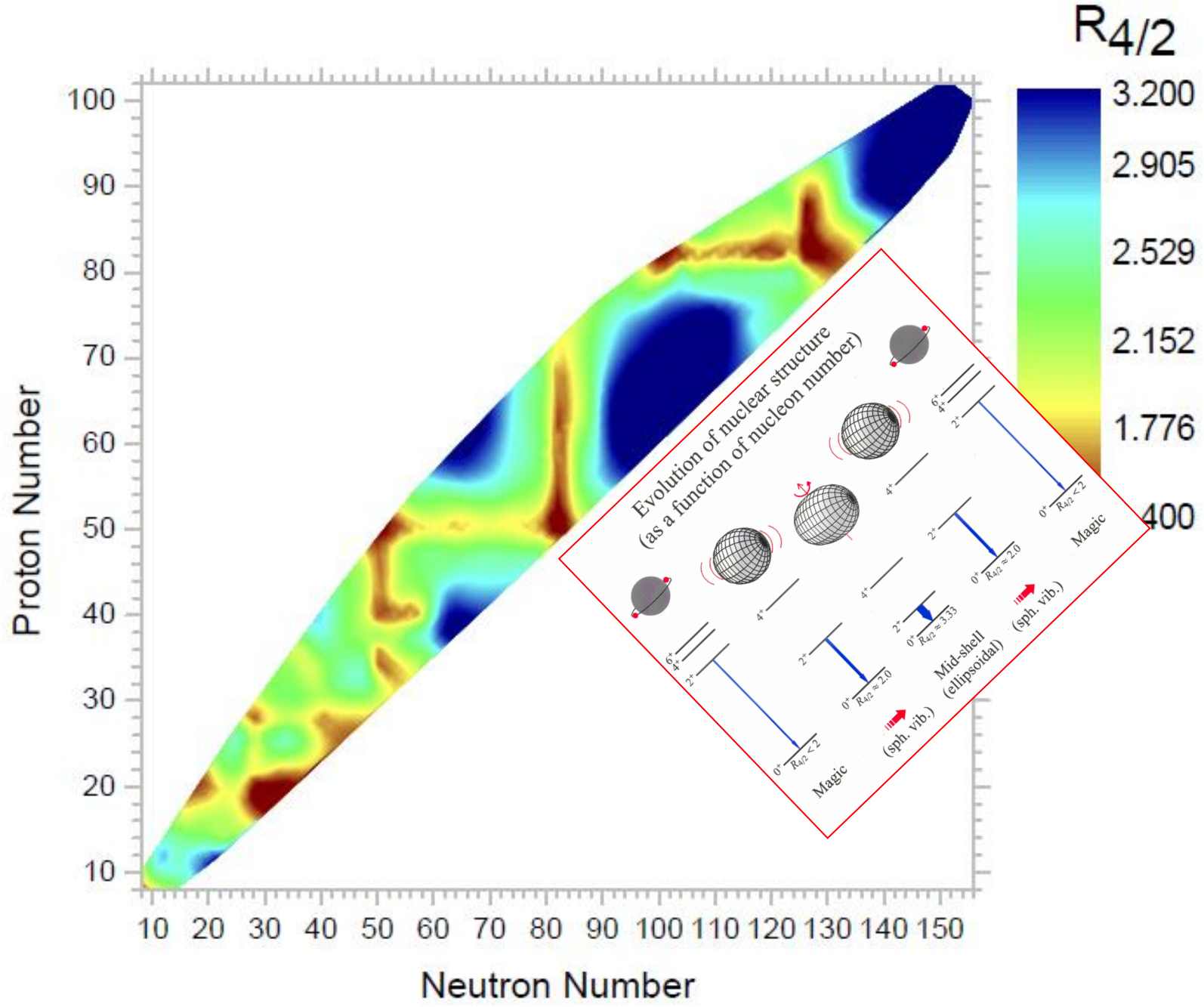
2_1^+ state at higher energy



Low values of $B(E2: 2_1^+ \rightarrow 0^+)$
longer lifetimes of first 2^+ state
(i.e. small transition probability)

$E(2^+)$ and $B(E2)$ correlated:

Small $E(2^+) \rightarrow$ large $B(E2)$.



Measuring gamma rays:

Two main families of detectors for gamma spectroscopy.

- 1) Semiconductor materials, mainly Hyper-pure germanium (**HPGe**) detectors, superior energy resolution requires ultra-pure semiconductor material, need cooling to LN2 temp (77K).
- 1) Scintillation materials such as NaI(Tl), BGO, LYSO, **LaBr₃(Ce)** & **CeBr₃** - generally poorer energy resolution but cheaper, high efficiency and in some cases very fast timing properties. Require some form of photomultiplier (PMT or SIPAD diode?)

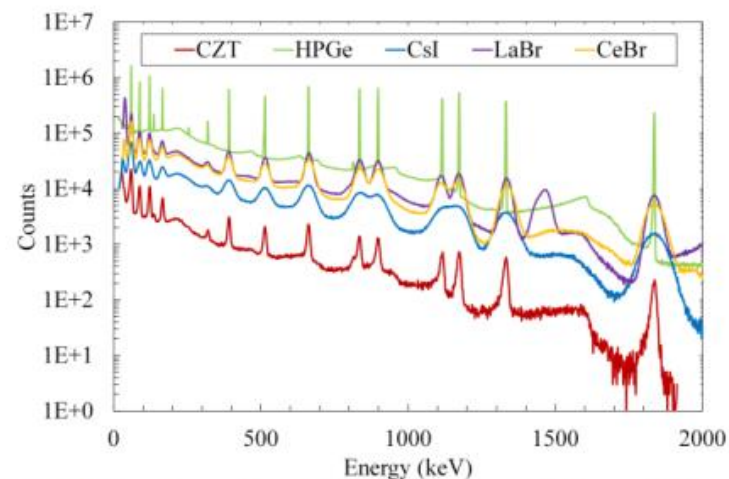
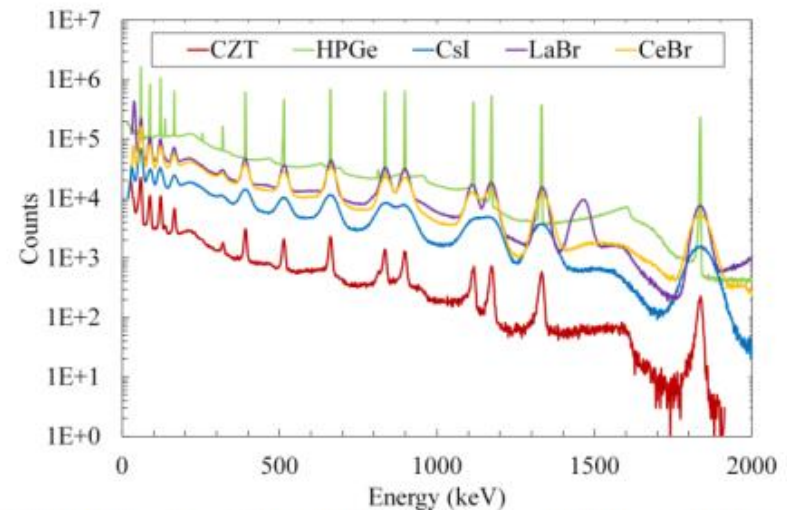
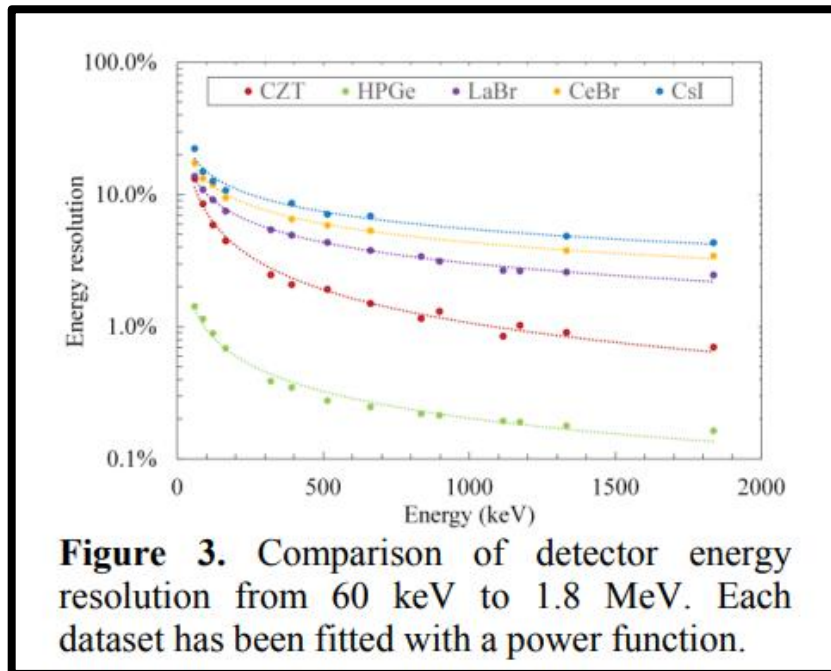


Figure 2. Comparison of energy spectra measured by detectors exposed to 29 kBq mixed radionuclide filter source for 24 hr.

Measuring gamma rays

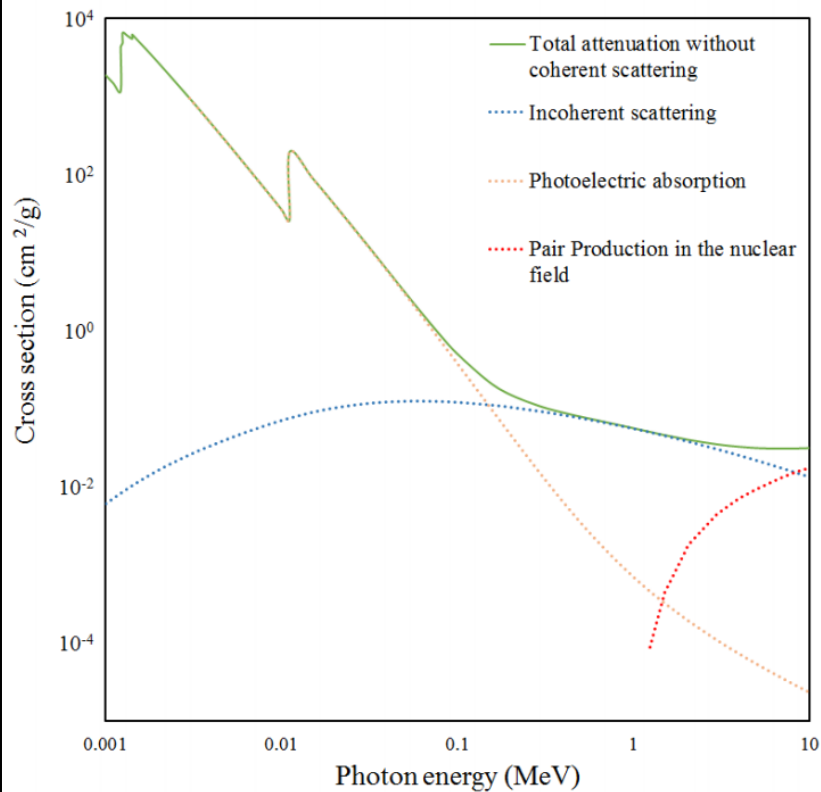
Two main families of detectors for gamma spectroscopy.

- 1) Semiconductor materials, Hyper-pure germanium (**HPGe**) detectors, superior energy resolution, need ultra-pure Ge and LN2 (77K).
- 2) Scintillation materials such as NaI(Tl), BGO, CsI, LYSO, **LaBr₃(Ce)** & **CeBr₃** - cheaper than HPGe but poorer energy resolution, operate at room temp, some very fast timing properties. Requires PMT / SiPAD

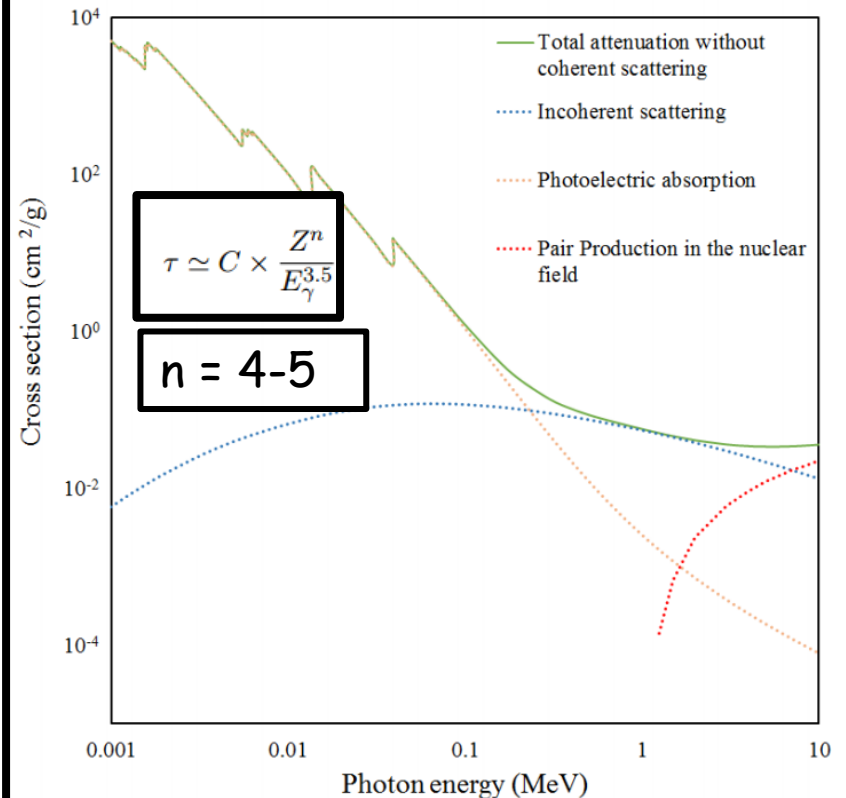


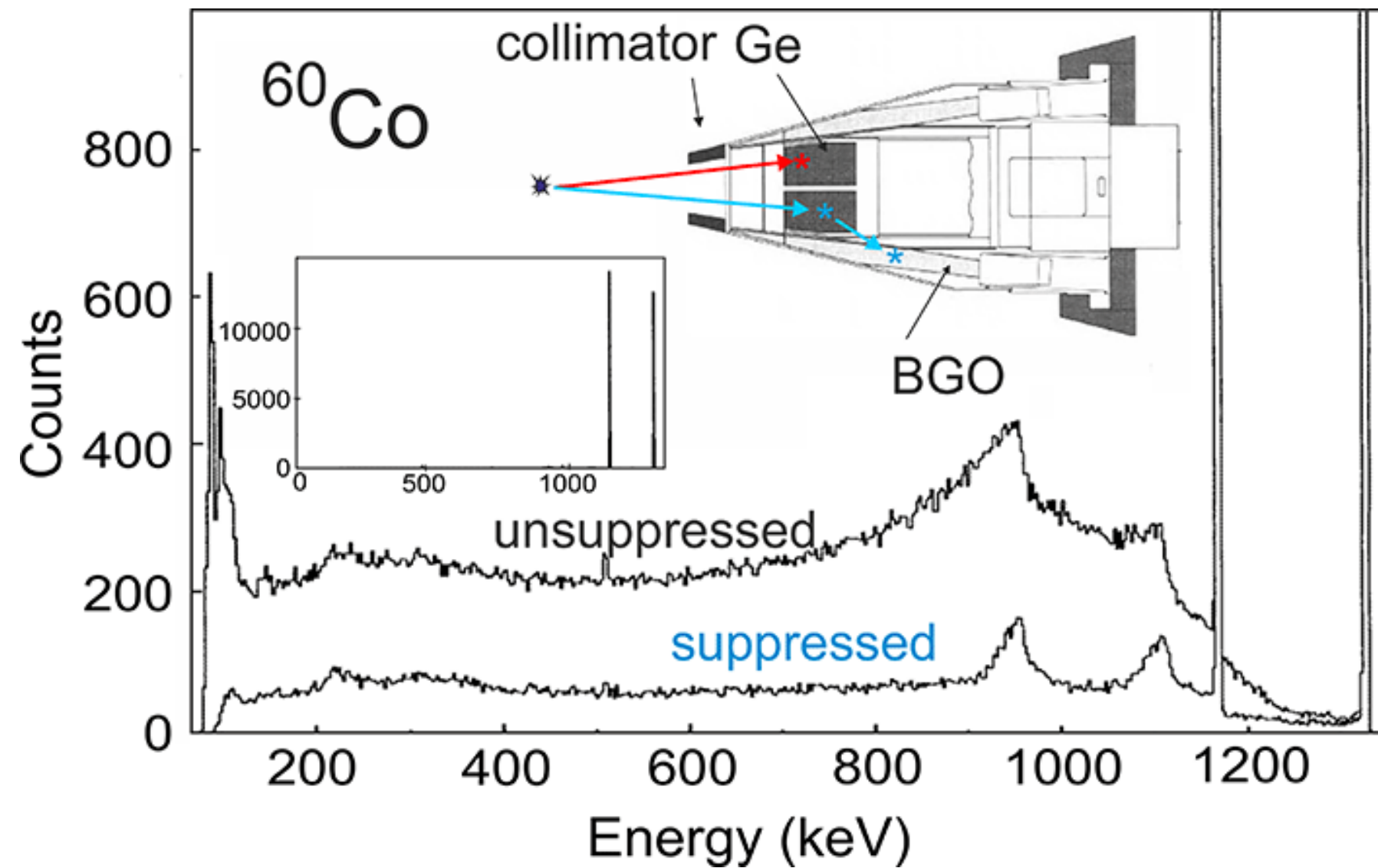
Material	HPGe	LaBr ₃	CeBr ₃	NaI(Tl)	BGO	BaF ₂	
Type	S.S	Scint.	Scint.	Scint.	Scint.	Scint.	
Light yield (photons per keV)	-	63	44	38	8 - 10	1.8	10
Resolution at 662 keV	0.2	2 - 3	5.2	7	10	10	
Decay time (ns) -		16	17.4	250	300	0.6 - 0.8	630
Wavelength of max emission	-	380	390	415	480	220	310
Density (g cm ⁻³)	5.3	5.08	5.2	3.67	7.13	4.88	

HPGe XCOM



LaBr₃ XCOM

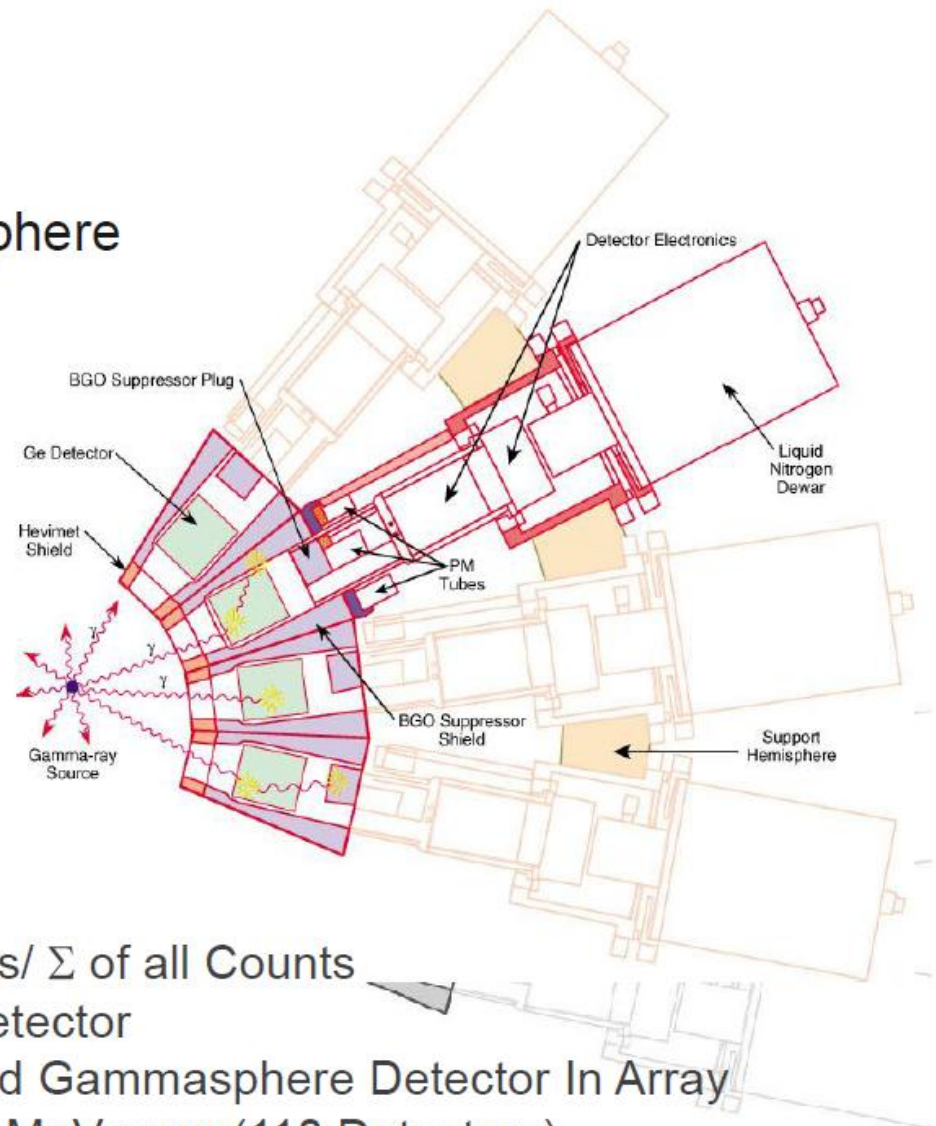
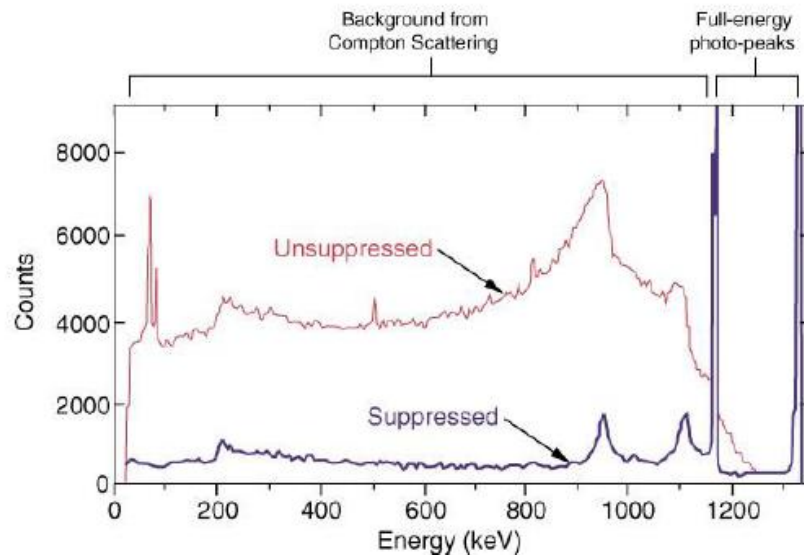




<https://doi.org/10.1093/acrefore/9780190871994.013.93>

Compton Suppression

Gammasphere



- Peak to Total (P/T) = Σ Photo Peaks / Σ of all Counts
- P/T ~ 0.20 for 70% Co-axial Ge Detector
- P/T ~ 0.55 for Compton Suppressed Gammasphere Detector In Array
- Photopeak efficiency is ~10% for 1 MeV γ ray (110 Detectors)
- $\delta E = 2.5$ keV at 1MeV

Coincidence counting in nuclear physics is an 'established' idea.

MAY, 1940

R. S. I.

VOLUME 11

The Application of the Method of Coincidence Counting to Experiments in Nuclear Physics

J. V. DUNWORTH

Denman Baynes Research Student, Clare College, Cambridge, England

(Received September 27, 1939)

The paper describes the principles involved in the application of coincidence counting to problems in nuclear physics, and gives details of the various methods of approach to the solution of nuclear level schemes, with some of the difficulties encountered. It is shown that the maximum source strength which can be used is inversely proportional to the coincidence resolving time and that the method of experiment has the great advantage over most other methods in that it can be used with very weak sources (sources having an activity of about 10^{-5} millicurie). An accurate knowledge of the absolute net efficiency of a Geiger counter for all types of radiation is required in the interpretation of the coincidence rates, and the method of achieving this at the same time as information is obtained about nuclear level schemes is explained. Further, it is pointed out that the method makes possible a simple and rapid determination of the total energy of disintegration of β -radioactive nuclei and therefore of the mass differences between parent and daughter nuclei.

COINCIDENCE COUNTING AND NUCLEAR PHYSICS

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times used* and demonstrating its constancy for all arrangements of Geiger counters used.

The errors shown are the theoretical statistical r.m.s. errors. The experimental weighted r.m.s. error of the resolving times in column 6 is 0.05×10^{-7} min. agreeing very closely with the statistical r.m.s. error of 0.03×10^{-7} min. Any lack of constancy of τ would have caused the former to be much greater than the latter. No genuine coincidence rates were operative due to the sources used in the above measurements (i.e., $G=0$).

Some idea of the order of magnitude of the various quantities involved in a nuclear coincidence experiment together with an indication of the method of experiment may be obtained

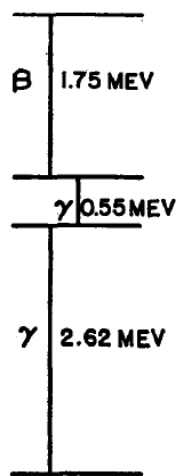


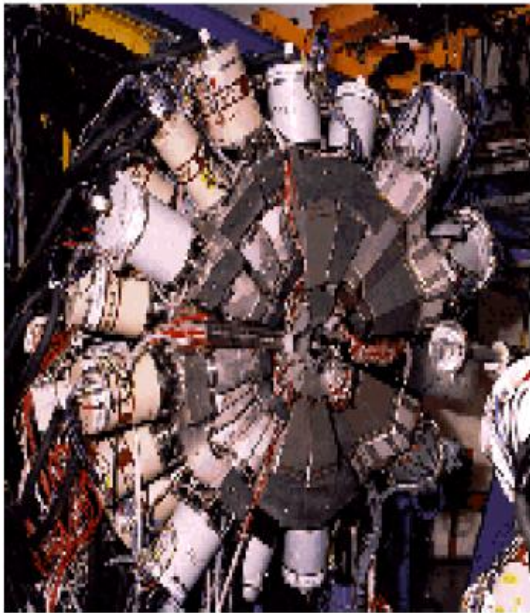
FIG. 1. Modified level scheme of ThC''.



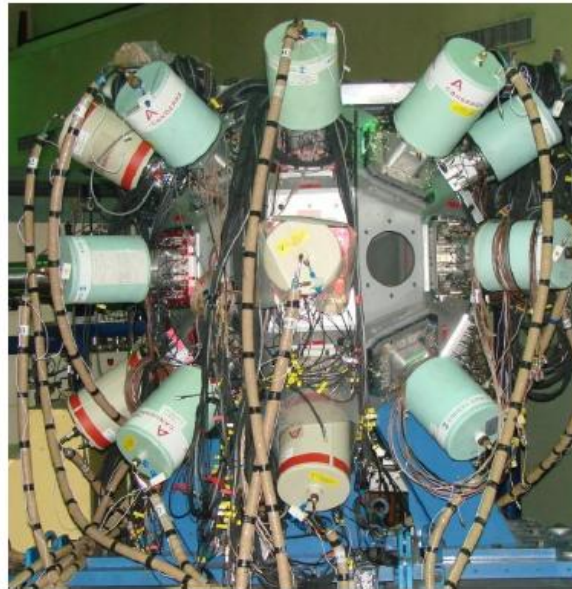
John Vernon Dunworth,
Director, NPL 1964–1977
CIPM President 1975–1985

Compton Suppressed HpGe Arrays:

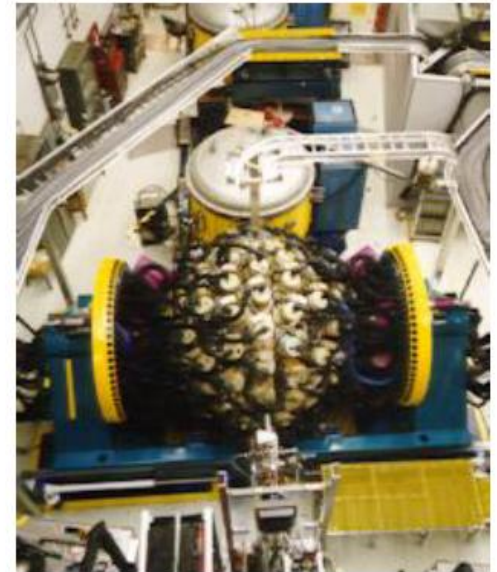
From the 1980s to the mid 2020s, arrays of Compton Suppressed Ge Detectors such as TESSA, HERA, 8π , GASP, EUROBALL GAMMASPHERE, TIGRESS, INGA, RoSPHERE,, Miniball, JUROSPHERE, AFRODITE, etc have been the tools of choice for nuclear spectroscopy



EUROBALL

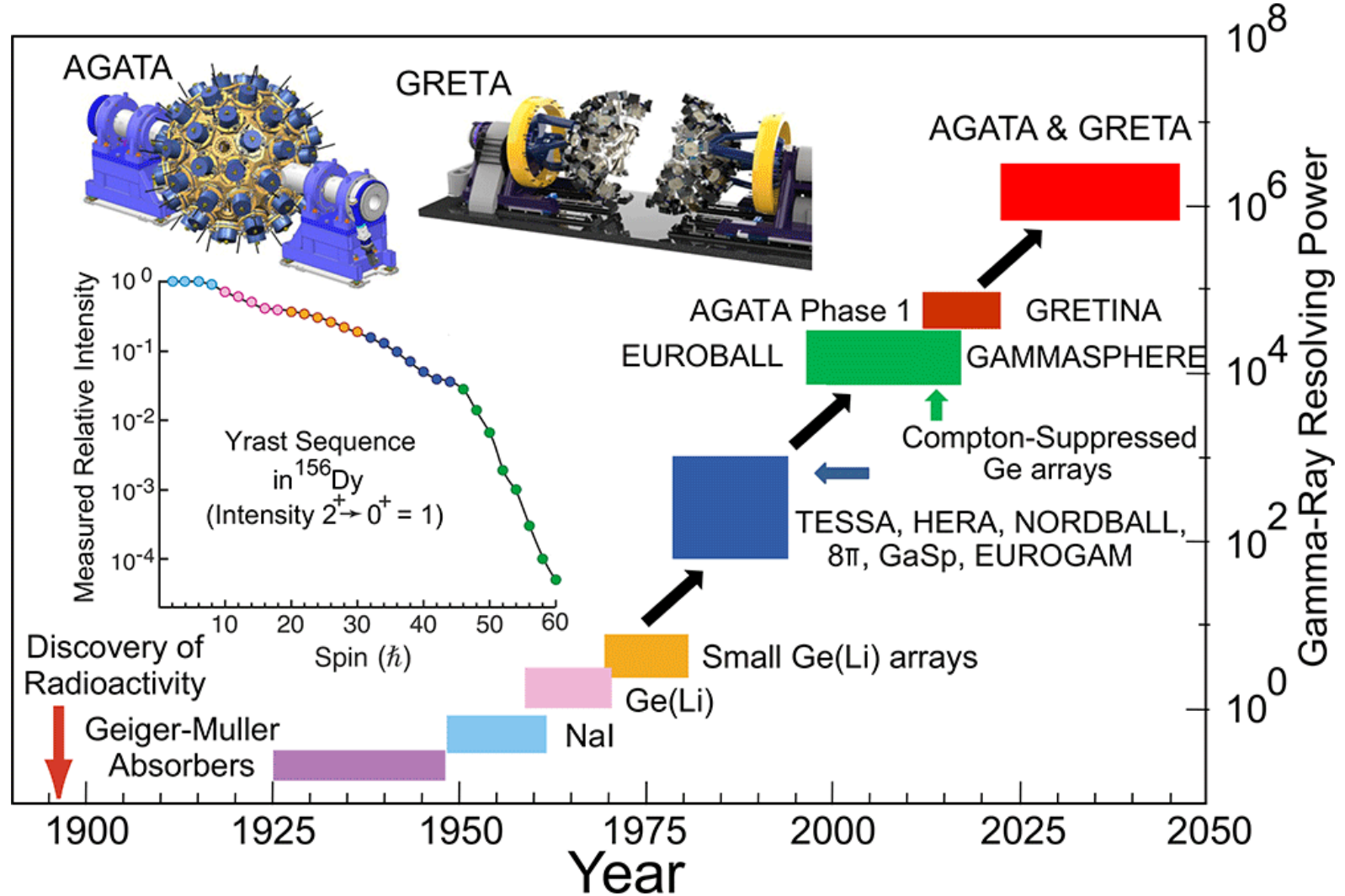


INGA



Gammasphere

Recent development include TRACKING arrays (GRETINA / GRETA, AGATA...) Also Fragmentation Decay arrays (RISING; EURICA; DESPEC etc.) and 'Hybrid' arrays (e.g., EXILL+FATIMA, RoSPHERE, NuBALL, GRIFFIN etc.)

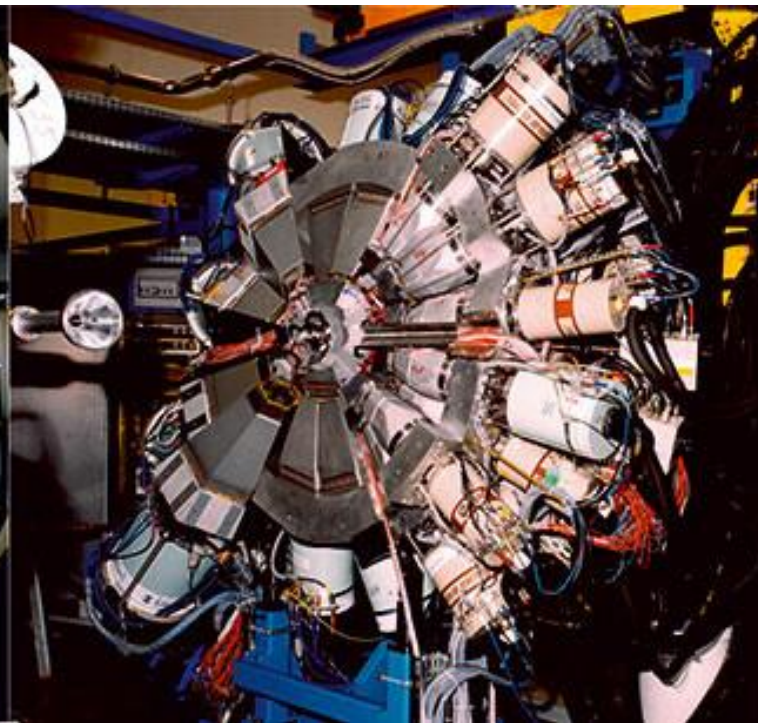
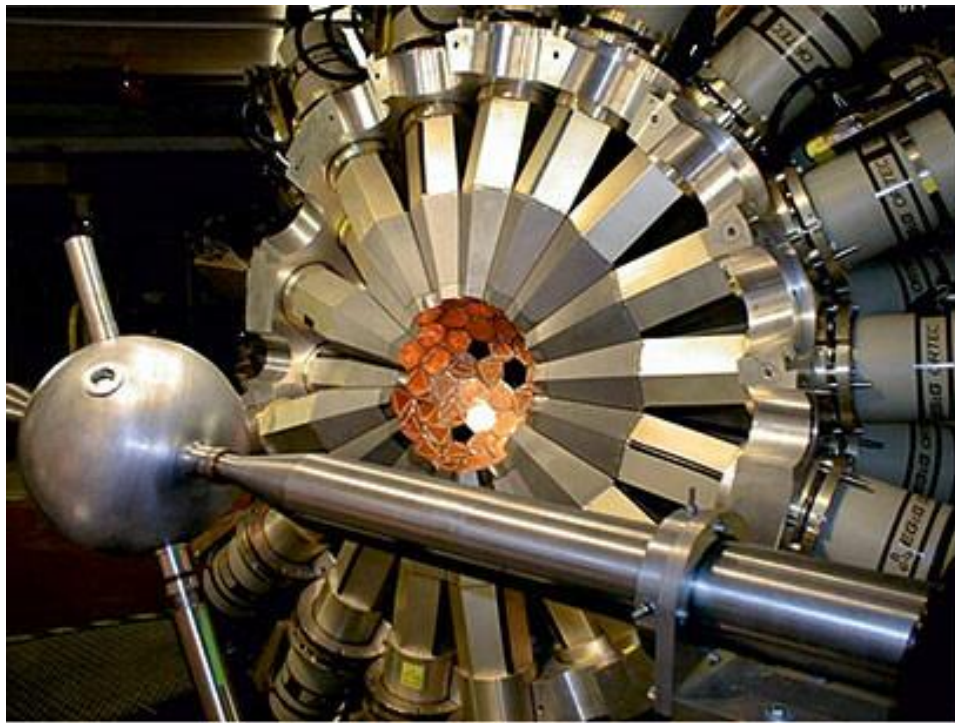


Simpson, J., & Boston, A, (2024, January 30)

Progress in Gamma Detection for Basic Nuclear Science and Applications.

Oxford Research Encyclopedia of Physics. Retrieved 3 Oct. 2025, from

<https://oxfordre.com/physics/view/10.1093/acrefore/9780190871994.001.0001/acrefore-9780190871994-e-93> .



(a)

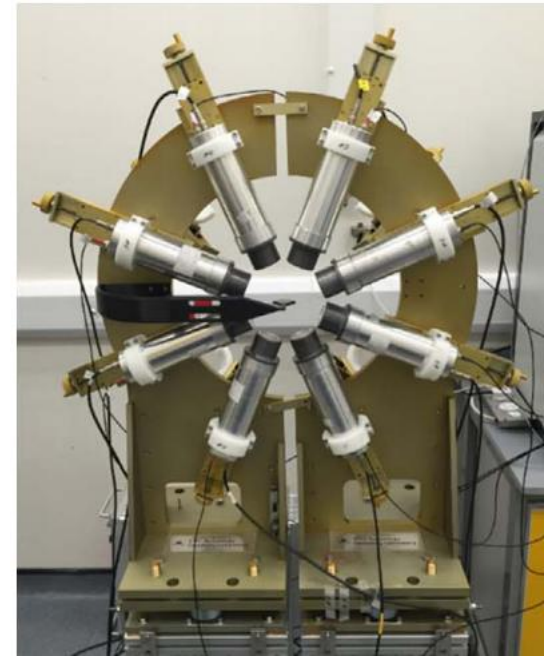
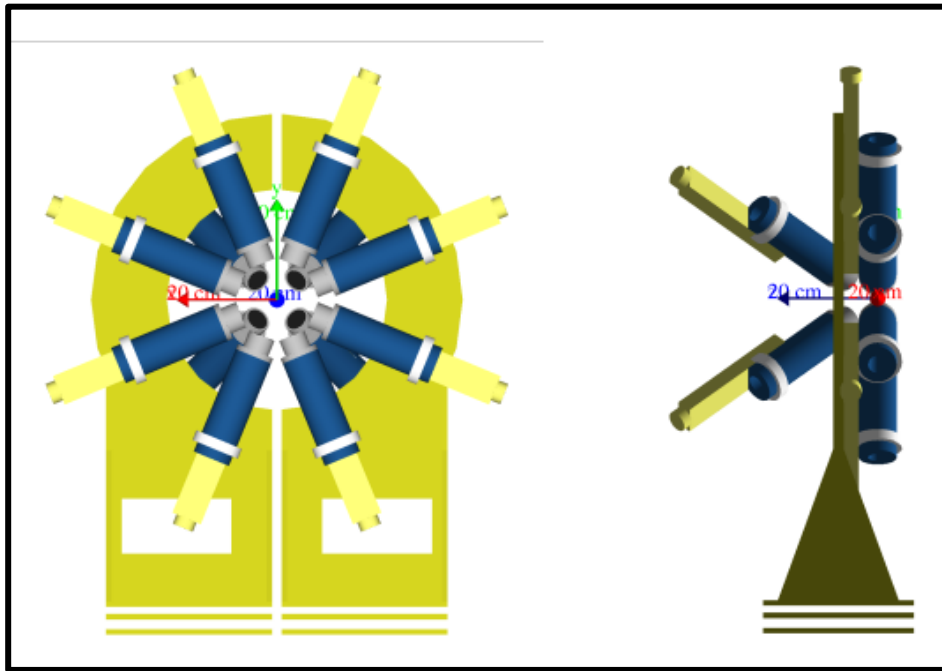


(b)

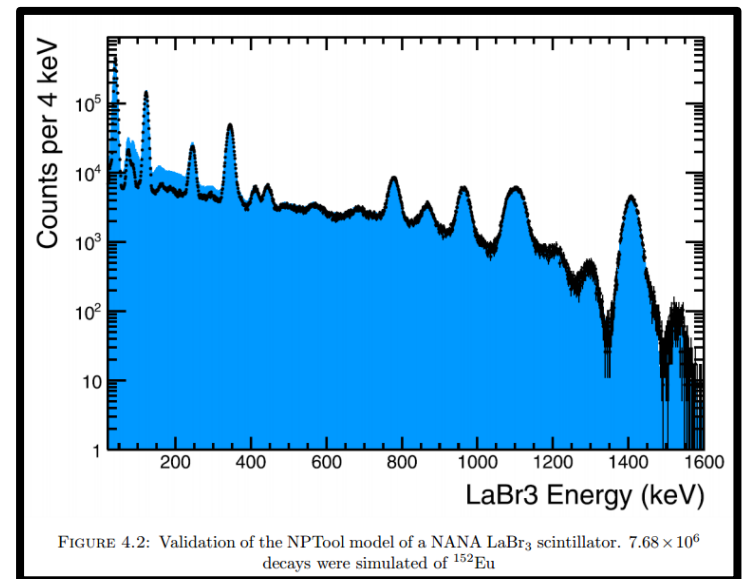
Simpson, J., & Boston, A, (2024, January 30)

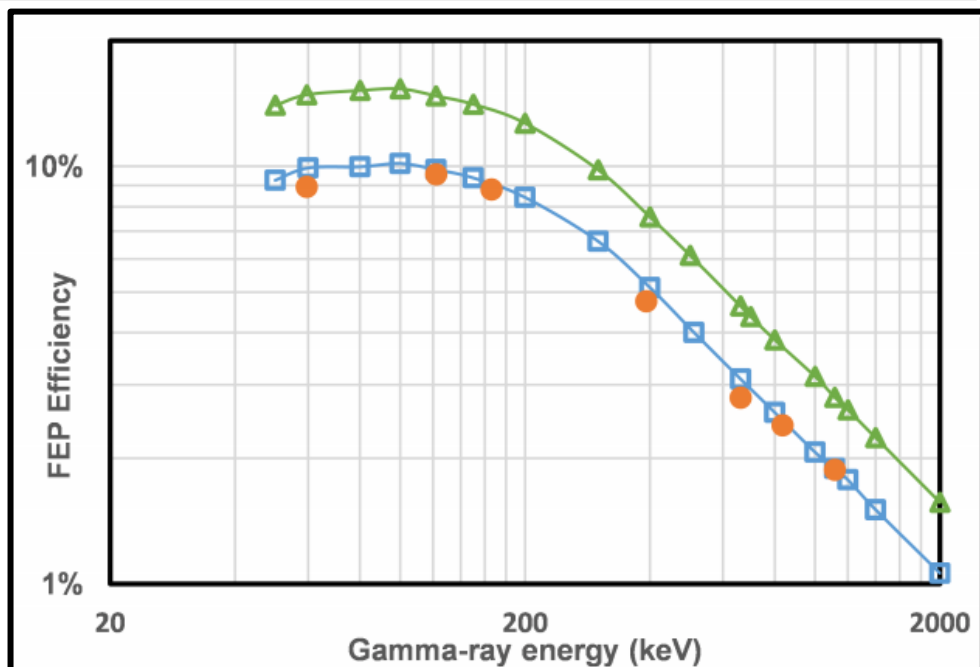
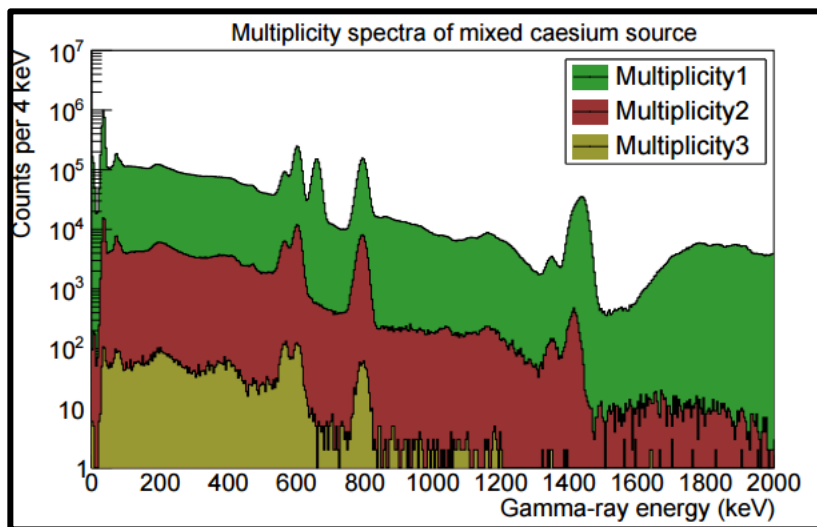
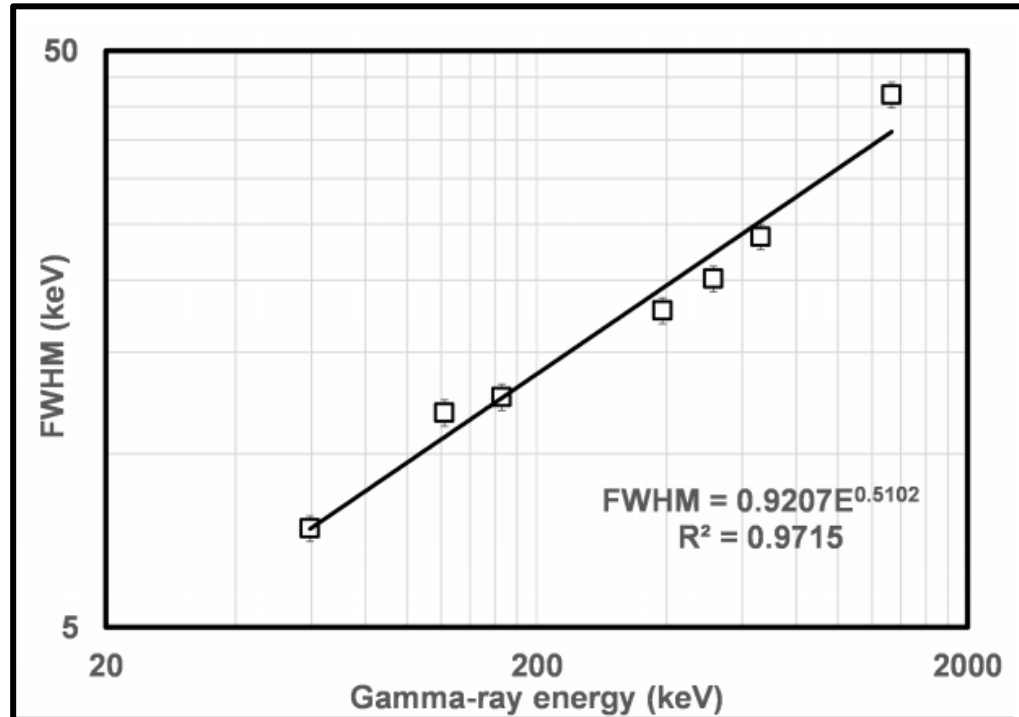
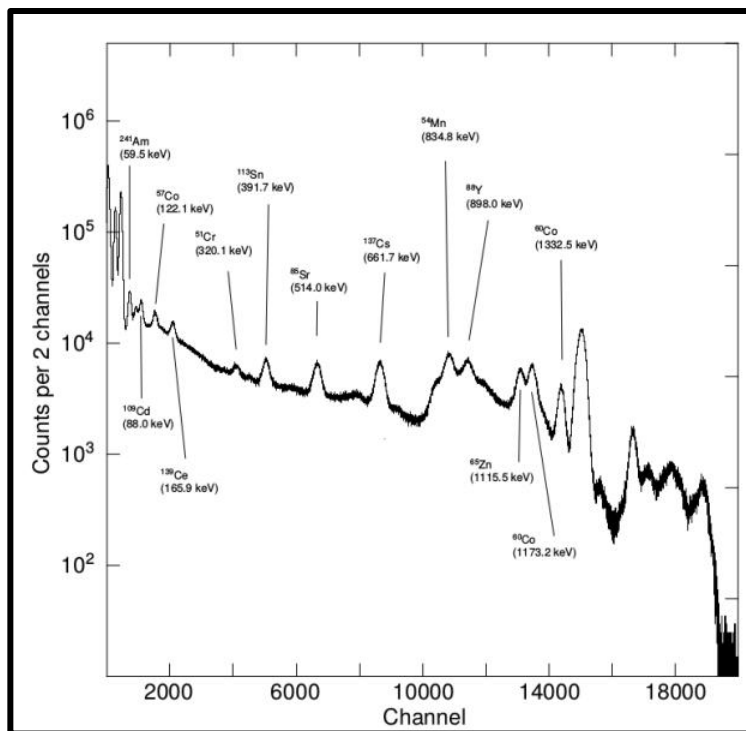
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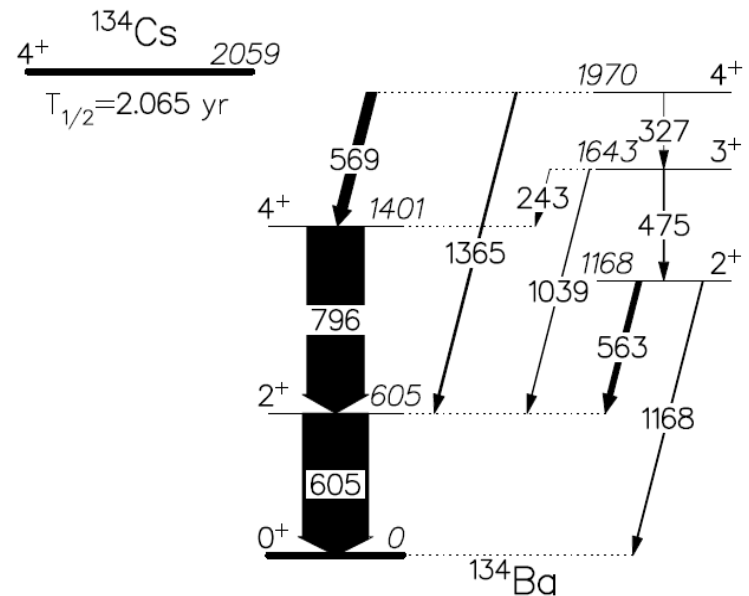
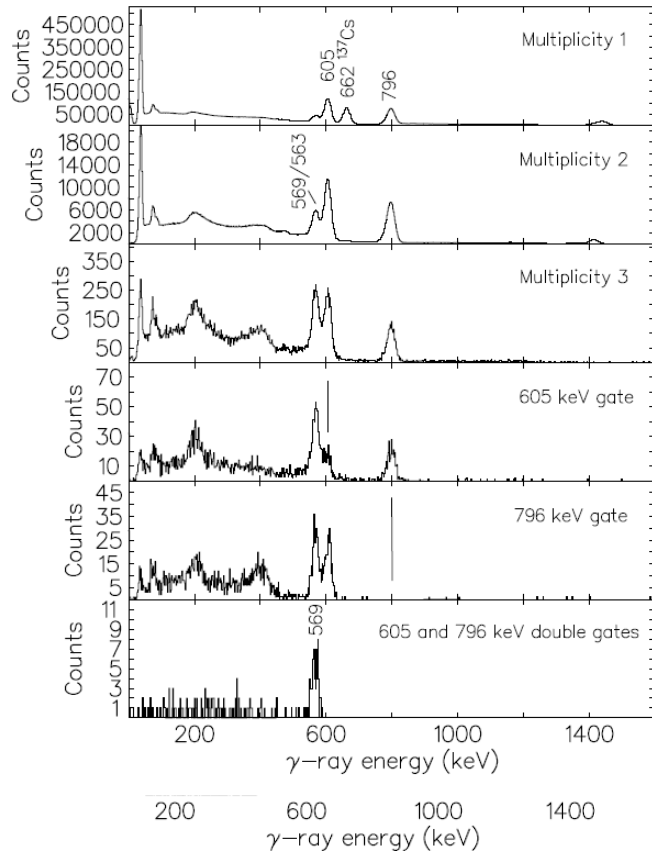
Detector number	Polar angle θ (degrees)	Azimuthal angle ϕ (degrees)
0	90	112.5
1	90	157.5
2	90	202.5
3	90	247.5
4	90	292.5
5	90	337.5
6	90	22.5
7	90	67.5
8	45	45
9	45	135
10	45	225
11	45	315





Nuclear level schemes can be constructed using gamma-ray (time-correlated) energy coincidences.

'Selecting' a particular discrete gamma-ray energy in one detector and observing which transitions are in temporal coincidence with this particular transition.



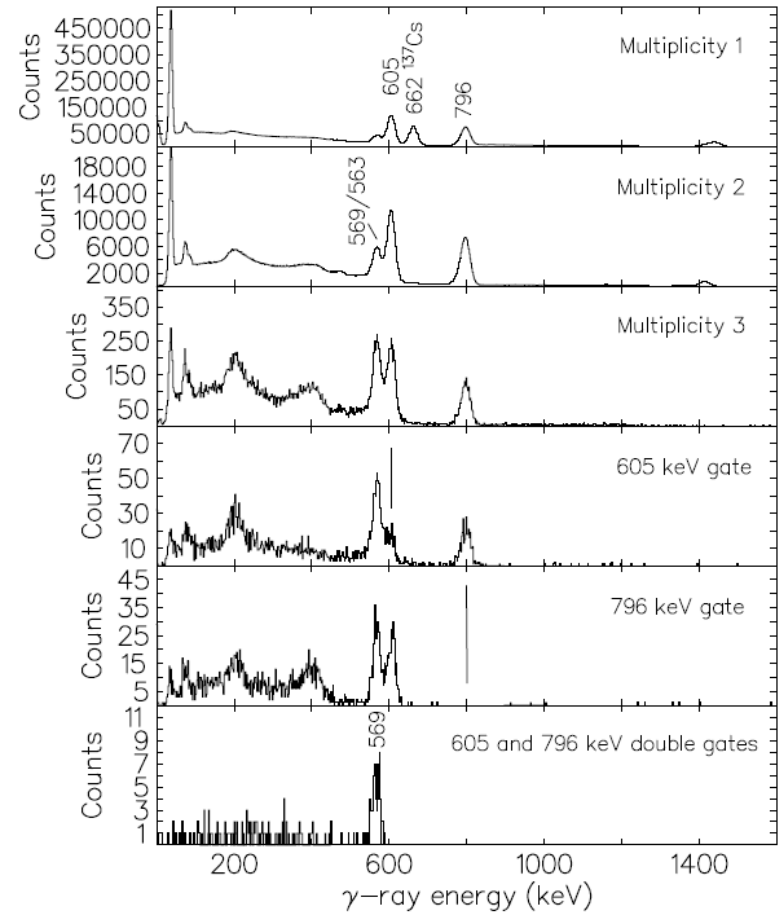
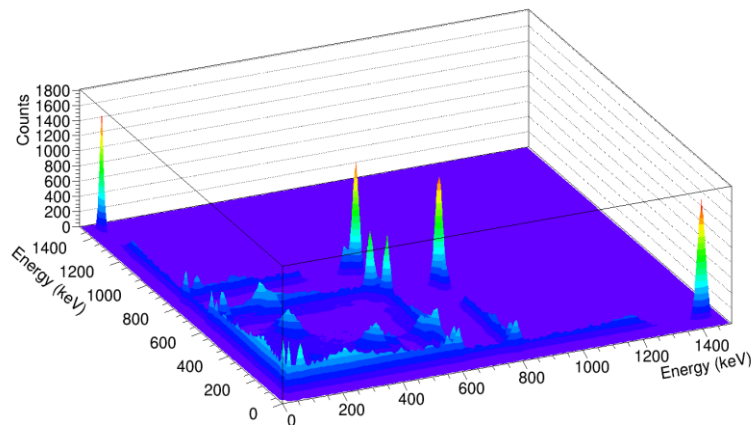
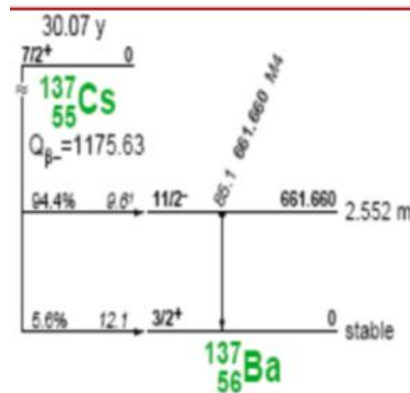
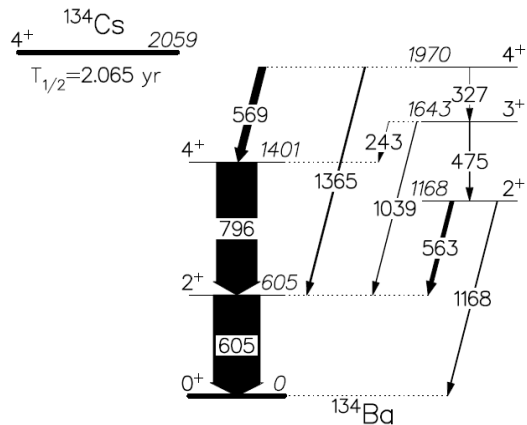
For 605 keV and 796 keV double gate, the peak-to-total of the 569 keV is 40 %!

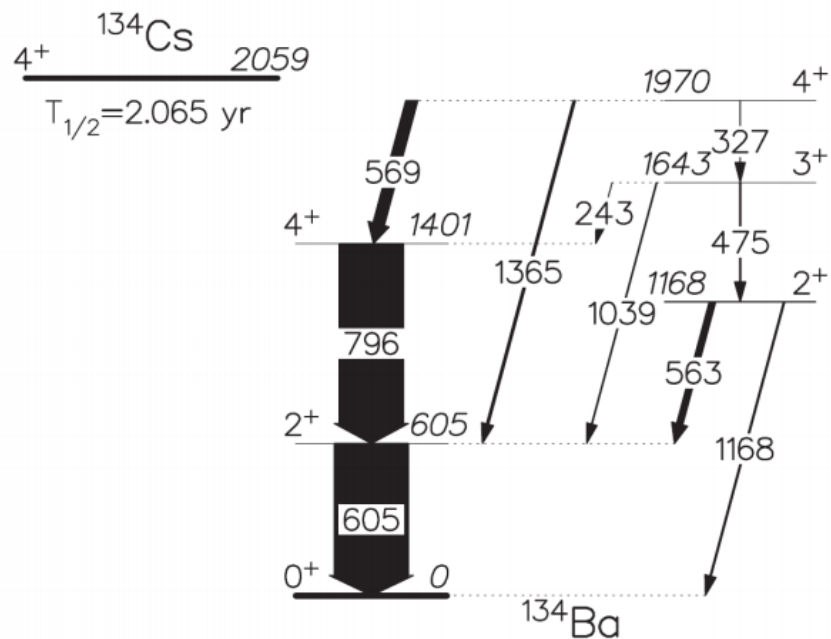
Loss of statistics but much improved signal cleanliness.

Resolving and selection of weakly populated decay channels

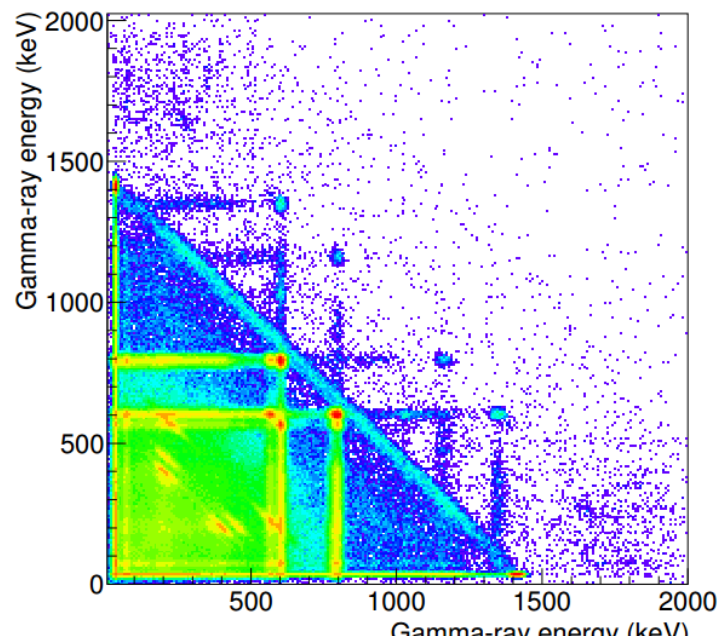
Opening a window and demanding two detectors fire within removes the strong ^{137}Cs 661.6 keV emission.

^{134}Cs enhanced compared to background with just a timing/ multiplicity gate!





Total γ - γ coincidence matrix for mixed caesium source

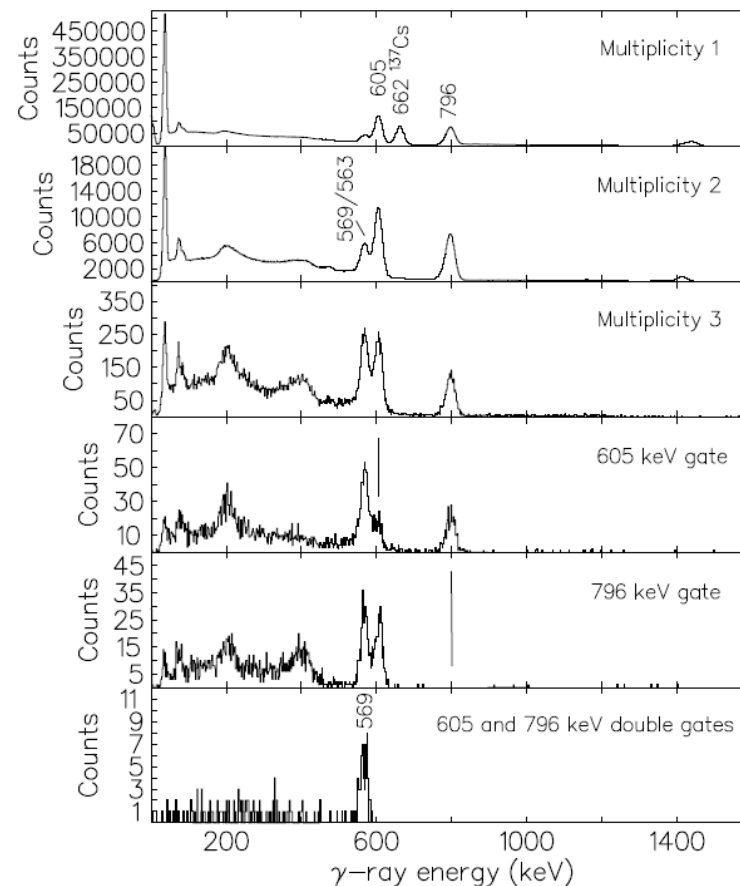


Commissioning of the UK National Nuclear Array

R. Shearman^{a,b,*}, S.M. Collins^a, G. Lorusso^{a,b}, M. Rudigier^b, S.M. Judge^{a,b}, S.J. Bell^a,
 Zs. Podolyak^b, P.H. Regan^{a,b}

^a National Physical Laboratory, Teddington, Middlesex TW11 0LW, UK

^b Department of Physics, University of Surrey, Guildford GU2 7XH, UK

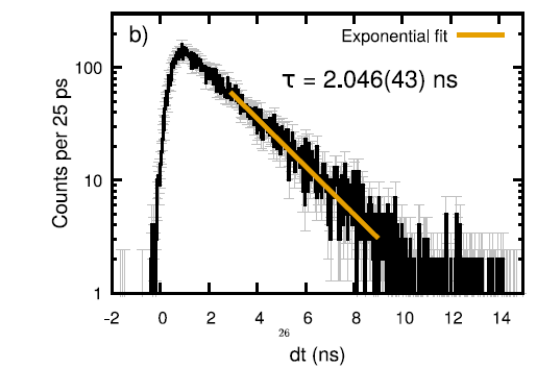
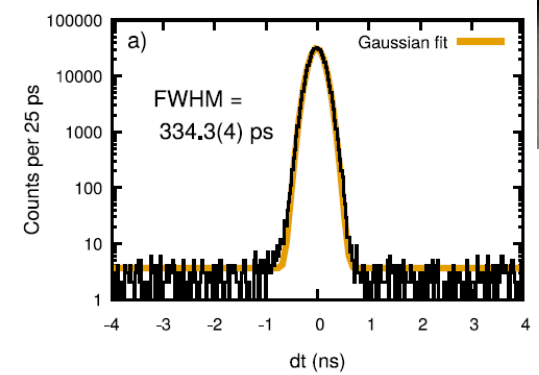
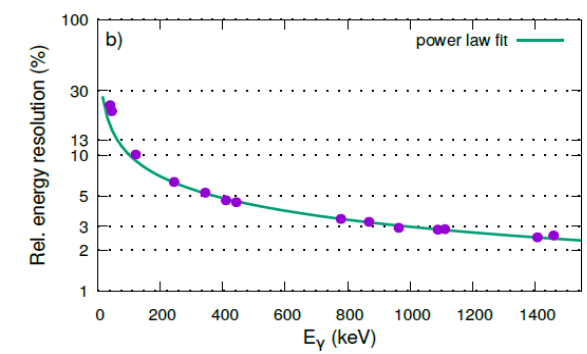
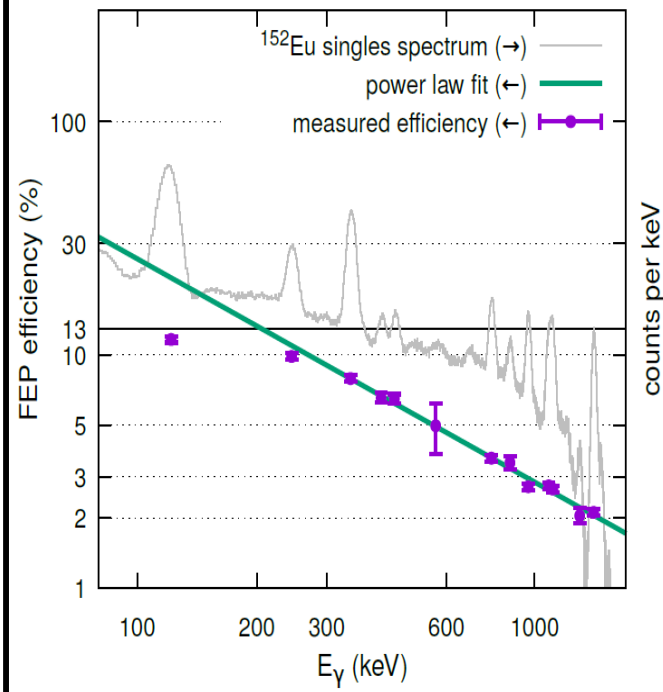
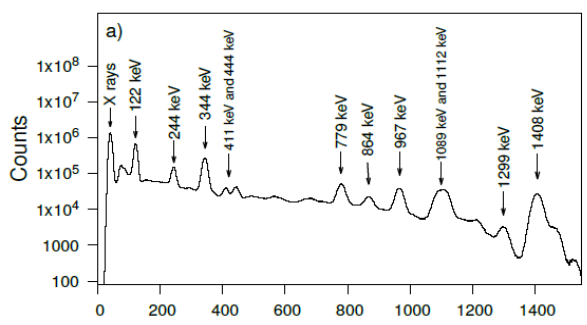
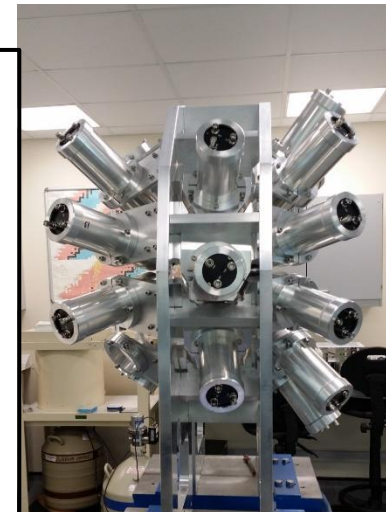
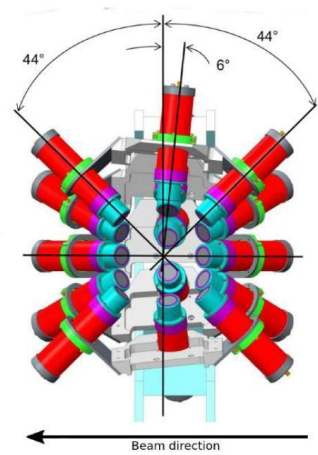




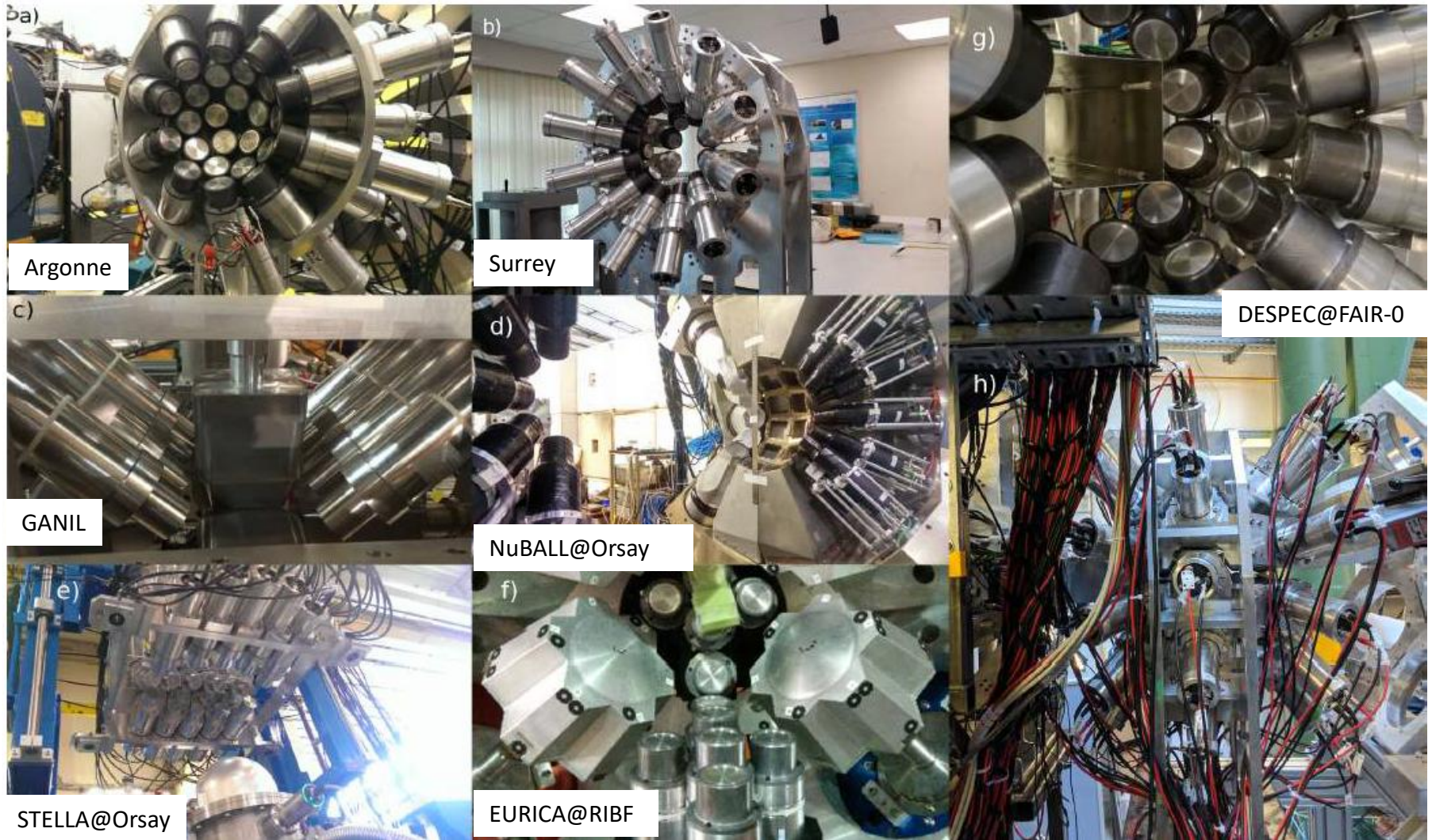
FATIMA — FAST TIMING Array for DESPEC at FAIR

M. Rudigier^{a,b,*}, Zs. Podolyák^a, P.H. Regan^{a,c}, A.M. Bruce^d, S. Lalkovski^{a,e}, R.L. Canavan^{a,c}, E.R. Gamba^d, O. Roberts^d, I. Burrows^f, D.M. Cullen^g, L.M. Fraile^h, L. Gerhard^j, J. Gerl^l, M. Gorskaⁱ, A. Grant^f, J. Jolie^j, V. Karayonchev^j, N. Kurzⁱ, W. Korten^k, I.H. Lazarus^f, C.R. Nita^l, V.F.E. Pucknell^f, J.-M. Régis^j, H. Schaffnerⁱ, J. Simpson^f, P. Singh^k, C.M. Townsley^a, J.F. Smith^m, J. Vesic^{l,n}

^a Department of Physics, University of Surrey, Guildford, GU2 7XH, United Kingdom
^b Institut für Kernphysik, Technische Universität Darmstadt, Schlossgartenstrasse 9, 64289, Darmstadt, Germany
^c National Physical Laboratory, Teddington, Middlesex, TW11 0LW, United Kingdom
^d School of Computing Engineering and Mathematics, University of Brighton, Brighton BN2 4GJ, United Kingdom
^e Faculty of Physics, University of Sofia, 1164 Sofia, Bulgaria

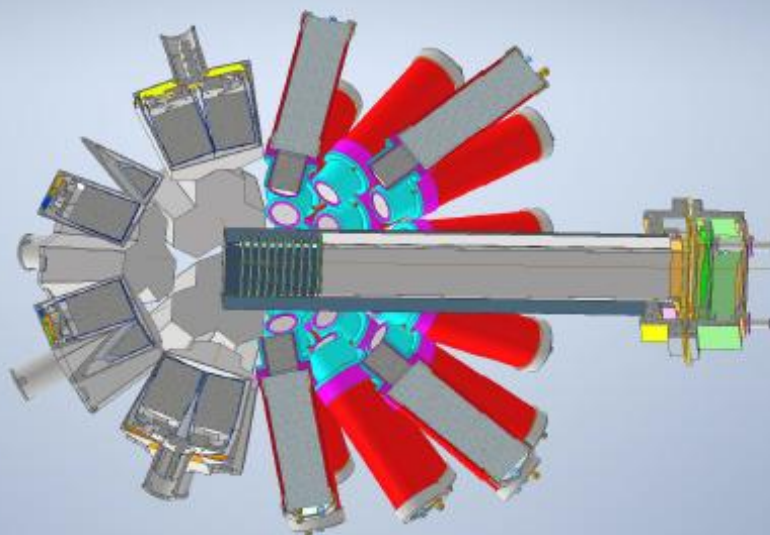
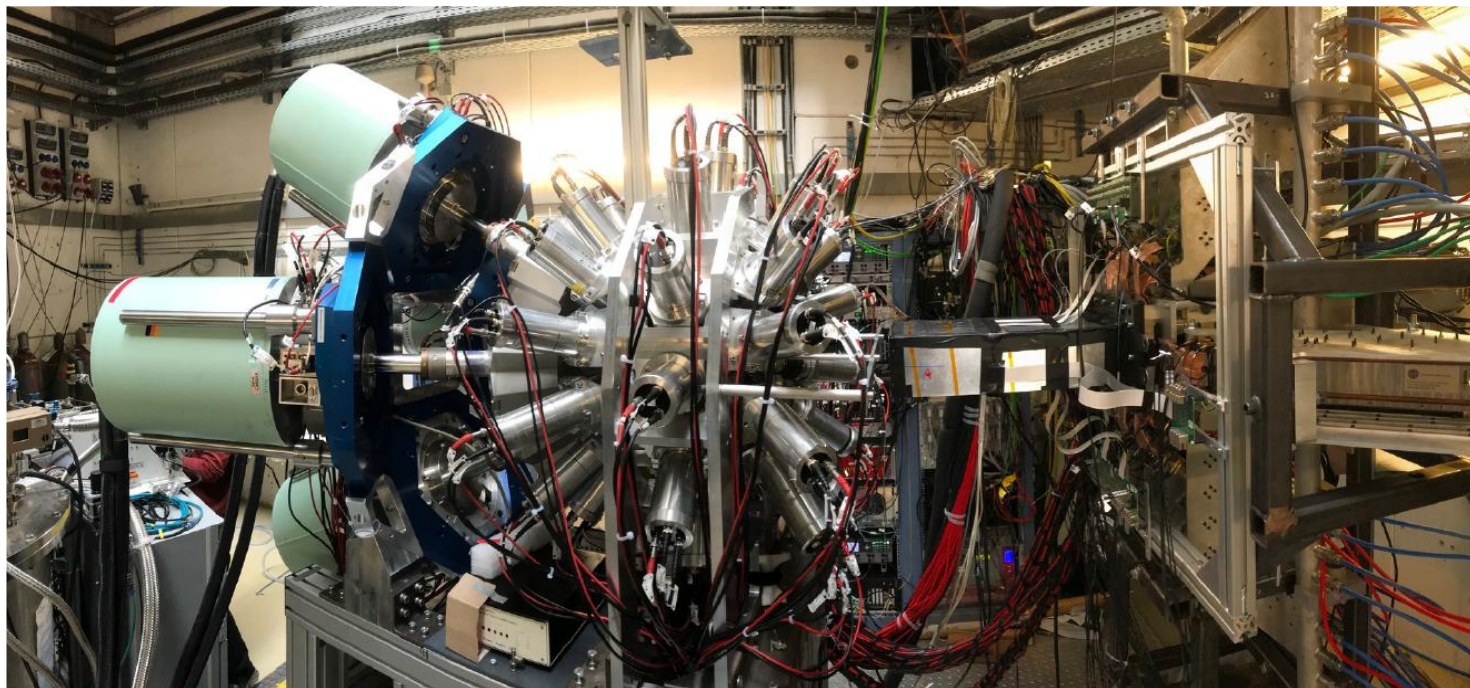


FATIMA LaBr_3 Detectors, used around the world



M. Rudigier, Zs. Podolyák, P.H. Regan et al.

Nuclear Inst. and Methods in Physics Research, A 969 (2020) 163967



Nuclear Inst. and Methods in Physics Research, A 969 (2020) 163967

Nuclear Inst. and Methods in Physics Research, A

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



FATIMA — FAST TIMING Array for DESPEC at FAIR

M. Rudigier^{a,b,*}, Zs. Podolyák^a, P.H. Regan^{a,c}, A.M. Bruce^d, S. Lalkovski^{a,e}, R.L. Canavan^{a,c}, E.R. Gamba^d, O. Roberts^d, I. Burrows^f, D.M. Cullen^g, L.M. Fraile^h, L. Gerhardⁱ, J. Gerl^j, M. Gorska^k, A. Grant^l, J. Jolie^l, V. Karayonchev^j, N. Kurz^l, W. Korten^k, I.H. Lazarus^l, C.R. Nita^l, V.F.E. Pucknell^l, J.-M. Régis^l, H. Schaffner^l, J. Simpson^l, P. Singh^k, C.M. Townsley^a, J.F. Smith^m, J. Vesicⁿ

^a Department of Physics, University of Surrey, Guildford, GU2 7XH, United Kingdom

^b Institut für Kernphysik, Technische Universität Darmstadt, Schlossgartenstrasse 9, 64289, Darmstadt, Germany

^c National Physical Laboratory, Teddington, Middlesex, TW11 0LW, United Kingdom

^d School of Computing Engineering and Mathematics, University of Brighton, Brighton BN2 4GJ, United Kingdom

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^f STFC Daresbury Laboratory, Daresbury, Warrington WA4 4AD, United Kingdom

^g Nuclear Physics Group, Schuster Laboratory, University of Manchester, Manchester, M13 9PL, United Kingdom

^h Grupo de Física Nuclear e IPARCOS, Universidad Complutense de Madrid, C31 Moncloa, 28040 Madrid, Spain

ⁱ GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany

^j Institut für Kernphysik der Universität zu Köln, Zùlpicher Strasse 77, D-50937 Köln, Germany

^k IfG, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France

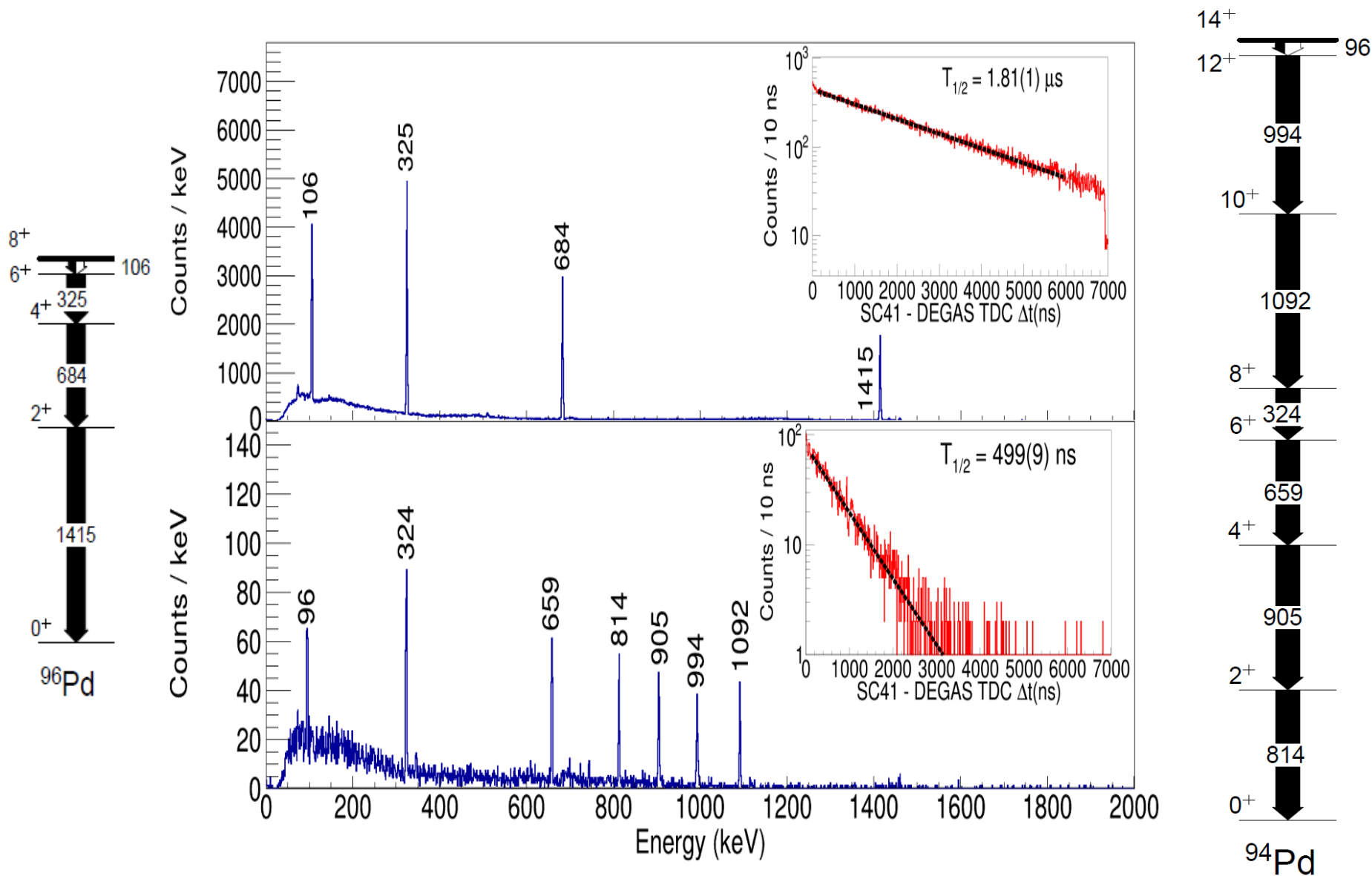
^l Horia Hulubei National Institute of Physics and Nuclear Engineering (HIN-HE), RO-077125 Bucharest, Romania

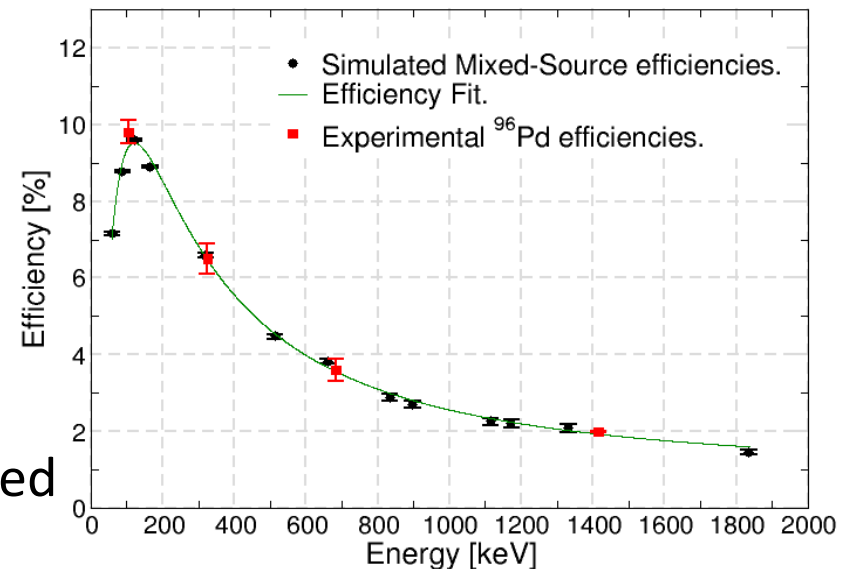
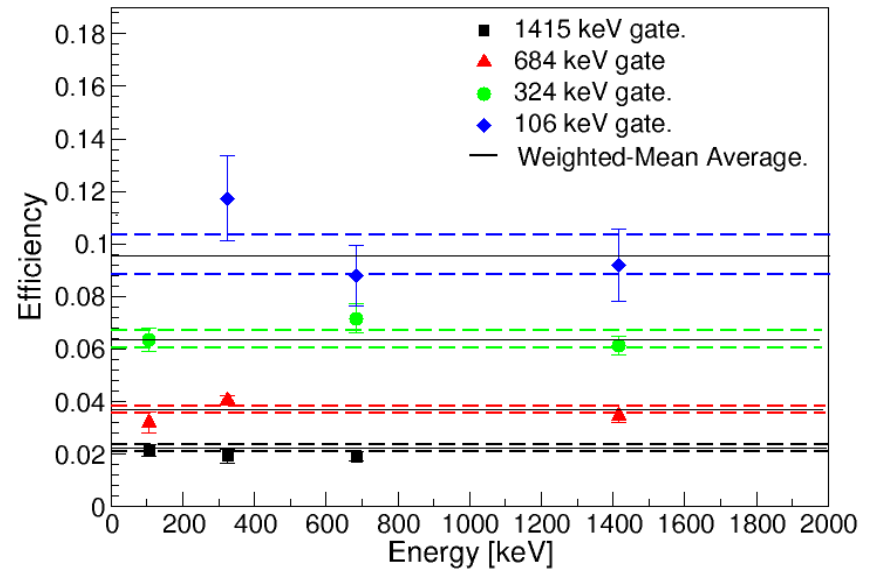
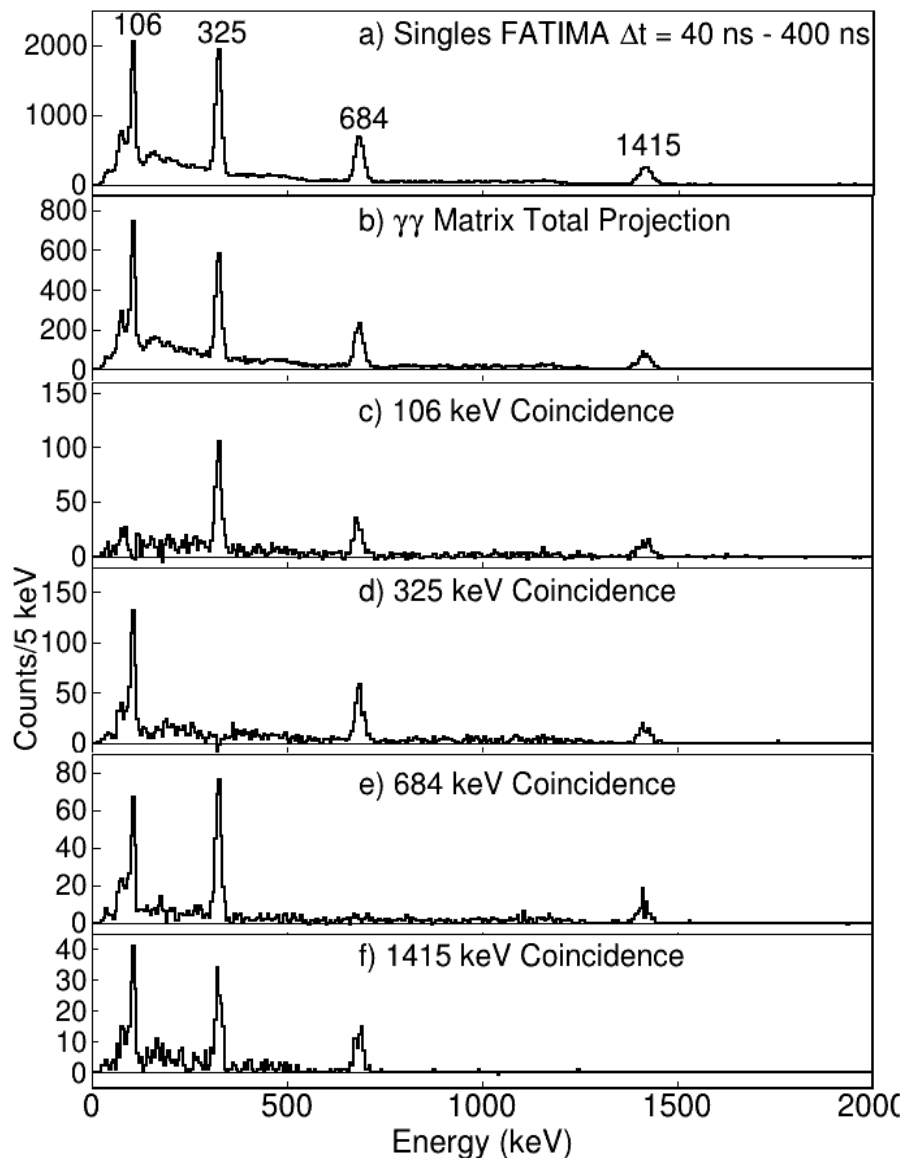
^m School of Engineering, University of the West of Scotland, Paisley PA1 2BE, United Kingdom

ⁿ Jozef Stefan Institute, Jamova cesta 39, 1000 Ljubljana, Slovenia

A.K.Mistry, H Albers et al. NIM **A1033** (2022) 166662

$^{94,96}\text{Pd}$ isomers and lifetime analysis from DESPEC with HPGe





FATIMA FEP efficiency response measured

By γ - γ to singles ratios in ^{96}Pd .

GEANT4 simulations for array (Chishti, Jazrawi et al., NIM)



Full Length Article

Response of the FAST Timing Array (FATIMA) for DESPEC at FAIR Phase-0

M.M.R. Chishti^{a,b,*}, S. Jazrawi^{a,c}, R. Shearman^c, P.H. Regan^{a,c}, Zs. Podolyák^a, S.M. Collins^{a,c}, M. Górski^a, B. Cederwallⁱ, A. Yaneva^{a,o}, G.X. Zhang^{d,e}, J. Cederkall^b, A. Goasduff^f, H.M. Albers^g, S. Alhomaidhi^g, A. Banerjee^g, A.M. Bruce^k, G. Benzoni^{h,t}, B. Dasⁱ, T. Davinson^l, L.M. Fraile^m, J. Gerl^g, G. Häfner^{o,n}, J. Jolie^o, N. Hubbard^{j,g}, P.R. John^j, R. Lozevaⁿ, A.K. Mistry^g, B.S. Nara Singh^p, M. Mikolajczuk^g, M. Polettini^{h,t}, N. Pietralla^j, J.M. Regis^o, M. Rudigier^g, E. Sahin^q, A. Sharma^{g,s}, M. Siⁿ, J. Vesic^q, V. Wernerⁿ

^a School of Mathematics & Physics, University of Surrey, GU2 7XH, United Kingdom

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^d Dipartimento di Fisica, Università di Padova, I-35131 Padova, Italy

^e Istituto Nazionale di Fisica Nucleare, Sezione di Padova, Padova, Italy

^f INFN, Laboratori Nazionali di Legnaro, Legnaro (PD), Italy

^g GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany

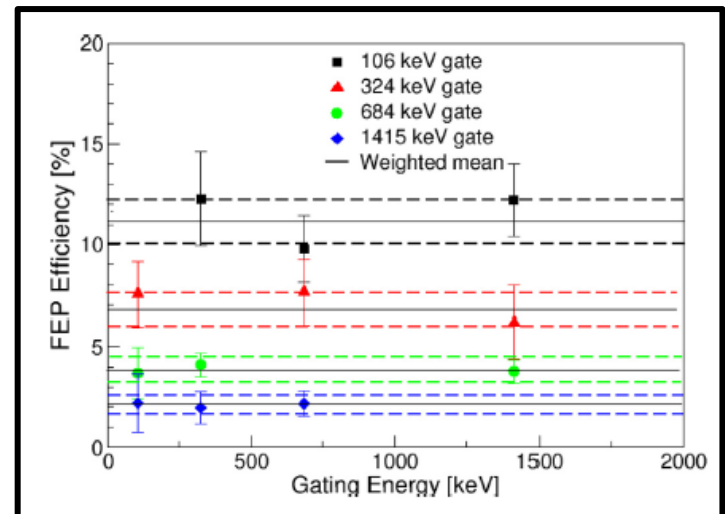
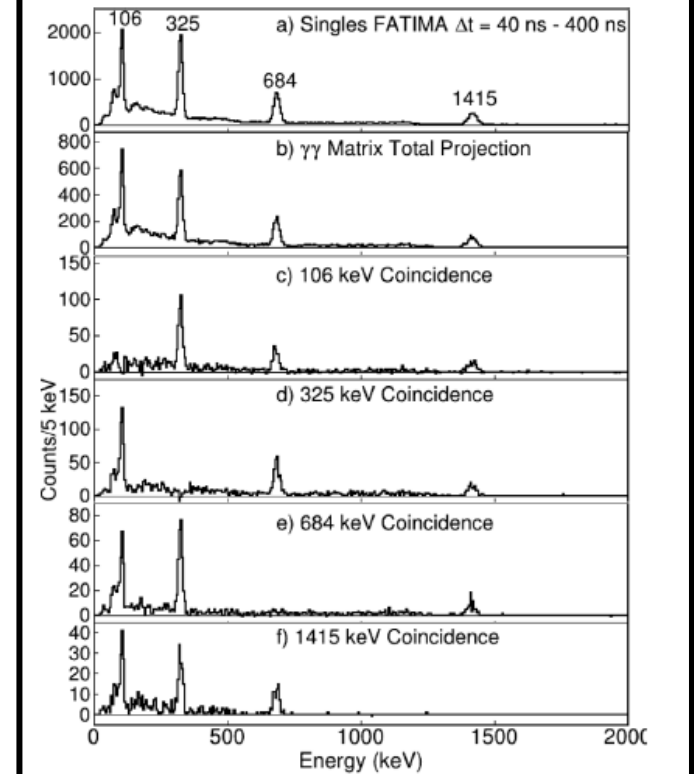
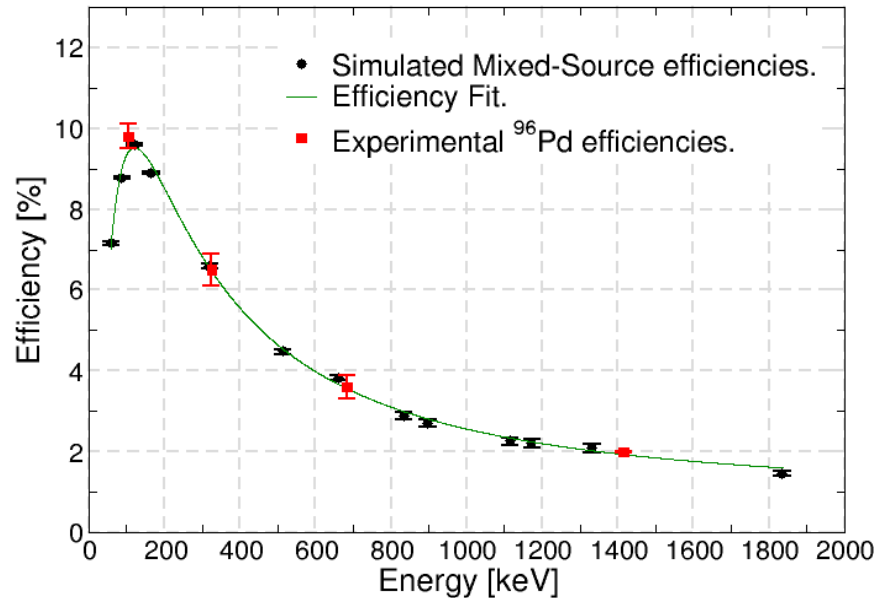
^h INFN, Sezione di Milano, Italy

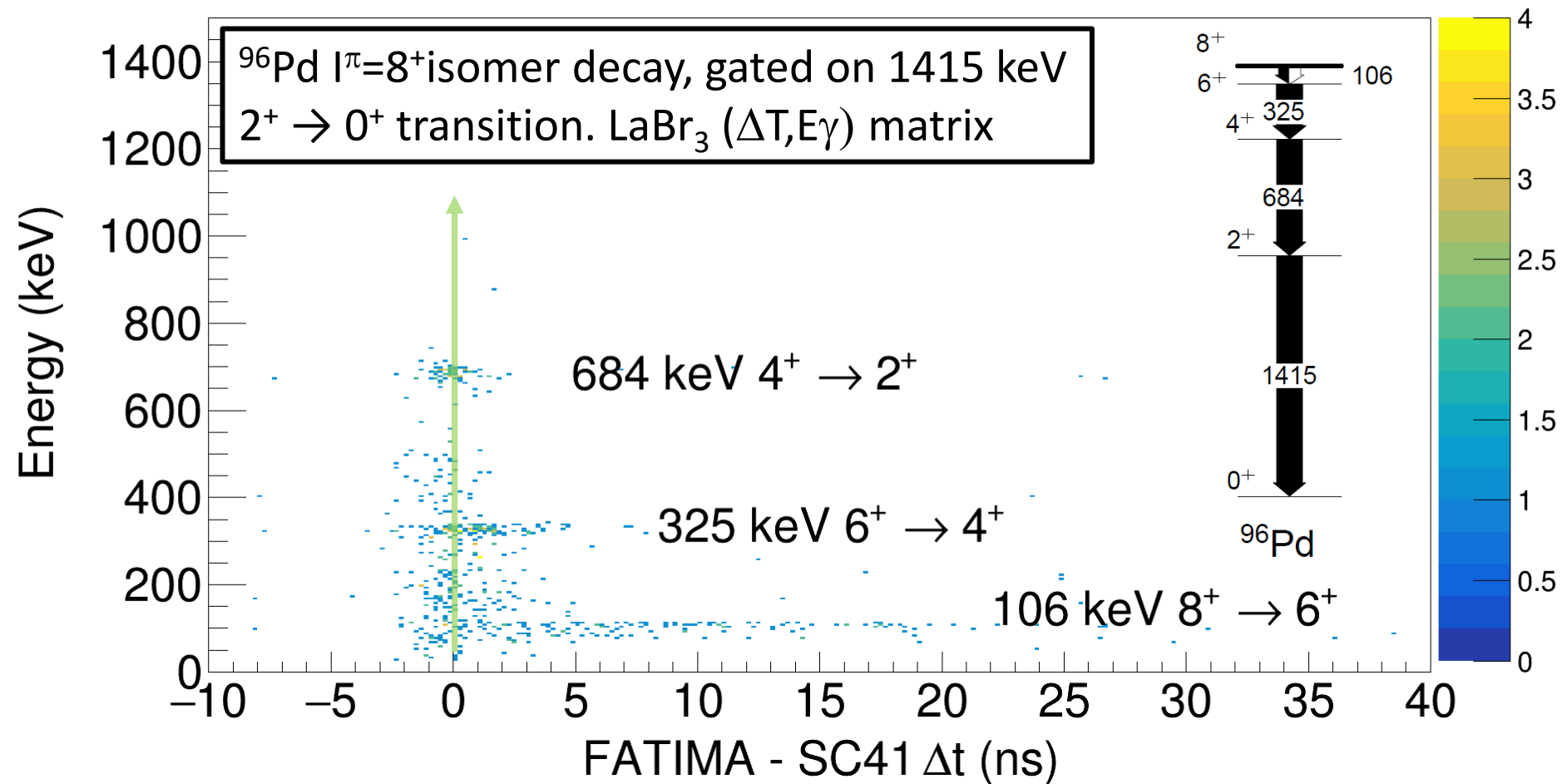
ⁱ KTH Royal Institute of Technology, Sweden

^j Institut für Kernphysik TU Darmstadt, Darmstadt, Germany



$$\epsilon_{\gamma_1} = \frac{I_{\gamma_1 \gamma_2} (1 + \alpha_2)}{I_{\gamma_2}}$$







$^{96}\text{Pd}_{50} \text{ } I^{\pi}=8^{+}$ isomer,
H. Mach et al., PRC95,
014313 (2017), with BaF_2

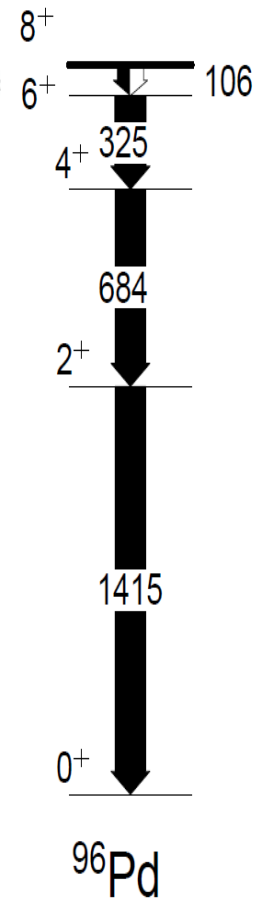
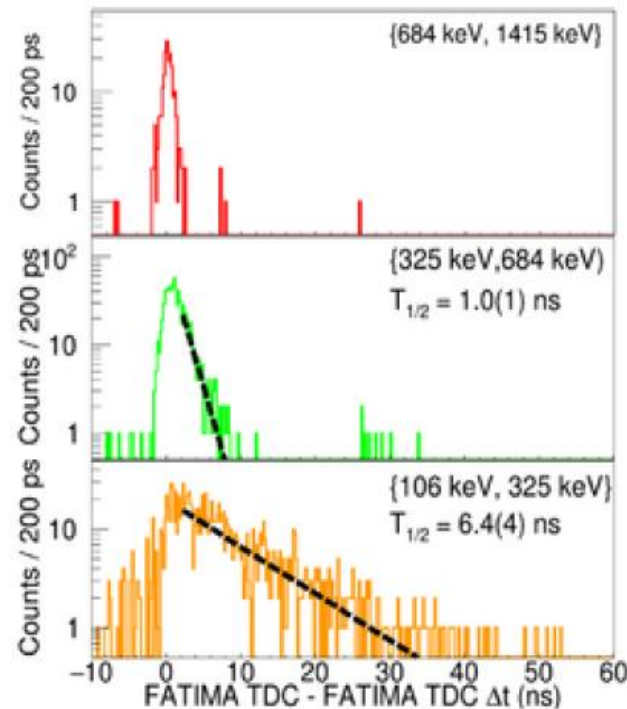
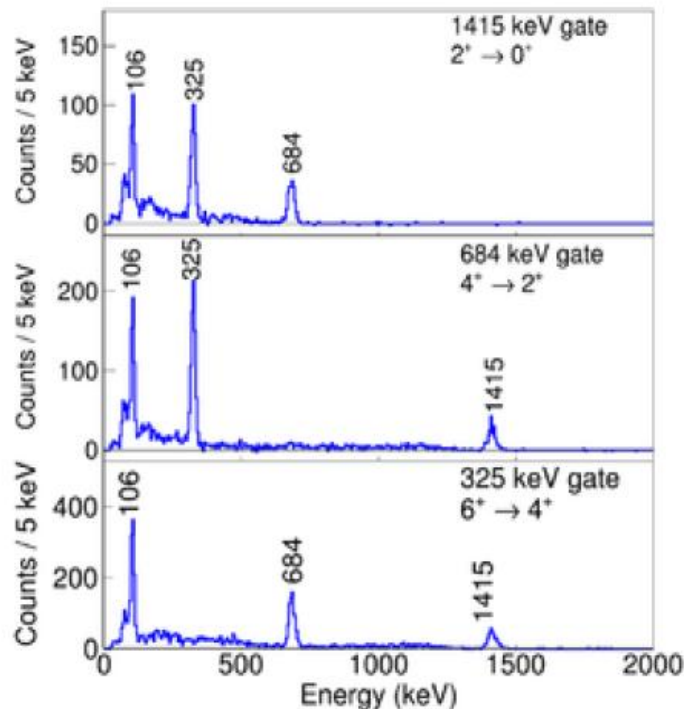
$T_{1/2}(6^{+}) = 6.3(6) \text{ ns}$

$T_{1/2}(4^{+}) = 1.0(1) \text{ ns}$

$T_{1/2}(2^{+}) < 17 \text{ ps}$

Commissioning the Fast TIMing array (FATIMA) at FAIR Phase-0: Half-lives of excited states in the $N = 50$ isotones ^{96}Pd and ^{94}Ru

S. Jazrawi^{a, b, *}, A. Yaneva^{c, d}, M. Polettini^e, B. Das^f, P.H. Regan^{a, b, **}, M. Górski^c, B. Cederwall^f, J. Jolie^d, H.M. Albers^c, M.M.R. Chishti^a, A. Banerjee^c, N. Hubbard^{c, g}, A.K. Mistry^{c, g}, M. Rudigier^g, G. Benzoni^e, J. Gerl^c, A.M. Bruce^b, Zs Podolyák^a, B.S. Nara Singhⁱ, G.X. Zhang^{j, k}, S. Alhomaidhi^{c, g}, C. Appleton^l, T. Arici^c, A. Blazhev^d, T. Davinson^l, A. Esmaylzadeh^d, L.M. Fraile^m, G. Häfner^{d, q}, O. Hall^l, P.R. John^g, V. Karayonchev^d, I. Koujoharov^c, N. Kurz^c, M. Mikolajczuk^{c, n}, N. Pietralla^g, S. Pietri^c, J.M. Regis^d, E. Sahin^{c, g}, L. Sexton^l, H. Schaffner^c, C. Scheidenberger^c, A. Sharma^{c, o}, J. Vesic^p, H. Weick^c, V. Werner^g for the DESPEC collaboration



$\gamma\text{-}\gamma\text{-}\Delta T$ for transitions across individual states $^{96}\text{Pd}_{50}$



Measurements of high-energy γ -rays with $\text{LaBr}_3 : \text{Ce}$ detectors

M. Ciemała^{a,*}, D. Balabanski^b, M. Csatlós^c, J.M. Daugas^d, G. Georgiev^e, J. Gulyás^c, M. Kmiecik^a,
A. Krasznahorkay^c, S. Lalkovski^f, A. Lefebvre-Schuhl^e, R. Lozeva^g, A. Maj^a, A. Vitez^c

^a The Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences, ul. Radzikowskiego 152, 31-342 Kraków, Poland

^b INRNE, Bulgarian Academy of Sciences, BG-1784 Sofia, Bulgaria

^c Institute of Nuclear Research of the Hungarian Academy of Sciences (ATOMKI), P.O. Box 51, H-4001 Debrecen, Hungary

^d CEA, DAM, DIF, F-91297 Arpajon Cedex, France

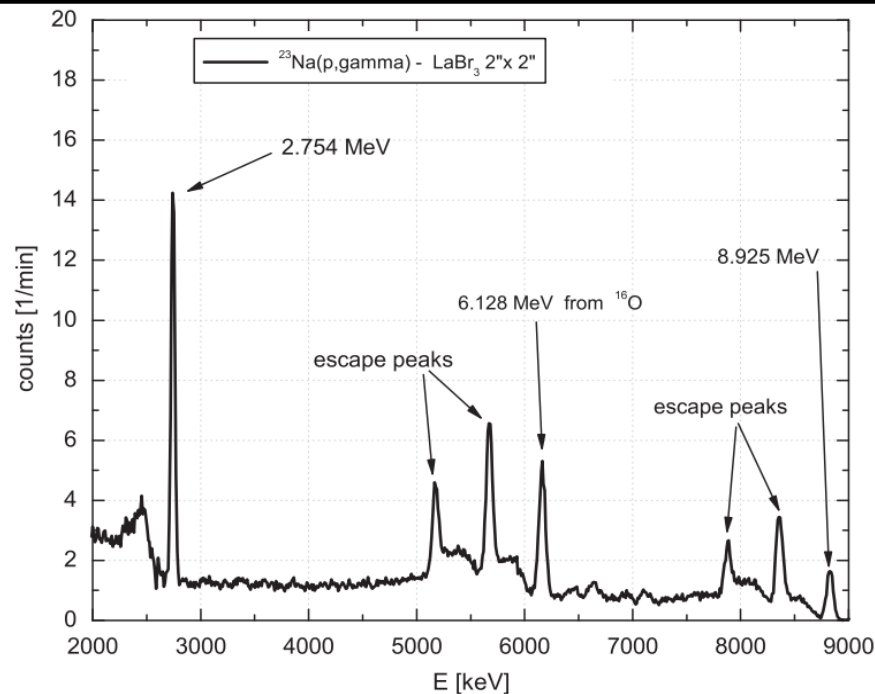


Fig. 1. Gamma-ray spectrum emitted by ^{24}Mg nuclei created in the $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$ reaction at the 1.318 MeV resonance energy, measured by a $\text{LaBr}_3 : \text{Ce}$ 2 in. $\times$ 2 in. scintillation detector.

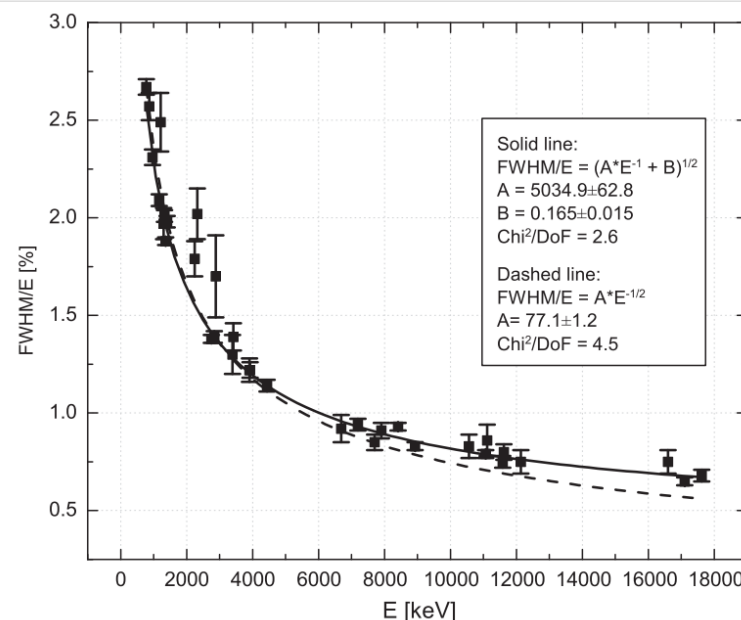
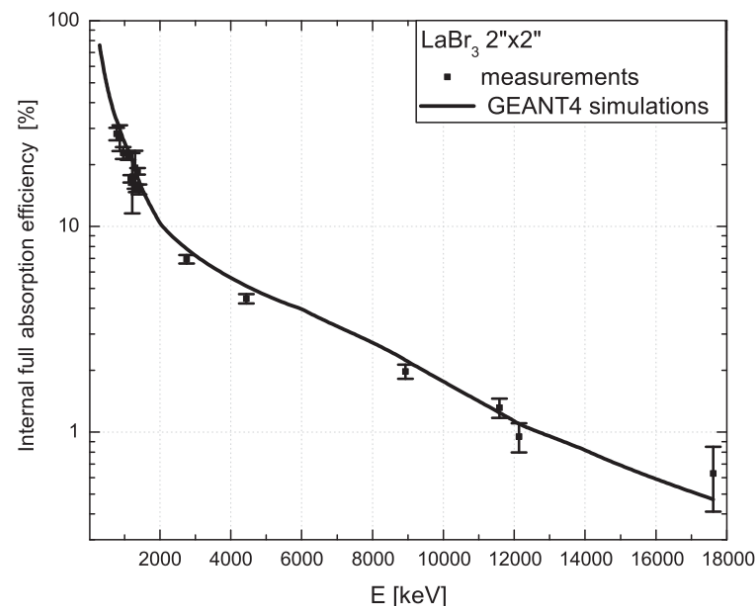


Fig. 4. Relative energy resolution of a $\text{LaBr}_3 : \text{Ce}$ 2 in. $\times$ 2 in. scintillation detector.



Full Length Article

A setup for high-energy γ -ray spectroscopy with the ELI-NP large-volume $\text{LaBr}_3:\text{Ce}$ and CeBr_3 detectors at the 9 MV Tandem accelerator at IFIN-HH

S. Aogaki^a, D.L. Balabanski^a, R. Borcea^b, P. Constantin^a, C. Costache^b, M. Cuciu^a, A. Kuşoğlu^{a,c}, C. Mihai^b, R.E. Mihai^b, L. Stan^b, P.-A. Söderström^{a,d}, D. Testov^a, A. Turturică^b, S. Ujeniu^b, S. Adachi^d, F. Camera^e, Gh. Ciocan^{a,b}, F.C.L. Crespi^e, N.M. Florea^b, Y. Fujikawa^f, T. Furuno^g, E. Gamba^g, R.A. Guţoiu^{a,b}, T. Kawabata^{a,b}, N.M. Mărginean^b, B. Million^e, C. Neacsu^b, D. Nichita^a, R. Niinaⁱ, S. Okamoto^f, H. Pai^a, A. Pappalardo^a, K. Sakanashi^g, A. Tamiiⁱ, C.A. Ur^a, O. Wieland^a

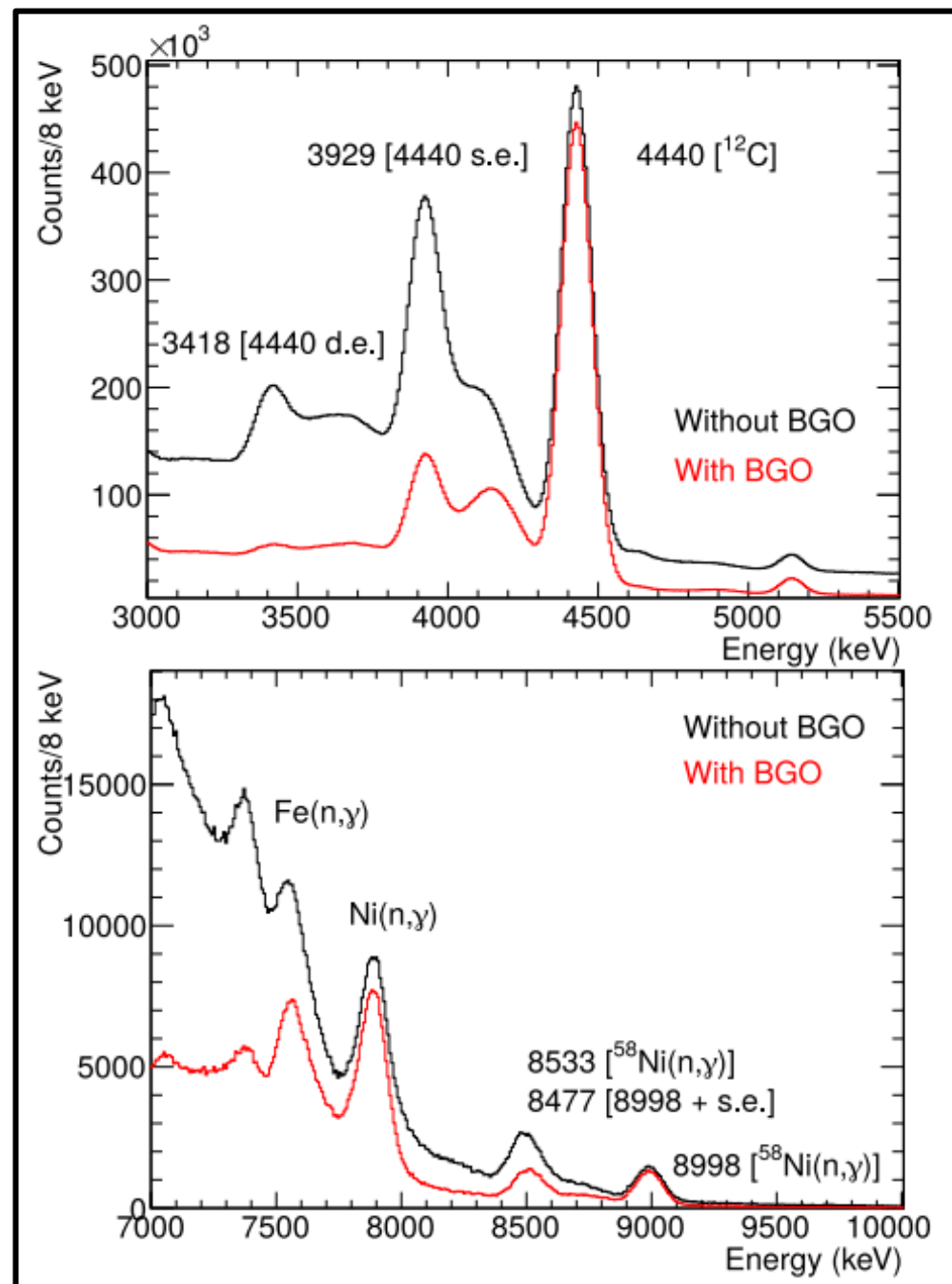
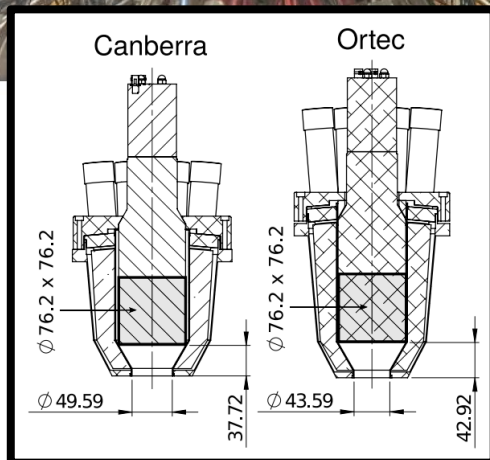
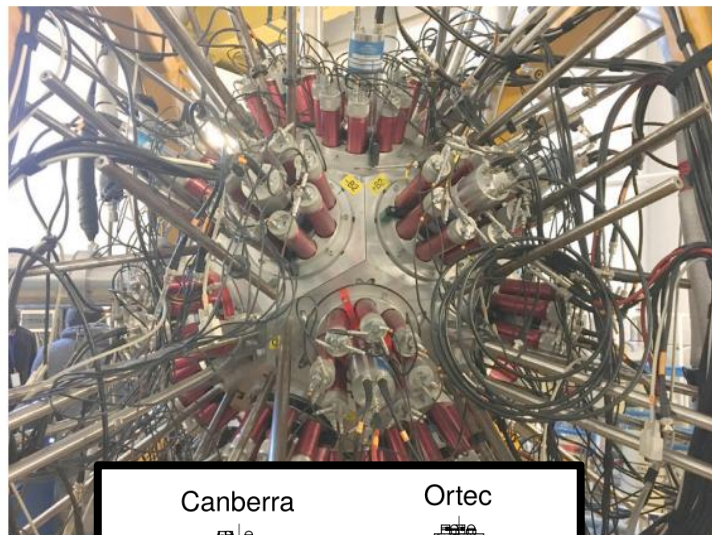
^a Extreme Light Infrastructure-Nuclear Physics (ELI-NP)/Horia Hulubei National Institute for Physics and Nuclear Engineering (IFIN-HH), Str. Reactorului

30, Bucharest-Măgurele 077125, Romania

^b Department of Nuclear Physics (DNP)/Horia Hulubei National Institute for Physics and Nuclear Engineering (IFIN-HH), Str. Reactorului

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^c Department of Physics, Faculty of Science, Istanbul University, Vezirler/Fatih, 34134, Istanbul, Turkey



Lecture 2

Some useful nuclear structure reactions

- 1) Heavy-Ion Fusion.
- 2) Coulomb Excitation
- 3) Projectile Fragmentation /decay
- 4) Deep-inelastic reactions

Different nuclear reaction mechanisms?

- Heavy-ion fusion-evaporation reactions (HIFE) $E_b \sim 5 \text{ MeV/u}$
- Spontaneous fission (e.g. ^{252}Cf) for neutron-rich nuclei.
- Deep-inelastic and heavy-ion fusion-fission reactions (makes near-stable/slightly neutron-rich residual nuclei).
- High-energy Projectile fragmentation / projectile fission at e.g., GSI / FAIR, RIKEN-RIBF, GANIL, MSU / FRIB.
- Coulomb excitation, EM excitations via E2 (usually).
- Single particle transfer reactions (p,d)
- Radioactivity, β decay ; α decay ; proton radioactivity
- Other probes (e,e' γ), (γ,γ'), (n, γ), (p, γ), (n,n' γ) etc.

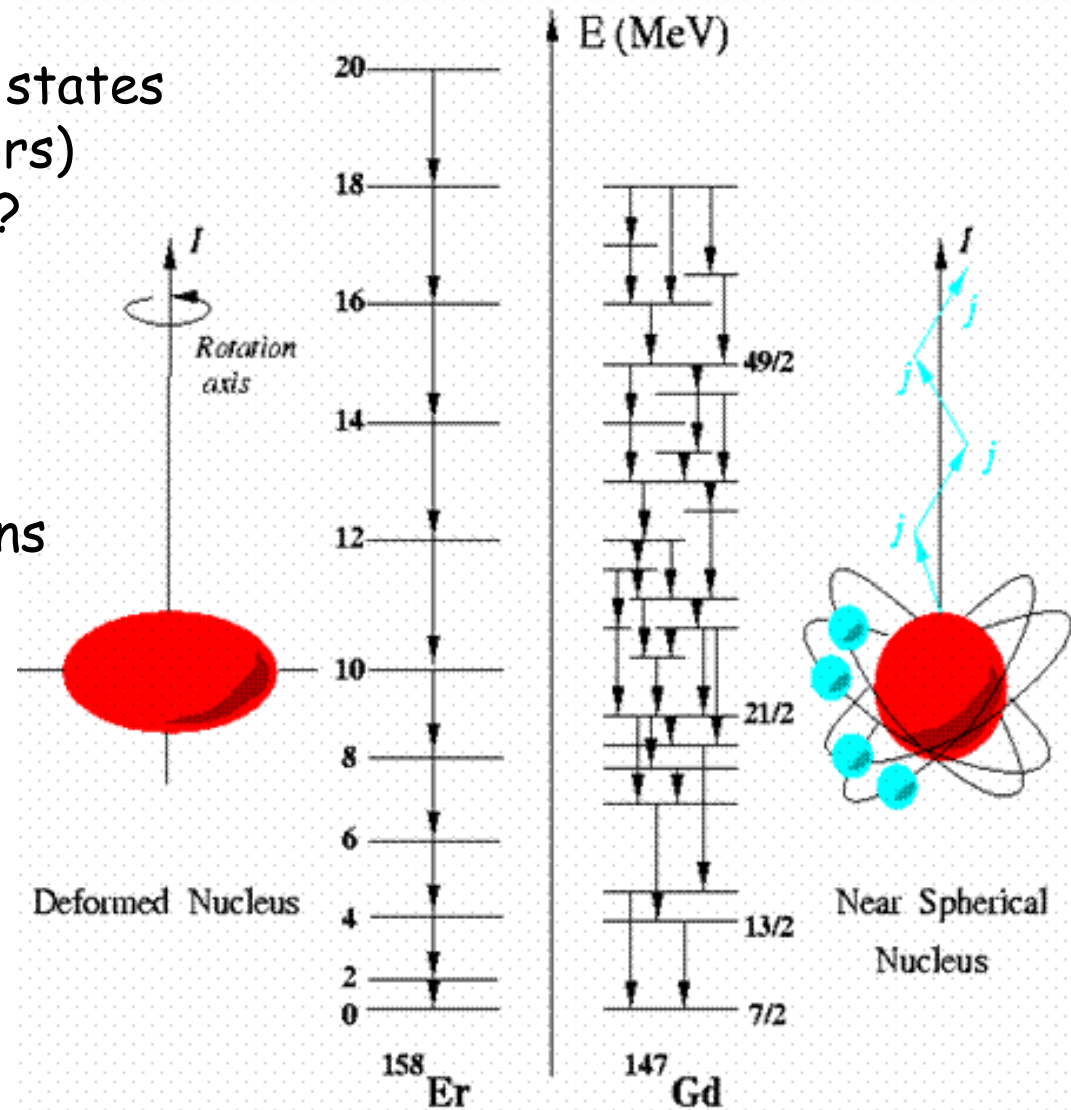
First four generally populate 'near-yrast' states
- most useful to see 'higher' spins states and excitations.

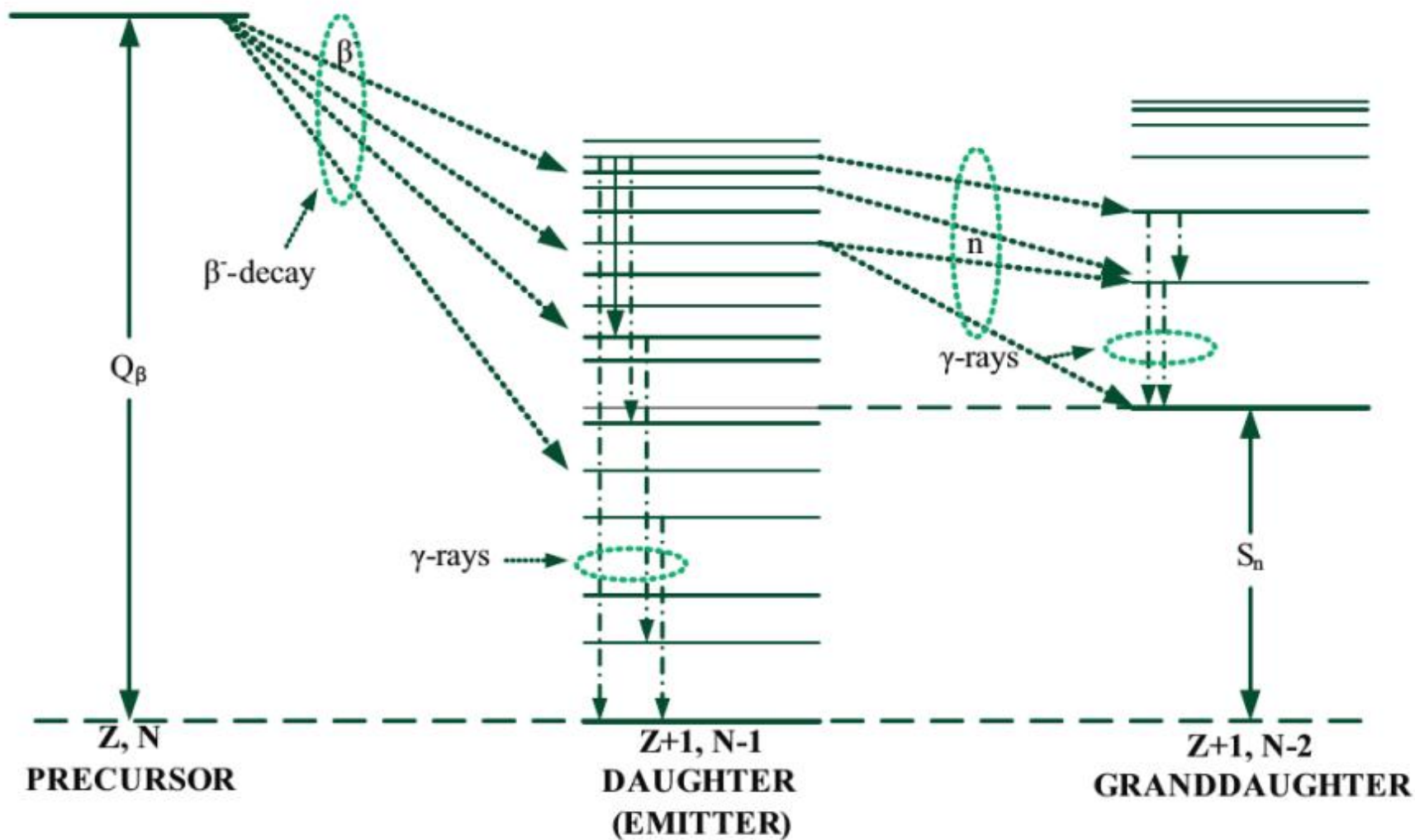
Some nuclear observables.

- 1) Masses and energy differences
- 2) Energy levels
- 3) Level spins and parities
- 4) EM transition rates between states
- 5) Magnetic properties (g-factors)
- 6) Electric quadrupole moments?

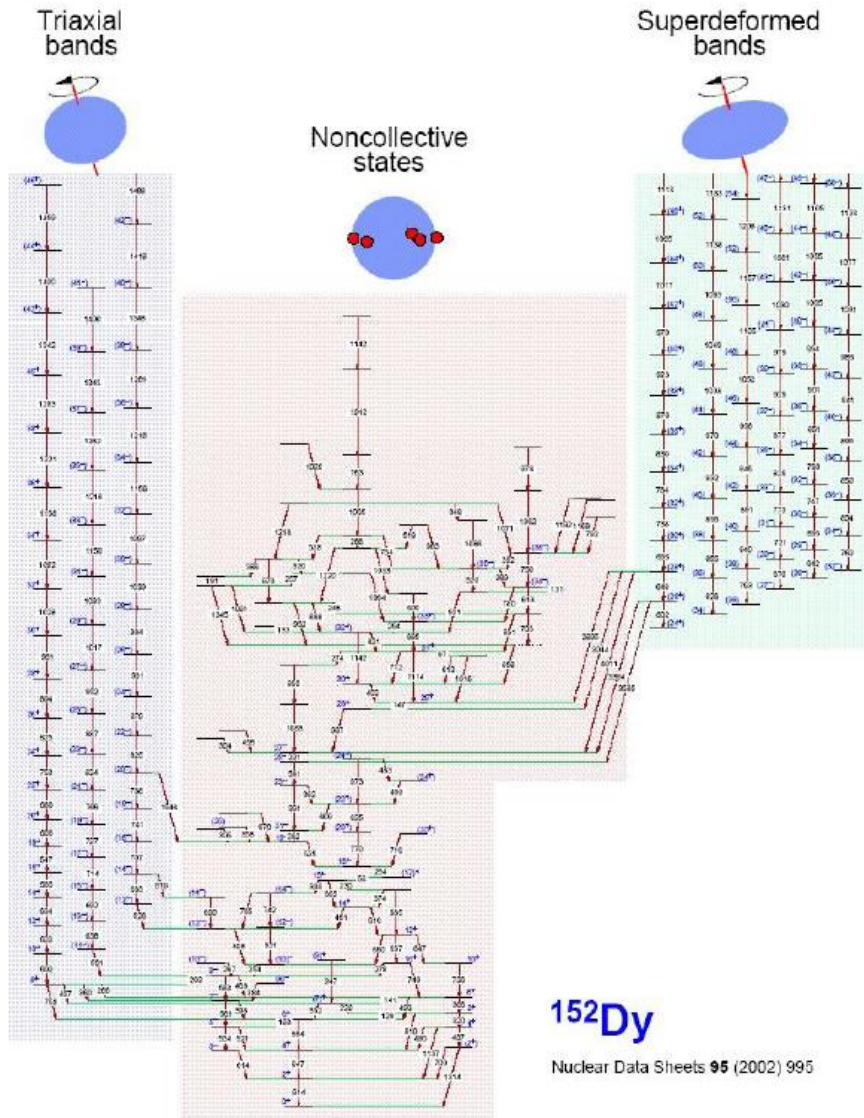
This is the essence of nuclear structure physics.

How do these change as functions of N , Z , I , E_x ?





Coexistence of collective and noncollective motion



Energy levels are determined by measuring gamma-rays decaying from excited states.

Many, many possible states can be populated...many different gamma-ray energies need to be measured at the same time (in coincidence).

(LN₂ cooled) germanium detectors have the combination of good energy resolution ($\Delta E \sim 2 \text{ keV}$ @ $E_\gamma = 1 \text{ MeV}$) and acceptable detection efficiency.

Various multi-detector 'arrays' of germanium detectors around the World. e.g., GAMMASPHERE, MINIBALL, GaSp JUROGAM, RISING, INGA, EXOGAM, AGATA, GREINA, NuBALL, EXILL+FATIMA, RoSPHERE

Fusion-evaporation reactions best way to make the **highest spins**. Nuclear EM decay usually decay via 'near yrast' sequence (since decay prob $\sim E_\gamma^{2L+1}$)

The ROSPHERE γ -ray spectroscopy array

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D. Filipescu^{a,c}, N. Florea^a, D.G. Ghiță^a, T. Glodariu^a, M. Ivașcu^a, R. Lică^a, N. Mărginean^a,
R. Mărginean^a, C. Mihai^{a,*}, A. Negret^a, C.R. Niță^a, A. Olăcel^a, S. Pascu^a, T. Sava^a, L. Stroe^a,
A. Șerban^{a,i}, R. Șuvăilă^a, S. Toma^a, N.V. Zamfir^{a,c}, G. Căta-Danil^b, I. Gheorghe^c, I.O. Mitu^c,
G. Suliman^c, C.A. Ur^c, T. Braunroth^d, A. Dewald^d, C. Fransen^d, A.M. Bruce^e, Zs. Podolyák^f,
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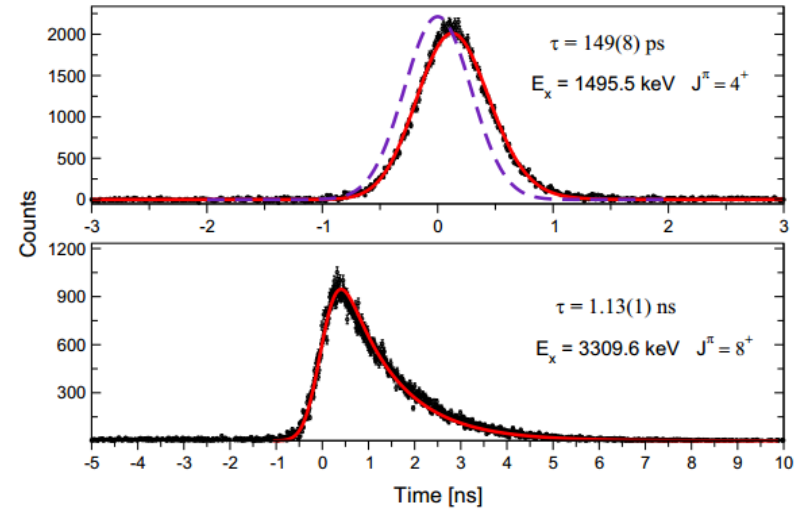


Fig. 11. Time distributions for the yrast 4^+ (upper panel) and 8^+ (bottom panel) states in ^{92}Zr , obtained by gating on the 462–561 keV and 988–352 keV, respectively as start-stop in the $E_{\gamma 1} - E_{\gamma 2} - \Delta T$ cubes. For both states, the half-life was obtained from the fit of the experimental data with the convoluted exponential decay function (red line), while the prompt response curve is shown in blue in the upper panel. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

Table 3

Performance parameters of the ROSPHERE array in the usual “mixed” configuration, measured with a ^{60}Co calibration source.

Sub-array	No. of detectors	Absolute efficiency @1332 keV	Peak/total	Timing FWHM
HPGe	14	1.10(3)%	42%	≈ 15 ns
LaBr ₃ (Ce)	11	1.75(5) %	22%	347(10) ^a ps

^a Overall FWHM of the time spectra for the 1173–1332 keV coincident γ -rays from a ^{60}Co source.

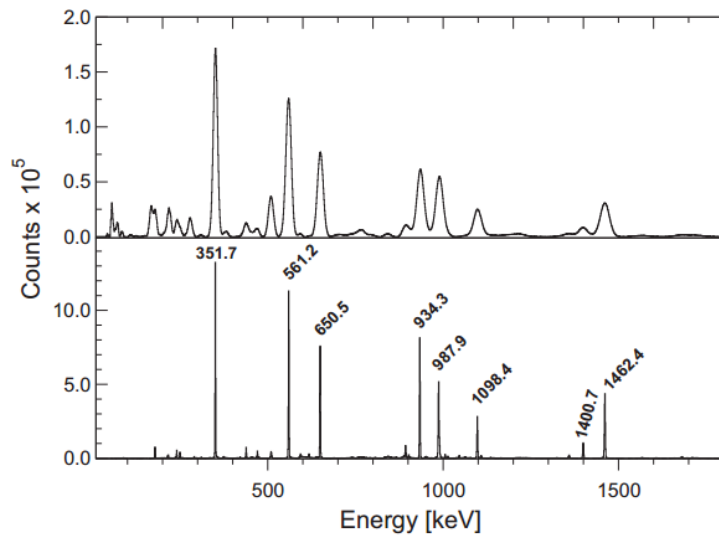


Fig. 10. γ -Ray energy spectra obtained by gating on the 934, 561, 1462, 352 and 988-keV yrast transitions in ^{92}Zr . Bottom: Summed gates in the HPGe-HPGe symmetric matrix; Top: Summed spectra from the LaBr₃(Ce) scintillators obtained with the same HPGe gates. The peaks are marked by their energy in keV.

What can we measure with the different population mechanisms?

1) Low-spin, limited-excitation energy and angular momentum population via radioactive (ground state and isomeric) decay.

Can also use $(n, n'\gamma)$, (γ, γ') , Coulomb Excitation.

2) High(er) Spin, HIFE and in-beam reactions, lead to higher excitation energy and higher angular momentum (spin) transferred.

Populate near-yrast states in Fusion-evaporation reactions, projectile fragmentation, (fusion?)-fission, deep-inelastic reactions.

(γ, γ') e.g. from ELI-NP, populates $I^\pi=1^-$ (and some 1^+) states.

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The high-efficiency γ -ray spectroscopy setup γ^3 at H γ S

B. Löher^{a,c,*}, V. Derya^g, T. Aumann^{h,f}, J. Beller^h, N. Cooperⁱ, M. Duchêne^h, J. Endres^g,
E. Fiori^{a,c}, J. Isaak^{a,c}, J. Kelley^{b,c}, M. Knörzer^h, N. Pietralla^h, C. Romig^h, D. Savran^{a,c},
M. Scheck^h, H. Scheit^h, J. Silva^{a,c}, A. Tonchev^d, W. Tornow^b, H. Weller^b, V. Wernerⁱ,
A. Zilges^g

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^b Department of Physics, Duke University, Triangle Universities Nuclear Laboratory, Durham, NC 27708-0308, USA

^c Frankfurt Institute for Advanced Studies FIAS, Ruth-Moufang-Str. 1, 60438 Frankfurt am Main, Germany

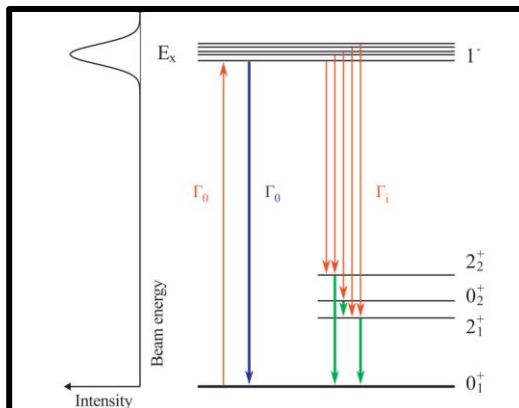


Fig. 1. After resonant excitation of a $J=1$ state within the narrow energy profile of an incident photon beam, this state can de-excite either directly to the ground state, or via intermediate states. Triggering on coincidences and gating on the secondary transition allows to isolate the primary transitions.

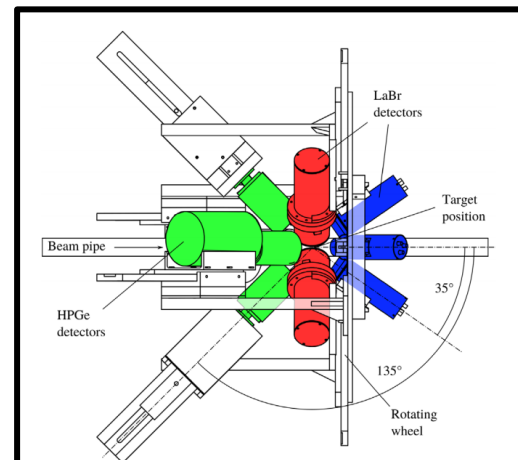
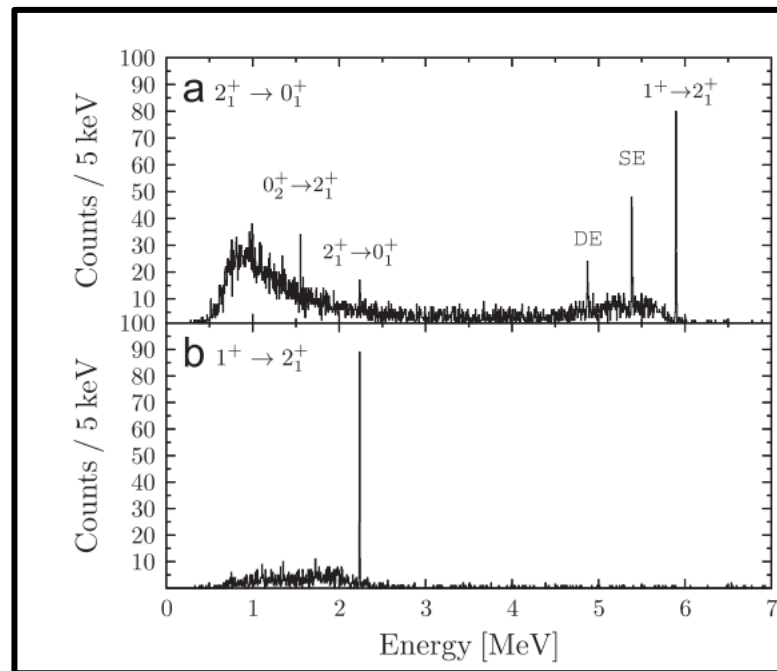
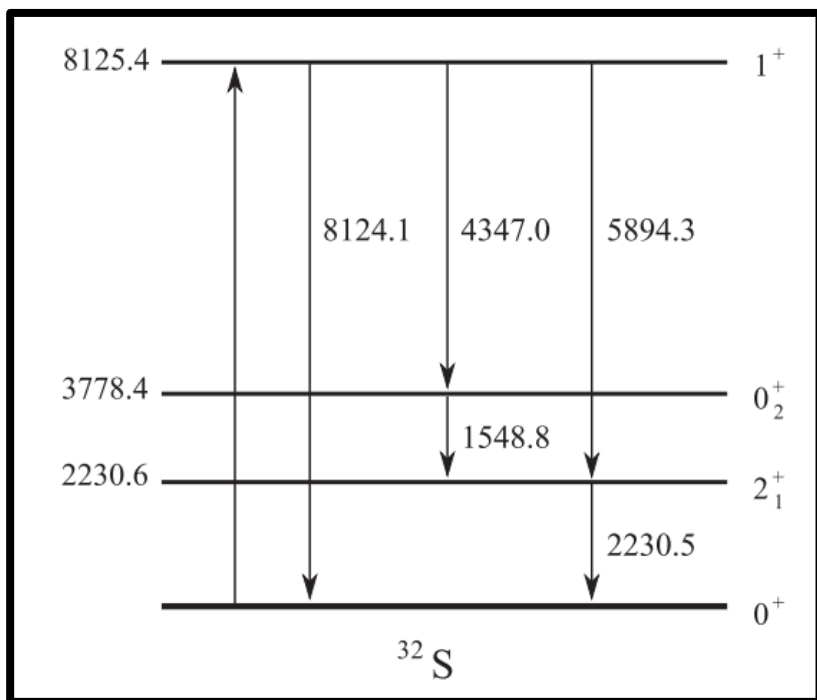


Fig. 2. Schematic drawing of the γ^3 experimental setup. HPGe detectors are positioned at an angle of $\theta = 135^\circ$ with respect to the beam pipe. The LaBr₃Ce detectors are used at $\theta = 90^\circ$ and $\theta = 30^\circ$ with respect to the beam pipe. The 3 in. $\times$ 3 in. LaBr₃Ce detectors can also be exchanged with the HPGe detectors, and the wheel can be rotated by $\Delta\phi = 45^\circ$ around the beam axis.



Parity Measurements of Nuclear Levels Using a Free-Electron-Laser Generated γ -Ray BeamN. Pietralla^{1,2} and Z. Berant^{1,3}¹A. W. Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06520²Institut für Kernphysik, Universität zu Köln, D-50937 Köln, Germany³Department of Physics, Clark University, Worcester, Massachusetts 10610
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V.N. Litvinenko, S. Hartman, F.F. Mikhailov, I.V. Pinayev, and G. Swift

Free Electron Laser Laboratory, Department of Physics, Duke University, Durham, North Carolina 27708

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(Received 18 July 2001; published 20 December 2001)

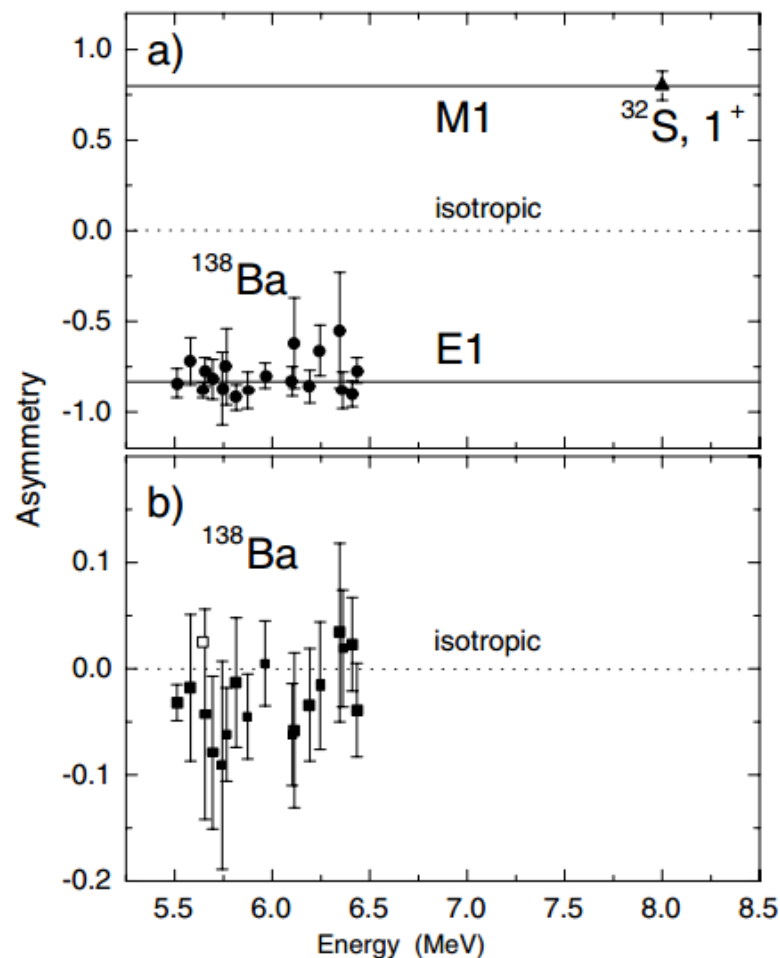
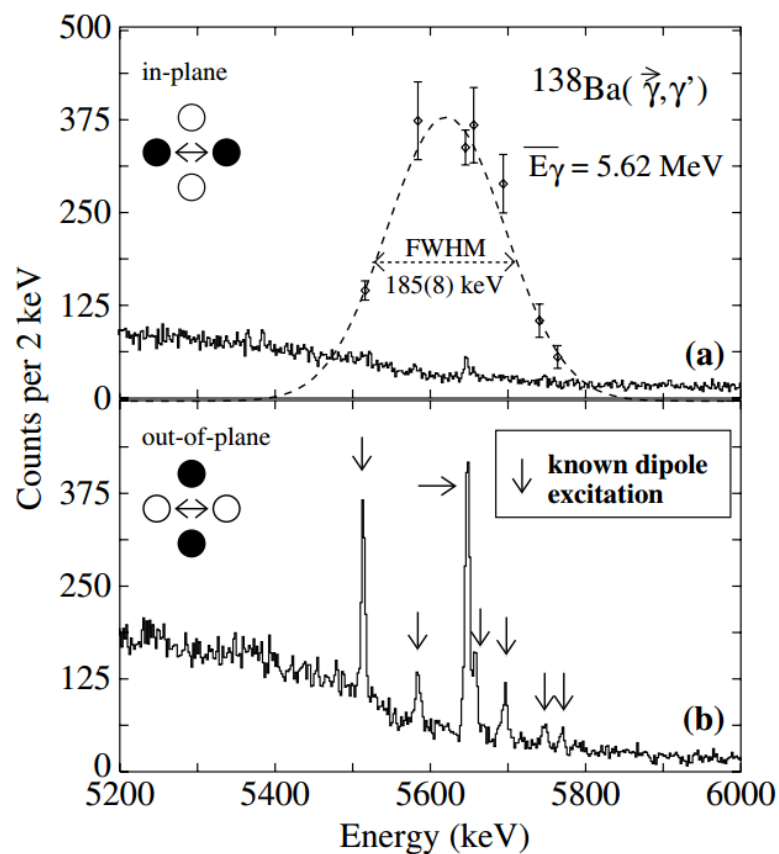
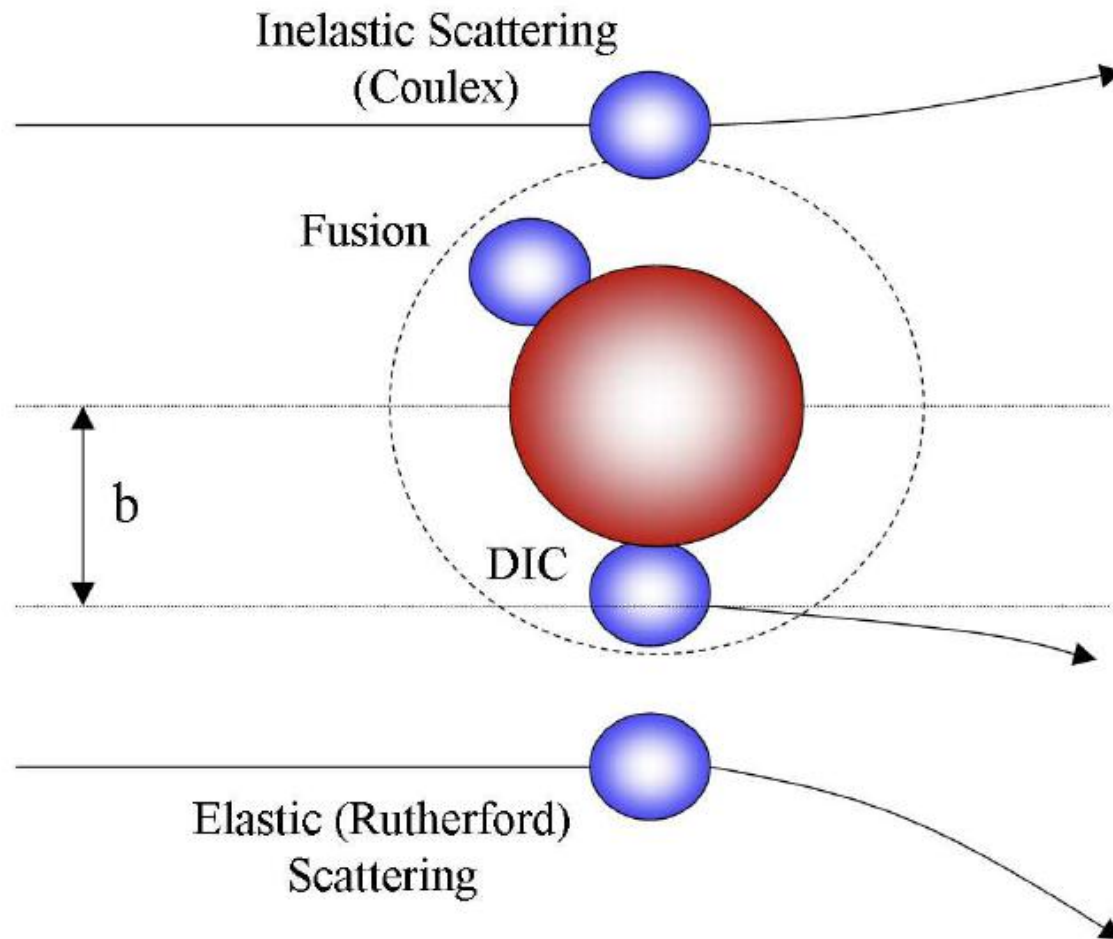


FIG. 2. Measured NRF intensity asymmetries obtained from this experiment on ^{138}Ba (a) and coincidence asymmetries from previous [23] Compton polarimetry (b). Note the different scales in parts (a) and (b). The solid lines in part (a) indicate the expected values of the asymmetry (± 0.83) obtained from the simulation. The open symbol in (b) indicates the result for the 5.644 MeV level which was assigned $1^{(+)}$ in Ref. [23]. The triangle represents the NRF intensity asymmetry of the 8.13 MeV $1^+ \rightarrow 0_1^+$ transition in ^{32}S measured with our setup.

'In-beam' (heavy)-ion induced nuclear reactions on fixed targets can result in a range of different nuclear reactions taking place.



The specifics depends on the (1) beam and target nuclei (A, Z, I); (2) the beam energy (higher or lower than the Coulomb repulsion between the two nuclei), and (3) the impact parameter, b .

Coulex – $E_b < E_{\text{Coul}}$: EM interaction between beam and target protons (Z_B, Z_T) only.

Ann. Rev. Nucl. Part. Sci. 1986, 36: 683–716
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NUCLEAR SHAPES 691

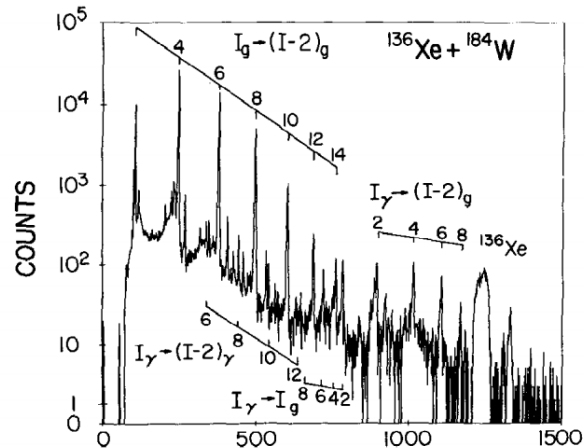
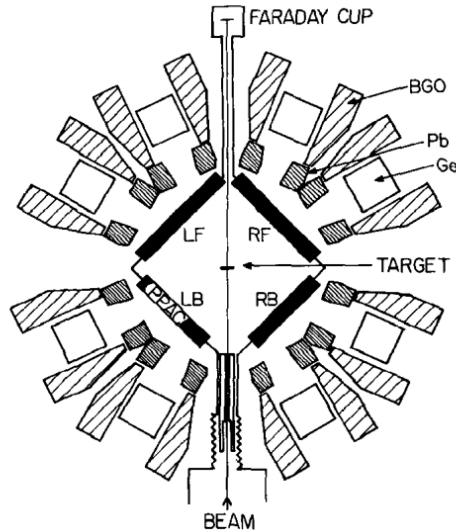


Figure 2 Coincident γ -ray spectrum for Coulomb excitation (42) of ^{184}W by 4.125 MeV per nucleon ^{136}Xe detected at scattering angles between 54° and 74° using the experimental geometry shown in Figure 1. The spectrum has been corrected for the Doppler effect on an event-by-event basis resulting in a γ -ray energy resolution of 0.5% FWHM.

NUCLEAR SHAPES STUDIED BY COULOMB EXCITATION

Douglas Cline

Nuclear Structure Research Laboratory,¹ University of Rochester,
Rochester, New York 14627

704 CLINE

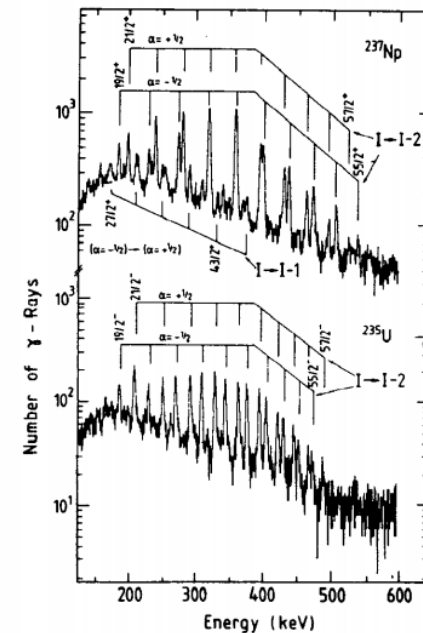
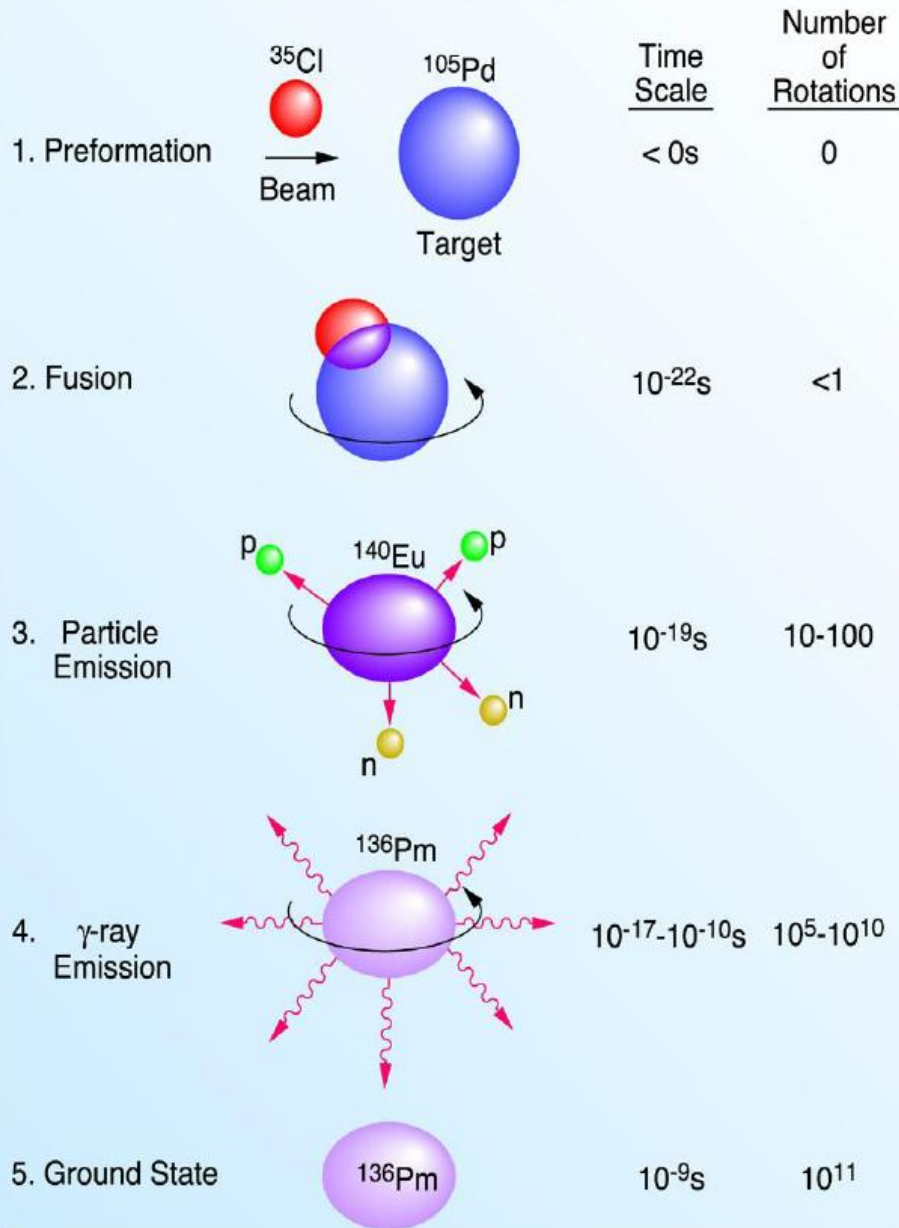


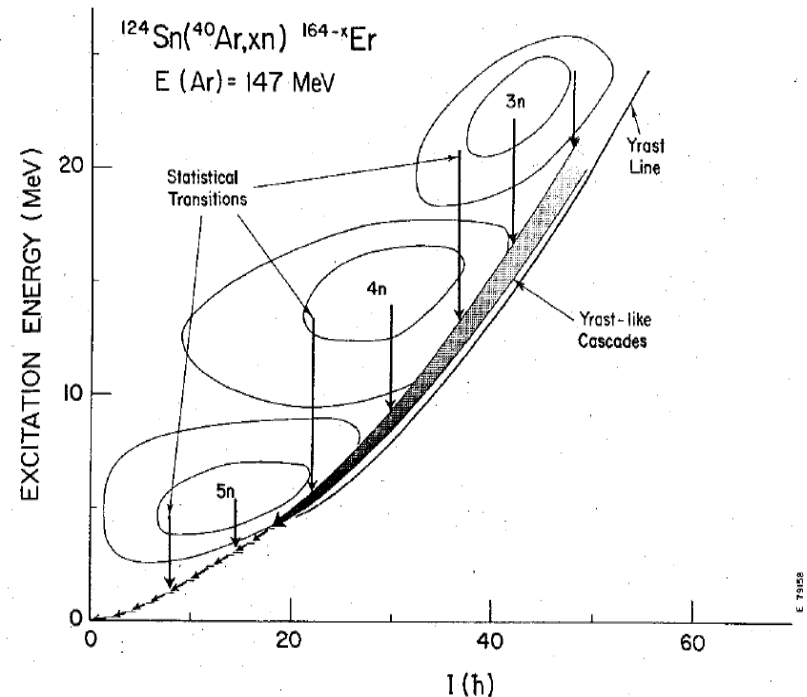
Figure 6 Gamma spectra resulting from Coulomb excitation (77) of ^{237}Np and ^{235}U by 5.3 MeV per nucleon ^{208}Pb in coincidence with ions at center-of-mass scattering angles between 96° and 145° .

How to Make High Spin Nuclei



$$E_R^* = E_{\text{Beam}} + Q_{\text{reaction}} - KE_{\text{recoil}}$$

Less particle evaporation corresponds to higher spins states for a particular bombarding energy.



Maximum angular momentum input to compound system (I_{max}) depends on $\mathbf{l} = \mathbf{r} \times \mathbf{p}$ i.e. beam energy (linked to $\mathbf{p}$) and maximum overlap of nuclear radii ($\mathbf{r}$)

Decay (coincidence) gamma-rays measured using the YRÄSTBALL HpGe gamma-ray array.

PHYSICAL REVIEW C **66**, 024302 (2002)

High- j proton and neutron alignments in γ -soft ^{101}Ru

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C. Hutter,¹ R. Krücken,¹ S. D. Langdown,^{1,2} D. Meyer,¹ J. J. Ressler,¹ and N. V. Zamfir,^{1,5,6}

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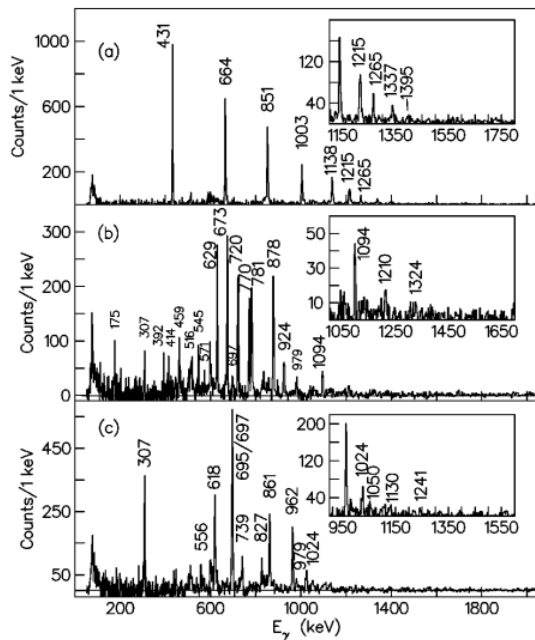
PHYSICAL REVIEW C **66**, 024302 (2002)

FIG. 4. Sums of double-gated gamma-triples coincidence spectra highlighting the (a) $\frac{11}{2}^-$ band, (b) the $\frac{5}{2}^+$ band, and (c) the $\frac{7}{2}^+$ band. Band members are shown in larger font with links to other structures in ^{101}Ru highlighted with the smaller sized labels. The insets correspond to expanded regions of the main figures.

D. YAMAMOTO *et al.*

PHYSICAL REVIEW C 66, 024302 (2002)

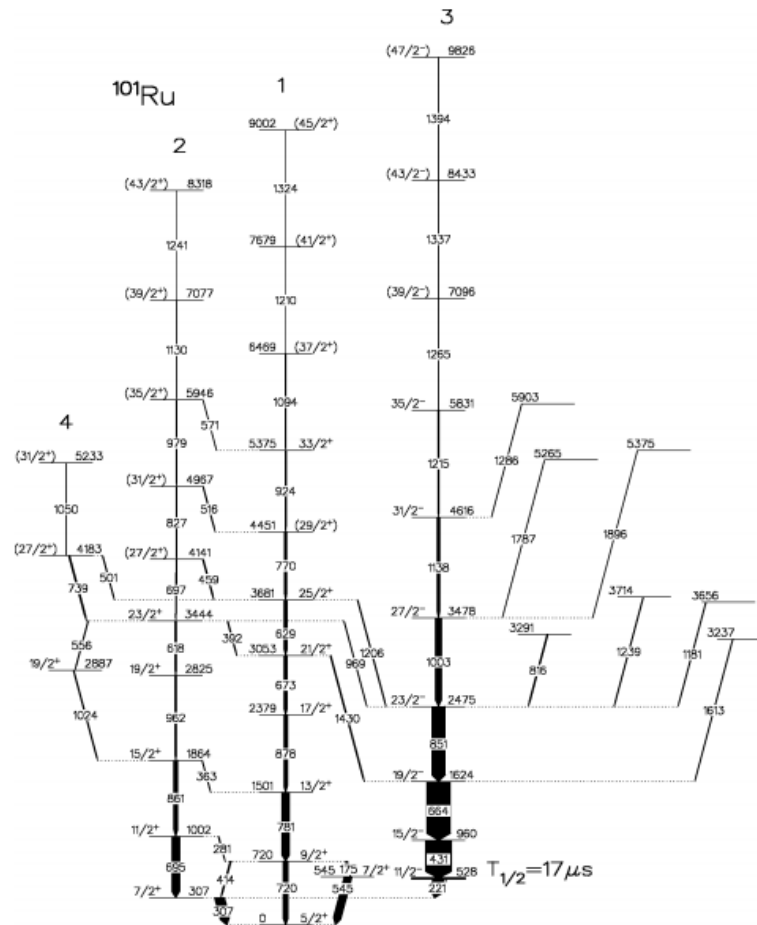
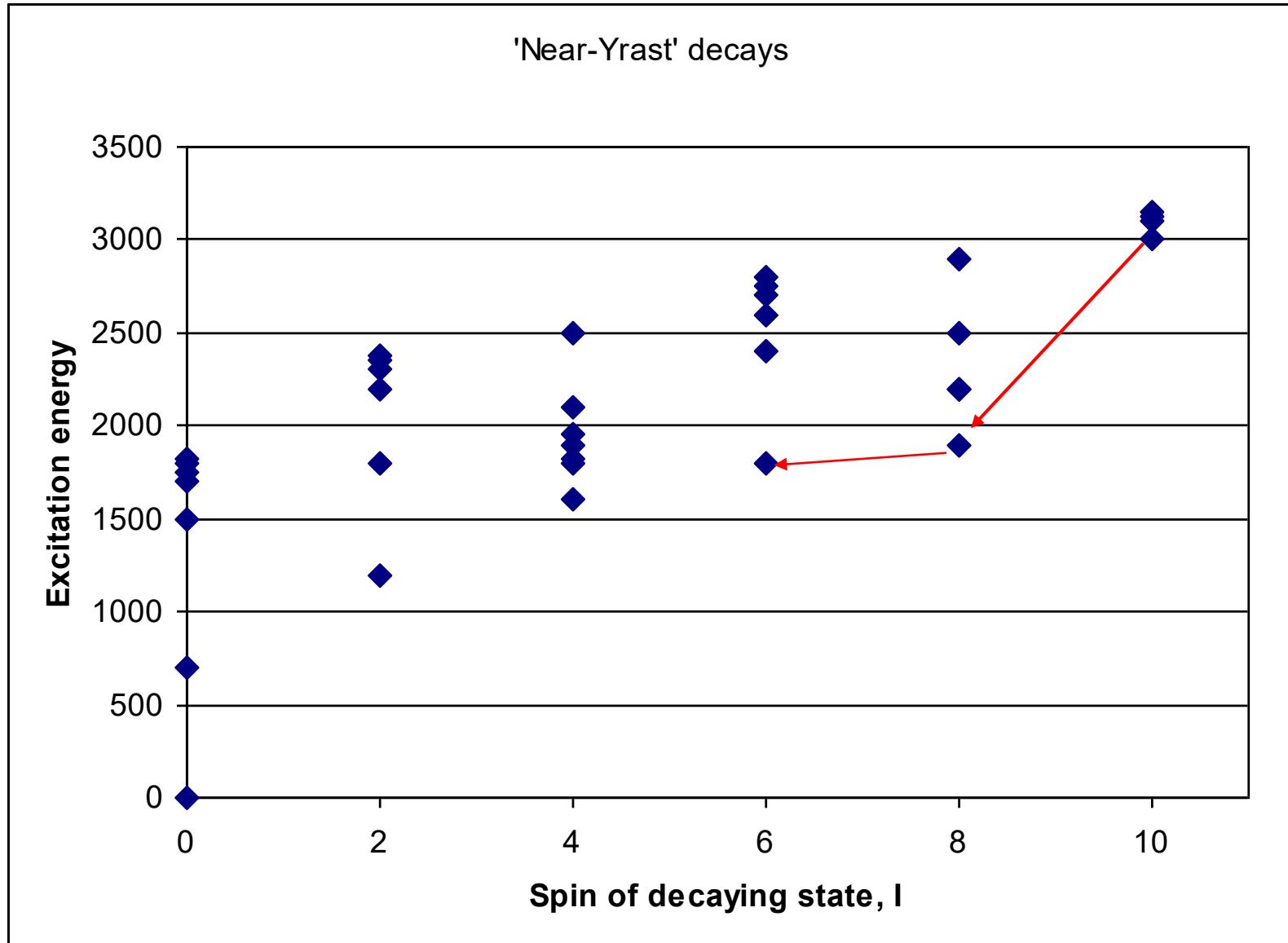


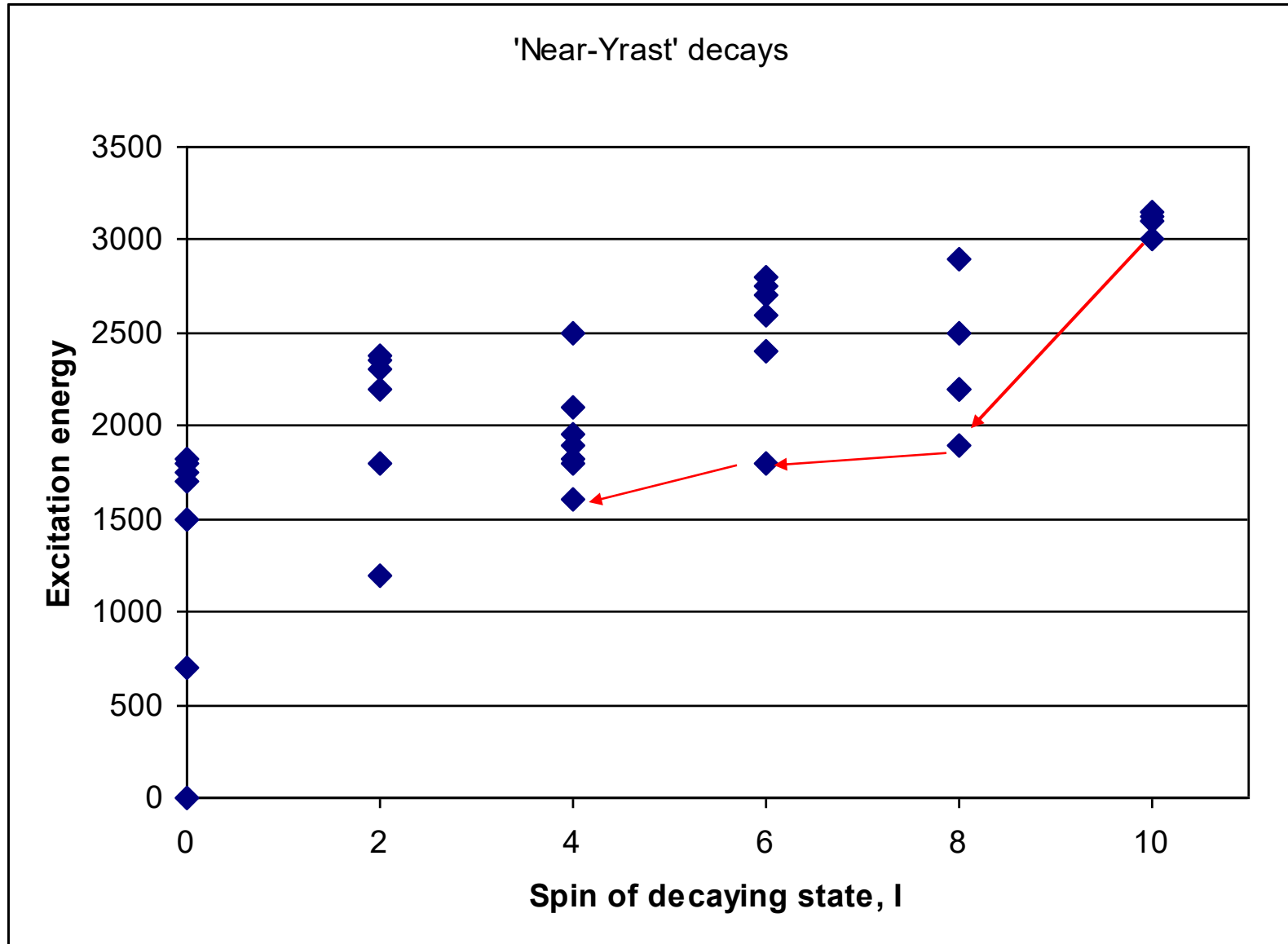
FIG. 1. Decay scheme for ^{101}Ru deduced from the current work.

The EM transition rate depends on $E_\gamma^{2\lambda+1}$, the highest energy transitions for the lowest λ are (generally) favoured.

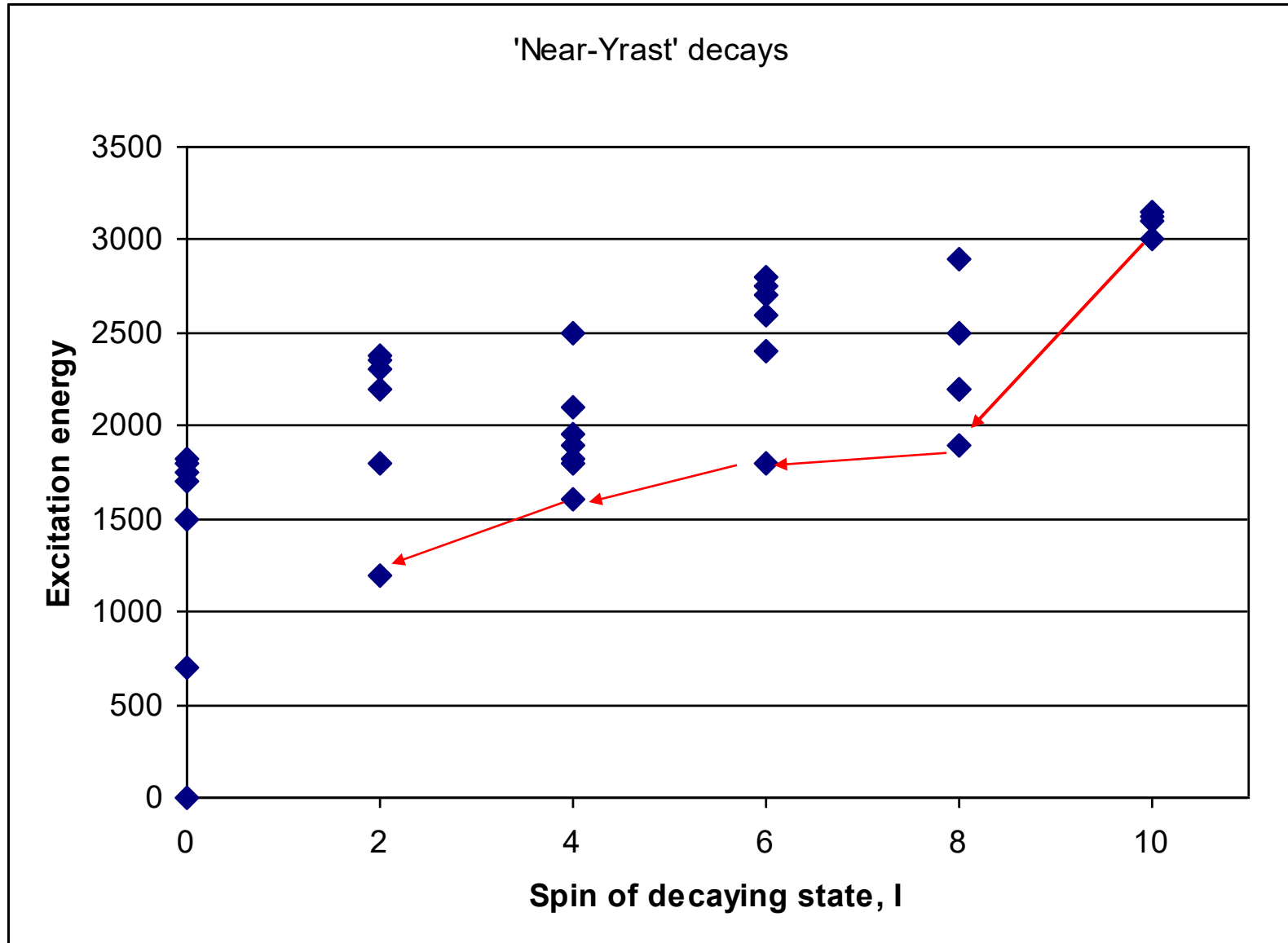
This results in the preferential population of yrast and near-yrast states.



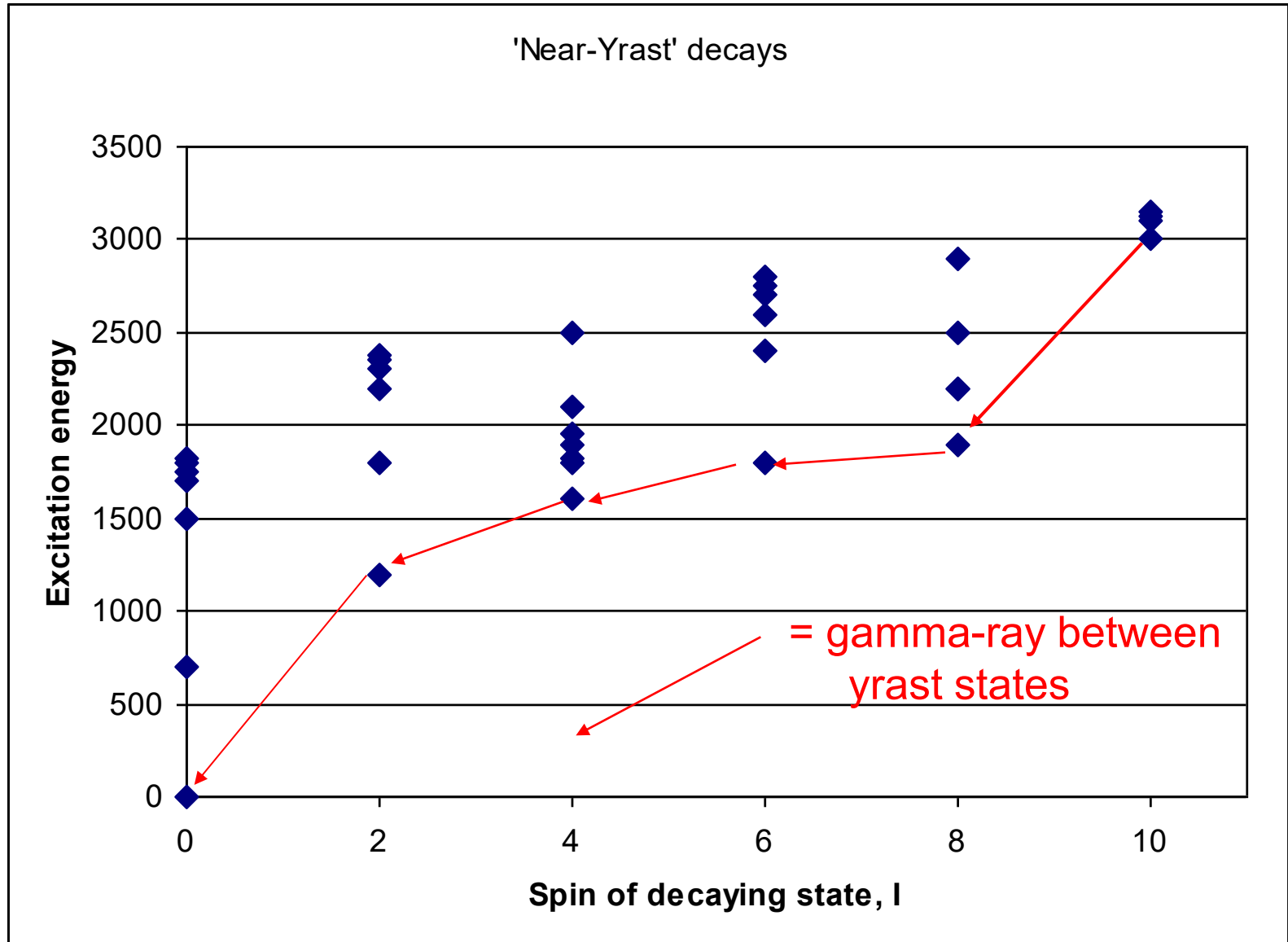
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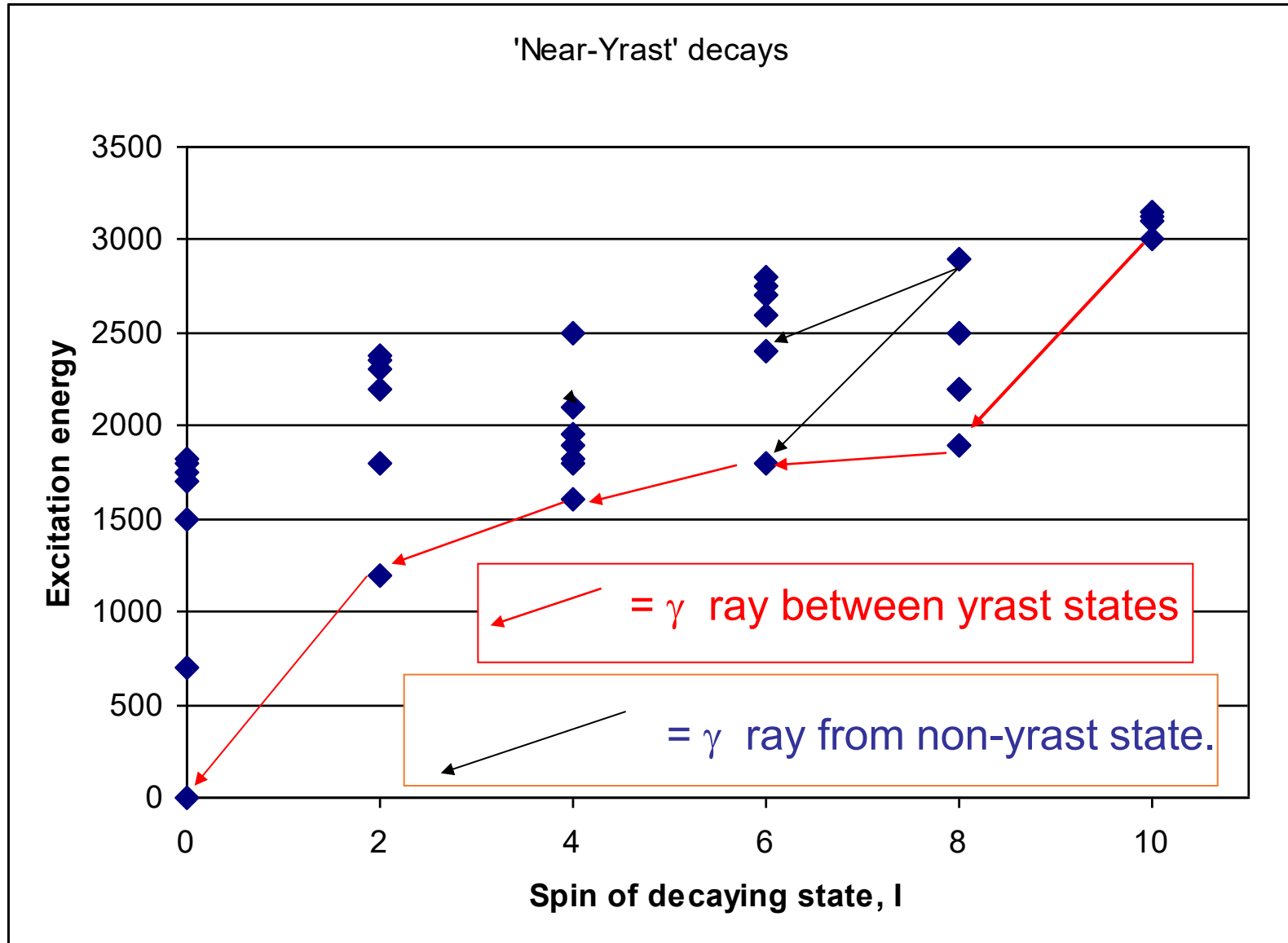
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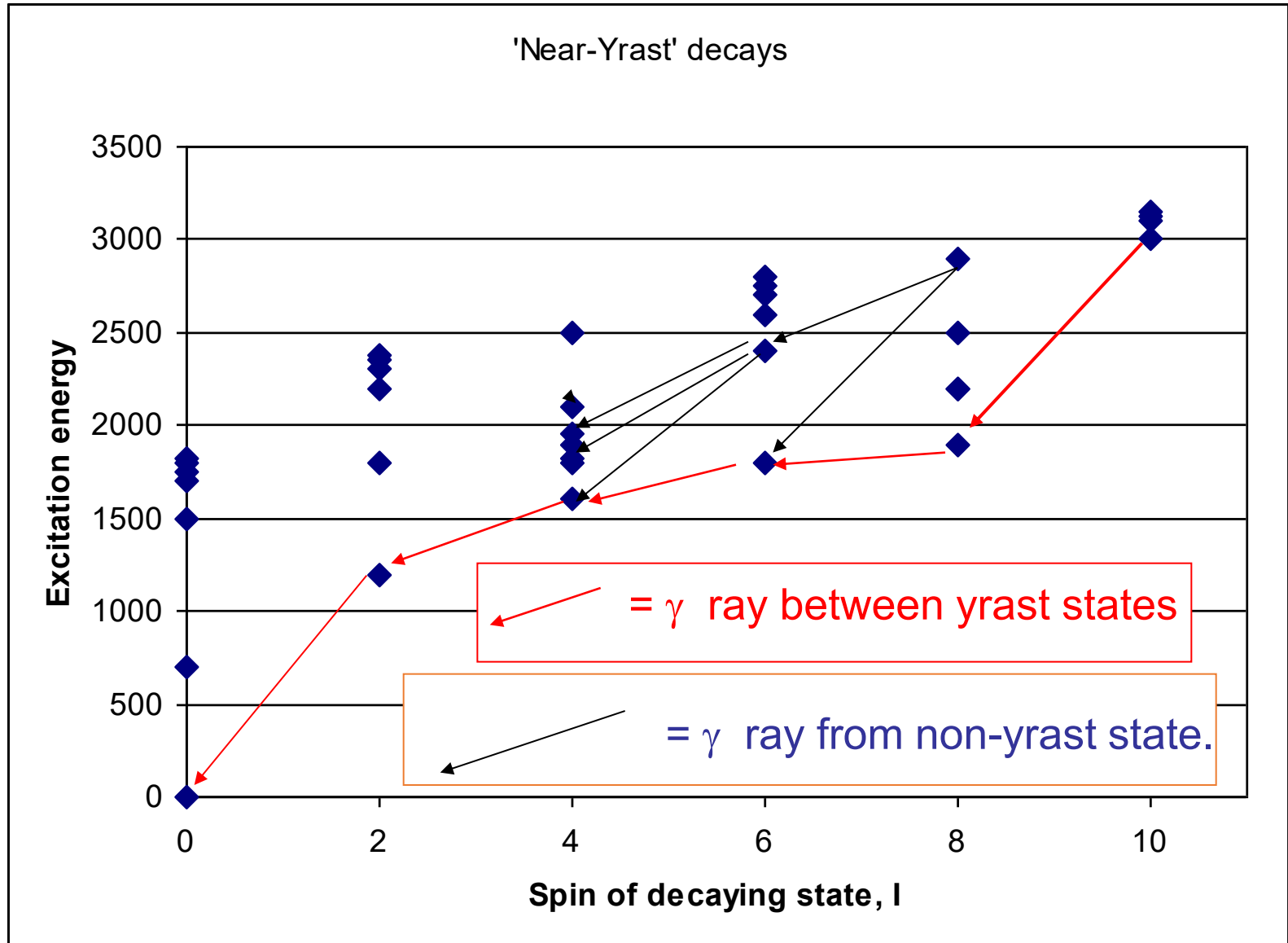
The EM transition rate depends on $E_\gamma^{2\lambda+1}$, the highest energy transitions for the lowest λ are (generally) favoured.
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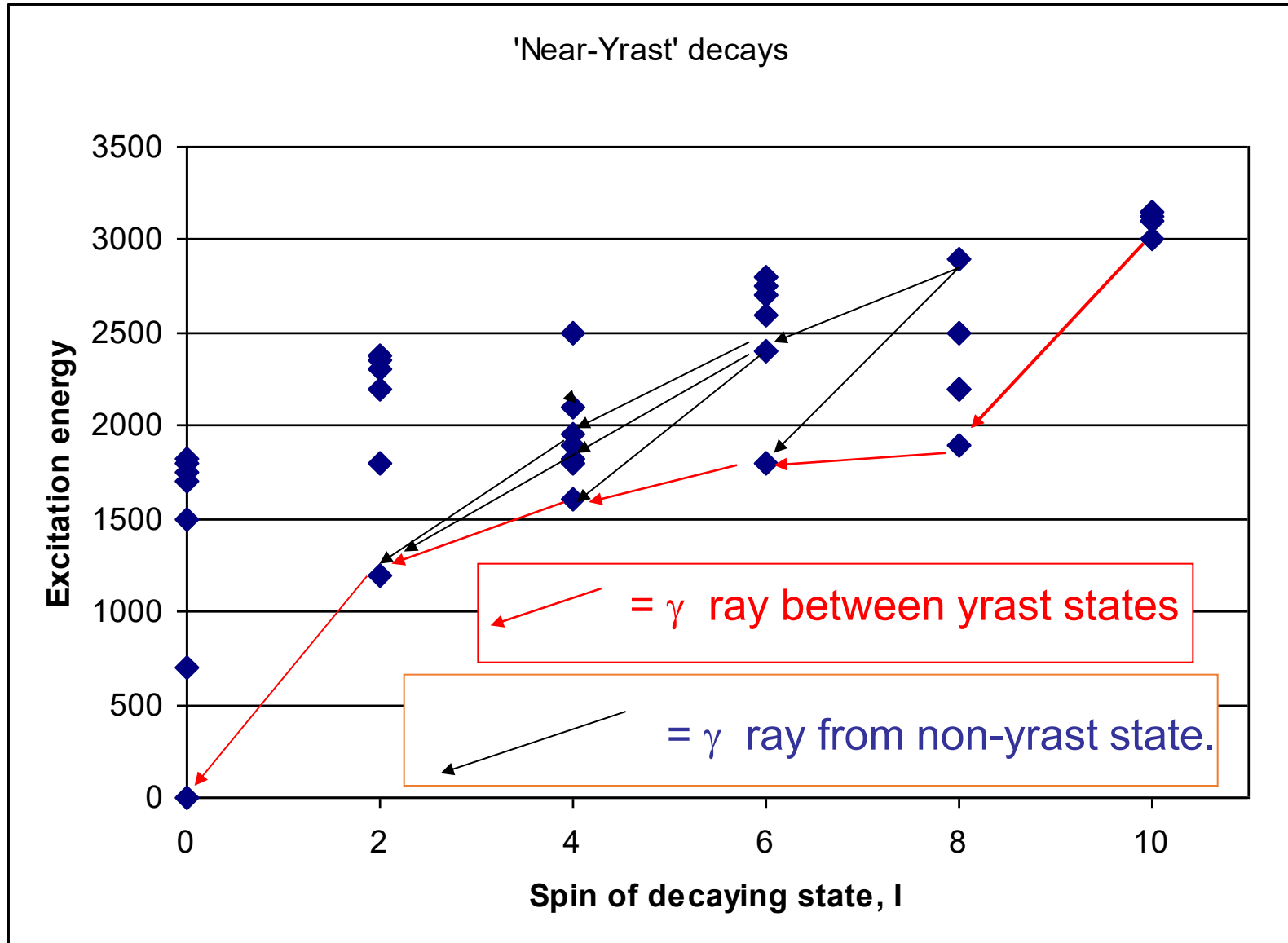
The EM transition rate depends on $E_\gamma^{2\lambda+1}$, (for E2 decays E_γ^5)
 Thus, the highest energy transitions for the lowest λ are usually favoured.
 Non-yrast states decay to yrast ones (unless very different ϕ , K-isomers)



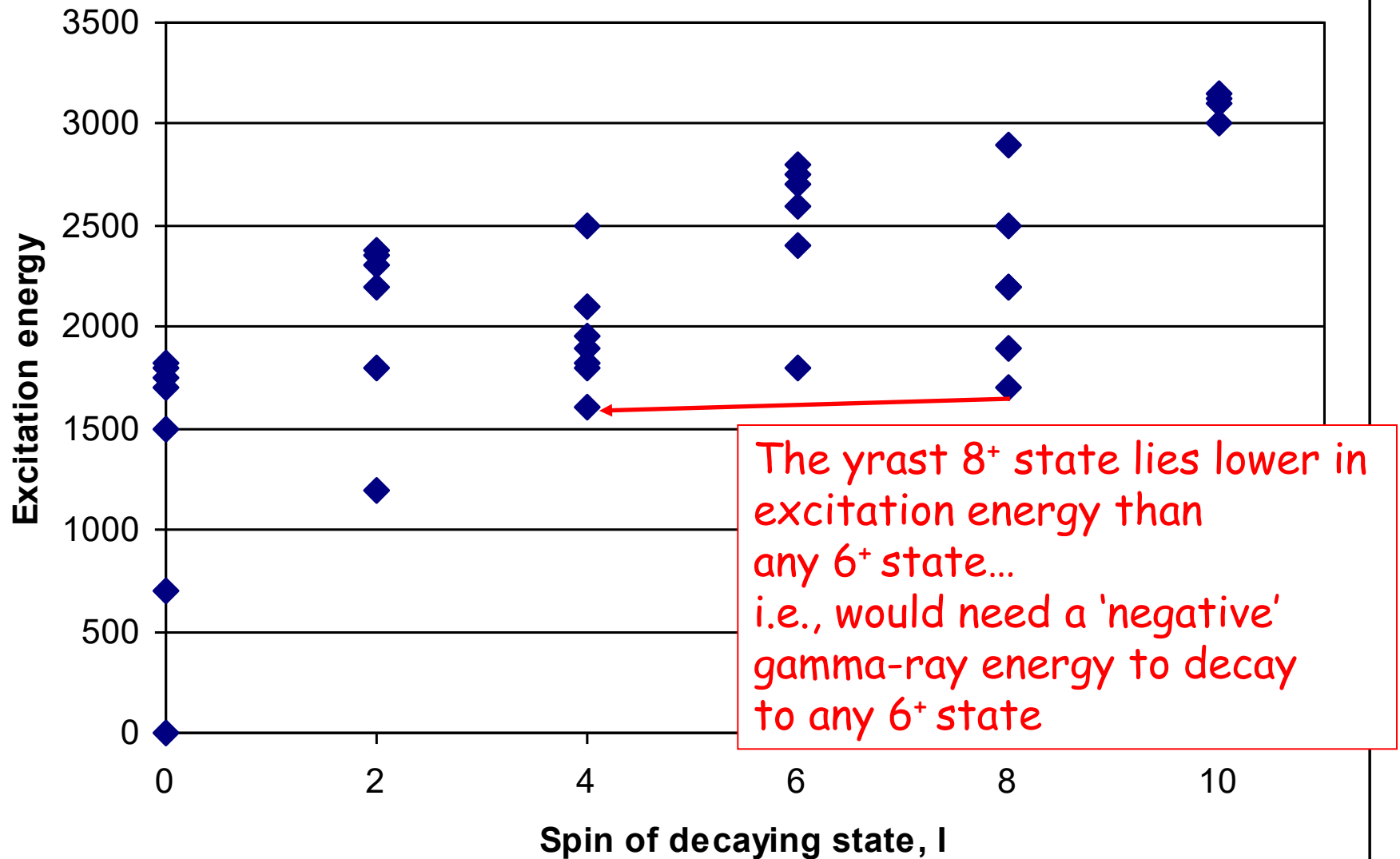
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The EM transition rate depends on $E_\gamma^{2\lambda+1}$, (for E2 decays E_γ^5)
 Thus, the highest energy transitions for the lowest λ are usually favoured.
 Non-yrast states decay to yrast ones (unless very different ϕ , K-isomers)



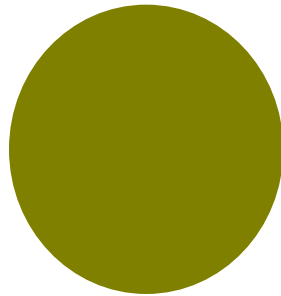
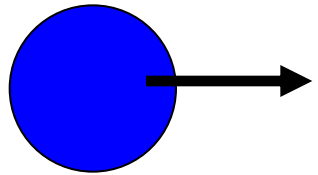
Yrast Traps



Selection and identification of high-spins states.

- Need a top quality gamma-ray spectrometer to measure full-energies of emitted gamma rays from (high-spin) excited nuclear states.
- Helpful to have some sort of channel selection device (e.g., recoil separator; fragment detector).
- Timing between reaction and detection of gamma ray(s) and also the time differences between individual gamma rays in a decay sequences can also be helpful in channel selection and decay scheme building.
- Use EM selection rules, transition rates and $\text{DCO}/W(\theta)$ etc. to assign spin and parities to excited states.

Example: $^{96}\text{Ru}(^{40}\text{Ca},xpyn)^{136}\text{Gd}-xp-yn$



^{40}Ca

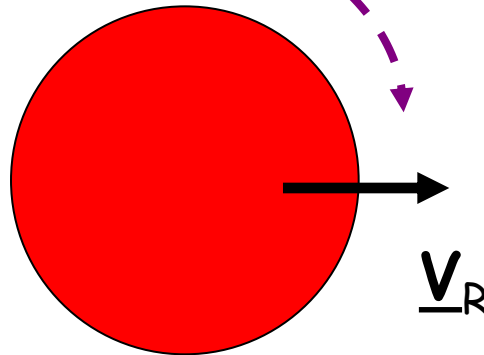
$Z=20$

$N=20$

^{96}Ru

$Z=44$

$N=52$



$\underline{v}_R$

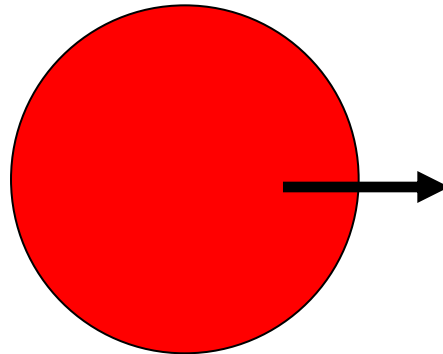
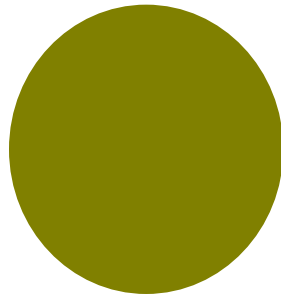
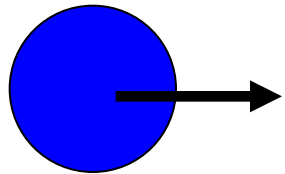
^{136}Gd ($Z=64$ $N=72$).

Hot, compound
system recoils
backwards at 0°
in the lab frame.

Example: $^{96}\text{Ru}(^{40}\text{Ca},xpyn)^{136}\text{Gd}-xp-yn$

$$m_B \underline{V}_B$$

$$m_T \underline{V}_T = 0$$



^{40}Ca

^{96}Ru

^{136}Gd ($Z=64$ $N=72$).

$Z=20$

$Z=44$

Hot, compound nucleus

$N=20$

$N=52$

recoils backwards at

0° in the lab frame with

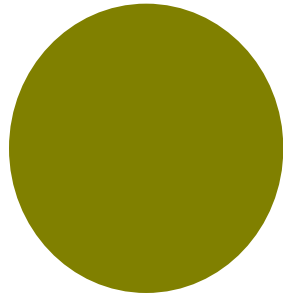
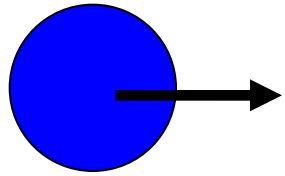
$$\text{KE of beam} = \frac{1}{2} m_B V_B^2$$

velocity, $\underline{V}_R$.

Example: $^{96}\text{Ru}(^{40}\text{Ca},xpyn)^{136}\text{Gd}-xp-yn$

$$m_B \underline{V}_B$$

$$m_T \underline{V}_T = 0$$



^{40}Ca

$Z=20$

$N=20$

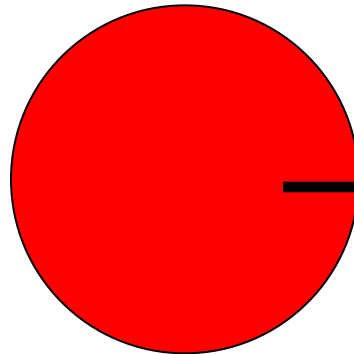
^{96}Ru

$Z=44$

$N=52$

$$\text{KE of beam} = \frac{1}{2} m_B V_B^2$$

$$m_R \underline{V}_R = (m_B + m_T) \underline{V}_R = m_B \underline{V}_B. \text{ Therefore, } \underline{V}_R = (m_B) \underline{V}_B / (m_B + m_T)$$



$$\underline{V}_R$$

^{136}Gd ($Z=64$ $N=72$).

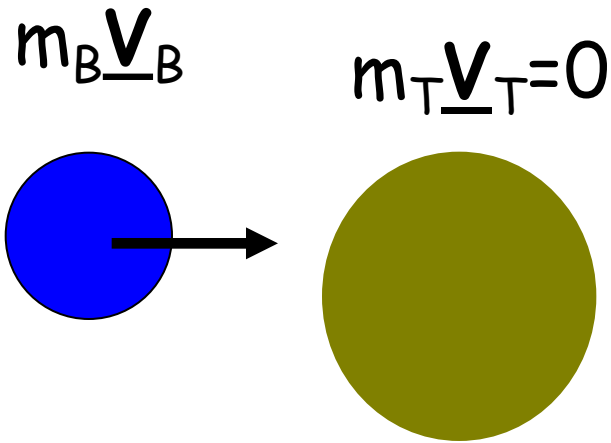
Hot, compound nucleus

recoils backwards at

0° in the lab frame with

velocity, $\underline{V}_R$.

Example: $^{96}\text{Ru}(^{40}\text{Ca},xpyn)^{136}\text{Gd}-xp-yn$

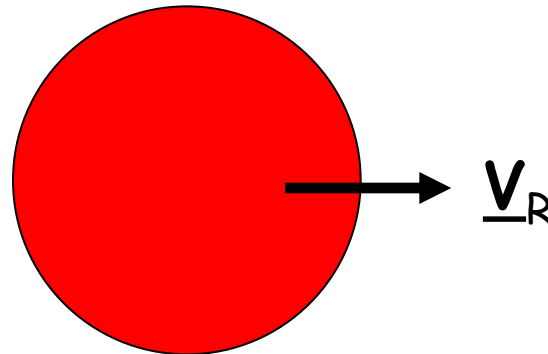


^{40}Ca
 $Z=20$
 $N=20$

^{96}Ru
 $Z=44$
 $N=52$

KE of beam = $\frac{1}{2} m_B v_B^2$

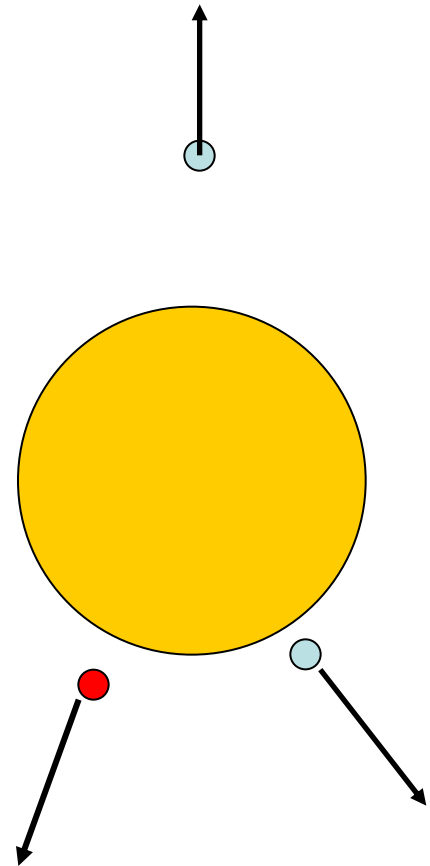
$$m_R \underline{v}_R = (m_B + m_T) \underline{v}_R = m_B \underline{v}_B. \text{ Therefore, } \underline{v}_R = (m_B) \underline{v}_B / (m_B + m_T)$$



^{136}Gd ($Z=64$ $N=72$).

Hot, compound nucleus recoils backwards at 0° in the lab frame with velocity, v_R .

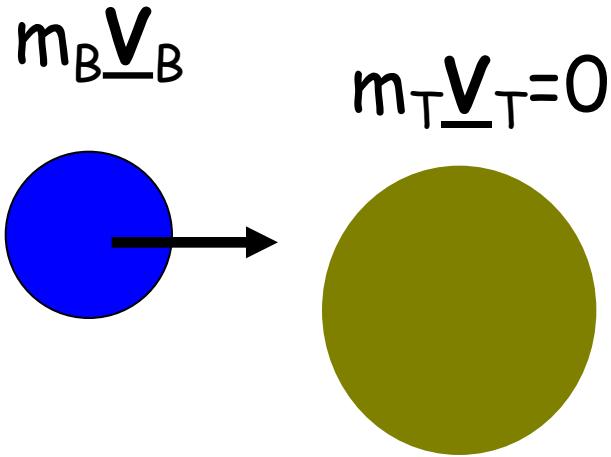
KE of recoiling nucleus
 $= \frac{1}{2} (M_B + M_T) v_R^2$



Light particles p, n, α evaporated.

Sn, Sp $\sim 1-15$ MeV.

Example: $^{96}\text{Ru}(^{40}\text{Ca},xpyn)^{136}\text{Gd}-xp-yn$

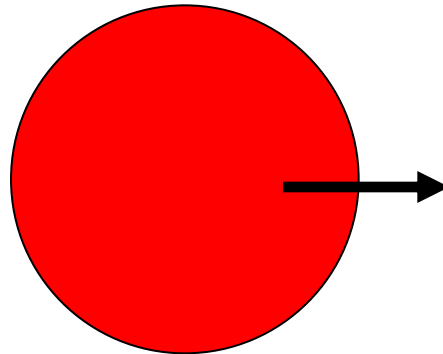


^{40}Ca
 $Z=20$
 $N=20$

^{96}Ru
 $Z=44$
 $N=52$

$$\text{KE of beam} = \frac{1}{2} m_B v_B^2$$

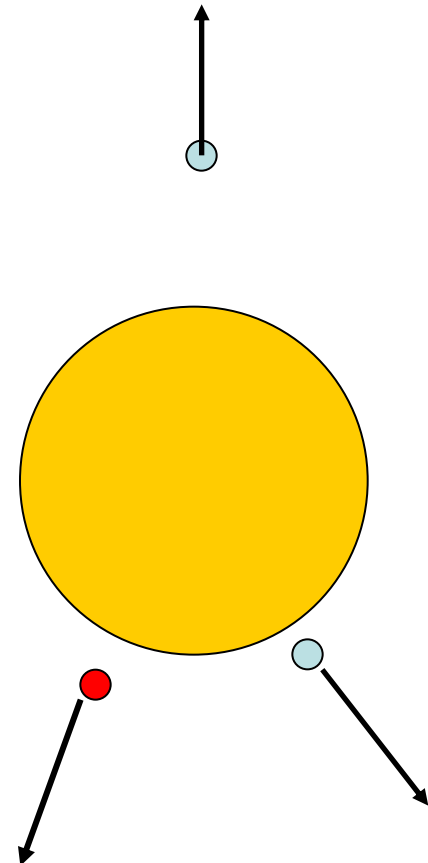
$$m_R \underline{v}_R = (m_B + m_T) \underline{v}_R = m_B \underline{v}_B. \text{ Therefore, } \underline{v}_R = (m_B) \underline{v}_B / (m_B + m_T)$$



^{136}Gd ($Z=64$ $N=72$).

Hot, compound nucleus recoils backwards at 0° in the lab frame with velocity, v_R .

$$\text{KE of recoiling nucleus} = \frac{1}{2} (M_B + M_T) v_R^2$$



$^{136}\text{Gd} + 3p = ^{133}\text{Pm}$

$^{136}\text{Gd} + 2pn = ^{133}\text{Sm}$

$^{136}\text{Gd} + 3pn = ^{134}\text{Pm}$

$^{136}\text{Gd} + 2p2n = ^{132}\text{Sm}$

Production of High-Spin States

$$E_{ex} = E_{cm} + Q_{fus} \quad (2.1.1)$$

E_{cm} is the kinetic energy of the collision which is transferred to the compound system. It can be calculated by taking the kinetic energy of the beam, E_B and subtracting the kinetic energy of the recoiling compound system, E_R . Thus

$$E_{cm} = E_B - E_R \quad (2.1.2)$$

By conservation of momentum, for beam and target masses of M_B and M_T respectively, the velocity of the recoiling compound, V_R can be calculated using

$$M_B V_B = (M_T + M_B) V_R \quad (2.1.3)$$

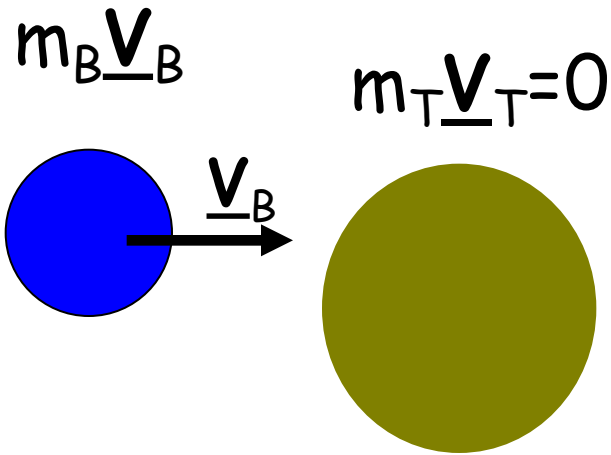
and by conservation of energy,

$$E_{cm} = E_B - \frac{1}{2} (M_T + M_B) V_R^2 \quad (2.1.4)$$

substituting in for V_R , and recalling that $E_B = \frac{1}{2} M_B V_B^2$, we obtain

$$E_{cm} = E_B \left(1 - \frac{M_B}{M_T + M_B} \right) \quad (2.1.5)$$

Example: $^{96}\text{Ru}(^{40}\text{Ca},xpyn)^{136}\text{Gd}-xp-yn$

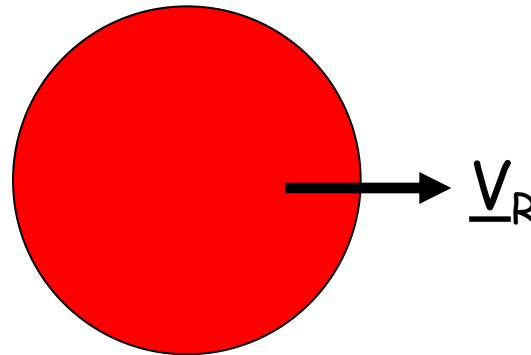


^{40}Ca
 $Z=20$
 $N=20$

^{96}Ru
 $Z=44$
 $N=52$

$$\text{KE of beam} = \frac{1}{2} m_B v_B^2$$

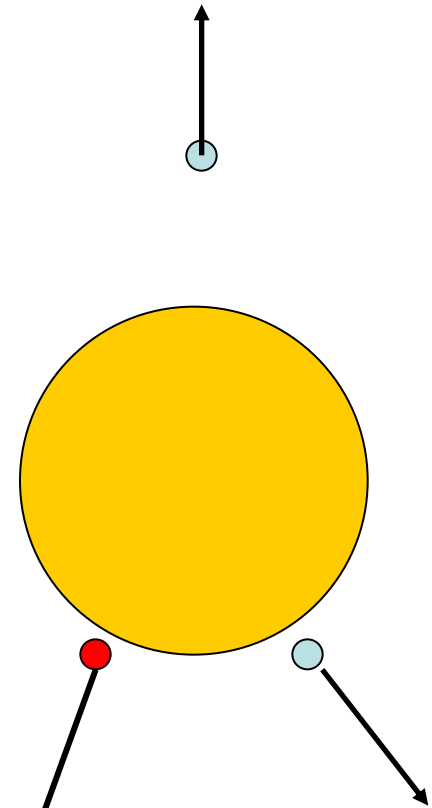
$$m_R \underline{v}_R = (m_B + m_T) \underline{v}_R = m_B \underline{v}_B. \text{ Therefore, } \underline{v}_R = (m_B) \underline{v}_B / (m_B + m_T)$$



^{136}Gd ($Z=64$ $N=72$).

Hot, compound nucleus recoils backwards at 0° in the lab frame with velocity, $\underline{v}_R$.

$$\text{KE of recoiling nucleus} = \frac{1}{2} (M_B + M_T) v_R^2$$



Light particle emission causes small recoil cone in lab frame due to cons. of linear momentum.

Doppler Shifts

Moving source - nucleus which emits gamma-ray ;
Stationary observer - Ge detector.

$$E_S = E_0 \frac{\sqrt{1 - \beta^2}}{1 - \beta \cos \theta} \approx E_0 (1 + \beta \cos \theta)$$

germanium
detector

θ

$\Delta\theta$ $\Delta\theta$

γ

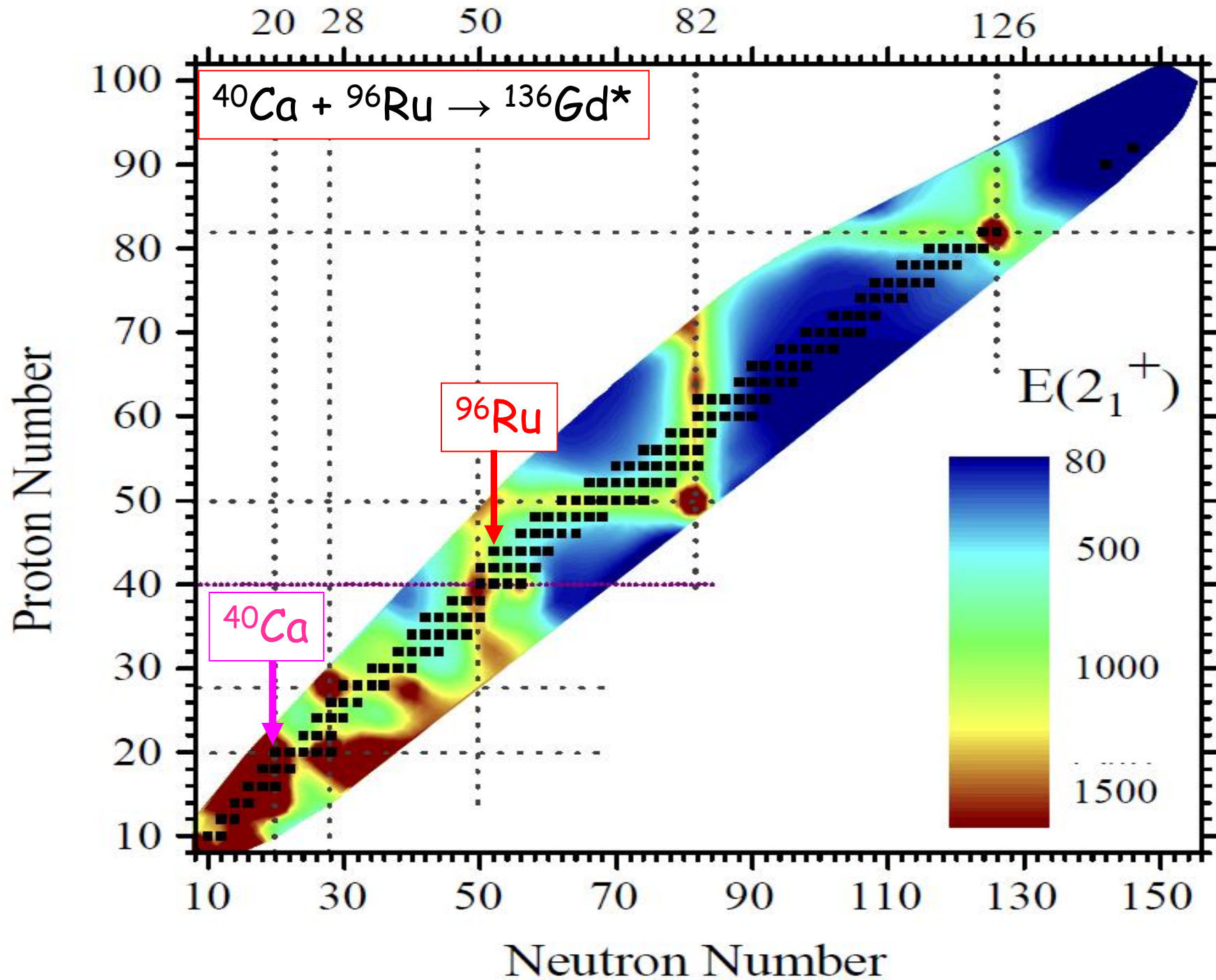
The range in Doppler shifted energy across the finite opening angle of a detector ($\Delta\theta$) Causes a reduction in measured energy resolution due to Doppler Broadening.

This is made worse if there is also a spread in the recoil velocities (Δv) for the recoils.

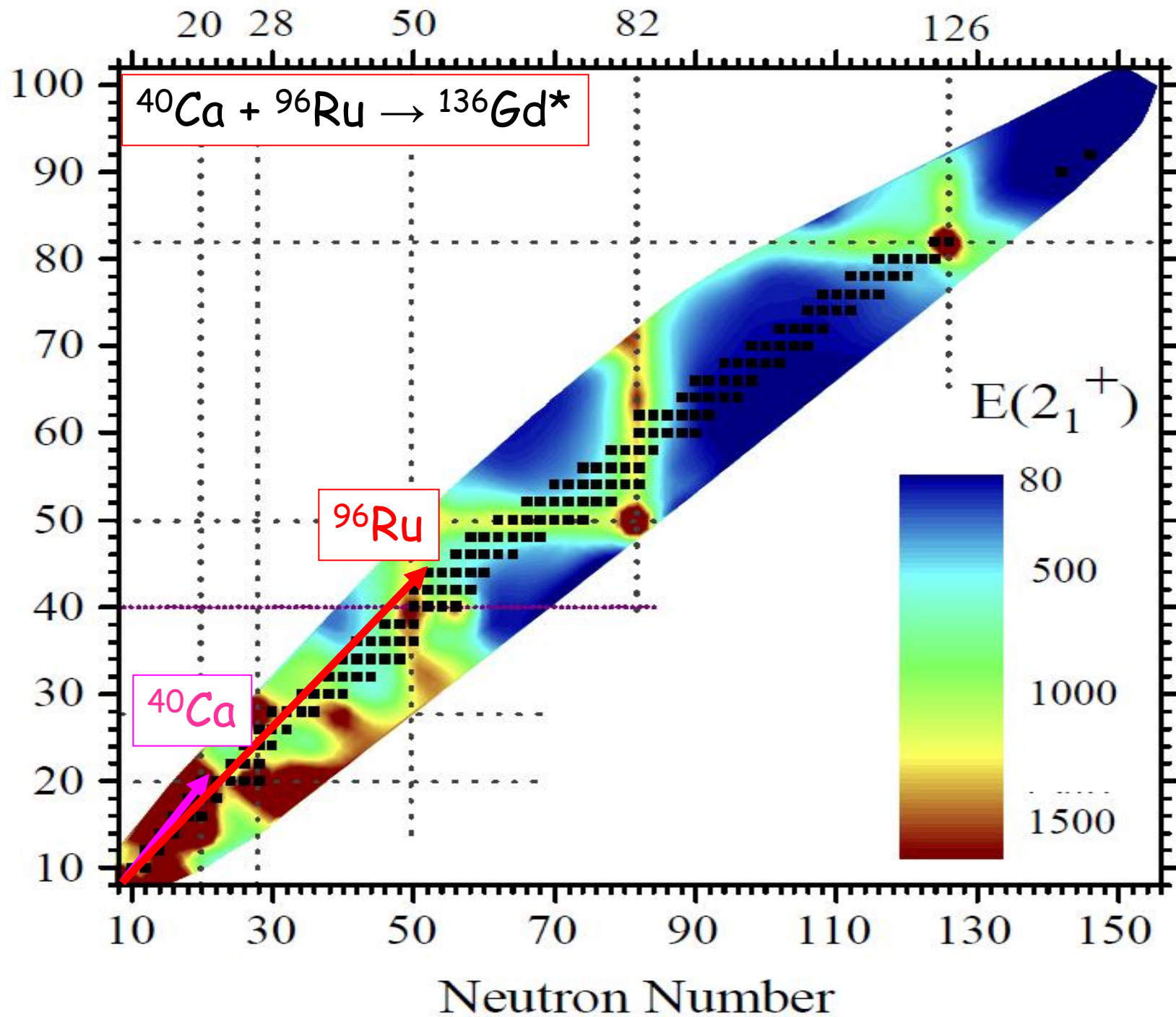
$$\Delta E_s \approx E_0 \cos \theta \frac{\Delta v}{c} - E_0 \frac{v}{c} \sin \theta \Delta \theta$$

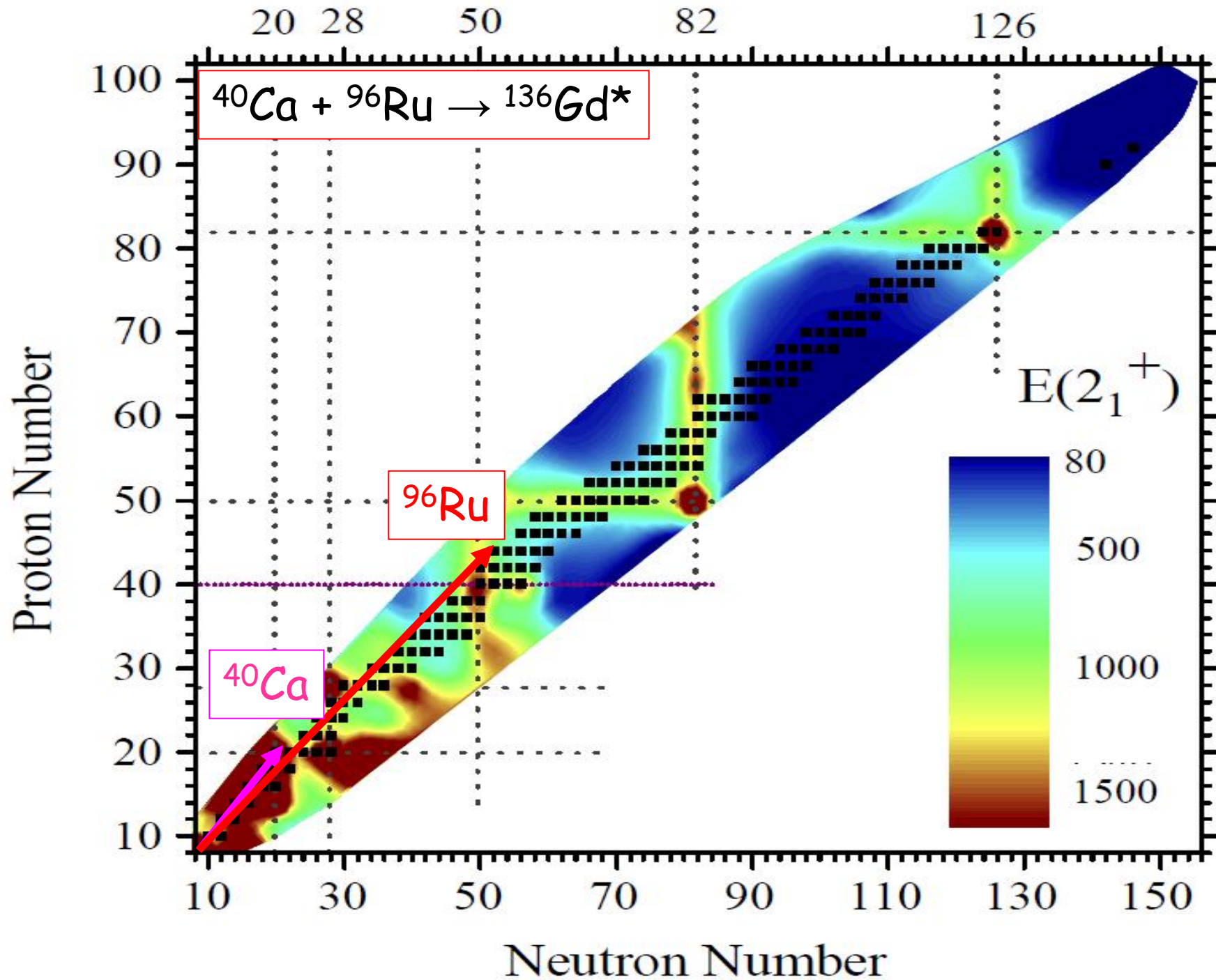


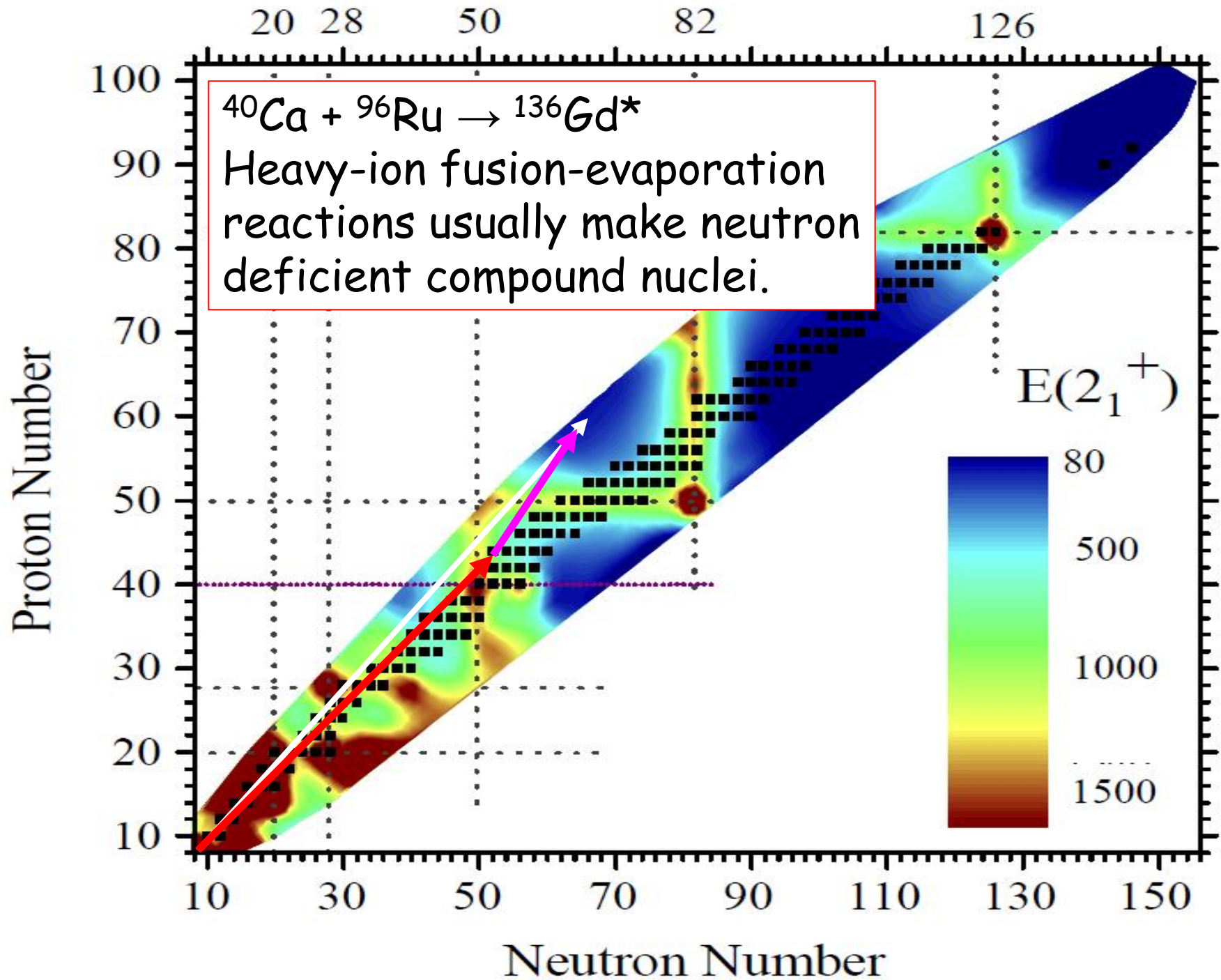
beam direction, velocity, v

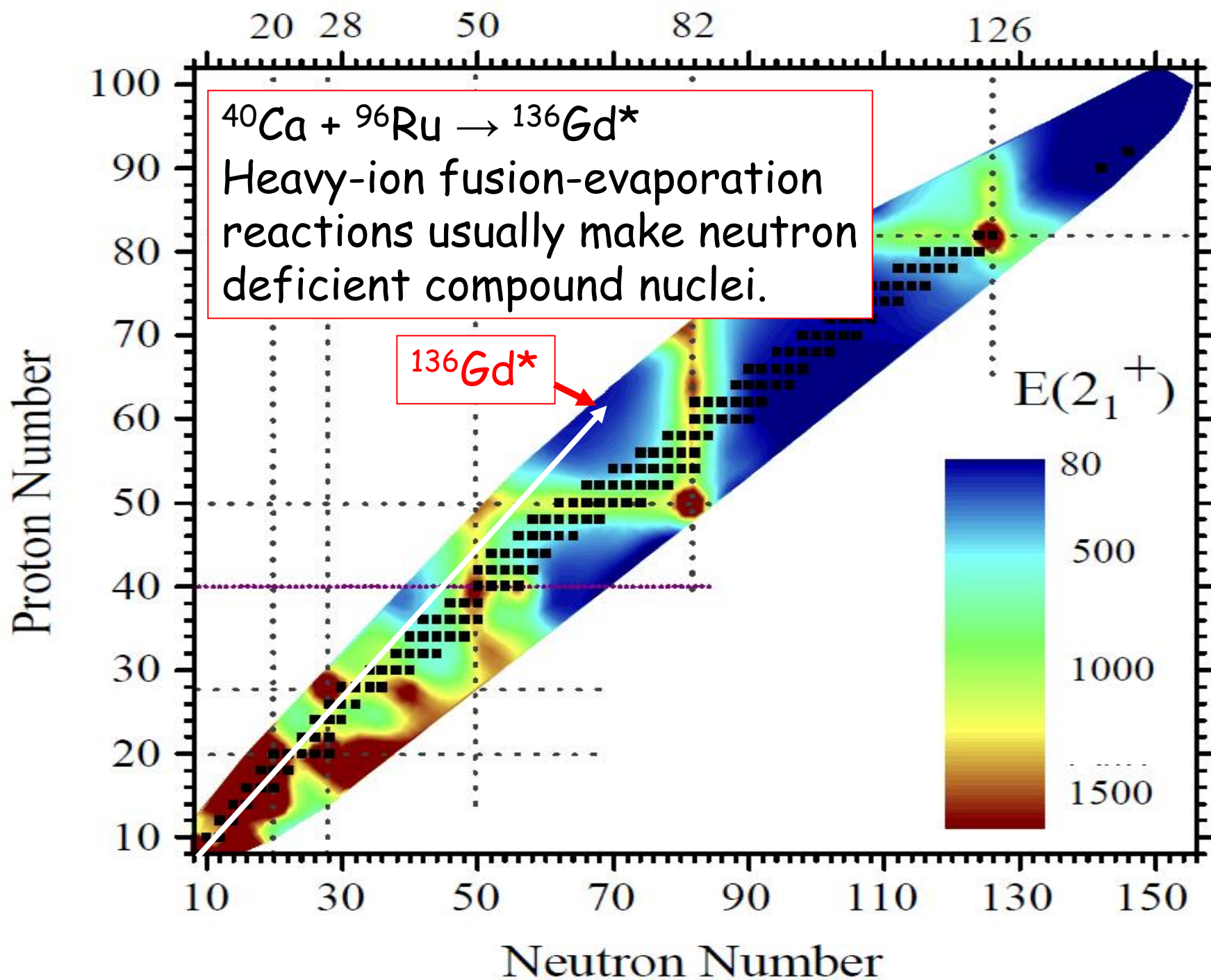


Proton Number









Channel Selection in Fusion-Evaporation Reactions

- **Calorimetry (HI,xn).**
 - (Sum Energy, Fold) proxy to select out different evaporation channels, e.g. 3, vs 4n vs 5n.
- **Evaporated Light- Particle Detection.**
 - Measure coincident neutrons (neutron walls, NE213 scintillators) and/or light charged particles p and α (e.g. with the microball) to reconstruct evaporation channels
- **Recoil Residue Detection.**
 - Measure recoiling final nucleus (A/q) using EM spectrometer. e.g. Argonne FMA, EMMA,
 - Can also use focal plane Ionization Chamber to select Z.
 - Recoil-decay tagging (discrete p, α tags) for weak channels.

Determining spins from
gamma-ray multipolarities

DCO and DCO Ratios

JULY 15, 1940

PHYSICAL REVIEW

VOLUME 58

On Directional Correlation of Successive Quanta

DONALD R. HAMILTON*

Harvard University, Cambridge, Massachusetts

(Received May 6, 1940)

A theoretical investigation shows that there should be a correlation between the directions of propagation of the quanta emitted in two successive transitions of a single radiating system. This correlation is described by a function $W(\theta)$ which gives the relative probability that the second quantum will be emitted at an angle θ with the first; W is determined by the angular momenta of the three levels involved in the two transitions and by the multipole order of the radiation emitted in these transitions. The explicit

forms of W for all angular momenta and for dipole and quadrupole radiation are given; experimental determination of W in any given case should limit these factors to a small number of possibilities. This has particular interest as a means of investigating the nuclear energy levels involved in γ -radiation; here W should be observable by measuring the variation with θ of gamma-gamma coincidence counting rates.

Dropping a constant factor, our correlation function for calculation is

$$W(\theta) = 1 + (R/Q) \cos^2 \theta + (S/Q) \cos^4 \theta.$$

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DONALD R. HAMILTON

TABLE I. R/Q , for both transitions dipole.

	$\Delta J = -1$	$\Delta J = 0$	$\Delta J = 1$
$\Delta j = -1$	$\frac{1}{13}$	$-\frac{(2J-1)}{(14J+13)}$	$\frac{J(2J-1)}{(26J^2+67J+40)}$
$\Delta j = 0$	$-\frac{(2J+3)}{(14J+1)}$	$\frac{(2J-1)(2J+3)}{(12J^2+12J+1)}$	
$\Delta j = 1$	$\frac{(J+1)(2J+3)}{(26J^2-15J-1)}$		

TABLE II. R/Q , for first transition quadrupole, second dipole.

	$\Delta J = 1$	$\Delta J = 0$	$\Delta J = -1$
$\Delta j = 2$	$-\frac{3}{29}$	$\frac{3(2J+3)}{(26J-3)}$	$-\frac{3(J+1)(2J+3)}{(58J^2-23J+3)}$
$\Delta j = 1$	$\frac{3(J-5)}{(55J+61)}$	$-\frac{3(2J+3)(J-5)}{(58J^2+49J-15)}$	$\frac{3(2J+3)(J-5)}{(110J^2-49J+15)}$
$\Delta j = 0$	$\frac{(2J-3)(2J+5)}{(36J^2+92J+61)}$	$-\frac{(2J-3)(2J+5)}{5(4J^2+4J-1)}$	$\frac{(2J-3)(2J+5)}{(36J^2-20J+5)}$
$\Delta j = -1$	$\frac{3(2J-1)(J+6)}{(110J^2+269J+174)}$	$-\frac{3(2J-1)(J+6)}{(58J^2+67J-6)}$	$\frac{3(J+6)}{(55J-6)}$
$\Delta j = -2$	$-\frac{3J(2J-1)}{(58J^2+139J+84)}$	$\frac{3(2J-1)}{(26J+29)}$	$-\frac{3}{29}$

First real 'evidence' of angular correlations between successive gamma rays;

Radioactive decays of

^{60}Co ($I^\pi=5^+$, $T_{1/2}=5.27$ yrs to ^{60}Ni)
 ^{46}Sc ($I^\pi=4^+$, $T_{1/2}=84$ days to ^{46}Ti)
 ^{88}Y ($I^\pi=4^-$, $T_{1/2}=107$ days to ^{88}Sr)
 ^{134}Cs ($I^\pi=4^+$, $T_{1/2}=2.1$ yrs to ^{134}Ba).

(note, says ^{86}Y in paper, means ^{88}Y)

Angular Correlation of Successive Gamma-Ray Quanta

EDWARD L. BRADY AND MARTIN DEUTSCH

Massachusetts Institute of Technology, Cambridge, Massachusetts

September 10, 1947

THEORETICAL considerations^{1,2} predict a directional correlation of successive quanta of the form

$$W(\theta) = 1 + \sum_{i=1}^l A_i \cos^2 i \theta$$

if $2l$ is the highest multipole order occurring. Attempts to demonstrate this effect experimentally have heretofore been inconclusive.³ We have studied coincidences between successive gamma-rays of Co^{60} , Sc^{46} , Y^{86} (106 day), and Cs^{134} at angles 180° and 90° between the counters, and found a pronounced anisotropy in the first two named and no correlation within the experimental error in the last two. Our results, together with the gamma-ray energies concerned, are shown in Table I. The quantity $(W(\pi)$

TABLE I. Anisotropy of gamma-ray coincidences.

Source	Co^{60}	Sc^{46}	Y^{86}	Cs^{134}
ϵ	0.21 ± 0.025	0.20 ± 0.035	-0.05 ± 0.03	0.01 ± 0.04
Gamma-rays	1.1, 1.3	0.89, 1.12	0.91, 1.89	0.58, 0.78
Mev				
Reference	4	5	6	7

$-W(\pi/2))/W(\pi/2)$ should be equal to $\sum A_i$. Our results

High-precision γ -ray spectroscopy of the cardiac PET imaging isotope ^{82}Rb and its impact on dosimetry

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(Received 2 October 2015; revised manuscript received 21 December 2015; published 1 February 2016)

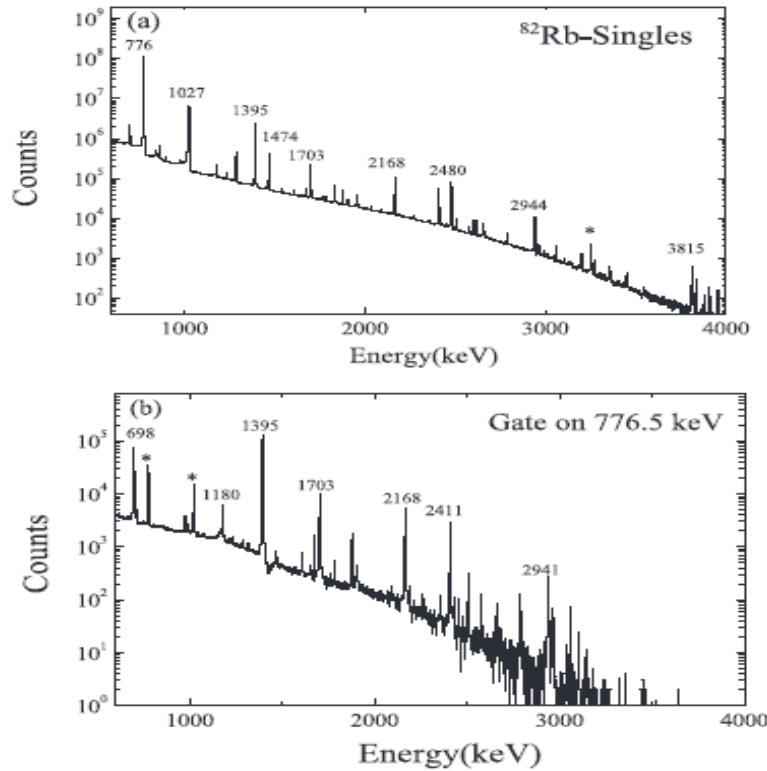


FIG. 1. (a) Singles spectrum from the decay of ^{82}Rb . (b) Spectrum obtained by gating on the 776-keV transition in ^{82}Kr . In both panels, strong transitions belonging to the decay of ^{82}Rb are labeled by their energy in keV, while background lines are indicated with a *.

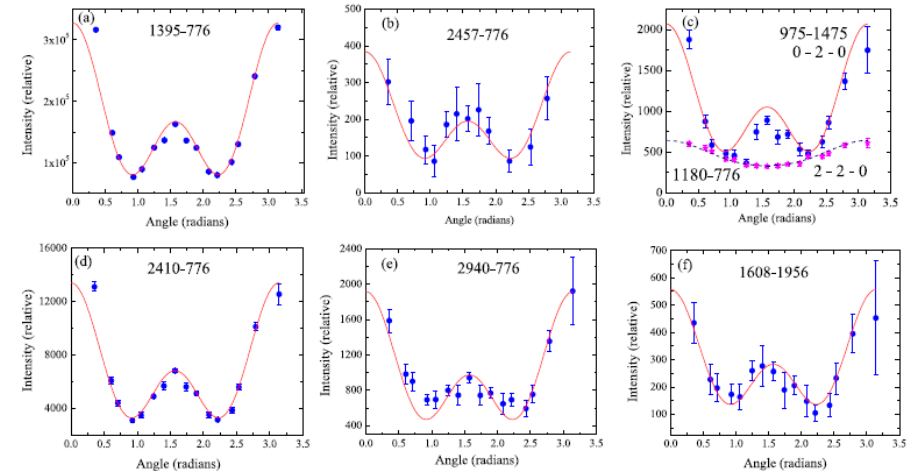
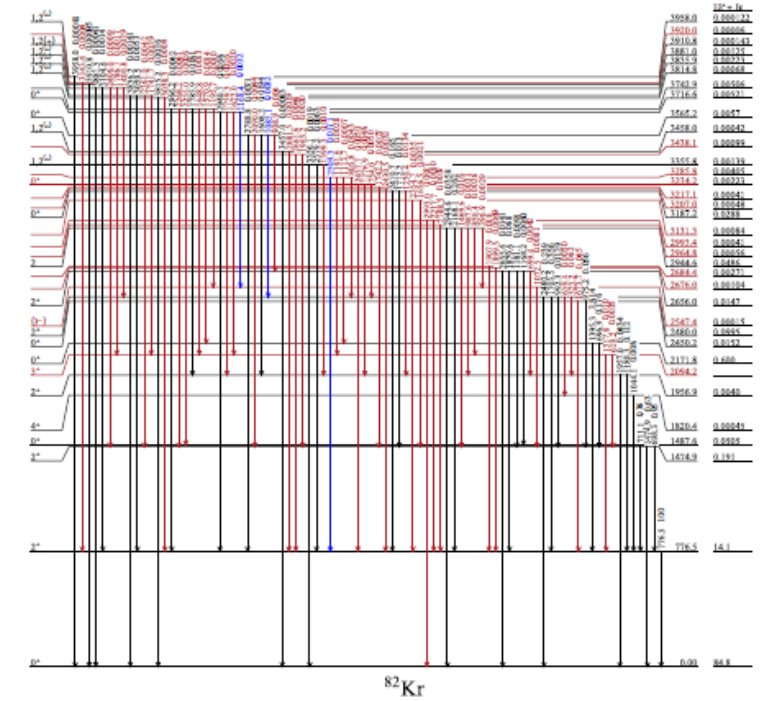


FIG. 6. Angular correlation analysis of confirmed and newly identified $0^+ \rightarrow 2^+ \rightarrow 0^+$ cascade transitions in ^{82}Kr . Solid circles give the measured intensity as a function of angle between detectors while solid lines are the theoretical predictions for a 0-2-0 sequence. Numbers in each panel give the cascade energies, in keV. In panel (c), the angular correlation of the 1180-776.5 cascade (stars) is given along with the theoretical predictions for a 2-2-0 sequence with $\delta = -0.52$ (dotted line).

Neutron-Rich Nuclei?

How do you make and study neutron-rich nuclei ?

- (low-cross-section) fusion evap. reactions, e.g., $^{18}\text{O} + ^{48}\text{Ca} \rightarrow 2\text{p} + ^{64}\text{Fe}$
 - Limited compound systems using stable / beam target combinations.
 - Highly selective reactions (if good channel selection applied).
- Spontaneous fission sources (e.g., ^{244}Cm)
 - Good for some regions of the nuclear chart, but little/no selectivity in the 'reaction' mechanism.
 - Can make quite high spins in each fragment ($10 \rightarrow 20\hbar$)
- Fusion fission reactions
 - e.g., $^{18}\text{O} + ^{208}\text{Pb} \rightarrow ^{226}\text{Th}^* \rightarrow f_1 + f_2 + xn$ (e.g., $^{112}_{44}\text{Ru} + ^{112}_{46}\text{Pd} + 2n$)
 - Doesn't make very neutron-rich, little selectivity.
 - Medium spins ($\sim 10\hbar$ in each fragment) populated
- Heavy-ion deep-inelastic / multi-nucleon transfer reactions (e.g.,
 - e.g. $^{136}\text{Xe} + ^{198}\text{Pt} \rightarrow ^{136}\text{Ba} + ^{194}\text{Os} + 2n$.
 - Populations Q-value dependent; medium spins accessed in products, make nuclei 'close' to the original (stable) beam and target species.
 - Selectivity can be a problem, large Doppler effects.
- Projectile fragmentation (or Projectile Fission)
 - (v. different energy regime)
 - Need a fragment separator.

Spectroscopy of neutron-rich $^{168,170}\text{Dy}$: Yrast band evolution close to the $N_p N_n$ valence maximum

P.-A. Söderström,¹ J. Nyberg,¹ P. H. Regan,² A. Algora,³ G. de Angelis,⁴ S. F. Ashley,² S. Aydin,⁵ D. Bazzacco,⁵ R. J. Casperson,⁶ W. N. Catford,² J. Cederkäll,^{7,8} R. Chapman,⁹ L. Corradi,⁴ C. Fahlander,⁸ E. Farnet,⁹ E. Fioretto,⁴ S. J. Freeman,¹⁰ A. Gadea,^{3,4} W. Gelletly,² A. Gottardo,⁴ E. Grodner,⁴ C. Y. He,⁴ G. A. Jones,² K. Keyes,⁹ M. Labiche,⁹ X. Liang,⁹ Z. Liu,² S. Lunardi,⁵ N. Mărginean,^{4,11} P. Mason,⁵ R. Menegazzo,⁵ D. Mengoni,⁵ G. Montagnoli,⁵ D. Napoli,⁴ J. Ollier,¹² S. Pietri,² Zs. Podolyák,² G. Pollaro,¹³ F. Recchia,⁴ E. Şahin,⁴ F. Scarlassara,⁵ R. Silvestri,⁴ J. F. Smith,⁹ K.-M. Spohr,⁹ S. J. Steer,² A. M. Stefanini,⁴ S. Szilner,¹⁴ N. J. Thompson,² G. M. Tveten,^{7,15} C. A. Ur,⁵ J. J. Valiente-Dobón,⁴ V. Werner,⁶ S. J. Williams,² F. R. Xu,¹⁶ and J. Y. Zhu¹⁶

Use spectrometer to 'tag' on one of the reaction fragments for Doppler Correction.
e.g., ^{82}Se ($Z=34$) beam on thin ^{170}Er ($Z=68$) target at INFN-Legnaro.

Measure BLFs directly in PRISMA spectrometer and gammas in CLARA gamma-ray array. Reverse correct for heavier TLF using 2-bo kinematics.

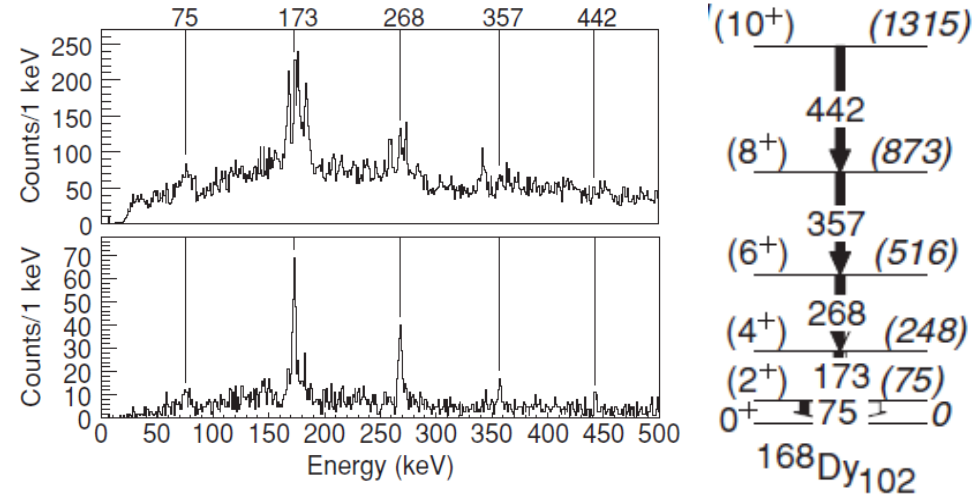
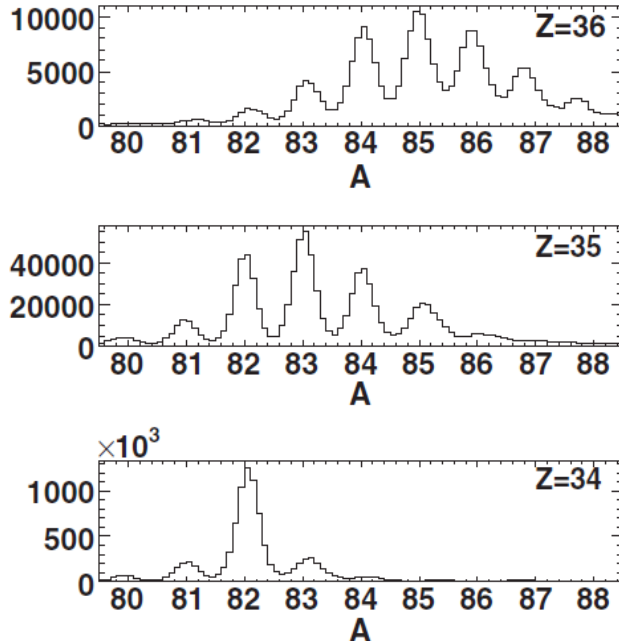


FIG. 3. Spectrum of γ -ray energies from targetlike fragments gated on the beamlike fragments ^{84}Kr (top) and on beamlike fragments ^{84}Kr plus a short time of flight (bottom). The transitions identified as the rotational band in ^{168}Dy are marked with solid lines.

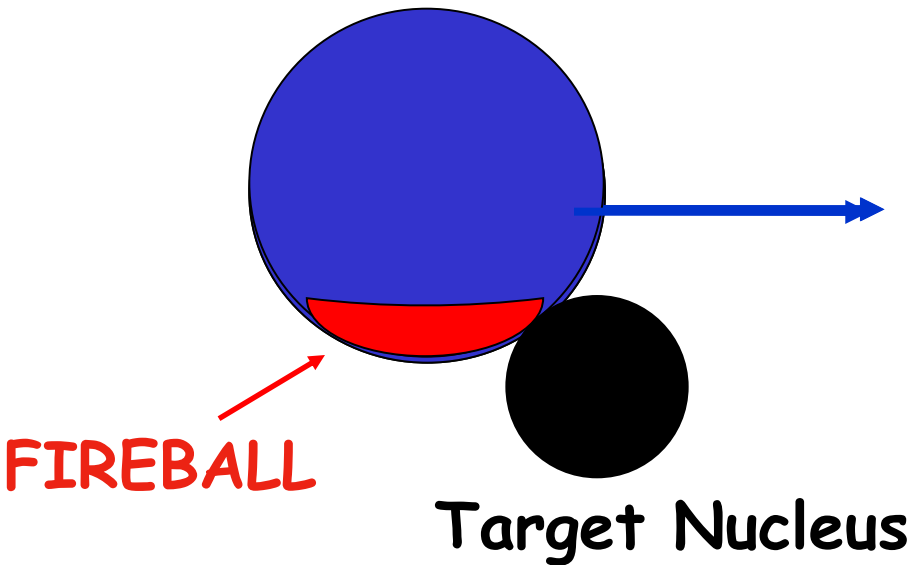
Gate on ^{84}Kr ($Z=36$) fragment in PRISMA. Complementary fragment (assuming no neutron evaporation) for $^{82}\text{Se}+^{170}\text{Er}$ reaction for ^{84}Kr is ^{168}Dy ($Z=66$) (+2p transfer channel). Shortest time of flight in PRISMA associated with least neutron evaporation.

Nuclear Structure at Relativistic Energies

- $E_b > E_{\text{Fermi}}$ (i.e. beam moved faster than internal nucleon motion in nucleus) $\sim 10\text{-}50 \text{ MeV/u}$.
- Projectile fragmentation - a useful tool to exotic nuclei. $E_b \sim 100 \text{ MeV/u} - 1 \text{ GeV/u}$.
- Need 'fragment separator' to separate and identify produced fragments. Typical ToF $\sim 1\text{ms}$.
- Prompt decays happen at production target...but can do 'delayed' spectroscopy (e.g. isomer delayed ; radioactive decay delayed) at the focal plane.

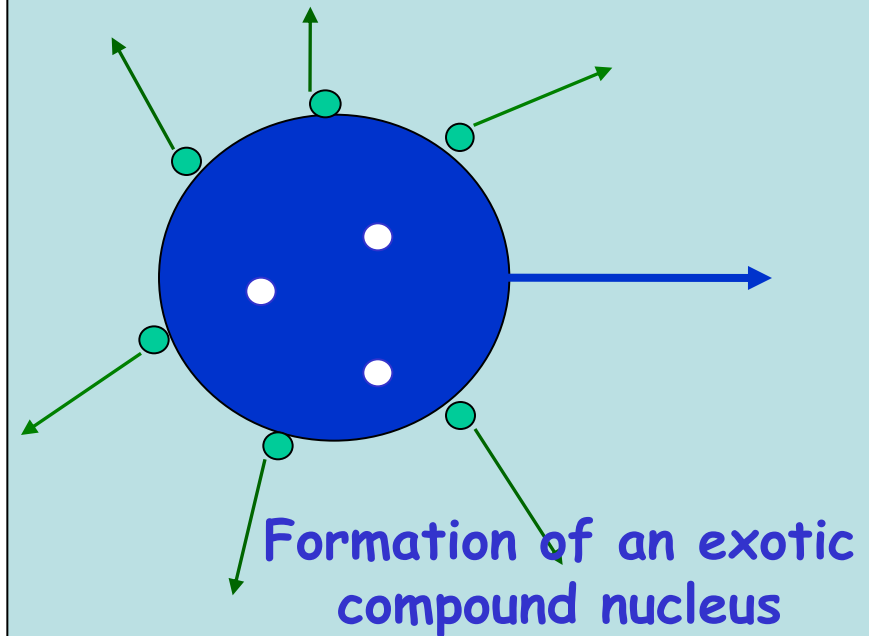
(Another Way) to Make Exotic Nuclei: Projectile Fragmentation Reaction Process

Beam at Relativistic
Energy $\sim 0.5-1 \text{ GeV/A}$



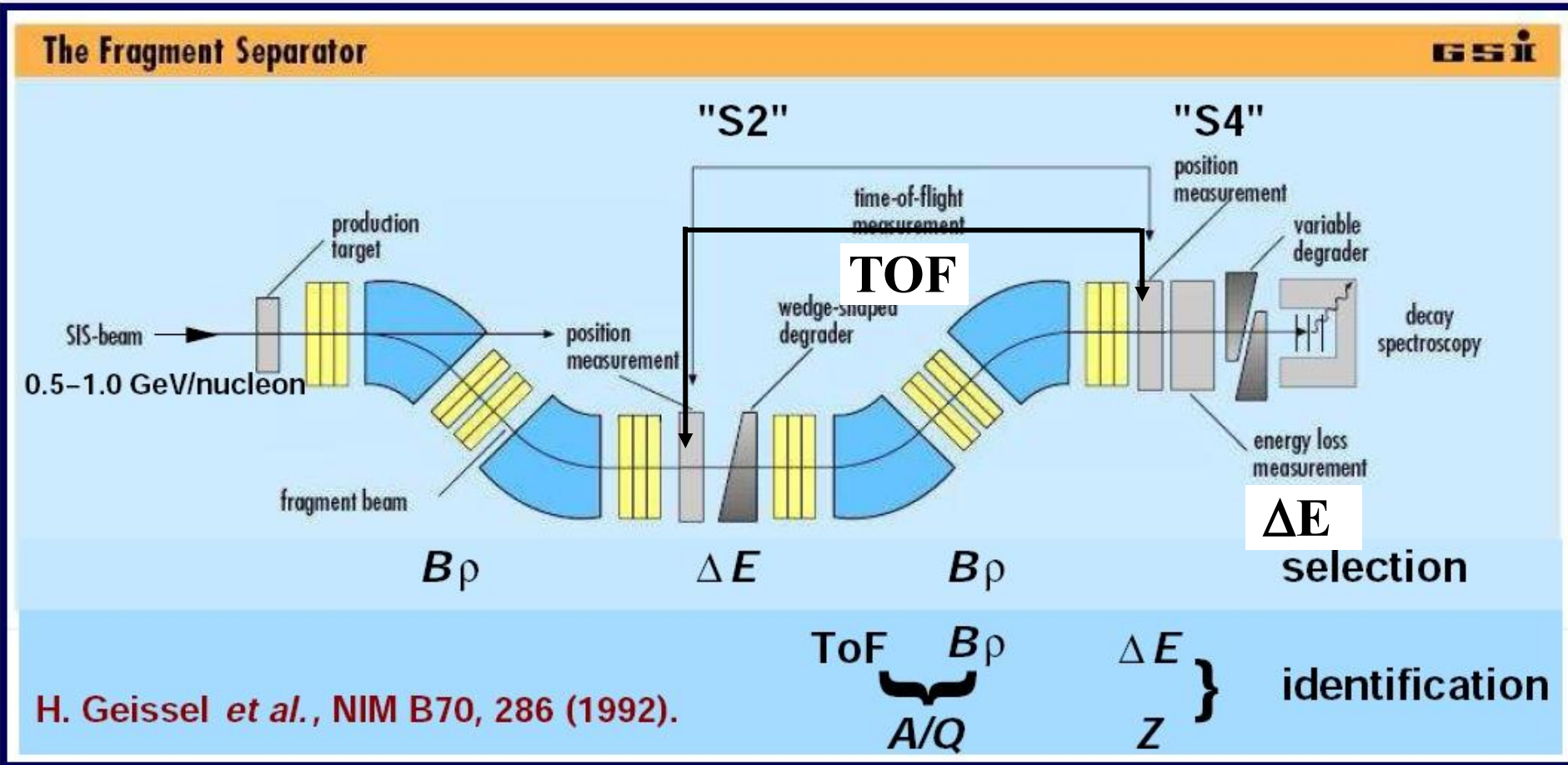
Abrasion

Reaction products travelling
at Relativistic Energies



Ablation

Ion-by-ion identification with the FRS



Cocktail of secondary, exotic fragments with $\sim x00$ MeV/u thru. FRS.
Separate and identify event-by-event. Chemically independent.



**ionization
chambers
(MUSIC41,42)**

**scintillators
(SC41, SC42)**

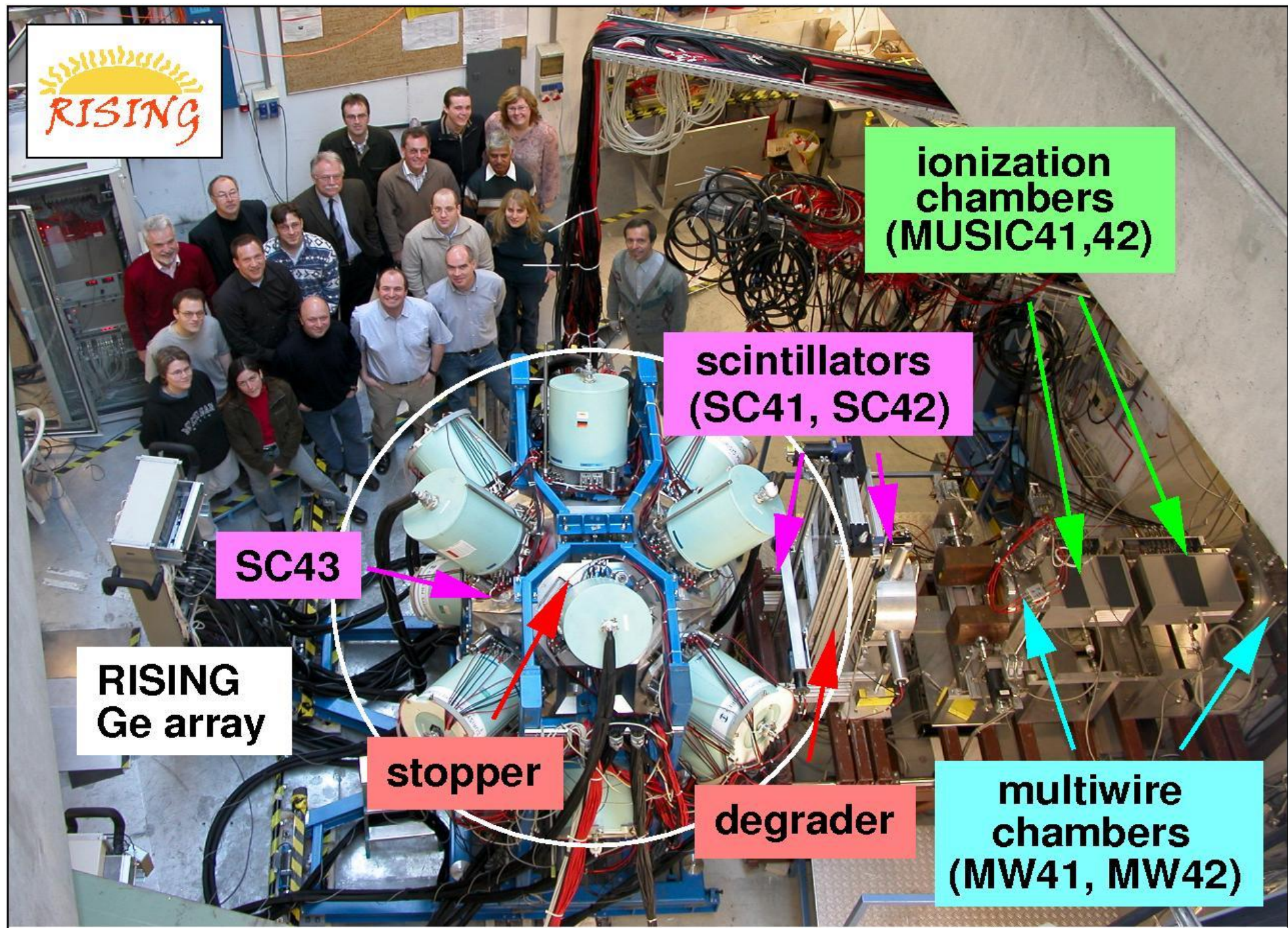
SC43

**RISING
Ge array**

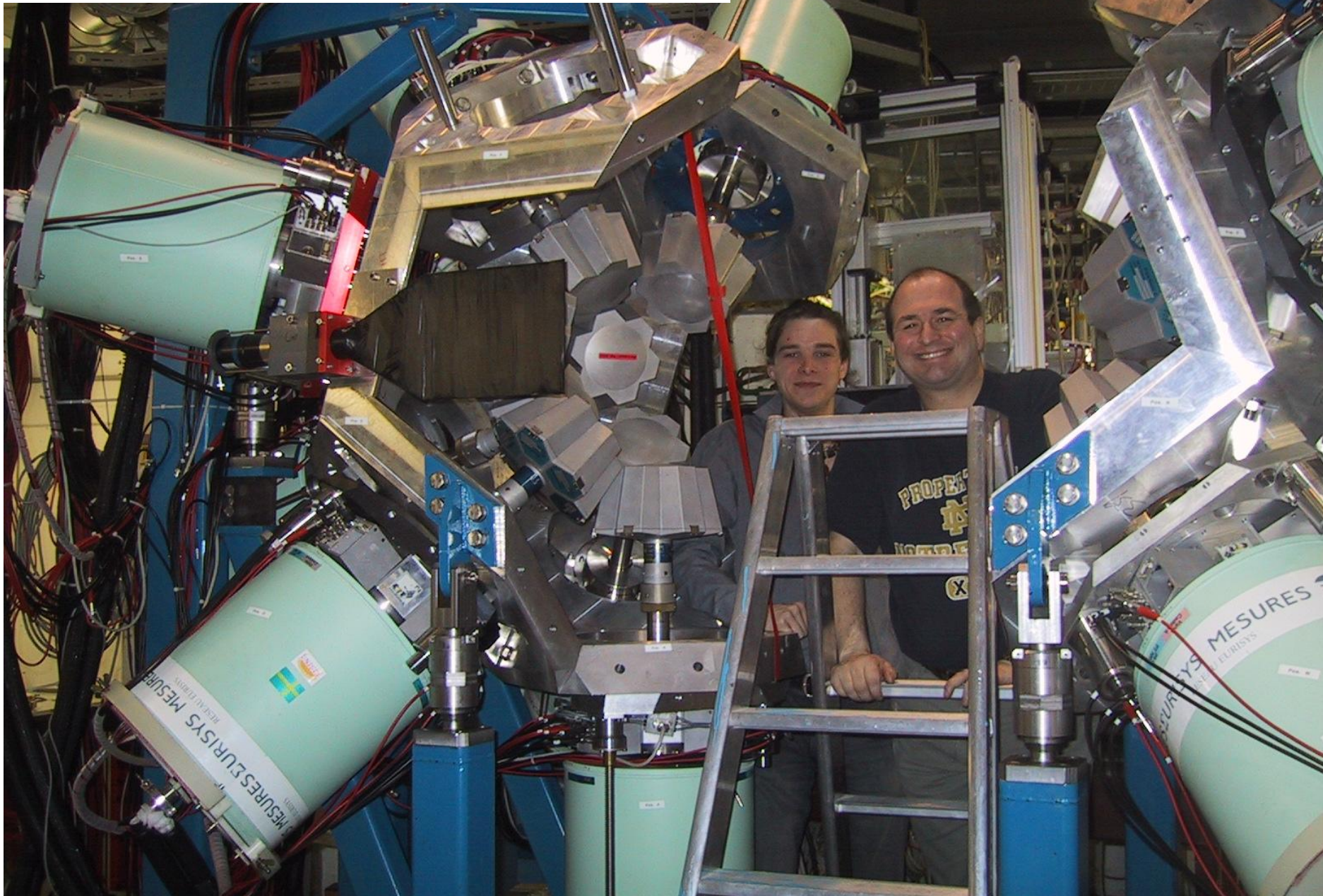
stopper

degrader

**multiwire
chambers
(MW41, MW42)**

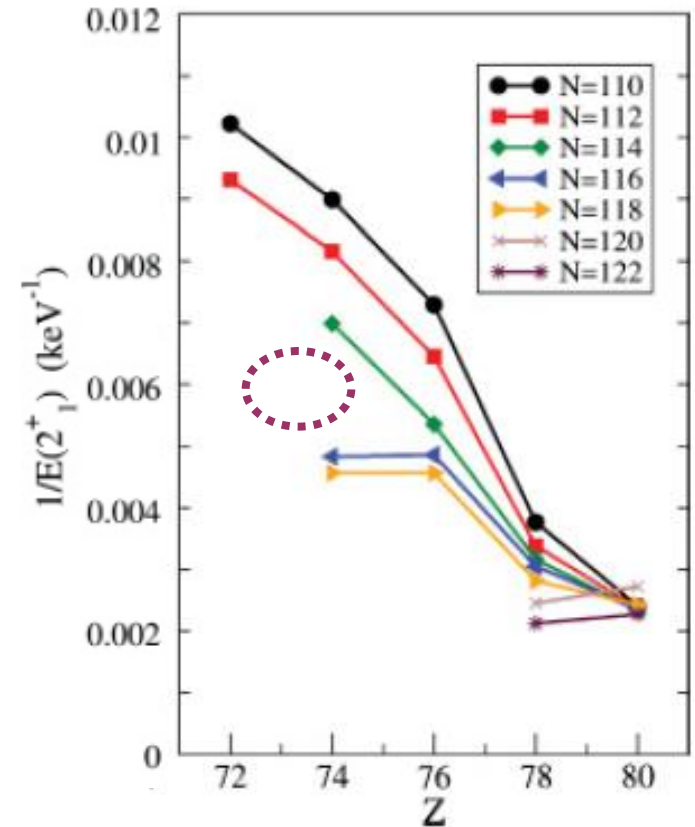
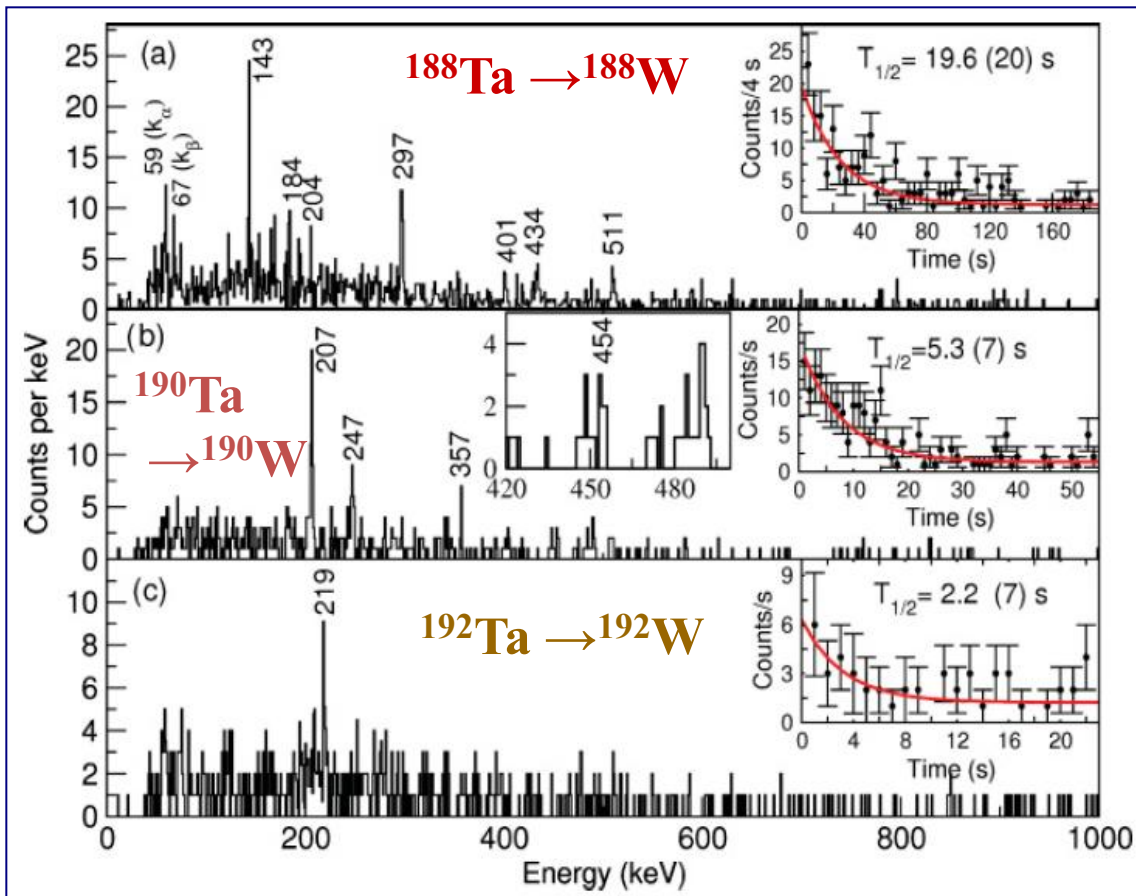


The RISING array at GSI-Darmstadt, Germany,
105 Germanium detectors

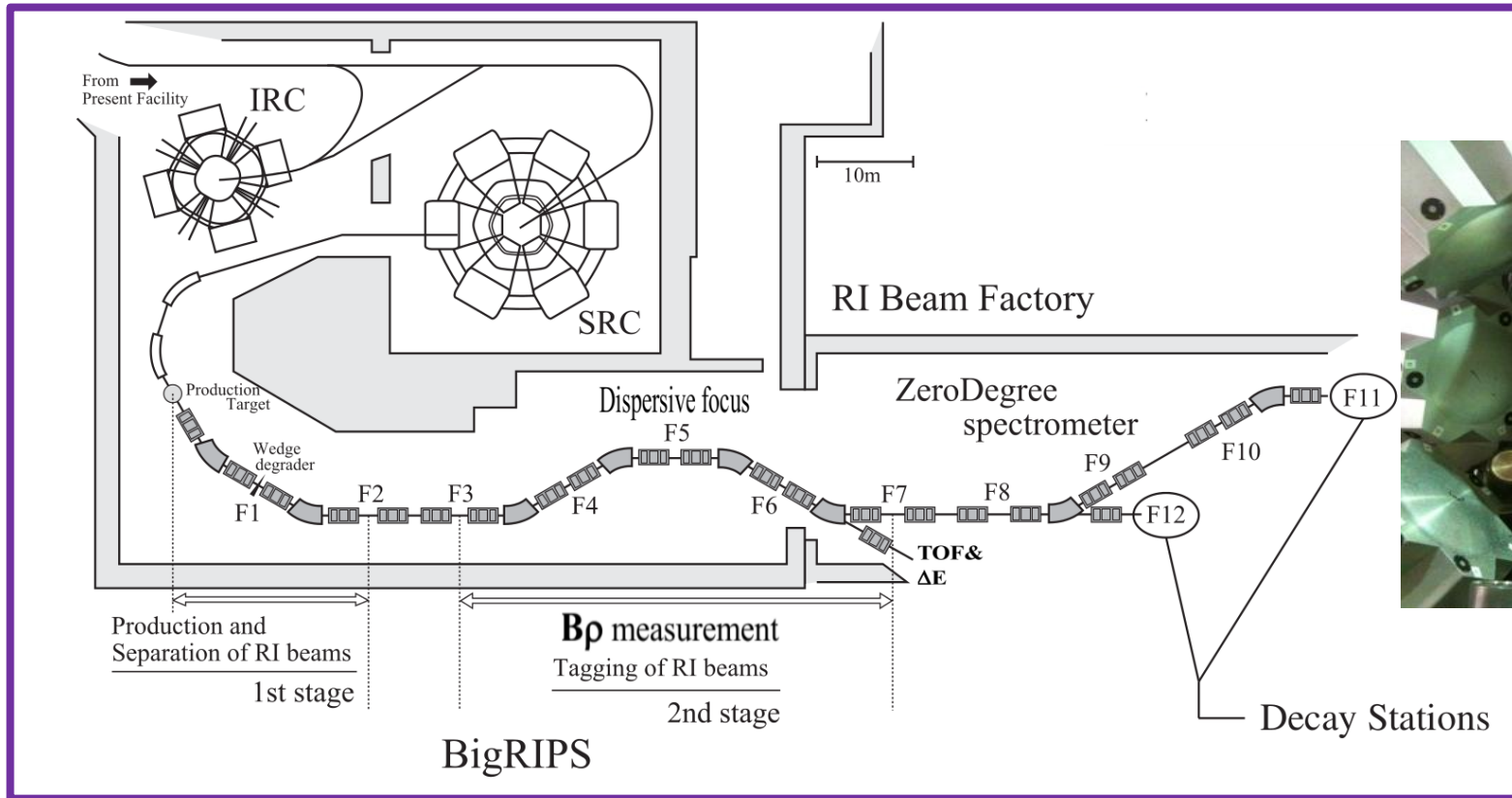


β^- -delayed spectroscopy of neutron-rich tantalum nuclei: Shape evolution in neutron-rich tungsten isotopes

N. Alkhomashi,^{1,*} P. H. Regan,¹ Zs. Podolyák,¹ S. Pietri,¹ A. B. Garnsworthy,¹ S. J. Steer,¹ J. Benlliure,² E. Caserejos,² R. F. Casten,³ J. Gerl,⁴ H. J. Wollersheim,⁴ J. Grebosz,⁵ G. Farrelly,¹ M. Górska,⁴ I. Kojouharov,⁴ H. Schaffner,⁴ A. Algara,^{6,7} G. Benzoni,⁸ A. Blazhev,⁹ P. Boutachkov,⁴ A. M. Bruce,¹⁰ A. M. Denis Bacelar,¹⁰ I. J. Cullen,¹ L. Cáceres,⁴ P. Doornenbal,⁴ M. E. Estevez,² Y. Fujita,¹¹ W. Gelletly,¹ R. Hoischen,^{4,12} R. Kumar,¹³ N. Kurz,⁴ S. Lalkovski,¹⁰ Z. Liu,¹⁴ C. Mihai,¹⁵ F. Molina,⁶ A. I. Morales,² D. Múcher,⁹ W. Prokopowicz,⁴ B. Rubio,⁶ Y. Shi,¹⁶ A. Tamii,¹⁷ S. Tashenov,⁴ J. J. Valiente-Dobón,¹⁸ P. M. Walker,¹ P. J. Woods,¹⁴ and F. R. Xu¹⁶



RIBF @ RIKEN = Radioactive Ion Beam Production Factory.



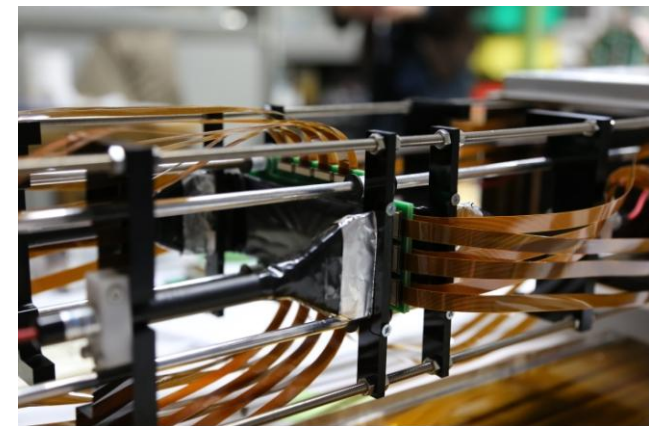
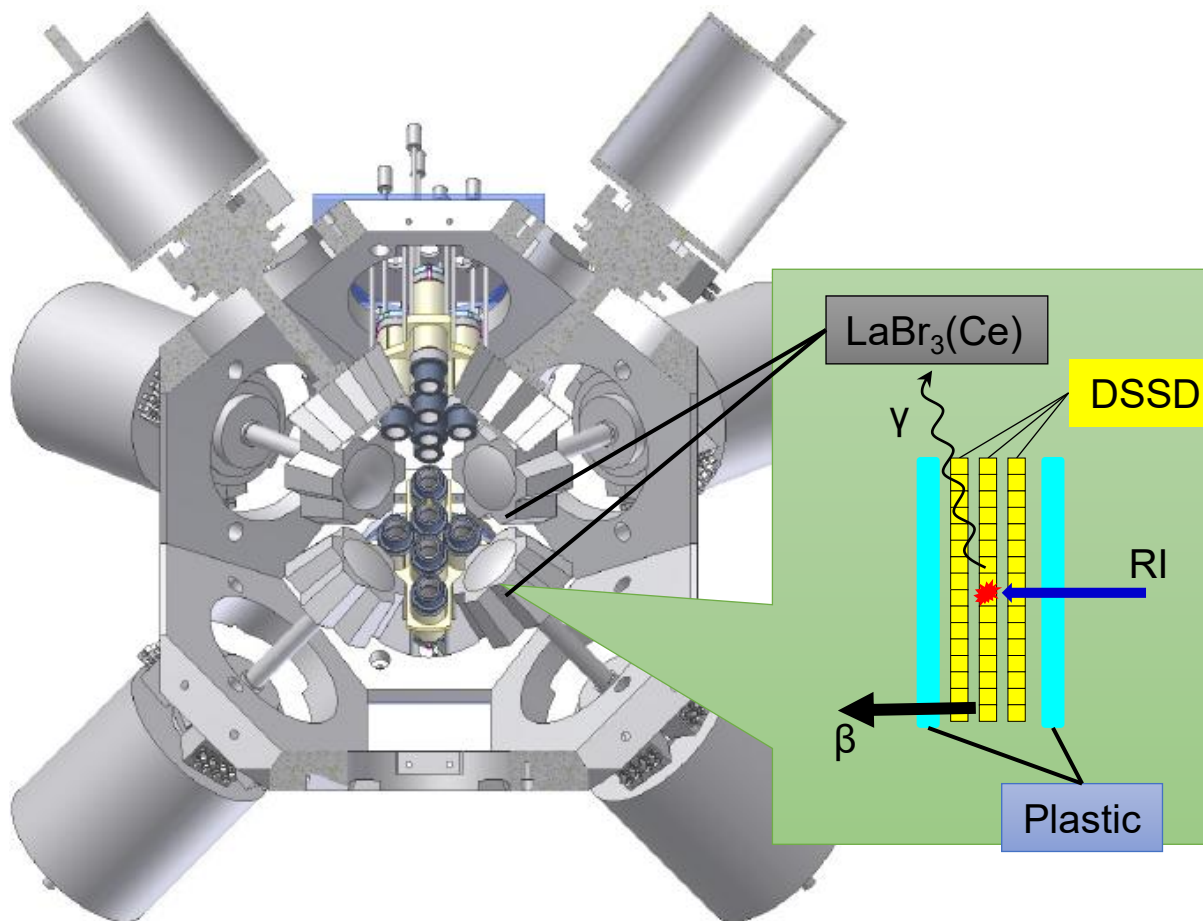
Radioactive Ion Beam Production Factory (RIBF) @ RIKEN, Wako Shi.

Beams of fission fragments, produced via high-energy (345 MeV/u) projectile fission of ^{238}U (time through BIG RIPS ~ 1 microsecond)

Nuclear decay measurements at the end of BigRIPS separator.

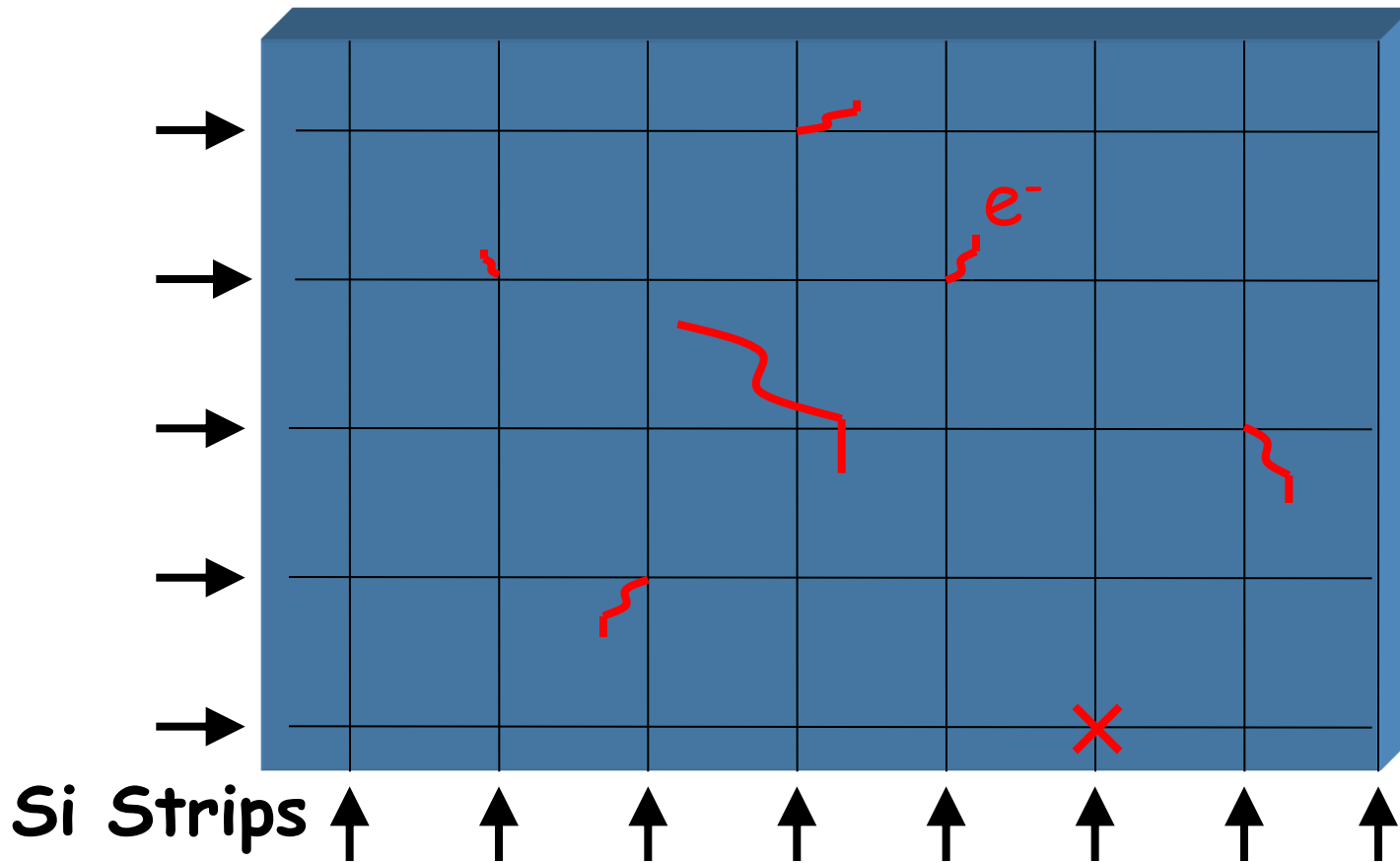
Experimental setup for decay spectroscopy @ RIKEN

- 84 HPGe detectors from the EURICA collaboration
- 18 UK $\text{LaBr}_3(\text{Ce})$ scintillators ($\Phi 1.5'' \times 2''$) for γ rays
- BC-418 plastic counters (2-mm thick) + DSSDs for β rays



The EURICA Active Stopper

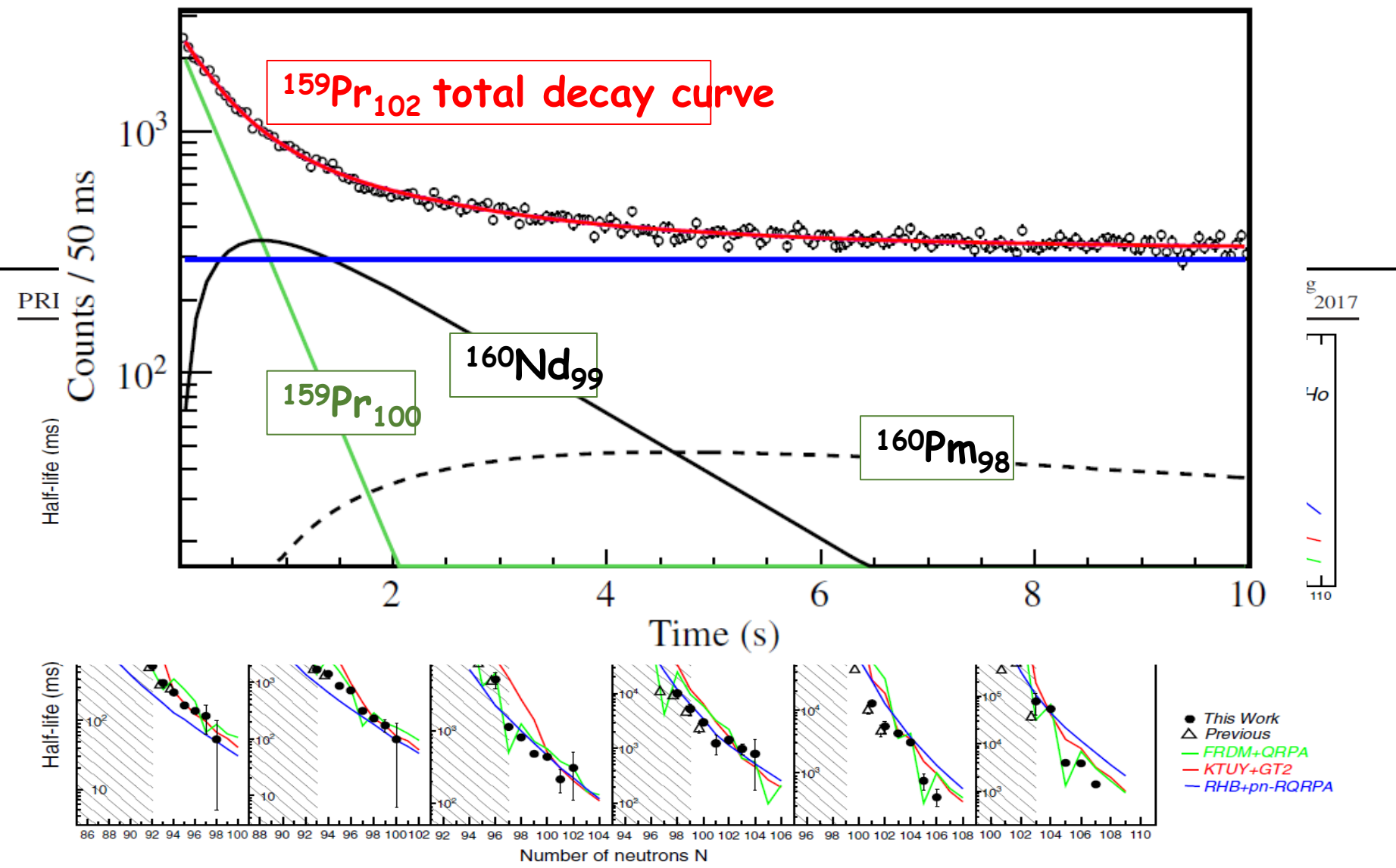
Focal plane implantation detector sensitive to beta-particles which can be correlated with defined radionuclide implants.



The time between particle implantation and β -particle is a measure of the decay half-life.

94β -Decay Half-Lives of Neutron-Rich $_{55}\text{Cs}$ to $_{67}\text{Ho}$: Experimental Feedback and Evaluation of the r -Process Rare-Earth Peak Formation

J. Wu,^{1,2,*} S. Nishimura,² G. Lorusso,^{2,3,4} P. Möller,⁵ E. Ideguchi,⁶ P.-H. Regan,^{3,4} G. S. Simpson,^{7,8,9} P.-A. Söderström,²
P. M. Walker,⁴ H. Watanabe,^{10,2} Z. Y. Xu,^{11,12} H. Baba,² F. Browne,^{13,2} R. Daido,¹⁴ P. Doornenbal,² Y. F. Fano,¹⁴



Lecture 3

Measuring Half-lives of excited nuclear states
i.e. determining electromagnetic transition rates,

Outline

- Electromagnetic transition rates.
- Isomers and metastable / long-lived excited states.
- Weisskopf Single-Particle Estimates
- Shell Structure in near spherical nuclei.
 - Odd-A singly magic nuclei (e.g., $^{205}\text{Au}_{126}$; $^{131}\text{In}_{82}$)
 - Why are E1s 'naturally' hindered ?
- Seniority isomers, j^2 & j^n configurations ?
- Near Magic nuclei.
 - Limited valence space and core breaking.
- Deformed Nuclei.
 - the Nilsson Model, K-isomers.
- Measurements of excited state nuclear lifetimes
 - Electronic coincidences (Fast-timing with $\text{LaBr}_3(\text{Ce})$)
 - Doppler Shift methods (RDM, DSAM)
 - Transition quadrupole moments (Q_0)

EM Transition Rates

Classically, the average power radiated by an EM multipole field is given by

$$P(\sigma L) = \frac{2(L+1)c}{\epsilon_0 L [(2L+1)!!]^2} \left(\frac{\omega}{c} \right)^{2L+2} [m(\sigma L)]^2$$

$m(\sigma L)$ is the time-varying electric or magnetic multipole moment.

ω is the (circular) frequency of the EM field

For a quantized (nuclear) system, the decay probability is determined by the **MATRIX ELEMENT** of the **EM MULTIPOLE OPERATOR**, where

$$m_{fi}(\sigma L) = \int \psi_f^* m(\sigma L) \psi_i dV \quad \text{i.e., integrated over the nuclear volume.}$$

We can then get the general expression for the probability per unit time for gamma-ray emission, $\lambda(\sigma L)$, from:

$$\lambda(\sigma L) = \frac{1}{\tau} = \frac{P(\sigma L)}{\hbar \omega} = \frac{2(L+1)}{\epsilon_0 \hbar L [(2L+1)!!]^2} \left(\frac{\omega}{c} \right)^{2L+1} [m_{fi}(\sigma L)]^2$$

(see Introductory Nuclear Physics, K.S. Krane (1988) p330).

How is measuring the lifetime useful?

Nuclear structure information.
The 'reduced matrix element', $B(\lambda L)$ tells us the overlap between the initial and final nuclear single-particle wavefunctions.

$$T_{fi}(\lambda L) = \frac{8\pi(L+1)}{\hbar L((2L+1)!!)^2} \left(\frac{E_\gamma}{\hbar c}\right)^{2L+1} B(\lambda L : J_i \rightarrow J_f)$$

Transition probability (i.e., 1/mean lifetime as measured for state which decays by EM radiation)

(trivial) gamma-ray energy dependence of transition rate, goes as. E_γ^{2L+1} e.g., E_γ^5 for $E2s$ for example.

Measurements of EM Transition Rates

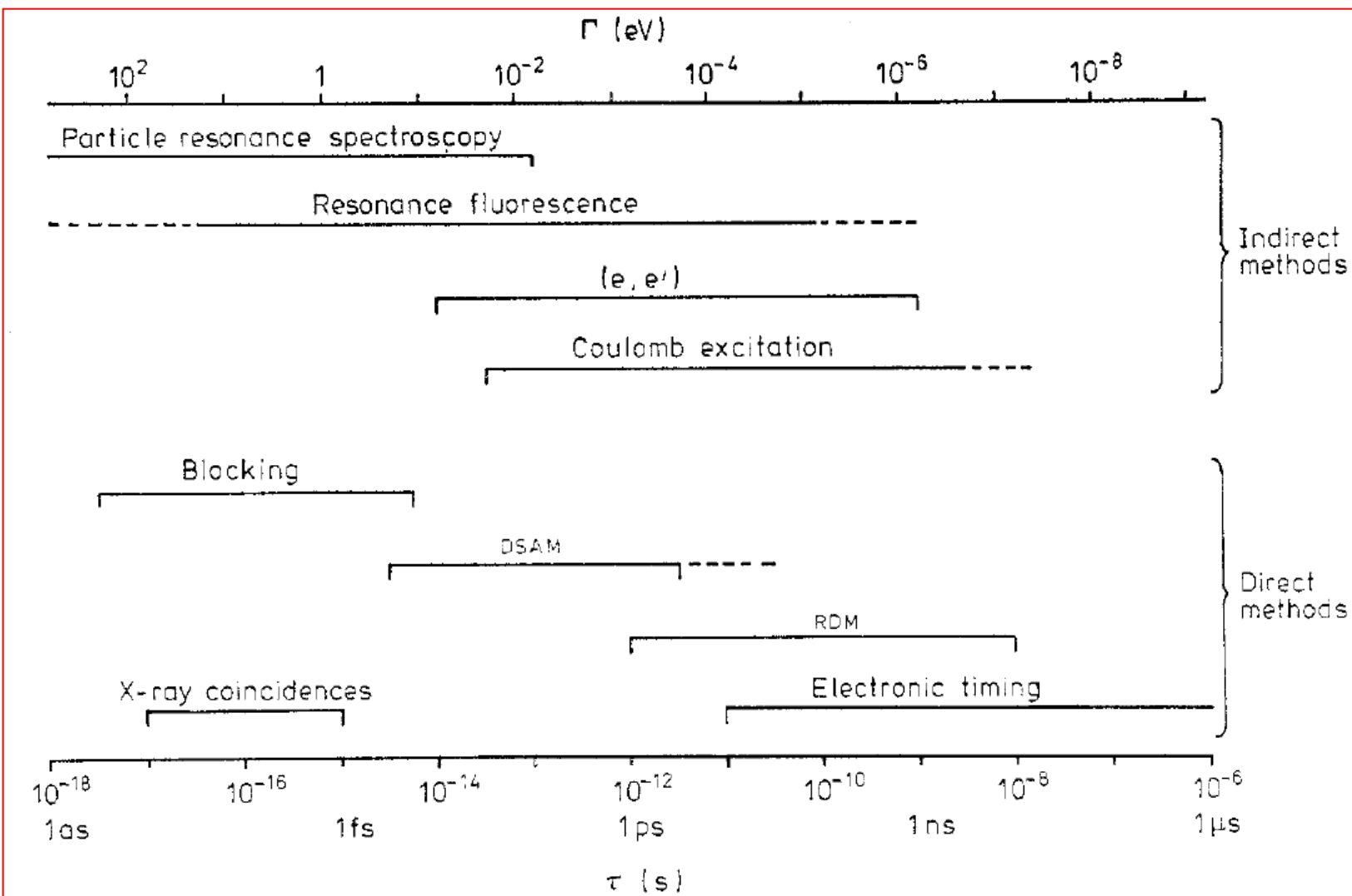
$$\Gamma\tau = \hbar.$$

The measurement of the lifetimes of excited nuclear states

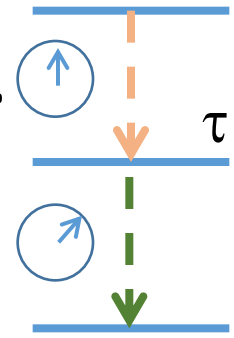
$$\Gamma \propto |\langle \psi_f | \hat{O}_{\text{decay}} | \psi_i \rangle|^2$$

PJ NOLAN† and JF SHARPEY-SCHAFFER‡

$$\Gamma_{\text{total}} = \sum_j \Gamma_j.$$



Extracting (nuclear excited state) lifetimes.



- Assuming no background contribution, the experimentally measured, 'delayed' time distribution for a $\gamma\text{--}\gamma\text{--}\Delta t$ measurement is given by:

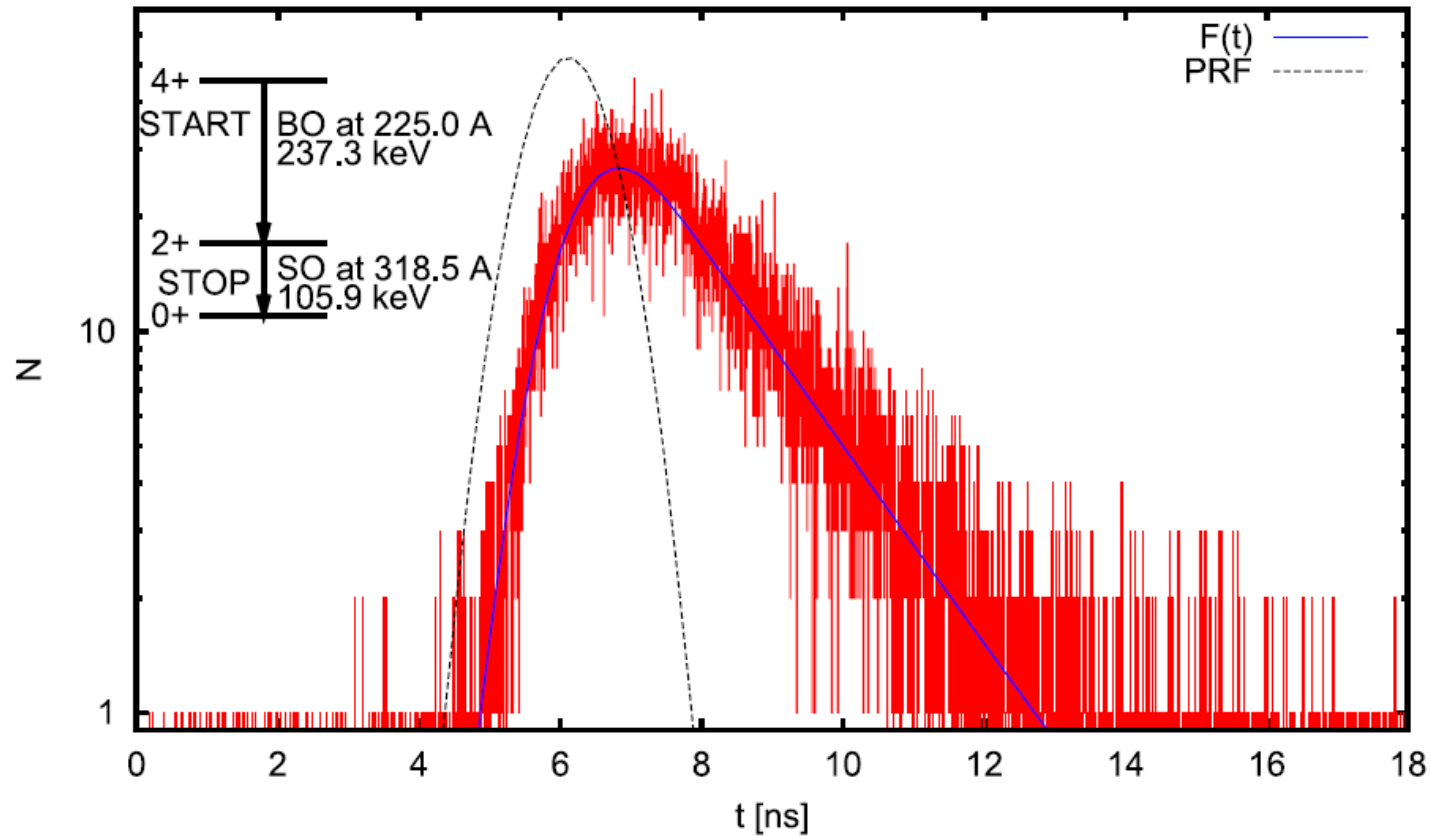
$$D(t) = n\lambda \int_{-\infty}^t P(t' - t_0) e^{-\lambda(t - t')} dt' \quad \text{with} \quad \lambda = 1/\tau,$$

- $P(t' - t_0)$ is the (Gaussian) prompt response function and $\lambda = 1/\tau$, where τ is the mean lifetime of the intermediate state.

See e.g., Z. Bay, Phys. Rev. **77** (1950) p419;
T.D. Newton, Phys. Rev. **78** (1950) p490;
J.M.Regis et al., EPJ Web of Conf. **93** (2015) 01014

Fast-timing Techniques

M. Rudigier et al. / Nuclear Physics A 847 (2010) 89–100



Gaussian-exponential convolution to account for timing resolution

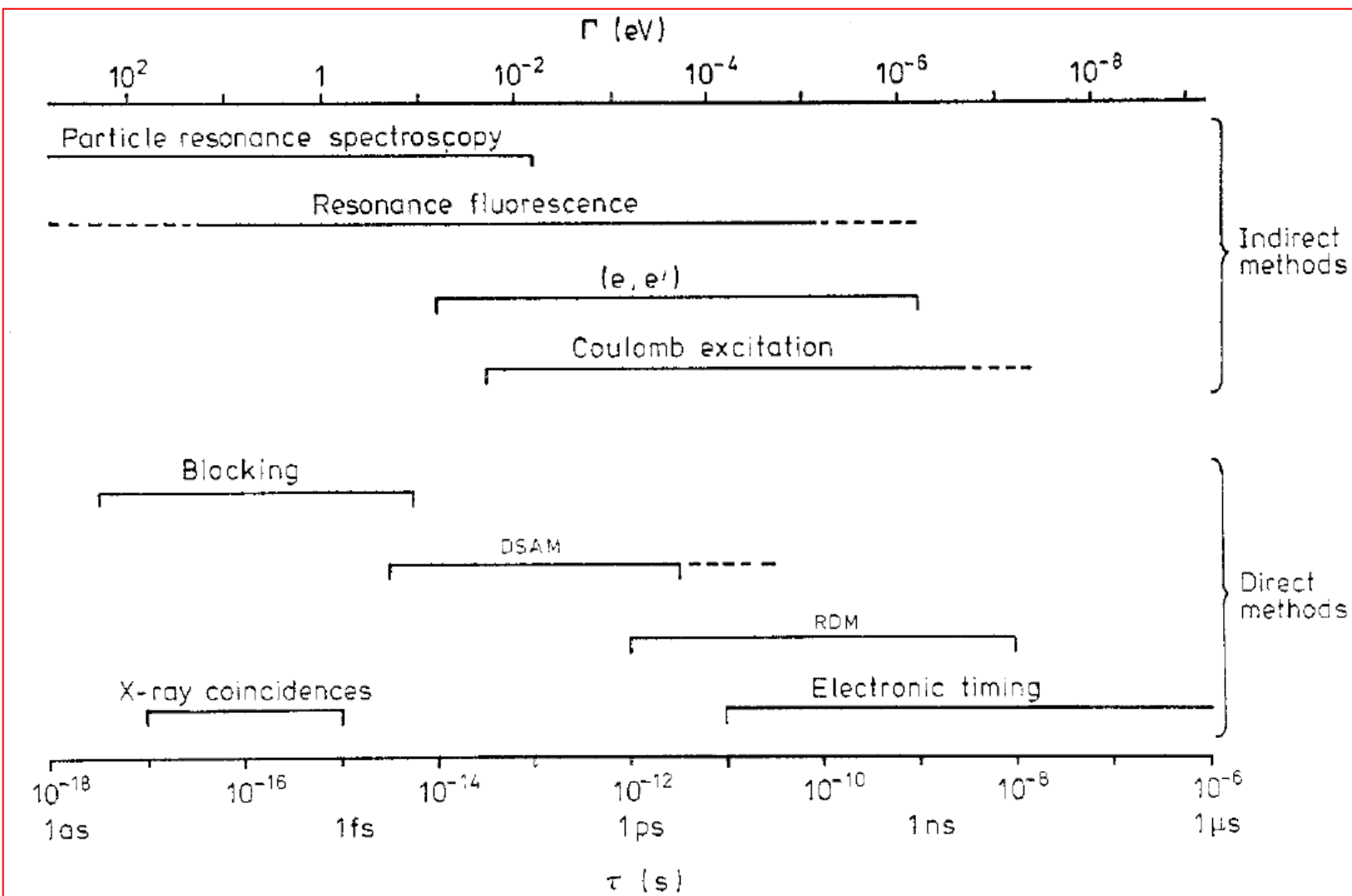
$$\Gamma\tau = \hbar.$$

The measurement of the lifetimes of excited nuclear states

PJ NOLAN† and JF SHARPEY-SCHAFFER‡

$$\Gamma \propto |\langle \psi_f | \hat{O}_{\text{decay}} | \psi_i \rangle|^2$$

$$\Gamma_{\text{total}} = \sum_j \Gamma_j.$$



**TRANSITION PROBABILITY FROM THE GROUND TO THE FIRST-EXCITED
2⁺ STATE OF EVEN–EVEN NUCLIDES***

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Adopted values for the reduced electric quadrupole transition probability, $B(E2)\uparrow$, from the ground state to the first-excited 2⁺ state of even–even nuclides are given in Table I. Values of τ , the mean life of the 2⁺ state; E , the energy; and β , the quadrupole deformation parameter, are also listed there. The ratio of β to the value expected from the single-particle model is presented. The intrinsic quadrupole moment, Q_0 , is deduced from the $B(E2)\uparrow$ value. The product $E \times B(E2)\uparrow$ is expressed as a percentage of the energy-weighted total and isoscalar $E2$ sum-rule strengths.

Table II presents the data on which Table I is based, namely the experimental results for $B(E2)\uparrow$ values with quoted uncertainties. Information is also given on the quantity measured and the method used. The literature has been covered to November 2000.

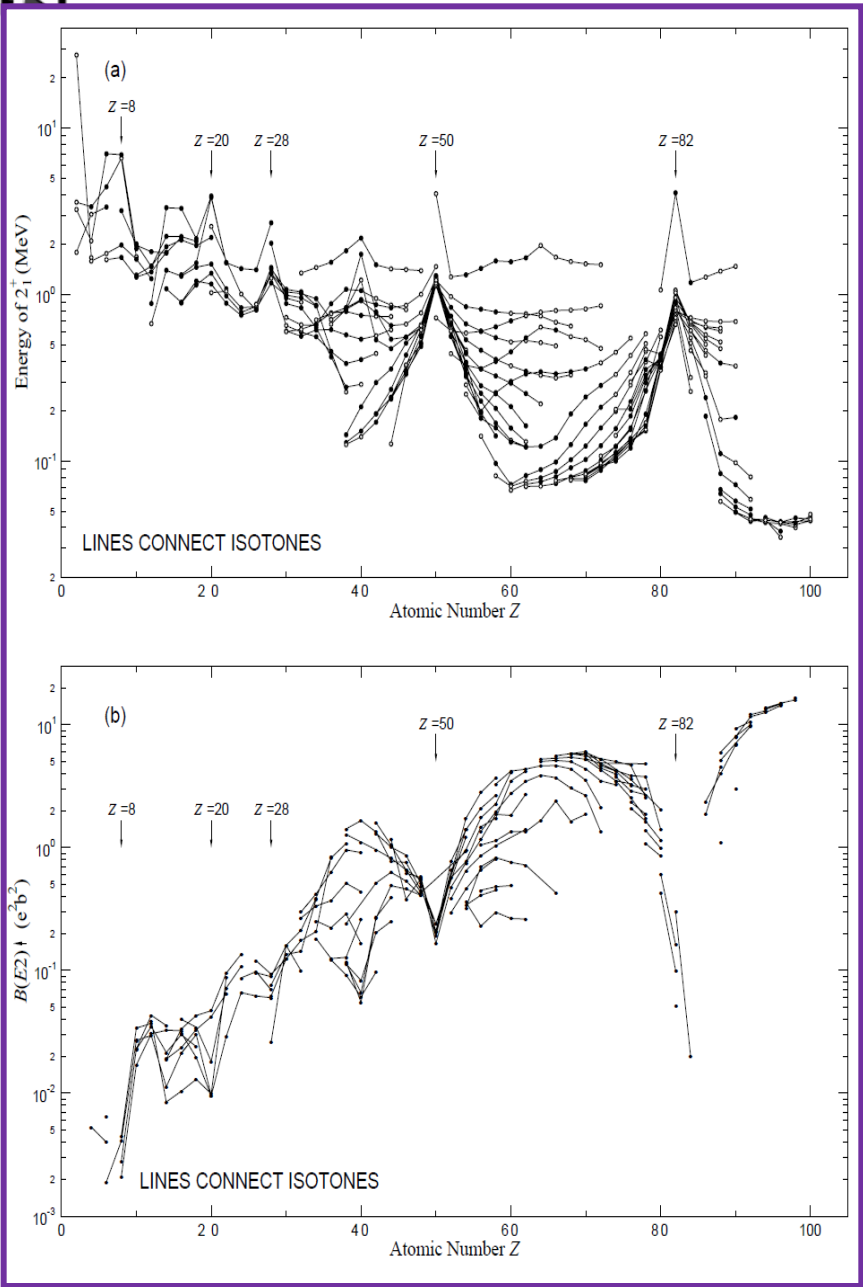
The adopted $B(E2)\uparrow$ values are compared in Table III with the values given by systematics and by various theoretical models. Predictions of unmeasured $B(E2)\uparrow$ values are also given in Table III. © 2001 Academic Press

EXPLANATION OF TABLES

TABLE I. Adopted Values of $B(E2)\uparrow$ and Related Quantities

Throughout this table, italicized numbers refer to the uncertainties in the last digits of the quoted values.

Nuclide	The even Z , even N nuclide studied
$E(\text{level})$	Energy of the first excited 2 ⁺ state in keV either from a compilation or from current literature
$B(E2)\uparrow$	Reduced electric quadrupole transition rate for the ground state to 2 ⁺ state transition in units of e ² b ²
τ	Mean lifetime of the state in ps $\tau = 40.81 \times 10^{13} E^{-5} [B(E2)\uparrow / \text{e}^2 \text{b}^2]^{-1} (1 + \alpha)^{-1}$ (see Table II for the α values when $\alpha > 0.001$)
β	Deformation parameter $\beta = (4\pi/3ZR_0^2)[B(E2)\uparrow / \text{e}^2]^{1/2}$, where $R_0^2 = (1.2 \times 10^{-13} A^{1/3} \text{ cm})^2$ $= 0.0144 A^{2/3} \text{ b}$
$\beta_{(\text{sp})}$	β from the single-particle model $\beta_{(\text{sp})} = 1.59/Z$
Q_0	Intrinsic quadrupole moment in b $Q_0 = \left[\frac{16\pi}{5} \frac{B(E2)\uparrow}{\text{e}^2} \right]^{1/2}$



EM decay selection rules reminder.

Suppose we are concerned with a transition between the states i and f of characters (spin, parity) (J_i, π_i) and (J_f, π_f) respectively; defining a quantity p , which is 0 for even parity and $+1$ for odd parity, we see that the multipoles that can contribute are delimited by

$$J_i + J_f \geq L \geq |J_i - J_f|,$$

and by the further conditions:

$$p_i + p_f + L = \text{odd for magnetic multipoles}$$

$$p_i + p_f + L = \text{even for electric multipoles.}$$

TABLE I

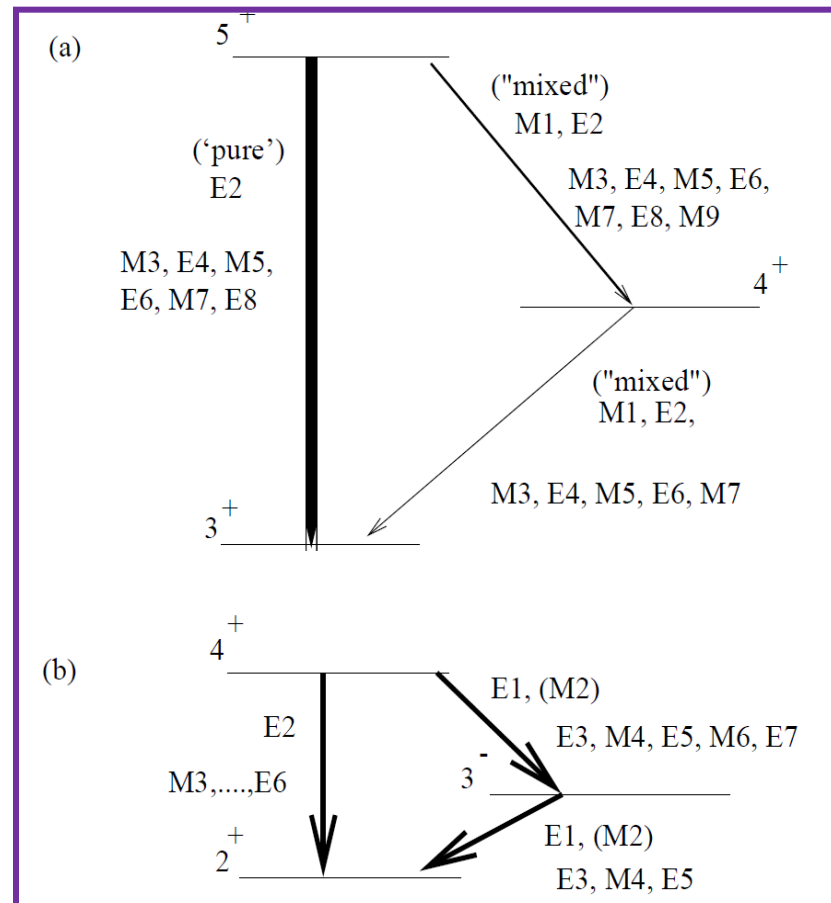
OBSERVED MULTIPOLE TRANSITIONS

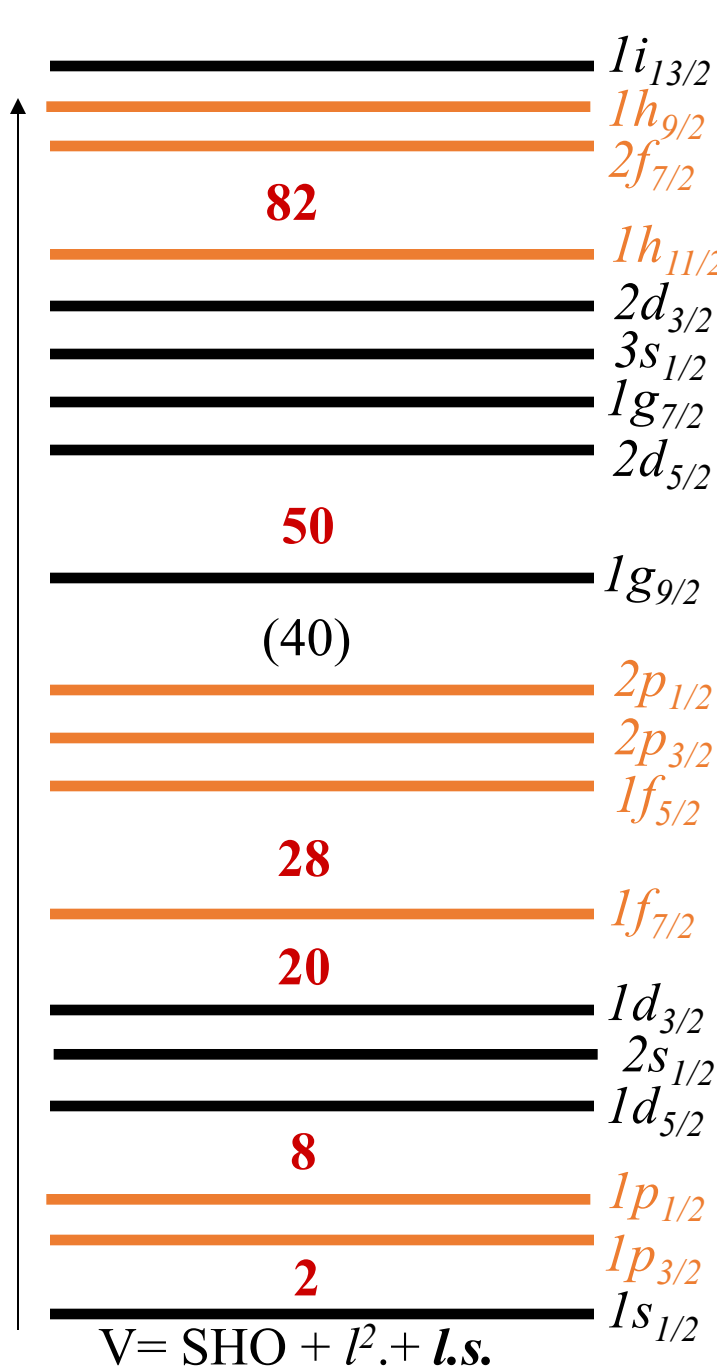
Multipole L	1	2	3	4	5
Parity change $\left\{ \begin{array}{l} \text{Yes} \\ \text{No} \end{array} \right.$	$E1 \longleftrightarrow M2$	$E3$	$M4$	$E5$	
	$M1 \longleftrightarrow E2$	$M3$	$E4$		

Since the quantity that enters in the vector potential of the L -multipole is:

$$j_L(kr) \cong \frac{(kr)^L}{(2L+1)!}, \quad 9.$$

we see that the lowest possible multipole transition is greatly favored for $kr \ll 1$. The range of energies for which $(kr) \ll 1$ is frequently called the "long wave-length" region. In fact, usually only the lowest possible multipole contributes, but sometimes also the next order will appear. It is this fact that makes the measurement of multipole order so useful a tool in the assignment of characters to levels. The most important examples of mixed multipoles are found for $M1+E2$ and $E1+M2$ transitions; these are indicated in the above table by connecting lines.





Independent particle model (from 1950s)

Protons & neutron (fermions) fill orbits by PEP.

Each $j = l \pm s$ level has $2j+1$ projections of m_j

e.g., $g_{9/2}$ orbit can have

$[(2 \times 9/2) + 1] = 10$ protons
with m_j from $-9/2, -7/2, \dots, +7/2, +9/2$.

Clustering of levels causes energy 'gaps'
leading to **MAGIC NUMBERS**.

Can 'approximate' the average / mean field
experienced by each nucleon by e.g.,
as:

$$H = H_0 + a \underline{l} \cdot \underline{l} + b \underline{l} \cdot \underline{s}$$

Changes in the Hamiltonian alters the level ordering.

Nuclear EM transition rates between excited states are fundamental in nuclear structure research.

$$T_{fi} = \frac{1}{\tau} = \frac{8\pi(L+1)}{\hbar((2L+1)!!)^2} \left(\frac{E_\gamma}{\hbar c}\right)^{2L+1} B(\lambda L: I_i \rightarrow I_f)$$

The extracted reduced matrix elements, $B(\lambda L)$ give insights e.g.,

- Single particle / shell model-like: ~ 1 Wu (NOT for E1s)
- Deformed / collective: faster lifetimes, ~ 10 s to 1000 s of Wu (in e.g., superdeformed bands)
- Show underlying symmetries and related selection rules such as K-isomerism: MUCH slower decay rates $\sim 10^{-3 \rightarrow 9}$ Wu and slower).

Multipolarity	Electric Transition Rate (s^{-1})	Magnetic Transition Rate (s^{-1})
1	$1.587 \times 10^{15} E_\gamma^3 B(E1)$	$1.779 \times 10^{13} E_\gamma^3 B(M1)$
2	$1.223 \times 10^9 E_\gamma^5 B(E2)$	$1.371 \times 10^7 E_\gamma^5 B(M2)$
3	$5.689 \times 10^2 E_\gamma^7 B(E3)$	$6.387 \times 10^0 E_\gamma^7 B(M3)$
4	$1.649 \times 10^{-4} E_\gamma^9 B(E4)$	$1.889 \times 10^{-6} E_\gamma^9 B(M4)$
5	$3.451 \times 10^{-11} E_\gamma^{11} B(E5)$	$3.868 \times 10^{-13} E_\gamma^{11} B(M5)$

Table 2.2: Transition probabilities $T(s^{-1})$ expressed by $B(EL)$ in $(e^2(fm)^{2L})$ and $B(ML)$ in $(\frac{e\hbar}{2mc}(fm)^{2L-2})$. E_γ is the γ -ray energy, in MeV. (Taken from ref [69]).

Transition rates get slower (i.e., longer lifetimes associated with) higher order multipole decays

Weisskopf Single Particle Estimates:

- These are 'yardstick' estimates for the speed of EM transitions for a given electromagnetic multipole order.
- They depend on the size of the nucleus (i.e., A) and the energy of the transition / gamma-ray energy (E_γ^{2L+1})
- They estimate the transition rate for spherically symmetric proton orbitals for nuclei of radius $r=r_0A^{1/3}$.

The **half-life** (in $10^{-9}s$), equivalent to 1 Wu is given by (DWK):

$$T_{1/2}(E1) = 6.76 \times A^{-2/3} E^{-3} \times 10^{-6}$$

$$T_{1/2}(M1) = 2.20 \times E^{-3} \times 10^{-5}$$

$$T_{1/2}(E2) = 9.52 \times A^{-4/3} E^{-5}$$

$$T_{1/2}(M2) = 3.10 \times A^{-2/3} E^{-5} \times 10^1$$

$$T_{1/2}(E3) = 2.04 \times A^{-2} E^{-7} \times 10^7$$

where the transition energy E is in MeV and A is the atomic mass number

Weisskopf, V.F., 1951.

Radiative transition probabilities in nuclei.

Physical Review, 83(5), p.1073.

where K is the low frequency dielectric constant, K_0 is the optical constant, ρ the density, and χ the compressibility. In Table I are listed the values of $\partial \ln K / \partial \rho$ calculated from (4) and (1) next to the experimental values of $\partial \ln K / \partial \rho$. The calculated values of $\partial \ln K / \partial \rho$ differ from those of Rao by the term $a(K - K_0)/K$, which arises from the difference between (1a) and (2a).

Equation (4) is derived assuming that the inner field polarizing the dielectric is independent of pressure. Since the values of $-\partial \ln K / \partial \rho$ obtained from (4) do not account for all the change in the dielectric constant, it seems consistent to expect that the inner field is not constant but does decrease with increasing pressure. This conclusion agrees with the one reached in my original paper using the theories of Hojendahl and Mott and Littleton.

¹D. A. A. S. Narayana Rao, *Phys. Rev.* **82**, 118 (1951).
²S. Mayburg, *Phys. Rev.* **79**, 375 (1950).

Radiative Transition Probabilities in Nuclei

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(Received July 20, 1951)

CONSIDER a transition from nuclear state a to nuclear state b with emission of a quantum of multipole radiation of angular momentum l (2^l-pole) and s component m . The transition probability per unit time is given by¹

$$T(l, m) = \frac{8\pi(l+1)}{l[(2l+1)!!]^2} \frac{\kappa^{2l+1}}{\hbar} |A(l, m) + A'(l, m)|^2, \quad (1)$$

where $\kappa = 2\pi\nu/c$ is the wave number of the emitted radiation, and the quantities A , A' are the multipole matrix elements caused by the electric currents and by the magnetization (spins), respectively. We find for electric radiation

$$A(l, m) = Q(l, m) = e \sum_{k=1}^Z \int r_k^l Y_{lm}^*(\theta_k, \phi_k) \varphi_b^* \varphi_a d\tau, \quad (2)$$

$$A'(l, m) = Q'(l, m) = -\frac{ie\hbar}{l+1} \frac{e\hbar}{2Mc} \sum_{k=1}^A \mu_k \times \int r_k^l Y_{lm}^*(\theta_k, \phi_k) \operatorname{div}(\varphi_b^* \mathbf{r}_k \times \boldsymbol{\sigma}_k \varphi_a) d\tau, \quad (3)$$

where φ_a and φ_b are the wave functions of the nuclear states, M is the mass of each nucleon, $\mathbf{r}_k = (r_k, \theta_k, \phi_k)$ is the position vector of the k th nucleon, $\boldsymbol{\sigma}_k$ is its Pauli spin vector, and μ_k is its magnetic moment in nuclear magnetons. The sum in (2) extends over the protons, the sum in (3) over both protons and neutrons. These expressions are approximations valid for $\kappa R \ll 1$, where R is the nuclear radius.

The corresponding expressions for magnetic multipole radiation are

$$A(l, m) = M(l, m) = -\frac{1}{l+1} \frac{e\hbar}{Mc} \sum_{k=1}^Z \times \int r_k^l Y_{lm}^*(\theta_k, \phi_k) \operatorname{div}(\varphi_b^* \mathbf{L}_k \varphi_a) d\tau, \quad (4)$$

$$A'(l, m) = M'(l, m) = -\frac{e\hbar}{2Mc} \sum_{k=1}^A \mu_k \times \int r_k^l Y_{lm}^*(\theta_k, \phi_k) \operatorname{div}(\varphi_b^* \boldsymbol{\sigma}_k \varphi_a) d\tau, \quad (5)$$

where $\mathbf{L}_k = -i\mathbf{r}_k \times \nabla_k$ is the orbital angular momentum operator (in units of $\hbar$) for the k th nucleon.

We can estimate these matrix elements by the following exceedingly crude method. We assume that the radiation is caused by a transition of one single proton which moves independently within the nucleus, its wave function being given by $u(r)Y_{lm}(\theta, \phi)$. In addition we also assume that the final state of the proton is an S state.² We then obtain

$$Q(l, m) \sim [e/(4\pi)^{1/2}] [3/(l+3)] R^l \quad (6)$$

where the integral $\int r^l u_b(r) u_a(r) r^2 dr$ over the radial parts of the proton wave functions was set approximately equal to $3R^l/(l+3)$. The other matrix elements are estimated by replacing div by R^{-1} . We get the rough order-of-magnitude guess

$$M(l, m) \sim [e/(4\pi)^{1/2}] [3/(l+3)] [\hbar/Mc] R^{l-1}, \quad (7)$$

$$M'(l, m) \sim [e/(4\pi)^{1/2}] [3/(l+3)] \mu_p [\hbar/Mc] R^{l-1}, \quad (8)$$

where μ_p is the magnetic moment of the proton ($=2.78$). $Q'(l, m)$ can be neglected compared to $Q(l, m)$. We therefore get a ratio of roughly

$$(1 + \mu_p^2)(\hbar/McR)^2 \sim 10(\hbar/McR)^2$$

between the transition probability of a magnetic multipole and an electric one of the same order. This ratio is energy-independent in contrast to widespread belief.

Inserting these estimates into (1) we get for the transition probability of an electric 2^l-pole

$$T_E(l) \cong \frac{4.4(l+1)}{l[(2l+1)!!]^2} \left(\frac{3}{l+3}\right)^2 \left(\frac{\hbar\omega}{197 \text{ Mev}}\right)^{2l+1} \times (R \text{ in } 10^{-13} \text{ cm})^{2l} 10^{21} \text{ sec}^{-1} \quad (9)$$

and for a magnetic 2^l-pole

$$T_M(l) \cong \frac{1.9(l+1)}{l[(2l+1)!!]^2} \left(\frac{3}{l+3}\right)^2 \left(\frac{\hbar\omega}{197 \text{ Mev}}\right)^{2l+1} \times (R \text{ in } 10^{-13} \text{ cm})^{2l-2} 10^{21} \text{ sec}^{-1}. \quad (10)$$

The assumptions made in deriving these estimates are extremely crude and they should be applied to actual transitions with the greatest reservations. They are based upon an extreme application of the independent-particle model of the nucleus and it was assumed that a proton is responsible for the transition. On the basis of our assumptions the electric multipole radiation with $l > 1$ should be much weaker for transitions in which a single neutron changes its quantum state. No such differentiation is apparent in the data.

In spite of these difficulties it may be possible that the order of magnitude of the actual transition probabilities is correctly described by these formulas. We have published these exceedingly crude estimates only because of the rather unexpected agreement with the experimental material which was pointed out to us by many workers in this field.

The author wishes to express his appreciation especially to Dr. M. Goldhaber and Dr. J. M. Blatt for their great help in discussing the experimental material and in improving the theoretical reasoning.

¹ We use the notation $(2l+1)!! = 1 \cdot 3 \cdot 5 \cdots (2l+1)$.

² This latter assumption can be removed; the corrections consist in unimportant numerical factors.

Nuclear Magnetic Resonance in Metals: Temperature Effects for Na²³

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(Received July 2, 1951)

K NIGHT reported¹ that nuclear magnetic resonance frequencies are higher in metals than in chemical compounds. It has been proposed² that such frequency shifts are primarily the result of the contribution of conduction electrons to the magnetic field at the nuclei in the metal. This note gives an account of some related preliminary results including temperature and chemical effects, and also detailed line shape studies. Our experiments have been at fixed frequency using equipment and procedures outlined previously.^{3,4}

The effect of temperature on the Na²³ magnetic resonance shift in the metal, relative to a sodium chloride solution, is given in

What are isomers ?

Metastable (long-lived) nuclear excited state.

'Long-lived' could mean:

$\sim 10^{-19}$ seconds, shape isomers in α -cluster resonances or

$\sim 10^{15}$ years $^{180}\text{Ta } 9^- \rightarrow 1^+$ decay.

Why/when do nuclear isomers occur ?

(i) large change in spin (spin-trap)

(ii) small transition energy between states (seniority isomers)

(iii) dramatic change in structure/shape (fission isomers)

and/or underlying symmetry (K-isomers)

What information do isomers gives you ?

Isomers occur due to differences in single-particle structure.

EM transitions are hindered between states with very different underlying structures.

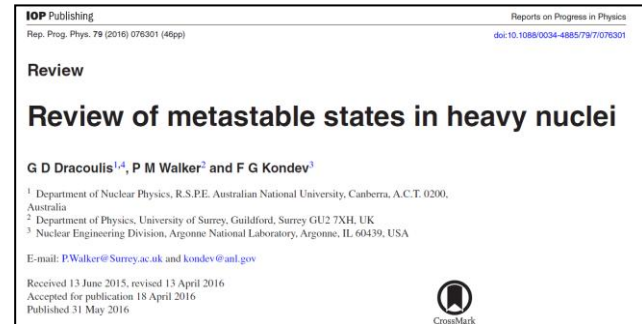
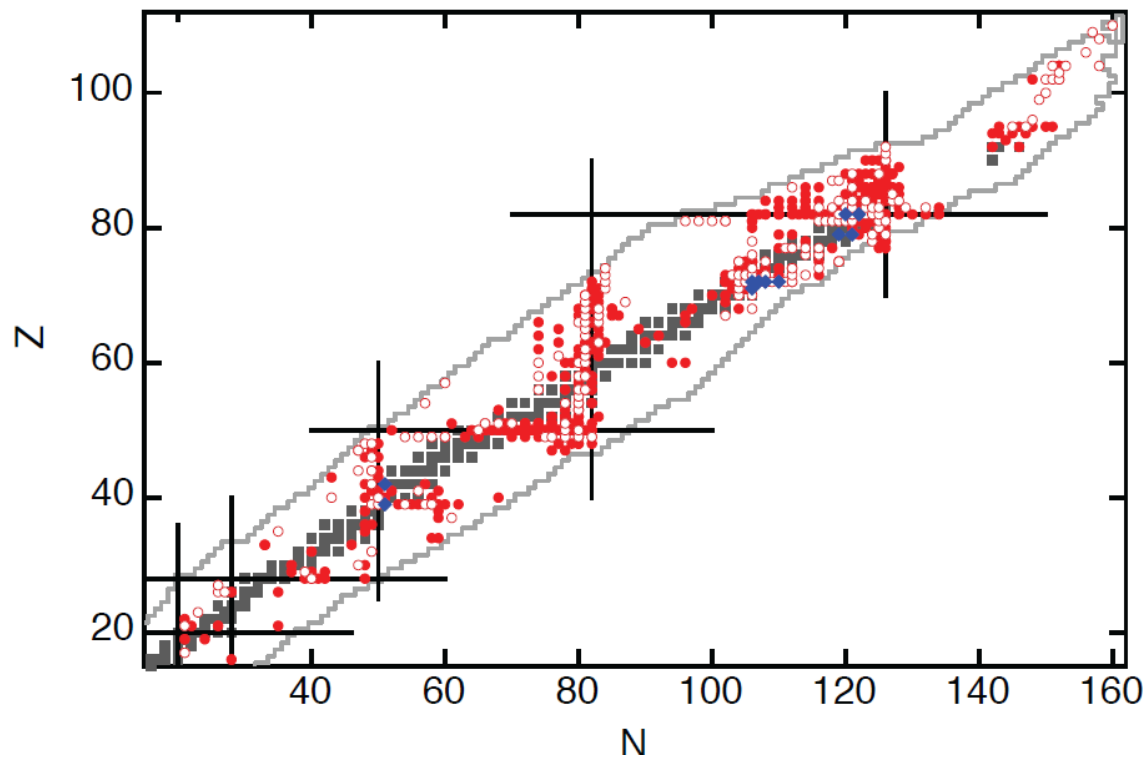


Figure 1. Nuclear chart illustrating the distribution of isomers with excitation energies greater than 600 keV, with data from Audi *et al.* [44]. The filled red circles correspond to $200 \text{ ns} < T_{1/2} < 100 \mu\text{s}$, the open red circles correspond to $100 \mu\text{s} < T_{1/2} < 1 \text{ hr}$, and the filled blue diamonds are for $T_{1/2} > 1 \text{ hr}$.

P.M.Walker and G.D.Dracoulis. *Nature*, **399** (1999) p35

EM Selection Rules and their Effects on Decays

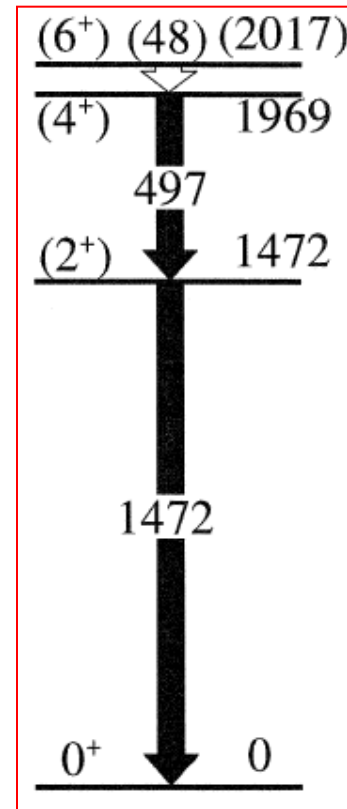
- Allowed decays have:

$$|I_i - I_f| \leq \lambda \leq |I_i + I_f|$$

e.g., decays from $I^\pi = 6^+$ to $I^\pi = 4^+$ are allowed to proceed with photons carrying angular momentum of $\lambda = 2, 3, 4, 5, 6, 7, 8, 9$ and $10 \hbar$.

Need also to conserve parity between initial and final states, thus, here the transition can not change the parity.

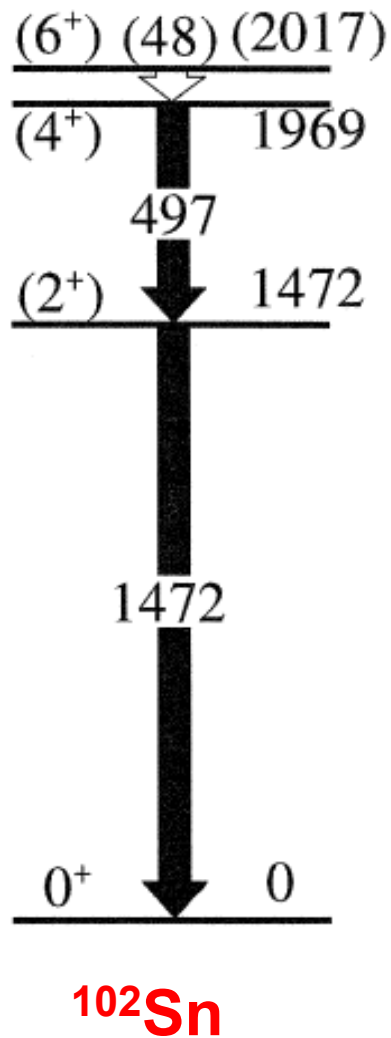
This adds a further restriction : Allowed decays now restricted to E2, E4, E6, E8 and E10 ; and M3, M5, M7, M9



e.g., $^{102}\text{Sn}_{52}$

Why do we only observe the E2 decays ?

Are the other multipolarity decays allowed / present ?



E_γ	E2 (1Wu)	M3 (1Wu)	E4 (1Wu)
48 ($6^+ \rightarrow 4^+$)	112 μs	782,822 s	2.5E+14s
555 ($6^+ \rightarrow 2^+$)			66,912s

497 ($4^+ \rightarrow 2^+$)	0.9ns	61ms	180,692s
1969 ($4^+ \rightarrow 0^+$)			751ms

Conclusion, in general see a cascade of (stretched) E2 decays in near-magic even-even nuclei.

Weisskopf single-particle estimates

τ_{sp} for 1 Wu at $A \sim 100$ and $E_\gamma = 200$ keV

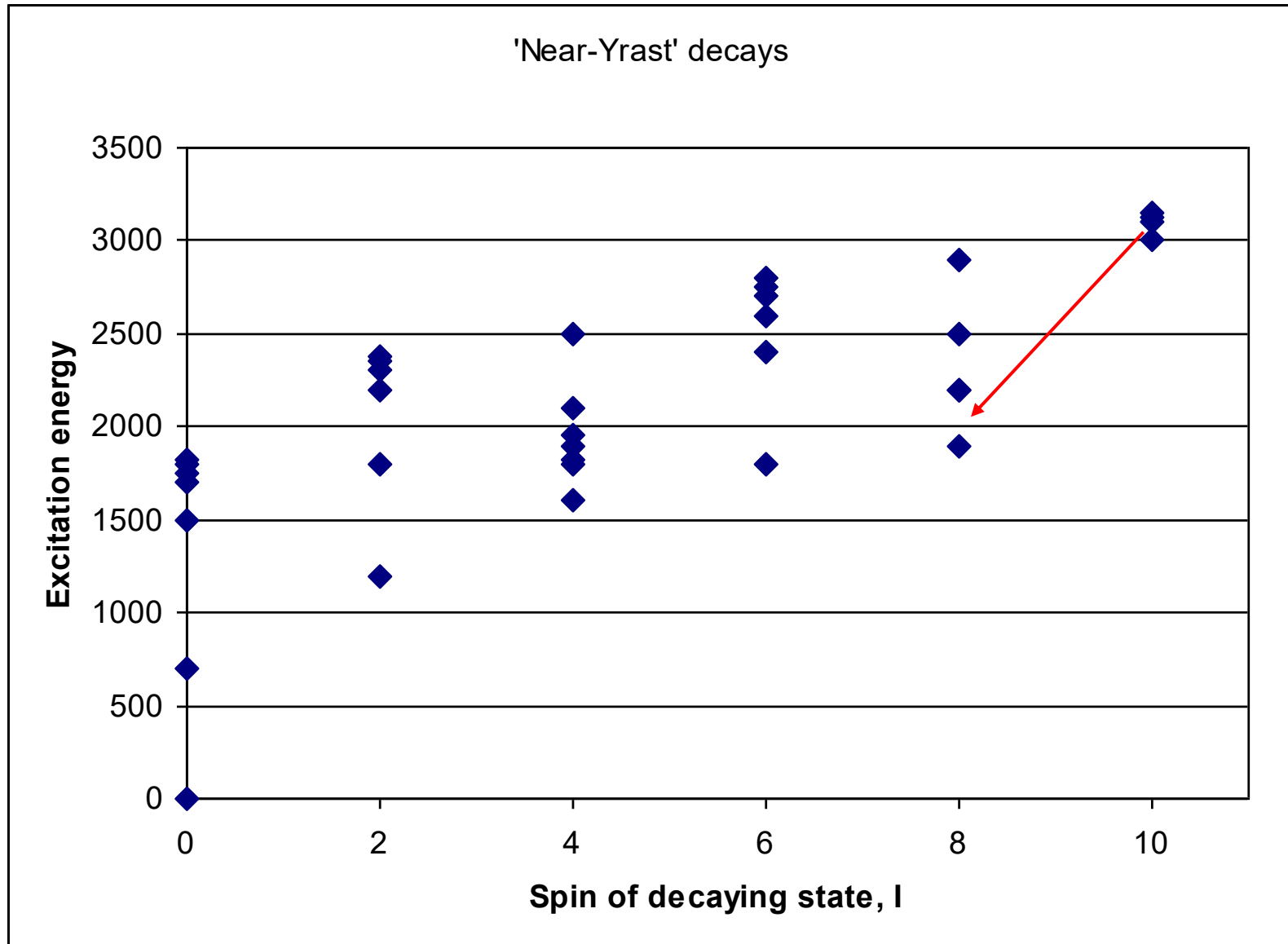
M1 2.2 ps	M2 4.1 ms	M3 36 s
E1 5.8 fs	E2 92 ns	E3 0.2 s

The lowest order multipole decays are highly favoured.

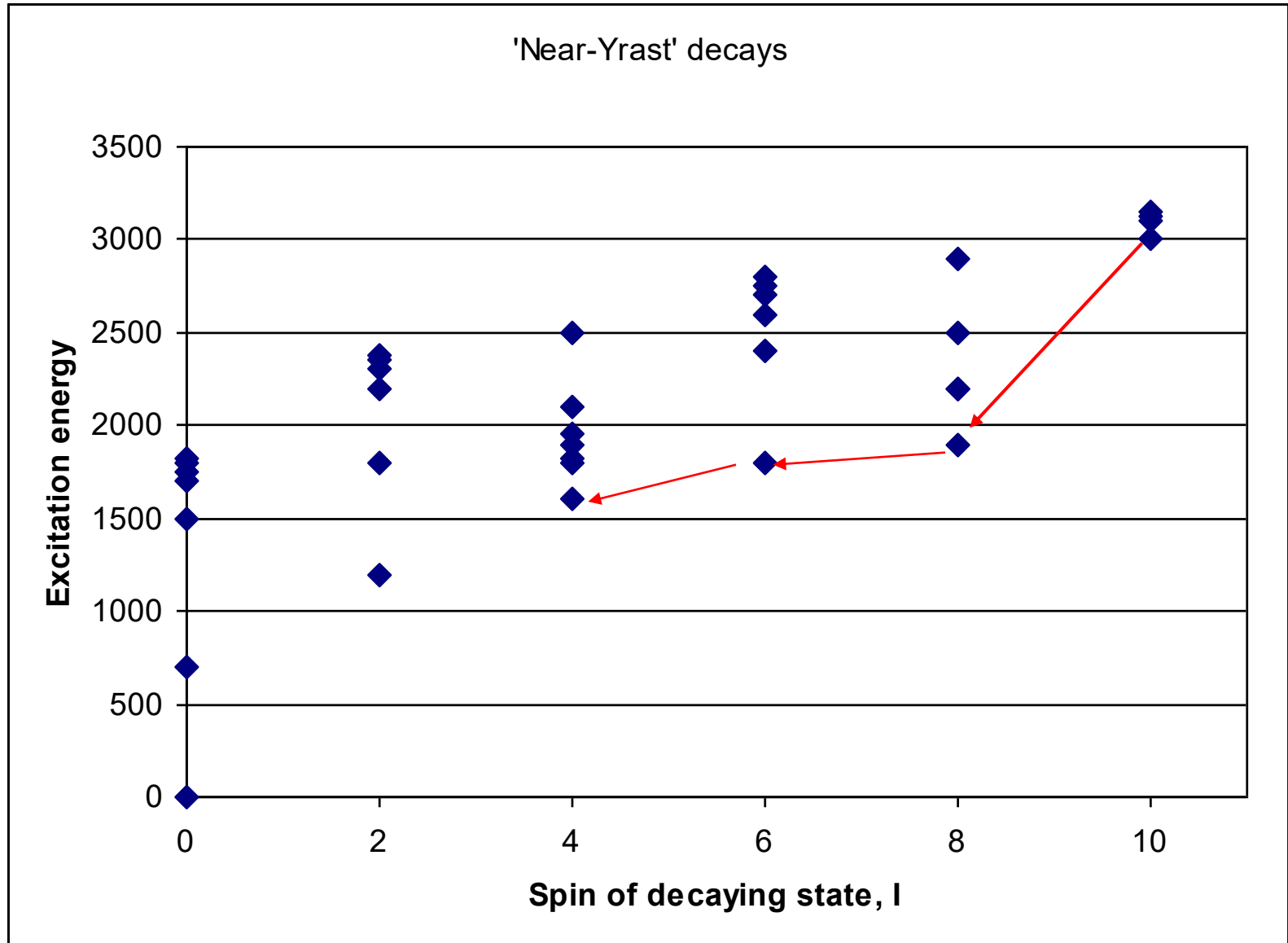
BUT need to conserve angular momentum so need at minimum $\lambda = |I_i - I_f|$ is needed for the transition to take place.

Note, for low E_γ and high - λ , internal conversion also competes/dominates.

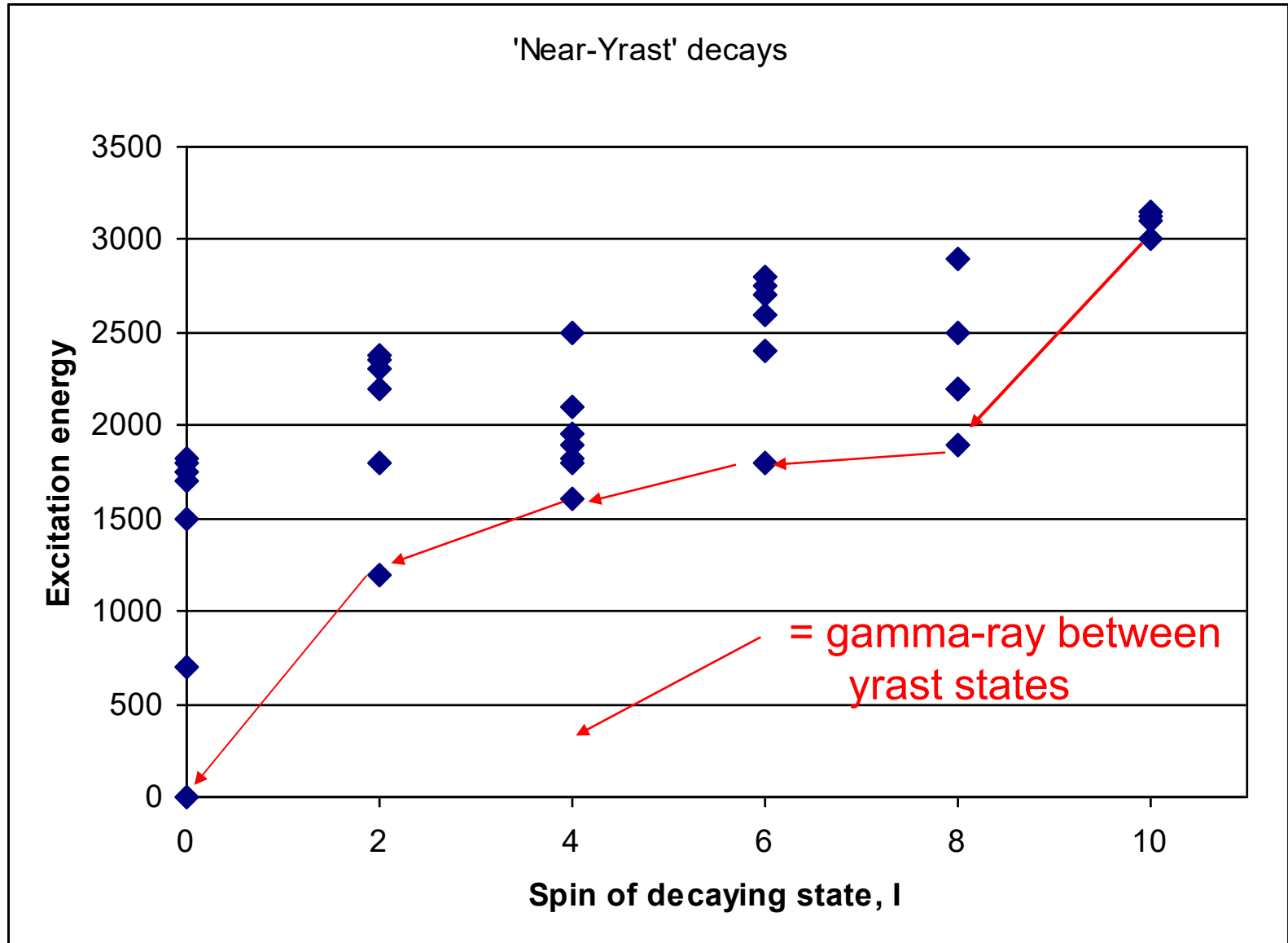
The EM transition rate depends on $E_\gamma^{2\lambda+1}$; the highest energy transitions for the lowest λ are (usually) favoured.
This results in the preferential population of yrast and near-yrast states.



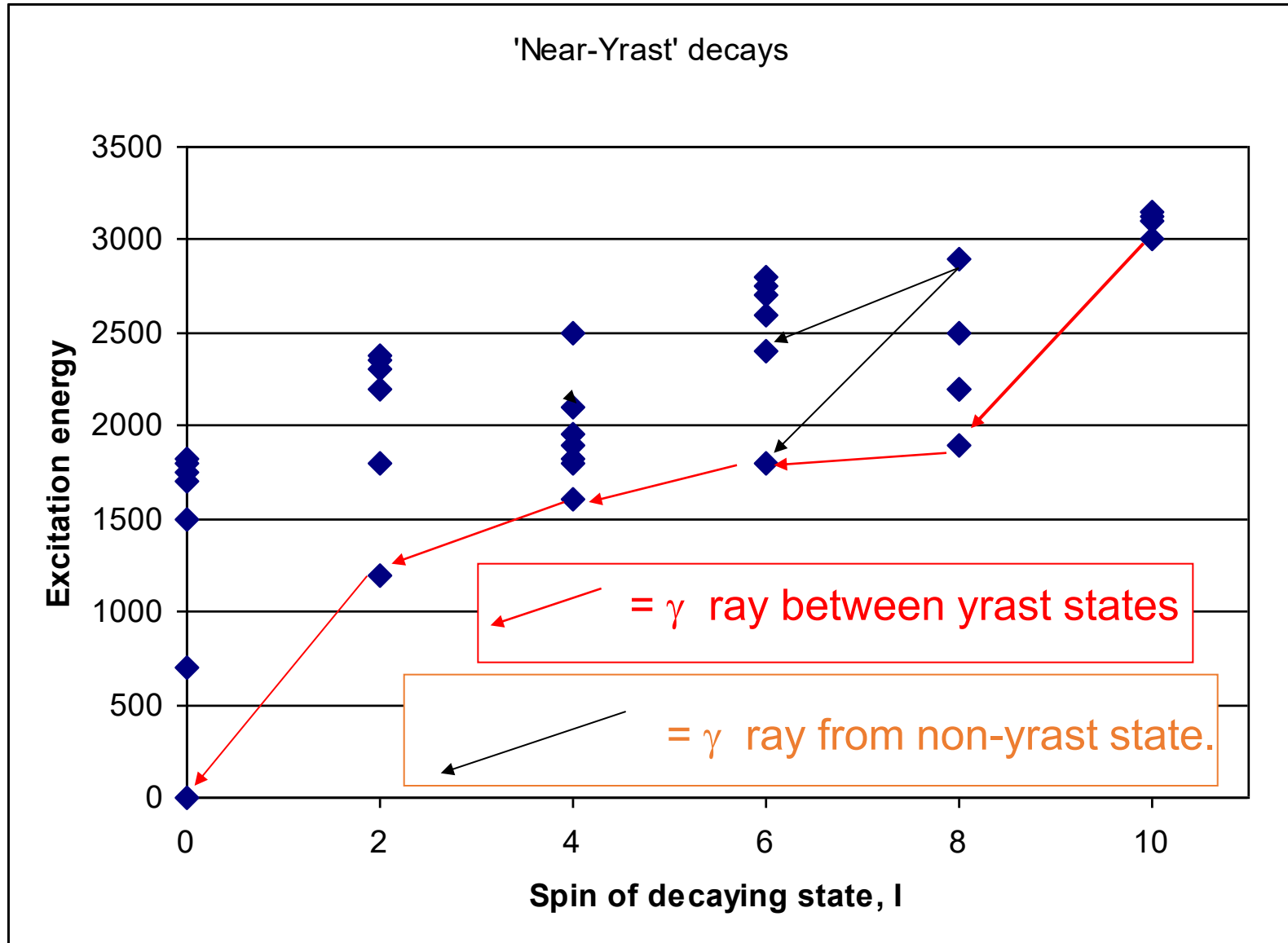
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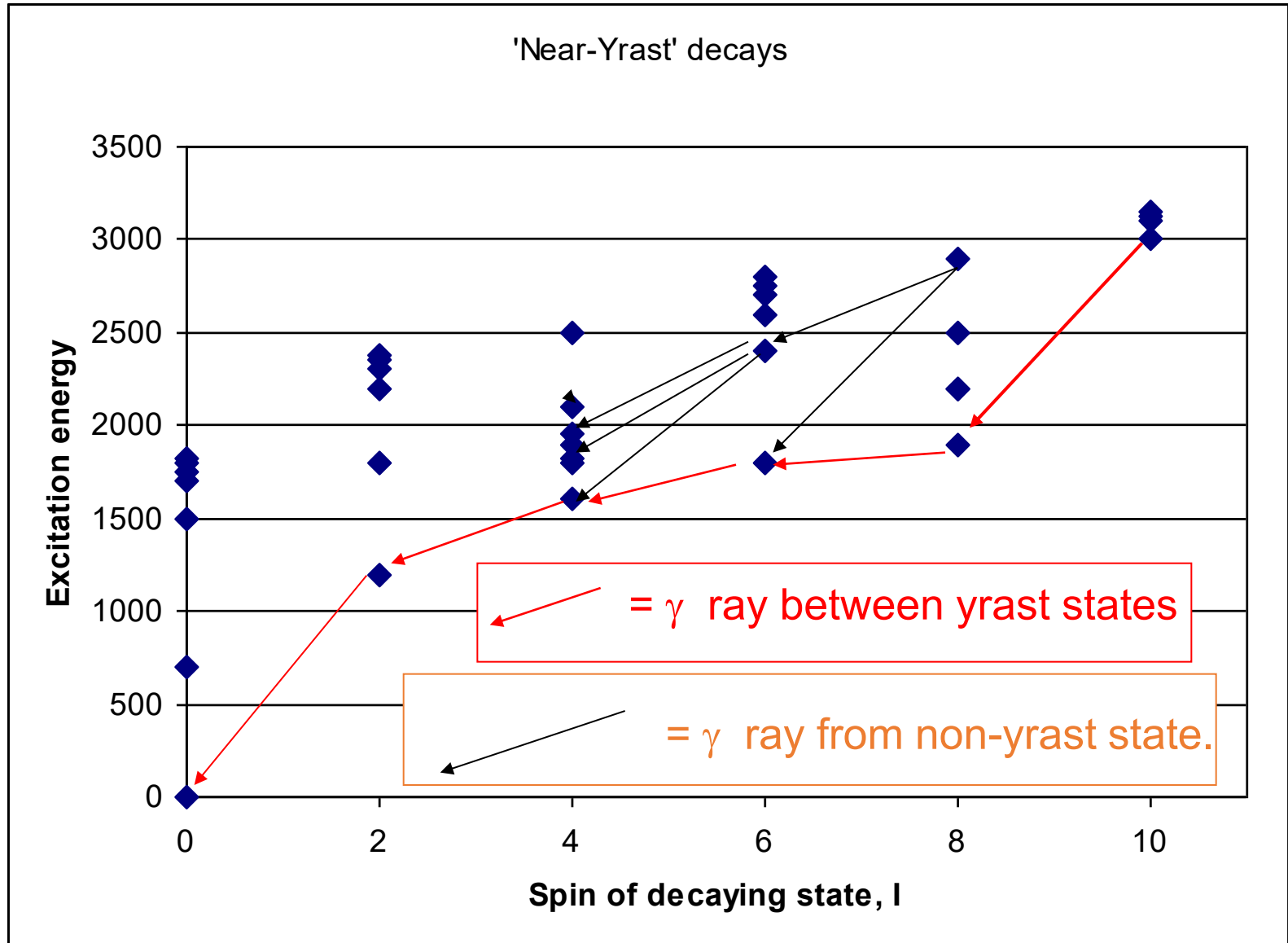
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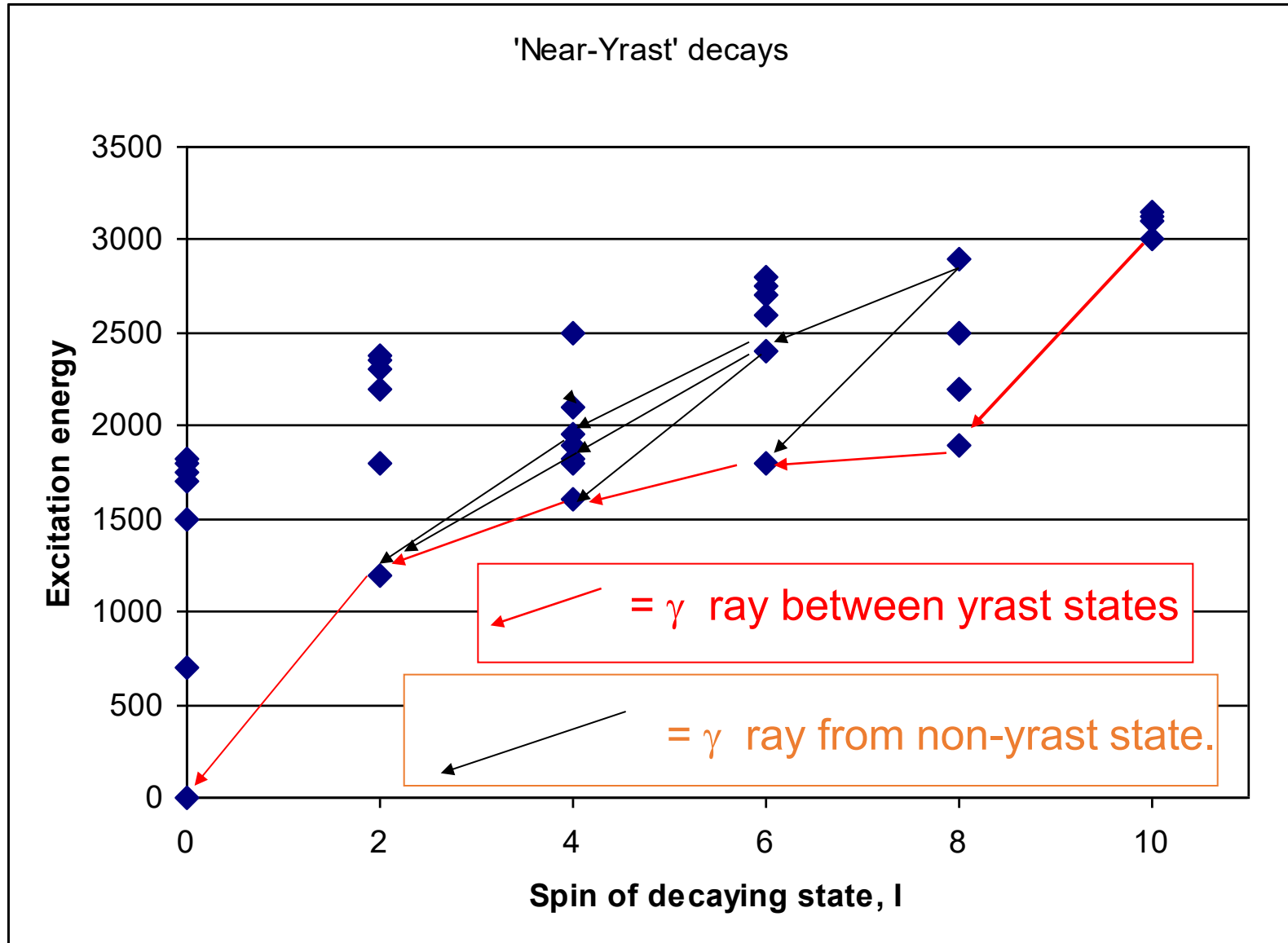
The EM transition rate depends on $E_\gamma^{2\lambda+1}$, (for E2 decays E_γ^5)
 Thus, the highest energy transitions for the lowest λ are usually favoured.
 Non-yrast states decay to yrast ones (unless very different ϕ , K-isomers)



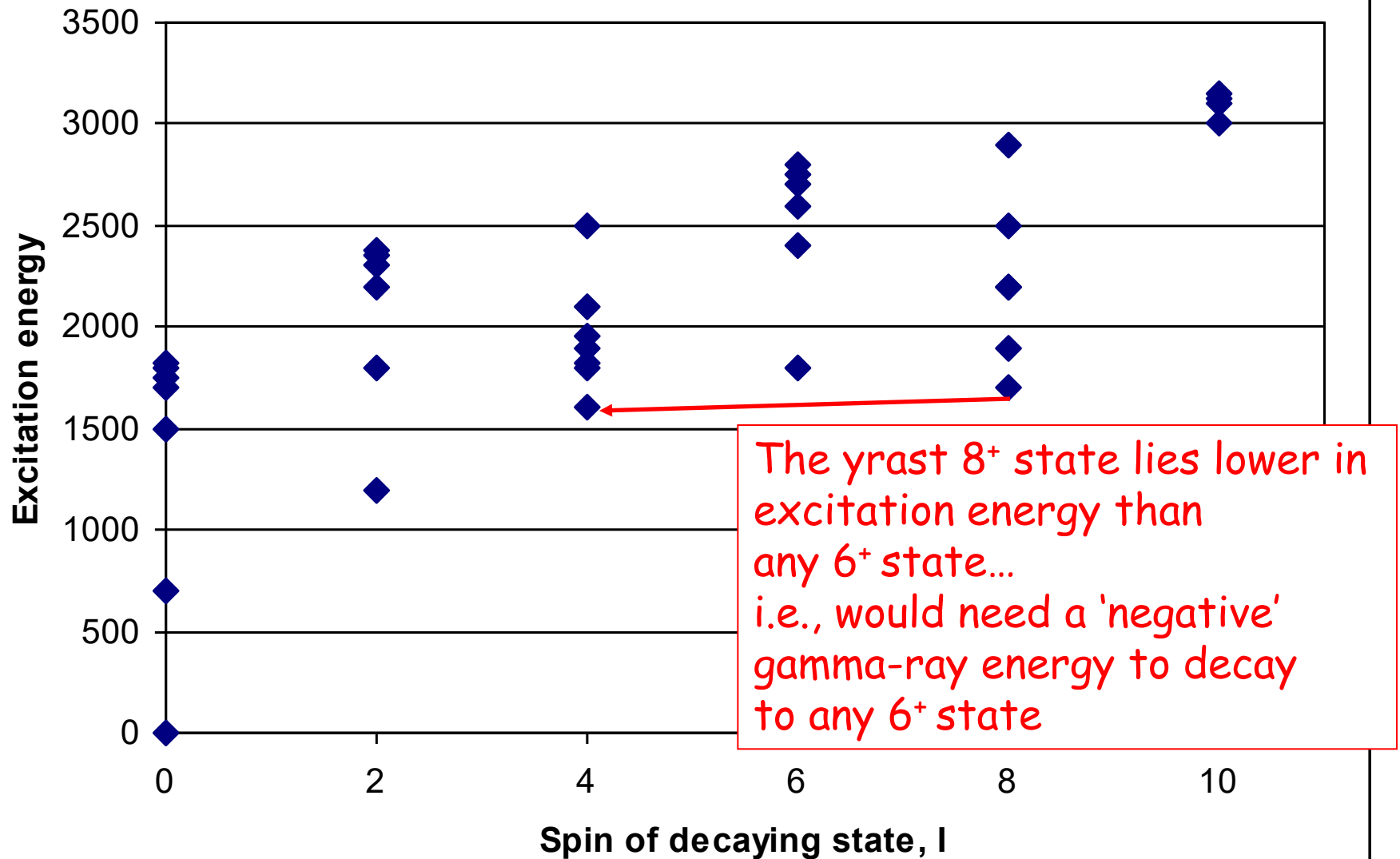
The EM transition rate depends on $E_\gamma^{2\lambda+1}$, (for E2 decays E_γ^5)
 Thus, the highest energy transitions for the lowest λ are usually favoured.
 Non-yrast states decay to yrast ones (unless very different ϕ , K-isomers etc.)



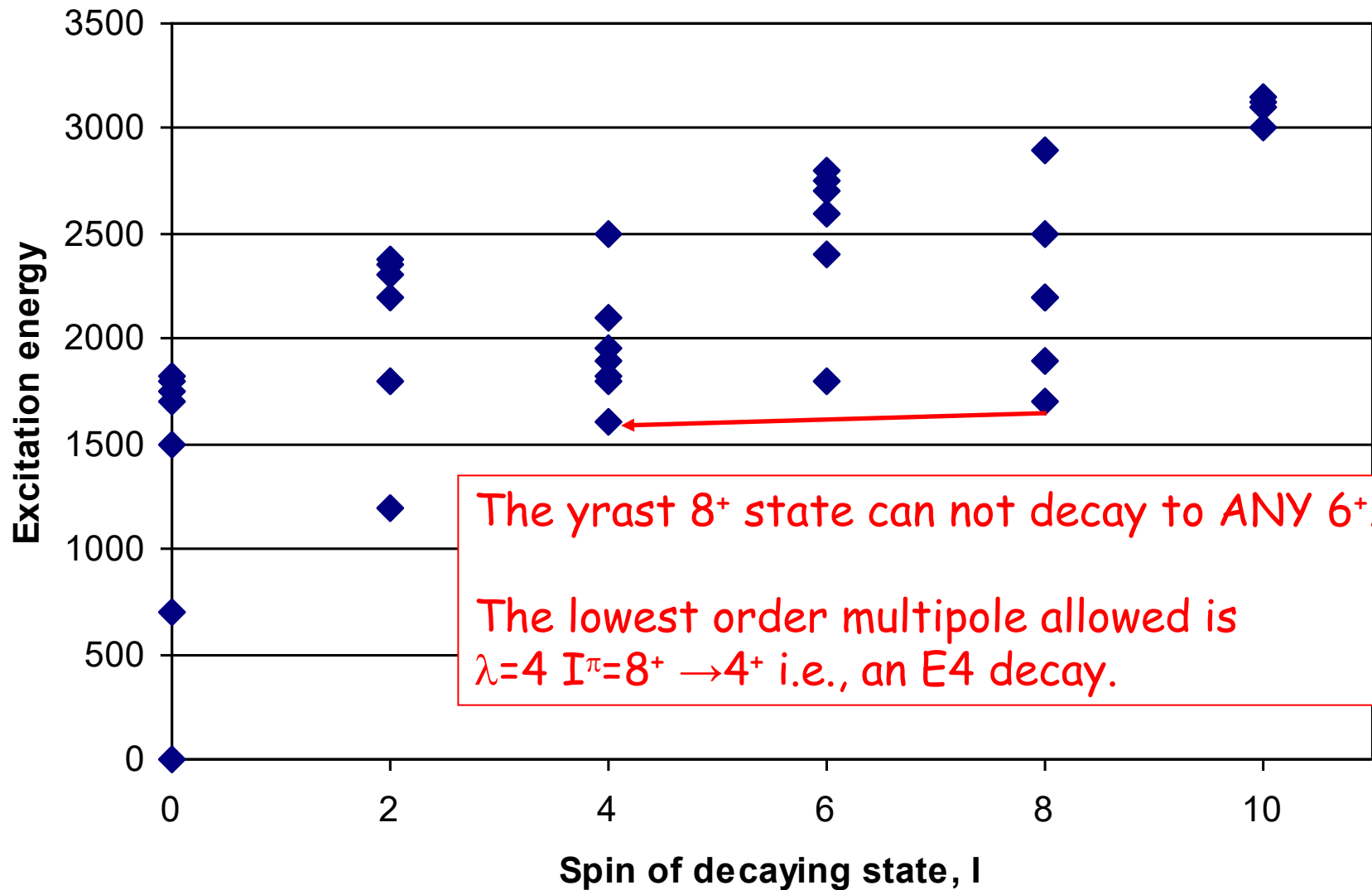
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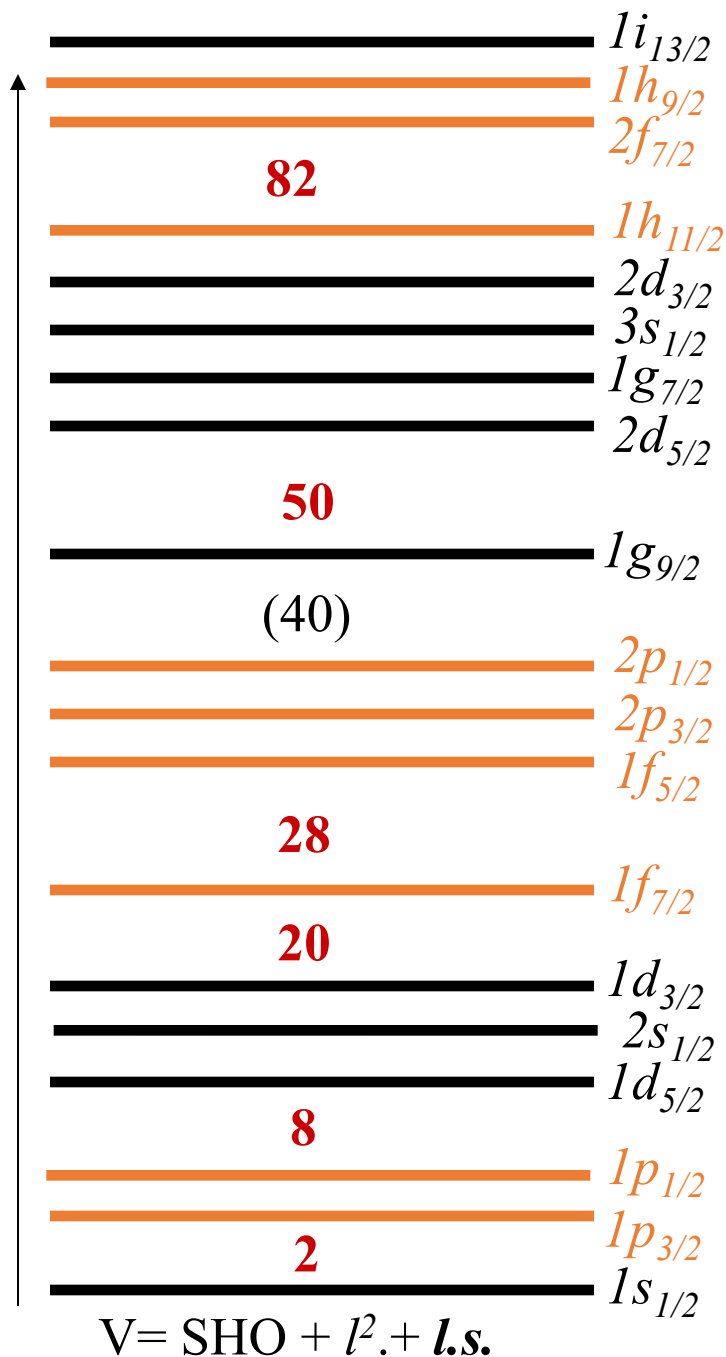
Yrast Traps



Yrast Traps



'single-particle'-like transitions.



Basic, independent particle model (with very simple residual interactions added, such as δ - (contact) interaction) predicts large host of *isomers in the vicinity of closed shells / magic numbers.*

Two categories

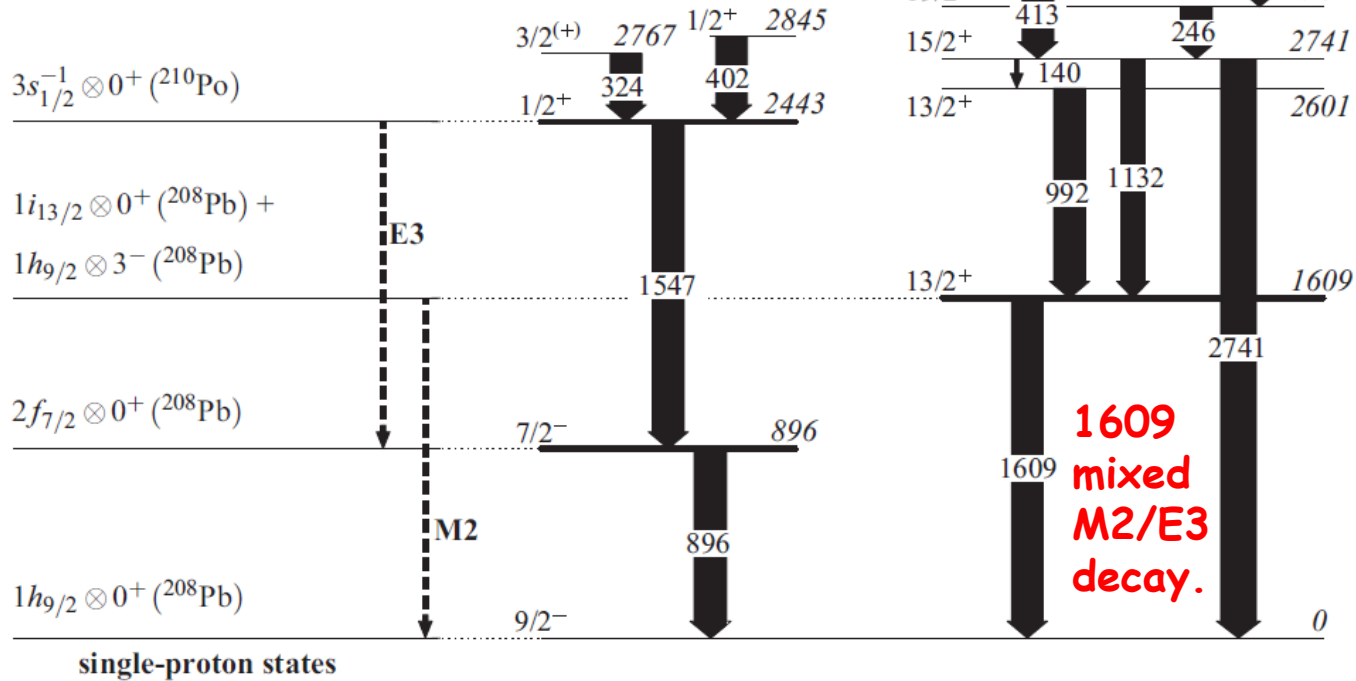
- 1) **Spin-trap isomers** - from particularly favoured coupling of (often high-j intruder) particles gives rise to high-spin state at low excitation energy. This state 'has nowhere to decay to' unless decays by high multipolarity (thus slow) transition.

$$|J_i + J_f| > \Delta J > |J_i - J_f|$$

- 2) **Seniority isomers** – δ -interaction can demonstrate with geometric picture how (single) jn multiplet looks like j^2 multiplet. Small energy difference between J_{max} and $(J_{max}-2)$ states cause 'seniority isomers'.

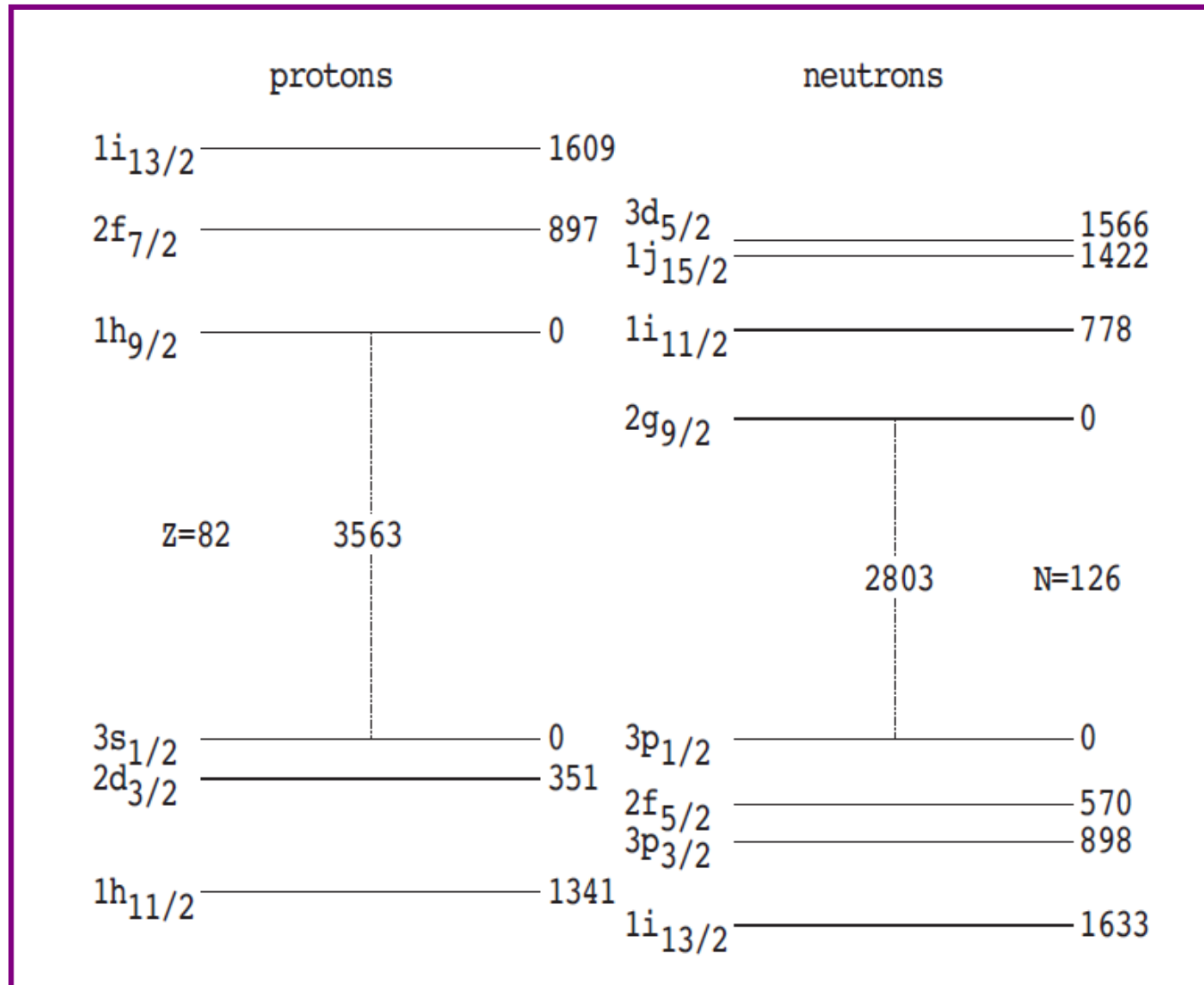
E3 and M2 transition strengths in $^{209}_{83}\text{Bi}$

O. J. Roberts,^{1,2,*} C. R. Niță,^{1,3} A. M. Bruce,¹ N. Mărginean,³ D. Bucurescu,³ D. Deleanu,³ D. Filipescu,³ N. M. Florea,^{3,4} I. Gheorghe,^{3,5} D. Ghiță,³ T. Glodariu,³ R. Lica,³ R. Mărginean,³ C. Mihai,³ A. Negret,³ T. Sava,³ L. Stroe,³ R. Șuvăilă,³ S. Toma,³ T. Alharbi,^{6,7} T. Alexander,⁶ S. Aydin,⁸ B. A. Brown,⁹ F. Browne,¹ R. J. Carroll,⁶ K. Mulholland,¹⁰ Zs. Podolyák,¹¹ P. H. Regan,^{6,11} J. F. Smith,¹⁰ M. Smolen,¹⁰ and C. M. Townsley⁶



E_x (keV)	J_i^π	$T_{1/2}$ (ns)	E_γ (keV)	J_f^π	$L\lambda$	Measured transitions	$B(L\lambda)$ ($\times 10^3 e^2 \text{ fm}^6$ or $\mu_N^2 \text{ fm}^2$)	SM ($\times 10^3 e^2 \text{ fm}^6$ or $\mu_N^2 \text{ fm}^2$)	FFS ($\times 10^3 e^2 \text{ fm}^6$ or $\mu_N^2 \text{ fm}^2$)
1609	$\frac{13}{2}^+$	0.120(15)	1609	$\frac{9}{2}^-$	$E3$	$(^{208}_{82}\text{Pb } 3^- \otimes \pi 1h_{9/2}) \rightarrow (^{208}_{82}\text{Pb } 0^+ \otimes \pi 1h_{9/2})$	12(2)	0.52	9.8 [40]
					$M2$	$(^{208}_{82}\text{Pb } 0^+ \otimes \pi 1i_{13/2}) \rightarrow (^{208}_{82}\text{Pb } 0^+ \otimes \pi 1h_{9/2})$	0.038(5)	0.43	0.033 [41]
2443	$\frac{1}{2}^+$	9.02(24)	1547	$\frac{7}{2}^-$	$E3$	$(^{210}_{84}\text{Po } 0^+ \otimes \pi 3s_{1/2}) \rightarrow (^{208}_{82}\text{Pb } 0^+ \otimes \pi 2f_{7/2})$	6.3(2)	0	

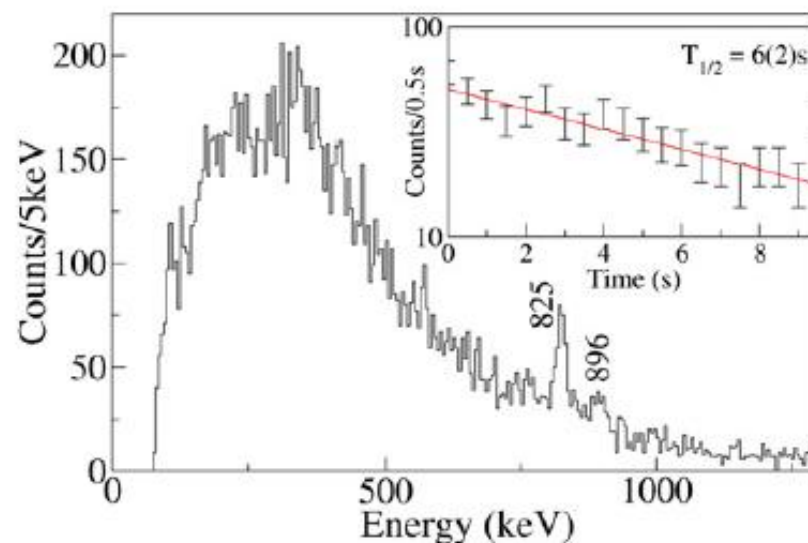
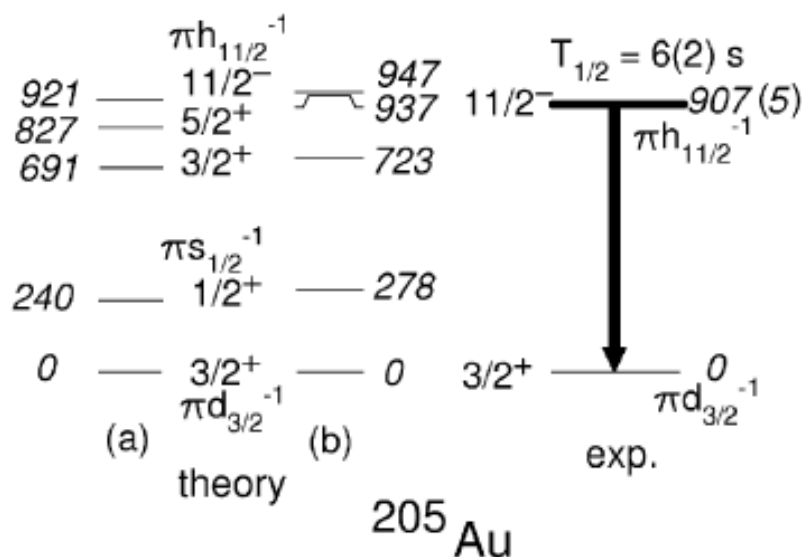
Relative energies of orbits close to ^{208}Pb

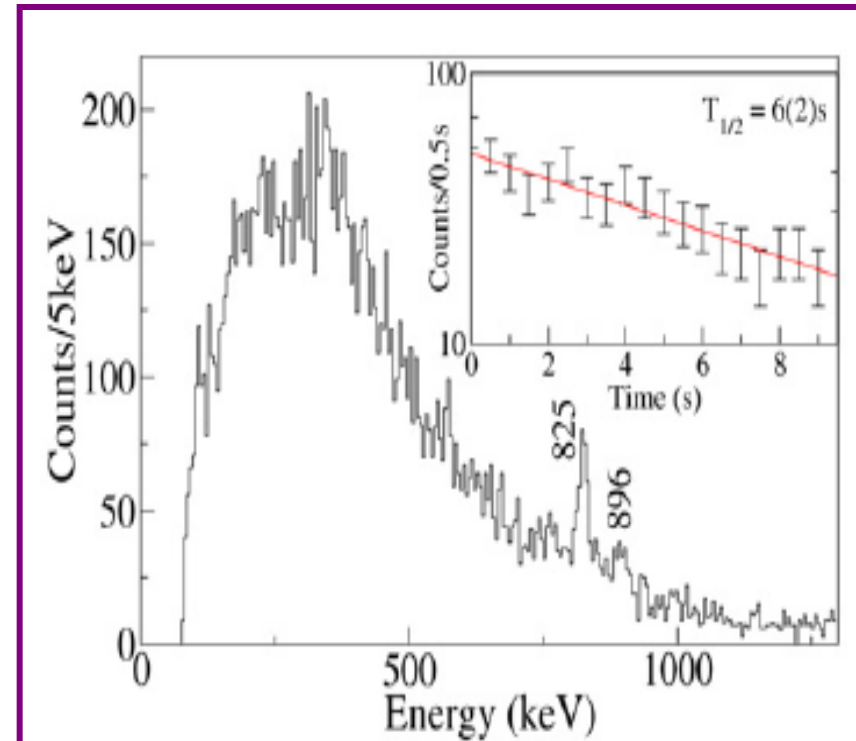
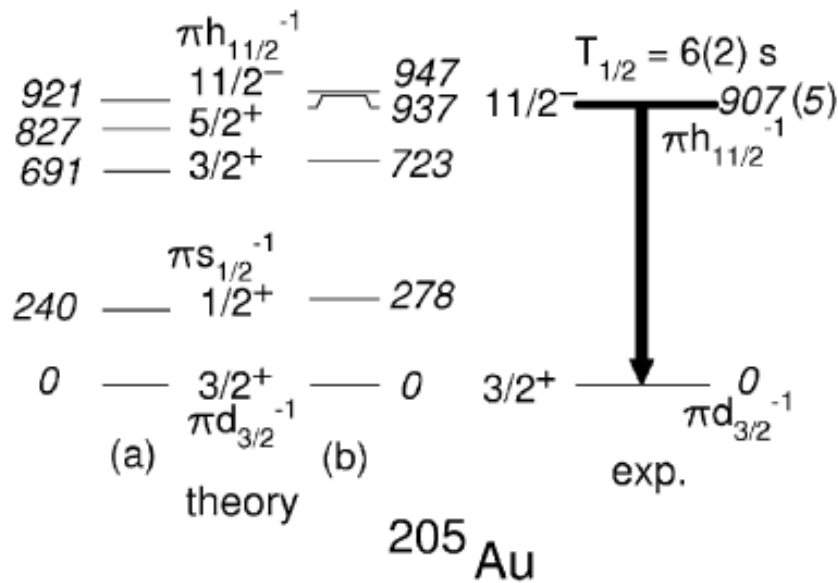




Proton–hole excitation in the closed shell nucleus ^{205}Au

Zs. Podolyák^{a,*}, G.F. Farrelly^a, P.H. Regan^a, A.B. Garnsworthy^a, S.J. Steer^a, M. Górská^b, J. Benlliure^c, E. Casarejos^c, S. Pietri^a, J. Gerl^b, H.J. Wollersheim^b, R. Kumar^d, F. Molina^e, A. Algara^{e,f}, N. Alkhomashi^a, G. Benzonig^g, A. Blazhev^h, P. Boutachkov^b, A.M. Bruceⁱ, L. Caceres^{b,j}, I.J. Cullen^a, A.M. Denis Bacelarⁱ, P. Doornenbal^b, M.E. Estevez^c, Y. Fujita^k, W. Gelletly^a, H. Geissel^b, H. Grawe^b, J. Grębosz^{b,l}, R. Hoischen^{m,b}, I. Kojouharov^b, S. Lalkovskiⁱ, Z. Liu^a, K.H. Maier^{n,l}, C. Mihai^o, D. Mürcher^h, B. Rubio^e, H. Schaffner^b, A. Tamii^k, S. Tashenov^b, J.J. Valiente-Dobón^p, P.M. Walker^a, P.J. Woods^q





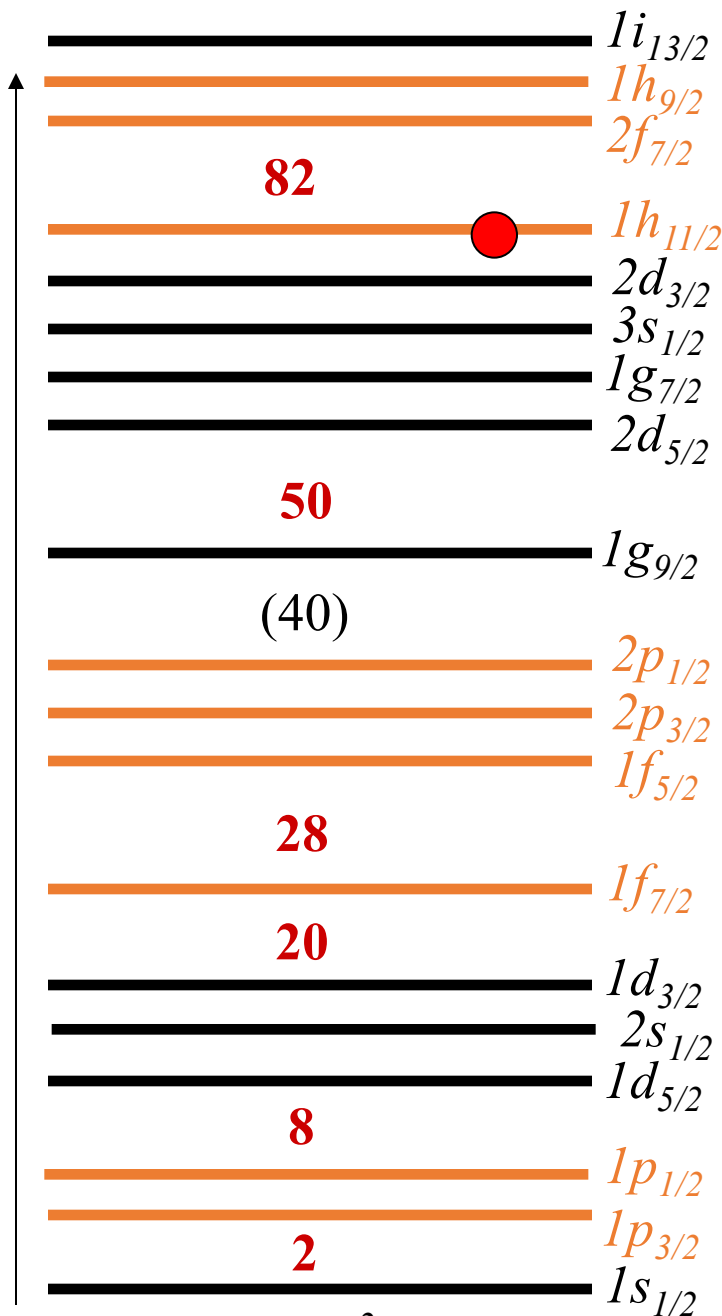
$N=126$; $Z=79$. Odd, single proton transition;
 $h_{11/2} \rightarrow d_{3/2}$ state (holes in $Z=82$ shell).

Angular momentum selection rule says lowest multipole decay allowed is
 $\lambda = (11/2 - 3/2) = \Delta L = 4$

Change of parity means lowest must transition be M4.

1Wu 907 keV M4 in ^{205}Au has $T_{1/2} = 8 \text{ secs}$; corresponding to a near 'pure' single-particle (proton) transition from ($h_{11/2}$) 11/2⁻ state to ($d_{3/2}$) 3/2⁺ state.

(Decay here is observed following INTERNAL CONVERSION).
 These competing decays to gamma emission are often observed in isomeric decays



$$V = \text{SHO} + l^2 + l.s.$$

Why are E1 transitions usually isomeric?

E1 single particle decays need to proceed between orbitals which have $\Delta L=1$ and change parity, e.g.,

$f_{7/2}$ and $d_{5/2}$

or $g_{9/2}$ and $f_{7/2}$

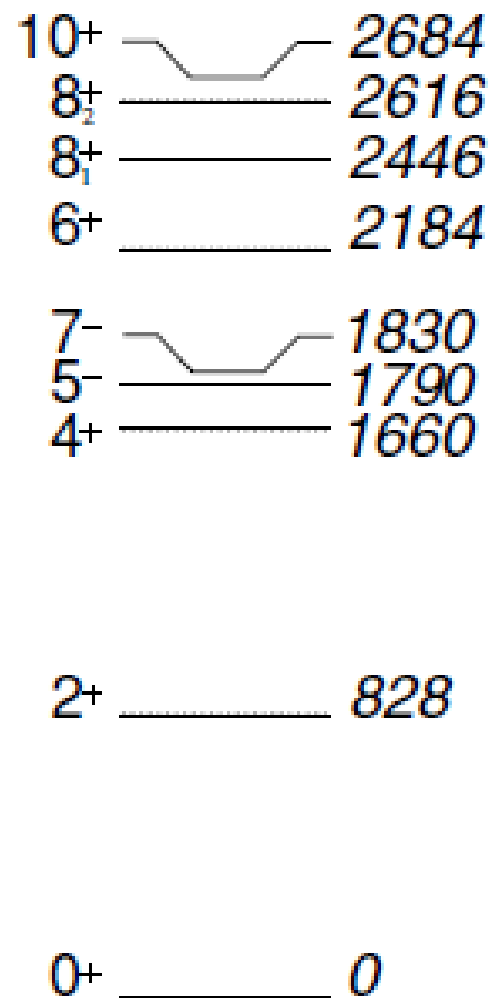
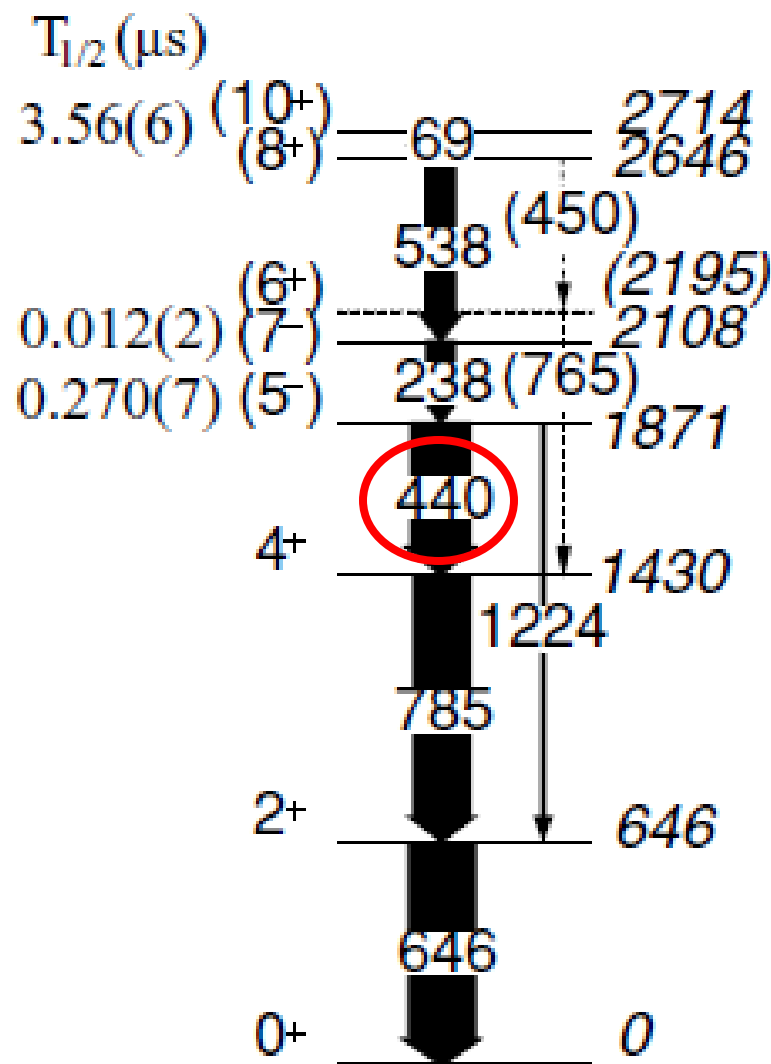
or $h_{11/2}$ and $g_{9/2}$

or $p_{3/2}$ and $d_{5/2}$

What about typical 2-particle configs.
e.g.,

$$I^\pi = 5^- \text{ from } (h_{11/2})^{-1} \times (s_{1/2})^{-1}$$

$$I^\pi = 4^+ \text{ from } (d_{3/2})^{-1} \times (s_{1/2})^{-1}$$



e.g., $^{128}\text{Cd}_{80}$, isomeric 440 keV E1 decay.

A 1 Wu 440 keV E1 should have $T_{1/2} \sim 4 \times 10^{-15} \text{s}$;
actually has 270 ns (i.e hindered by $\sim 10^8$)

L. Cáceres,^{1,2,*} M. Górska,¹

PHYSICAL REVIEW C 79, 011301(R) (2009)

Why are E1 s isomeric?

E1s often are observed with decay probabilities of $10^{-5} \rightarrow 10^{-9}$ Wu

E1 single particle decays need to proceed between orbitals which have $\Delta L = 1$ and change parity, e.g.,

$f_{7/2}$ and $d_{5/2}$

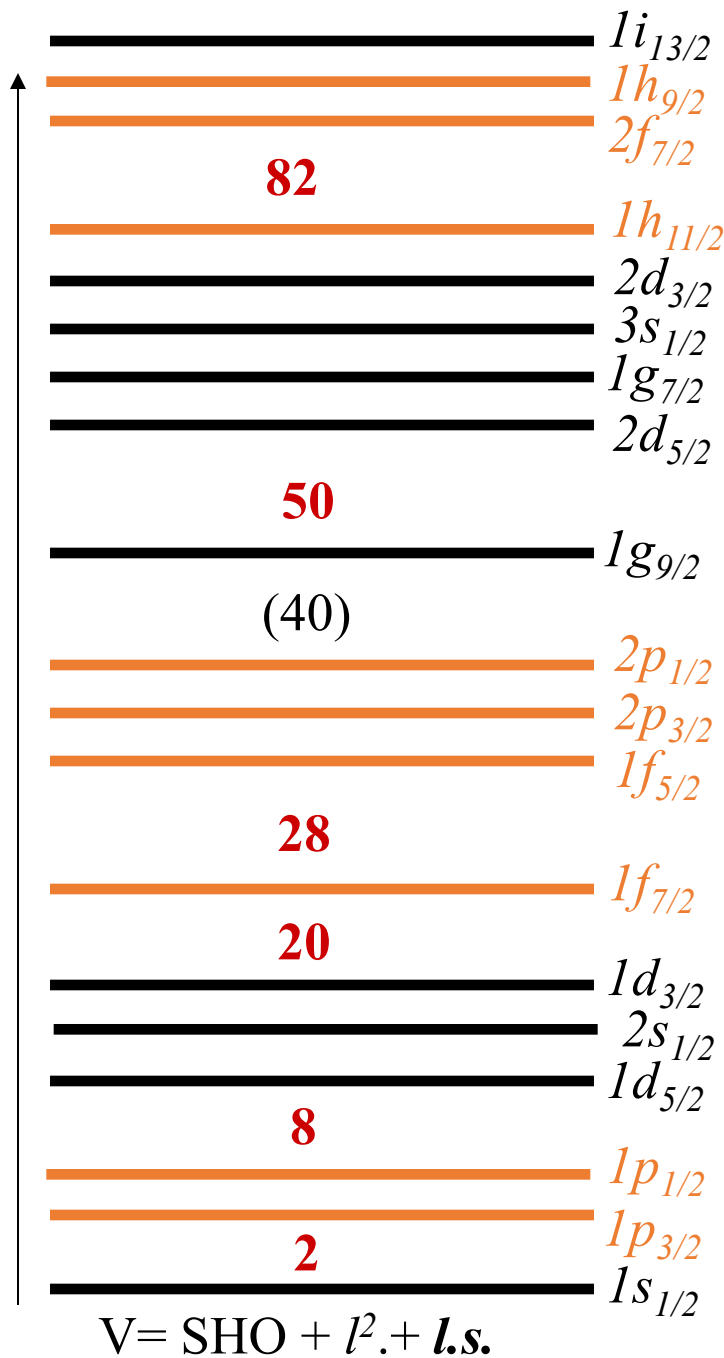
or $g_{9/2}$ and $f_{7/2}$

or $h_{11/2}$ and $g_{9/2}$

or $i_{13/2}$ and $h_{11/2}$

or $p_{3/2}$ and $d_{5/2}$

BUT these orbitals are along way from each other in terms of energy / other orbitals between them in the (spherical) mean-field single-particle spectrum.



Why are E1 s isomeric?

E1 single particle decays need to proceed between orbitals which have $\Delta L=1$ and change parity, e.g.,

What about typical 2-particle configs.
e.g.,

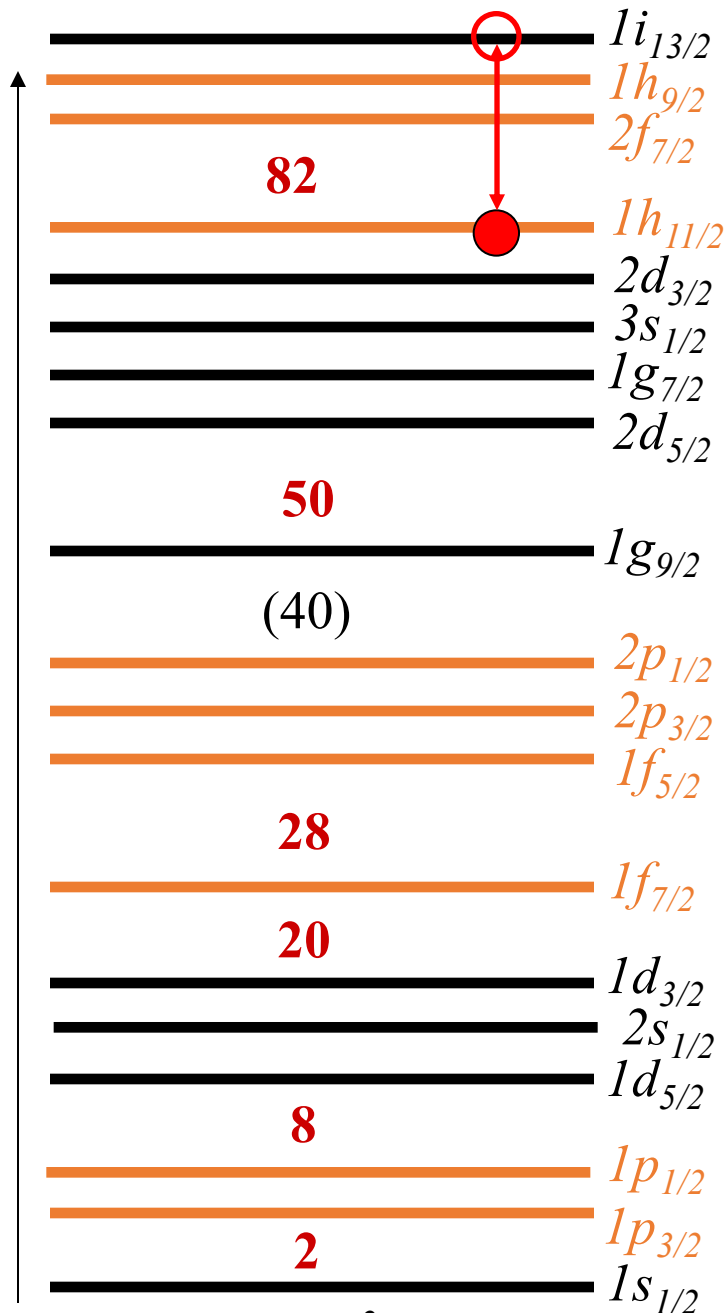
$I^\pi=5^-$ from mostly $(h_{11/2})^{-1} \times (s_{1/2})^{-1}$

$I^\pi=4^+$ from mostly $(d_{3/2})^{-1} \times (s_{1/2})^{-1}$

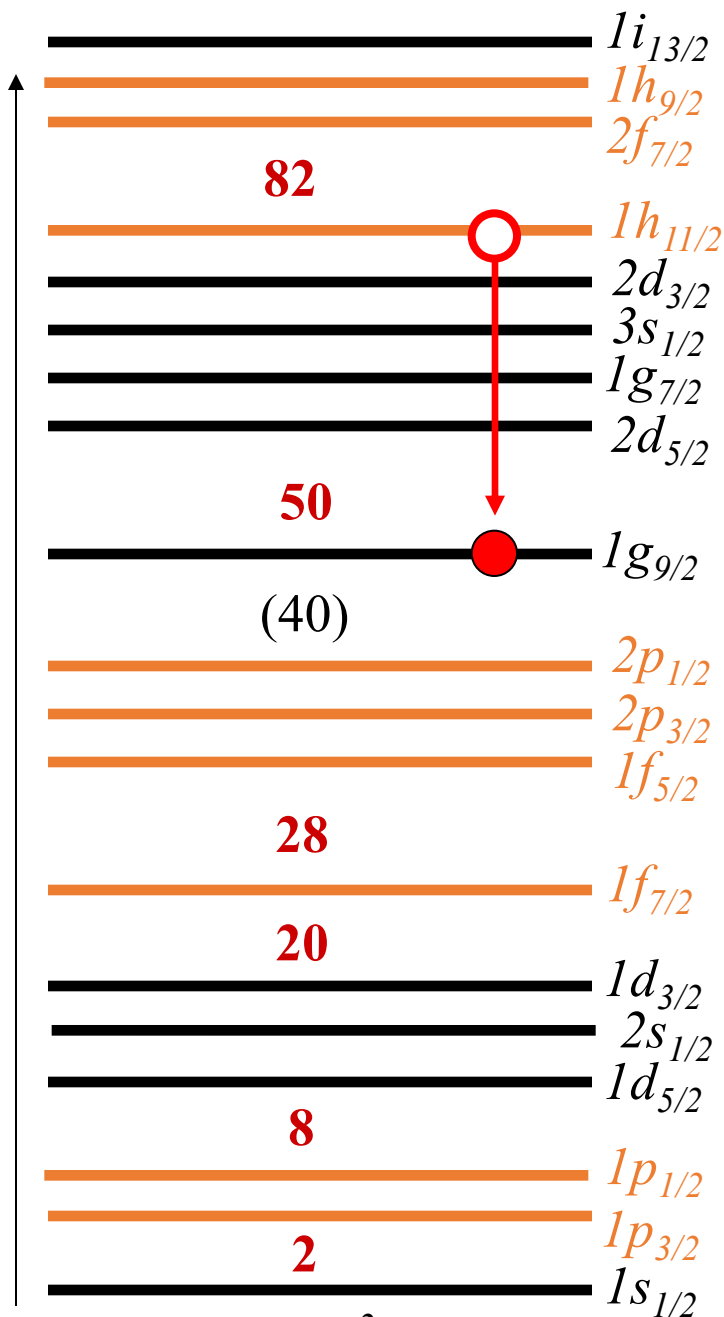
No E1 'allowed' between such orbitals.

E1 occur due to (very) small fractions of the wavefunction from orbitals originating in higher shells.

Small overlap wavefunction in multipole matrix element allows 'slow' E1s to proceed.



$$V = \text{SHO} + l^2 + l.s.$$



Why are E1 s isomeric?

E1s often observed with decay probabilities Of $10^{-5} \rightarrow 10^{-8}$ Wu

E1 single particle decays need to proceed between orbitals which have $\Delta L=1$ and change parity, e.g.,

$f_{7/2}$ and $d_{5/2}$

or $g_{9/2}$ and $f_{7/2}$

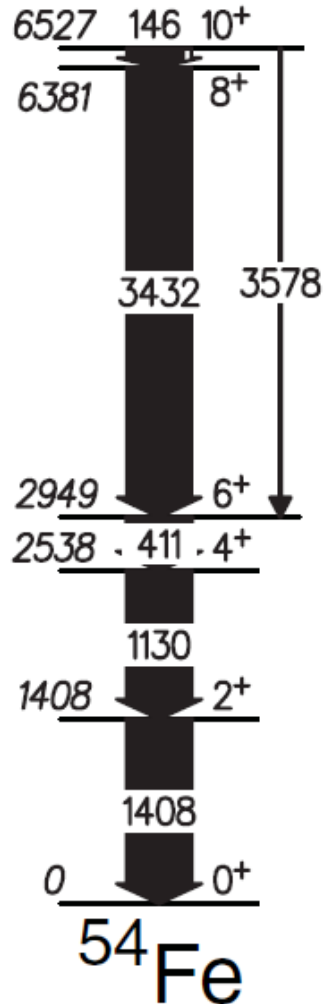
or $h_{11/2}$ and $g_{9/2}$

or $p_{3/2}$ and $d_{5/2}$

BUT these orbitals are along way from each other in terms of energy in the mean-field single particle spectrum.

Competing E4 and E2 transitions with core breaking?

We can have cases where low-energy (~ 100 keV) E2 decays competing with high-energy (~ 4 MeV) E4 transitions across magic shell closures, e.g. $^{54}\text{Fe}_{28}$.

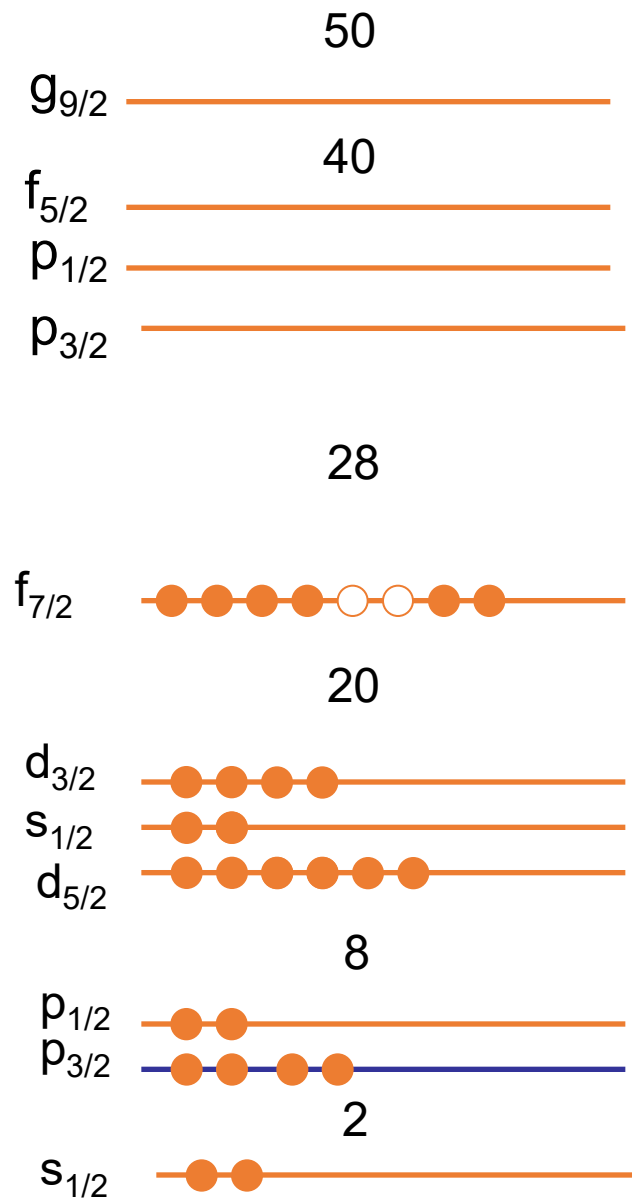
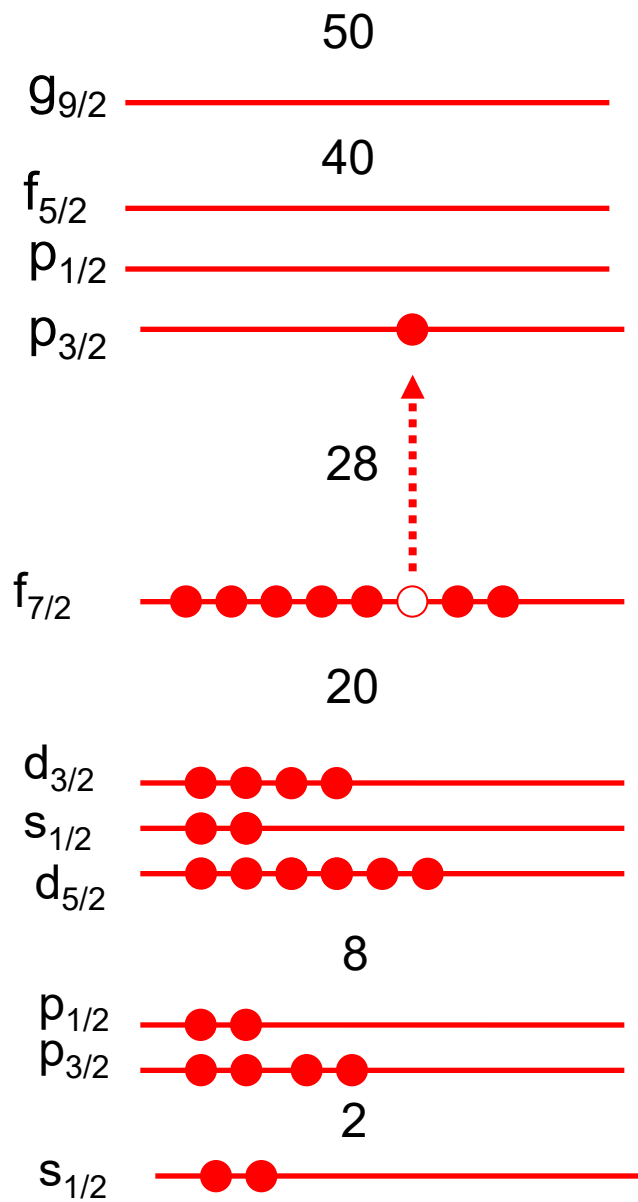


$Z=26; N=28$ case.

- 2 proton holes in $f_{7/2}$ shell.
- Maximum spin in simple valence space is $I^\pi=6^+$.
- i.e., $(\pi f_{7/2})^{-2}$ configuration coupled to $I^\pi=6^+$

Additional spin requires exciting (pairs) of nucleons across the N or $Z=28$ shell closures into the $f_{5/2}$ shell.

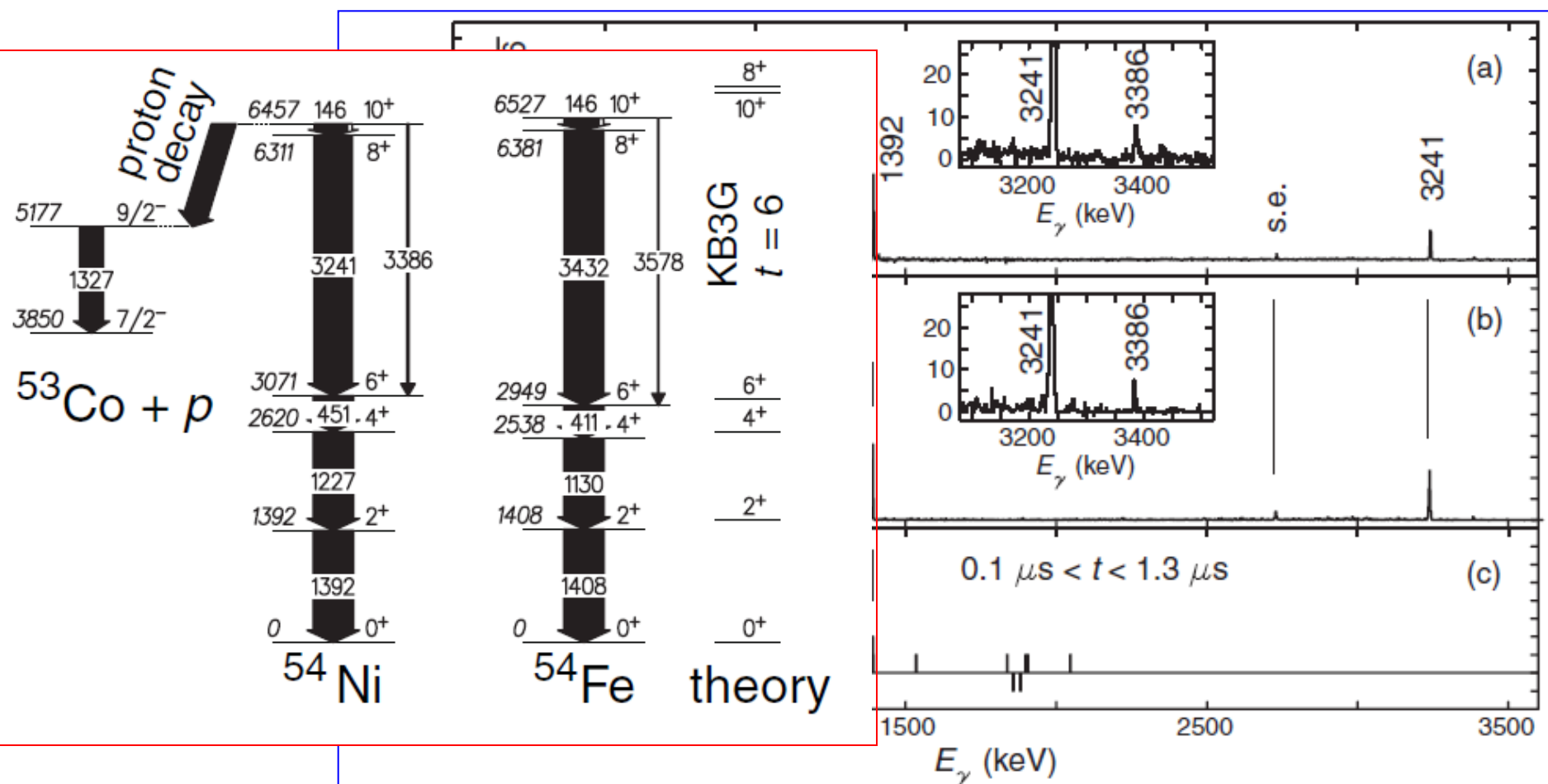
E_γ	E2 (1Wu)	M3 (1Wu)	E4 (1Wu)
146 keV ($10^+ \rightarrow 8^+$)	1.01 ms	613 s	21 E+6s
3578 keV ($10^+ \rightarrow 6^+$)			6.5 ms

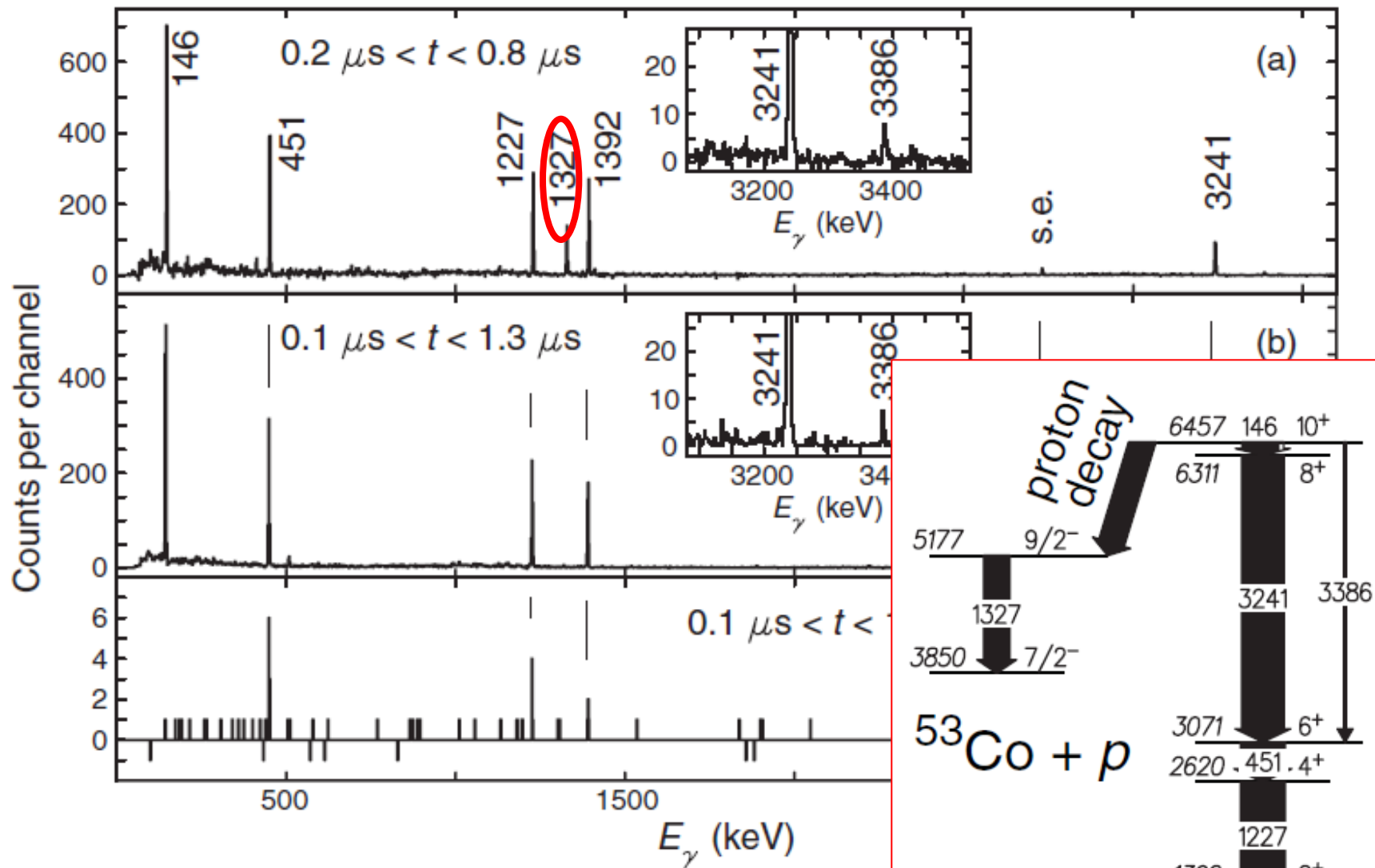


break core $I^{\pi}=10^{+}$ from $(\nu f_{7/2})^{-2}_{6^{+}} \times (\pi f_{7/2} \times \pi p_{1/2}, p_{3/2})_{4^{+}}$

Isospin symmetry and proton decay: Identification of the 10^+ isomer in ^{54}Ni

D. Rudolph,¹ R. Hoischen,^{1,2} M. Hellström,¹ S. Pietri,³ Zs. Podolyák,³ P. H. Regan,³ A. B. Garnsworthy,^{3,4} S. J. Steer,³ F. Becker,^{2,*} P. Bednarczyk,^{2,5} L. Cáceres,^{2,6} P. Doornenbal,^{2,7,†} J. Gerl,² M. Górska,² J. Grębosz,^{2,5} I. Kojouharov,² N. Kurz,² W. Prokopowicz,^{2,5} H. Schaffner,² H. J. Wollersheim,² L.-L. Andersson,¹ L. Atanasova,⁸ D. L. Balabanski,^{8,9} M. A. Bentley,¹⁰ A. Blazhev,⁷ C. Brandau,^{2,3} J. R. Brown,¹⁰ C. Fahlander,¹ E. K. Johansson,¹ A. Jungclaus,⁶ and S. M. Lenzi¹¹

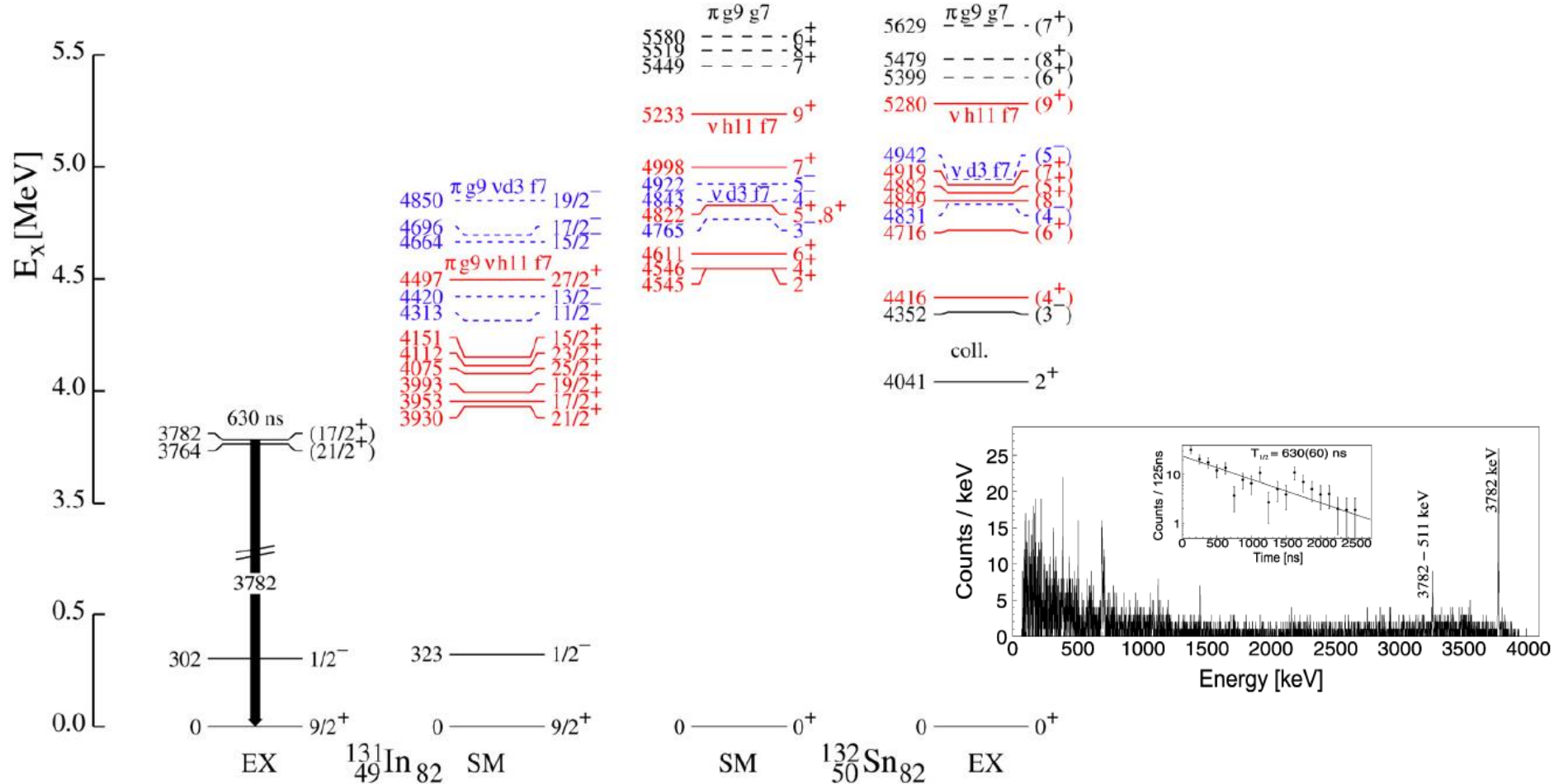




L=5 proton radioactivity transition
for $^{54}\text{Ni}(10^+) \rightarrow ^{53}\text{Co}(9/2^-)$
(Small) effect of at $h_{11/2}$ orbits in wf ?

Other examples of 'core' breaking isomeric decay:
Signature is a ~ 4 MeV decay from isomeric state.
see e.g. around $^{132}\text{Sn}_{82}$ doubly-magic closed core.

$17/2^+ \rightarrow 9/2^+$ (E4) in ^{131}In ; $T_{1/2}=630$ ns, $B(E4)=1.48(14)$ Wu.



Lecture 4: More complex nuclei: Highly deformed shapes and collective structures..

More complex nuclei.

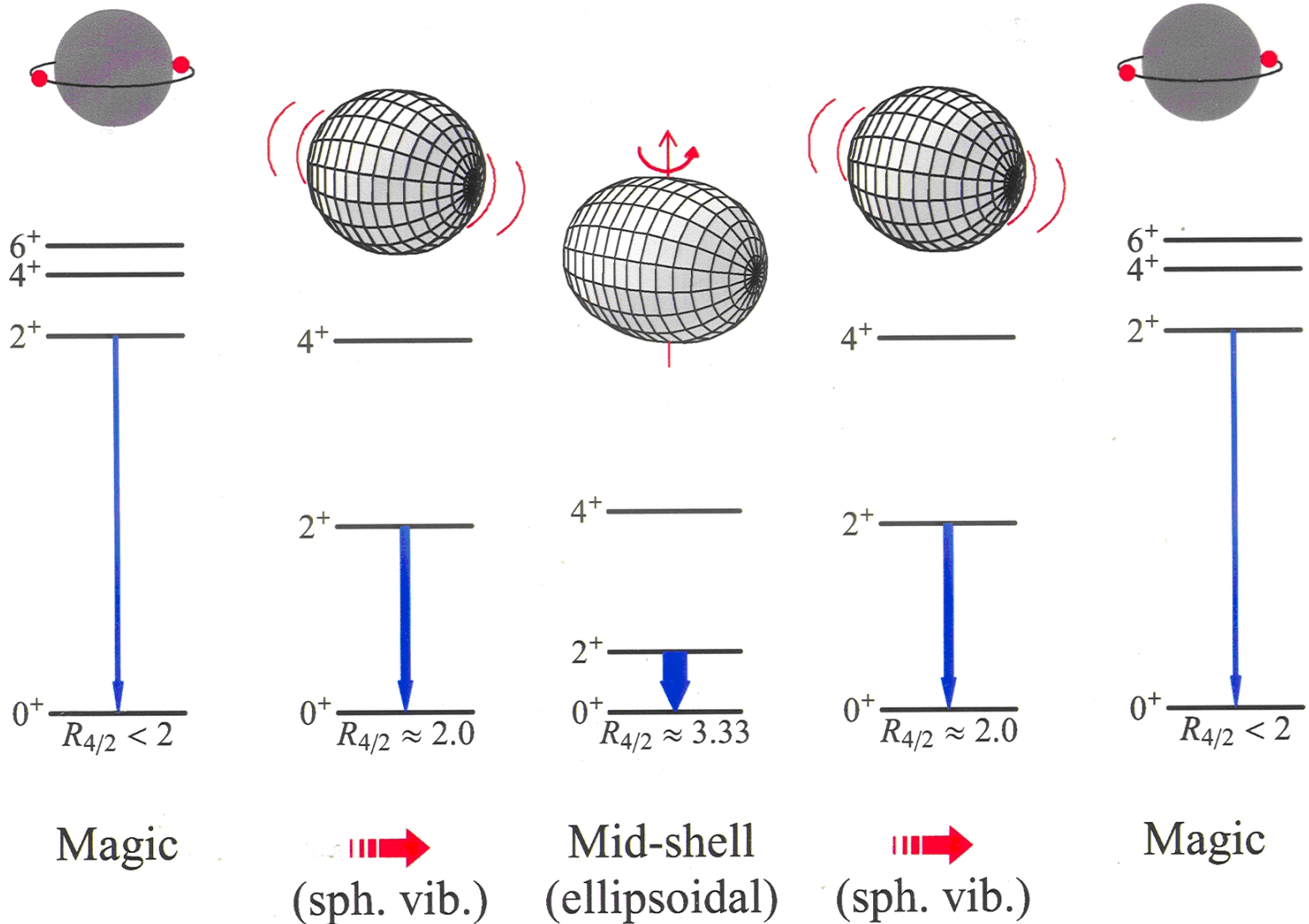
Simple signatures of nuclear structure such as $E(2^+)$ and $R(4/2)$ can help show us which regions of the nuclear chart are best explained by:

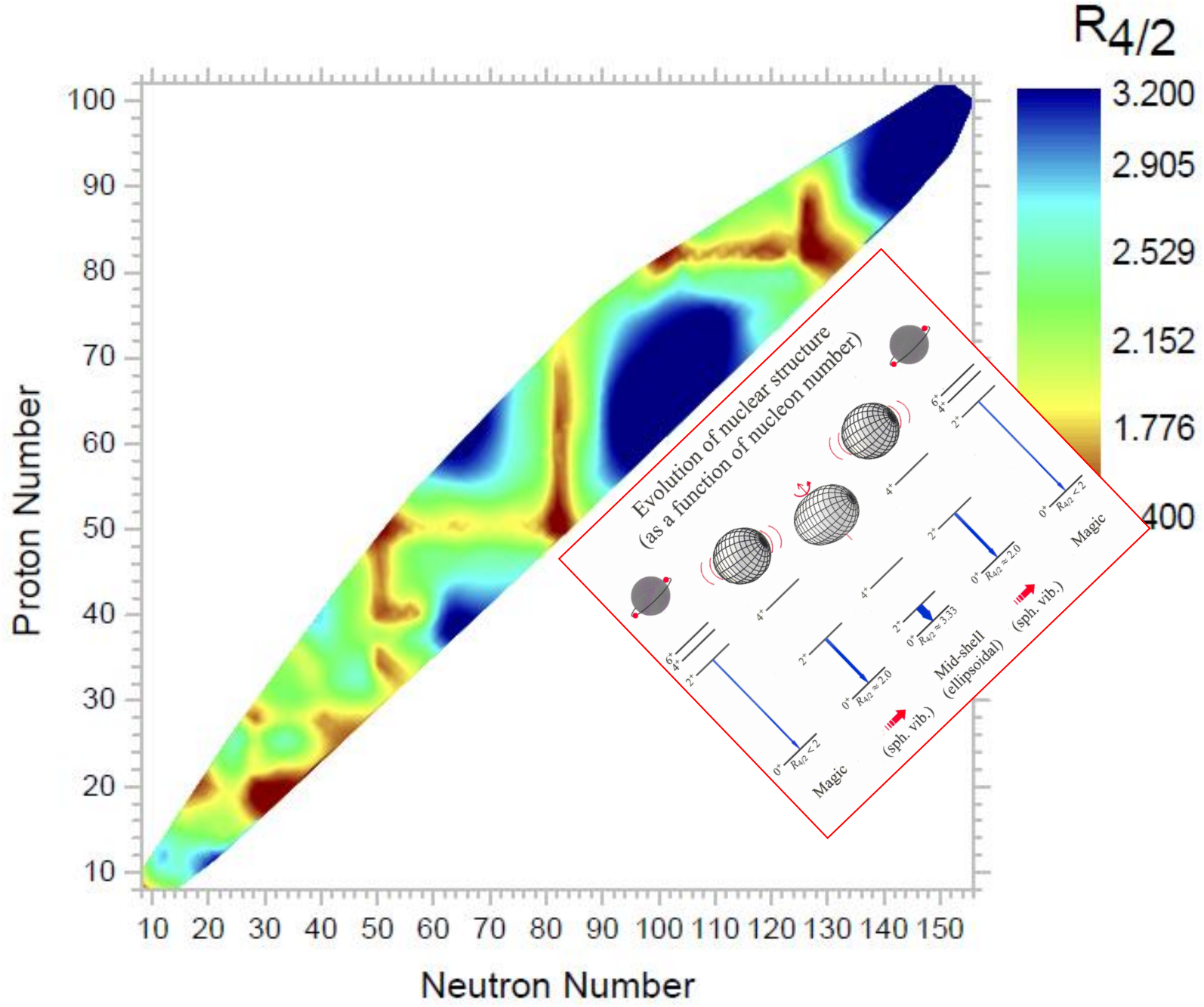
- Spherical 'single-particle' excitations

or

- Quadrupole deformed regions (Nilsson model)

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





K-isomers in deformed nuclei

In the strong-coupling limit, for orbitals where Ω is large, unpaired particles can sum their angular momentum projections on the nuclear axis if symmetry to give rise to 'high-K' states, such that the total spin/parity of the high-K Multi-particle state is give by:

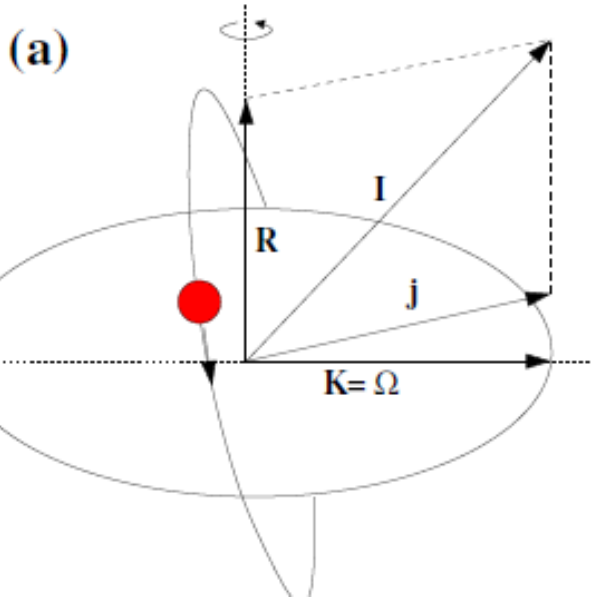
$$J^\pi = K^\pi = \sum_i \Omega_i^{\Pi(\pi_i)}$$

These, high-K multi-quasi-particle states are expected to occur at excitations energies of:

$$E^* \approx \sum_k \sqrt{(\epsilon_k - \epsilon_F)^2 + \Delta^2}$$

where ϵ_k is the single-particle energy; ϵ_F is the Fermi energy and Δ is the pair gap (which can be obtained from odd-even mass differences)

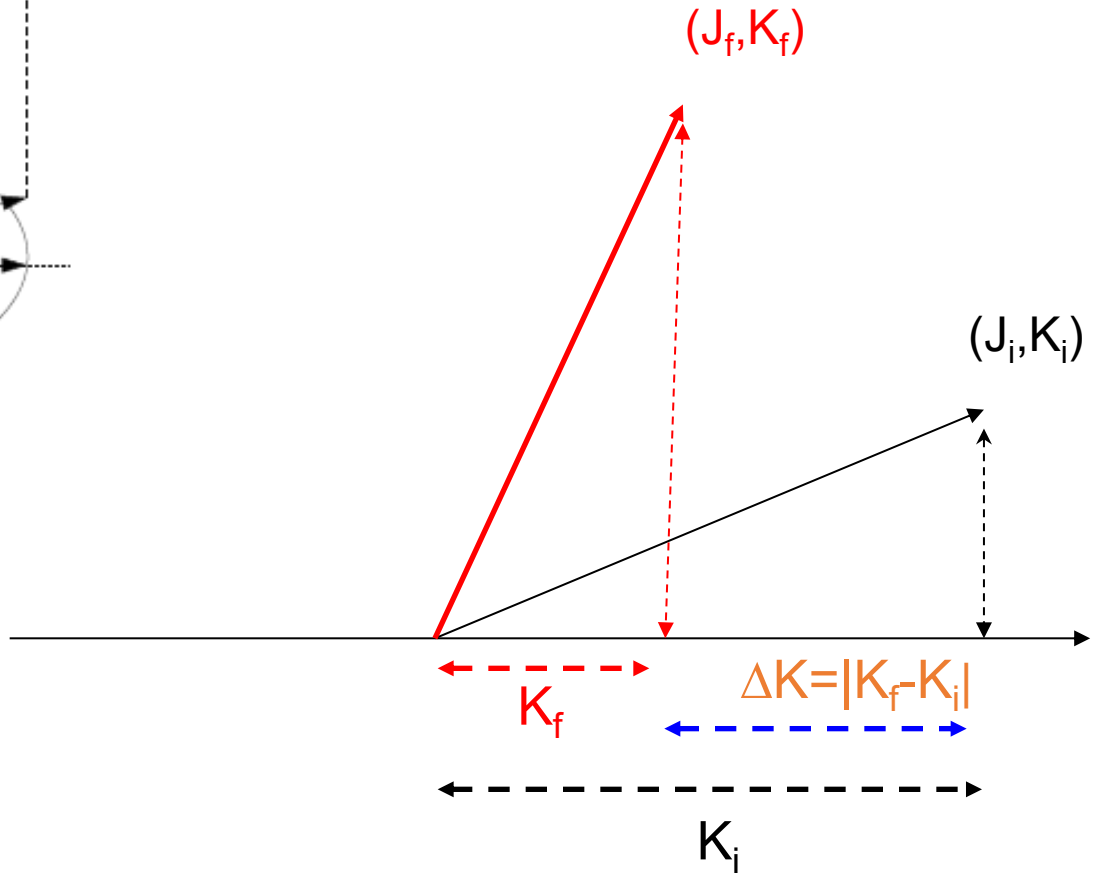
K isomers



$$|K_i - K_f| = \Delta K \leq \lambda$$

$$\nu = \Delta K - \lambda$$

$$f_\nu = \left[\frac{T_{1/2}^\gamma}{T_{1/2}^W} \right]^{1/\nu} = \text{reduced hindrance for a K-isomeric decay transition.}$$



Effect of Nuclear Deformation on K-isomers

Spherical, harmon. oscillator

$$H = \hbar\omega + a\mathbf{l} \cdot \mathbf{l} + b\mathbf{l} \cdot \mathbf{s},$$

quantum numbers j^π, m_j

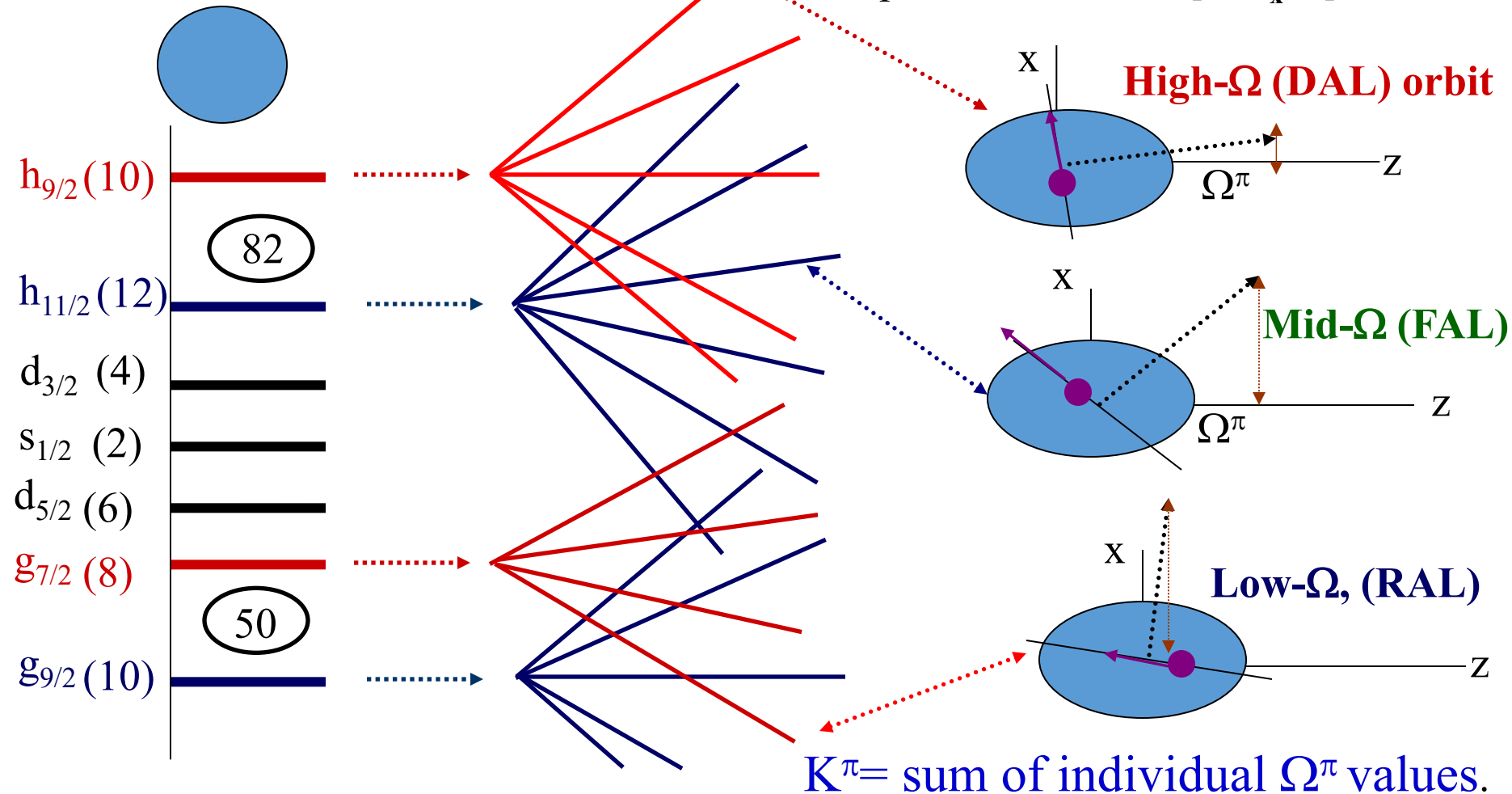
Nilsson scheme: Quadrupole deformed

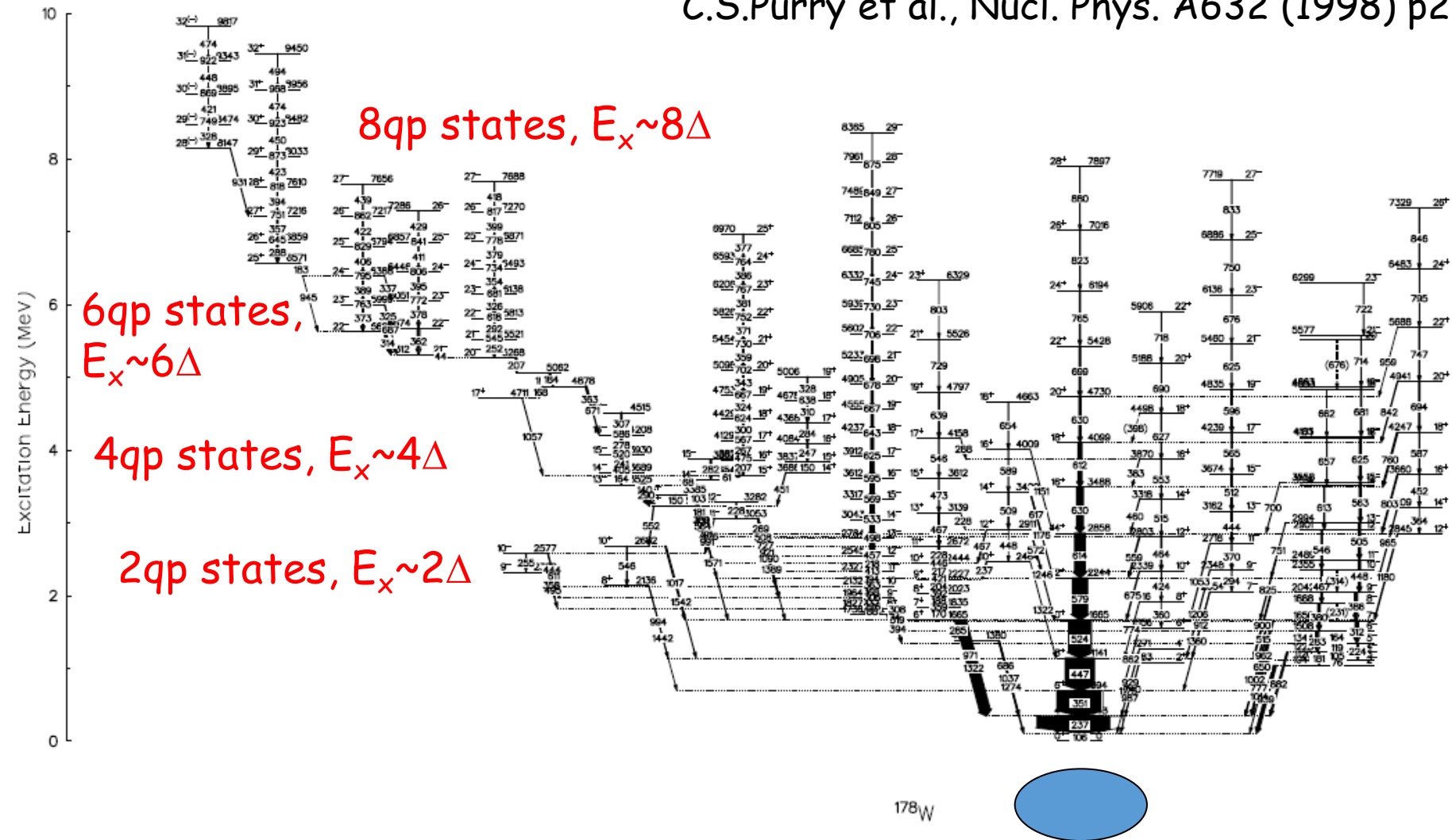
3-D HO. where $\hbar\omega \rightarrow \hbar\omega_x + \hbar\omega_y + \hbar\omega_z$

axial symmetry means $\omega_x = \omega_y$

quantum numbers $[N, n_x, \Lambda] \Omega^\pi$

$> \text{prolate } \beta_2$





^{178}W : different and discrete 0, 2, 4, 6 and 8 quasi-particle band structures are all observed:

These are built on different underlying single-particle (Nilsson) orbital configurations.

'Forbiddenness' in K isomers

We can use single particle ('Weisskopf') estimates for transitions rates for a given multipolarity. (E_γ (keV) , $T_{1/2}$ (s), Firestone and Shirley, *Table of Isotopes* (1996).

Weisskopf Estimates for $T^{1/2}$ $A=180$, $E_\gamma = 500$ keV

$$E1 \rightarrow T_W^{1/2} = 6.76 \times 10^{-6} E_\gamma^{-3} A^{-2/3} \rightarrow 1.6 \times 10^{-15} s$$

$$M1 \rightarrow T_W^{1/2} = 2.20 \times 10^{-5} E_\gamma^{-3} \rightarrow 1.8 \times 10^{-13} s$$

$$E2 \rightarrow T_W^{1/2} = 9.52 \times 10^{-6} E_\gamma^{-5} A^{-4/3} \rightarrow 3.0 \times 10^{-10} s$$

$$M2 \rightarrow T_W^{1/2} = 3.10 \times 10^{-7} E_\gamma^{-5} A^{-2/3} \rightarrow 3.1 \times 10^{-8} s$$

Hindrance (F) (removing dependence on multipolarity and E_γ) is defined by

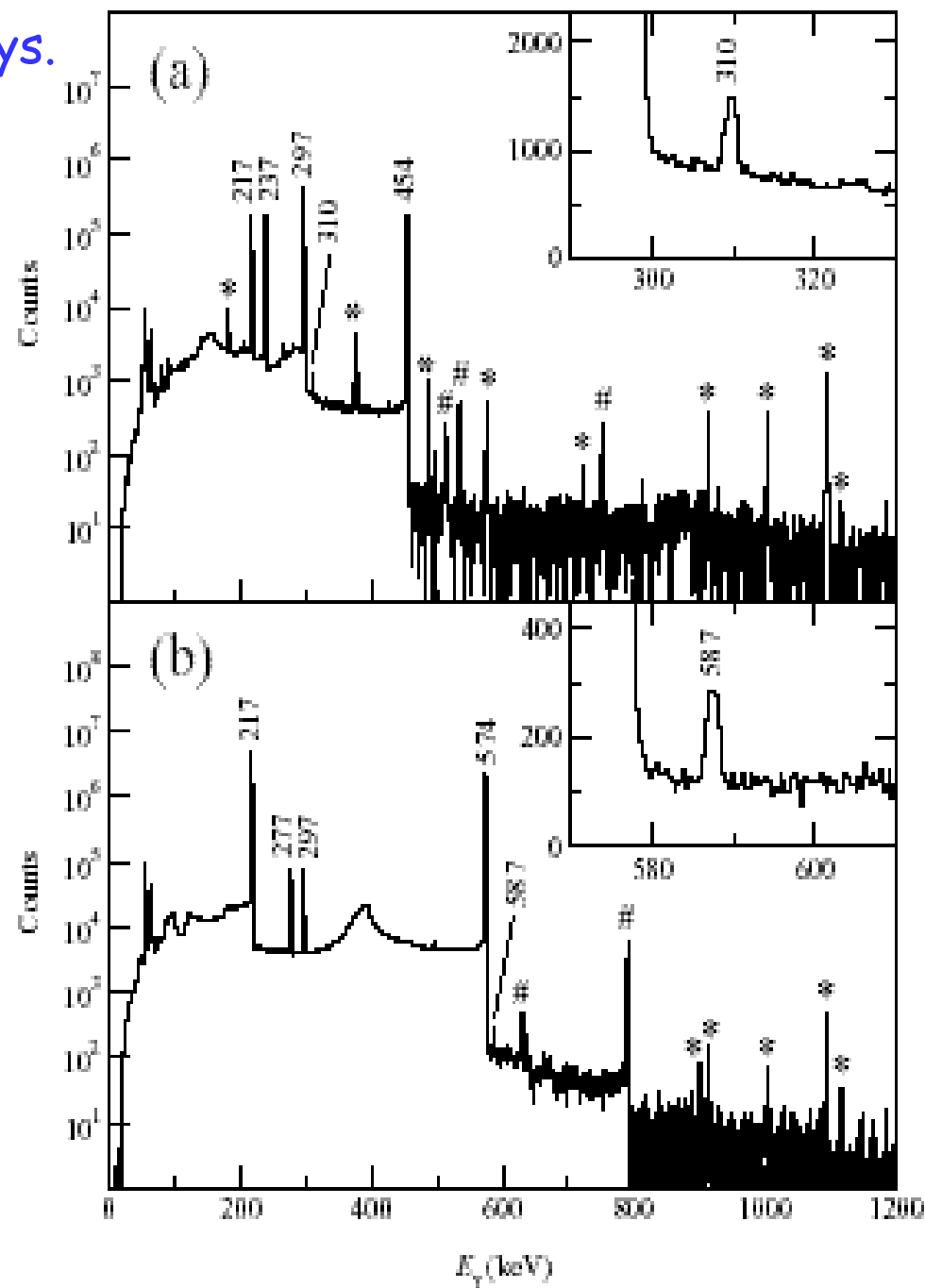
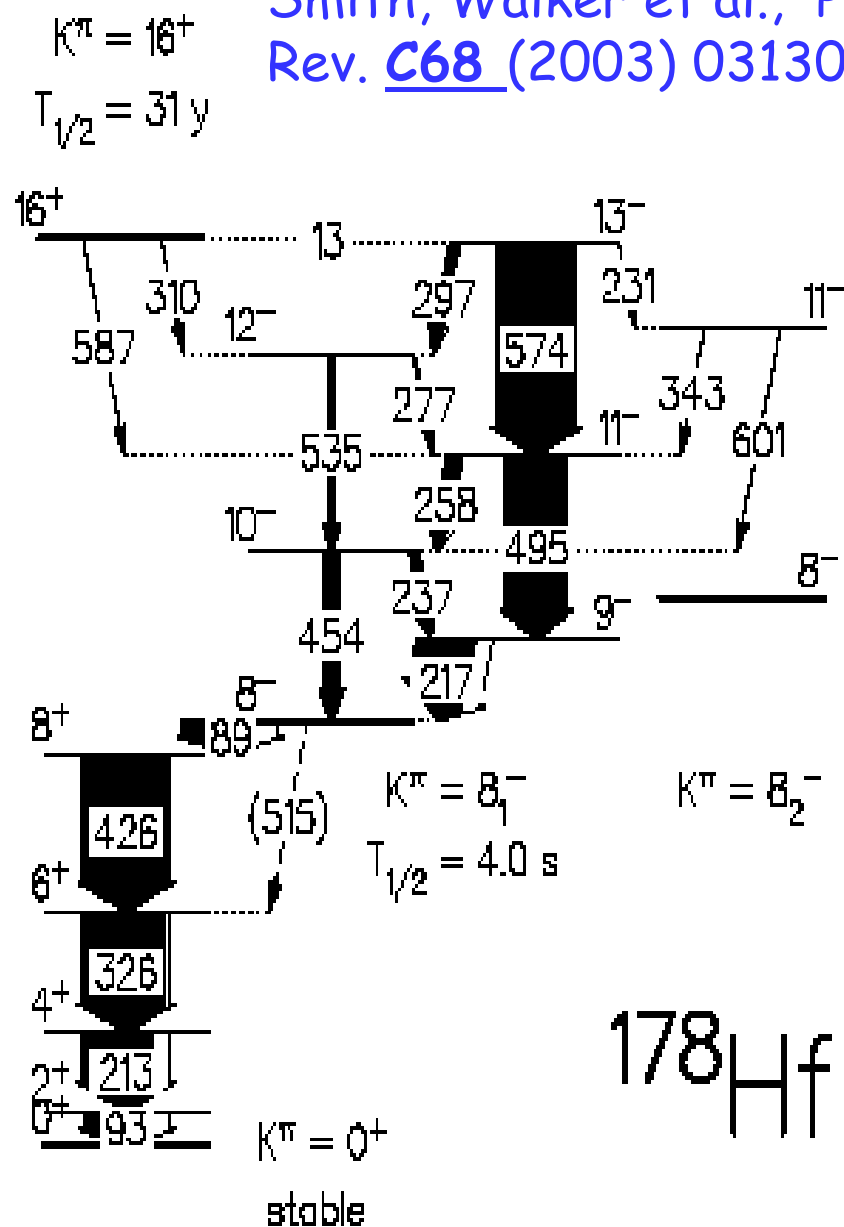
$$F = \left(\frac{T_{1/2}^\gamma}{T_{1/2}^W} \right) = \text{ratio of expt. and Weisskopf trans. rates}$$

Reduced Hindrance (f_ν) gives an estimate for the 'goodness' of K- quantum number and validity of K-selection rule (= a measure of axial symmetry).

$$f_\nu = F^{1/\nu} = \left(\frac{T_{1/2}^\gamma}{T_{1/2}^W} \right)^{1/\nu}, \quad \nu = \Delta K - \lambda$$

$f_\nu \sim 100$ typical value for 'good' K isomer (see Lobner Phys. Lett. **B26** (1968) p279)

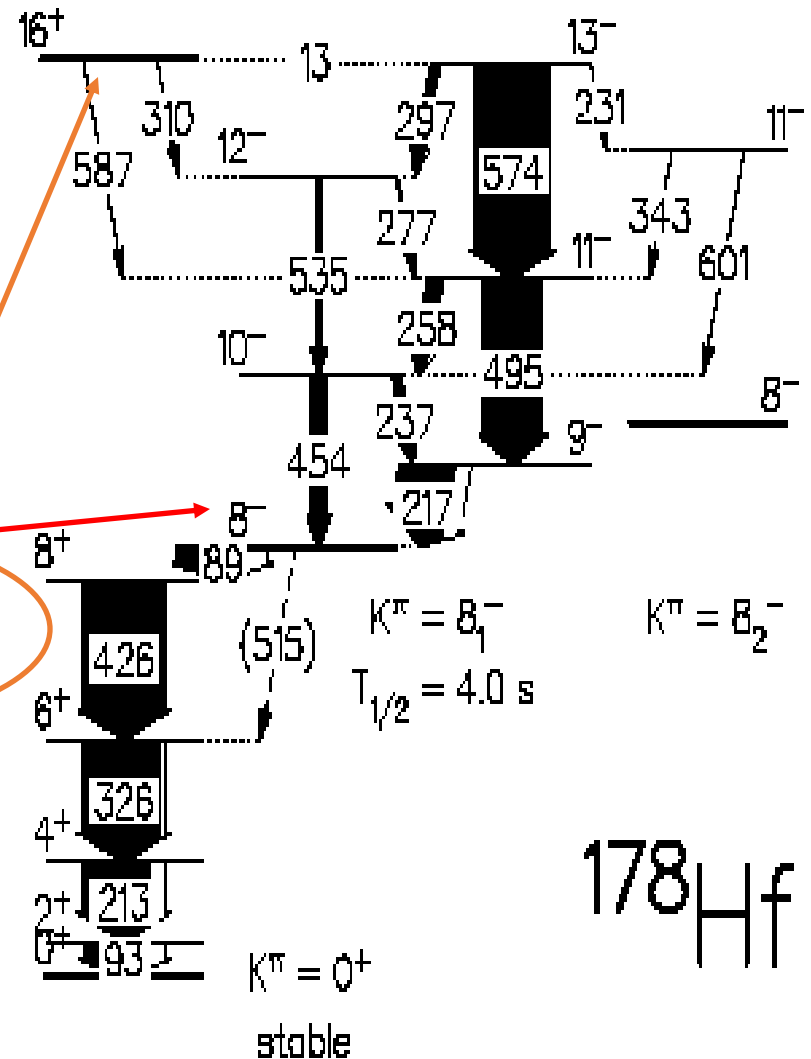
Smith, Walker et al., Phys.
Rev. C68 (2003) 031302



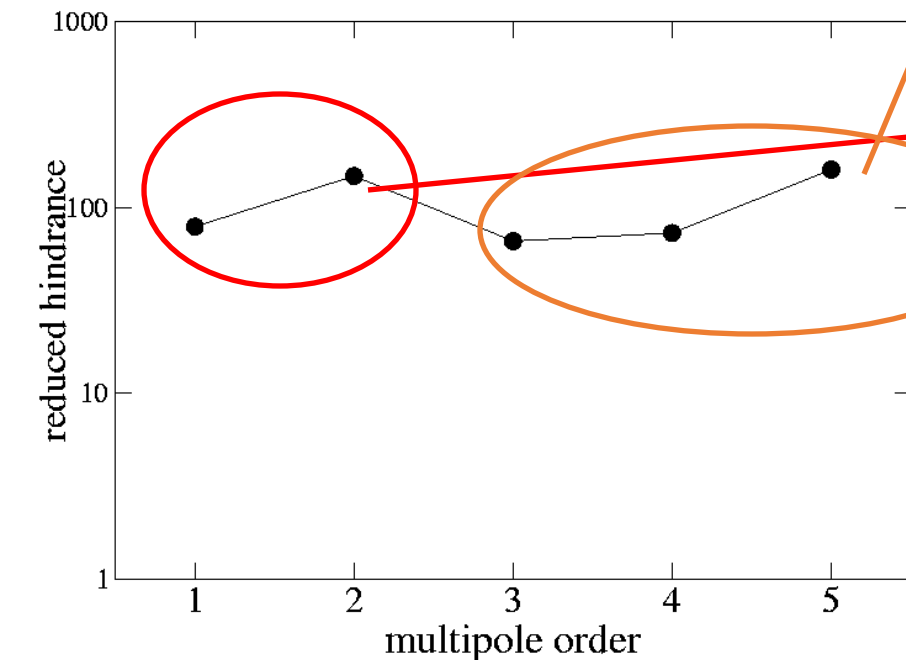
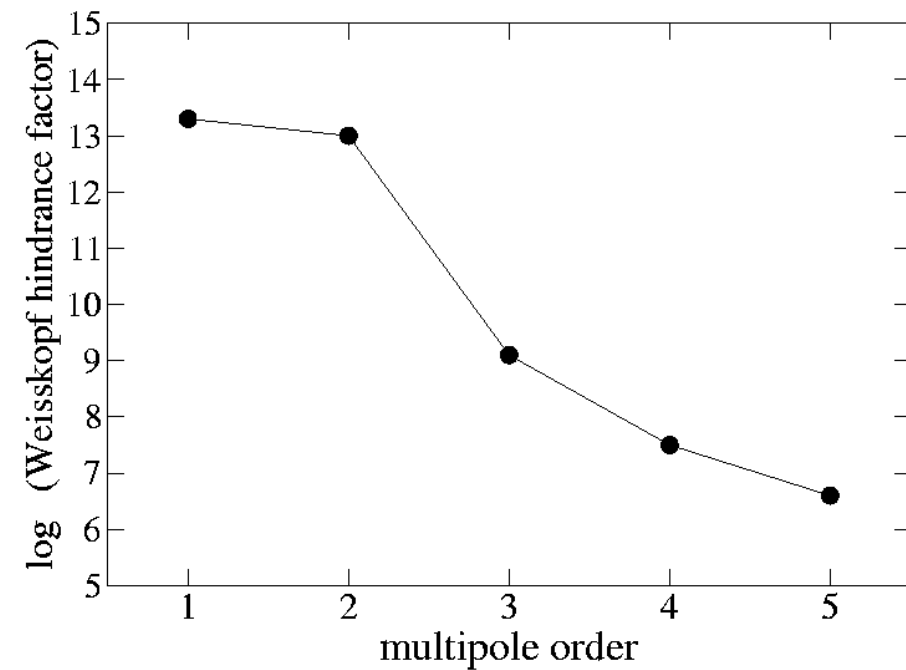
Smith, Walker et al., Phys. Rev.
C68 (2003) 031302

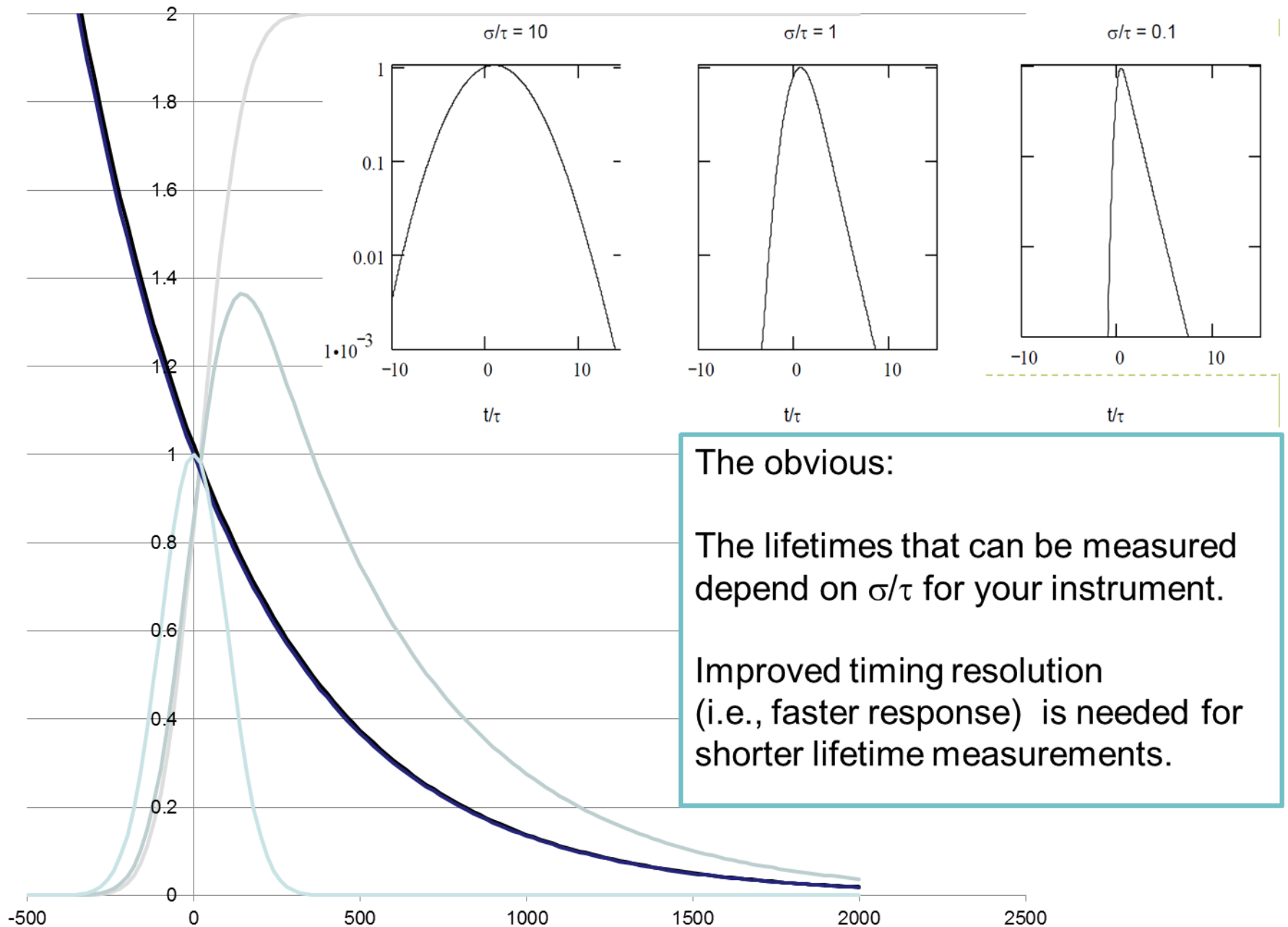
$$K^\pi = 16^+$$

$$T_{1/2} = 31 \text{ y}$$

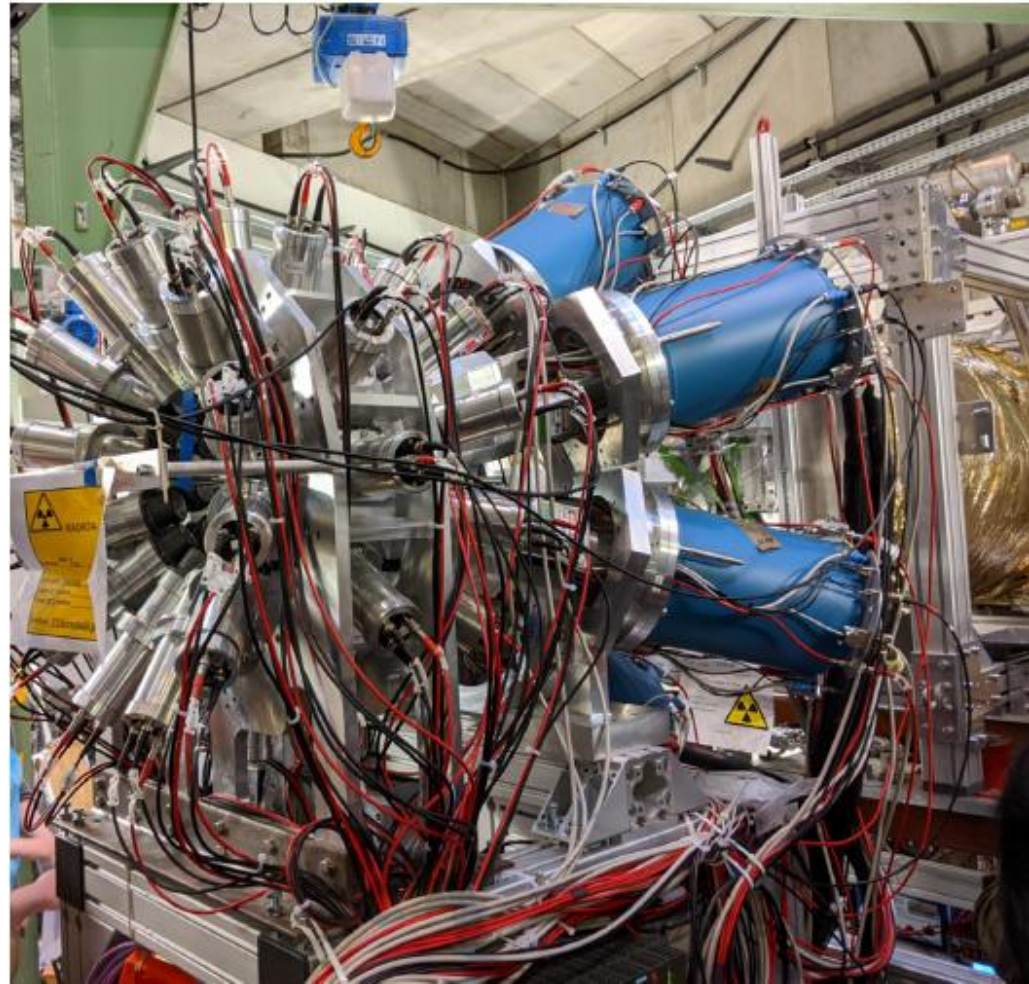


^{178}Hf



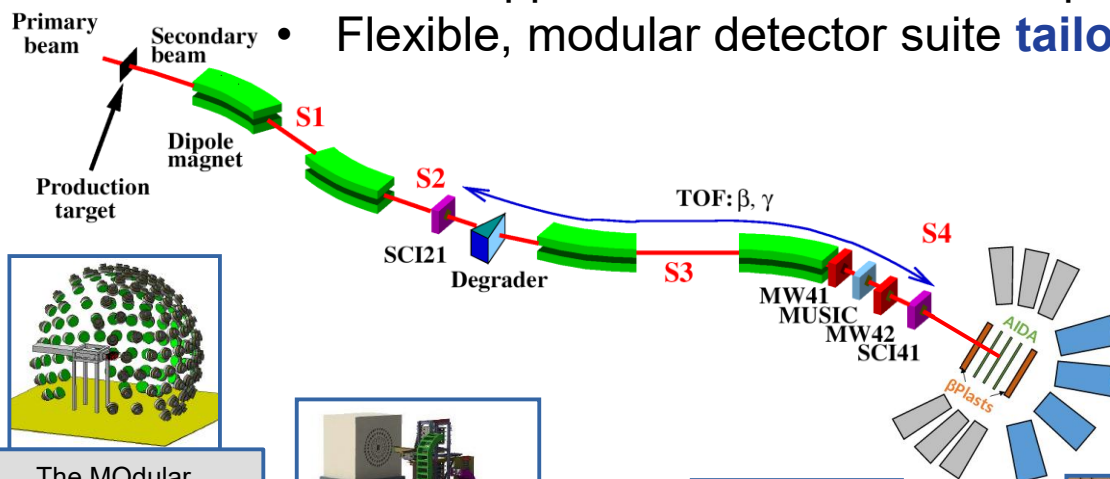


FATIMA in DESPEC at FAIR Phase -0



DESPEC Setup Overview

- **Exotic beams** delivered by the FRagment Separator
- Ions stopped inside DESPEC setup
- Flexible, modular detector suite **tailored to physics goals**



A.K. Mistry *et al.*, The DESPEC setup for GSI and FAIR, NIM A, 166662 (2022)

The MODular Neutron SpectromETER (MONSTER)

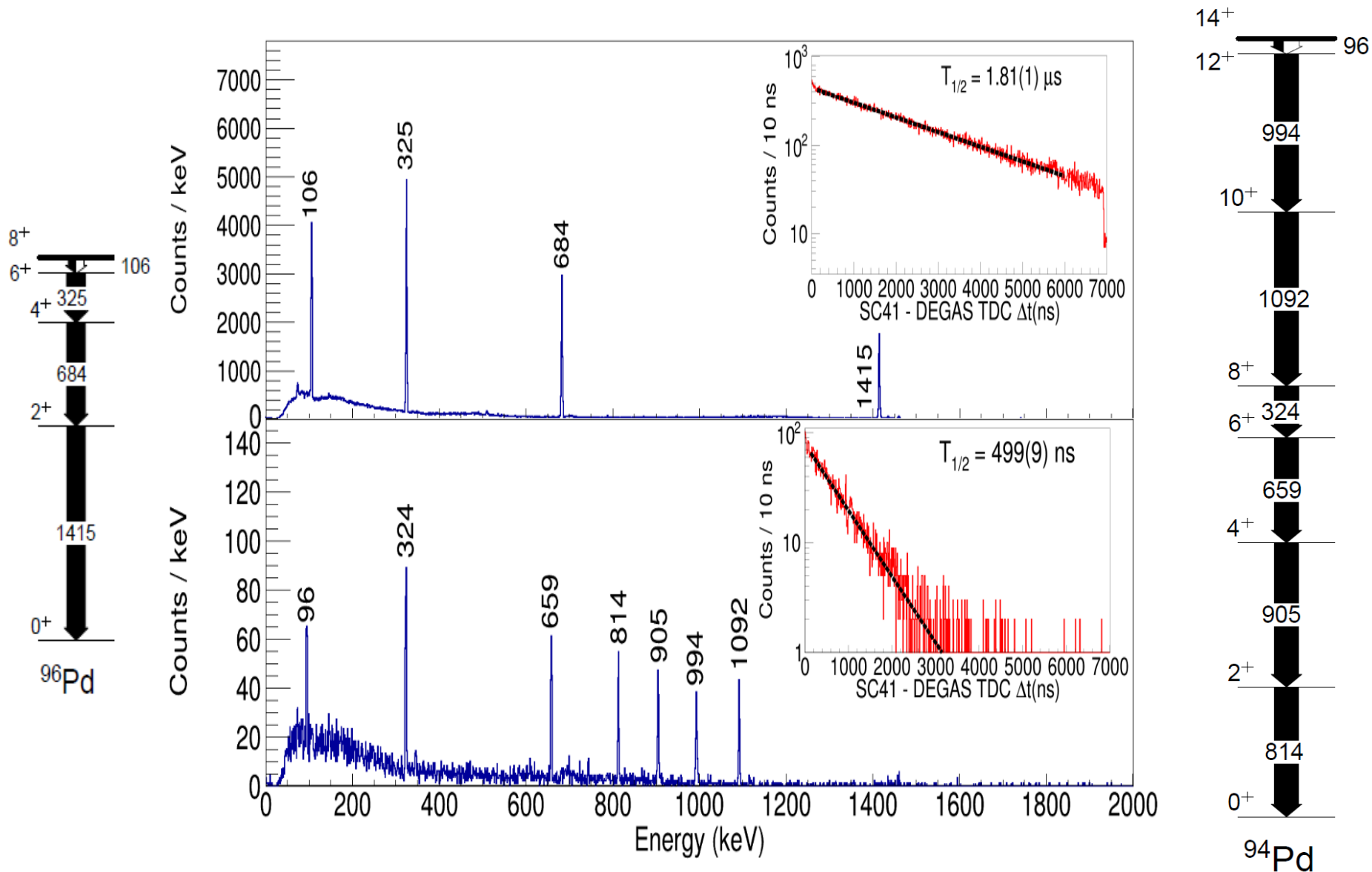
BEta-deLayEd Neutron detector (BELEN)
48 ^3He cylindrical counters

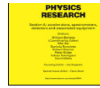
Decay Total Absorption γ -ray Spectrometer (DTAS)
 NaI(Tl) modules

FAst TIMing Array $\text{LaBr}_3(\text{Ce})$ modules (FATIMA)

DESPEC Ge Array Spectrometer (DEGAS)

GTC analysis highlighting $^{94,96}\text{Pd}$ isomers and lifetime analysis





Full Length Article

Response of the FAST Timing Array (FATIMA) for DESPEC at FAIR Phase-0

M.M.R. Chishti^{a,b,*}, S. Jazrawi^{a,c}, R. Shearman^c, P.H. Regan^{a,c}, Zs. Podolyák^a, S.M. Collins^{a,c}, M. Górski^g, B. Cederwallⁱ, A. Yaneva^{g,o}, G.X. Zhang^{d,e}, J. Cederkall^b, A. Goasduff^f, H.M. Albers^g, S. Alhomaidhi^g, A. Banerjee^g, A.M. Bruce^k, G. Benzoni^{h,t}, B. Dasⁱ, T. Davinson^l, L.M. Fraile^m, J. Gerl^g, G. Häfner^{o,n}, J. Jolie^o, N. Hubbard^{j,g}, P.R. John^j, R. Lozevaⁿ, A.K. Mistry^g, B.S. Nara Singh^p, M. Mikolajczuk^g, M. Polettini^{h,t}, N. Pietralla^j, J.M. Regis^o, M. Rudigier^g, E. Sahin^{g,q}, A. Sharma^{g,s}, M. Siⁿ, J. Vesic^q, V. Wernerⁿ

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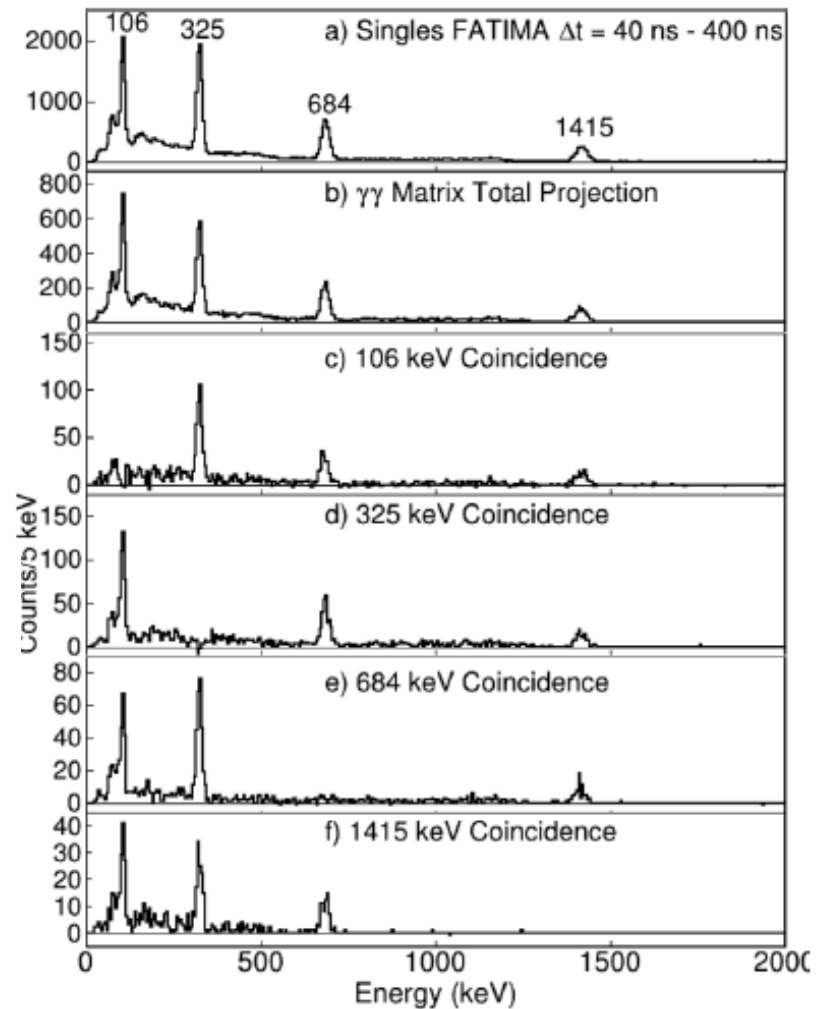
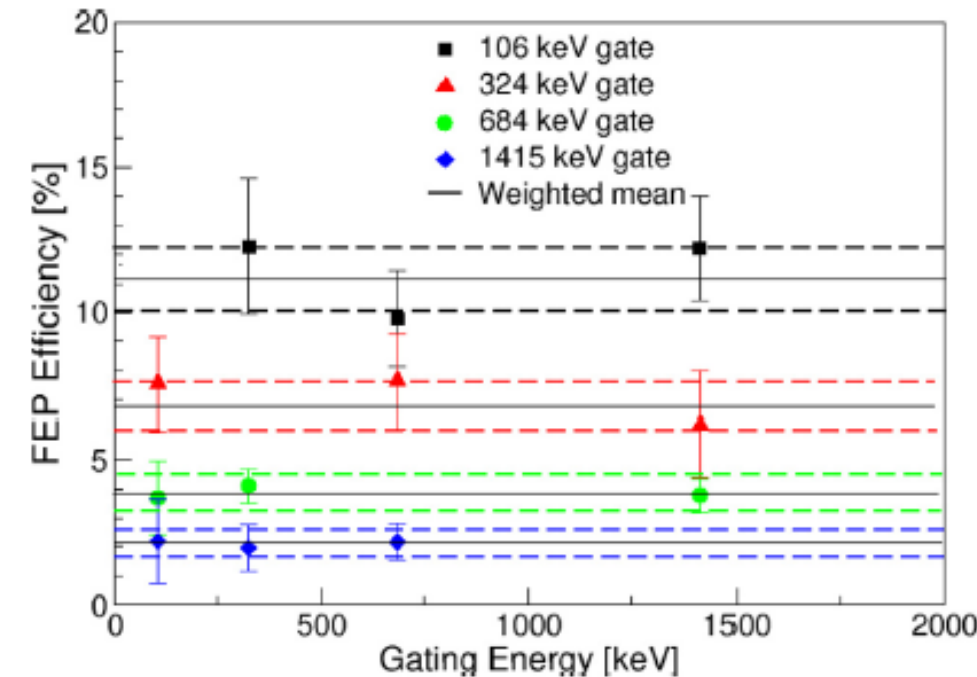
^{bh} Institut für Kernphysik TU Darmstadt, Darmstadt, Germany

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^{bl} Institut für Kernphysik TU Darmstadt, Darmstadt, Germany



$$\epsilon_{\gamma_1} = \frac{I_{\gamma_1 \gamma_2} (1 + \alpha_2)}{I_{\gamma_2}}$$

^{96}Pd $I^\pi=8^+$ isomer decay, gated on 1415 keV $2^+ \rightarrow 0^+$ transition.
 LaBr_3 ($\Delta T, E_\gamma$) matrix

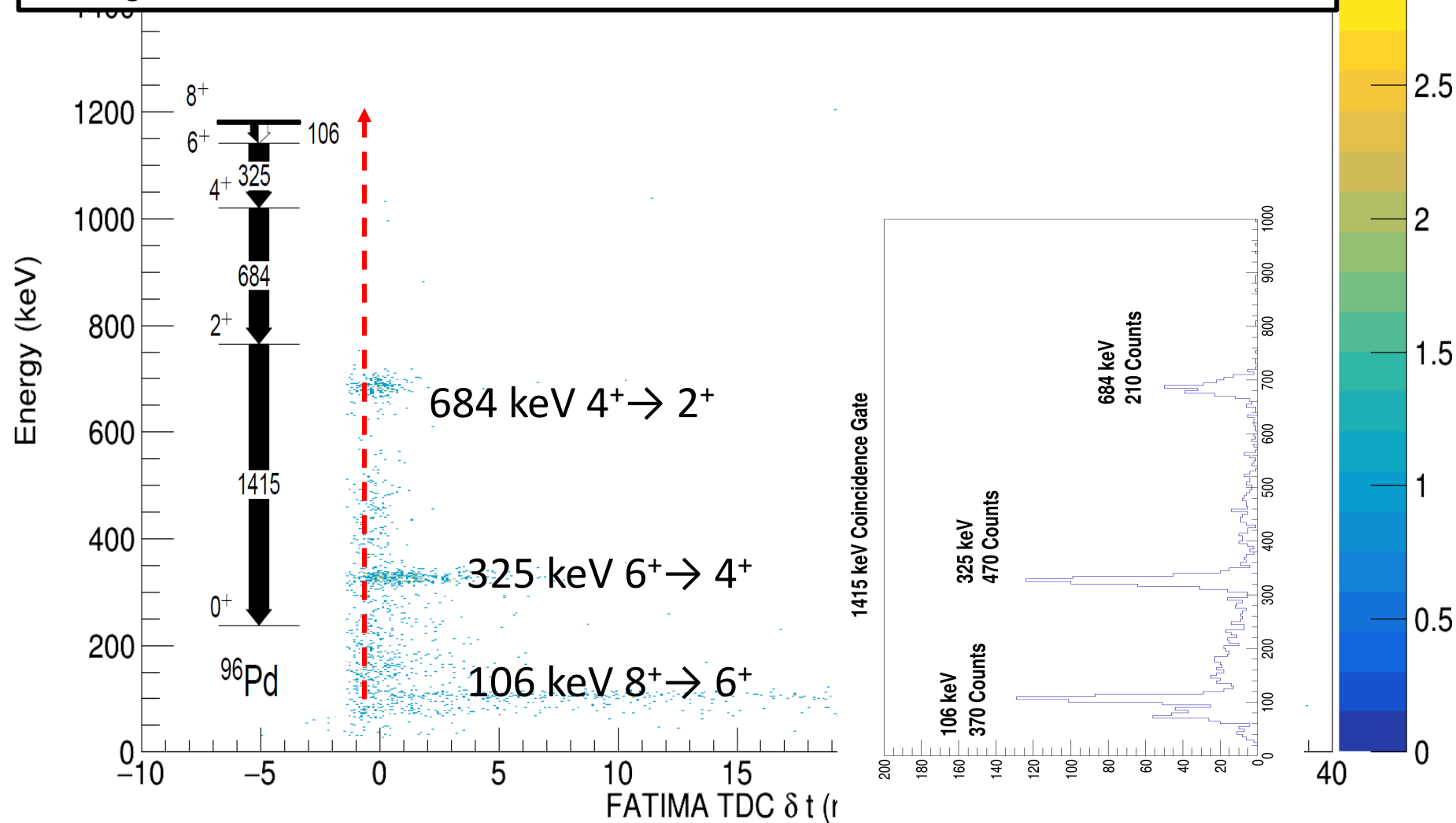


Figure S.Jazrawi, PhD thesis, U. Surrey 2022.,



$^{96}\text{Pd}_{50} \text{ } I^{\pi}=8^{+}$ isomer,
H. Mach et al., PRC95,
014313 (2017), with BaF_2

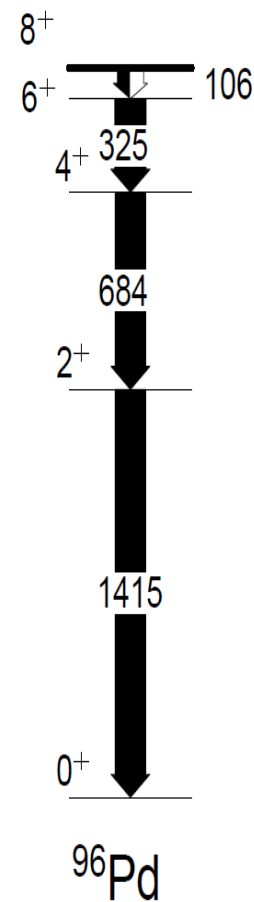
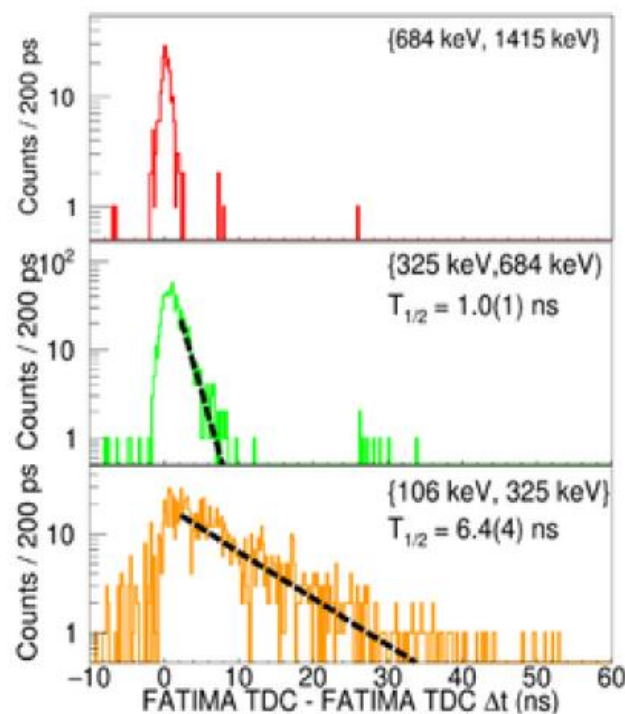
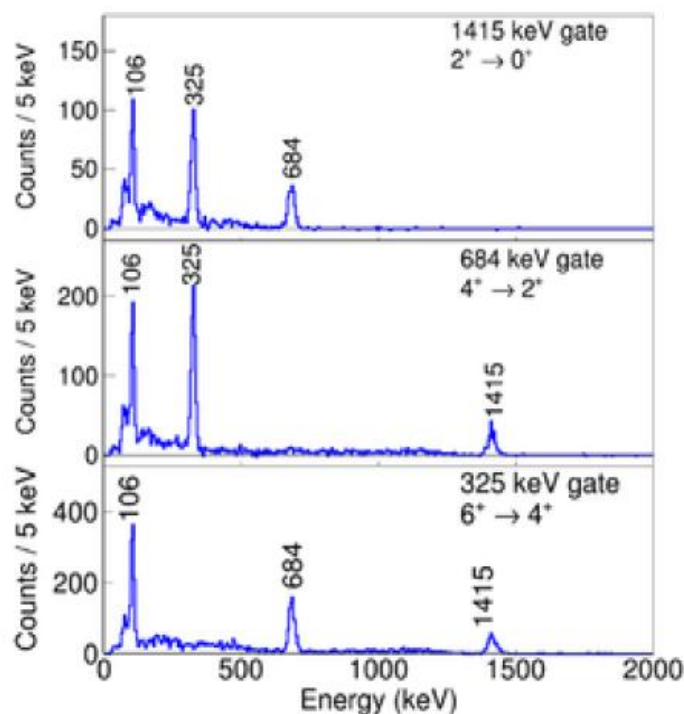
$T_{1/2}(6^{+}) = 6.3(6) \text{ ns}$

$T_{1/2}(4^{+}) = 1.0(1) \text{ ns}$

$T_{1/2}(2^{+}) < 17 \text{ ps}$

Commissioning the Fast TIMing array (FATIMA) at FAIR Phase-0: Half-lives of excited states in the $N = 50$ isotones ^{96}Pd and ^{94}Ru

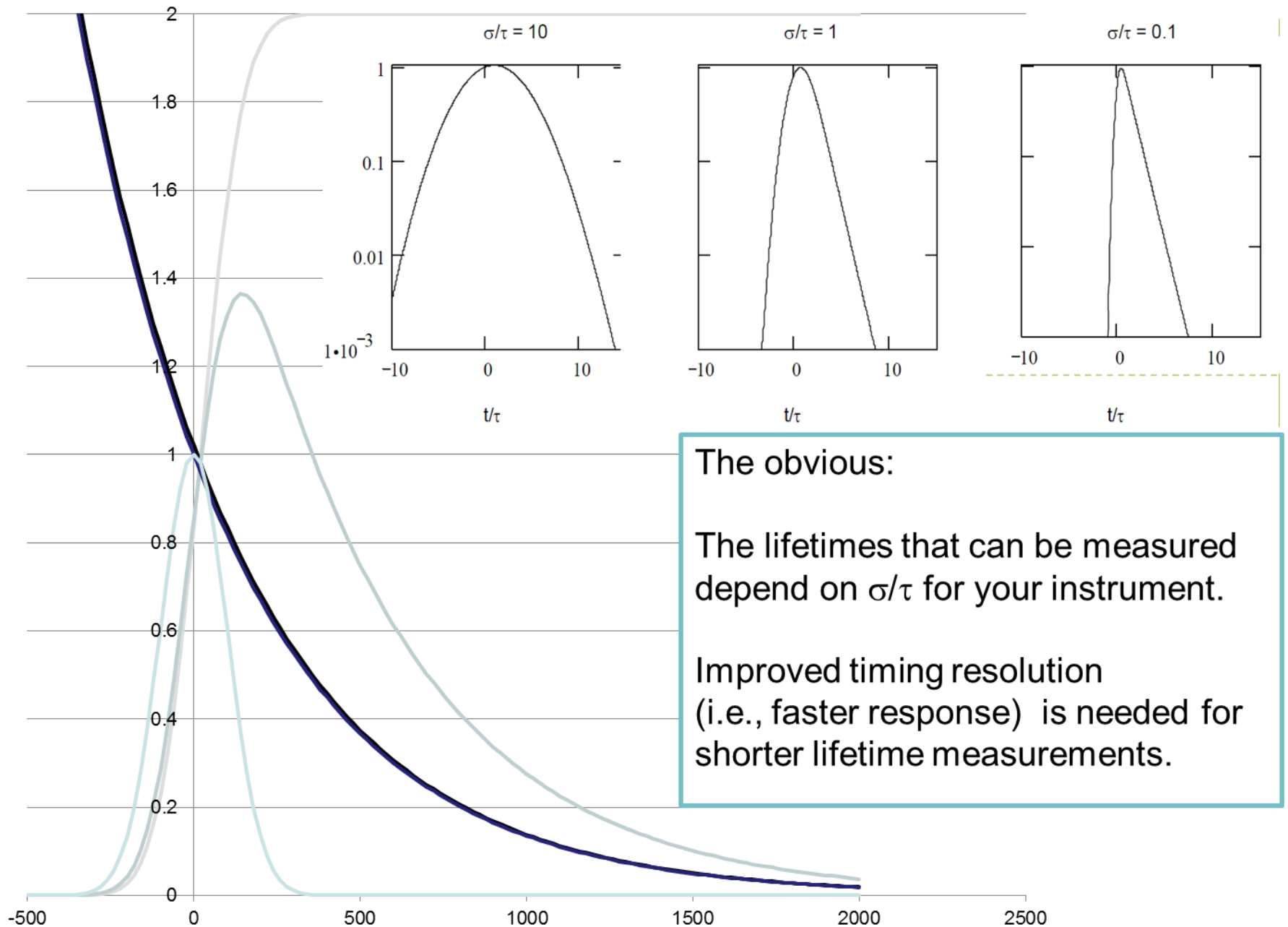
S. Jazrawi^{a, b, *}, A. Yaneva^{c, d}, M. Polettini^e, B. Das^f, P.H. Regan^{a, b, **}, M. Górska^c, B. Cederwall^f, J. Jolie^d, H.M. Albers^c, M.M.R. Chishti^a, A. Banerjee^c, N. Hubbard^{c, g}, A.K. Mistry^{c, g}, M. Rudigier^g, G. Benzoni^e, J. Gerl^c, A.M. Bruce^b, Zs Podolyák^a, B.S. Nara Singhⁱ, G.X. Zhang^{j, k}, S. Alhomaidhi^{c, g}, C. Appleton^l, T. Arici^c, A. Blazhev^d, T. Davinson^l, A. Esmaylzadeh^d, L.M. Fraile^m, G. Häfner^{d, q}, O. Hall^l, P.R. John^g, V. Karayonchev^d, I. Koujoharov^c, N. Kurz^c, M. Mikolajczuk^{c, n}, N. Pietralla^g, S. Pietri^c, J.M. Regis^d, E. Sahin^{c, g}, L. Sexton^l, H. Schaffner^c, C. Scheidenberger^c, A. Sharma^{c, o}, J. Vesic^p, H. Weick^c, V. Werner^g for the DESPEC collaboration



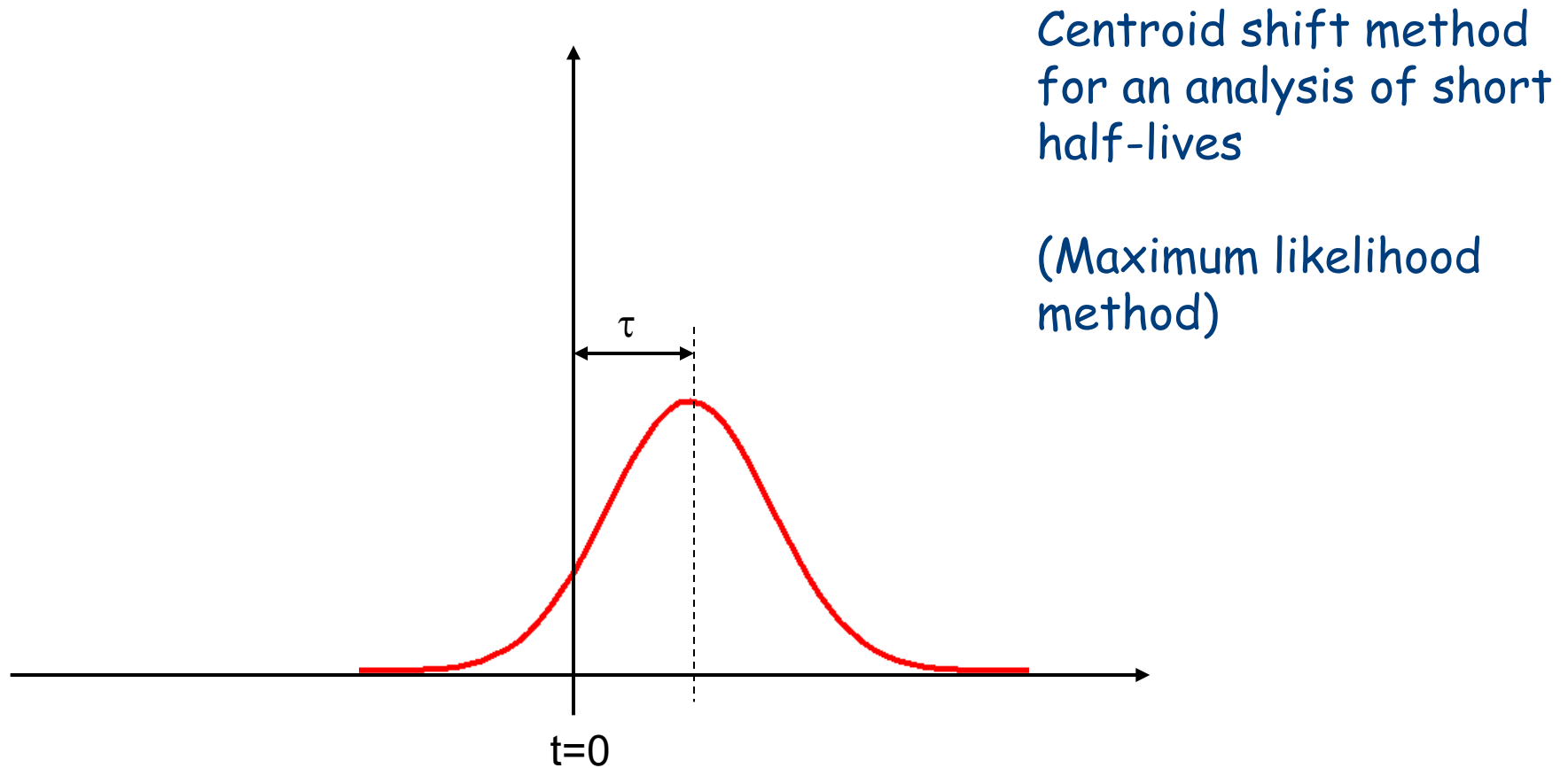
γ - γ - ΔT for transitions across individual states $^{96}\text{Pd}_{50}$

How to measure half-lives in the 10 ns - 10 fs range

- 1) Electronic co-incidence timing (~ 20 ps - 20 ns)
- 2) Recoil Doppler Distance method (~ 5 - ~ 500 ps)
- 3) Doppler Shift Attenuation Method (~ 5 ps to ~ 50 fs)

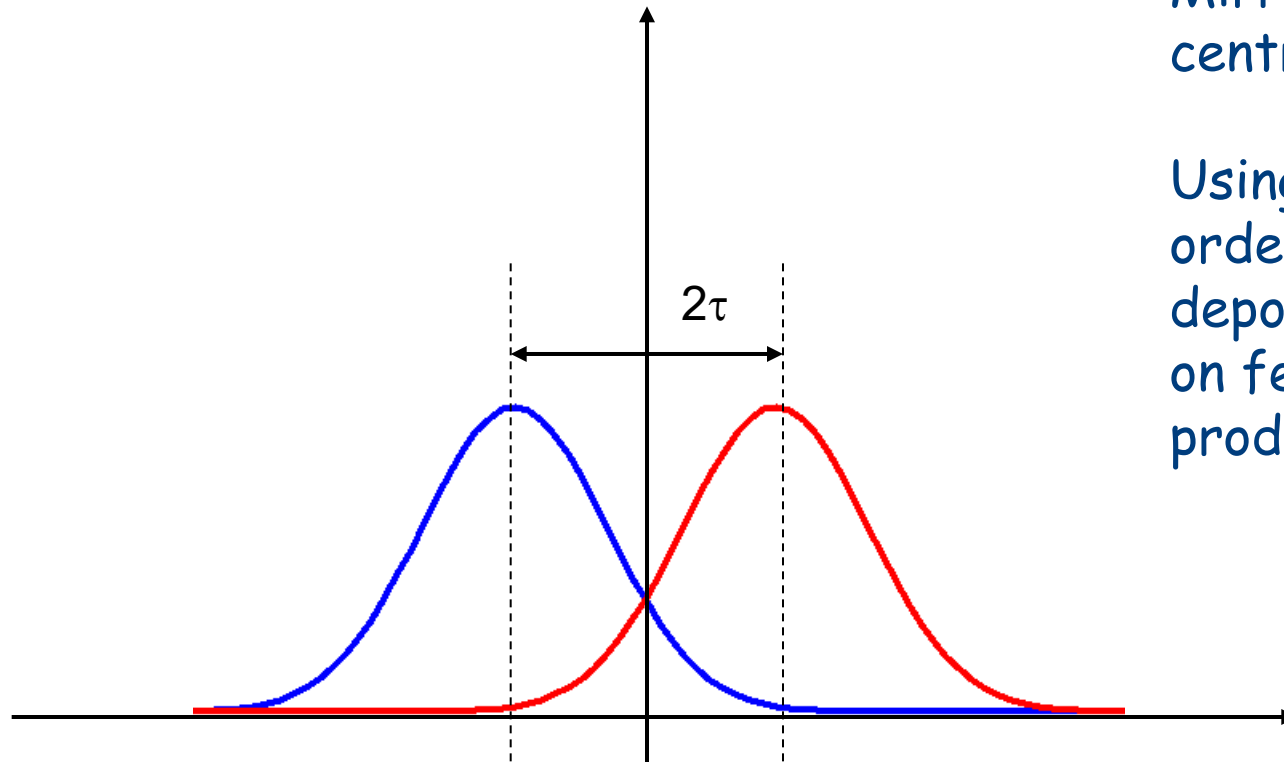


Fast-timing Techniques



Difference between the centroid of observed time spectrum and the prompt response give lifetime, τ

Fast-timing Techniques



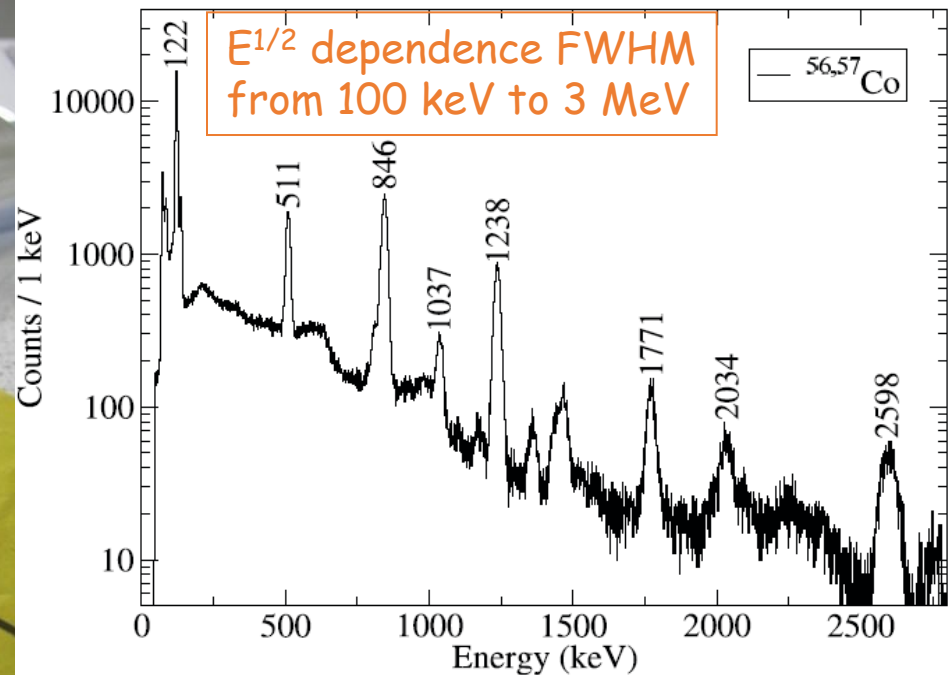
Mirror-symmetric
centroid shift method.

Using reversed gate
order (e.g. start TAC on
depopulating gamma, stop
on feeding gamma)
produces opposite shift

Removes the need to know where the prompt distribution is
and other problems to do with the prompt response of the
detectors

Gamma-ray Scintillation Detectors

- ▶ $\text{LaBr}_3(\text{Ce})$ has an energy-dependent timing-resolution FWHM of ~ 150 ps with ^{60}Co for a $\varnothing 1'' \times 1''$ crystal;
- ▶ an order of magnitude at least better than HpGe .
- ▶ Energy resolution $\sim 3\%$ FWHM at 662 keV.
- ▶ Peak emission wavelength ~ 380 nm, compatible with PMTs



e.g., P.H.Regan et al., Applied Radiation and Isotopes **70** (2012) p1125 ;
L. Fraile et al., Nucl. Inst. Meth. Phys. Res. B**463** (2020) p394

Mixed HPGe-LaBr3 'hybrid' arrays - ROSPHERE

Nuclear Instruments and Methods in Physics Research A 837 (2016) 1–10



Contents lists available at ScienceDirect

Nuclear Instruments and Methods in
Physics Research A

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

The ROSPHERE γ -ray spectroscopy array

D. Bucurescu^a, I. Căta-Danil^a, G. Ciocan^a, C. Costache^a, D. Deleanu^a, R. Dima^a,
D. Filipescu^{a,c}, N. Florea^a, D.G. Ghiță^a, T. Glodariu^a, M. Ivașcu^a, R. Lică^a, N. Mărginean^a,
R. Mărginean^a, C. Mihai^{a,*}, A. Negret^a, C.R. Niță^a, A. Olăcel^a, S. Pascu^a, T. Sava^a, L. Stroe^a,
A. Șerban^{a,i}, R. Șuvăilă^a, S. Toma^a, N.V. Zamfir^{a,c}, G. Căta-Danil^b, I. Gheorghe^c, I.O. Mitu^c,
G. Suliman^c, C.A. Ur^c, T. Braunroth^d, A. Dewald^d, C. Fransen^d, A.M. Bruce^e, Zs. Podolyák^f,
P.H. Regan^{f,g}, O.J. Roberts^h

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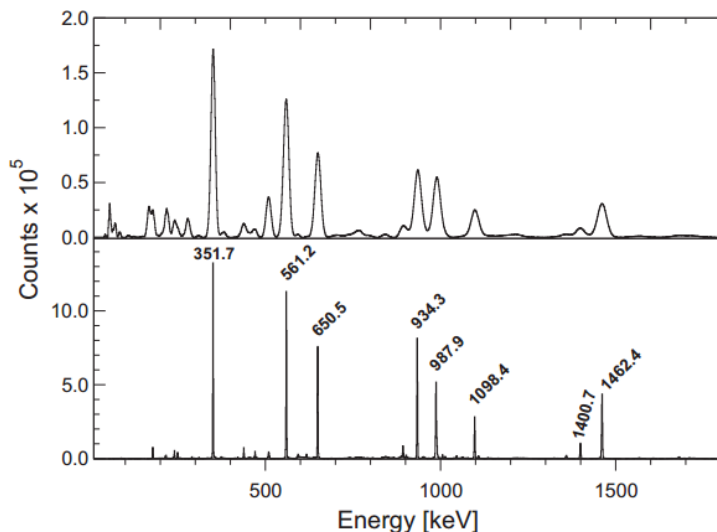


Fig. 10. γ -Ray energy spectra obtained by gating on the 934, 561, 1462, 352 and 988-keV yrast transitions in ^{92}Zr . Bottom: Summed gates in the HPGe-HPGe symmetric matrix; Top: Summed spectra from the $\text{LaBr}_3(\text{Ce})$ scintillators obtained with the same HPGe gates. The peaks are marked by their energy in keV.

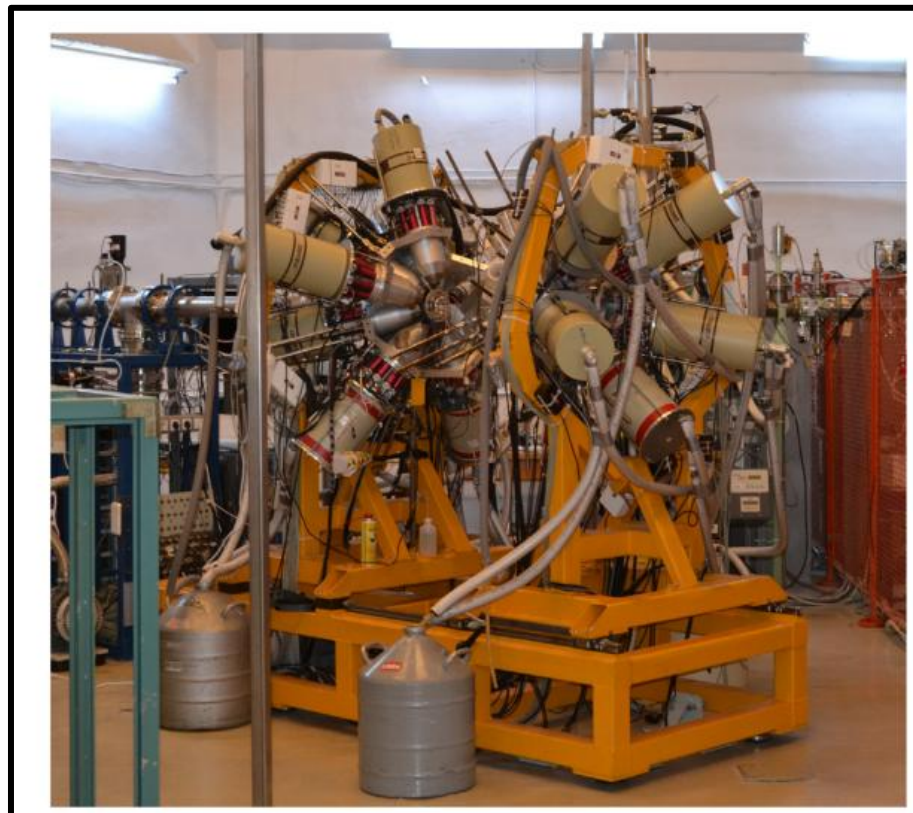
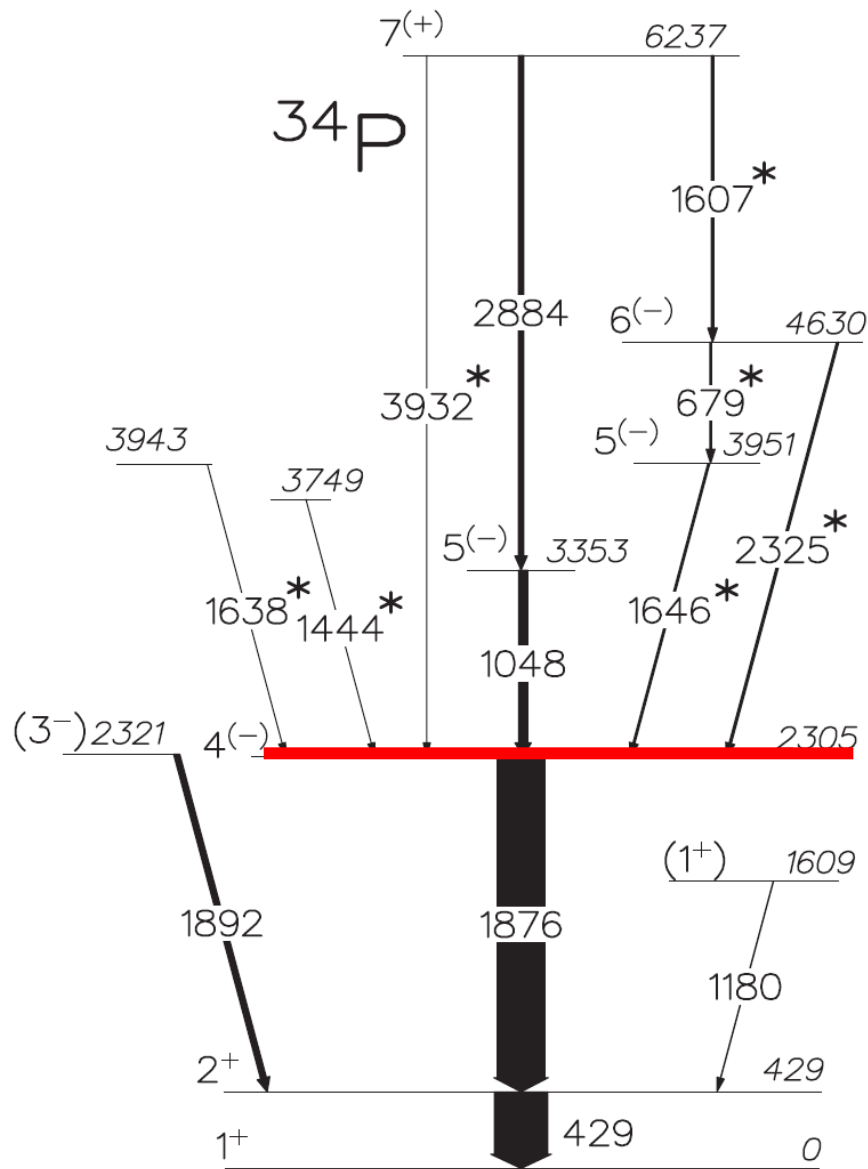


Table 1

Detector endcap to target distances for each type of HPGe detector and each ring.

Ring no.	No. of detectors	θ (degrees)	ϕ (degrees)	Distance type a (mm)	Distance type b (mm)
1 / 5	5 / 5	37 / 143	0, 72, 144, 216 and 288	179	210
2 / 4	5 / 5	70 / 110	36, 108, 180, 252 and 324	186	217
3	5	90	0, 72, 144, 216 and 288	176	208

An example, 'fast-timing' and id of M2 decay in ^{34}P .



P. C. BENDER *et al.* PHYSICAL REVIEW C 80, 014302 (2009)

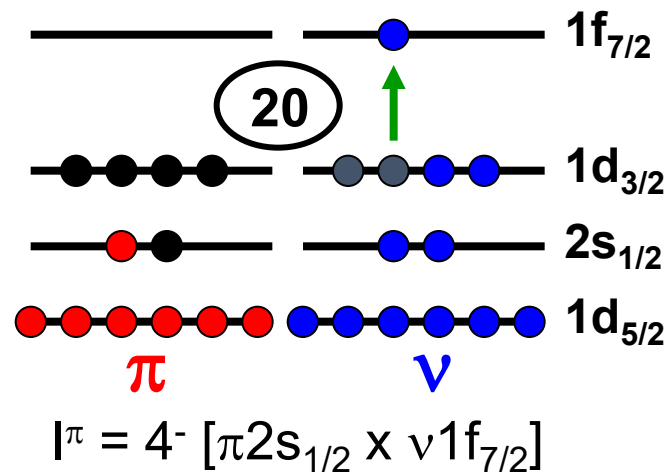
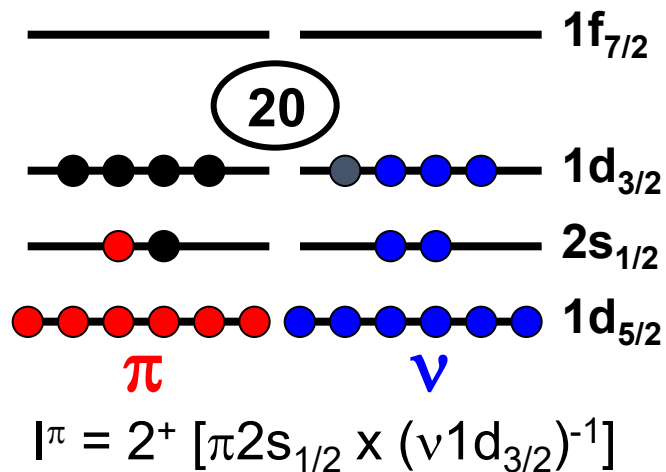
R. CHAKRABARTI *et al.* PHYSICAL REVIEW C 80, 034326 (2009)

- Study of ^{34}P identified low-lying $I^\pi=4^-$ state at $E=2305$ keV.
- $I^\pi=4^- \rightarrow 2^+$ transition can proceed by M2 and/or E3.
- Aim of experiment was to measure precision lifetime for 2305 keV state and obtain $B(\text{M2})$ and $B(\text{E3})$ values.
- Previous studies limit half-life to $0.3 \text{ ns} < t_{1/2} < 2.5 \text{ ns}$

P.J.R.Mason *et al.*, Phys. Rev. C85 (2012) 064303.

Physics....which orbitals are involved?

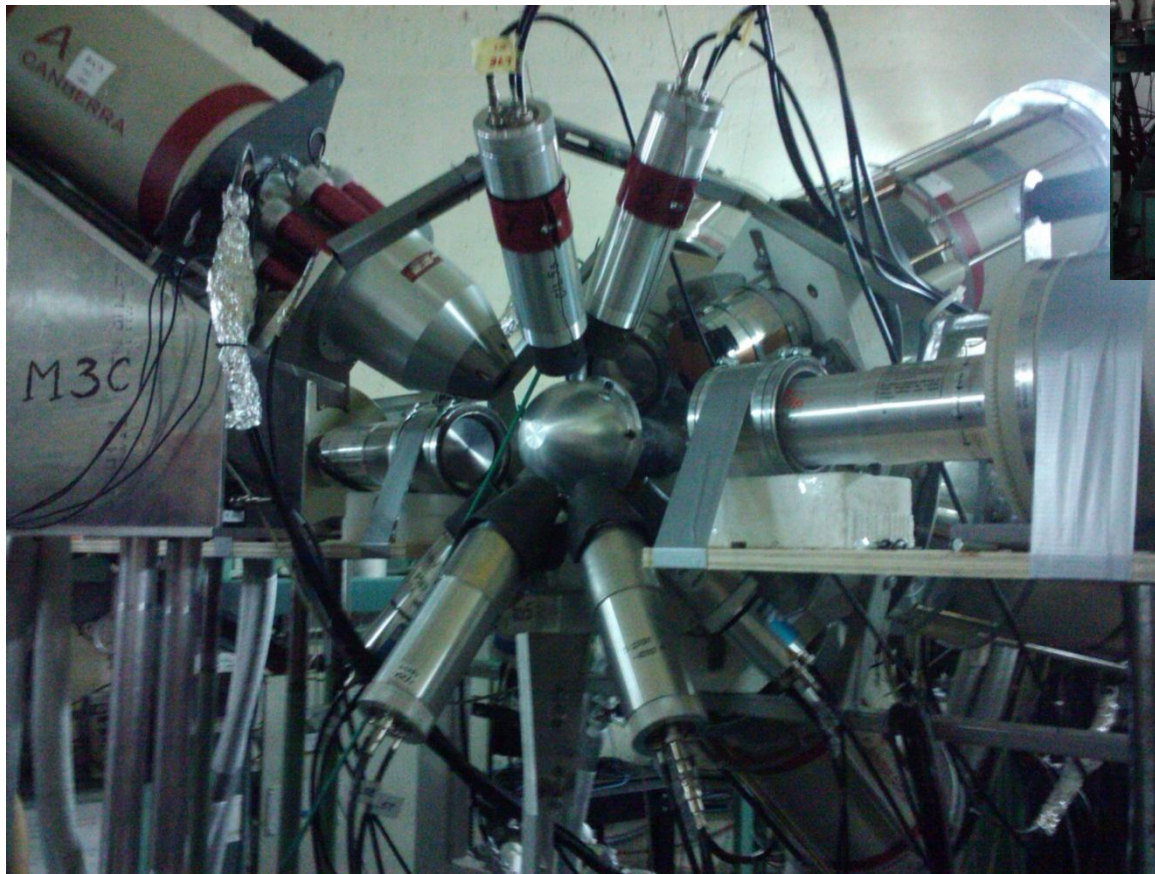
- Theoretical (shell model) predictions suggest 2^+ state based primarily on $[\pi 2s_{1/2} \times (\nu 1d_{3/2})^{-1}]$ configuration and 4^- state based primarily on $[\pi 2s_{1/2} \times \nu 1f_{7/2}]$ configuration.
- Thus expect transition to go mainly via $f_{7/2} \rightarrow d_{3/2}$, M2 transition.
- Different admixtures in 2^+ and 4^- states may also allow some E3 components (e.g., from, $f_{7/2} \rightarrow s_{1/2}$) in the decay.



Experiment to Measure Yrast 4- Lifetime in ^{34}P

$^{18}\text{O}(^{18}\text{O},\text{pn})^{34}\text{P}$ fusion-evaporation at 36 MeV $\sigma \sim 5 - 10$ mb

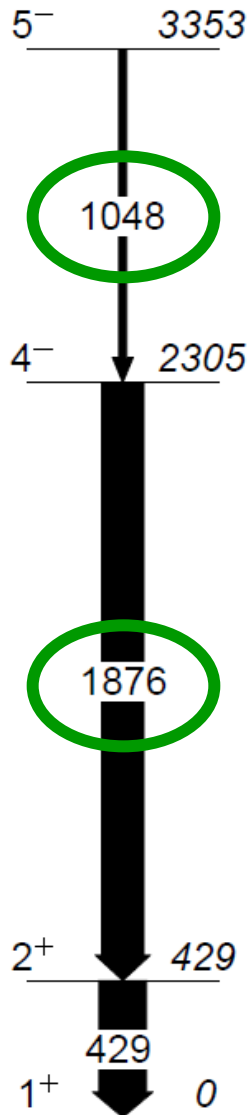
50mg/cm² Ta₂¹⁸O enriched foil; ^{18}O Beam from Bucharest Tandem (~20pA)



Array 8 HPGe
(unsuppressed) and 7
LaBr₃:Ce detectors

- 3 (2"x2") cylindrical
- 2 (1"x1.5") conical
- 2 (1.5"x1.5") cylindrical

Ge-Gated Time differences



PHYSICAL REVIEW C **85**, 064303 (2012)

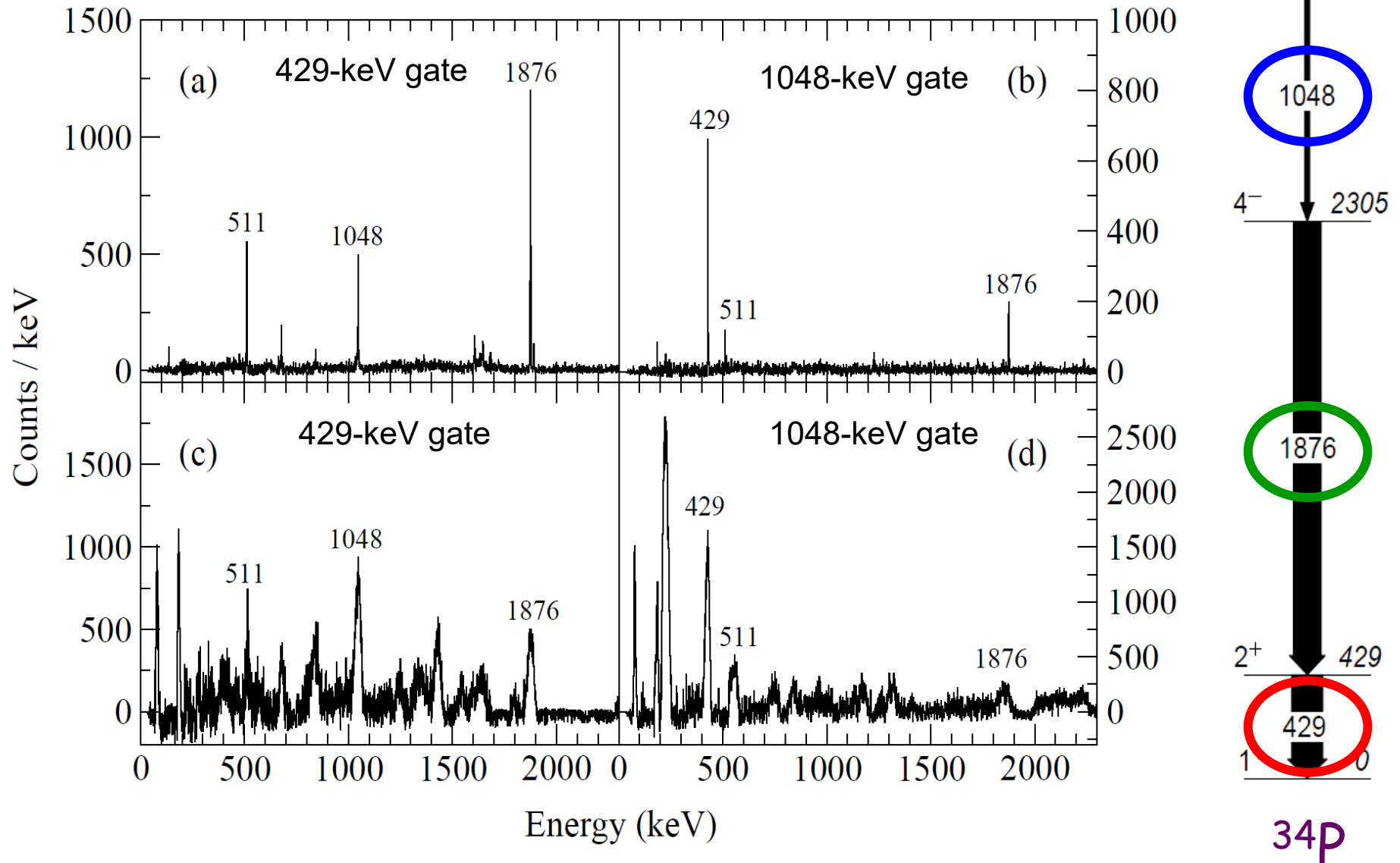
Half-life of the $I^\pi = 4^-$ intruder state in ^{34}P : $M2$ transition strengths approaching the island of inversion

P. J. R. Mason,¹ T. Alharbi,^{1,2} P. H. Regan,¹ N. Mărginean,³ Zs. Podolyák,¹ E. C. Simpson,¹ N. Alkhomashi,⁴ P. C. Bender,⁵ M. Bowry,¹ M. Bostan,⁶ D. Bucurescu,³ A. M. Bruce,⁷ G. Căta-Danil,³ I. Căta-Danil,³ R. Chakrabarti,⁸ D. Deleanu,³ P. Detistov,⁹ M. N. Erduran,¹⁰ D. Filipescu,³ U. Garg,¹¹ T. Glodariu,³ D. Ghiță,³ S. S. Ghugre,⁸ A. Kusoglu,⁶ R. Mărginean,³ C. Mihai,³ M. Nakhostin,¹ A. Negret,³ S. Pascu,³ C. Rodríguez Triguero,⁷ T. Sava,³ A. K. Sinha,⁸ L. Stroe,³ G. Suliman,³ and N. V. Zamfir³

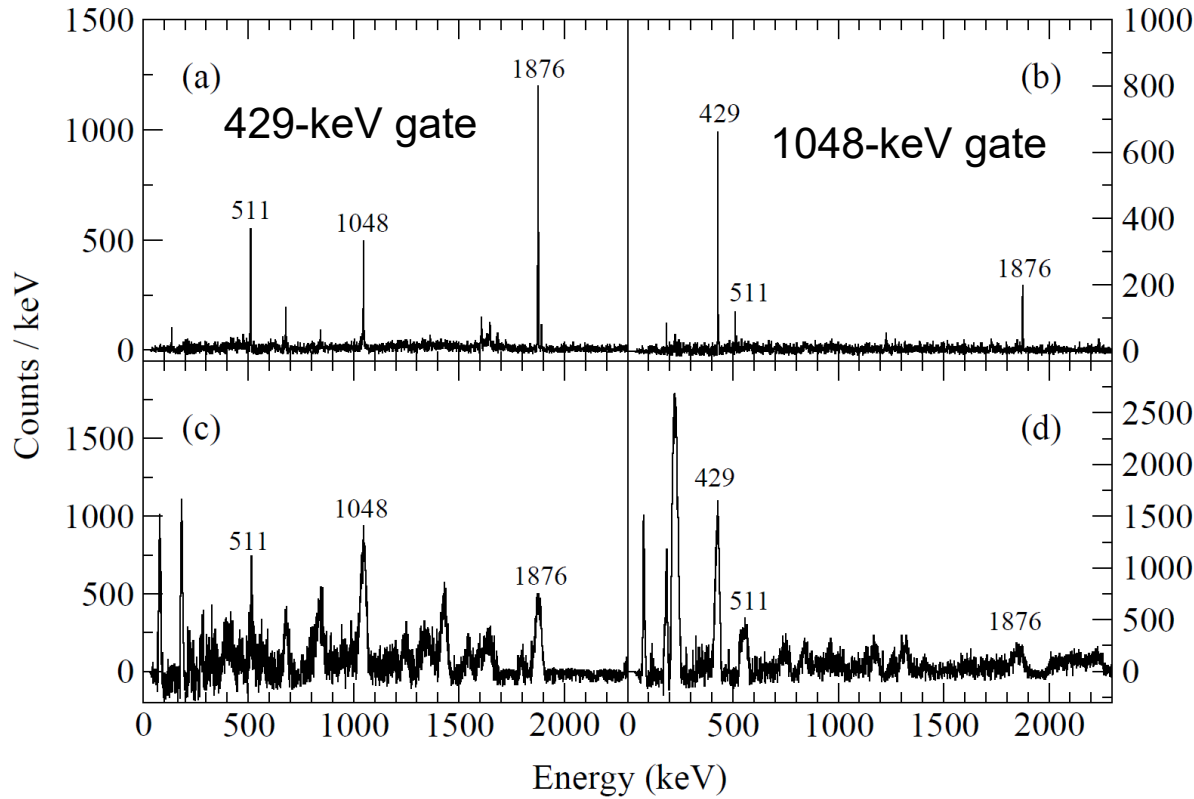
Gates in LaBr_3 detectors to observe time difference and obtain lifetime for state

Ideally, we want to measure the time difference between transitions directly feeding and depopulating the state of interest (4^-)

Gamma-ray energy coincidences 'locate' transitions above and below the state of interest....

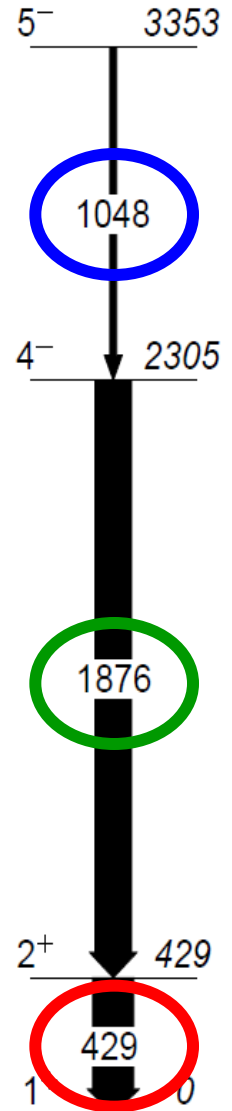
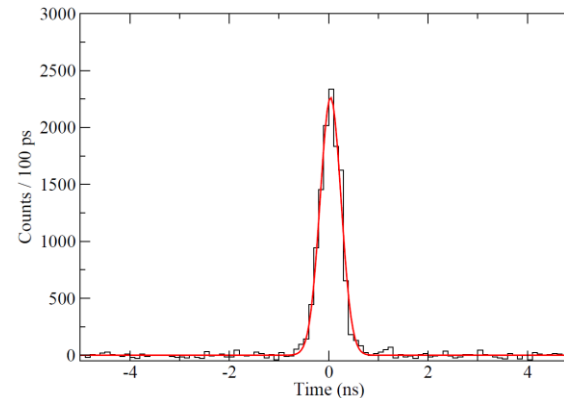


LaBr₃ - LaBr₃ Energy-gated time



The 1876-429-keV time difference in ³⁴P should show prompt distribution as half-life of 2⁺ is much shorter than prompt timing response.

Measured FWHM = 470(10) ps

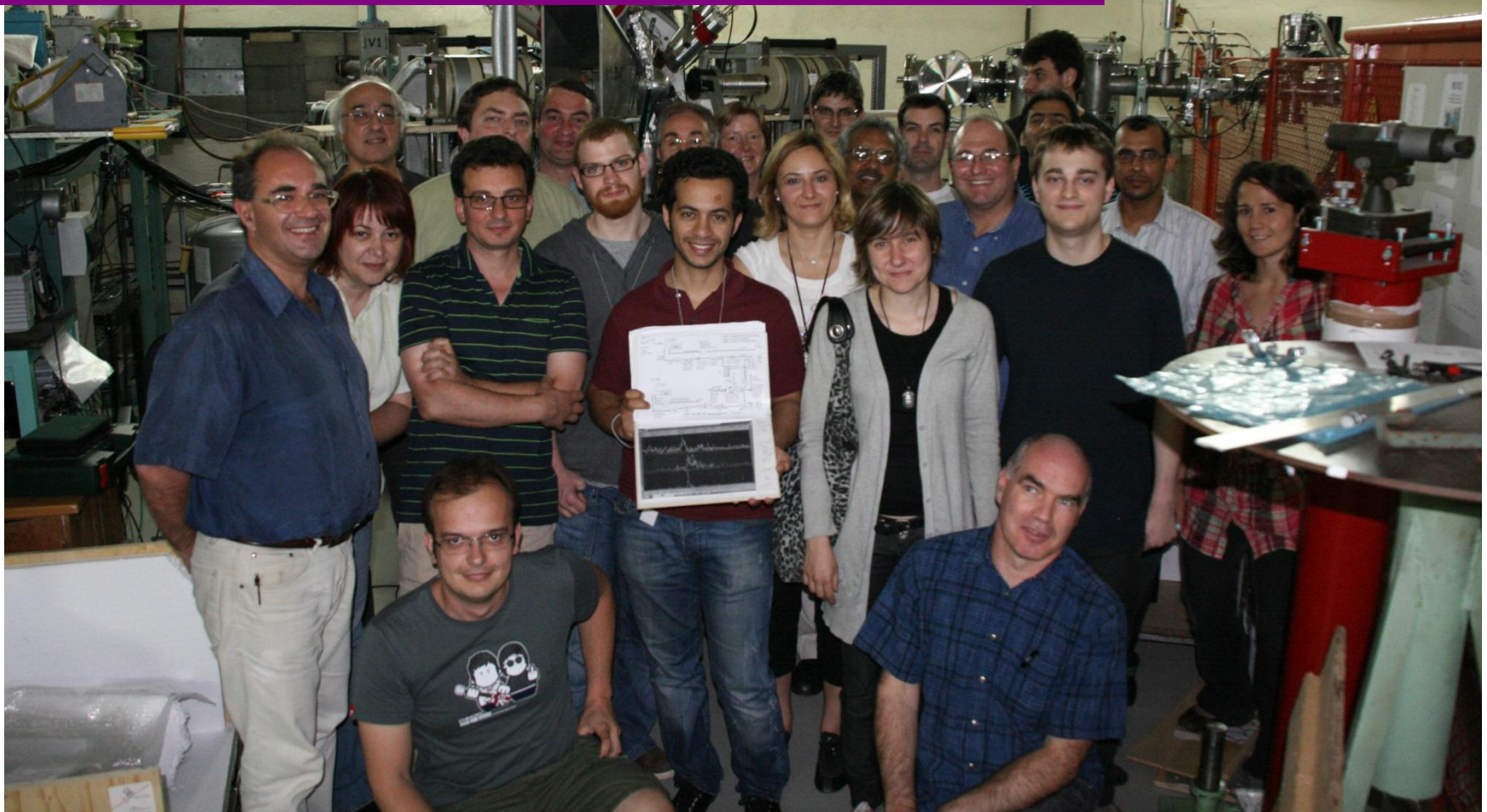


Successful nanosecond lifetime measurement in ^{34}P (June 2010)

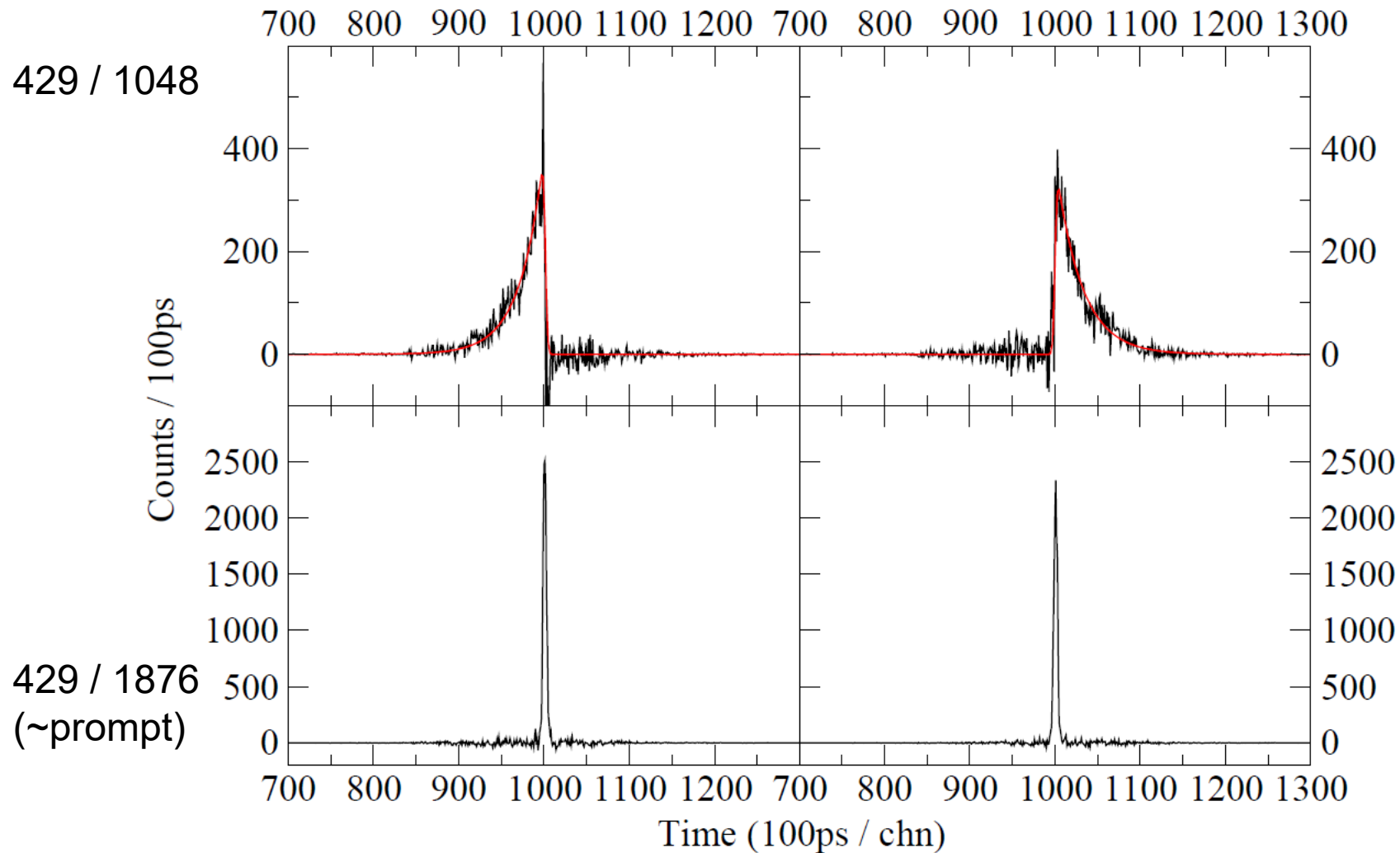
PHYSICAL REVIEW C **85**, 064303 (2012)

Half-life of the $I^\pi = 4^-$ intruder state in ^{34}P : $M2$ transition strengths approaching the island of inversion

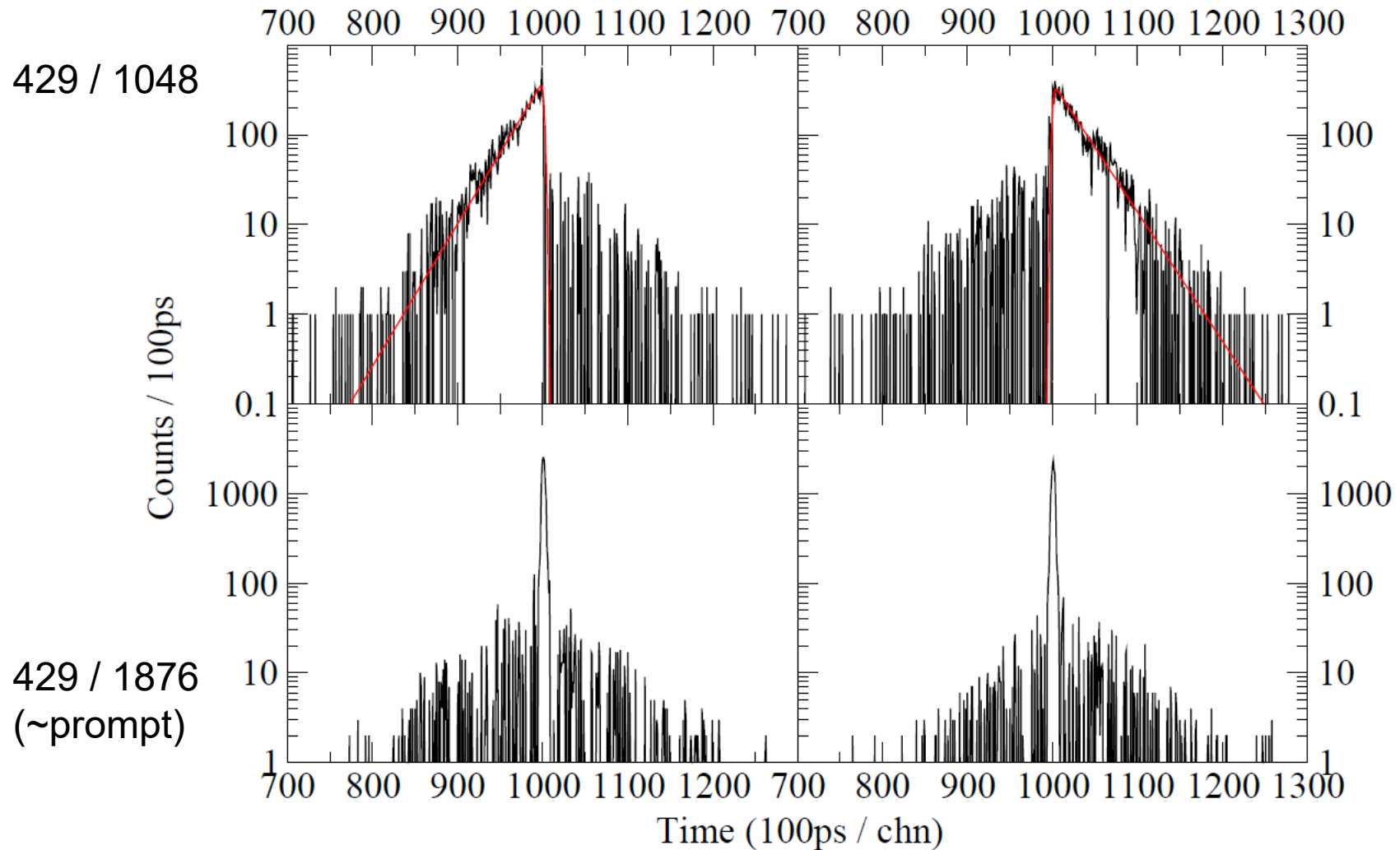
P. J. R. Mason,¹ T. Alharbi,^{1,2} P. H. Regan,¹ N. Mărginean,³ Zs. Podolyák,¹ E. C. Simpson,¹ N. Alkhomashi,⁴ P. C. Bender,⁵ M. Bowry,¹ M. Bostan,⁶ D. Bucurescu,³ A. M. Bruce,⁷ G. Căta-Danil,³ I. Căta-Danil,³ R. Chakrabarti,⁸ D. Deleanu,³ P. Detistov,⁹ M. N. Erduran,¹⁰ D. Filipescu,³ U. Garg,¹¹ T. Glodariu,³ D. Ghiță,³ S. S. Ghugre,⁸ A. Kusoglu,⁶ R. Mărginean,³ C. Mihai,³ M. Nakhostin,¹ A. Negret,³ S. Pascu,³ C. Rodríguez Triguero,⁷ T. Sava,³ A. K. Sinha,⁸ L. Stroe,³ G. Suliman,³ and N. V. Zamfir³



Result: $T_{1/2}$ ($I^\pi=4^-$) in $^{34}\text{P}= 2.0(1) \text{ ns}$



$T_{1/2} = 2.0(1)\text{ns} = 0.064(3) \text{ Wu}$ for 1876 M2 in ^{34}P .



Deconvolution and lineshapes

- If the instrument time response function $R(t)$ is Gaussian of width σ ,*

$$R(t) = A_1 \exp\left(-\frac{t^2}{2\sigma^2}\right)$$

- If the intermediate state decays with a mean lifetime τ , then*

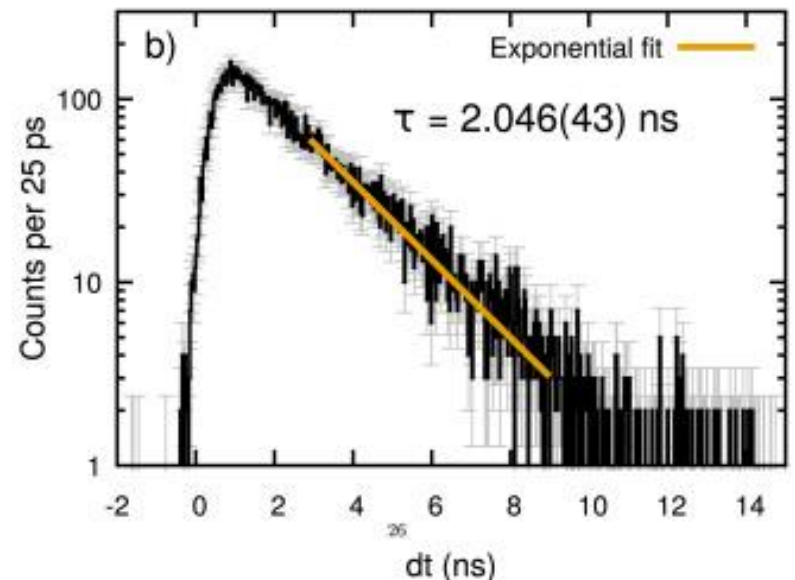
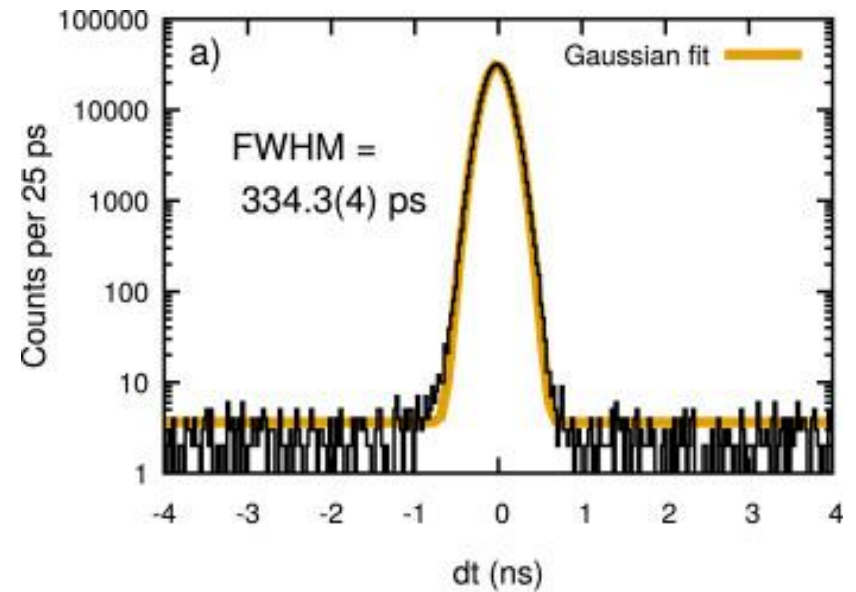
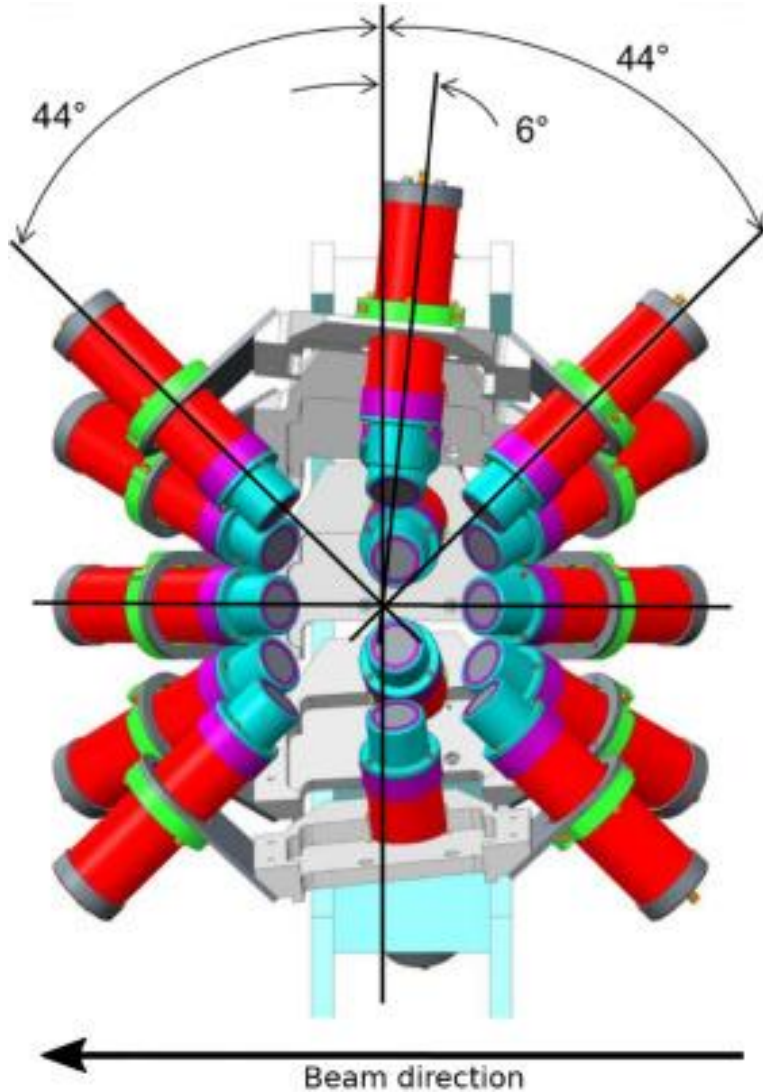
$$S(t) = A_2 \exp\left(-\frac{t}{\tau}\right)$$

- The deconvolution integral for a single state lifetime is given by (ignoring the normalisation coefficients).*

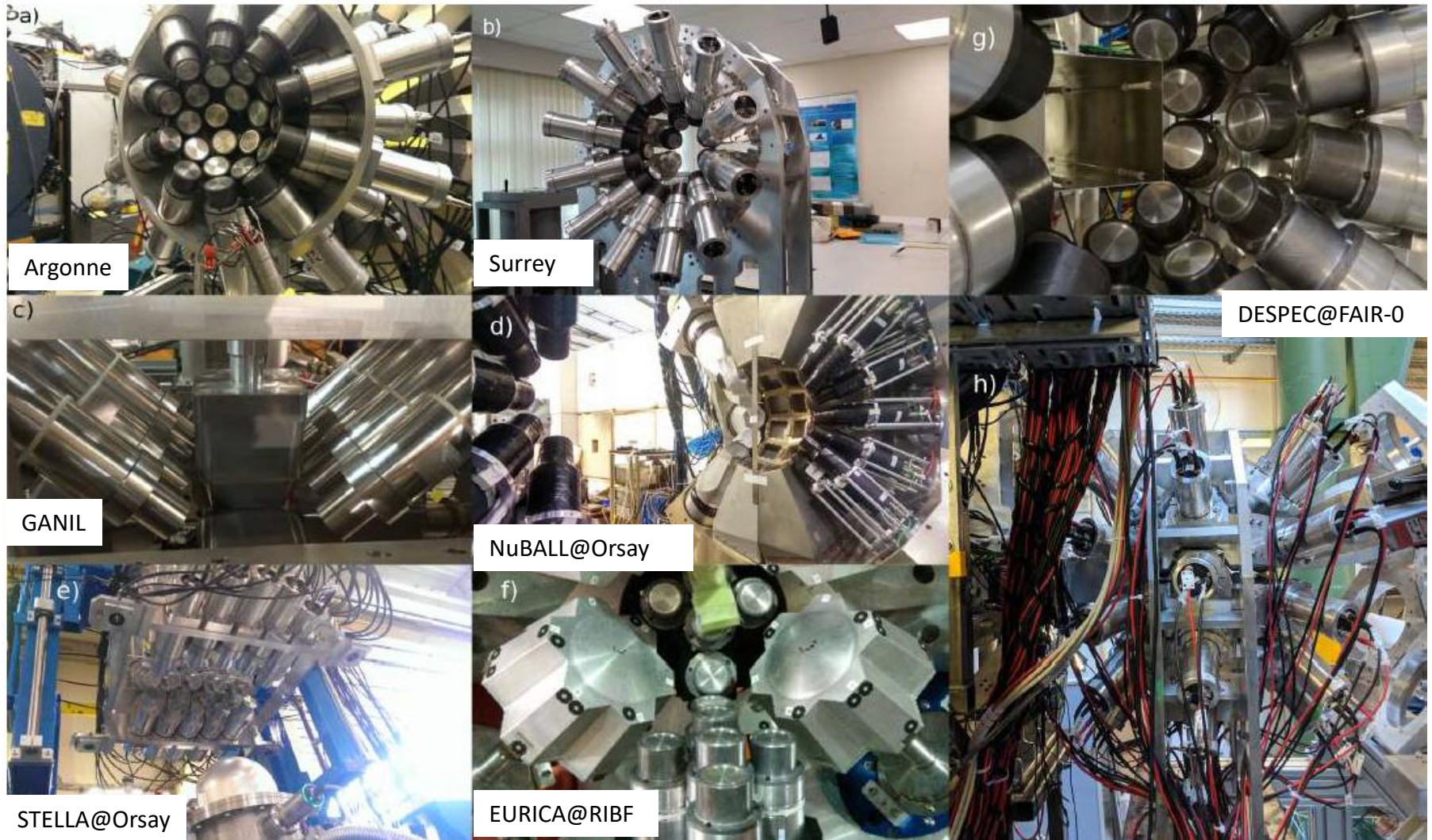
$$I(t) = \exp\left(\frac{\sigma^2}{2\tau^2} - \frac{t}{\tau}\right) \left(1 - \operatorname{erf}\left(\frac{\sigma^2 - \tau t}{\sqrt{2}\sigma\tau}\right)\right)$$

1-erf(x) is the complementary error function of the variable, x.

Fast TIMing Array = FATIMA



FATIMA LaBr_3 Detectors, used around the world



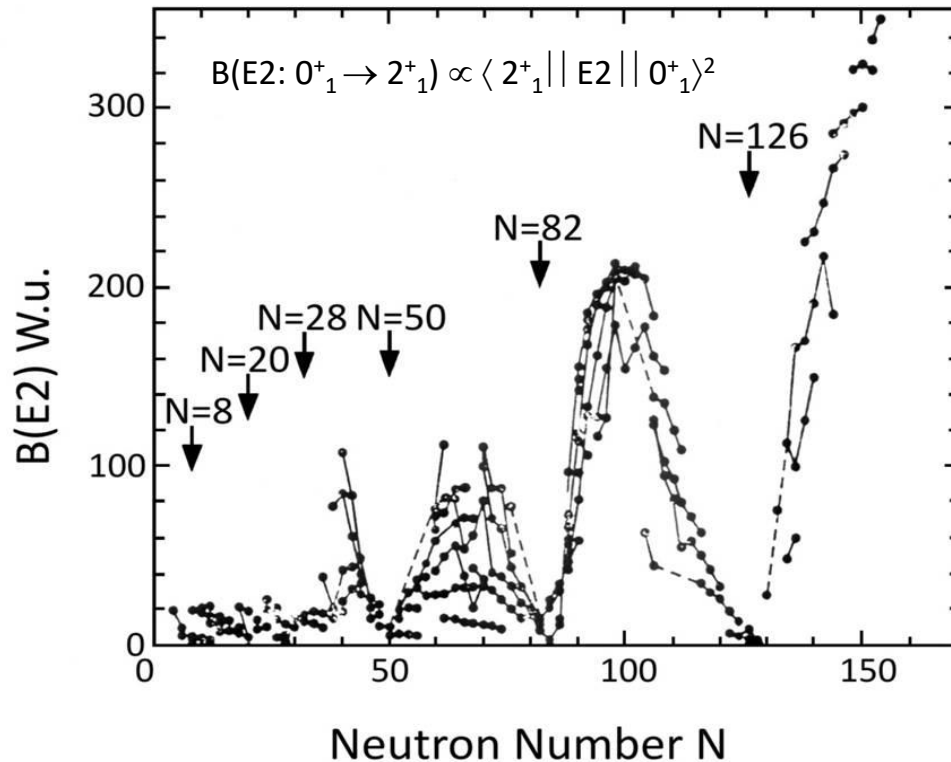
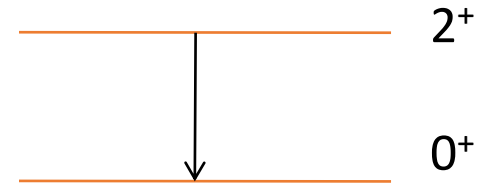
M. Rudigier, Zs. Podolyák, P.H. Regan et al.

Nuclear Inst. and Methods in Physics Research, A 969 (2020) 163967

$$T(E2) = 1.223 \times 10^9 E_\gamma^5 B(E2)$$

$T(E2)$ = transition probability = $1/\tau$ (secs);

E_γ = transition energy in MeV



Q_0 = (TRANSITION) ELECTRIC QUADRUPOLE MOMENT.

This is intimately linked to the electrical charge (i.e. proton) distribution within the nucleus.

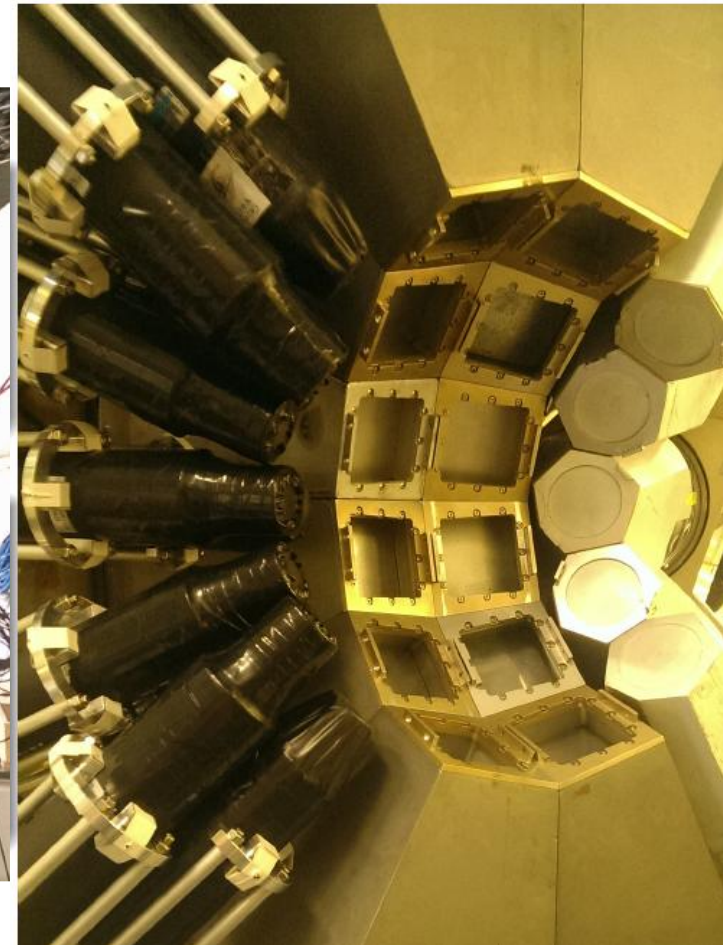
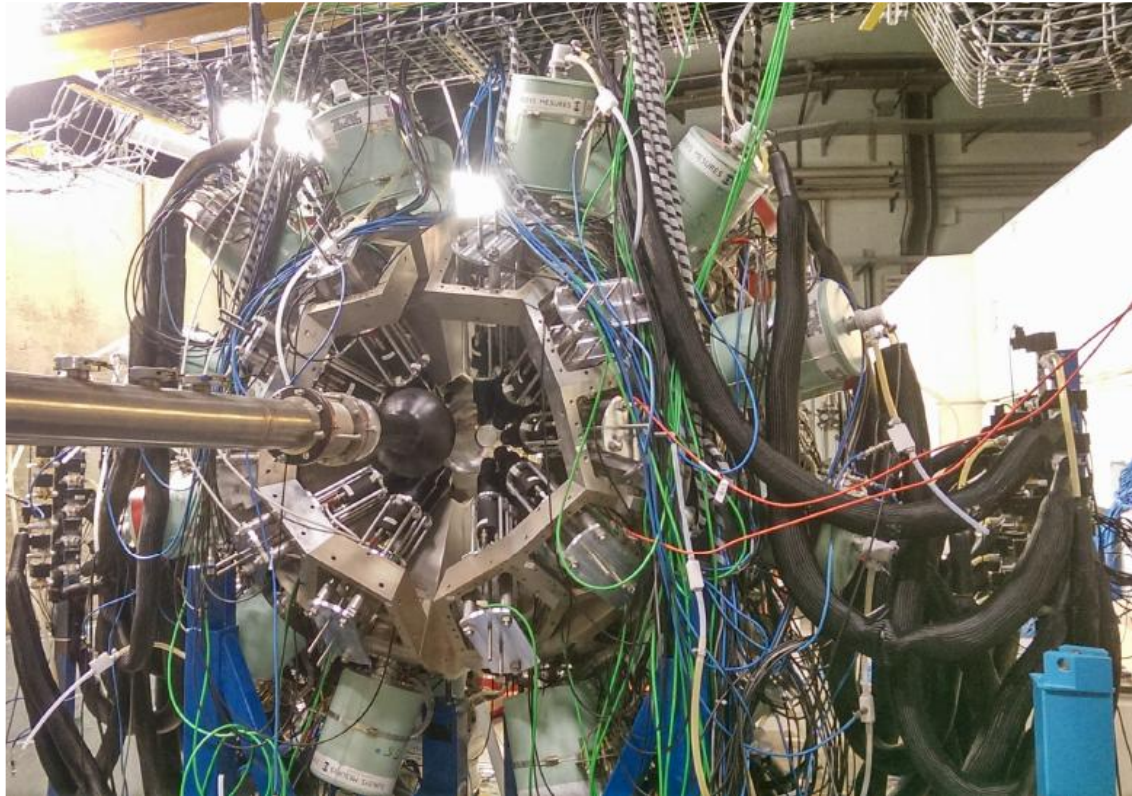
Non-zero Q_0 means some deviation from spherical symmetry and thus some quadrupole (β_2) 'deformation'.

The nuclear rotational model: $B(E2: I \rightarrow I-2)$ gives Q_0 by:

$$B(E2) = \frac{5}{16\pi} Q_0^2 \frac{3(I-K)(I-K-1)(I+K)(I+K-1)}{(2J-2)(2J-1)J(2J+1)}$$

NuBall at IPN-Orsay: 'Hybrid' HPGe -LaBr₃ combined array.

- 20 LaBr₃ detectors with from FATIMA -time resolution ~250 ps
- 24 HPGe clover detectors with BGO shielding for Compton Suppression
- 10 coaxial HPGe detectors with BGO shielding
- FASTER Digital DAQ; 500 MHz sampling for the LaBr₃ detectors; 125 MHz sampling for the HPGe and BGO detectors
- Internal pulse shape analysis



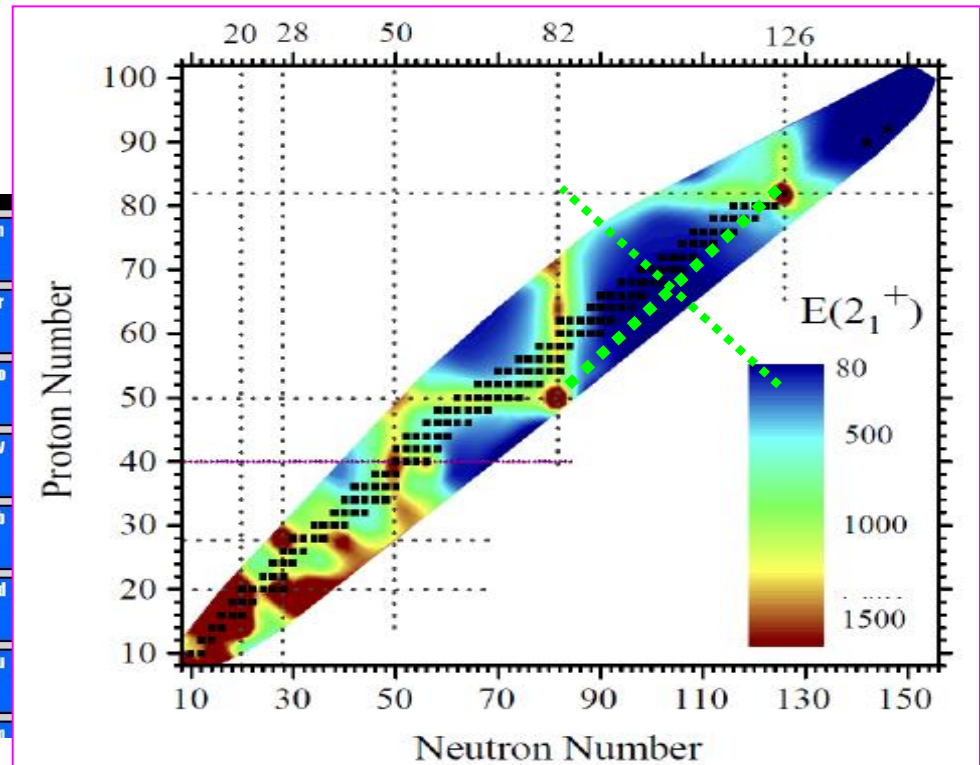
A Fundamental Nuclear Structure Physics Question?

'Simple' nuclear observables show a relation between the $B(E2)$ (proxy for $\sim \beta_2$) & the valence $N_p.N_n$ product.
[see Casten & Zamfir, Phys. Rev. Lett. **70**, 402 (1993)].

Are the most 'collective' nuclei at the valence maximum?

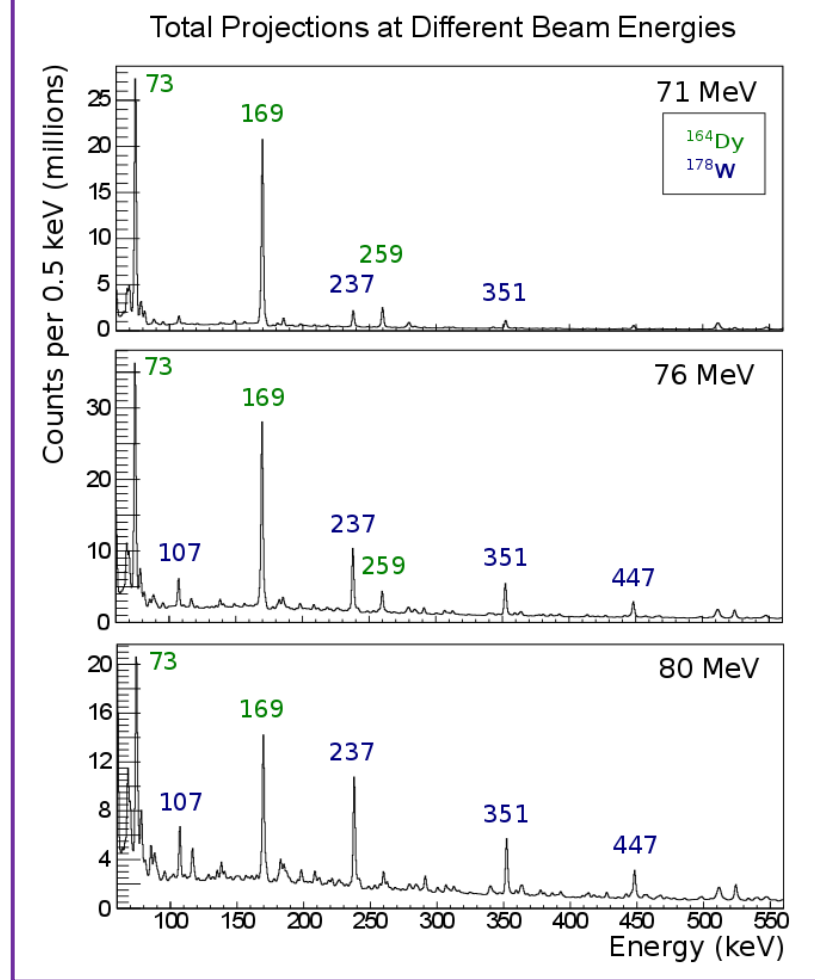
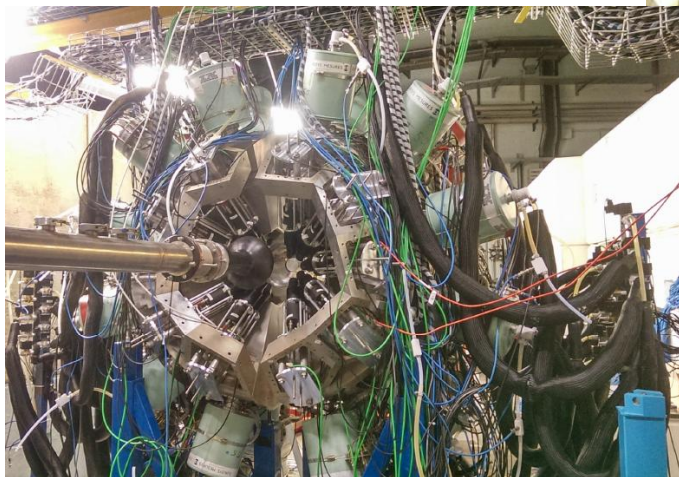
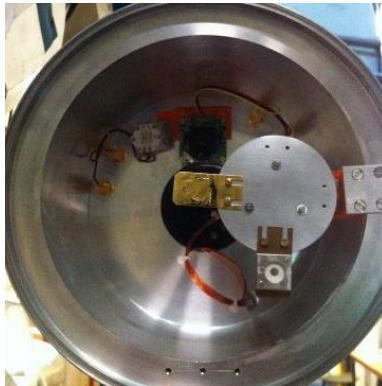
^{170}Dy = Valence Maximum Nucleus

50 $\rightarrow$ **66** $\rightarrow$ 82 protons &
82 $\rightarrow$ **104** $\rightarrow$ 126 neutrons



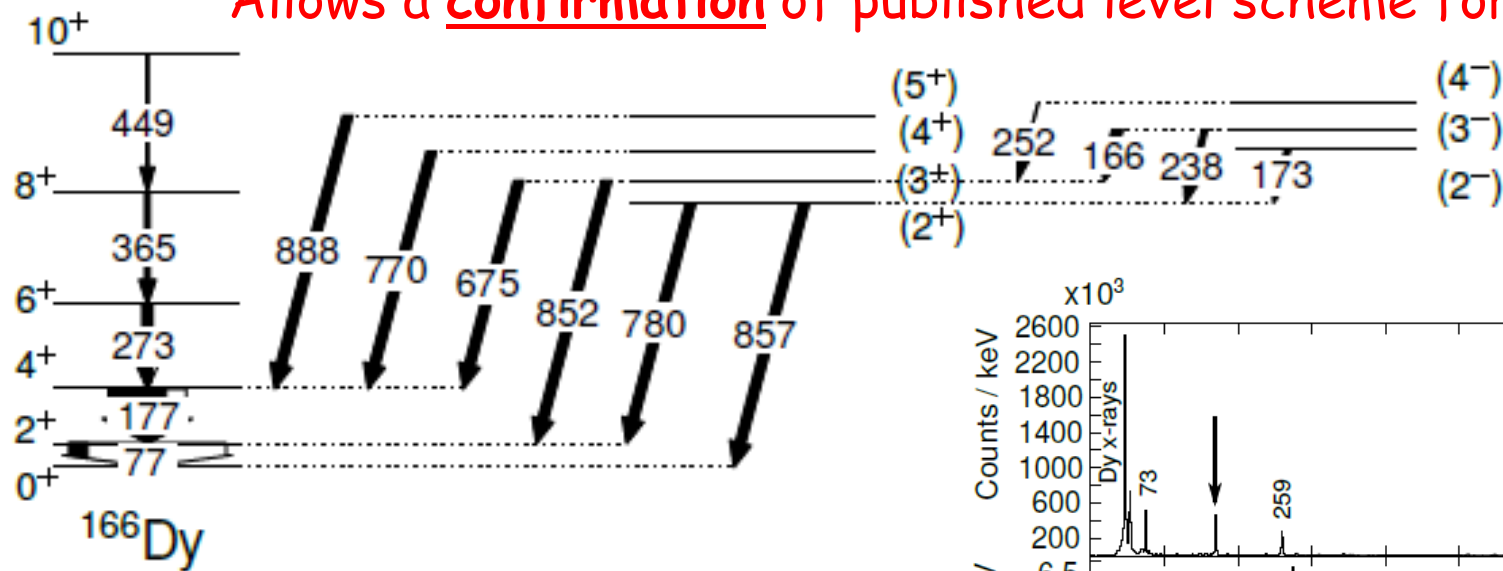
B(E2:2⁺ → 0⁺) in ¹⁶⁶Dy

- Pulsed ¹⁸O beam: 2 ns pulses, 400 ns period, ~35 enA, charge state Q=6⁺
- ¹⁶⁴Dy target: 95% purity, 6.3 mg/cm²
- **Desired reaction:** ¹⁶⁴Dy(¹⁸O, ¹⁶O)¹⁶⁶Dy
- 1 week beam time, 3 beam energies:
 - 71 MeV (2 days);
 - 76 MeV (2 days); &
 - 80 MeV (3 days)

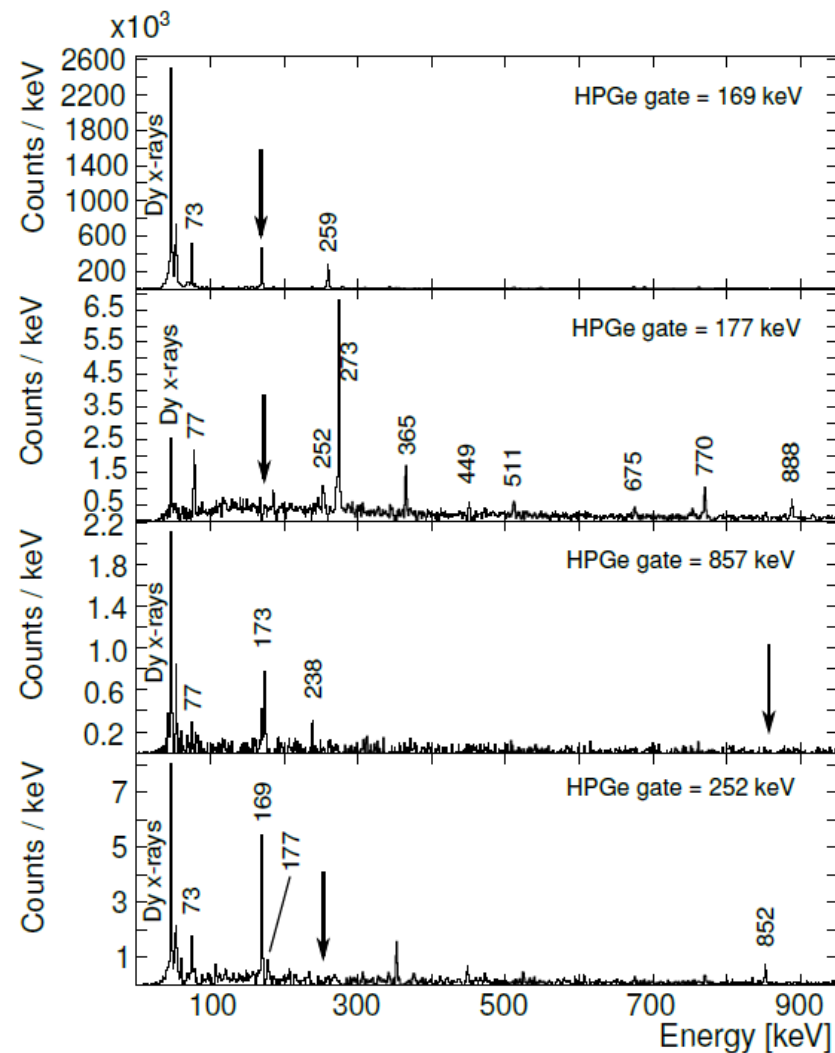


- Spectra dominated by ¹⁶⁴Dy from Coulomb excitation of the target & ¹⁶⁴Dy(¹⁸O, 4n)¹⁷⁸W fusion evap.
- ¹⁶⁶Dy **not clearly visible** in total projection spectrum;
- Channel selection needed

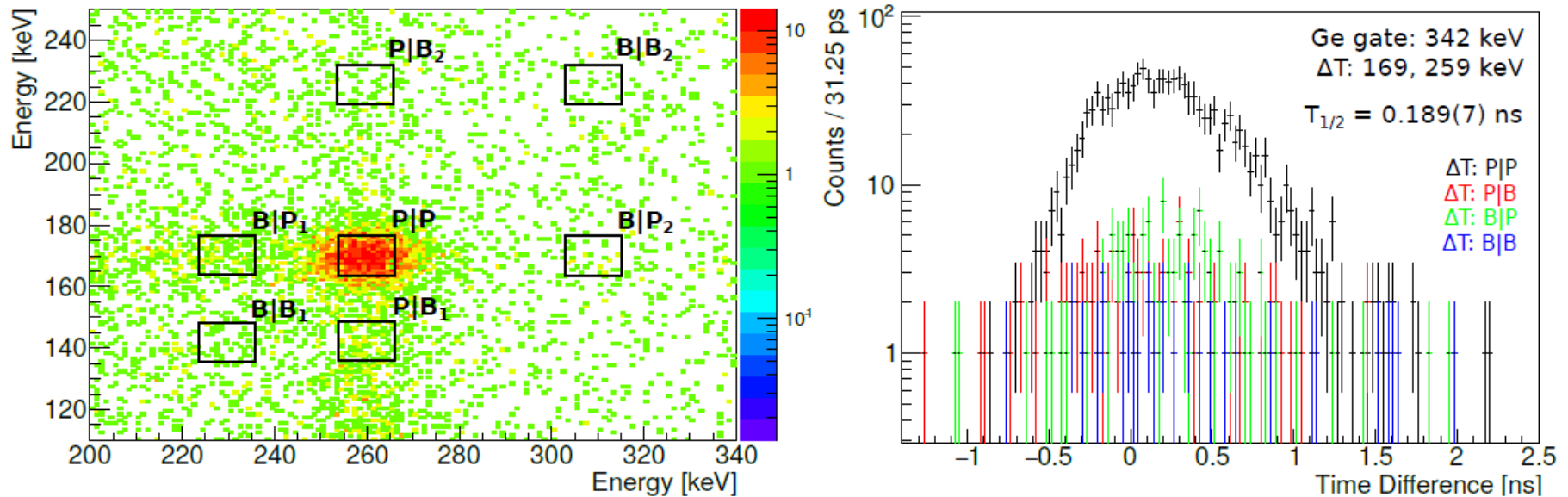
Allows a confirmation of published level scheme for ^{166}Dy .



E_γ	I_γ (Rel.)	$I_{Tot.}$	J_i^π	J_f^π	α_{ICC}	Transition $E_i \rightarrow E_f$
76.6	34(2)	287(15)	2^+	0^+	7.51(11)	$77 \rightarrow 0$
166.5			(3^-)	$(3)^+$	0.0790(11)	$1095 \rightarrow 929$
172.7			(2^-)	$(2)^+$	0.0716(10)	$1030 \rightarrow 857$
176.9			4^+	2^+	0.357(5)	$254 \rightarrow 77$
238.1			(3^-)	$(2)^+$	0.0309(5)	$1095 \rightarrow 857$
252.1	13(1)	13(1)	(4^-)	$(3)^+$	0.0267(4)	$1181 \rightarrow 929$
273.4	100(5)	109(6)	6^+	4^+	0.0859(12)	$527 \rightarrow 254$
365	28(2)	29(2)	8^+	6^+	0.0360(5)	$892 \rightarrow 527$
449	12(1)	12(1)	10^+	8^+	0.0202(3)	$1341 \rightarrow 892$
675.2	16(1)	16(1)	$(3)^+$	4^+		$929 \rightarrow 254$
769.9	43(2)	43(2)	$(4)^+$	4^+		$1023 \rightarrow 254$
780.6			$(2)^+$	2^+		$857 \rightarrow 77$
852.1			$(3)^+$	2^+		$929 \rightarrow 77$
857.2			$(2)^+$	0^+		$857 \rightarrow 0$
887.7	27(2)	27(2)	(5^+)	4^+		$1141 \rightarrow 254$



'Proof of Principle' Results using ^{164}Dy

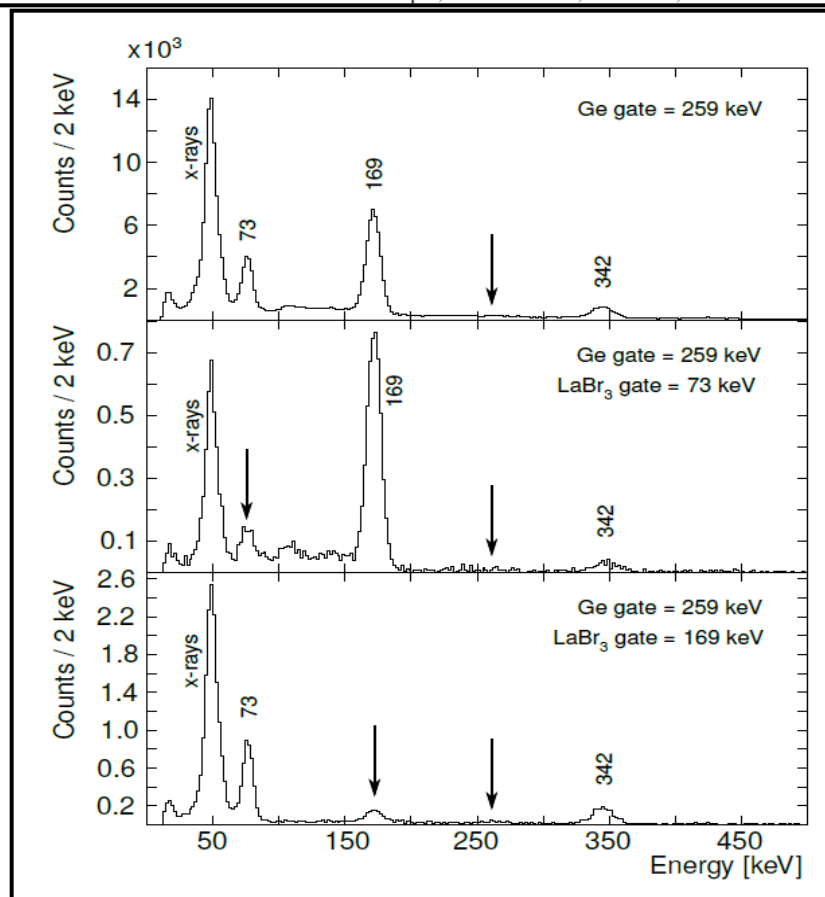


$T_{1/2}(2^+) = 2.35(6) \text{ ns}$, published $2.393(29) \text{ ns}$ [1]

$T_{1/2}(4^+) = 0.189(7) \text{ ns}$, published $0.201(8) \text{ ns}$ [1]

Half-life measurements in $^{164,166}\text{Dy}$ using γ - γ fast-timing spectroscopy with the ν -Ball spectrometer

R. L. Canavan^{1,2,*} M. Rudigier^{1,3} P. H. Regan^{1,2} M. Lebois^{4,5} J. N. Wilson^{4,5} N. Jovancevic^{4,5} P.-A. Söderström⁶
 S. M. Collins^{1,2} D. Thisse^{4,5} J. Benito⁷ S. Bottoni⁸ M. Brunet¹ N. Cieplicka-Oryńczak⁹ S. Courtin¹⁰ D. T. Doherty¹
 L. M. Fraile⁷ K. Hadyńska-Klęk^{1,11} G. Häfner^{12,13} M. Heine¹⁰ Ł. W. Iskra^{8,9} V. Karayonchev¹³ A. Kennington¹
 P. Koseoglou^{3,14} G. Lotay¹ G. Lorusso^{1,2} M. Nakhostin¹ C. R. Nijā¹⁵ S. Oberstedt¹⁶ Zs. Podolyák¹ L. Qi^{4,5} J.-M. Régis¹³
 V. Sánchez-Tembleque⁷ R. Shearman² V. Vedia⁷ and W. Witt^{3,14}

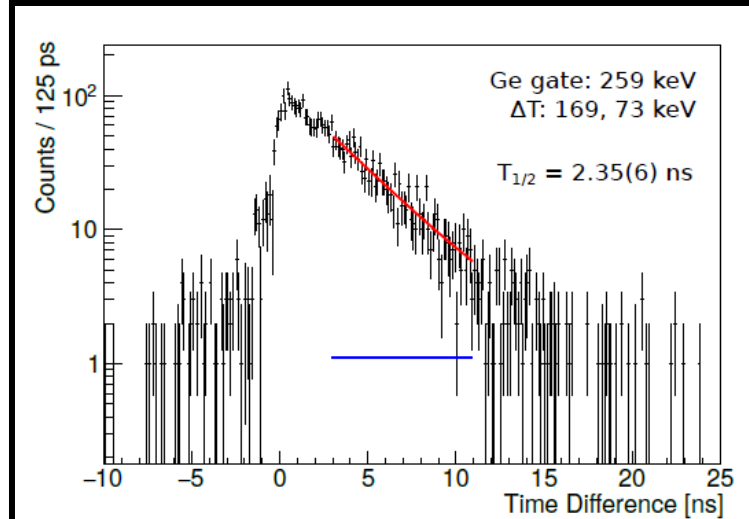
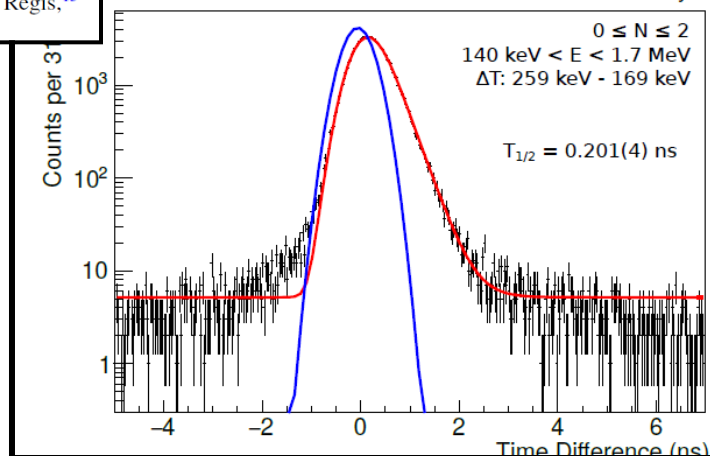


$T_{1/2}(2^+) = 2.35(6)$ ns. Evaluated value as 2.39(3) ns [1] ;

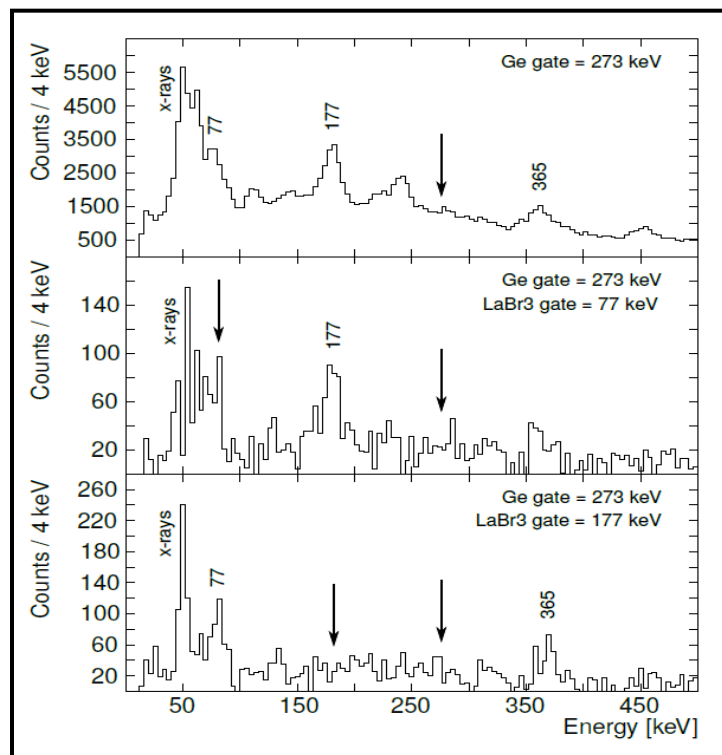
$T_{1/2}(4^+) = 0.201(4)$ ns ; cf. ENSDF evaluated value 0.201(8) ns [1]

[1] B. Singh & B. Chen Nucl. Data Sheets 147, 1 (2018)

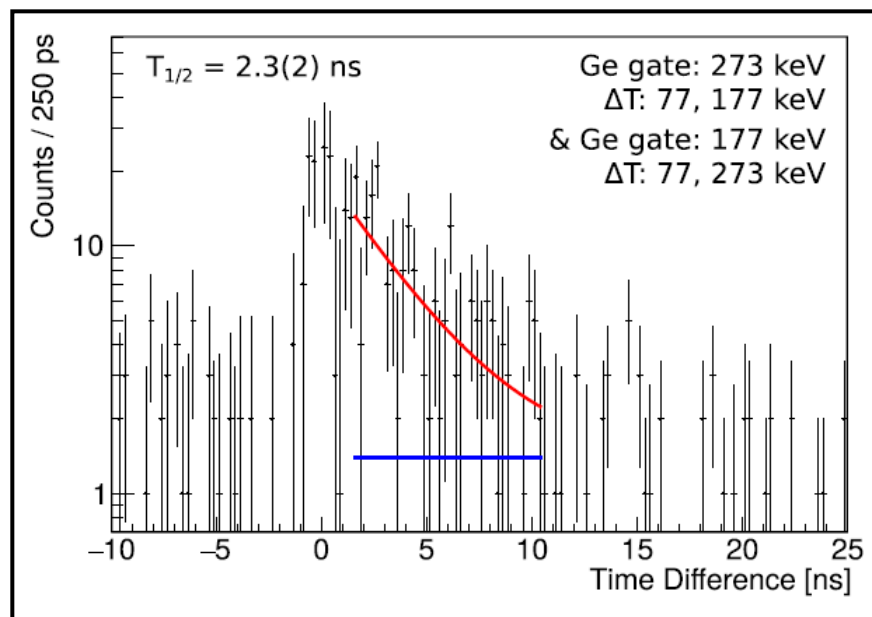
HK Selected Gamma-Gamma ΔT for 4^+ Half-Life in ^{164}Dy



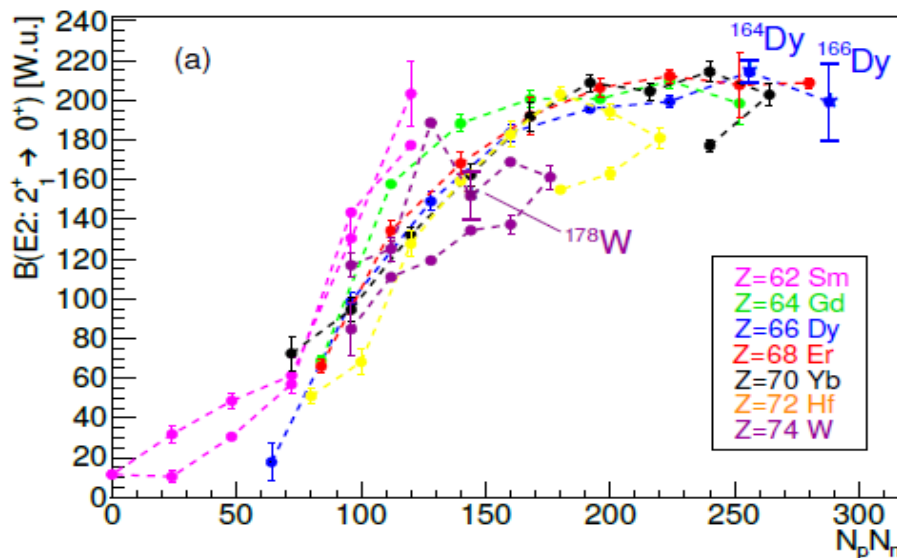
$^{166}\text{Dy}_{100}$ 2^+ lifetime from NuBALL, largest Np.Nn B(E2)



PHYSICAL REVIEW C **101**, 024313 (2020)



Nucleus	$E(2^+)$	$T_{1/2}(2^+)$	α_{ICC}	$B(E2) \downarrow$	β_2
^{160}Dy	86.78	2.02(1)	4.63	1.011(5)	0.3361(8)
^{162}Dy	80.66	2.19(2)	6.14	1.060(10)	0.3414(16)
^{164}Dy	73.39	2.35(6)	8.890	1.14(3)	0.352(4)
^{166}Dy	76.7	2.3(2)	7.480	1.12(11)	0.345(17)



What about 'faster' transitions..
i.e. $< \sim 10$ ps ?

THE MEASUREMENT OF SHORT NUCLEAR LIFETIMES¹

By A. Z. SCHWARZSCHILD AND E. K. WARBURTON

*Brookhaven National Laboratory, Upton, New York*²

Annual Review of Nuclear Science (1968) **18** p265-290

SCHWARZSCHILD & WARBURTON

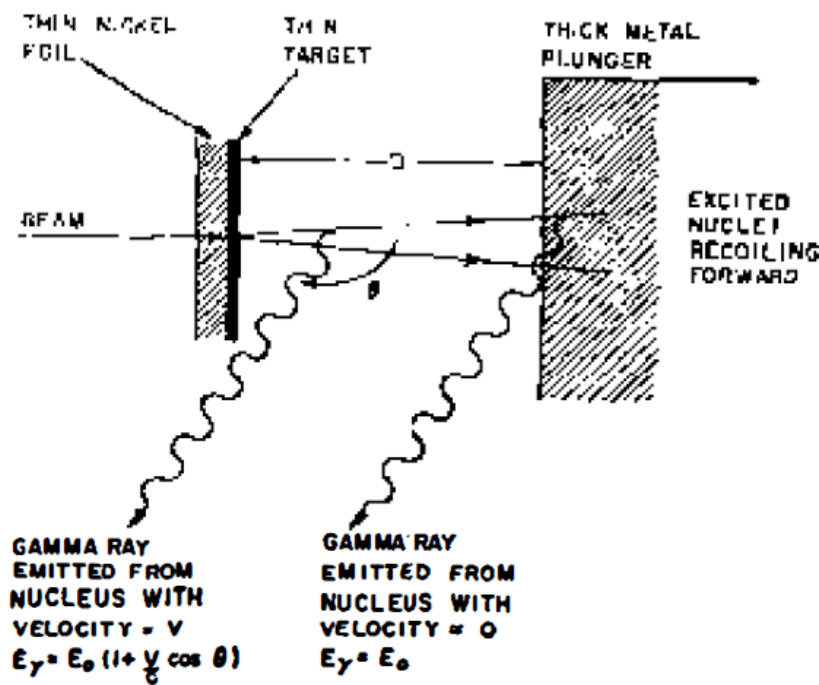
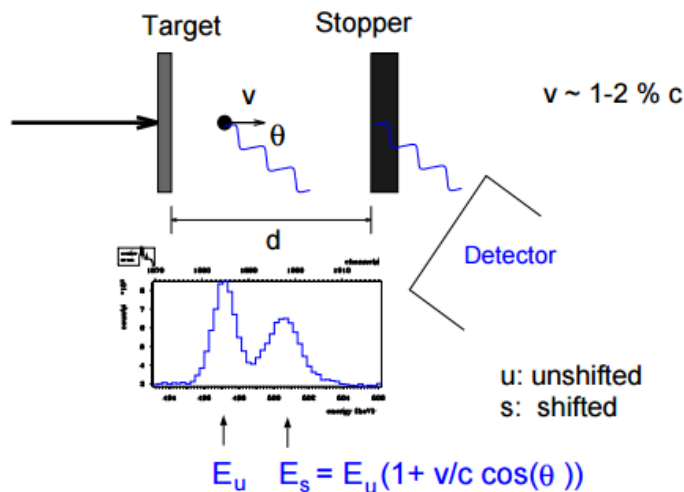
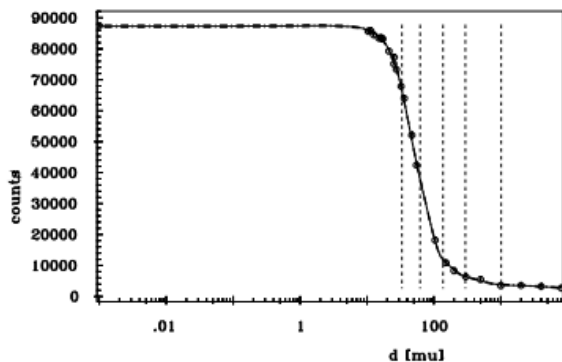


FIG. 5. Recoil method of measuring lifetimes of excited states.

The Recoil Distance Doppler-Shift Method (RDM/RDDS)



Decay Curve

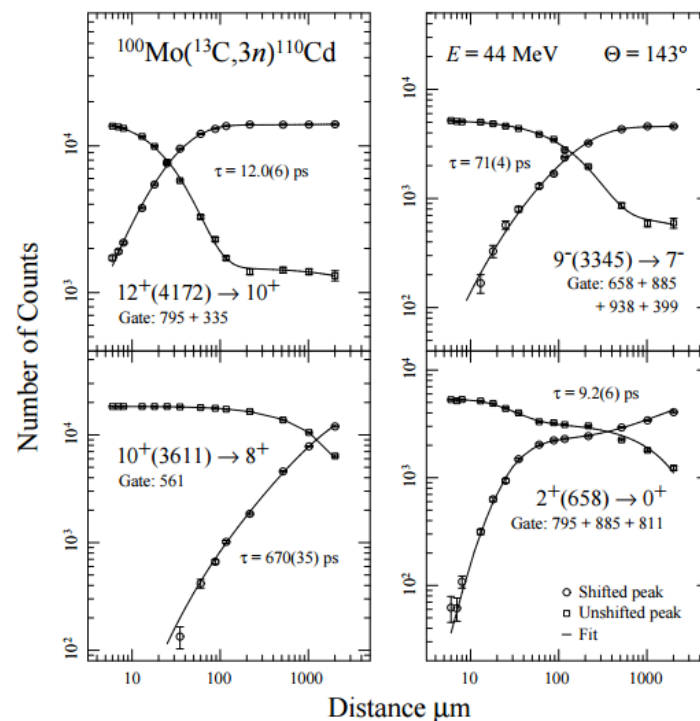


$$E_s(\theta, t) = E_o \frac{\sqrt{1 - \frac{v}{c}}}{1 - \frac{v}{c} \cos \theta} \approx E_o \left(1 + \frac{v}{c} \cos \theta \right)$$

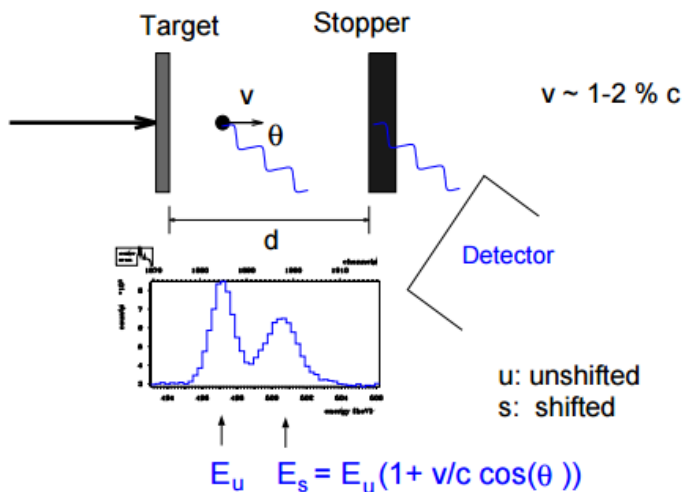
$$I_s = N_0 \left(1 - \exp \left(-\frac{d}{v\tau} \right) \right)$$

$$I_o = N_o \exp \left(-\frac{d}{v\tau} \right)$$

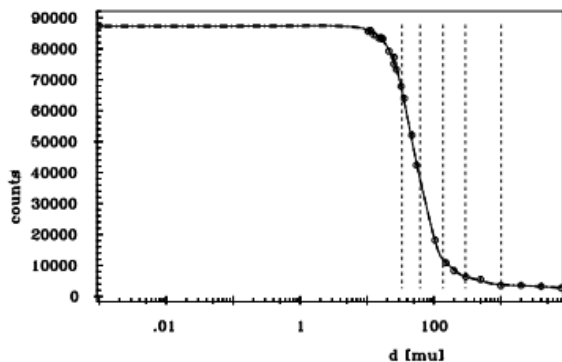
$$R = \frac{I_o}{I_o + I_s} = \exp \left(-\frac{d}{v\tau} \right)$$



The Recoil Distance Doppler-Shift Method (RDM/RDDS)



Decay Curve



$$I_s = N_0 \left(1 - \exp \left(-\frac{d}{v\tau} \right) \right)$$

$$I_o = N_o \exp \left(-\frac{d}{v\tau} \right)$$

$$R = \frac{I_o}{I_o + I_s} = \exp \left(-\frac{d}{v\tau} \right)$$

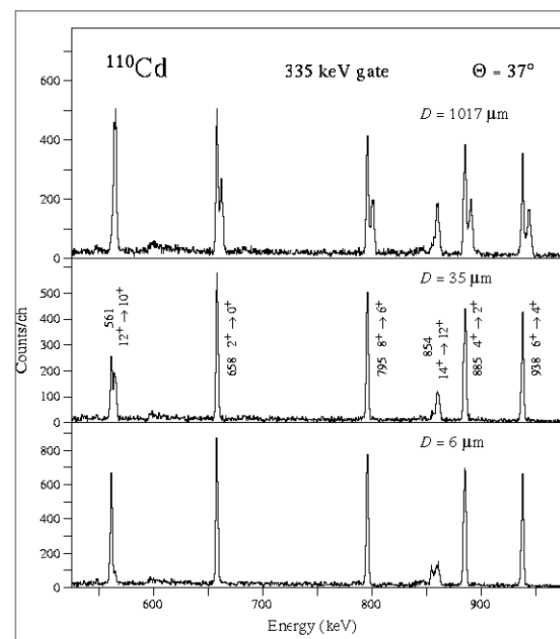
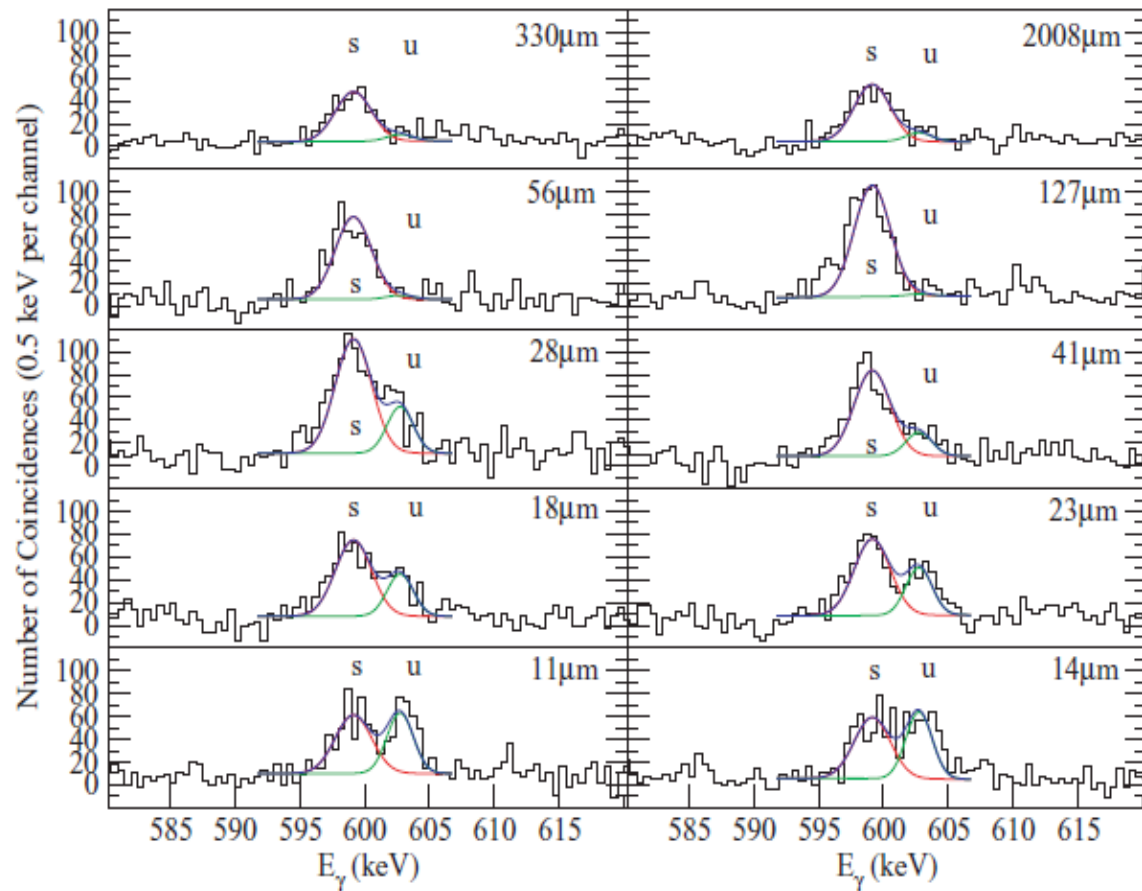
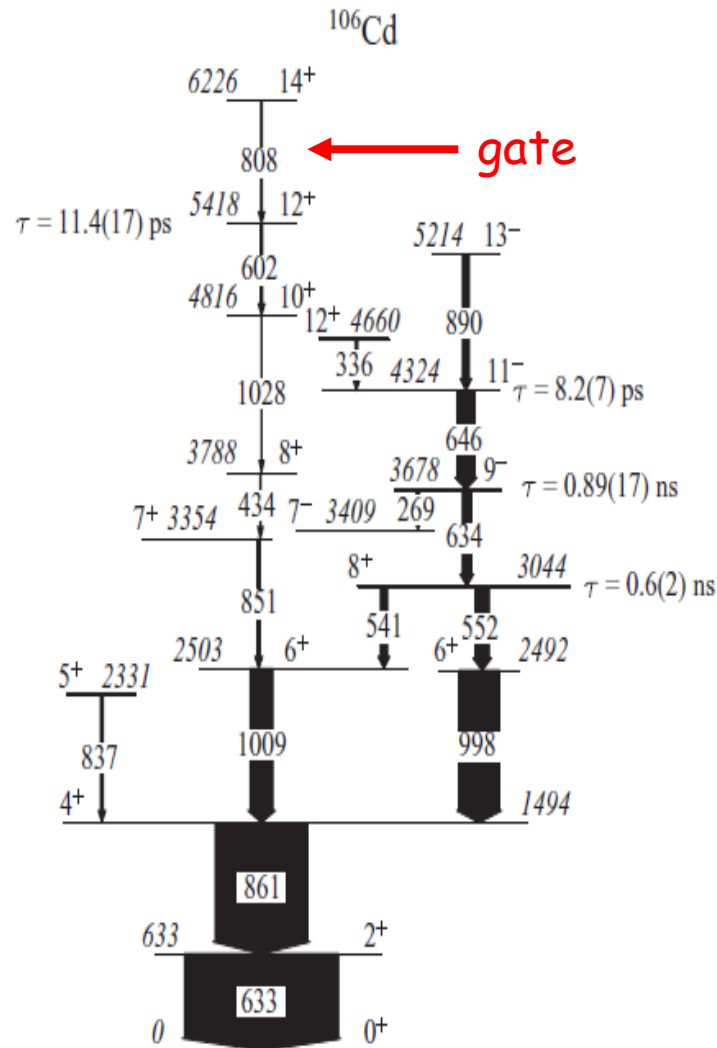


Figure 5.11: Coincident plunger spectra gated on the $10^+ \rightarrow 8^+$, 335 keV transition in ^{110}Cd . Taken from Piiparinen *et al.* [229].

$$E_s(\theta, t) = E_o \frac{\sqrt{1 - \frac{v}{c}}}{1 - \frac{v}{c} \cos \theta} \approx E_o \left(1 + \frac{v}{c} \cos \theta \right)$$

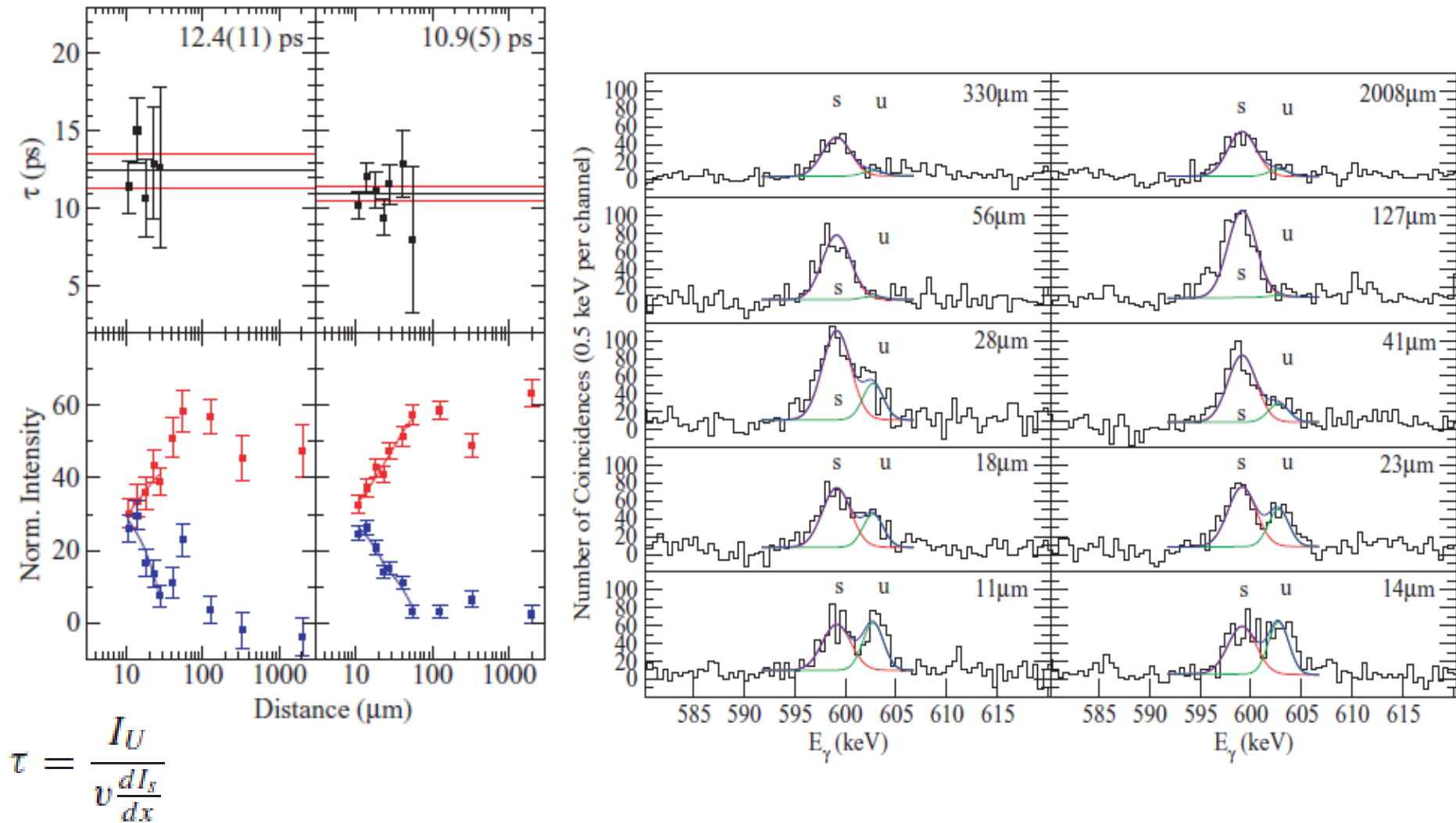
Intrinsic state lifetimes in ^{103}Pd and $^{106,107}\text{Cd}$

S. F. Ashley,^{1,2,*} P. H. Regan,¹ K. Andgren,^{1,3} E. A. McCutchan,² N. V. Zamfir,^{2,4,5} L. Amon,^{2,6} R. B. Cakirli,^{2,6} R. F. Casten,²
 R. M. Clark,⁷ W. Gelletly,¹ G. Gürdal,^{2,5} K. L. Keyes,⁸ D. A. Meyer,^{2,9} M. N. Erduran,⁶ A. Papenberg,⁸ N. Pietralla,^{10,11}
 C. Plettner,² G. Rainovski,^{10,12} R. V. Ribas,¹³ N. J. Thomas,^{1,2} J. Vinson,² D. D. Warner,¹⁴ V. Werner,²
 E. Williams,² H. L. Liu,¹⁵ and F. R. Xu¹⁵



Intrinsic state lifetimes in ^{103}Pd and $^{106,107}\text{Cd}$

S. F. Ashley,^{1,2,*} P. H. Regan,¹ K. Andgren,^{1,3} E. A. McCutchan,² N. V. Zamfir,^{2,4,5} L. Amon,^{2,6} R. B. Cakirli,^{2,6} R. F. Casten,² R. M. Clark,⁷ W. Gelletly,¹ G. Grdal,^{2,5} K. L. Keyes,⁸ D. A. Meyer,^{2,9} M. N. Erduran,⁶ A. Papenberg,⁸ N. Pietralla,^{10,11} C. Plettner,² G. Rainovski,^{10,12} R. V. Ribas,¹³ N. J. Thomas,^{1,2} J. Vinson,² D. D. Warner,¹⁴ V. Werner,² E. Williams,² H. L. Liu,¹⁵ and F. R. Xu¹⁵



Collective excitations in ^{150}Gd

S. Pascu^{1,2,*}, E. Yüksel¹, Abhishek¹, P. Stevenson¹, G. H. Bhat³, R. N. Mao⁴, K. Nomura^{5,6}, C. Costache²,
 Z. P. Li⁴, N. Mărginean², C. Mihai², T. Naz⁷, N. Paar⁸, Zs. Podolyák¹, P. H. Regan^{1,9}, A. E. Turturică²,
 R. Borcea², M. Boromiza², D. Bucurescu², S. Călinescu², C. Clisu², A. Coman², I. Dinescu², S. Doshi¹⁰,
 D. Filipescu², N. M. Florea², A. Gandhi², I. Gheorghe², A. Ionescu², R. Liță², R. Mărginean², R. E. Mihai^{2,11},
 A. Mitu², N. Nazir¹², A. Negret², C. R. Niță², E. B. O'Sullivan^{1,9}, C. Petrone², S. E. Poulton^{1,9},
 J. A. Sheikh¹³, H. K. Singh², L. Stan², S. Toma², G. Turturică² and S. Ujениу²

¹School of Mathematics and Physics, University of Surrey, Guildford GU2 7XH, United Kingdom

²"Horia Hulubei" National Institute for R&D in Physics and Nuclear Engineering, R-77125 Bucharest-Magurele, Romania

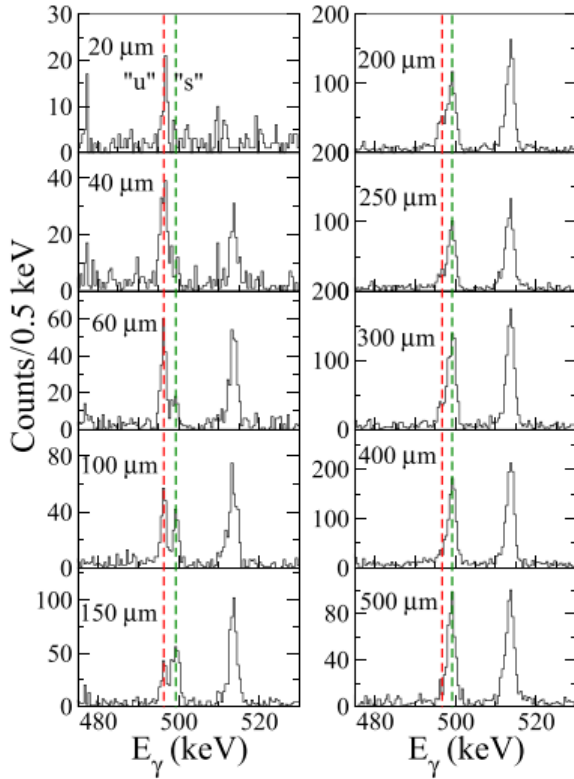
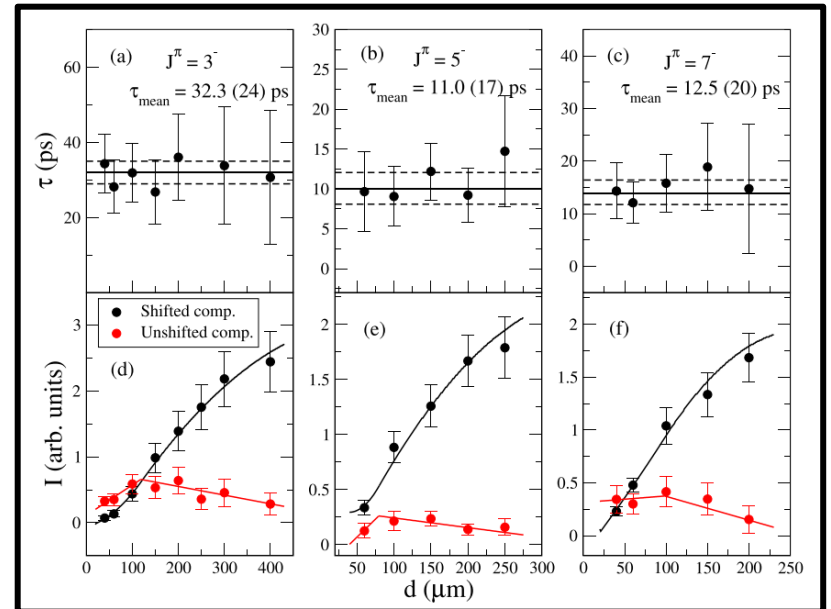
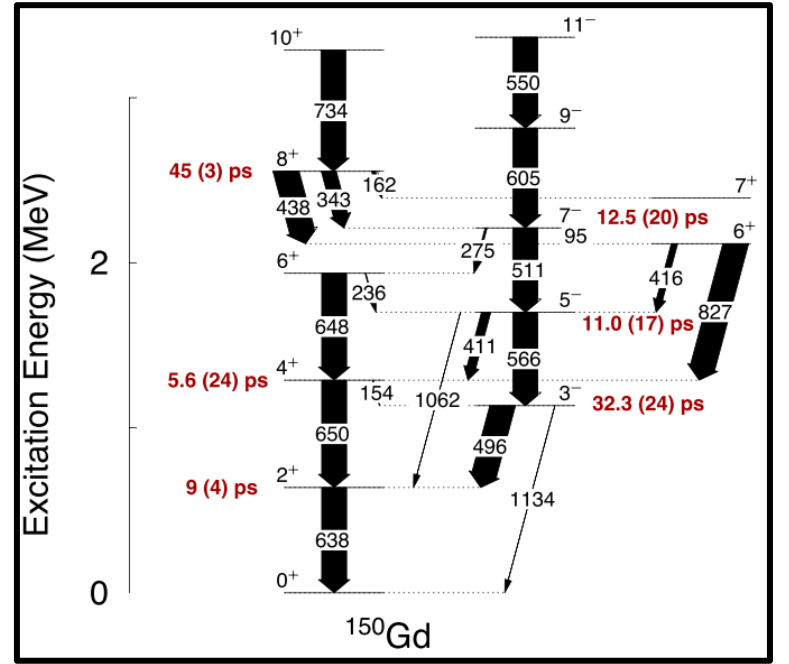


FIG. 1. Evolution of the shifted ("s", dashed green line) and unshifted ("u", dashed red line) components of the 496-keV γ line ($3^- \rightarrow 2^+$ transition), measured at 37° relative to the beam axis. Spectra were obtained by gating on the shifted component of the 566-keV transition ($5^- \rightarrow 3^-$) at 143° .

$$\tau_i(d) = \frac{I_{uA}^{SB}(d)}{v \frac{d}{dt} I_{sA}^{SB}(d)},$$



If the lifetime to be measured is so short that all of the states decay in flight, the RDM reaches a limit.

To measure even shorter half-lives ($<1\text{ps}$).

In this case, make the 'gap' distance zero !! i.e., have nucleus slow to do stop in a backing.

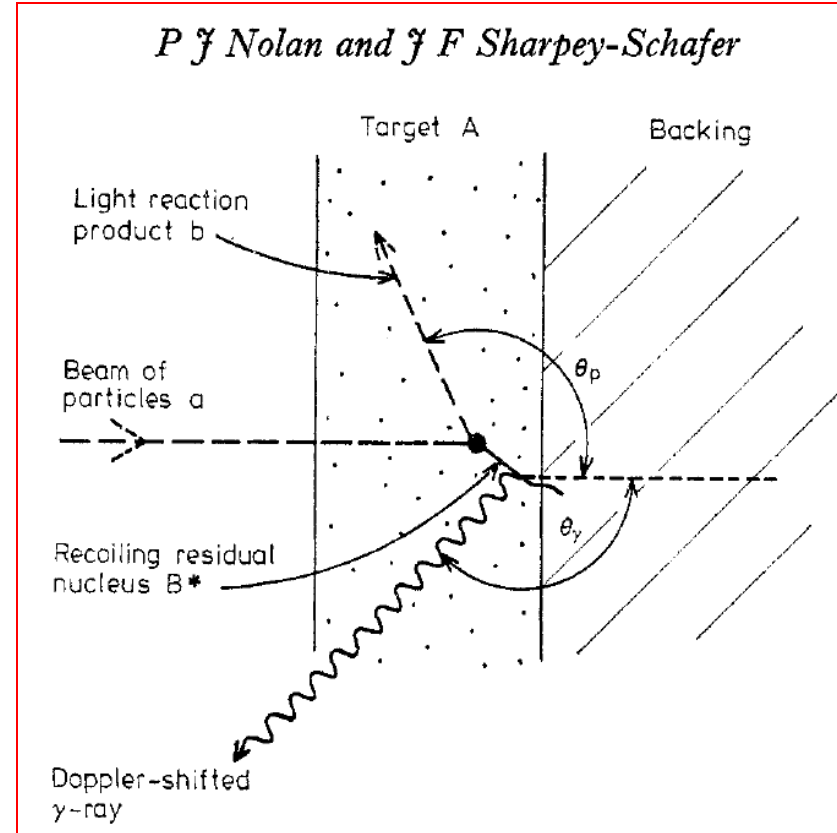
We can use the quantity

$$F(\tau) = (v_s / v_{\max}).$$

$$E_s(v, \theta) = E_0(1 + v/c \cos(\theta)) \quad (\text{for } v/c < 0.05)$$

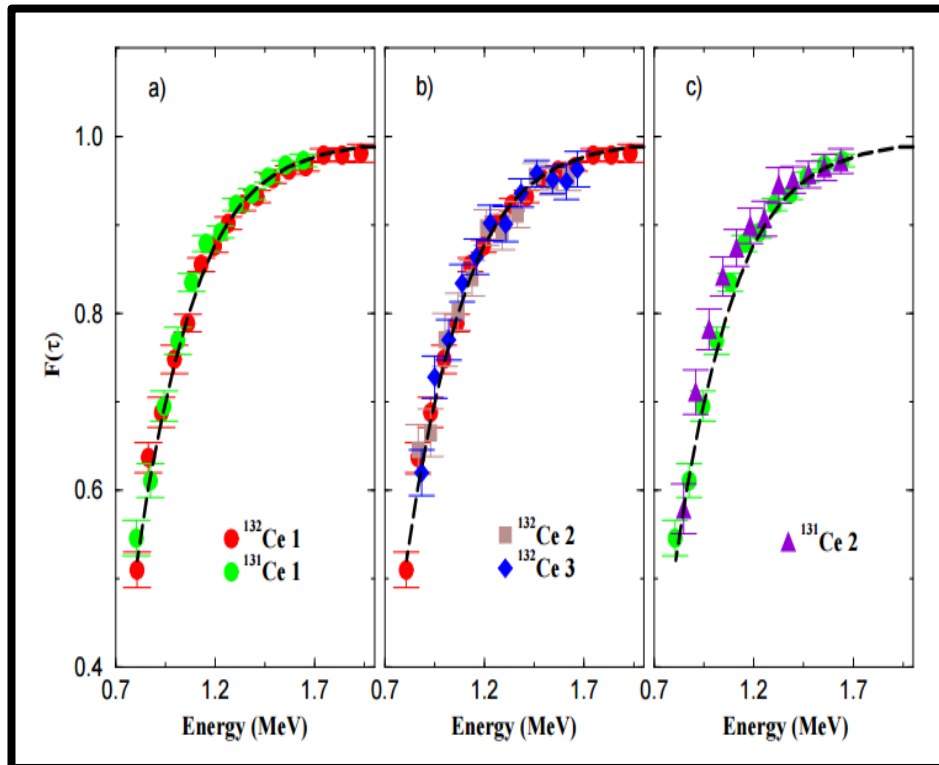
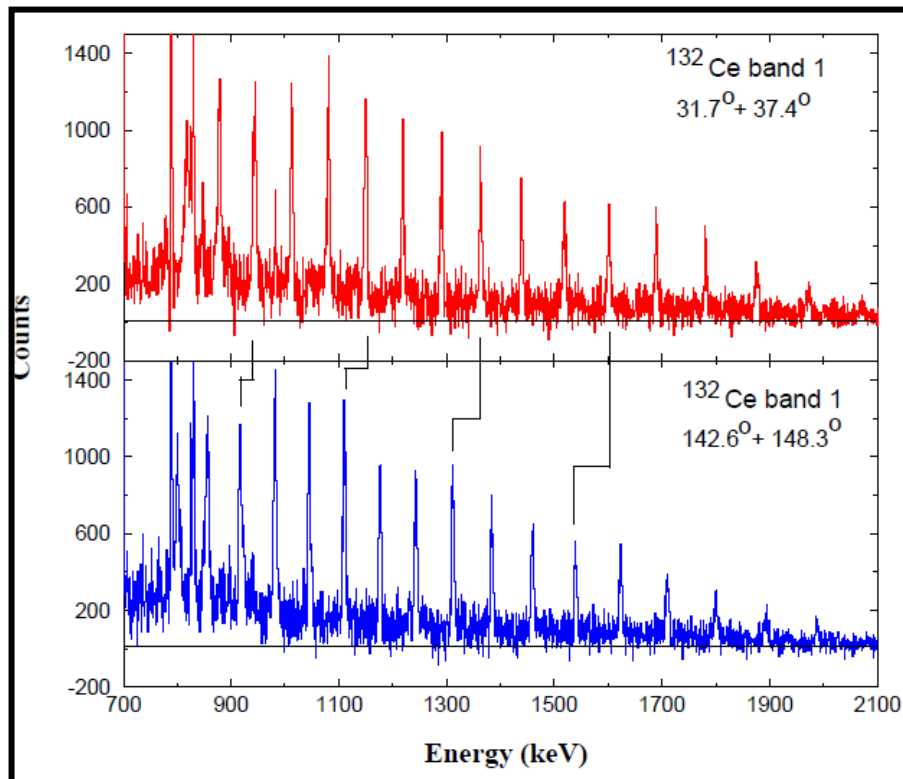
Measuring the centroid energy of the Doppler shifted line gives the average value for the quantity E_s (and this v) when transition was emitted.

The ratio of v_s divided by the maximum possible recoil velocity (at $t=0$) is the quantity, $F(\tau)$ = fractional Doppler shift.



$$E_s \approx E_o \left(1 + \frac{v}{c} \cos \theta \right)$$

$$F(\tau) = \frac{v_{av}}{v_o} = \frac{1}{v_o \tau} \int_0^\infty v(t) \exp \left(-\frac{t}{\tau} \right) dt$$



Lineshape Analysis.

Note that the half-life of an excited state can be obtained directly from the gamma-ray lineshape (dN / dE) since this gives directly the velocity distribution of the recoils as they emit the gamma-ray.

$$dN(t) = \frac{1}{\tau} \exp \left(-\frac{t}{\tau} \right) dt$$

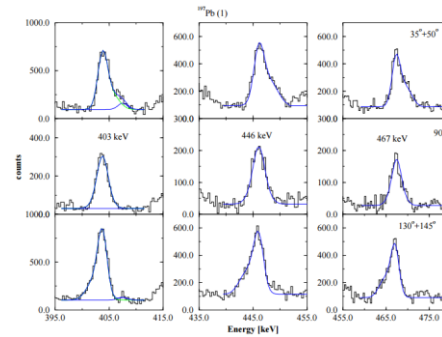


Figure 5.18: DSAM lineshape fits to transitions in the M1 band of ^{197}Pb [216].

A knowledge of the slowing down process or 'stopping power' of the recoil, (dv/dt) , allows the lineshape to be calculated for a given value of the mean lifetime, τ .

Since the Doppler shifted energy, E_s and recoil velocity at emission, v , have a linear relationship, one can translate from the measured (dN/dE) to the calculated (dN/dv) , via knowledge of the stopping power), since

$$(dN / dt) = (dN/dv) \cdot (dv/dt)$$

Lifetime measurements in ^{135}Sm : Large deformation in the $N=6$ intruder band and evidence for quenched proton pairing

P. H. Regan,⁽¹⁾ R. Wyss,⁽²⁾ R. Wadsworth,⁽¹⁾ D. B. Fossan,⁽³⁾ Y.-J. He,⁽⁴⁾ J. R. Hughes,⁽¹⁾ I. Jenkins,⁽⁴⁾ R. Ma,⁽³⁾ M. S. Metcalfe,⁽⁴⁾ S. M. Mullins,⁽⁴⁾ P. J. Nolan,⁽⁴⁾ E. S. Paul,⁽³⁾ R. J. Poynter,⁽¹⁾ and N. Xu⁽³⁾

⁽¹⁾Department of Physics, University of York, Heslington, York YO1 5DD, United Kingdom

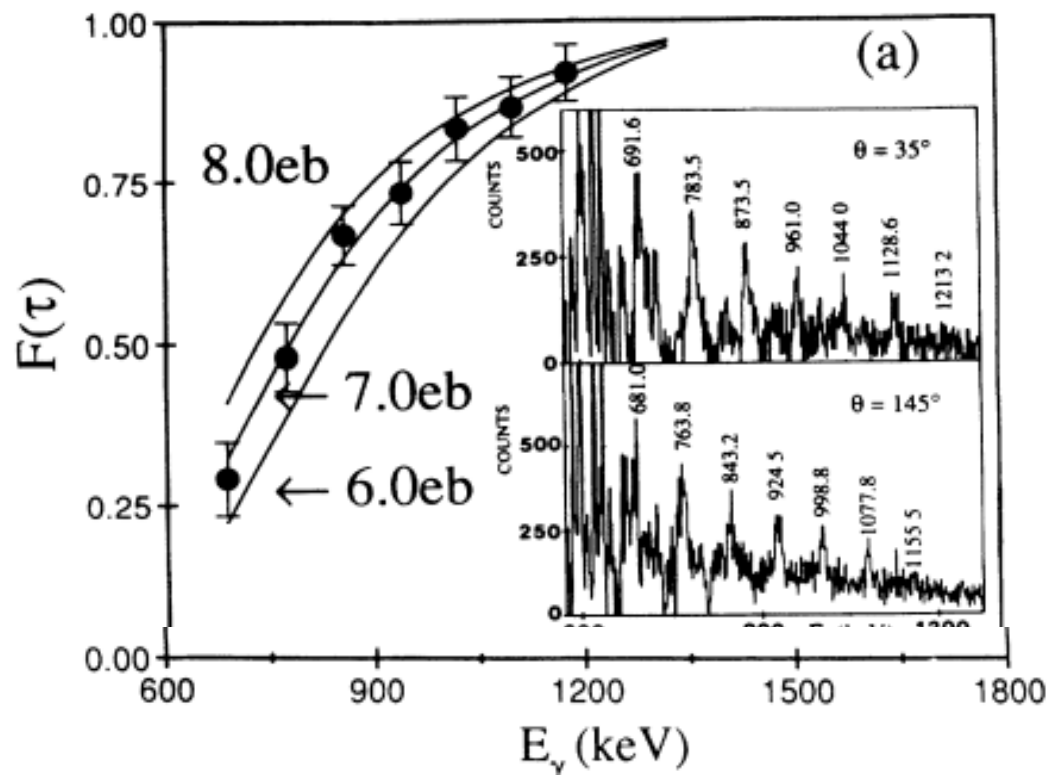
⁽²⁾Manne Siegbahn Institute of Physics, Frescativägen 24, S-104 05, Stockholm, Sweden
and Royal Institute of Technology, Physics Department I, S-104 44, Stockholm, Sweden

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⁽⁴⁾Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 3BX, United Kingdom
(Received 7 June 1990)

$$E_s = E_0 \left(1 + \frac{v}{c} \cos \theta \right)$$

$$F(\tau) = \frac{v(t)_{av}}{v_0}$$



$$Q_0 = \frac{3}{\sqrt{5}\pi} Z R_0^2 \beta_2 \left[1 + \frac{1}{8} (5/8)^{1/2} \beta_2 + \frac{5}{8\pi} \beta_2^2 \dots \right]$$

Measurement of the intrinsic quadrupole moments in the $\nu i_{13/2}$ bands of $^{135,137}\text{Sm}$

P H Regan^{a,f}, R Wadsworth^a, S M Mullins^{b,g}, J Nyberg^{c,h}, A Atac^c, S A Forbes^b, D B Fossan^d, Y-J He^{b,i}, J R Hughes^{a,d}, I Jenkins^{b,j}, R Ma^{d,k}, M S Metcalfe^b, P J Nolan^b, E S Paul^{b,d}, R J Poynter^a, D Santonico^e, A Virtanen^c and N Xu^d

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^c Niels Bohr Institute, Riso, Denmark

^d Department of Physics, State University of New York, Stony Brook, NY 11794, USA

^e INFN-LNS, Catania, Sicily, Italy

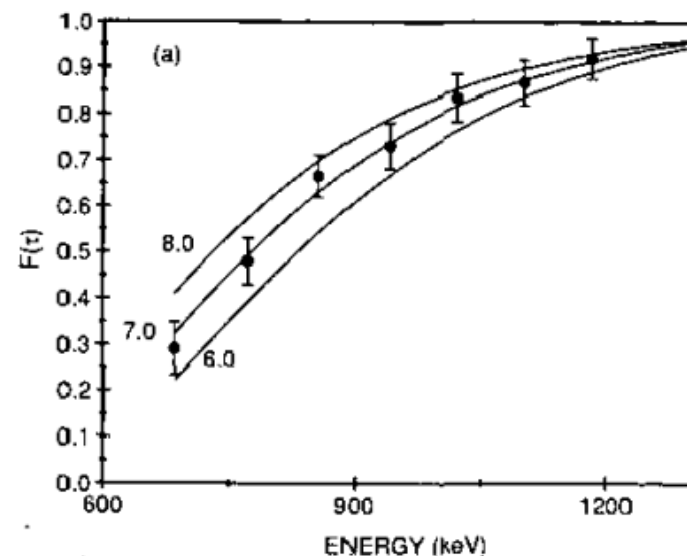
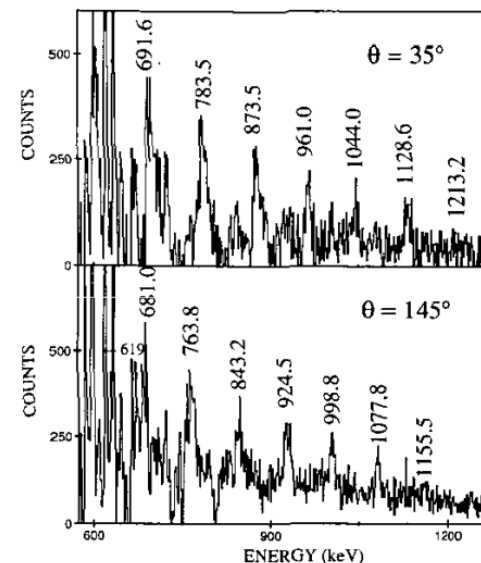
$$E_s = E_0 \left(1 + \frac{v}{c} \cos \theta \right)$$

In the rotational model, the mean lifetime of a state $\langle I_i K |$, given by τ in ps is related to the intrinsic quadrupole moment Q_0 in eb and the energy, E , of the E2 transition between the states, $\langle I_i K |$ and $\langle I_f K |$ in MeV, by

$$\frac{1}{\tau} = 1.22 E_\gamma^5 \times \frac{5}{16} Q_0^2 \langle I_i 2K0 | I_i 2I_f K \rangle^2.$$

$$F(\tau) = \frac{v(t)_{av}}{v_0}$$

Measurement of the quadrupole moments in $^{135,137}\text{Sm}$



Intrinsic Quadrupole Moment of the Superdeformed Band in ^{152}Dy

M. A. Bentley, G. C. Ball,^(a) H. W. Cranmer-Gordon, P. D. Forsyth, D. Howe, A. R. Mokhtar,
J. D. Morrison, and J. F. Sharpey-Schafer

Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 3BX, United Kingdom

P. J. Twin, B. Fant,^(b) C. A. Kalfas,^(c) A. H. Nelson, and J. Simpson

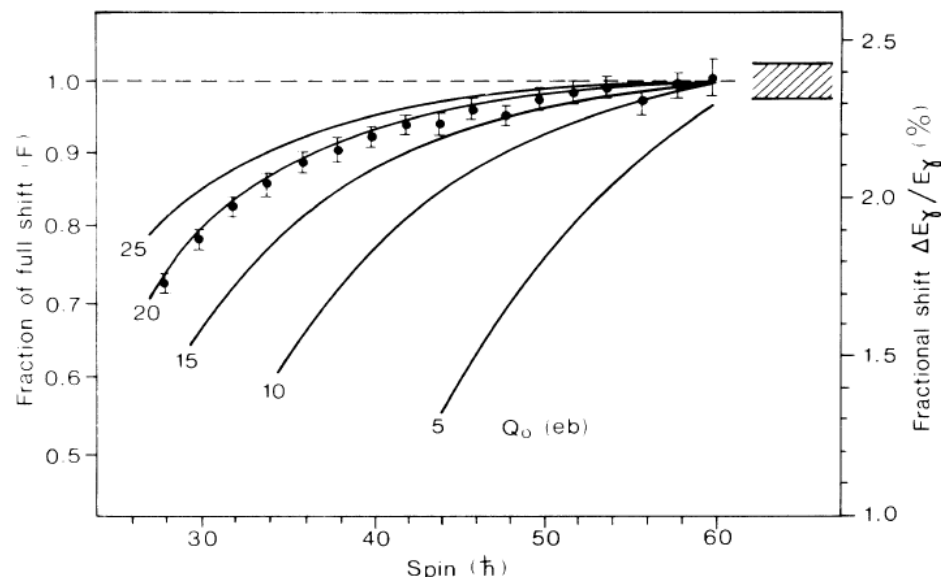
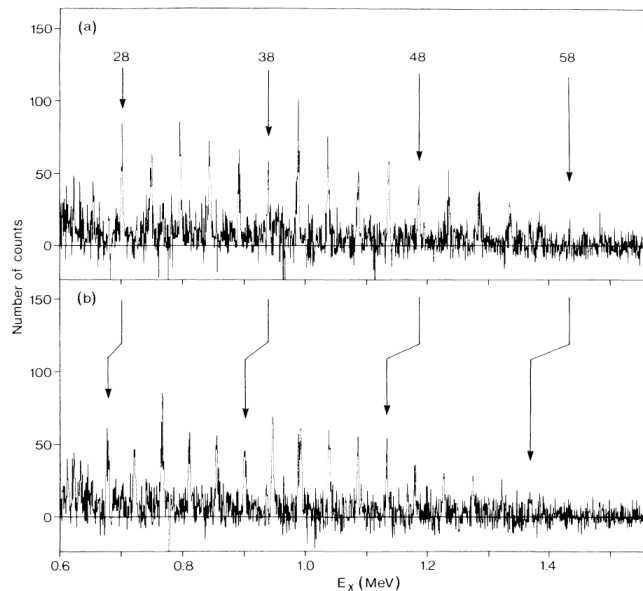
Science and Engineering Research Council, Daresbury Laboratory, Daresbury, Warrington WA4 4AD, United Kingdom

and

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Niels Bohr Institutet, DK-4000 Roskilde, Denmark

(Received 9 February 1987; revised manuscript received 3 June 1987)



If we can assume a constant quadrupole moment for a rotational band (Q_0), and we know the transition energies for the band, correcting for the feeding using the Bateman equations, we can construct 'theoretical' $F(\tau)$ curves for bands of fixed Q_0 values