Characterising Nuclear Decay Schemes: Nuclear Structure to Radiological Standards

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Outline:

- Introduction to radioisotope physics

- Some Current frontiers:
  - Gamma-ray energies and electromagnetic transition rates
  - Reaction/production mechanisms
  - Nuclear shape/shell evolution $E(2^+)$ evolution.

- Gamma-ray Detection - Singles and Coincidence Arrays:
  - NORMs
  - The DESPEC/**FATIMA** array at GSI/FAIR for DESPEC experiments.
  - Pre-DESPEC with EURICA: deformation in ^{104,6}Zr (β–γ timing).
  - **NuBALL** at IPN-Orsay, ^{164}Dy(^{18}O,^{16}O)^{166}Dy.

- Applications / impact at NMIs for absolute standards.
  - NORM measurements (mining; ^{223}Ra radioisotope standards).
  - **NANA** for ^{60}Co standardisation; ^{90}Sr $\rightarrow$ ^{90}Y $\rightarrow$ ^{90}Zr 'imaging'.

By 1930, the main 'NORM' decay chains were characterised....

JULY, 1931 REVIEWS OF MODERN PHYSICS VOLUME 3

THE RADIOACTIVE CONSTANTS AS OF 1930

REPORT OF THE INTERNATIONAL RADIUM-STANDARDS COMMISSION

BY M. CURIE, A. DEBIERNE, A. S. EVE, H. GEIGER, O. HAHN, S. C. LIND, ST. MEYER, E. RUTHERFORD, AND E. SCHWEIDLER

I. INTRODUCTION

FOLLOWING the reorganization of the International Union of Chemistry and of the International Atomic Weights Commission, the need has arisen for the publication of special Tables of the Radioactive Constants.

This responsibility has been assumed by the International Radium Standards Commission chosen in Brussels in 1910, which has expressed its willingness to cooperate with the International Union.

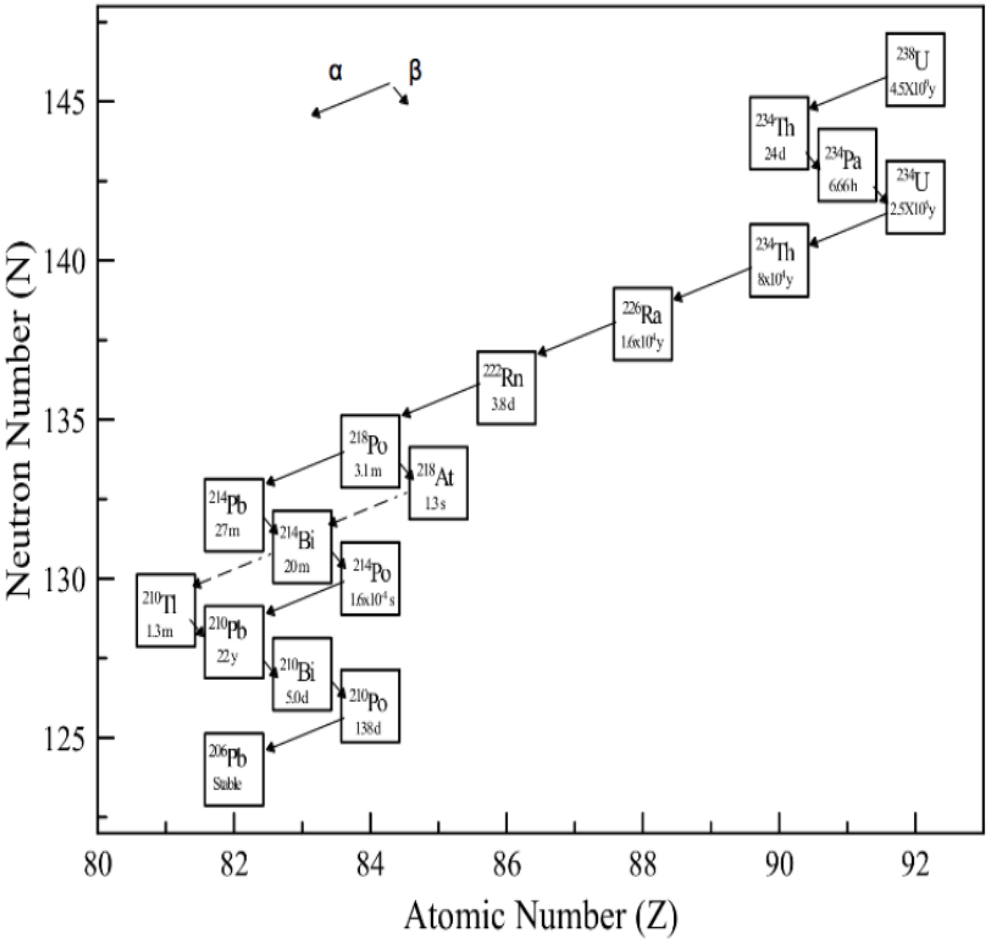
Besides the members, M. Curie, A. Debierne, A. S. Eve, H. Geiger, O. Hahn, S. C. Lind, St. Meyer, E. Rutherford, E. Schweidler, the following have taken part as experts: J. Chadwick, I. Joliot-Curie, K. W. F. Kohlrausch, A. F. Kovarik, L. W. McKeehan, L. Meitner and H. Schlundt, to whom it is desired to express especial obligations.

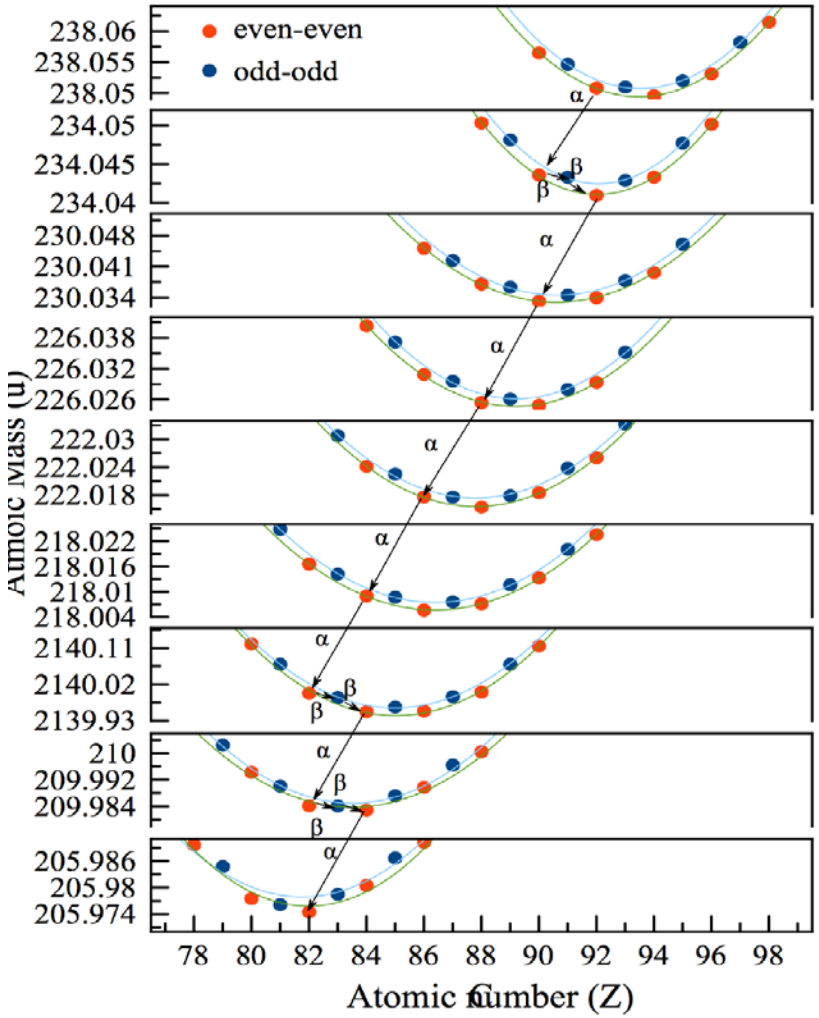
The following report will be simultaneously published* also in the Physikalische Zeitschrift, in the Journal of the American Chemical Society, Philosophical Magazine, and Journal de Physique et le Radium.

Naturally Occurring decay 'chains' (NORMs).

Sequences of α and β decaying radioisotopes from Uranium (Z=92) or Thorium (Z=90) to Lead (Z=82).

On earth since formation. Isotope/element ratios (e.g. $^{206}Pb/^{238}U$) can be used to date rocks / earth etc.





REVIEWS OF
MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

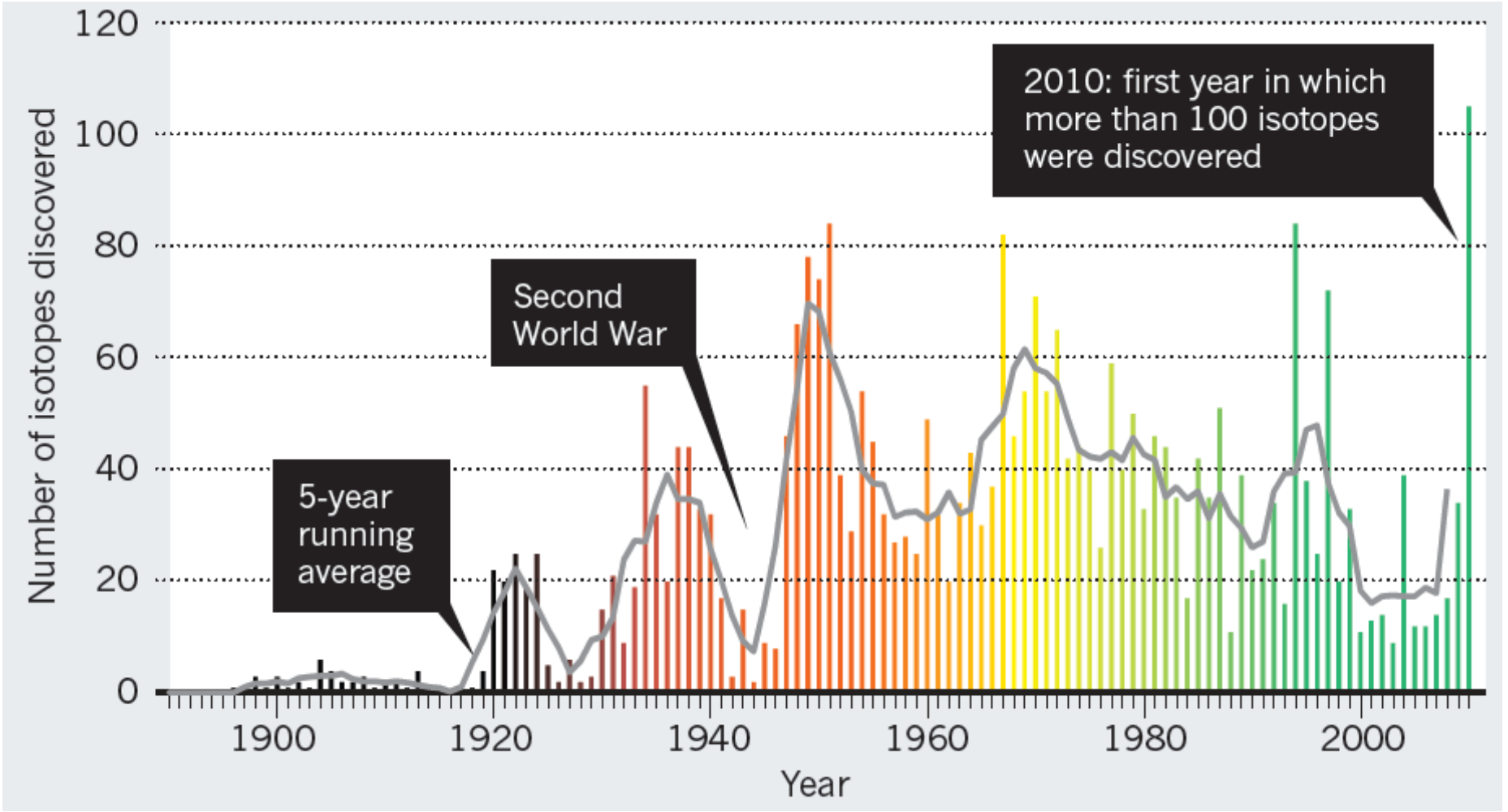
Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

TABLE I,1. Table of elements and isotopes [compiled from *Chart of the Nuclides* (Knolls Atomic Power Laboratory, April, 1956)].

Elements		Isotopes	
Stable	81	Stable	272
Radioactive:		Radioactive:	
Natural ($Z \leq 83$)	1[a]	Natural ($A < 206$)	11[d]
($Z > 83$)	9[b]	($A \geq 206$)	44
Natural:		Natural:	
Stable and Radioactive	91	Stable and Radioactive	327
Radioactive:		Radioactive:	
Artificial ($Z \leq 83$)	1[c]	Artificial ($A < 206$)	702
($Z > 83$)	10	($A \geq 206$)	169
Total	102	Total	1198
Neutron	1	Neutron	1
	103		1199

[a] Tc, observed in *S*-type stars.
[b] Including At and Fr produced in weak side links of natural radioactivity
[c] Pm, not observed in nature.
[d] Including H^3, C^{14}, and Tc^{99}.


120
100
80
60
40
20
0
Number of isotopes discovered
2010: first year in which more than 100 isotopes were discovered
Second World War
5-year running average
1900
1920
1940
1960
1980
2000
Year

‘new’ radioisotopes still being discovered ….

PRL 118, 072701 (2017) PHYSICAL REVIEW LETTERS week ending 17 FEBRUARY 2017

94β-Decay Half-Lives of Neutron-Rich $_{55}$Cs to $_{67}$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. Fang,[14] G. Gey,[7,15,2] T. Isobe,[2] P. S. Lee,[16] J. J. Liu,[11] Z. Li,[1] Z. Korkulu,[17] Z. Patel,[4,2] V. Phong,[18,2] S. Rice,[4,2] H. Sakurai,[2,12] L. Sinclair,[19,2] T. Sumikama,[2] M. Tanaka,[6] A. Yagi,[14] Y. L. Ye,[1] R. Yokoyama,[20] G. X. Zhang,[10] T. Alharbi,[21] N. Aoi,[6] F. L. Bello Garrote,[22] G. Benzoni,[23] A. M. Bruce,[13] R. J. Carroll,[4] K. Y. Chae,[24] Z. Dombradi,[17] A. Estrade,[25] A. Gottardo,[26,27] C. J. Griffin,[25] H. Kanaoka,[14] I. Kojouharov,[28] F. G. Kondev,[29] S. Kubono,[2] N. Kurz,[28] I. Kuti,[17] S. Lalkovski,[4] G. J. Lane,[30] E. J. Lee,[24] T. Lokotko,[11] G. Lotay,[4] C.-B. Moon,[31] H. Nishibata,[14] I. Nishizuka,[32] C. R. Nita,[13,33] A. Odahara,[14] Zs. Podolyák,[4] O. J. Roberts,[34] H. Schaffner,[28] C. Shand,[4] J. Taprogge,[35,36] S. Terashima,[10] Z. Vajta,[17] and S. Yoshida[14]

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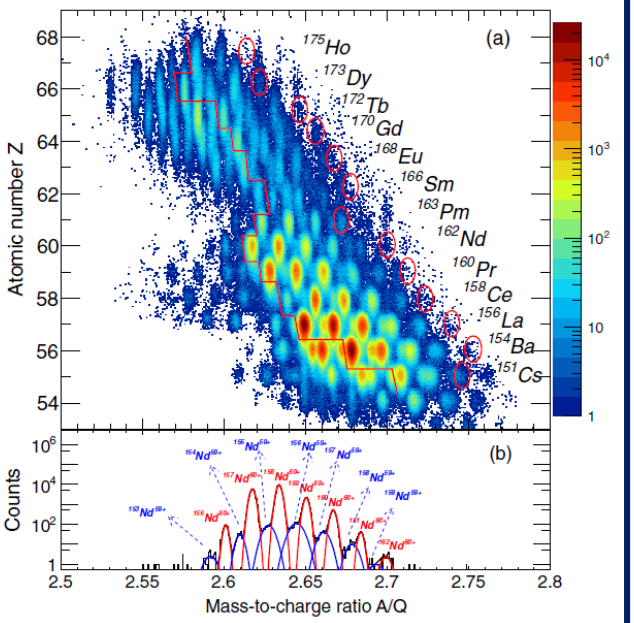
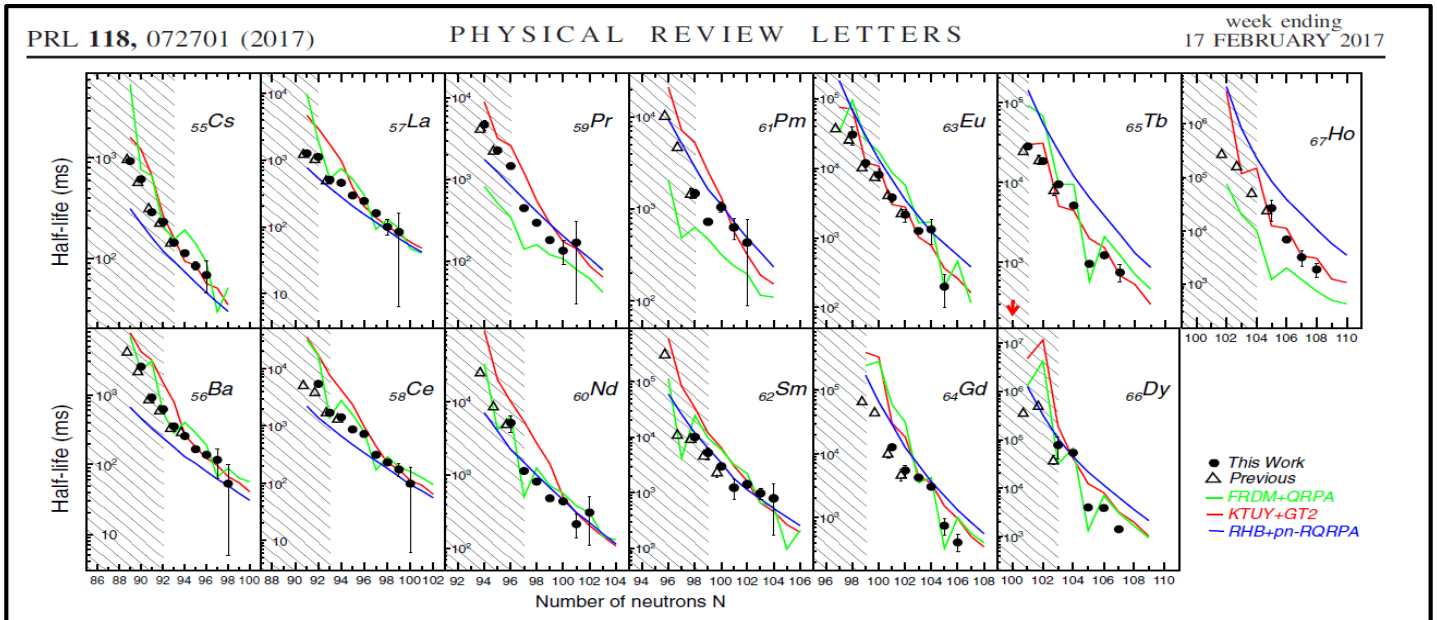




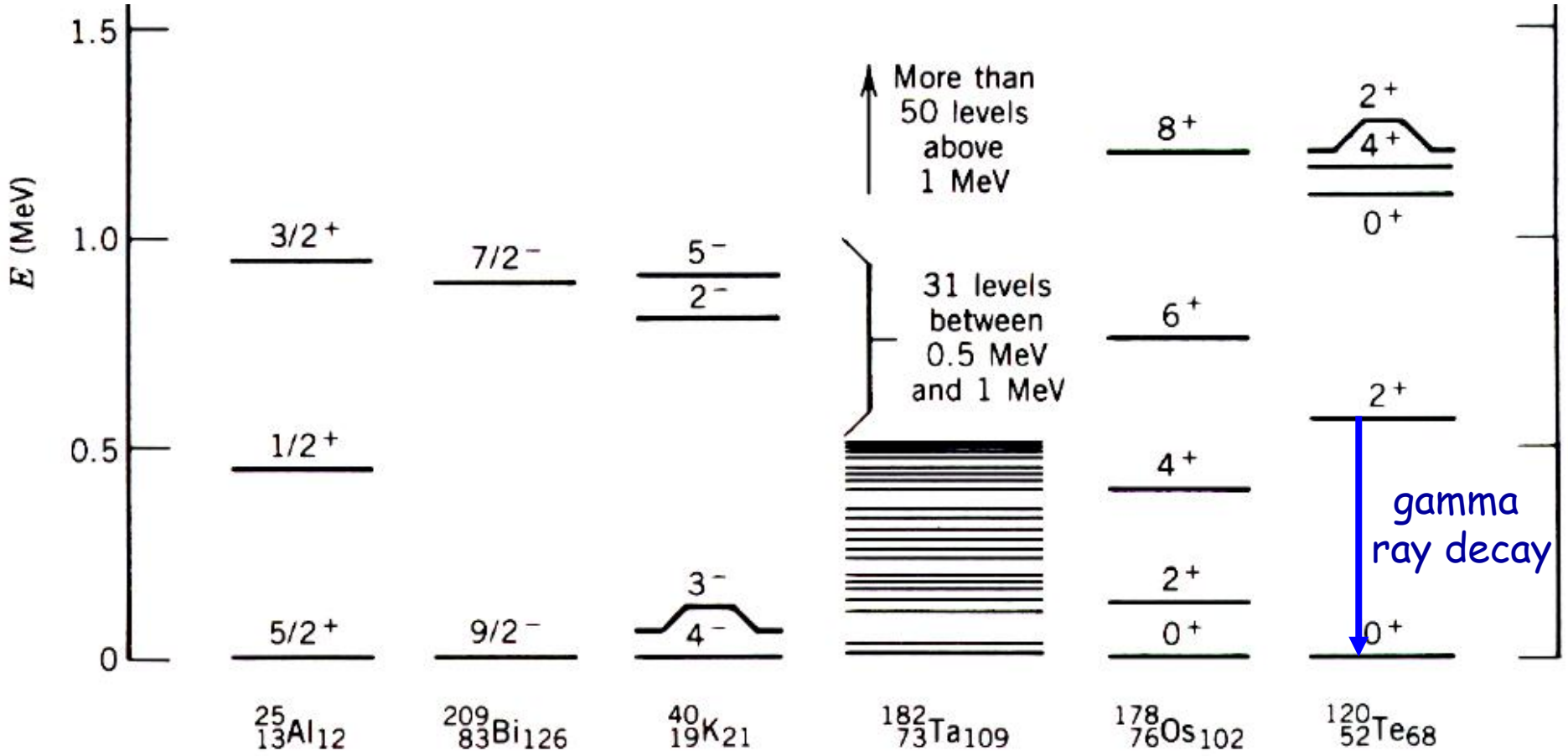
Different nuclear reaction mechanisms?

- Heavy-ion fusion-evaporation reactions (neutron-deficient).
- Spontaneous fission sources such as ^{252}Cf (neutron-rich).
- Deep-inelastic/multi-nucleon (near-stable/neutron-rich).
- High-energy Projectile fragmentation / fission at e.g., GSI, RIKEN, GANIL, FRIB (everything….)

- Beta decay ; alpha decay (e.g. NORMs); proton radioactivity
- Other probes (e,e′γ), (γ,γ′), (n,γ), (p,γ), (n,n′γ) etc.
- Coulomb excitation, EM excitations via E2 (usually).
- Single particle transfer reactions (p,d)

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

Measuring Excited 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.

How much radioactive material is present ? (= metrology)

Activity (*A*) = number of decays per second

$$A = \lambda N$$

λ is related to the **half-life** by $l = 0.693 / T_{1/2}$

A **signature** of radioactive decay is the subsequent emission of **characteristic energy gamma rays**

Measuring these provides accurate activities of the specific radionuclides in a sample.

Links between primary standards of activity & underpinning Nuclear Data

- Primary standards needed are needed to calibrate measurement systems.

- These can then be used for measuring **absolute γ-ray emission intensities per decay**, $P_\gamma(\%)$.

- These are needed for:
  - medical radiopharmaceutical dose evaluations;
  - nuclear security (e.g., CTBT verification, radioxenon)
  - nuclear waste assay (e.g, Np, Pu, Am, Cs isotopes);
  - environmental assay (NORMs);
  - nuclear forensics (e.g., ^{134,137}Cs and U isotope ratios);
  - nuclear structure / nuclear (astro)physics research.

Radionuclide Metrology and Standards in Nuclear Physics

Patrick H. Regan, Steven M. Judge, John D. Keightley & Andy K. Pearce

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Radionuclide Metrology and Standards in Nuclear Physics

The development of radionuclide standards for metrology has underpinned nuclear physics since its inception [1]. The current frontier of radionuclide metrology relies on developments in radiation detection and signal processing combined with accurate nuclear decay data evaluations [2] and contributes to a myriad of scientific disciplines. Radionuclide metrology represents a crucial part of the scientific jigsaw that enables societal benefits from nuclear physics research.

Measurements that are traceable to internationally accepted primary standards can give the public confidence in the characterization of civilian nuclear waste materials such as ^{90}Sr, ^{134,135,137}Cs, ^{237}Np, ^{239,240}Pu, and ^{241}Am and measurements of naturally occurring radioactive materials (NORMs) such as ^{3}H, ^{7}Be, ^{14}C, ^{210}Po, ^{210}Pb, ^{214}Bi, ^{214}Pb, ^{222}Rn, ^{223}Ra, ^{226}Ra, ^{228}Ac, and ^{234,235,238}U. Other applications include assay of Technologically Enhanced NORM with potential radiological impact on workers in the oil and mineral production industries, and the use of radiopharmaceutical isotopes such as ^{18}F, ^{82}Rb/^{82}Sr, ^{89}Zr, ^{99m}Tc, ^{124,131}I, ^{211}At, ^{223}Ra, and ^{227}Th for diagnostic imaging and therapy. This article explains the concept of international traceability and how accurate radiation standards are determined for different radioactive decay modes.

Primary Radioactivity Standards

National Measurement Institutes (NMIs) are responsible for the development and upkeep of primary measurement standards. Primary standards are used to calibrate instruments and/or to certify reference materials; these can then be distributed to other laboratories and used to calibrate their own instruments in an uninterrupted chain of calibrations to the final end-user. All measurements are essentially ratios back to these primary standards. NMIs cross-check their primary standards against sources from other countries through international comparison exercises co-ordinated by the Bureau International des Poids et Mesures (BIPM).

The first primary standard of radioactivity was based on radium. The inaugural Radium Standards Committee was held in Brussels in 1910 and chaired by Lord Rutherford at which 1 curie (Ci) was defined as the amount of radon in equilibrium with 1 g of radium [1]. The radioactivity measurement system based on radium standards became outdated following developments in accelerator technology, which led to an increased range of artificially created radionuclides. In 1950, the curie was redefined as 3.7×10^{10} disintegrations per second and, in 1975, the 15th Conférence Générale des Poids et Mesures adopted the becquerel (Bq), which is equal to one inverse second for the SI unit of activity [3, 4].

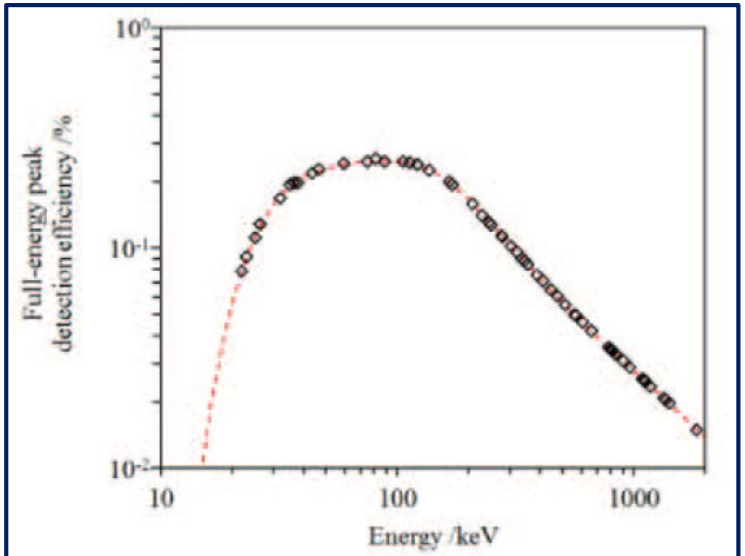
In 1958, The International Committee for Weights and Measures of the BIPM created the Comité Consultatif des Rayonnements Ionisants (CCRI). The CCRI is responsible for organizing international comparisons, enabling NMIs to cross-check their primary standards. The International Reference System, implemented in 1975, is based on a pressurized well-type ionization chamber based at BIPM [4]. This is a permanent, stable measurement instrument tool that is available to NMIs to compare primary standards of gamma emitters.

A primary standard of radioactivity allows the number of decays from a source in a finite time period to be determined using a technique that does not itself need calibration. Since the activity of each radionuclide species depends on unique decay properties, different experimental techniques are needed for the primary standardizations of individual radioisotopes. The particular technique depends on the radioactive decay mode(s), half-life, decay scheme of the daughter nucleus and branching ratios for competing decay modes. Most modern radioactivity standards are aqueous solutions, quantified by their activity per unit mass on a given reference date [3, 4]. The main methodologies used for primary radionuclide standardization are discussed below.

High-Geometry Methods

Perhaps the simplest method is to count the number of photons or particles emitted by a source into the full 4π steradians of solid angle [3]. The perfect 4π detector does not exist and the "non-detection" probability must be accounted for, either by examining the rate of coincidences between multiple detectors or using Monte-Carlo particle transport simulation codes.

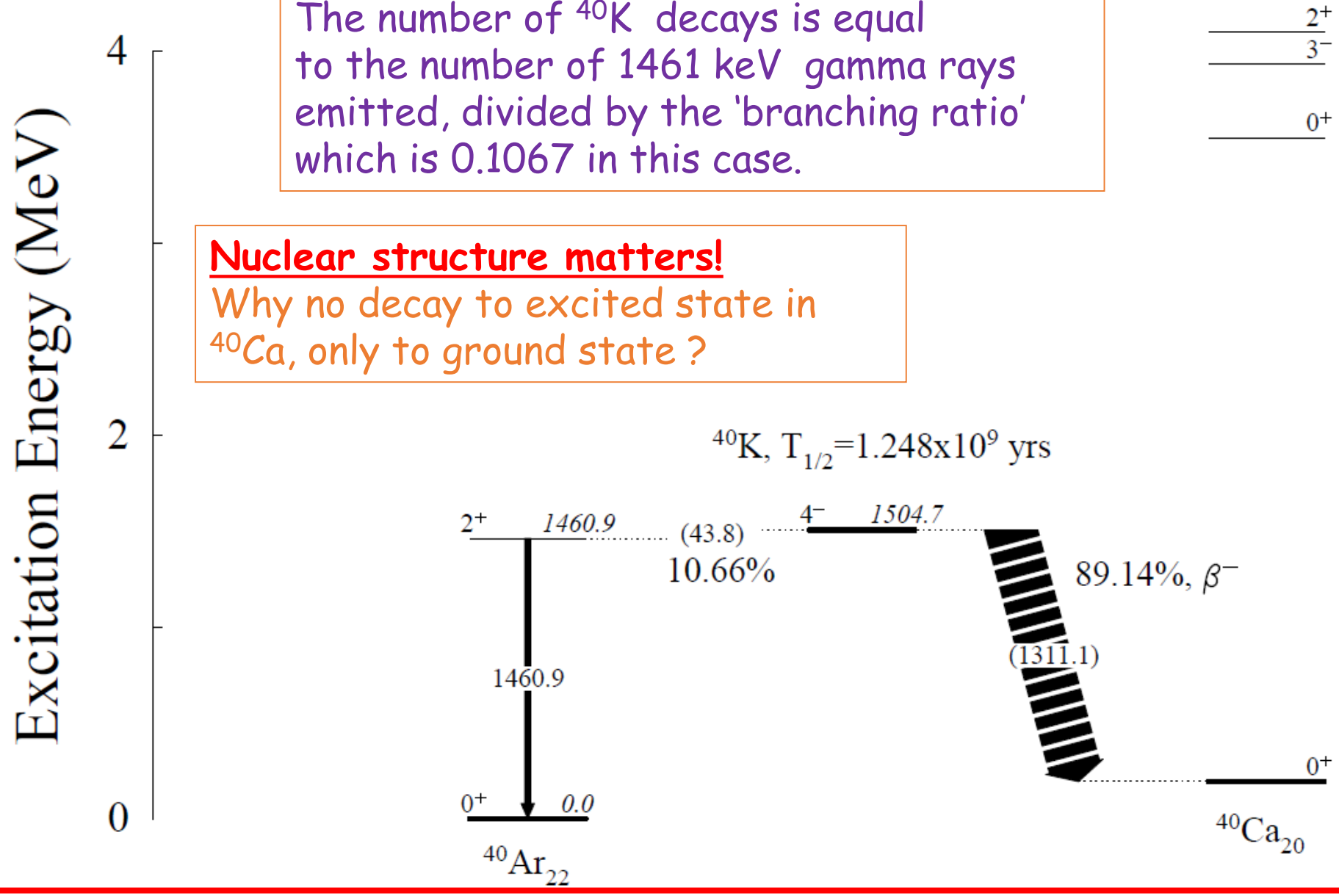
For a complex decay scheme of excited states populated in the daughter nucleus, the $4\pi\gamma$ counting technique can be exploited using either a single well-type NaI(Tl) or two NaI(Tl) detectors sandwiching the source. A higher number of coincident cascade gammas emitted per decay leads to reduced uncertainties from non-detec-



The number of ^{40}K decays is equal to the number of 1461 keV gamma rays emitted, divided by the 'branching ratio' which is 0.1067 in this case.

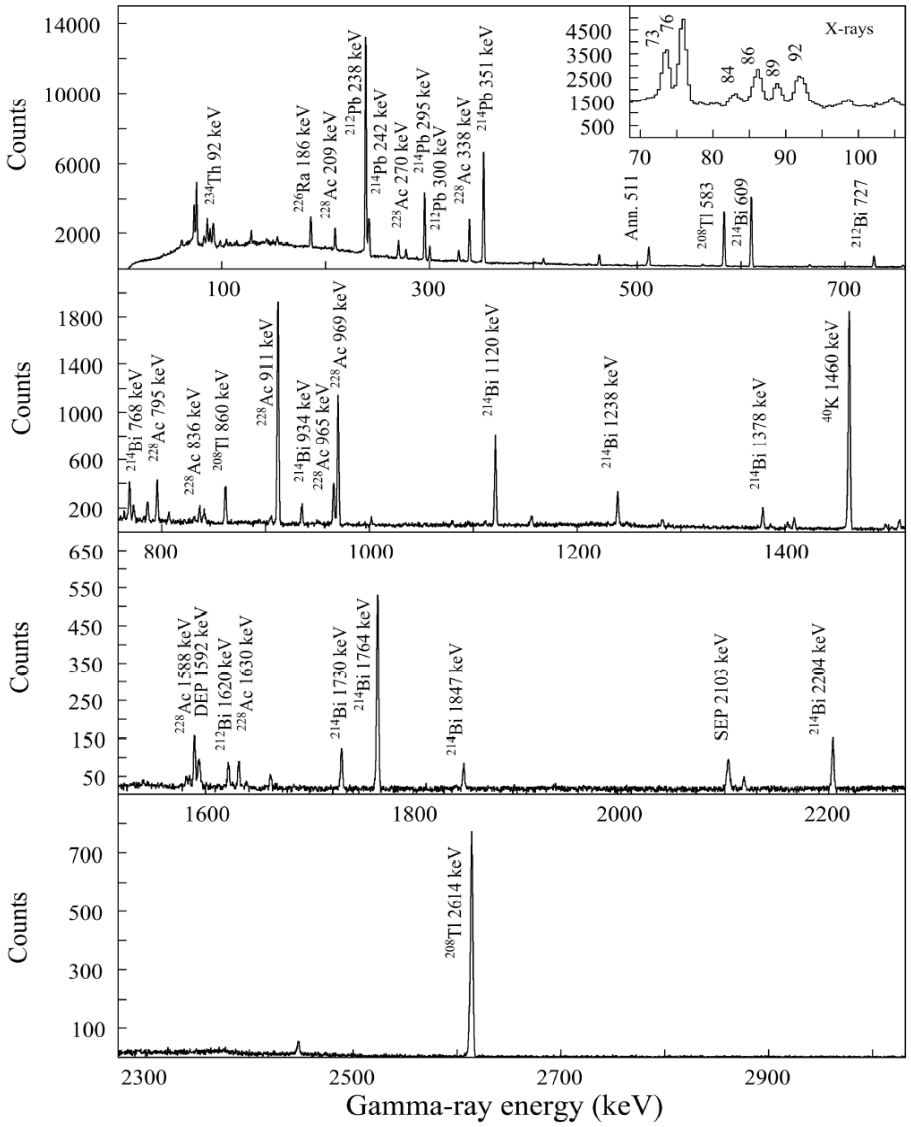
Nuclear structure matters!

Why no decay to excited state in ^{40}Ca, only to ground state ?



Not all the gamma rays observed have to originate from the same radionuclide.

Different radionuclides are identified by their characteristic gamma-ray energies.



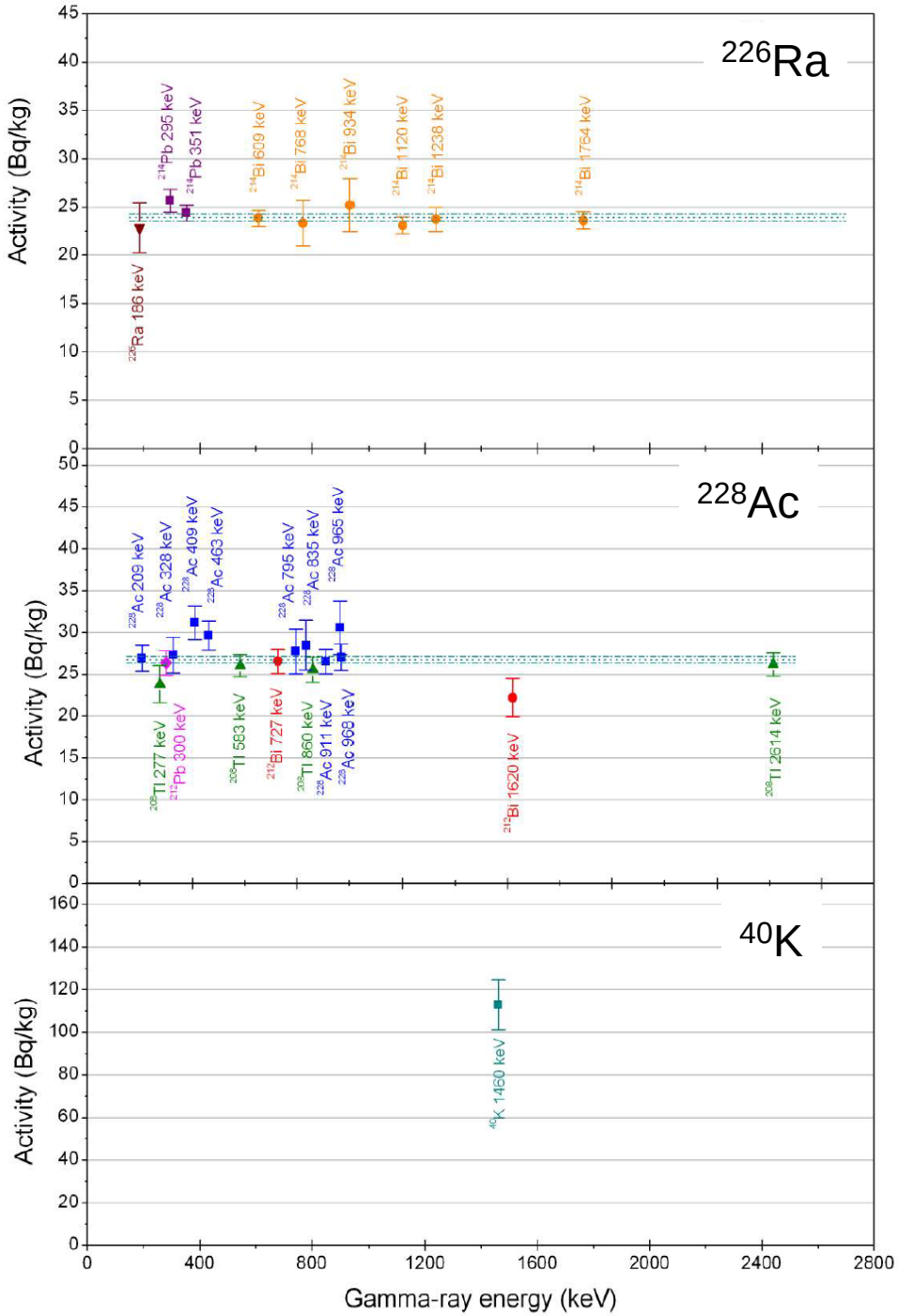


Figure 4.20: Radionuclide activity for the 'Mai Kao' beach sand sample. The dotted lines represent

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Determination of ^{238}U, ^{232}Th and ^{40}K activity concentrations in riverbank soil along the Chao Phraya river basin in Thailand

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P.H. Regan [a, c, *]

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[b] Centre for Environmental Health Engineering, Department of Civil Eng
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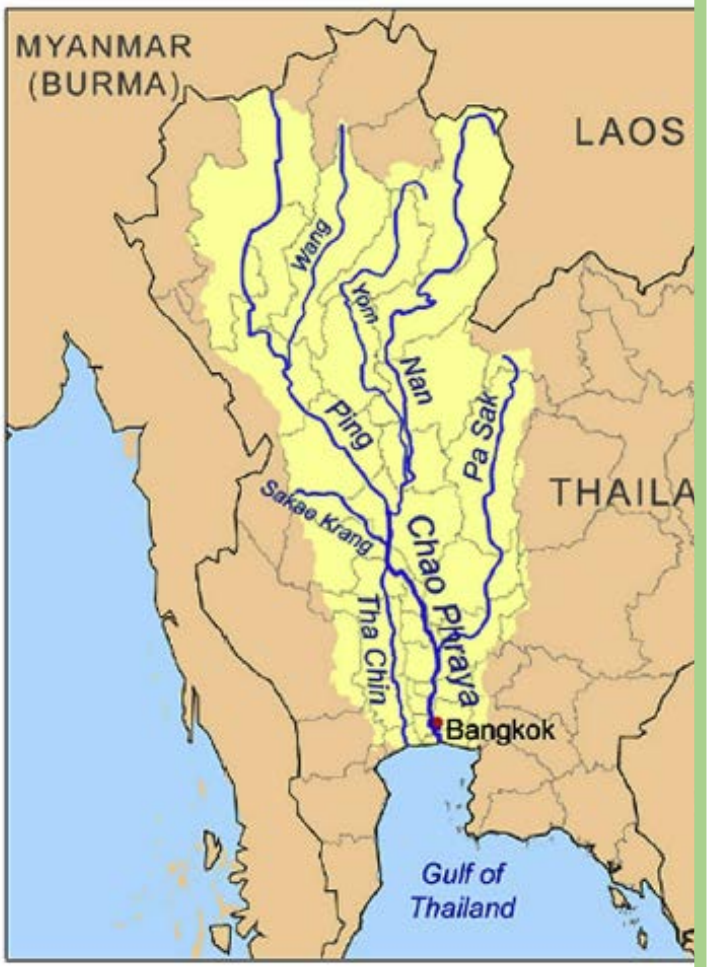
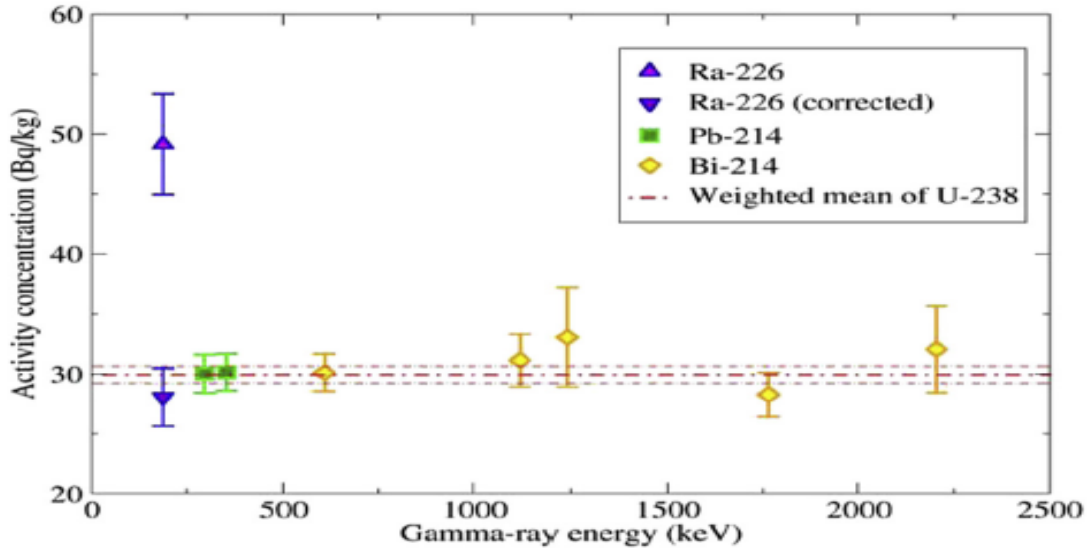
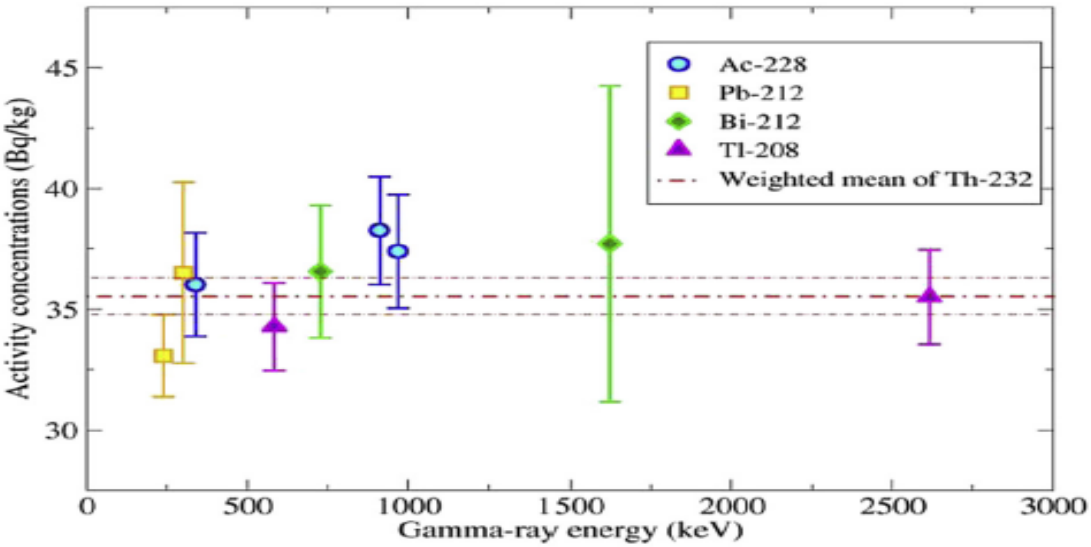




(a)



Other radionuclides in the 'background'?

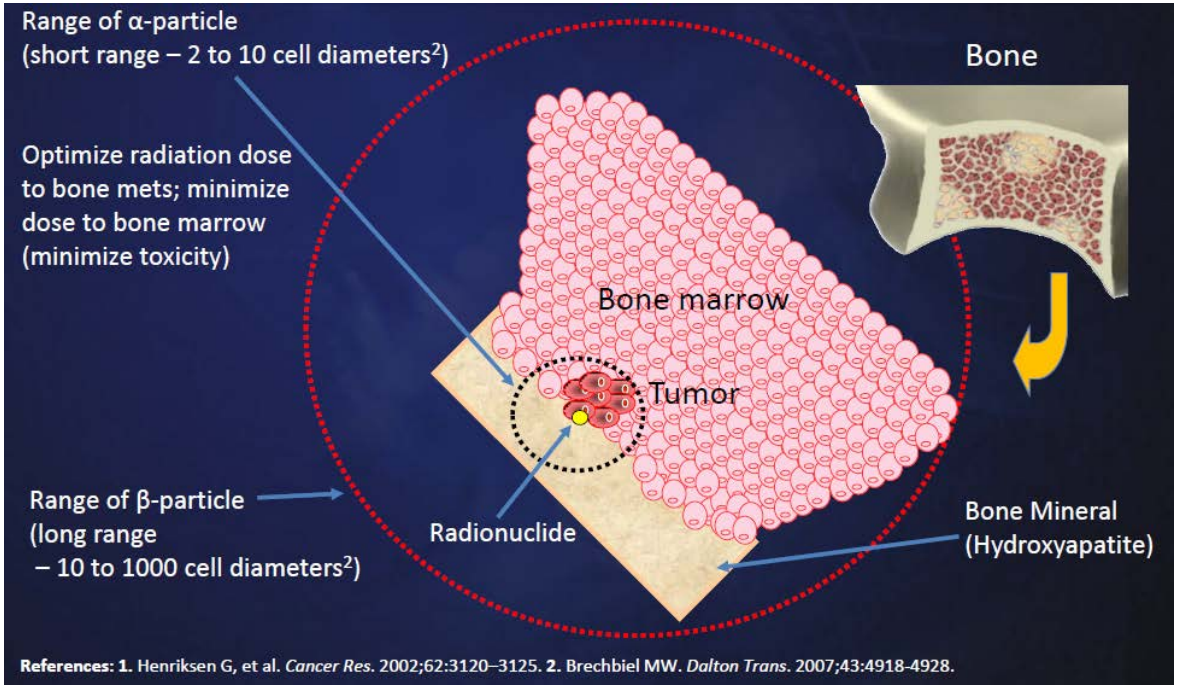
- Man-made ('anthropogenic') radionuclides also present in the wider environment, e.g.,
  - Fission fragment daughters such as ^{137}Cs, ^{90}Sr
  - ^{241}Am, decays to ^{237}Np ($T_{1/2}$~2 million years)
  - ^{239}Pu, ^{241}Am (from neutron capture on ^{238}U in fuel)
  - Neutron capture on fission residues (e.g., ^{134}Cs)
  - Medical isotopes released near hospitals (^{99m}Tc; ^{131}I)

More applications / impact?

Nuclear Medicine: Xofigo™

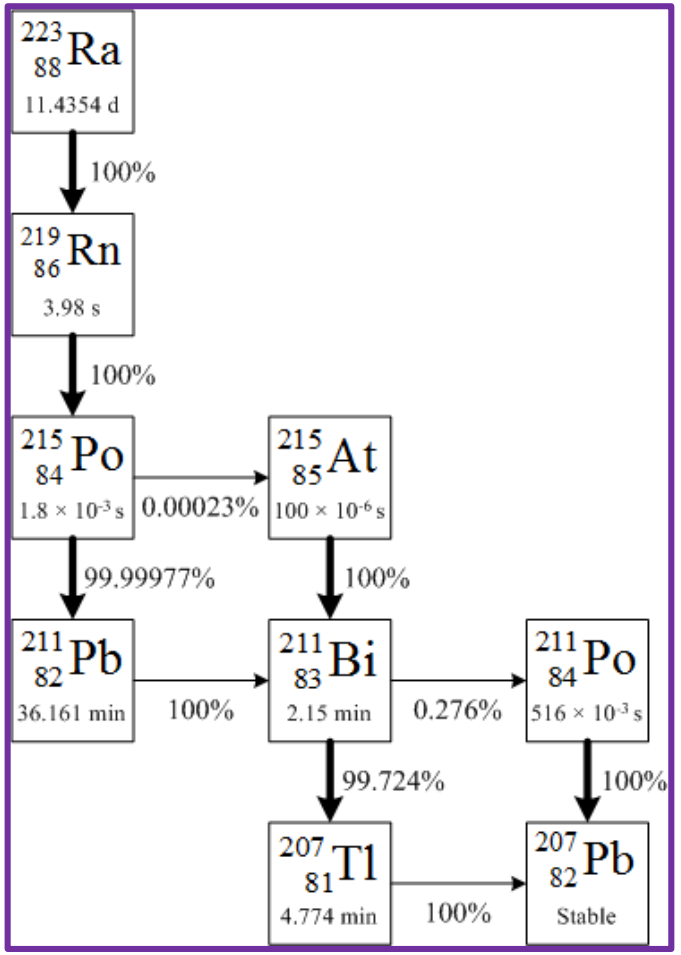
Xofigo® radium Ra 223 dichloride INJECTION

- First α emitting radionuclide approved by the US FDA and licensed in the EC from Nov. 2013 - $^{223}RaCl_2$ solution.
- Targeted palliative treatment of bone metastases from late stage castration resistant prostate cancer
- Extends patient life ~ average 3 months
- Under investigation for bone metastases from breast & ovarian cancer.
- Now used in >3,000 clinics worldwide; supplied through Bayer (formerly Algetha)



^{223}Ra Decay Series

- Decay progeny all have half-lives < 40 min
- Reach radioactive equilibrium within hours of chemical separation
  - ~ ×6 activity of the ^{223}Ra
- ^{223}Ra decay series has
  - 6 α-emitters
  - 2 β-emitters
- Decay progeny emit characteristic γ rays.
- 148 discrete energy γ ray transition from the decay series have been identified in literature (not including X-rays).



Applied Radiation and Isotopes 99 (2015) 46–53

Applied Radiation and Isotopes

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

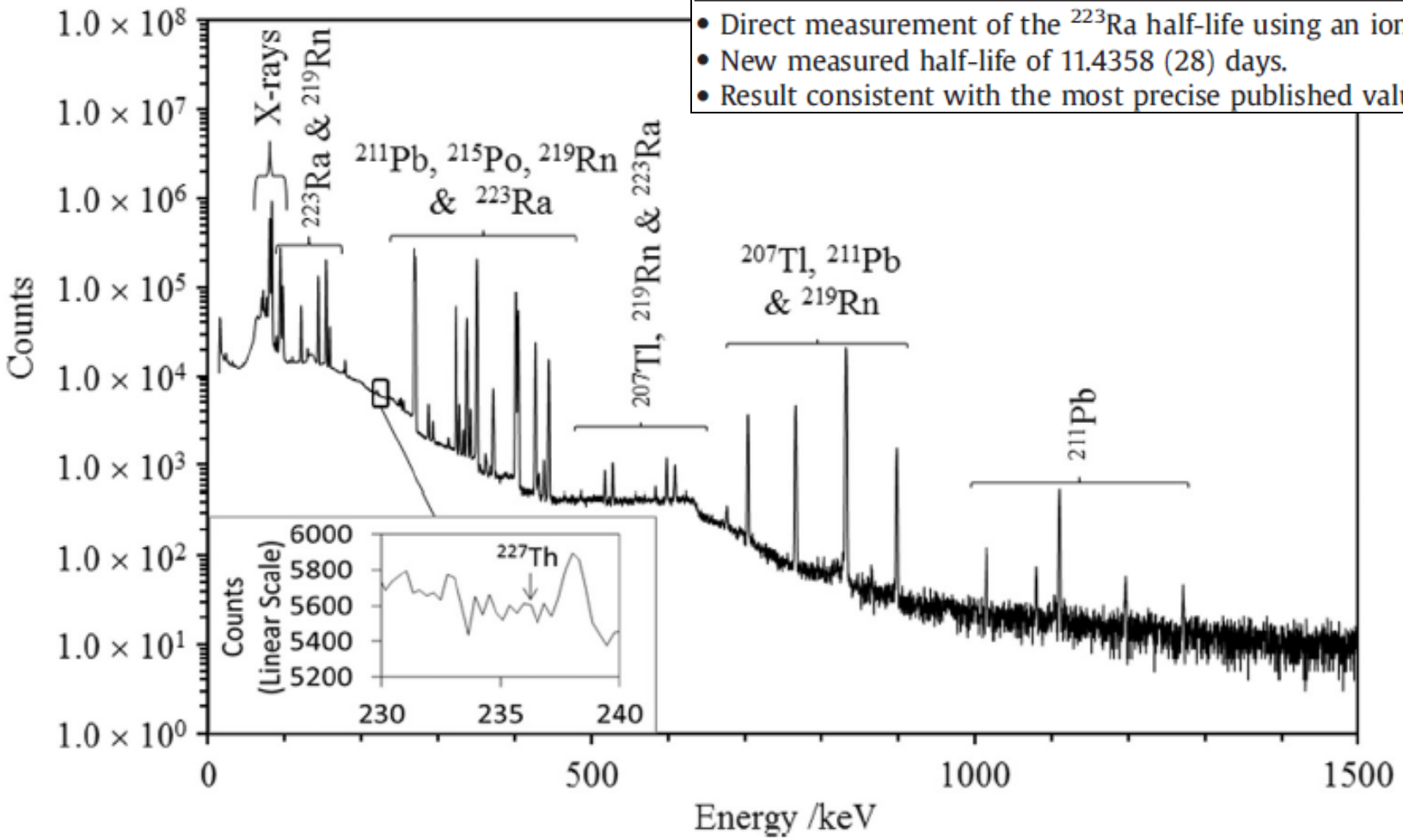
Direct measurement of the half-life of ^{223}Ra

S.M. Collins [a,*], A.K. Pearce [a], K.M. Ferreira [a], A.J. Fenwick [a], P.H. Regan [a,b], J.D. Keightley [a]

[a] National Physical Laboratory, Hampton Road, Teddington, Middlesex TW11 0LW, United Kingdom
[b] Department of Physics, University of Surrey, Guildford, Surrey GU2 7XH, United Kingdom

HIGHLIGHTS

- Direct measurement of the ^{223}Ra half-life using an ionisation chamber.
- New measured half-life of 11.4358 (28) days.
- Result consistent with the most precise published value.



Most up to date, accurate data on ^{223}Ra decay.

Applied Radiation and Isotopes 102 (2015) 15–28

Precise measurements of the absolute γ-ray emission probabilities of ^{223}Ra and decay progeny in equilibrium

S.M. Collins [a,*], A.K. Pearce [a], P.H. Regan [a,b], J.D. Keightley [a]

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[b] Department of Physics, University of Surrey, Guildford, Surrey GU2 7XH, United Kingdom

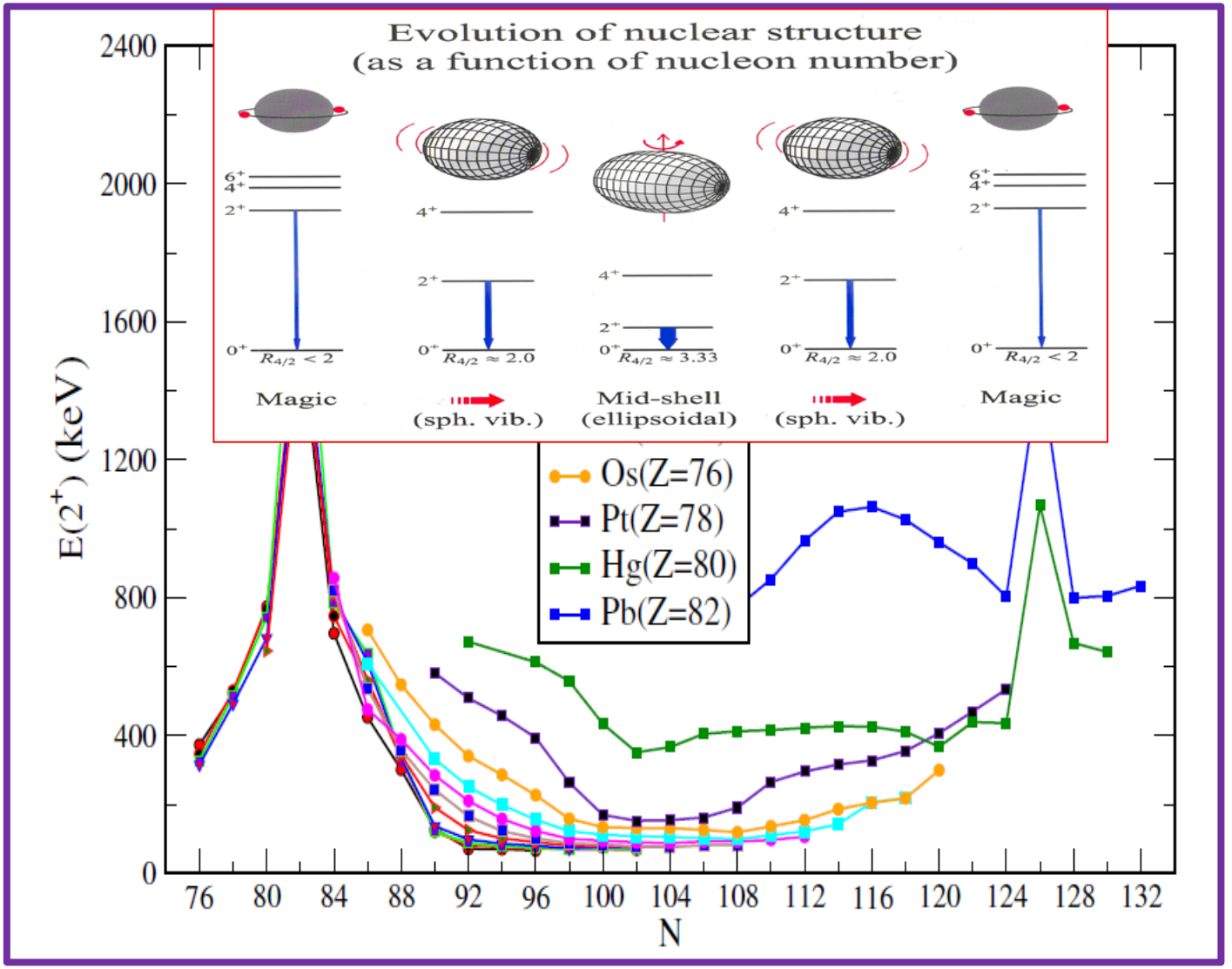
Table 4
Absolute γ-ray emission probabilities per 100 decays of ^{223}Ra and decay progeny in equilibrium.

Energy (keV)	Source	I_γ (%)	Energy (keV)	Source	I_γ (%)	Energy (keV)	Source	I_γ (%)	Energy (keV)	Source	I_γ (%)
103.9(5)	^{223}Ra	0.0119(6)	323.9(6)	^{223}Ra	3.655(18)	438.8(6)	^{215}Po	0.0533(7)	675.4(6)	^{211}Pb	0.0058(6)
106.7(4)	^{223}Ra	0.0213(11)	328.4(6)	^{223}Ra, ^{211}Po, ^{207}Tl	0.2021(16)	445.0(6)	^{223}Ra	1.218(6)	676.9(6)	^{219}Rn	0.0184(5)
110.8(5)	^{223}Ra	0.0512(10)	333.9(6)	^{223}Ra	0.0756(6)	462.8(6)	^{219}Rn	0.0011(5)	704.6(7)	^{211}Pb	0.498(3)
122.3(5)	^{223}Ra	1.312(6)	338.3(6)	^{223}Ra	2.605(13)	487.3(5)	^{223}Ra	0.0083(3)	707.8(7)	^{219}Rn	0.0034(4)
130.6(5)	^{219}Rn	0.1478(10)	342.9(6)	^{223}Ra, ^{211}Pb	0.1958(21)	500.2(6)	^{223}Ra	0.0013(5)	711.4(7)	^{223}Ra	0.0037(3)
144.3(5)	^{223}Ra	3.481(16)	351.1(6)	^{211}Bi	13.17(7)	504.1(6)	^{211}Pb	0.0022(4)	727.4(7)	^{223}Ra	0.0024(7)
154.2(5)	^{223}Ra	6.02(3)	355.5(6)	^{223}Ra	0.0124(15)	517.6(6)	^{219}Rn	0.0453(5)	766.4(7)	^{211}Pb	0.685(4)
158.7(5)	^{223}Ra	0.749(4)	361.7(6)	^{211}Pb	0.0341(7)	522.6(6)	^{223}Ra	0.0021(6)	831.9(7)	^{211}Pb	3.448(16)
175.6(5)	^{223}Ra	0.01578(10)	363.0(6)	^{223}Ra	0.0192(9)	527.6(6)	^{223}Ra	0.0659(8)	835.6(7)	^{219}Rn	0.00364(19)
177.4(5)	^{223}Ra	0.0426(8)	368.4(6)	^{223}Ra	0.0134(4)	531.4(6)	^{223}Ra	0.0028(9)	865.8(6)	^{211}Pb	0.00540(21)
179.7(5)	^{223}Ra	0.1613(10)	371.7(6)	^{223}Ra	0.435(3)	537.5(6)	^{223}Ra	0.0033(6)	891.3(7)	^{219}Rn	0.00107(20)
221.4(5)	^{223}Ra	0.0304(10)	372.9(6)	^{223}Ra	0.1133(13)	542.1(6)	^{223}Ra	0.0026(6)	897.8(7)	^{211}Po, ^{207}Tl	0.2725(15)
224.0(5)	^{219}Rn	0.0056(14)	376.2(6)	^{223}Ra	0.0056(4)	545.9(6)	^{223}Ra	0.0028(6)	1014.7(7)	^{211}Pb	0.0171(4)
249.4(5)	^{223}Ra	0.0375(9)	383.3(5)	^{223}Ra	0.0023(6)	555.9(5)	^{219}Rn	0.0026(7)	1074.5(7)	^{219}Rn	0.00044(12)
251.9(5)	^{223}Ra	0.0640(11)	386.3(5)	^{223}Ra, ^{219}Rn	0.0052(7)	564.4(5)	^{219}Rn	0.0035(4)	1080.1(7)	^{211}Pb	0.01228(21)
255.1(5)	^{223}Ra	0.0499(13)	390.1(5)	^{223}Ra	0.0053(7)	569.6(7)	^{211}Po, ^{207}Tl	0.0043(5)	1103.3(8)	^{211}Pb	0.00380(12)
269.5(6)	^{223}Ra	13.37(7)	401.8(6)	^{219}Rn	6.57(3)	573.7(7)	^{223}Ra	0.0029(13)	1109.5(8)	^{211}Pb	0.1113(7)
271.3(6)	^{219}Rn	10.75(6)	404.8(6)	^{211}Pb, ^{215}At	4.011(19)	598.6(7)	^{223}Ra	0.0867(12)	1196.2(8)	^{211}Pb	0.01052(17)
288.2(6)	^{223}Ra	0.1498(16)	427.1(6)	^{211}Pb	1.890(9)	609.3(7)	^{223}Ra, ^{219}Rn, ^{211}Pb	0.0543(7)	1234.3(8)	^{211}Pb	0.00092(8)
293.6(5)	^{219}Rn	0.0688(7)	430.4(6)	^{223}Ra, ^{211}Pb	0.0206(19)	619.8(6)	^{219}Rn	0.0056(12)	1270.7(8)	^{211}Pb	0.00624(19)
313.7(6)	^{211}Pb	0.0276(5)	432.4(6)	^{223}Ra	0.0297(14)	623.4(5)	^{223}Ra	0.0082(8)			

Some Nuclear Structure 'Big' Science Questions?

- 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' ?

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



Some nuclear observables?

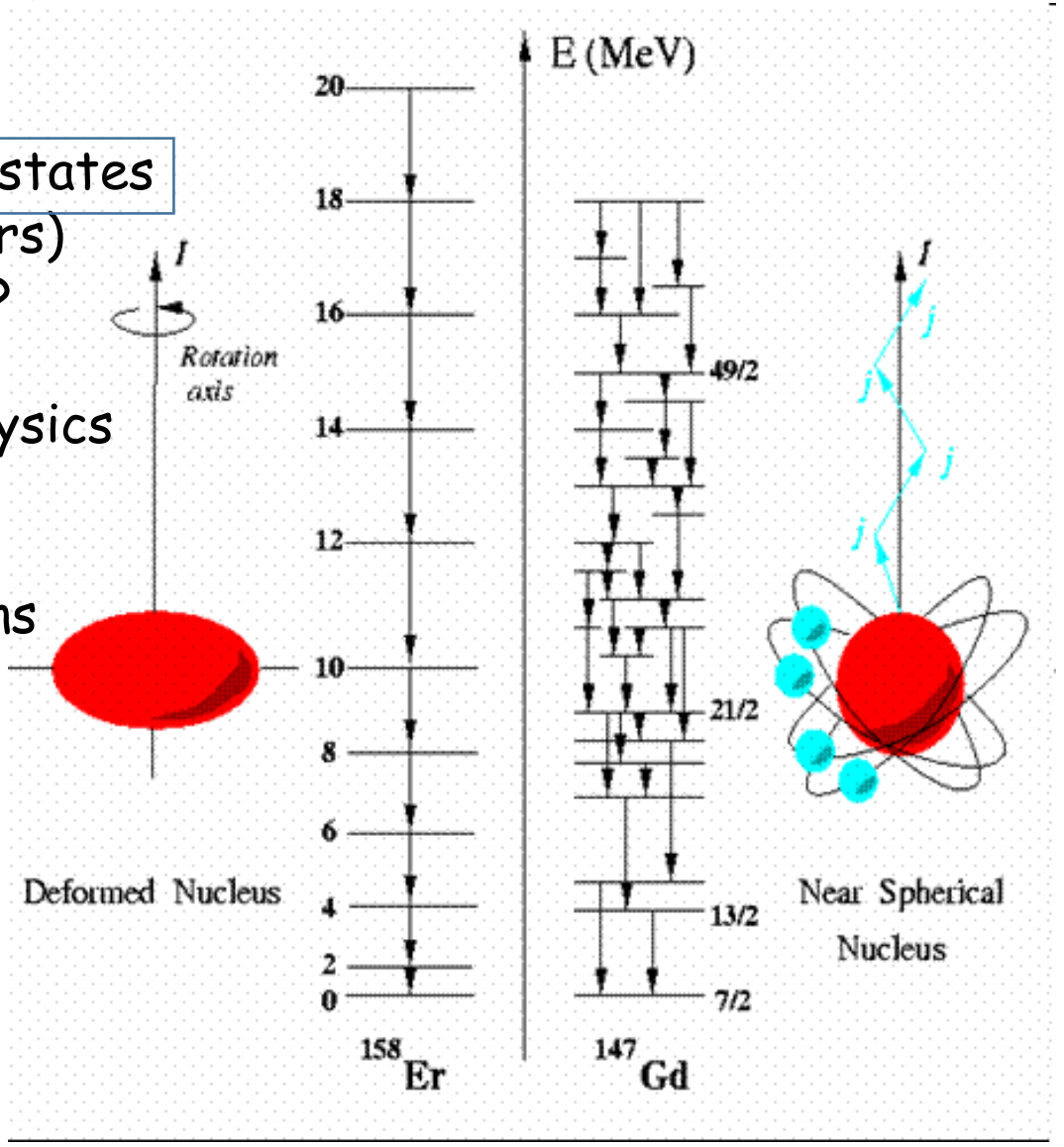
1) Masses and energy differences
2) Energy levels
3) Level spins and parities
4) EM transition rates between states
5) Magnetic properties (g-factors)
6) Electric quadrupole moments?

Essence of nuclear structure physics

……..

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

What are the most useful 'signatures' of nuclear structural evolution?



How is measuring the lifetime of excited nuclear states useful?

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

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

Transition probability (i.e., 1/mean lifetime (τ)

γ-ray energy dependence of transition rate: e.g. E_γ^5 for E2s

Weisskopf, V.F., 1951. *Radiative transition probabilities in nuclei.* Physical Review, **83**(5), 1073.

Transition rates can be described in terms of '**Weisskopf Estimates**'.

Classical estimates based on pure, spherical proton orbital transitions.

1 Wu is 'normal' expected (single particle) transition rate.....(sort of....)

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.

[1] D. A. A. S. Narayana Rao, Phys. Rev. **82**, 118 (1951).
[2] S. 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 z component m. The transition probability per unit time is given by[1]

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

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

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

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

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 kth 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

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

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

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

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

where the integral $\int r^l u_b(r)u_a(r)r^2dr$ 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

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

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

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

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

and for a magnetic 2^l-pole

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

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 $(2l+1)!!=1\cdot3\cdot5\cdots(2l+1)$.
[2] This latter assumption can be removed; the corrections consist in unimportant numerical factors.

Nuclear Magnetic Resonance in Metals: Temperature Effects for Na^{23}

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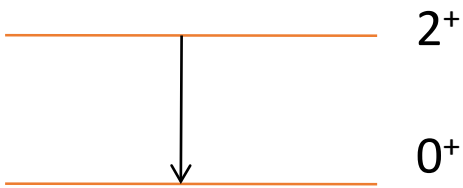
(Received July 2, 1951)

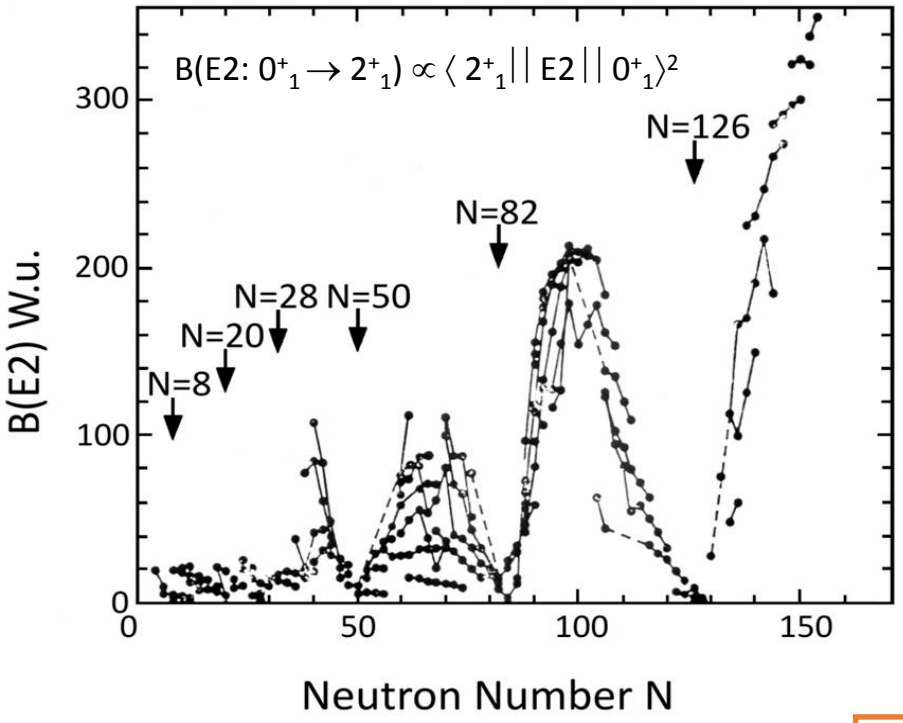
KNIGHT reported[1] that nuclear magnetic resonance frequencies are higher in metals than in chemical compounds. It has been proposed[2] that such frequency shifts are primarily the result of the contribution of conduction electrons to the magnetic field at the nuclei in the metal. This note gives an 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 Na^{23} magnetic resonance shift in the metal, relative to a sodium chloride solution, is given in

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

T(E2) = transition probability = 1/τ (secs);
E_γ = transition energy in MeV





Qo = (TRANSITION) ELECTRIC QUADRUPOLE MOMENT.

This is **linked to the charge distribution** within the nucleus.

Non-zero Qo means deviation from spherical symmetry and thus some quadrupole '**deformation**'.

B(E2: I→I-2) gives Qo by:

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

$$\beta_2 \approx \beta_{eff} = \left(4\pi/3ZR_0^2\right)\left[B(E2: 0^+ \rightarrow 2_1^+)/e^2\right]^{1/2}$$

FATIMA for DESPEC

- **FATIMA** = **FA**st **TIM**ing **A**rray = Gamma-ray detection array for precision measurements of nuclear structure in the most exotic and rare nuclei.
- 36 $LaBr_3$ detectors (1.5" x 2" cylinders in three rings of 12 detectors)
- Used to measure lifetimes of excited nuclear states.
- Energy resolution (better than 3% at 1 MeV).
- Total full-energy peak detection efficiency (>5% at 1 MeV).
- Excellent timing qualities (approaching 100 picoseconds FWHM).
- Uses a fully-digitised Data Acquisition System.

Nuclear Instruments and Methods in Physics Research A 748 (2014) 91–95

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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

Technical Notes

A $LaBr_3$: Ce fast-timing array for DESPEC at FAIR

Oliver J. Roberts [a,*], Alison M. Bruce [a], Patrick H. Regan [b,e], Zsolt Podolyák [b], Christopher M. Townsley [b], John F. Smith [c], Kieran F. Mulholland [c], Andrew Smith [d]

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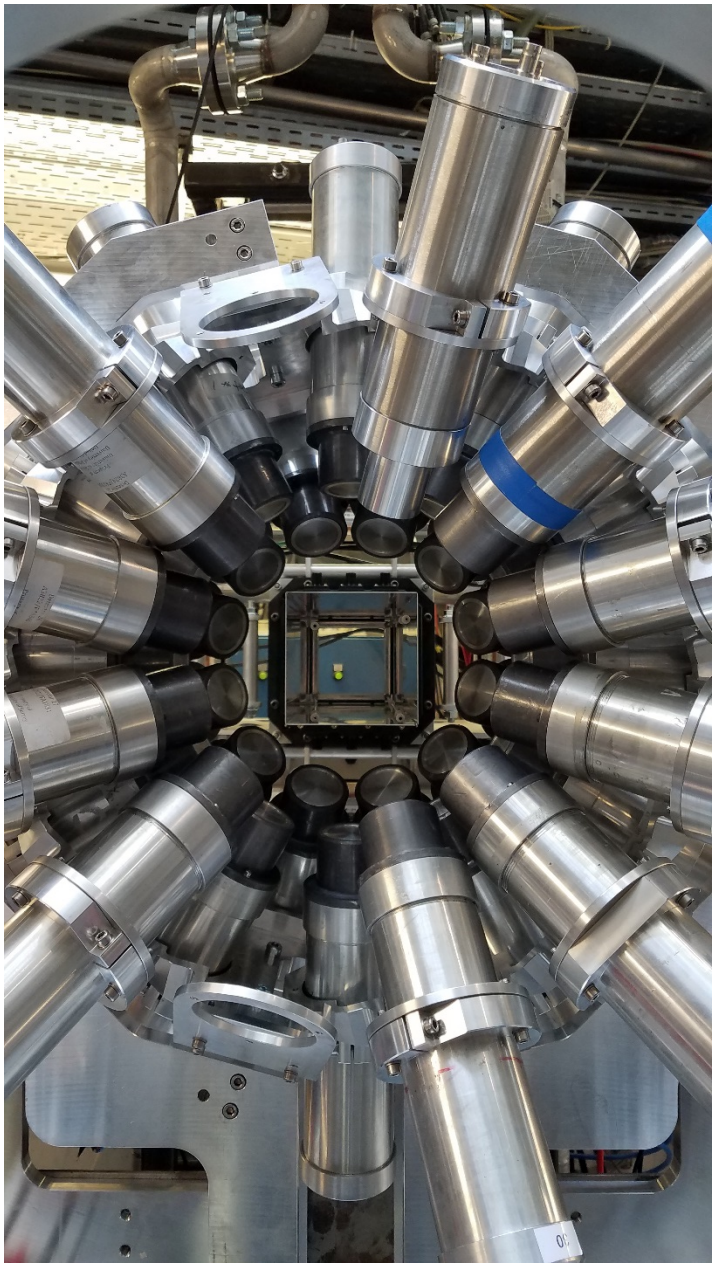
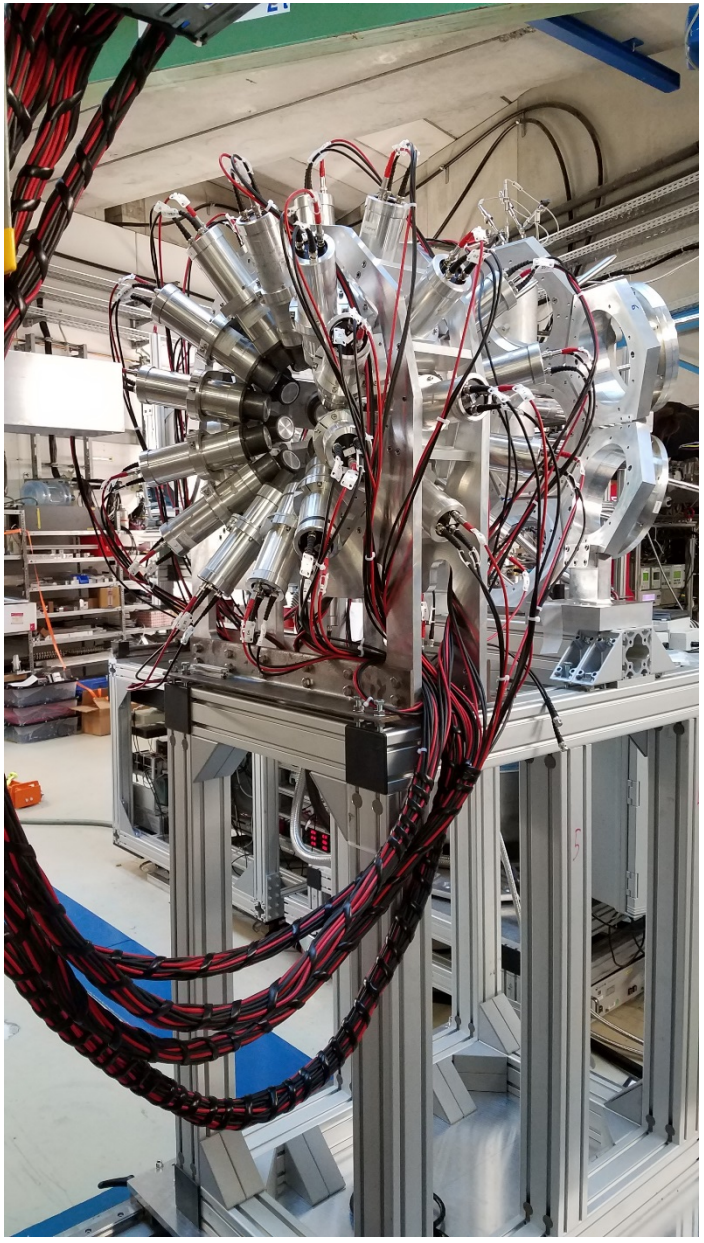
FATIMA-DESPEC array at GSI/FAIR (July 2018)



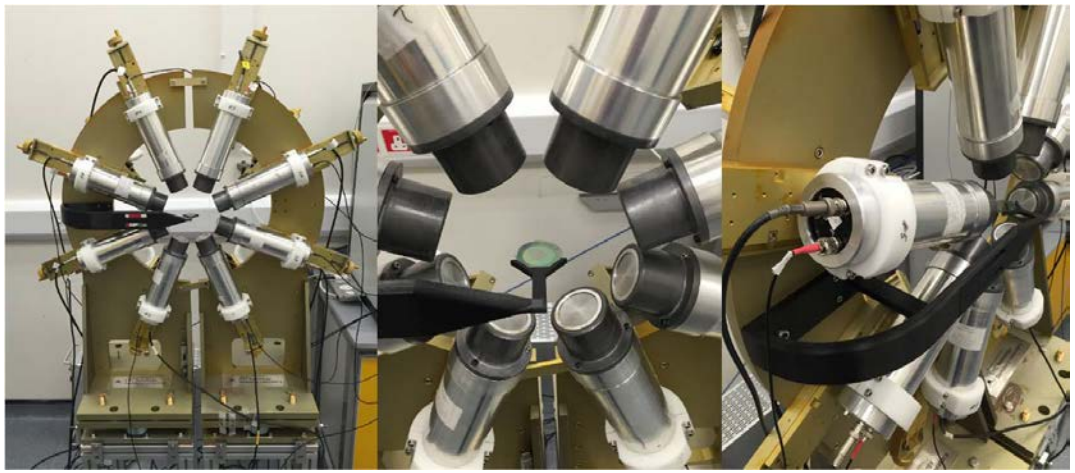


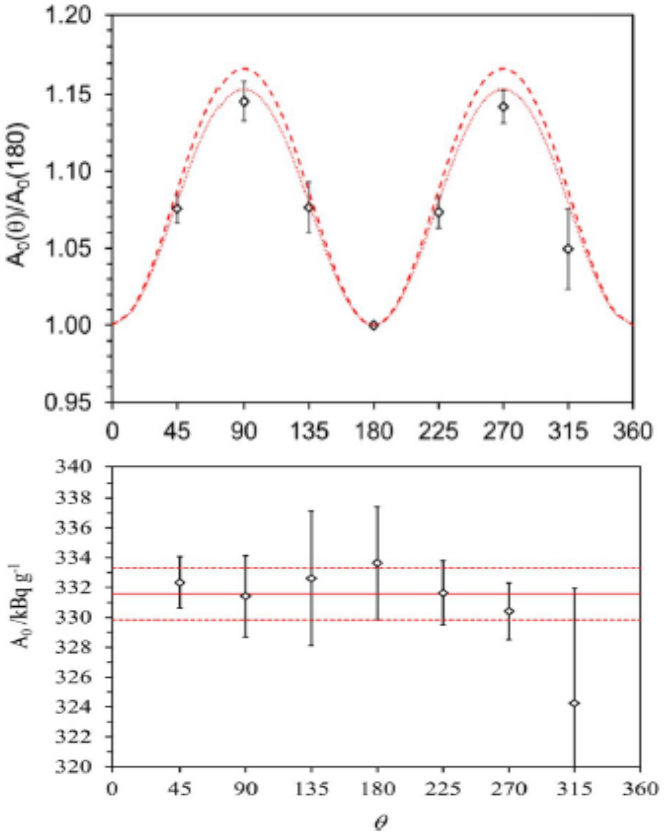
Applying the FATIMA detectors for absolute standards: NANA

Standardisation using the NAtional Nuclear Array (NANA@NPL)

- Use NANA used as a **primary radioactivity standard.**

- Absolute activity of ^{60}Co determined using the γ-γ coincidence technique.





Standardisation technique	A_0 /kBq g^{-1}	u (A_0) /kBq g^{-1}
NANA γ-γ coincidence counting	330.8	± 1.0
4π(LS)- γ DCC	330.92	± 0.86

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Applied Radiation and Isotopes

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

Investigation of γ-γ coincidence counting using the National Nuclear Array (NANA) as a primary standard

S.M. Collins[a,b,*], R. Shearman[a,b], J.D. Keightley[a], P.H. Regan[a,b]

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Radiation Physics and Chemistry 140 (2017) 475–479

Radiation Physics and Chemistry

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

Commissioning of the UK NAtional Nuclear Array

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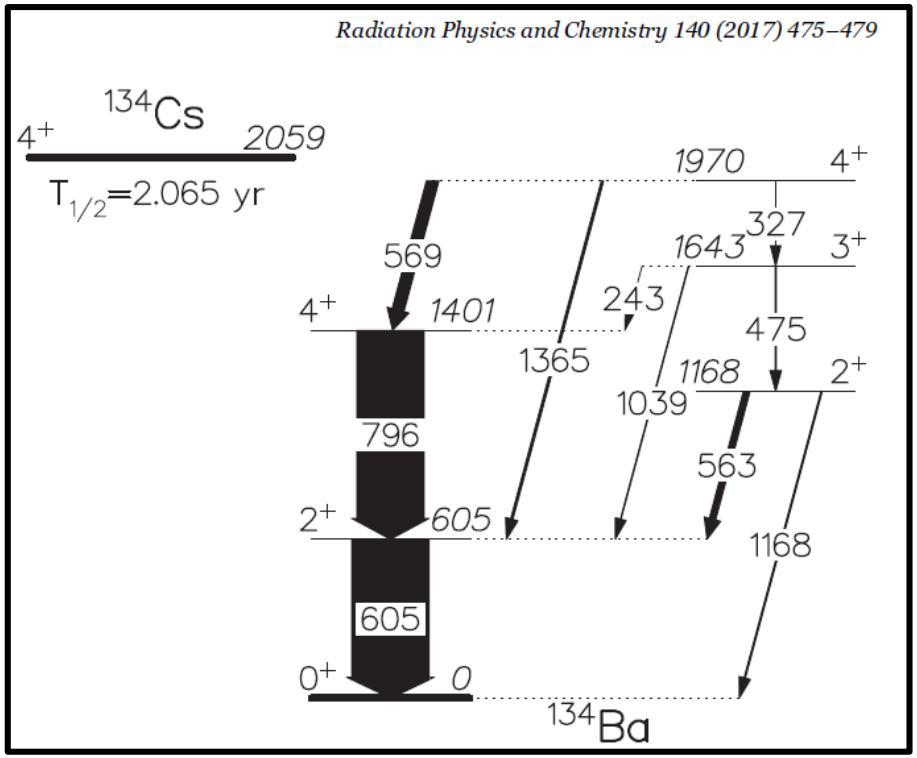
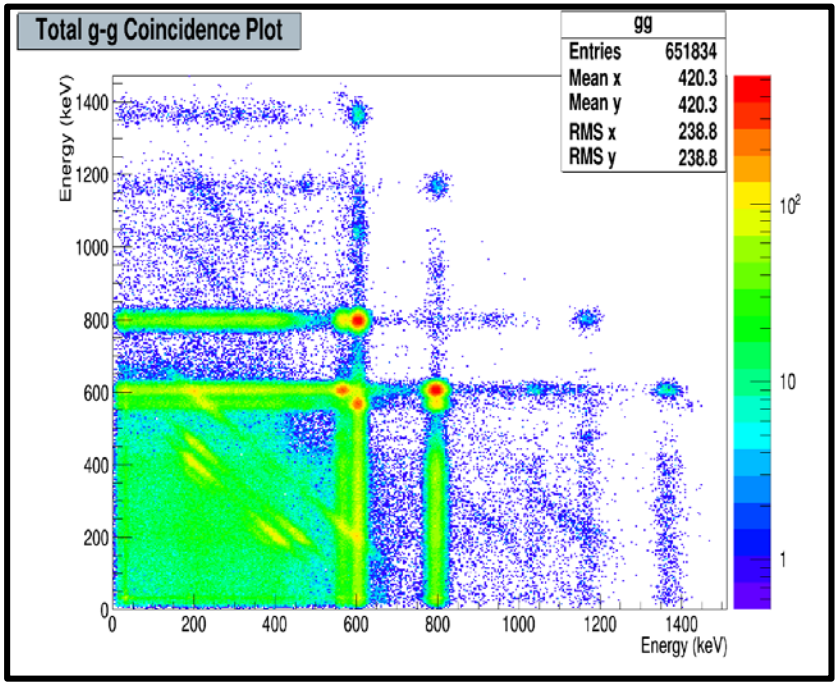
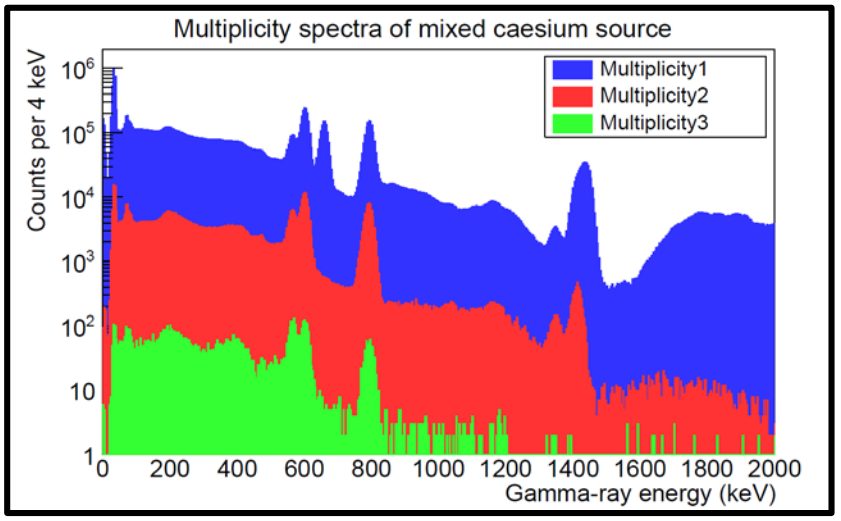




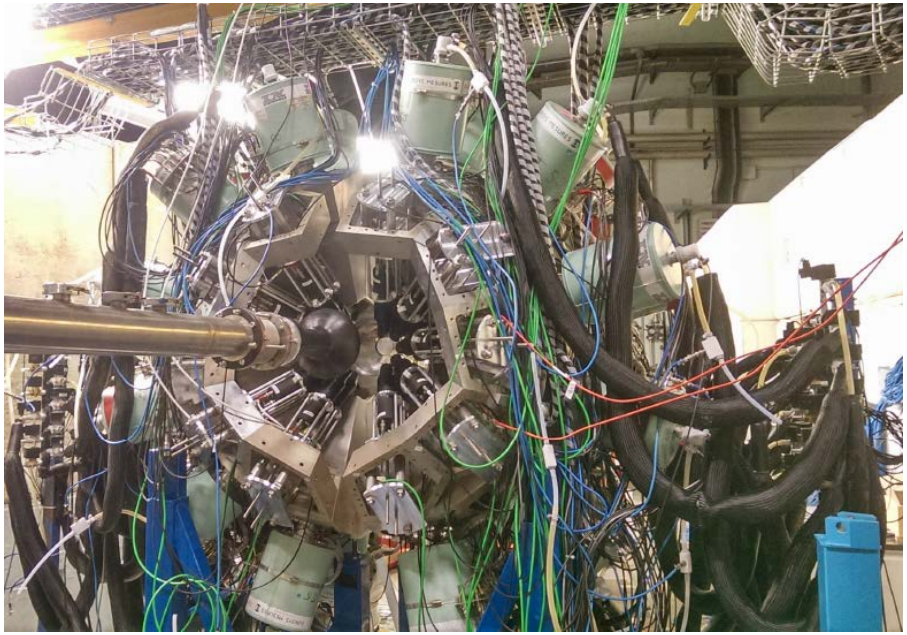


Use of NANA for assay and separation of ^{134}Cs and ^{137}Cs decay products from spent nuclear fuel: ^{134}Cs has gamma-ray decay coincidences; ^{137}Cs decay has a single decay transition (662 keV).

Some New Physics with FATIMA Detectors:

AIM: To accurately determine the lifetimes of (at least) the first 2^+ states in 'exotic' radioisotopes to infer their quadrupole deformation.

β^- - γ correlated decay spectroscopy via high-energy projectile fission of ^{238}U: EURICA+FATIMA at RIBF-RIKEN



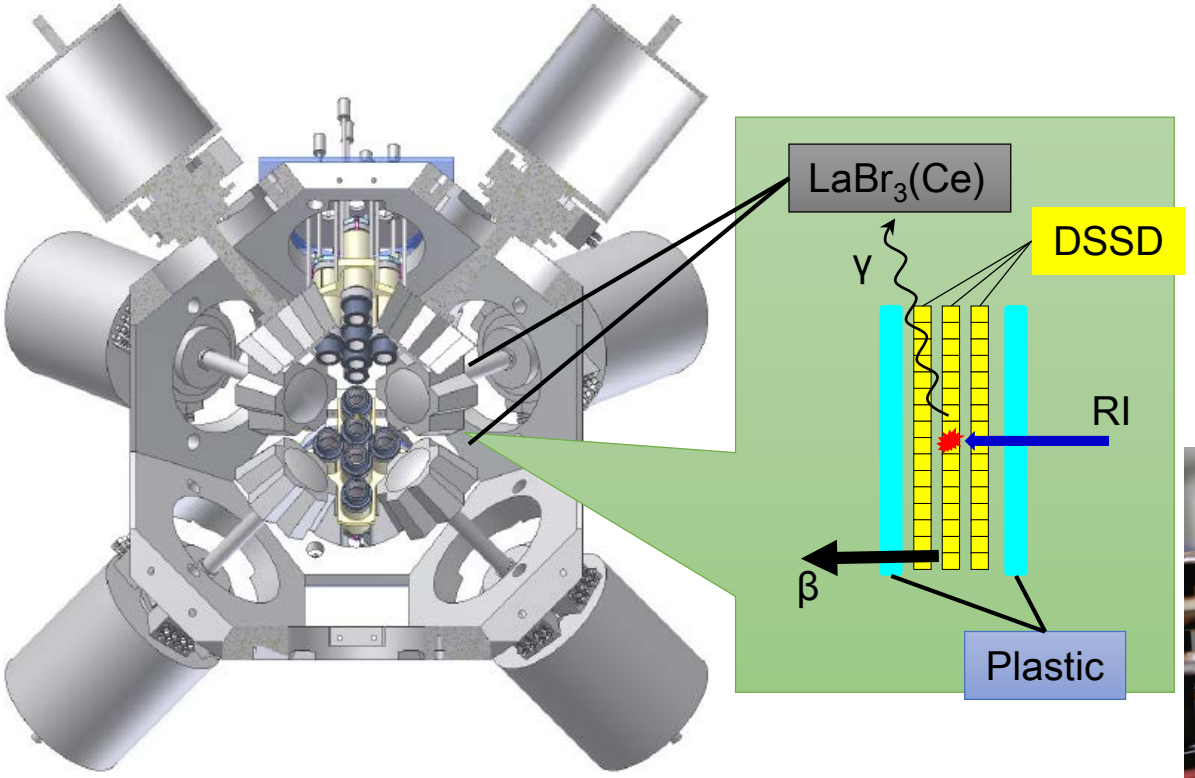
γ - γ correlated decay spectroscopy via Low-energy, 2 neutron-transfer reactions NuBALL @ IPN-Orsay

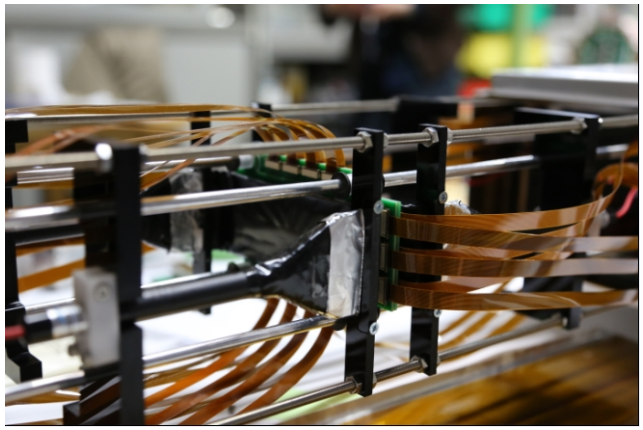
Fast-timing measurements @ RIKEN

18 $LaBr_3$(Ce) scintillators (Φ1.5”×2”) on three vacant slots for γ rays

BC-418 plastic counters (2-mm thick) beside the DSSDs for β rays

Courtesy of H. Watanabe





Physics Letters B 750 (2015) 448–452

Lifetime measurements of the first 2^+ states in ^{104,106}Zr: Evolution of ground-state deformations

F. Browne [a,b,*], A.M. Bruce [a], T. Sumikama [c,b], I. Nishizuka [c], S. Nishimura
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F. Didierjean [k], Y. Fang [e], N. Fukuda [b], G. Gey [l,m,b], E. Ideguchi [e], N. Inabe
D. Kameda [b], I. Kojouharov [n], N. Kurz [n], T. Kubo [b], S. Lalkovski [o], Z. Li [h], R.
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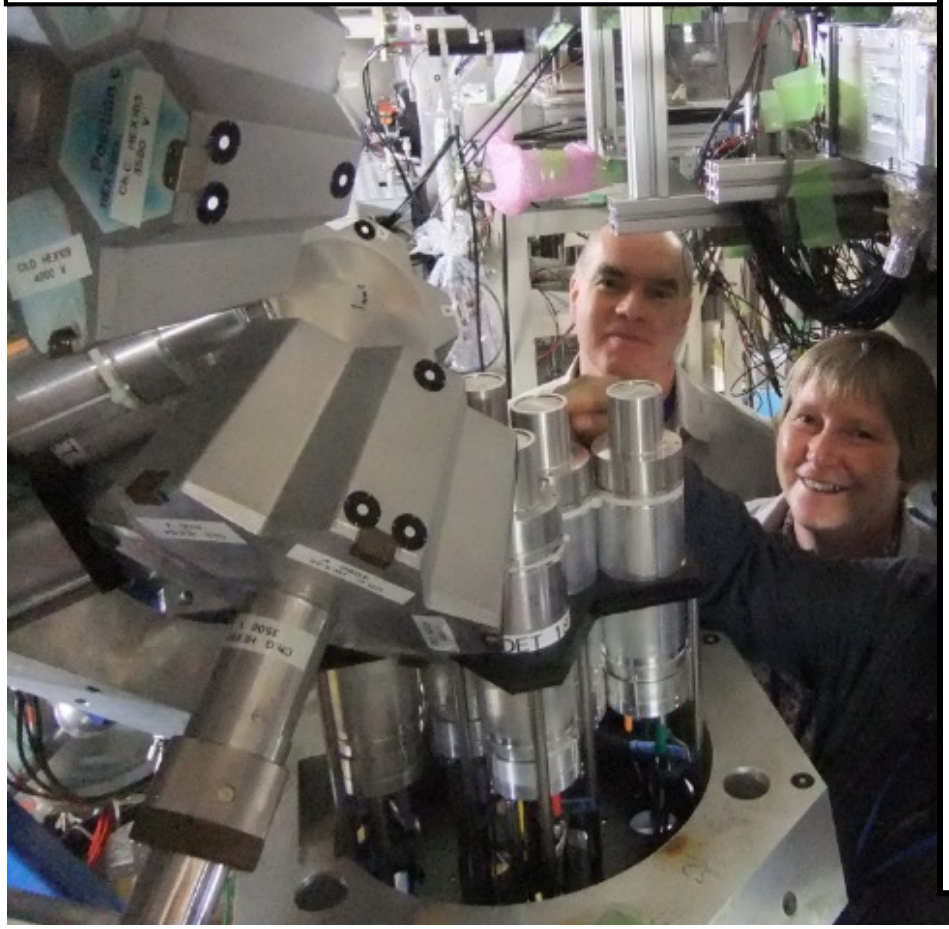
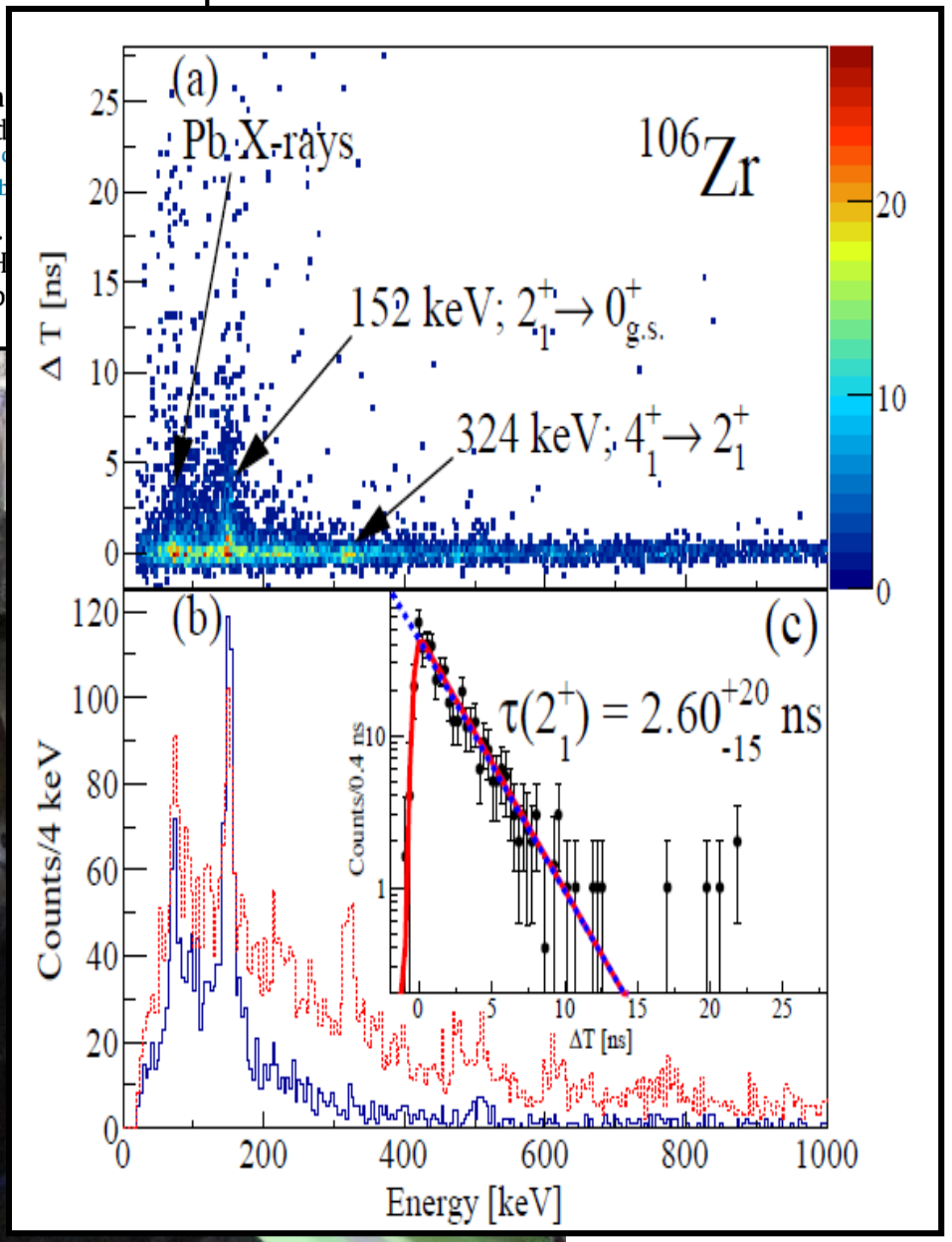
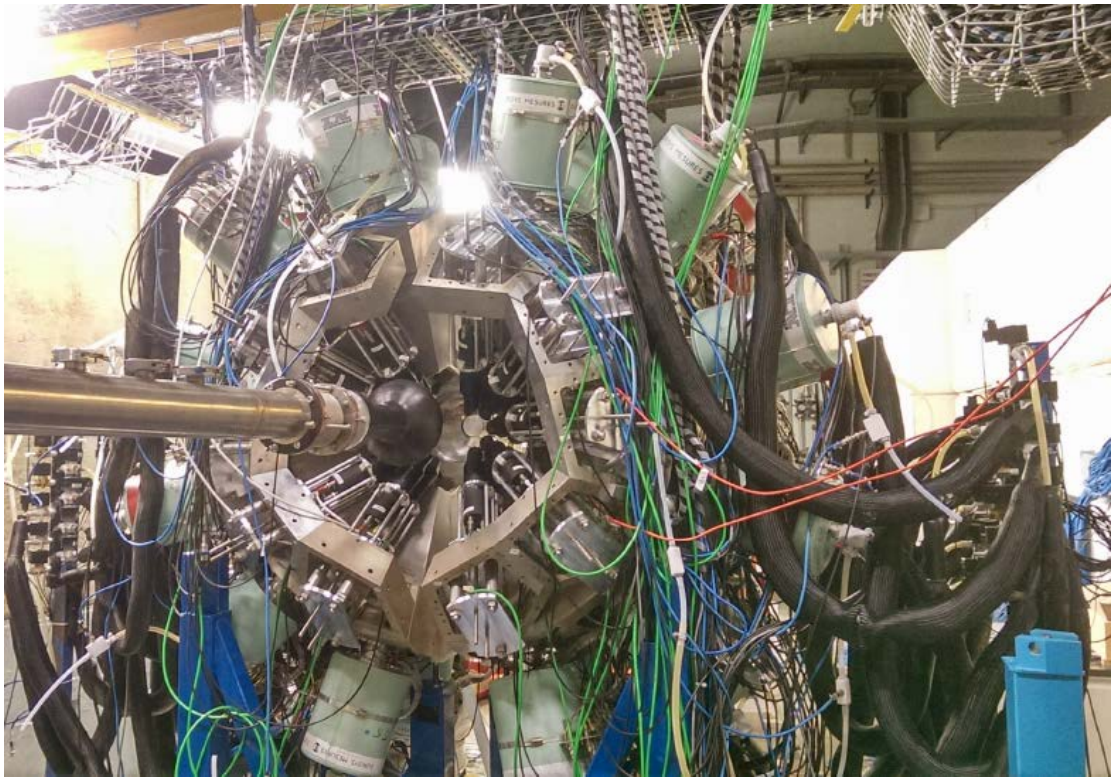
H. Schaffner [n], G.S. Simpson [l], H. Suzuki [b], H. Takeda [b], M. Tanaka [e], J. Tap
V. Werner [s,t], O. Wieland [u]

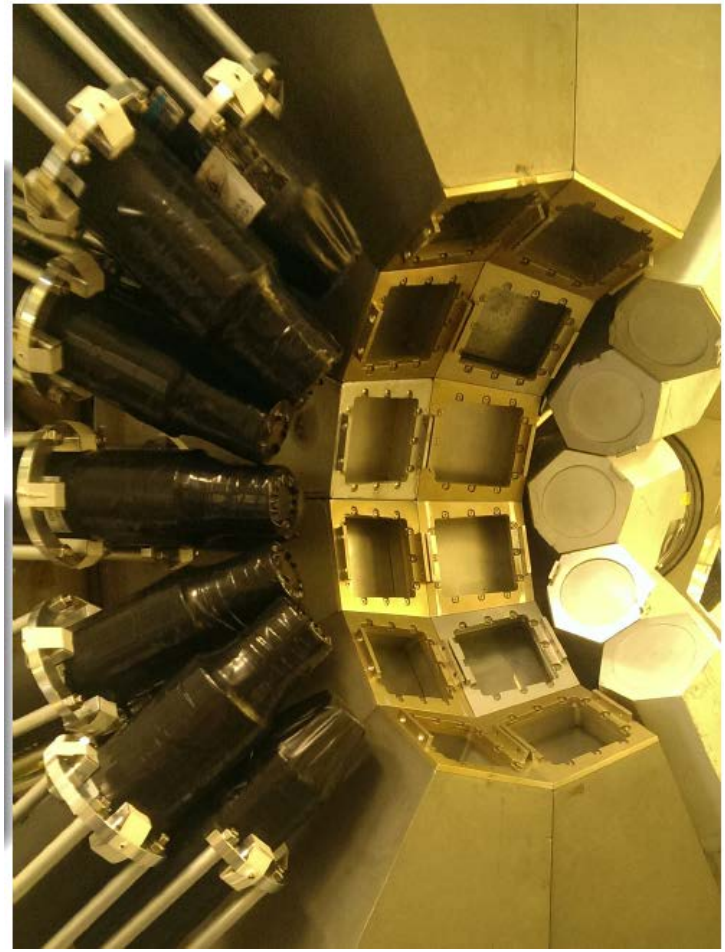




NuBall at IPN-Orsay: 'Hybrid' HPGe –$LaBr_3$ combined array.

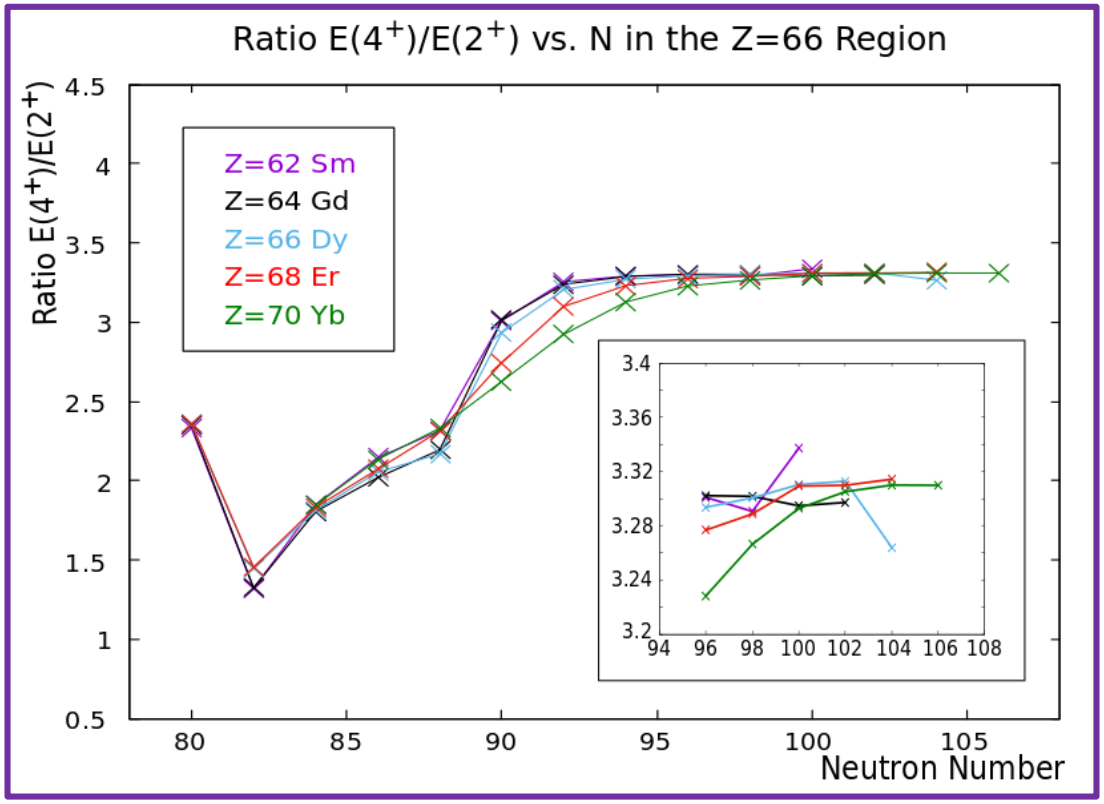
- **20 $LaBr_3$ detectors** with from FATIMA collaboration -time resolution ~250 ps
- **24 HPGe clover detectors** with BGO shielding for Compton Suppression
- **10 coaxial HPGe detectors** with BGO shielding
- **FASTER Digital DAQ;** 500 MHz sampling for the $LaBr_3$ detectors; 125 MHz sampling for the HPGe and BGO detectors
- Internal **pulse shape analysis**

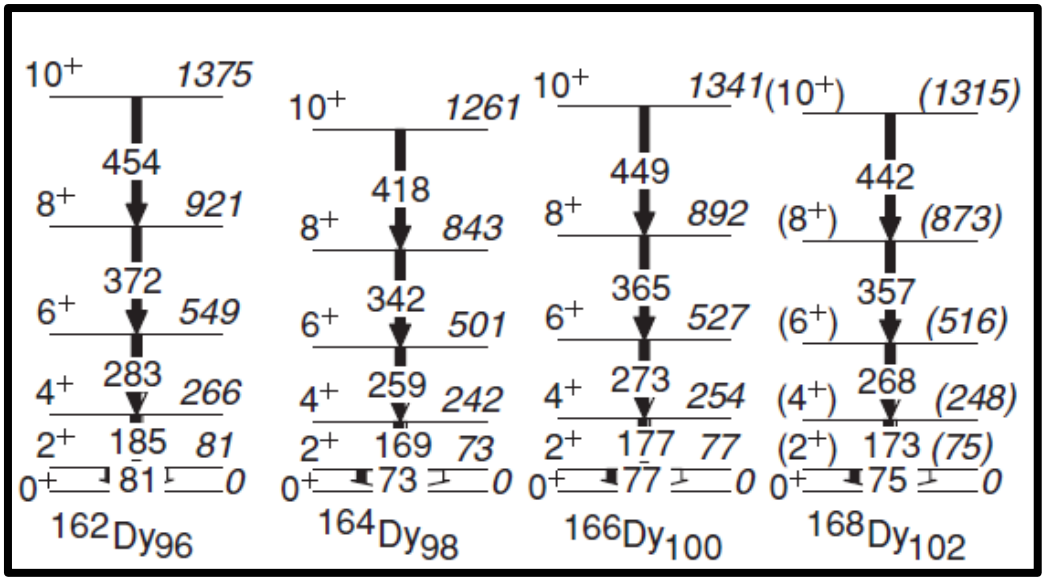


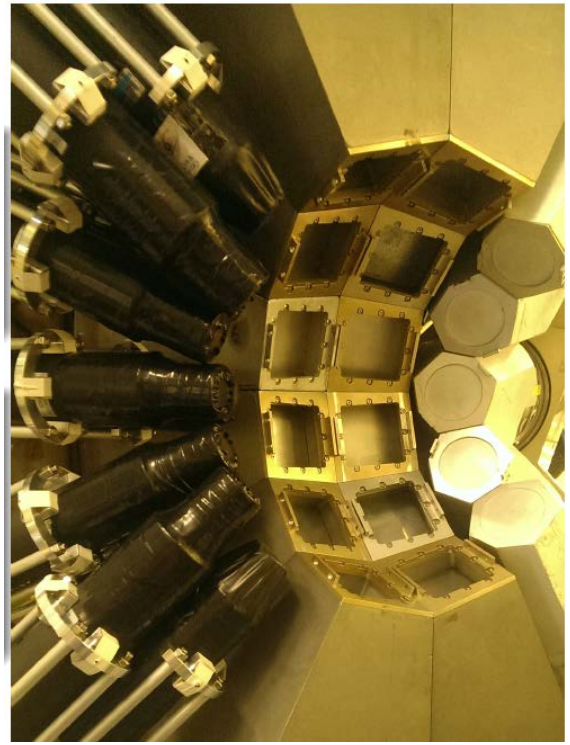


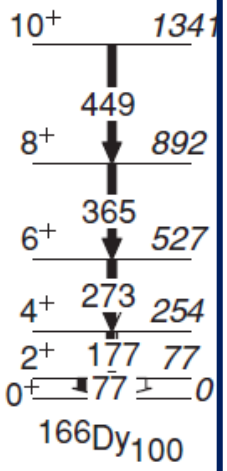
$^{164}Dy(^{18}O,^{16}O)^{166}Dy$

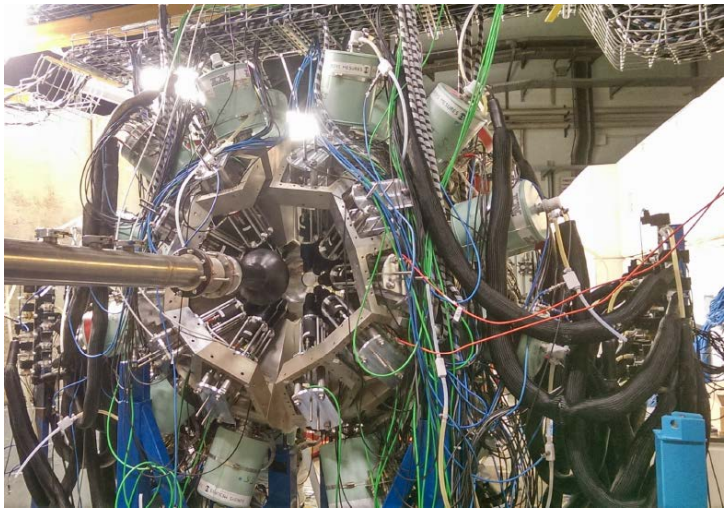
a way of getting to the most neutron-rich stable+2n isotope and measuring its deformation.

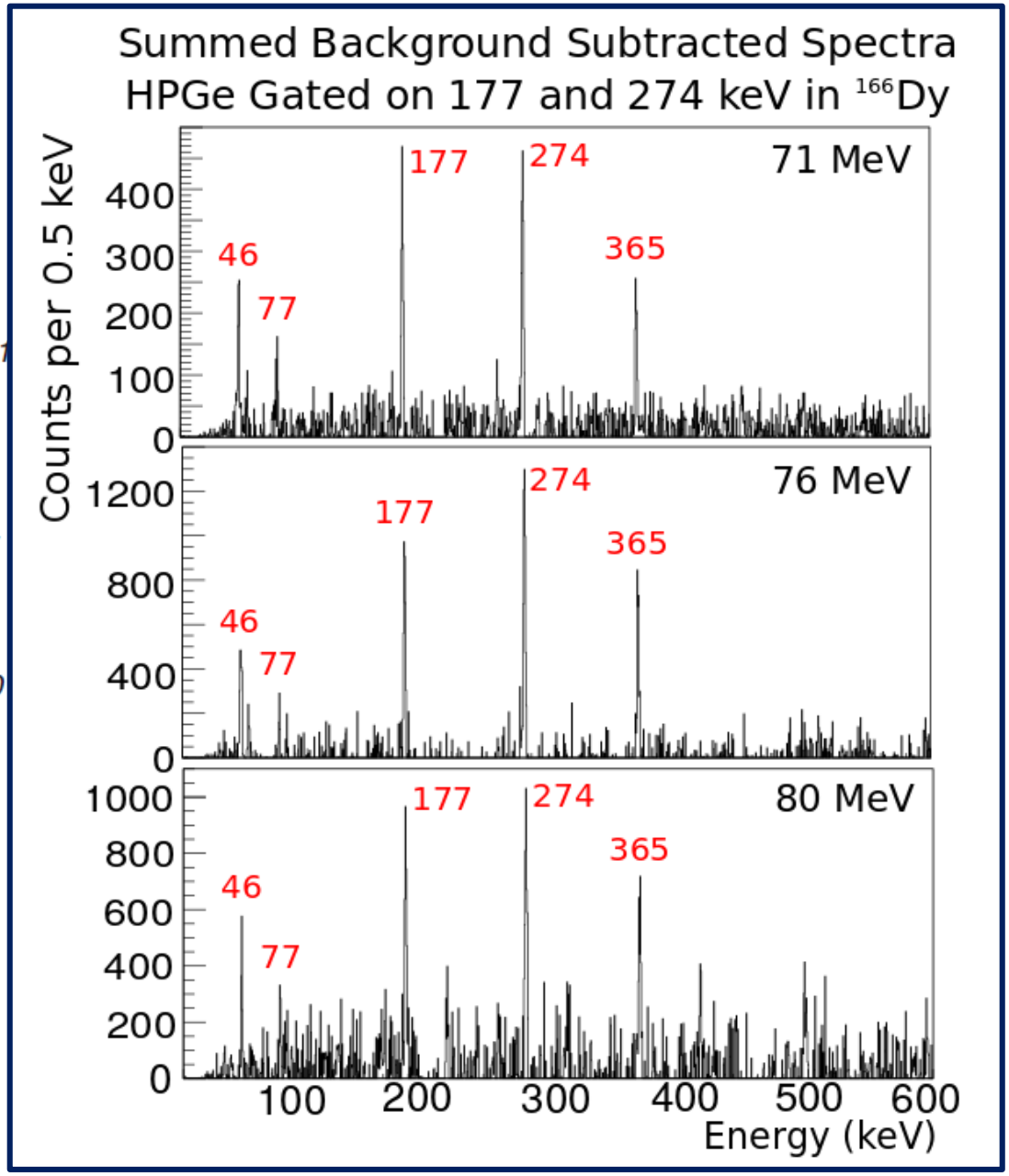

Ratio E(4+)/E(2+) vs. N in the Z=66 Region
Ratio E(4+)/E(2+)
Neutron Number
Z=62 Sm
Z=64 Gd
Z=66 Dy
Z=68 Er
Z=70 Yb


10+ 1375
454
8+ 921
372
6+ 549
283
4+ 266
185
2+ 81
81
0+ 0
162Dy96
10+ 1261
418
8+ 843
342
6+ 501
259
4+ 242
169
2+ 73
73
0+ 0
164Dy98
10+ 1341
449
8+ 892
365
6+ 527
273
4+ 254
177
2+ 77
77
0+ 0
166Dy100
(10+) (1315)
442
(8+) (873)
357
(6+) (516)
268
(4+) (248)
173
(2+) (75)
75
0+ 0
168Dy102

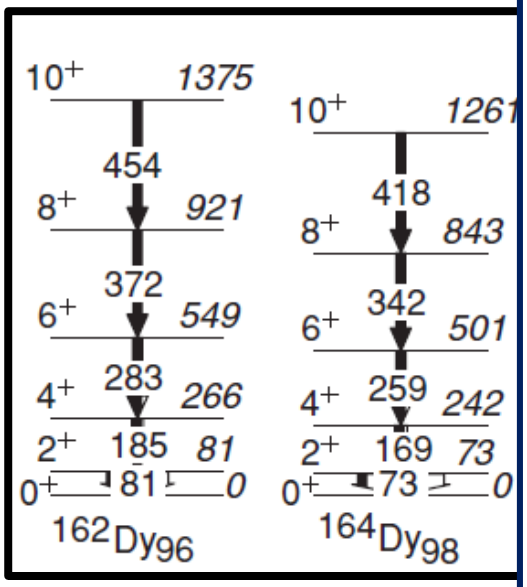


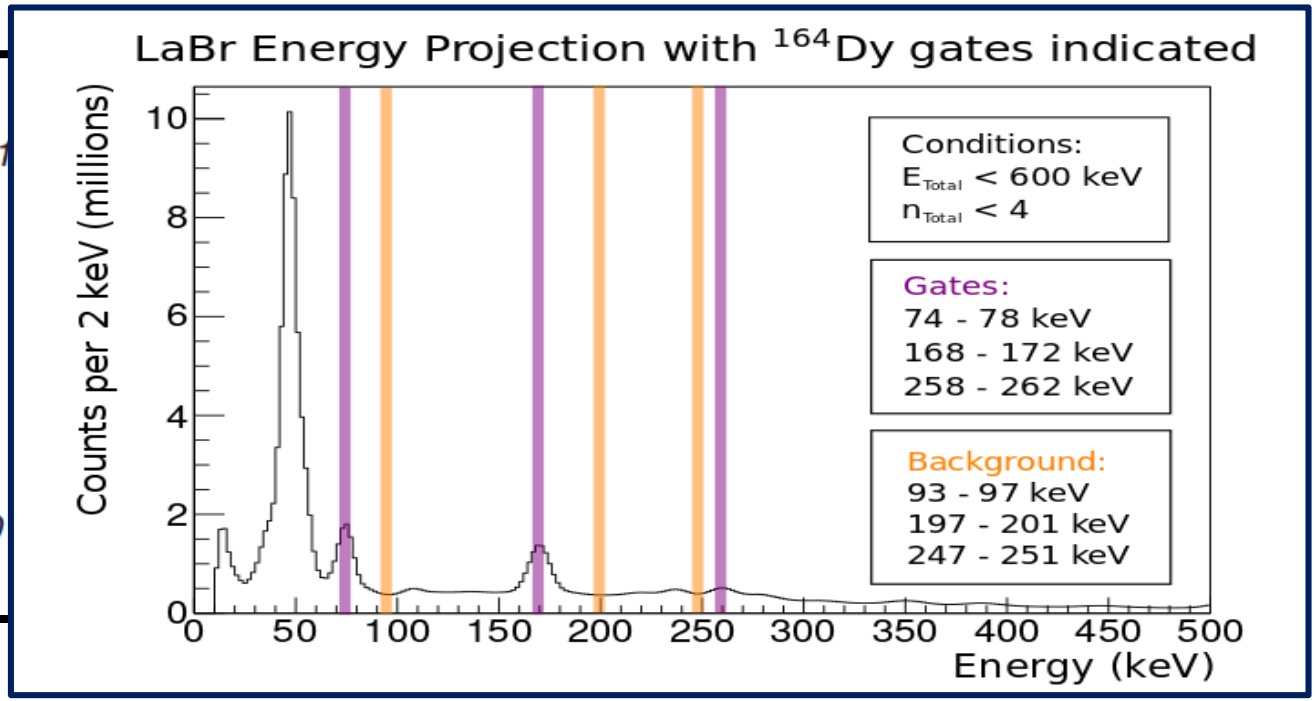

10+ 1341
449
8+ 892
365
6+ 527
273
4+ 254
177
2+ 77
77
0+ 0
166Dy100

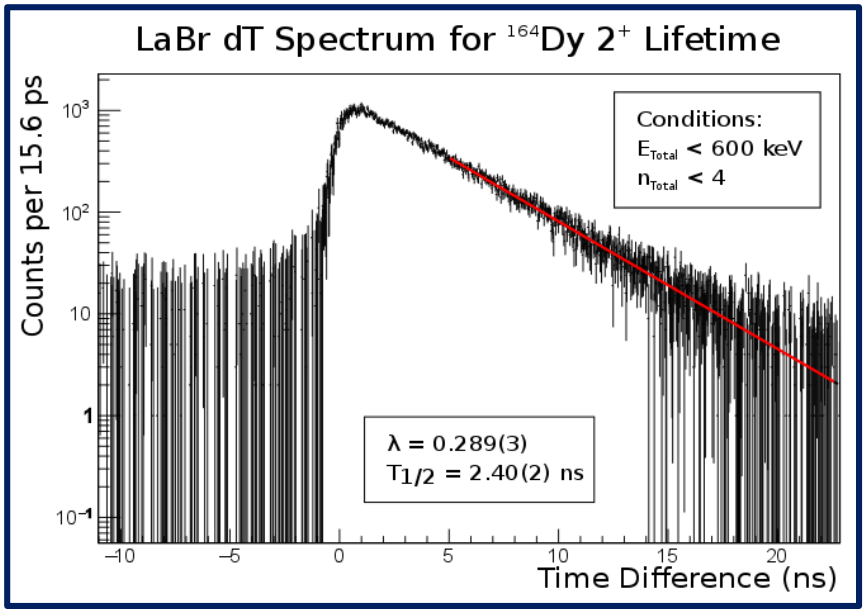


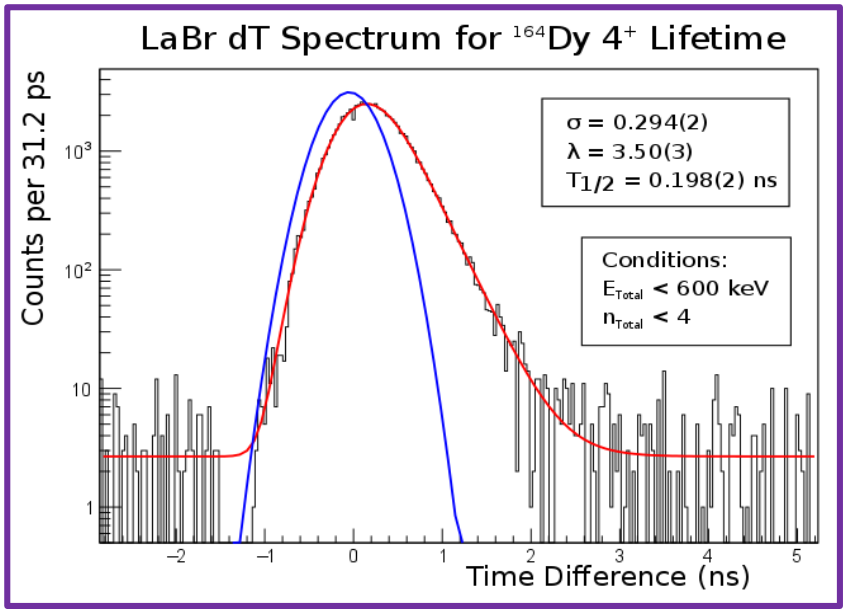

Summed Background Subtracted Spectra
HPGe Gated on 177 and 274 keV in 166Dy
Counts per 0.5 keV
71 MeV
76 MeV
80 MeV
46
77
177
274
365
Energy (keV)

$^{164}Dy(^{18}O,^{16}O)^{166}Dy$ – first NuBALL @Orsay experiment





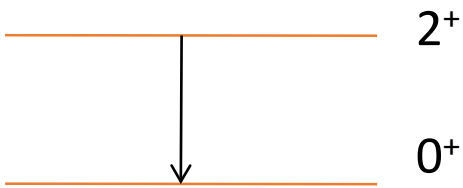




$$T(E2) = 1.223 \times 10^9 E_\gamma^5 B(E2)$$

T(E2) = transition probability = 1/τ (secs);

E_γ = transition energy in MeV

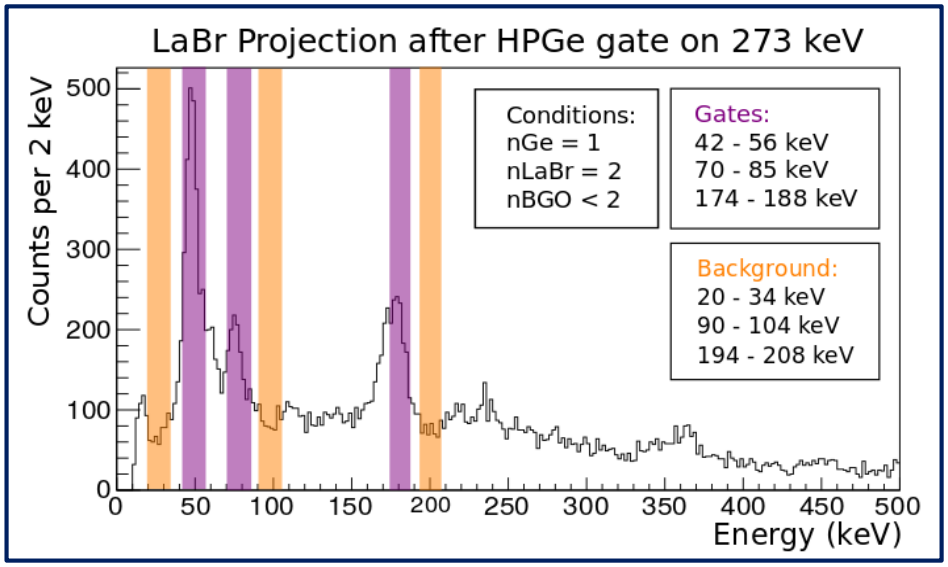


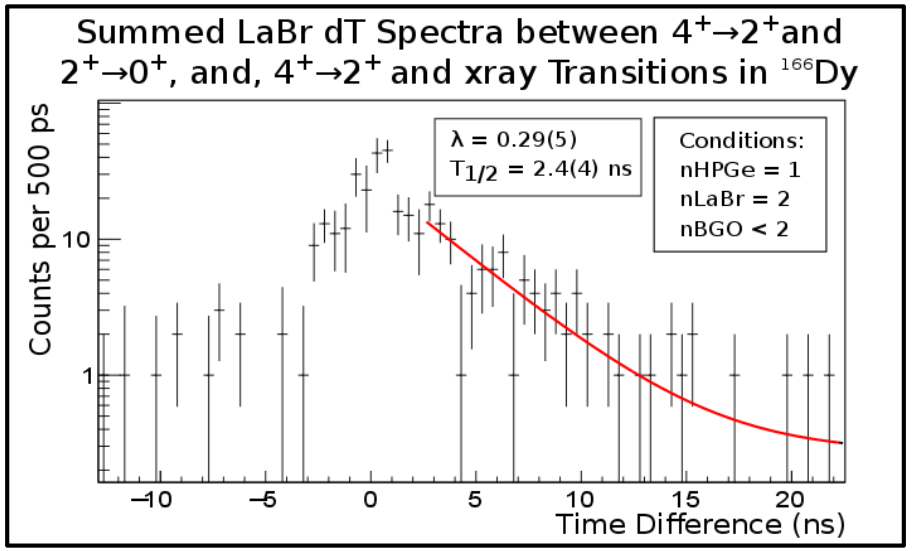
B(E2: I → I-2) gives Qo by:

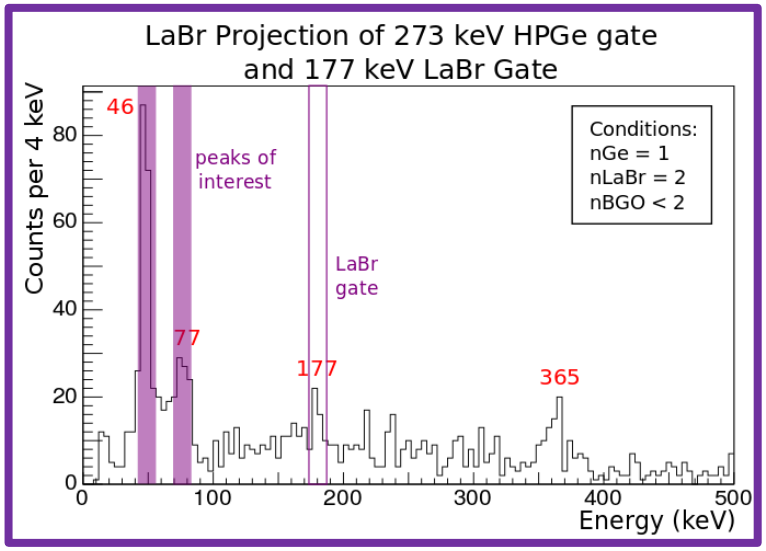
$$B(E2) = \frac{5}{16\pi} Q_o^2 \frac{3(I-K)(I-K-1)(I+K)(I+K-1)}{(2J-2)(2J-1)J(2J+1)}$$

$$\boldsymbol{\beta_2 \approx \beta_{eff} = \left(4\pi/3ZR_0^2\right)\left[B(E2: 0^+ \rightarrow 2_1^+)/e^2\right]^{1/2}}$$

^{166}Dy 2^+ lifetime and inferred deformation.







A	E(2^+) (keV)	$T_{1/2}$(2^+) (ns)	ICC(E2)	B(E2:$0^+\rightarrow 2^+$) (e^2b^2)	B_2(eff)
160	86.8	2.02(1)	4.63	5.05(2)	0.337(2)
162	80.7	2.19(2)	6.14	5.30(5)	0.342(2)
164	73.4	2.39(3)	8.89	5.61(5)	0.350(4)
166	**76.7**	**2.4(4)**	**7.48**	**5.0(10)**	**0.34(6)**

$$\beta_2 \approx \beta_{eff} = \left(4\pi/3ZR_0^2\right)\left[B(E2: 0^+ \rightarrow 2_1^+)/e^2\right]^{1/2}$$

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- Jon Wilson, Matthieu Lebois et al., (IPN-Orsay)
- Sean Collins, Giuseppe Lorusso, Peter Ivanov et al (NPL)