Research Opportunities with the X-array and Gammasphere

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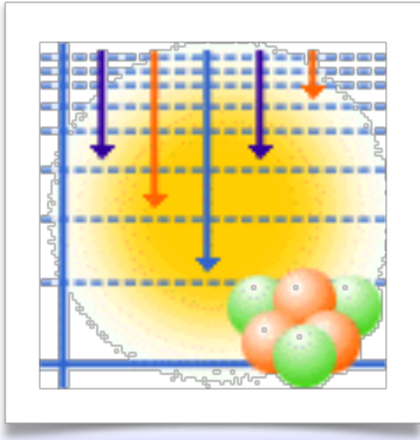
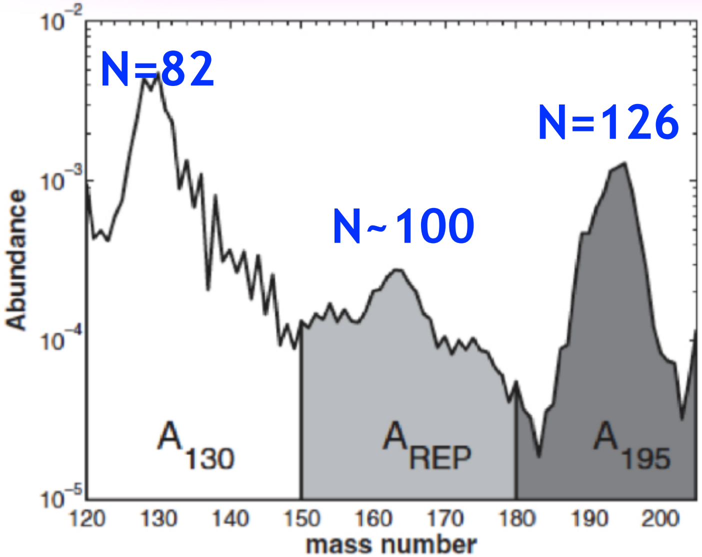
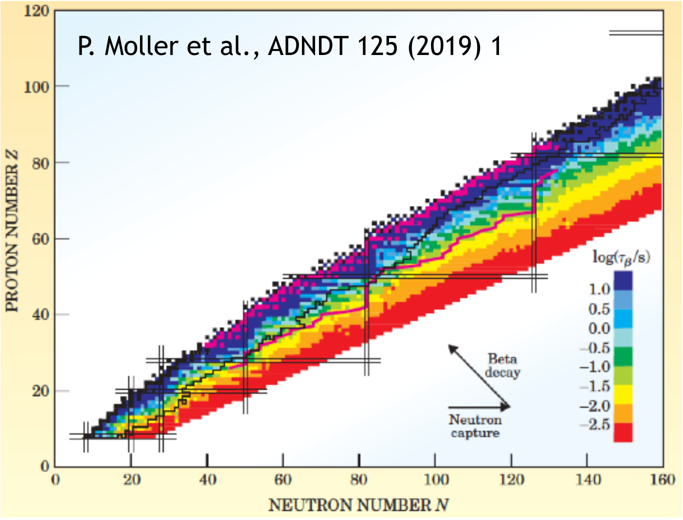


Nuclear Astrophysics Data Needs

What are the astrophysical cities of the production of heaviest elements in the *r* process?





What is needed?

✓ elemental & isotopic abundances of nuclei produced in stars and found in meteorites

✓ properties of unstable neutron-rich nuclei

- nuclear data: masses, $T_{1/2}$, P_n, BR (when long-lived isomers are presented), fission properties, neutron- and gamma-ray-induced cross sections

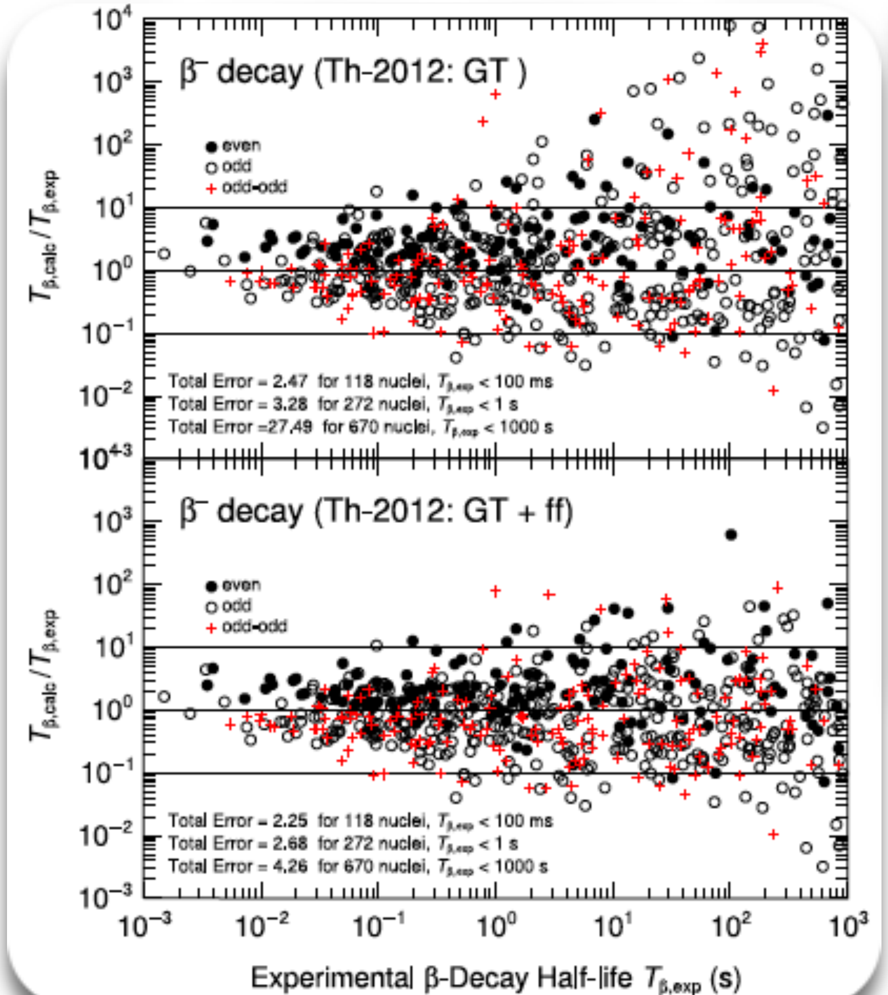
BUT

✓ even with such powerful facilities on the horizon, like FRIB, for much of the needed data **we will have to rely on theoretical predictions**

✓ **key need - to improve predictive power of nuclear models** - not a simple task - need to cover different regions of the nuclear chart, different nuclear shapes, structures, etc ...

Beta-decay half-life — example

folded Yukawa potential & pairing & QRPA



P. Moller et al., ADNDT 125 (2019) 1

Calculating $T_{1/2}$ is not trivial

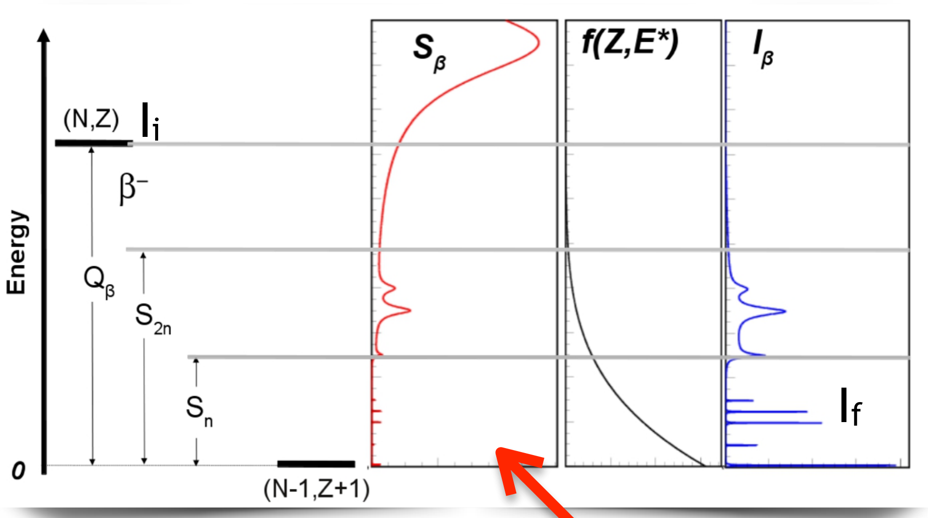
✓ **an accurate value for the decay energy,** Q_β-value, e.g. a good mass model:

$T_{1/2} \sim 1/(Q_\beta - E_f)^5$ (for allowed decay)

✓ **good knowledge of nuclear structure** - level energies, quantum numbers and projections, and matrix elements of **Fermi and Gamow-Teller** operators for allowed and **"forbidden"** operators for forbidden decays between the parent and daughter states

$$T_\beta \simeq \frac{Const}{\sum_{0<E_f<Q_\beta} \left|M_{fi}\right|^2 f(Z,R,Q_\beta - E_f)}$$

Beta-decay transition probability



β-decay

- the strength is (usually) outside the GT resonance region
- the process is sensitive to nuclear structure effects
  - ✓ connect a parent state that has well-defined quantum properties & configuration with daughter states that have related structures - it is not a statistical process

S_{if} - beta-decay strength

$$B_{if} \simeq \frac{\left|M_{if}\right|^2}{2J_i+1} = Const\,\frac{I_{\beta_{if}}}{f(Z,Q_\beta - E_f)\times T_{1/2}} = Const\,\frac{1}{ft}$$

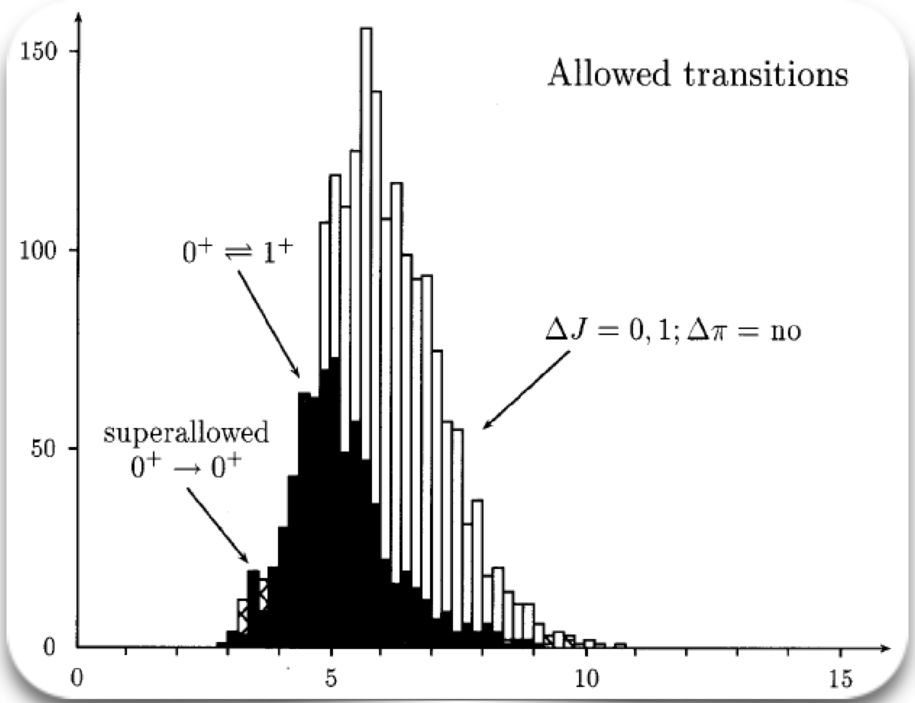
$\rightarrow$ log ft

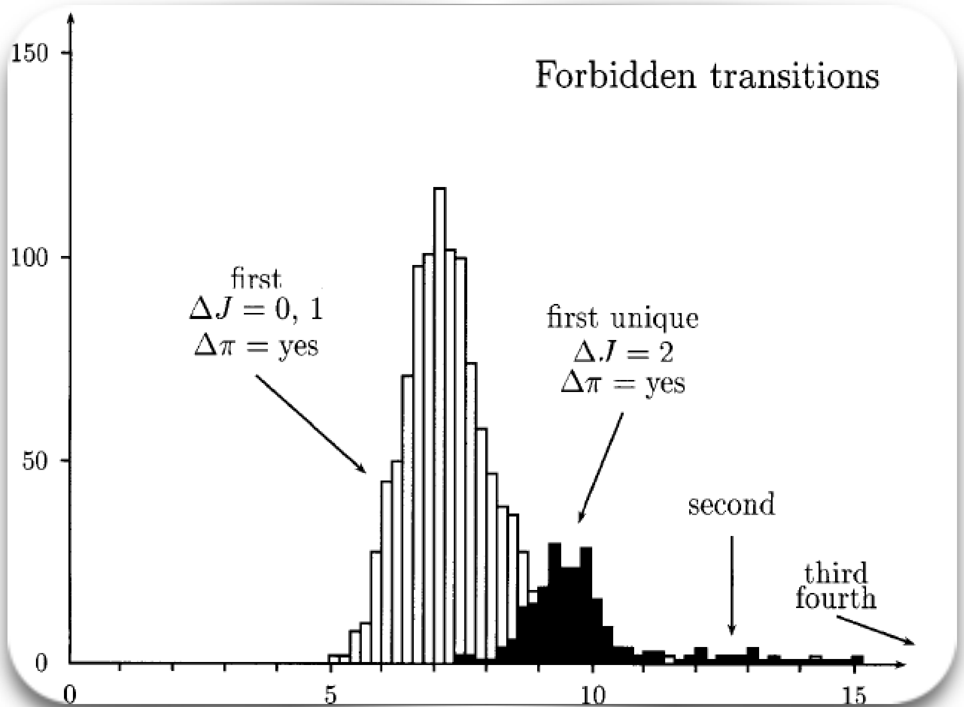
beta-decay transition probability

Review Of Logft Values In β Decay*

Nuclear Data Sheets 84, 487 (1998)
Article No. DS980015

B. Singh, J.L. Rodriguez, S.S.M. Wong & J.K. Tuli





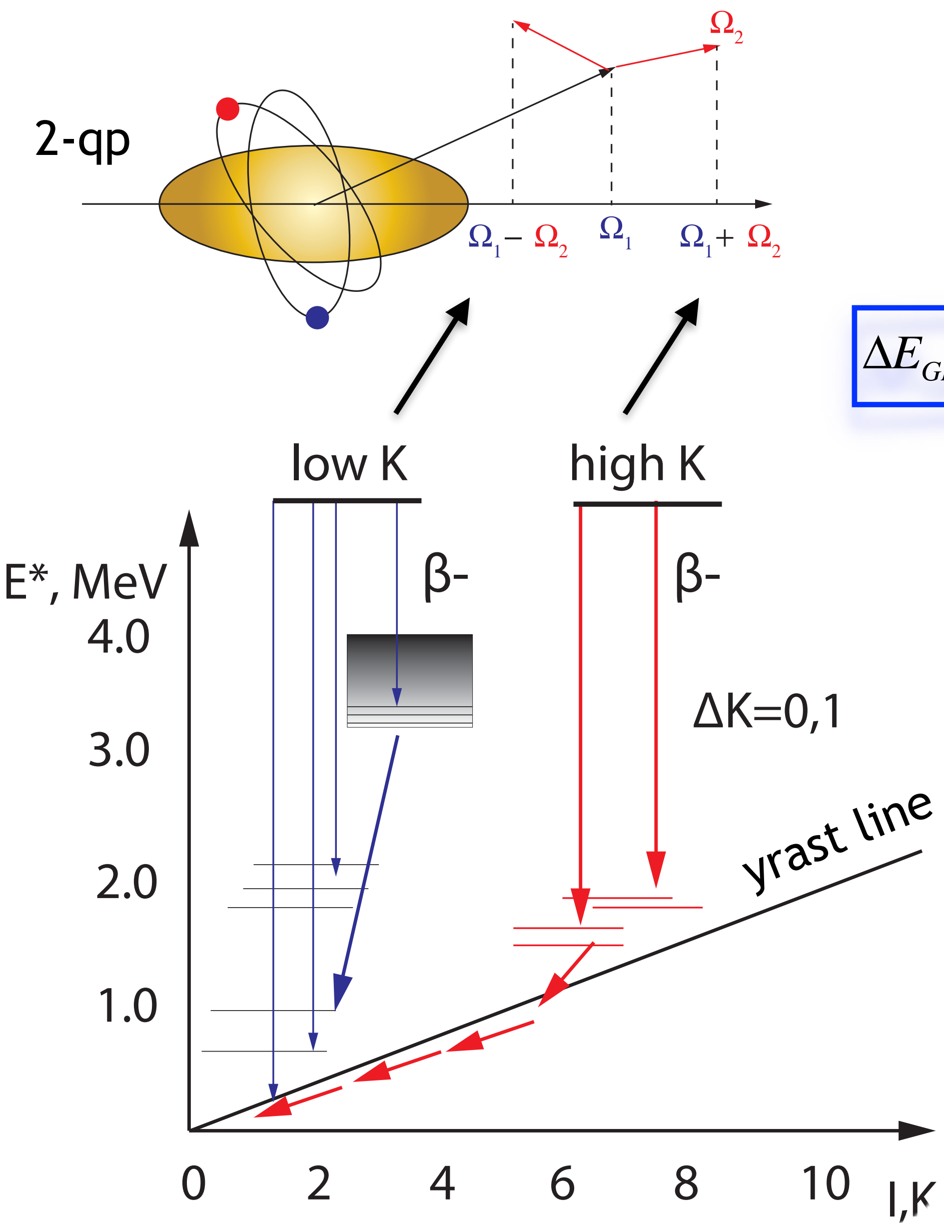
log ft 3-**10** -> hindered by ~**10^7**!

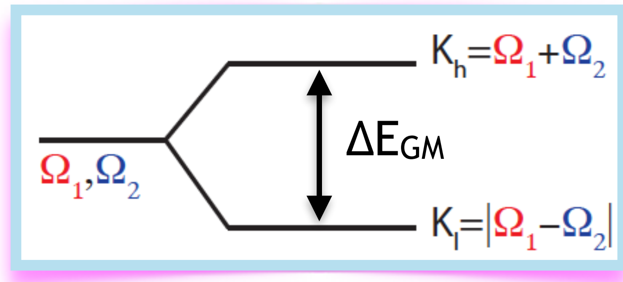
log ft

nuclear structure is important →

- *l* forbidden (near closed shells)
- K forbidden (deformed nuclei)
- isospin forbidden
- configuration hindrances

Beta decay of deformed, odd-odd nuclei





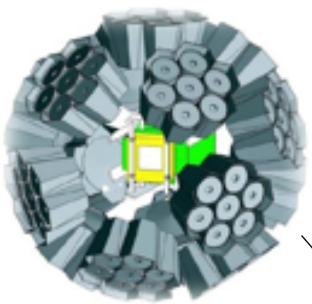
$$\Delta E_{GM} = \langle K_l | V_{pn} | K_l \rangle - \langle K_h | V_{pn} | K_h \rangle + \langle K=0 | V_{pn} | K=0 \rangle$$

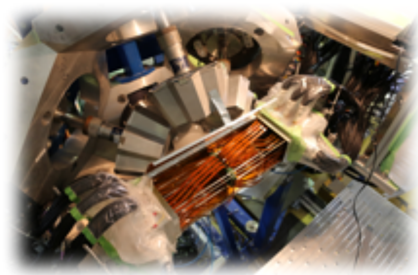
- high-Ω orbitals near both the **proton** & **neutron** Fermi surfaces favor the existence of β-decaying spin-trap isomers - two distinctive decay patterns

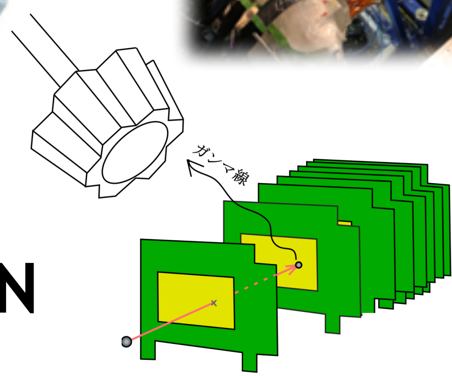
- which states will be populated in the daughter nucleus depend not only on **the spin (and K) differences**, but also on **their structure, e.g. configuration changes …**

Experimental Approaches

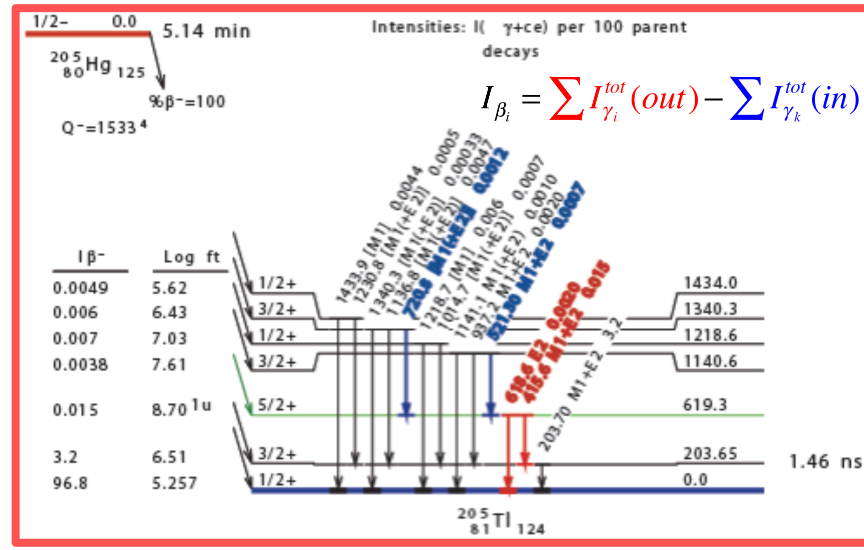
Discrete β-γ-γ Coincidence Spectroscopy - HPGe detectors







RIBF-RIKEN



Pros

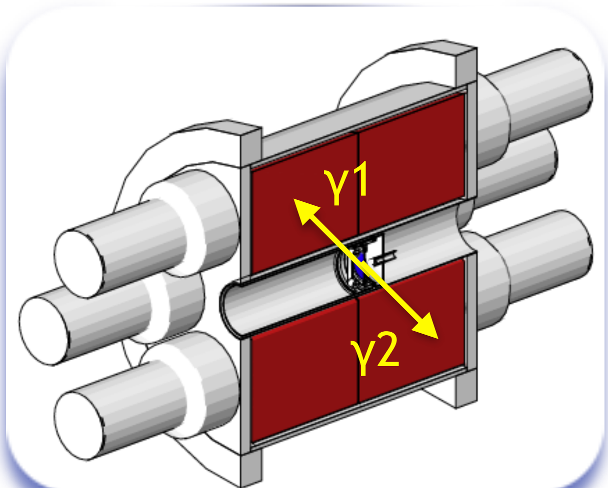
- determination of detailed decay scheme - powerful β—γ—γ coin analysis - high resolving power (ability to resolve week cascades)
- quantum numbers (Jπ, K) and configurations
- state-of-the-art detector equipment - problematic in the past

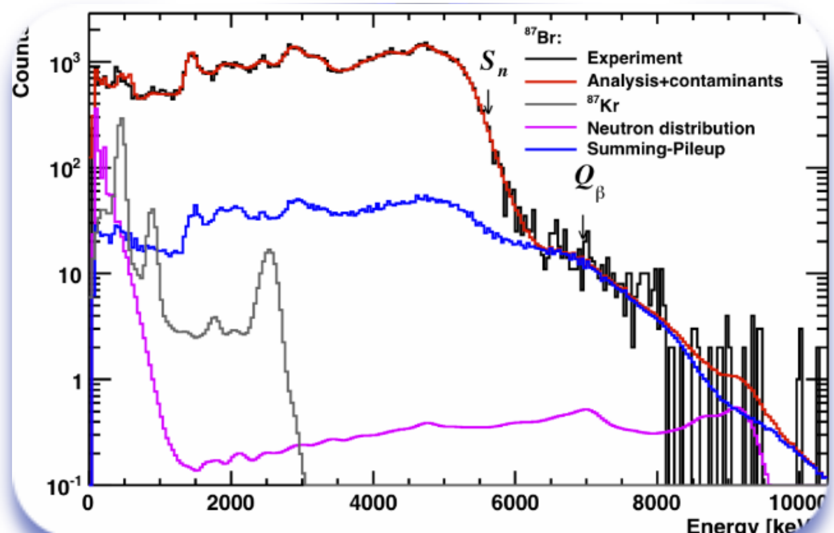
Cons

- HPGe efficiency for high-energy γ rays

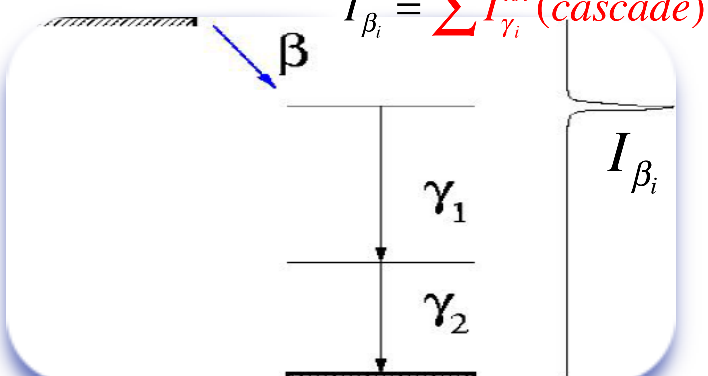
Experimental Approaches - cont.

Total Absorption Gamma-ray Spectroscopy - calorimetry - NaI





$$I_{\beta_i} = \sum I_{\gamma_i}^{tot}(cascade)$$



Pros

- large γ-ray singles efficiency

Cons

- low energy resolution and low resolving power
- **must** know details of the decay scheme - often this is not the case - simulations - uncertainties?
- complicated unfolding procedure - often non-unique solutions exist - unreliable results and uncertainties

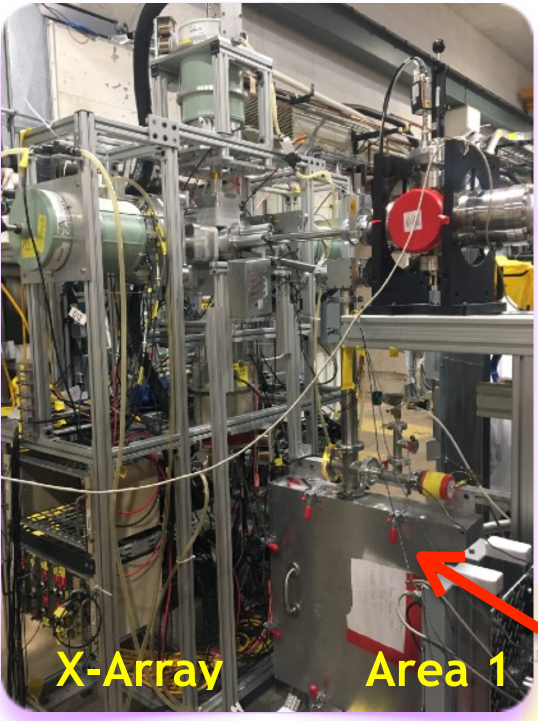
X - array

Contents lists available at ScienceDirect
Nuclear Instruments and Methods in Physics Research A
journal homepage: www.elsevier.com/locate/nima

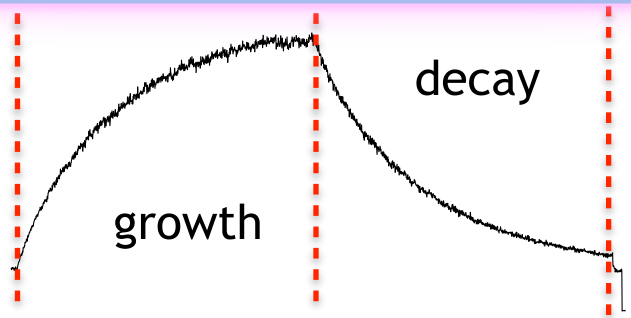
The X-Array and SATURN: A new decay-spectroscopy station for CARIBU

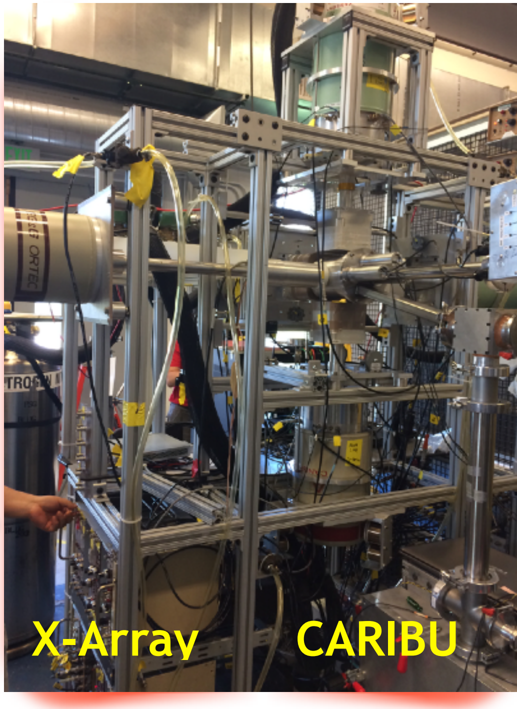
A.J. Mitchell[a,*], P.F. Bertone[b,1], B. DiGiovine[b], C.J. Lister[a], M.P. Carpenter[b], P. Chowdhury[a], J.A. Clark[b], N. D'Olympia[a], A.Y. Deo[a,2], F.G. Kondev[b,c], E.A. McCutchan[b,3], J. Rohrer[b], G. Savard[b,d], D. Seweryniak[b], S. Zhu[b]

- X-Array (5 Ge CLOVERs) - 10% full-peak efficiency
- large plastic scintillator for beta triggering
- SATURN moving tape system; digital DAQ
- future CE measurement capabilities (S. Marley -LSU)



- direct implantation on the tape
- control the growth & decay times
    - selectivity by $T_{1/2}$
- β-γ-γ(t) coincidences

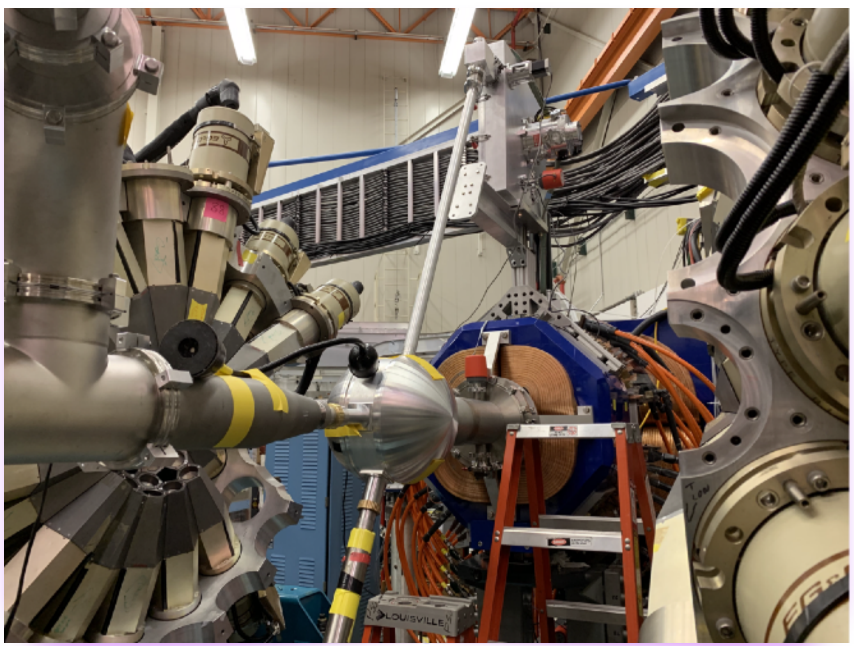


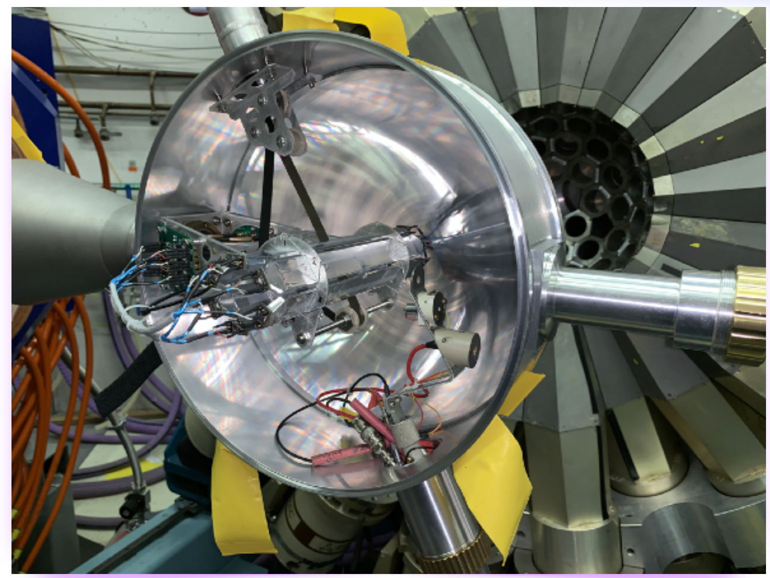


Gammasphere decay station

Advantages

- **discrete & calorimetry** γ-ray spectroscopy techniques within a single device
- **high granularity & resolving power** (ΔEγ=2 keV, P/T~60% and ε_{γ}~85%) - ability to resolve week γ-ray cascades (10^{-5}-10^{-6} %)
- **complete decay schemes** - angular correlations for transition multipolarities & Jπ assignments - end game in nuclear spectroscopy





- **HEART** - HExagonal ARray for Triggering
  - ✓ 6 EJ-204 plastic scint. & 12 SiPM
  - ✓ ε_{β}~75% from β-γ singles & coin.
- powerful γ-γ-β-t coincidence device

Studies of $^{162}Eu_{63}$ (N=99)

$^{160}_{65}$Tb$_{95}$ 72.3 d 3- Δ=-67835.5 (1.8) β-=100%	$^{161}_{65}$Tb$_{96}$ 6.89 d 3/2+ Δ=-67460.8 (1.8) β-=100%	$^{162}_{65}$Tb$_{97}$ 7.60 m (1-) Δ=-65670 (40) β-=100%	$^{163}_{65}$Tb$_{98}$ 19.5 m 3/2+ Δ=-64595 (4) β-=100%	$^{164}_{65}$Tb$_{99}$ 3.0 m (5+) Δ=-62080 (100) β-=100%	$^{165}_{65}$Tb$_{100}$ 2.11 m 3/2+# Δ=-60570# (200#) β-=100%	$^{166}_{65}$Tb$_{101}$ 25.1 s (2-) Δ=-57880 (70) β-=100%
$^{159}_{64}$Gd$_{95}$ 18.479 h 3/2- Δ=-68560.8 (1.6) β-=100%	$^{160}_{64}$Gd$_{96}$ Stable >31Ey 0+ Δ=-67940.9 (1.7) Abndnc=21.86% (19) 2β- ?	$^{161}_{64}$Gd$_{97}$ 3.646 m 5/2- Δ=-65505.0 (2.0) β-=100%	$^{162}_{64}$Gd$_{98}$ 8.4[illegible] Δ=-64[illegible] (4) β-=100%	$^{163}_{64}$Gd$_{99}$ 68 s 7/2+# Δ=-61314 (8) β-=100%	$^{164}_{64}$Gd$_{100}$ 45 s 0+ Δ=-59770# (200#) β-=100%	$^{165}_{64}$Gd$_{101}$ 10.3 s 1/2-# Δ=-56490# (300#) β-=100%
$^{158}_{63}$Eu$_{95}$ 45.9 m (1-) Δ=-67255 (10) β-=100%	$^{159}_{63}$Eu$_{96}$ 18.1 m 5/2+ Δ=-66043 (4) β-=100%	$^{160}_{63}$Eu$_{97}$ 38 s (1)(-#) Δ=-63480 (10) β-=100%	$^{161}_{63}$Eu$_{98}$ 26 s 5/2+# Δ=-61792 (10) β-=100%	$^{162}_{63}$Eu$_{99}$ 10.6 s Δ=-58690 (60) β-=100%	$^{163}_{63}$Eu$_{100}$ 7.7 s 5/2+# Δ=-56640 (70) β-=100%	$^{164}_{63}$Eu$_{101}$ 4.2 s Δ=-53330# (210#) β-=100%

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

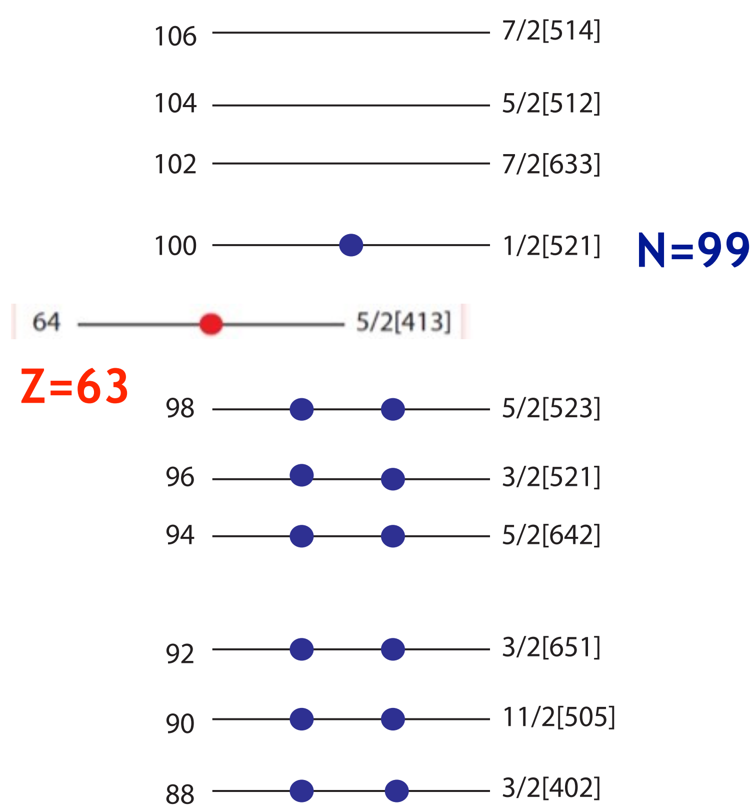
94 β-Decay Half-Lives of Neutron-Rich $_{55}$Cs to $_{67}$Ho: Experimental Feedback and Evaluation of the r-Process Rare-Earth Peak Formation

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]

^{152}Ba	0.139(8)	^{156}Pr	0.444(6)	^{161}Eu	30.1(90)	^{172}Dy	$3.94(^{+28}_{-37})$
^{153}Ba	0.116(52)	^{157}Pr	$0.295(^{+29}_{-11})$	^{162}Eu	11.8(14)	^{172m}Dy	0.674(66)

10.6 (1) s from Gd X-rays
Greenwood et al. PRC 35 (1987) 1065

What to expect:
π5/2[413] ν1/2[521] configuration
$K^{\pi}=3^{-}$ ground state - no isomers



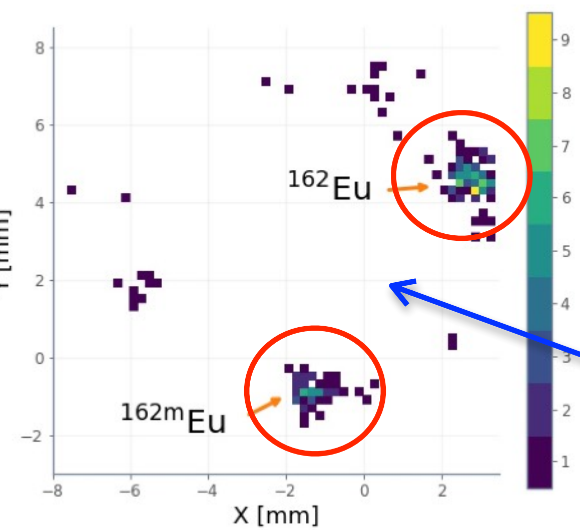
WS, Nilsson & folded-Yukawa

PHYSICAL REVIEW LETTERS 120, 262701 (2018)

Precision Mass Measurements on Neutron-Rich Rare-Earth Isotopes at JYFLTRAP: Reduced Neutron Pairing and Implications for *r*-Process Calculations

M. Vilen,[1,*] J. M. Kelly,[2,†] A. Kankainen,[1] M. Brodeur,[2] A. Aprahamian,[2] L. Canete,[1] T. Eronen,[1] A. Jokinen,[1] T. Kuta,[2] I. D. Moore,[1] M. R. Mumpower,[2,3] D. A. Nesterenko,[1] H. Penttilä,[1] I. Pohjalainen,[1] W. S. Porter,[2] S. Rinta-Antila,[1] R. Surman,[2] A. Voss,[1] and J. Äystö[1]

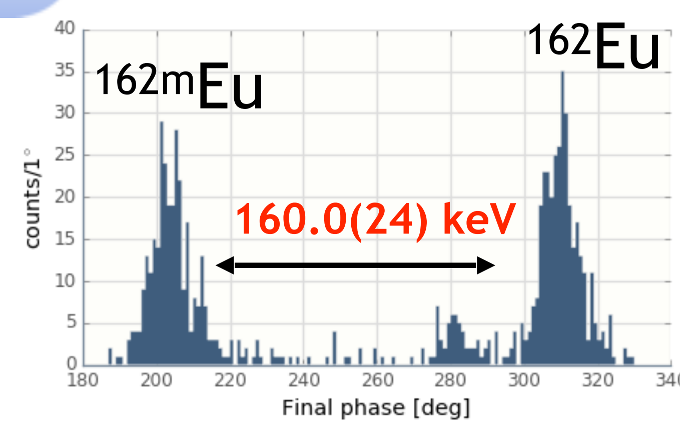
Isotope	Reference	ME_{REF}(keV)	$r = \nu_{c,ref}/\nu_c$	ME_{JYFL}(keV)	ME_{AME16}(keV)	$\Delta ME_{JYFL-AME16}$(keV)
^{156}Nd	^{136}Xe	-86429.159(7)	1.147 366 924(19)	-60210(2)	-60470(200)	260(200)
^{158}Nd	^{136}Xe	-86429.159(7)	1.162 132 772(290)	-53897(37)	-54060(200)#	160(200)#
^{158}Pm	^{158}Gd	-70689.5(12)	1.000 078 752(9)	-59104(2)	-59089(13)	-15(13)
^{160}Pm	^{136}Xe	-86429.159(7)	1.176 857 014(130)	-52851(16)	-53000(200)#	149(201)#
^{162}Sm	^{136}Xe	-86429.159(7)	1.191 560 914(39)	-54381(5)	-54530(200)#	149(200)#
^{162}Eu	^{136}Xe	-86429.159(7)	1.191 527 132(28)	-58658(4)	-58700(40)	42(40)
^{163}Eu	^{163}Dy	-66381.2(8)	1.000 065 633(23)	-56420(4)	-56480(70)	60(70)
^{163}Gd	^{163}Dy	-66381.2(8)	1.000 034 135(22)	-61200(4)[a]	-61314(8)	114(9)
^{164}Gd	^{171}Yb	-59306.810(13)	0.959 046 522(14)	-59694(3)	-59770(100)#	76(100)#
^{165}Gd	^{171}Yb	-59306.810(13)	1.058 489 243(23)[b]	-56522(4)	-56450(120)#	-72(120)#
^{166}Gd	^{136}Xe	-86429.159(7)	1.220 992 828(29)	-54387(4)	-54530(200)#	143(200)#
^{164}Tb	^{171}Yb	-59306.810(13)	0.959 031 473(21)	-62090(4)	-62080(100)	-10(100)



CPT mass measurements @ANL
ν_c relative to ^{84}Kr

ME(gs) =-58723.9 (15)
ME(is) =-58563.9 (19)

ME(JYFL) =-58658 (4)

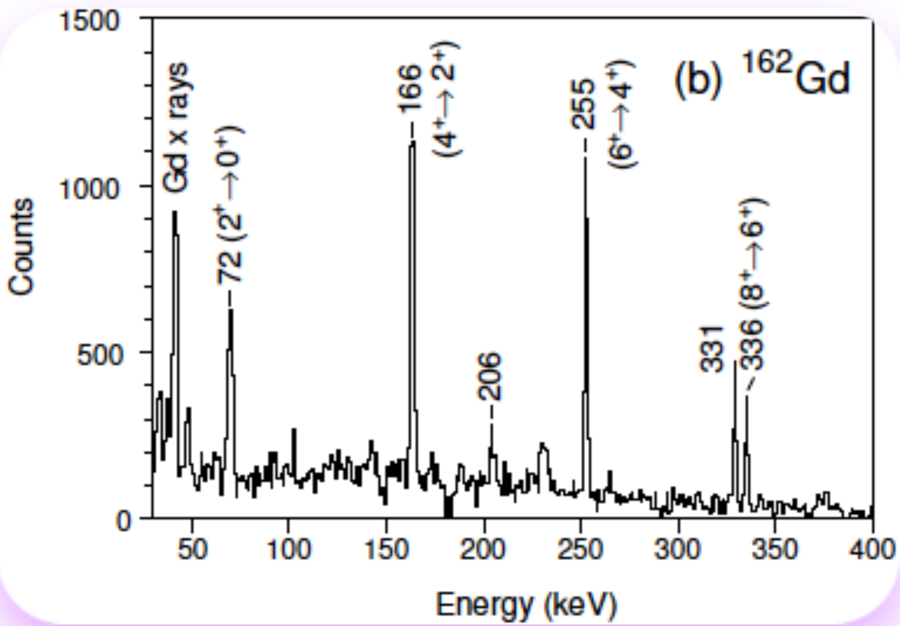


phase-imaging ion-cyclotron-resonance technique

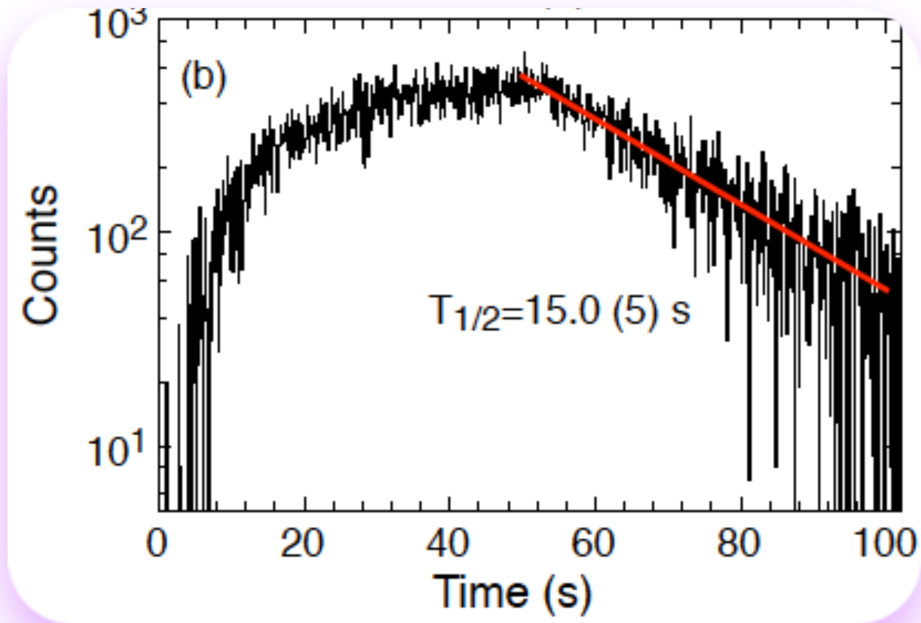
D.J. Hartley et al. PRL120 182502 2018

Studies of $^{162}Eu_{63}$ (N=99) - cont.

β-γ-γ coincidences



β-γ-t coincidences



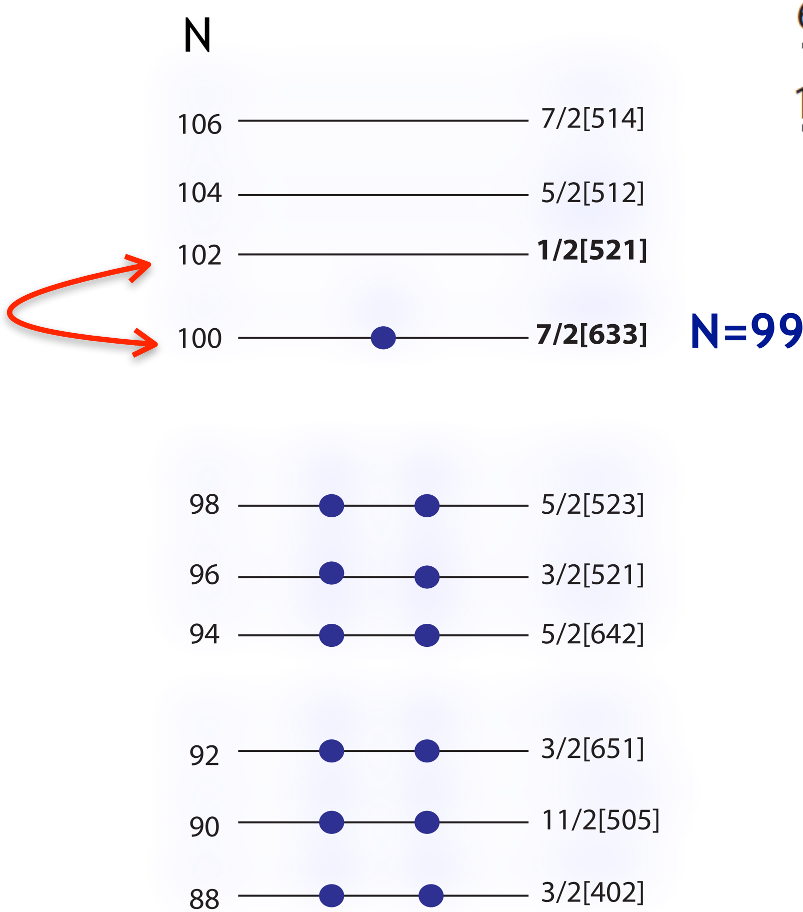
- high-spin β-decaying state - feeding of the I^{π}=8+ of the K^{π}=0+ band - inconsistent with the expected π5/2[413] ν1/2[521] configuration that would imply **I^{π}=3-** for the parent (^{162}Eu)

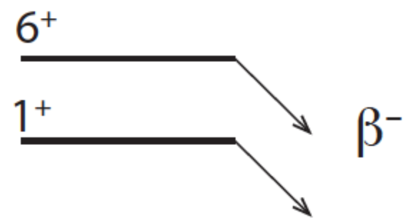
Compared to:

- 11.8 (14) s J. Wu *et al.*
- 10.6 (1) s Greenwood *et al.*

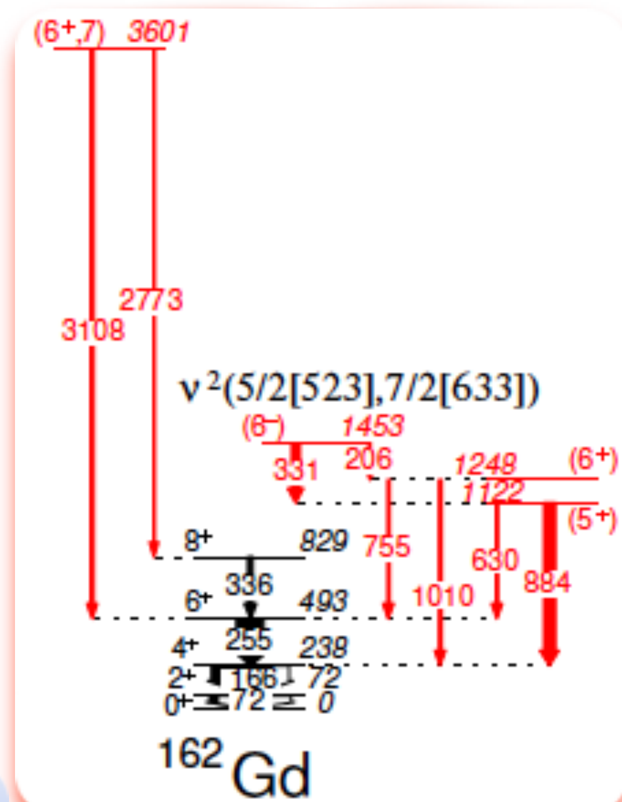
D.J. Hartley et al. PRL120 182502 2018

Studies of ^{162}Eu (N=99) cont.





π5/2[413] ν7/2[633]

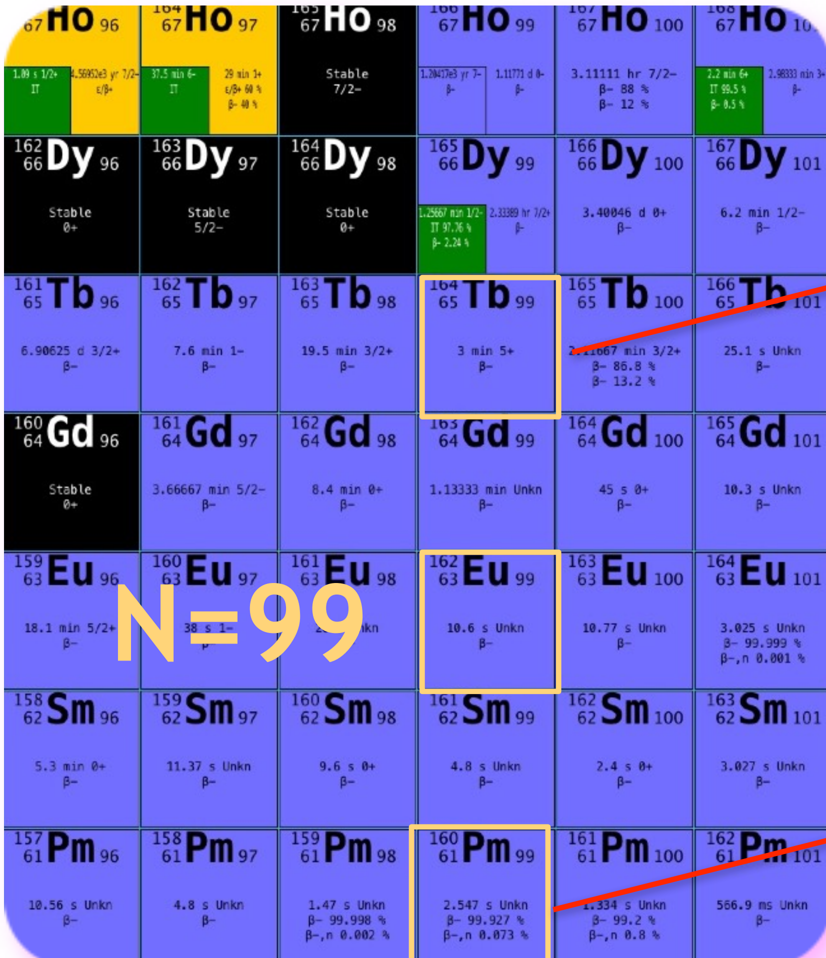


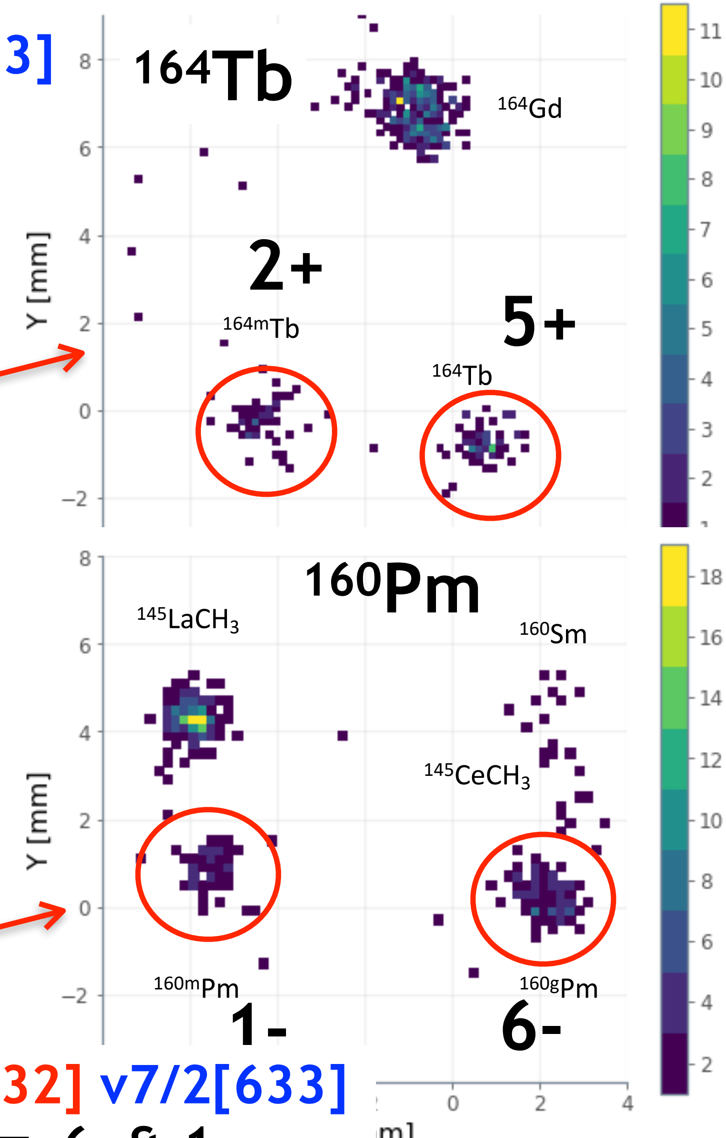
deviations from WS, Nilsson & folded-Yukawa
ordering of the 1/2[521] and 7/2[633] neutron orbitals

D.J. Hartley et al. PRL120 182502 2018

Isomers in ^{160}Pm and ^{164}Tb (N=99)

π3/2[411] ν7/2[633]
Kπ=5+ & 2+





π5/2[532] ν7/2[633]
Kπ=6- & 1-

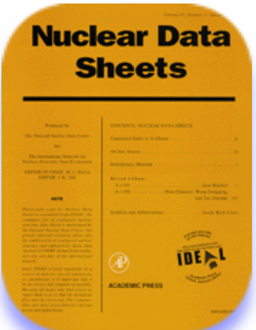
phase-imaging ion-cyclotron-resonance technique

Z

R. Orford *et al.*, in preparation

Commissioning experiment - ^{146}La decay

Y. Khazov et al., NDS **136** (2016) 163



(6⁻) 0.0+X

9.8 (4) s

(2⁻) 0.0

6.1 (3) s

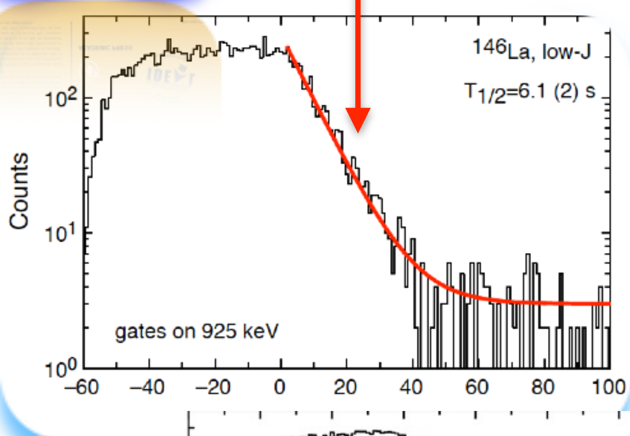
(1⁻,2⁻) 0.0+X

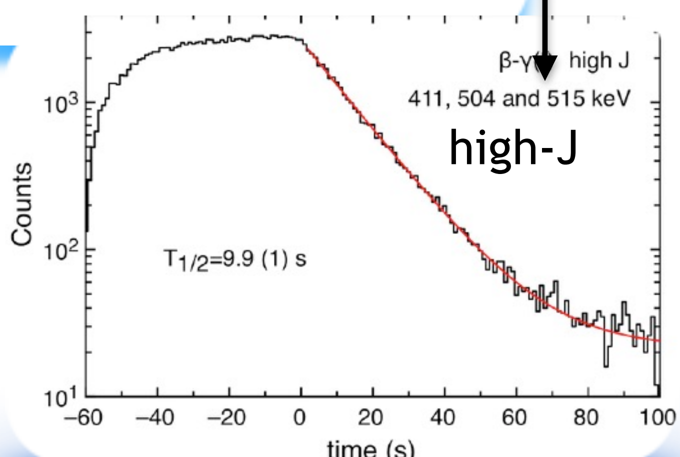
(5⁻) 0.0

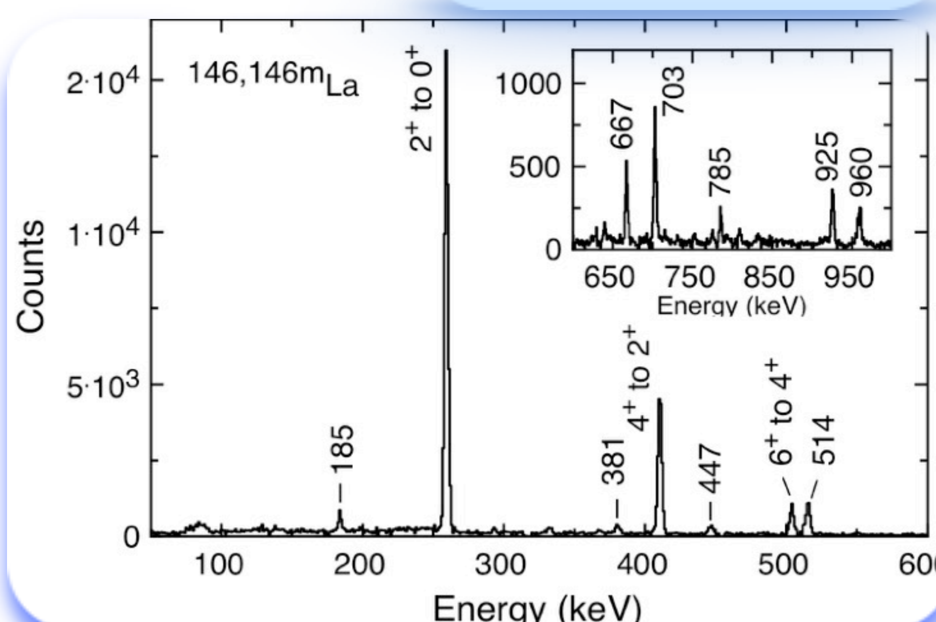
π5/2+[413] ν1/2[530]

π5/2+[413] ν5/2[523]

Nilsson assignment

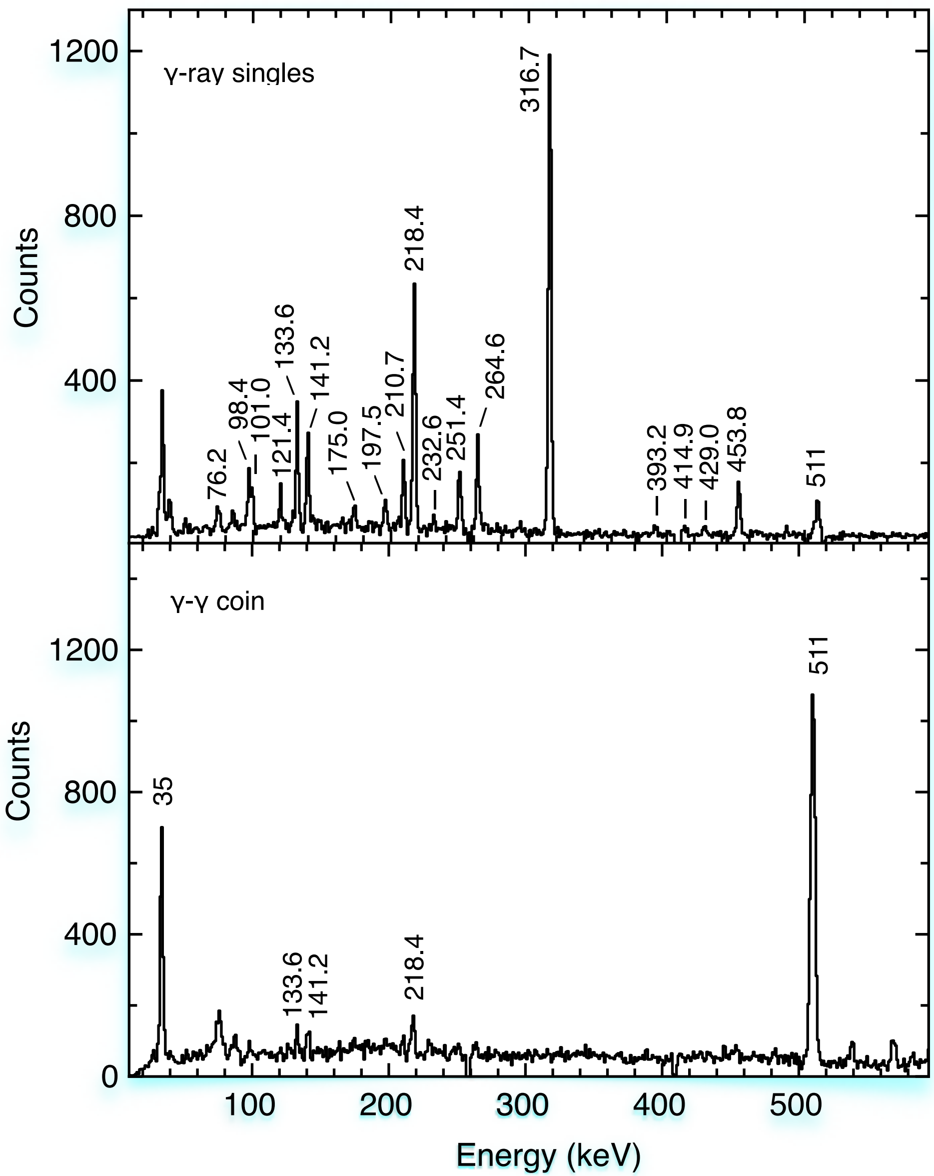






- resolved gs and isomer decays
- new levels and transitions
- new Jπ and configurations
- new nuclear structure interpretation
  - deformed shell model

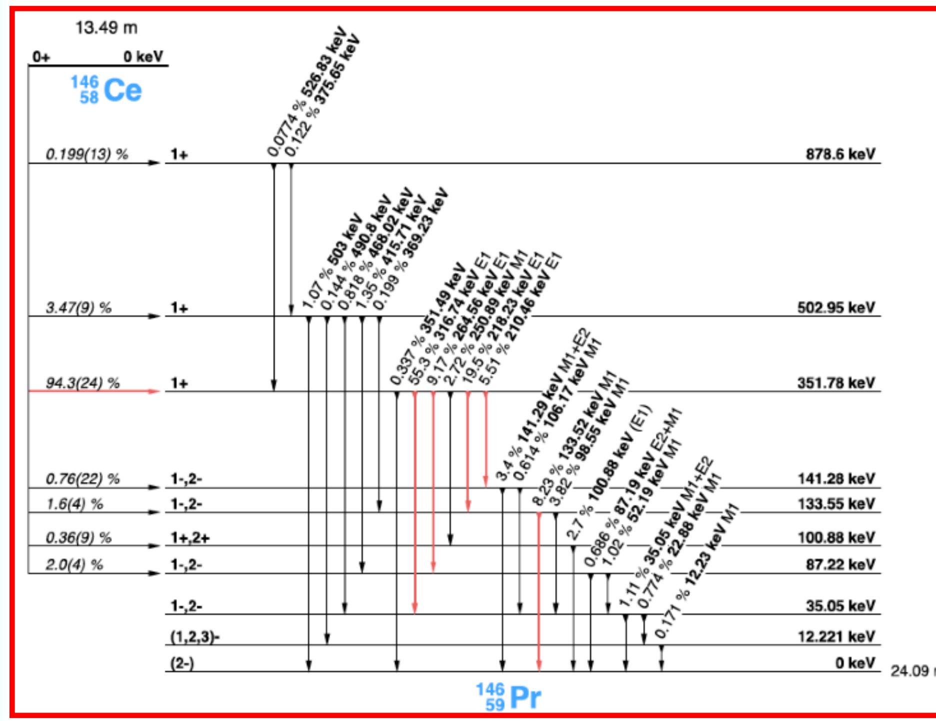
^{146}Ce decay



146Ce β- decay

- differ significantly from previous TAGS (calorimetric) studies with NaI

R.C. Greenwood et al. NIM **A390** (1997) 95



many even-even to odd-odd decays

Outlook & Conclusions

- direct mass measurements in conjunction with detailed β-decay studies are powerful tool to elucidate properties of neutron-rich nuclei - details matter!

- CARIBU produces high-quality LE beams with sufficient yield for **detailed** spectroscopy - examples on ^{162}Eu, ^{160}Pm & ^{164}Tb - decay properties, isomers, excitation energies, sub-shell closures ... **limitations** - the high background in the LE area - a new beam line has been built and will be operational later this year - continue exploring the A~160 light rare-earth region - last week we started the new experimental campaign!

- decay spectroscopy measurements with Gammasphere - new moving-tape system & beta-particle detector array - Decay Data Factory - bringing GS into the new LE area & run continuously for ~6 months - a future workshop is planed at ANL

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