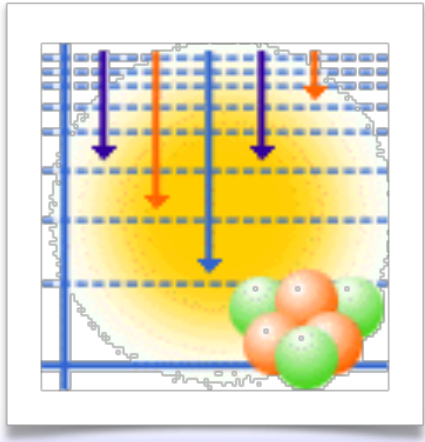
Masses & Beta-Decay Spectroscopy of Neutron-Rich Nuclei: Isomers & Sub-shell Gaps with Large Deformation

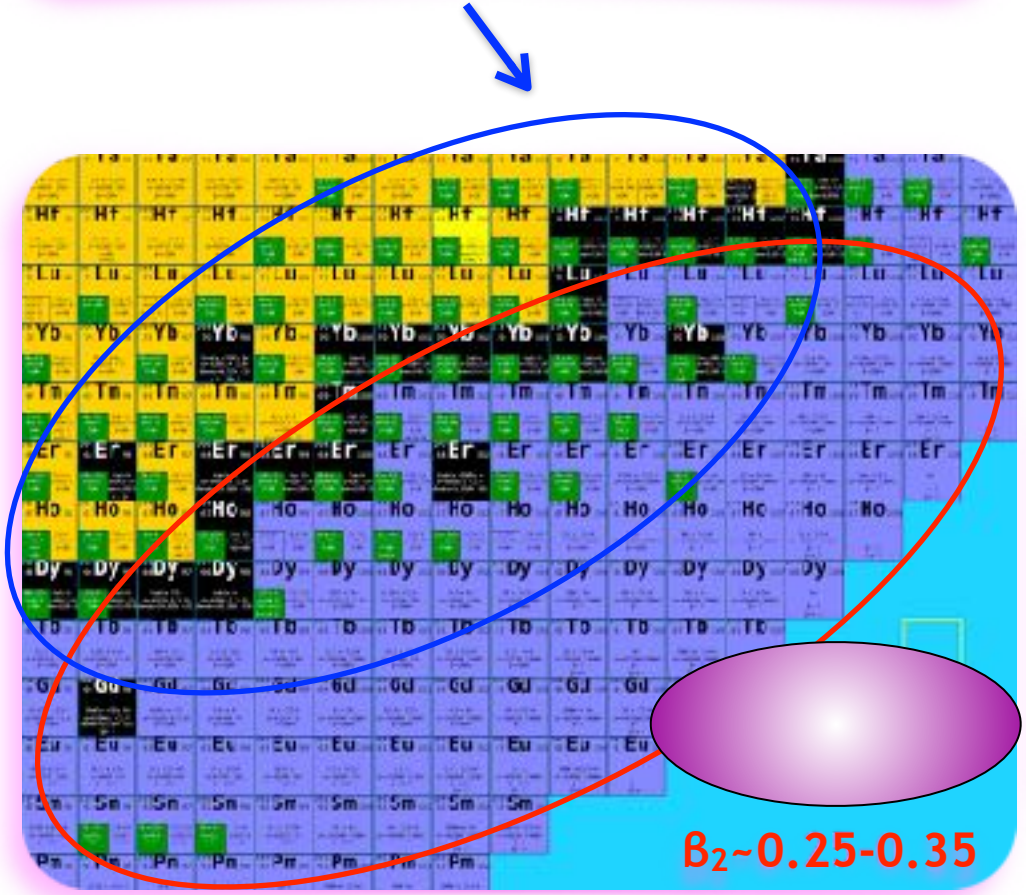
F.G. Kondev
Physics Division, Argonne National Laboratory

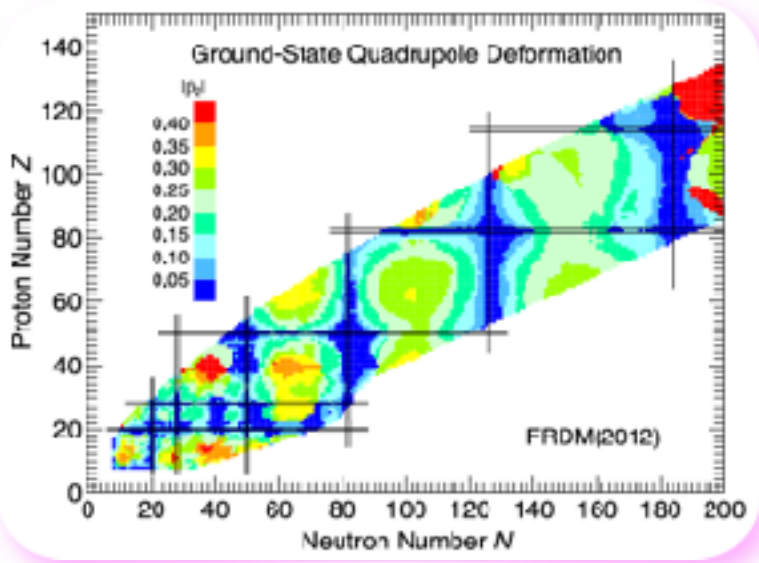


Nuclear Structure & Dynamics 2019, May 13-17, Venice, Italy

Introduction

- **classical rare-earth region** - close to stability - modest deformation - test ground for the development of deformed shell model



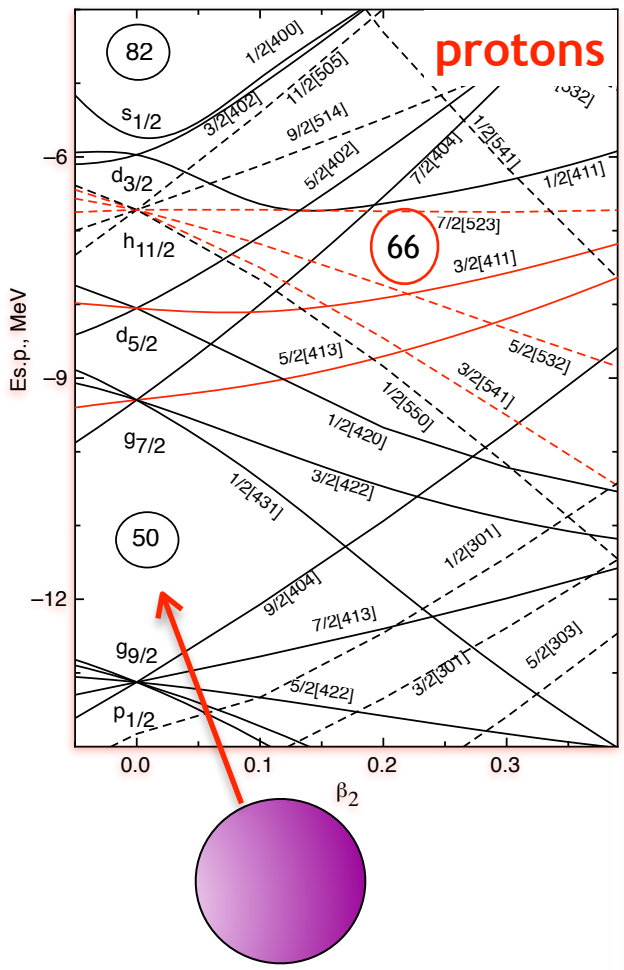


P. Moller *et al.*, ADNDT **109-110** (2016) 1

light rare-earth region

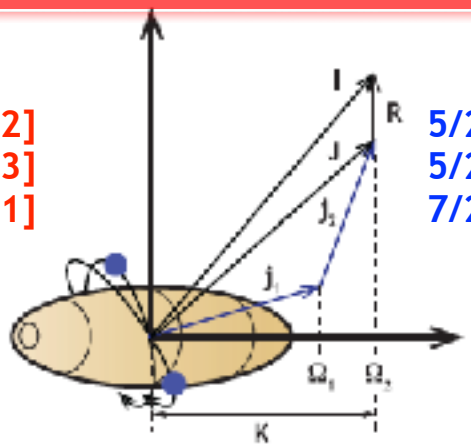
- terra incognita - not easy to get there …
  - ✓ prompt-fission studies with GS - mostly along the yeast line …
  - ✓ in-flight fission & fragmentation (RIKEN) - beta-decay studies …
- well-deformed *n*-rich nuclei

Deformed Nuclei & Shell Gaps



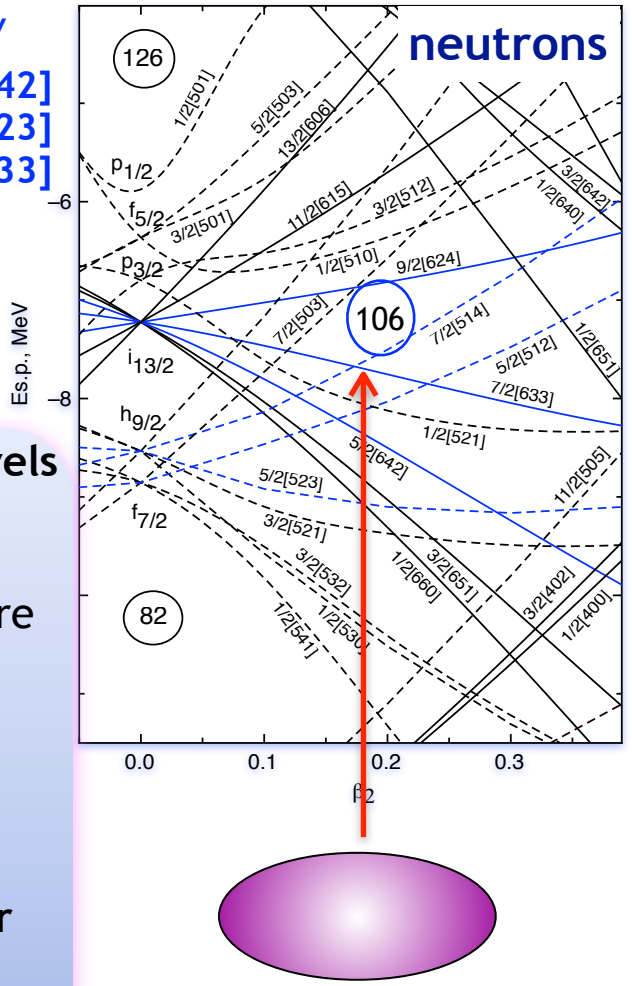
Ω_π

5/2[532]
5/2[413]
3/2[411]

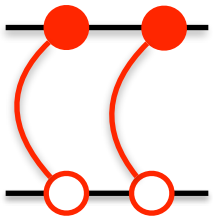


Ω_ν

5/2[642]
5/2[523]
7/2[633]



- **ordering of single-particle levels**
- **size of deformation**
  - ✓ how it evolves with N & Z; are there shape changes?
- **pairing and residual nucleon-nucleon interactions**
- role of the **K-quantum number**
  - ✓ both in γ-decay (K-isomers) and ß-decay (spin-trap isomers)



2+

0+

$$E = \frac{\hbar^2}{2\Im(\Delta,\beta)} I(I+1)$$

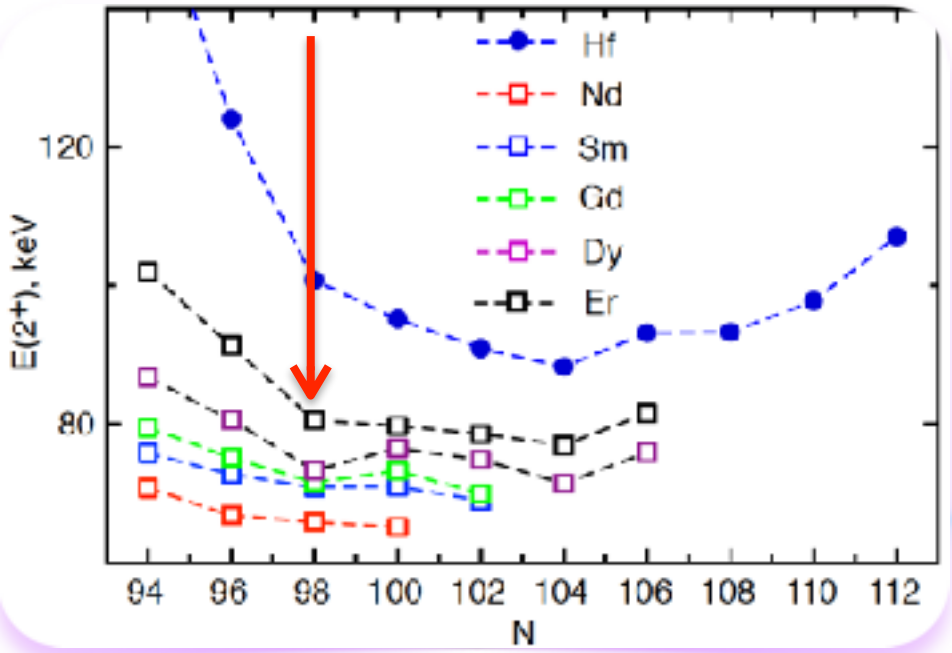
2+

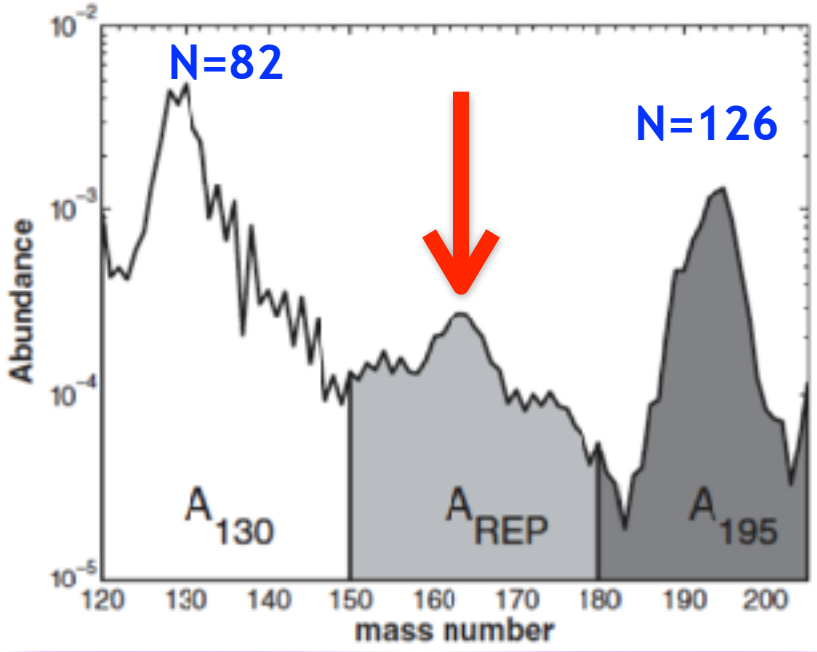
0+

Motivation

- basic nuclear data: masses, $T_{1/2}$, P_n, etc.,
  ✓ need detailed knowledge on nuclear structure to improve predictions for nuclei that won't be observed

M.R. Mumpower *et al.*, J. Phys. G **44 (2017)** 034003

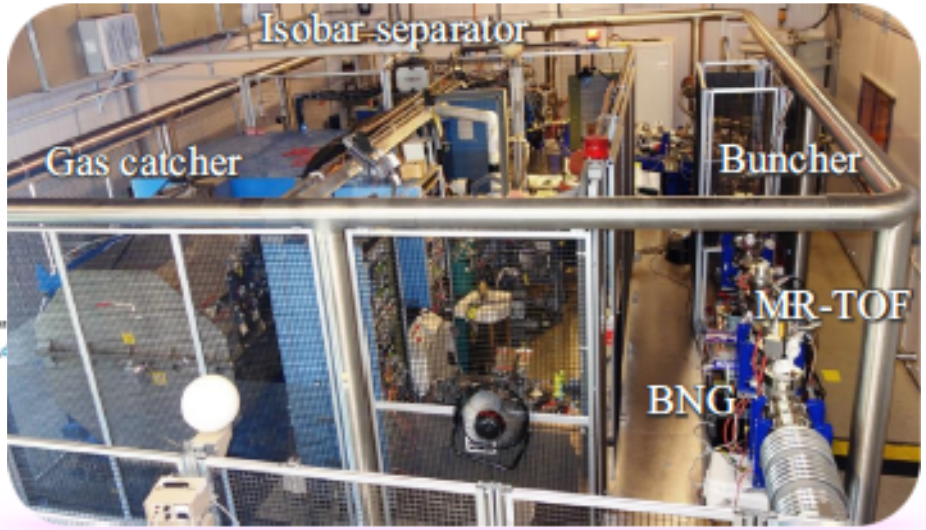




- unusual nuclear structure behavior near N= 98 (Gd,Dy,Sm)

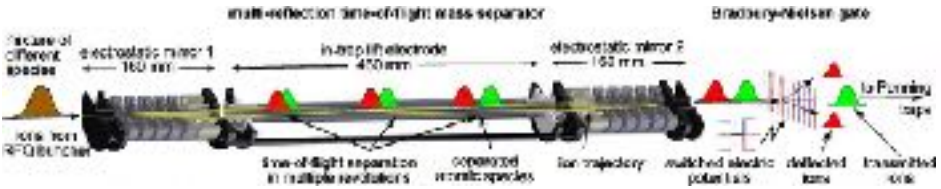
CARIBU & ANL

- SF fission of ^{252}Cf (3.1%) 1.7 Ci - 6.310^{10} dps
- Gas Catcher, Isobar Separator (m/Δm~10000), MR-TOF (m/Δm~100,000), CPT (m/Δm~1,000,000)
- LE, high-purity & high-quality beams



First operation and mass separation with the CARIBU MR-TOF

Tsviki Y. Hirsch [a,b,e], Nancy Paul [b,c], Mary Burkey [b,d], Ani Aprahamian [c], Fritz Buchinger [e], Shane Caldwell [b,c], Jason A. Clark [b], Anthony F. Levand [b], Lin Ling Ying [b], Scott T. Marley [c], Graeme E. Morgan [a,b], Andrew Nystom [b,c], Rodney Orford [b,c], Adrian Pérez Galván [b,a], John Rohrer [b], Guy Savard [b,d], Kumar S. Sharma [a], Kevin Siegl [b,c]



CARIBU LE area

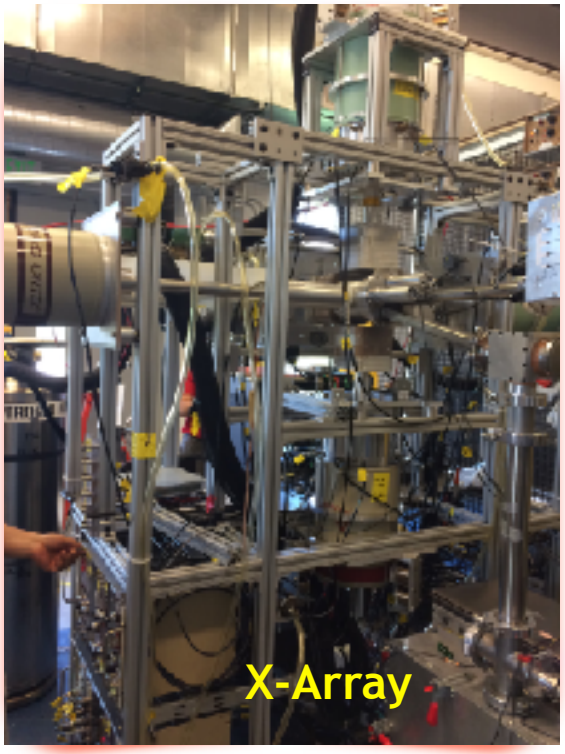
Contents lists available at ScienceDirect
Nuclear Instruments and Methods in Physics Research A
journal homepage: www.elsevier.com/locate/nima

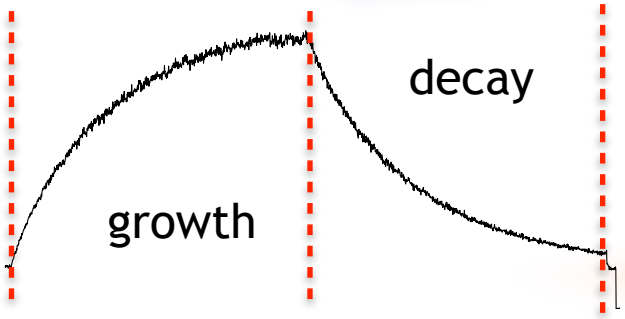
The X-Array and SATURN: A new decay-spectroscopy station for CARIBU

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,r], E.A. McCutchan[b,1], J. Rohrer[b], G. Savard[b,d], D. Seweryniak[b], S. Zhu[b]

- X-Array (4 Ge CLOVERs) & 1 LEPS
- large plastic scintillators
- SATURN moving tape station

- direct implantation on the tape
- control the growth & decay times - resolving states with different $T_{1/2}$
- detailed spectroscopy: β-γ-γ—time coin





- **CPT, MR-TOF & PI-ICR:** high purity & mass resolution - identification of **long-lived** isomers

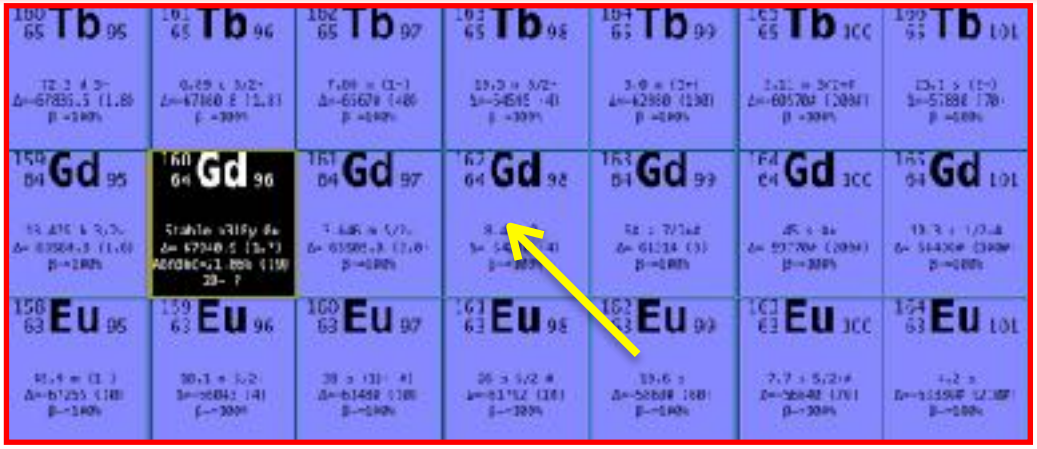
(selected) Experimental Results

PHYSICAL REVIEW LETTERS 120, 182502 (2018)

Masses and β-Decay Spectroscopy of Neutron-Rich Odd-Odd ^{160,162}Eu Nuclei: Evidence for a Subshell Gap with Large Deformation at $N=98$

D. J. Hartley,[1] F. G. Kondev,[2] R. Orford,[2,3] J. A. Clark,[2,4] G. Savard,[2,5] A. D. Ayangeakaa,[2,*] S. Bottoni,[2,†] F. Buchinger,[3] M. T. Burkey,[2,5] M. P. Carpenter,[2] P. Copp,[2,6] D. A. Gorelov,[2,4] K. Hicks,[1] C. R. Hoffman,[2] C. Hu,[7] R. V. F. Janssens,[2,‡] J. W. Klimes,[2] T. Lauritsen,[2] J. Sethi,[2,8] D. Seweryniak,[2] K. S. Sharma,[9] H. Zhang,[7] S. Zhu,[2] and Y. Zhu[7]

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



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

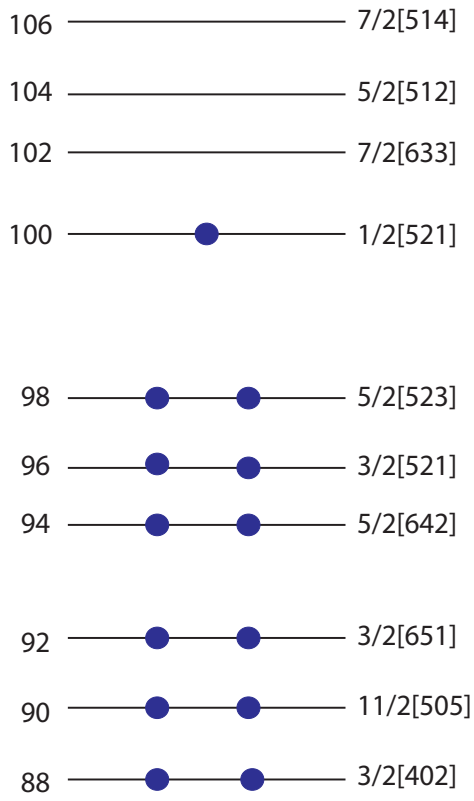
94 β-Decay Half-Lives of Neutron-Rich $_{55}$Cs to $_{67}$Ho: Experimental Feedback and Evaluation of the *r*-Process Rare-Earth Peak Formation

J. Wu, S. Nishimura, G. Lorusso, P. Möller, E. Ideguchi, P.-H. Regan, G. S. Simpson, P.-A. Söderström, P. M. Walker, H. Watanabe, Z. Y. Xu, H. Baba, F. Browne, R. Daido, P. Doornenbal, Y. F. Fang, G. Gey, T. Isobe, P. S. Lee, J. J. Liu, Z. Li, Z. Korkulu, Z. Patel, V. Phong, S. Rice, H. Sakurai, L. Sinclair, T. Sumikama, M. Tanaka, A. Yagi, Y. L. Ye, R. Yokoyama, G. X. Zhang, T. Alharbi, N. Aoi, F. L. Bello Garrote, G. Benzoni, A. M. Bruce, R. J. Carroll, K. Y. Chae, Z. Dombradi, A. Estrade, A. Gottardo, C. J. Griffin, H. Kanaoka, I. Kojouharov, P. G. Kordes, S. Kubono, N. Kurz, I. Kuti, S. Lalkovski, G. J. Lane, E. J. Lee, T. Lokotko, G. Lotay, C.-B. Moon, H. Nishibata, I. Nishizuka, C. R. Nita, A. Odahara, Zs. Podolyák, O. J. Roberts, H. Schaffner, C. Shand, J. Taprogge, S. Terashima, Y. Wada, and S. Yoshida

^{152}Ba	0.139(8)	^{156}Pr	0.444(6)	^{161}Eu	30.1(90)	^{172}Dy	3.94($^{+20}_{-37}$)
^{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

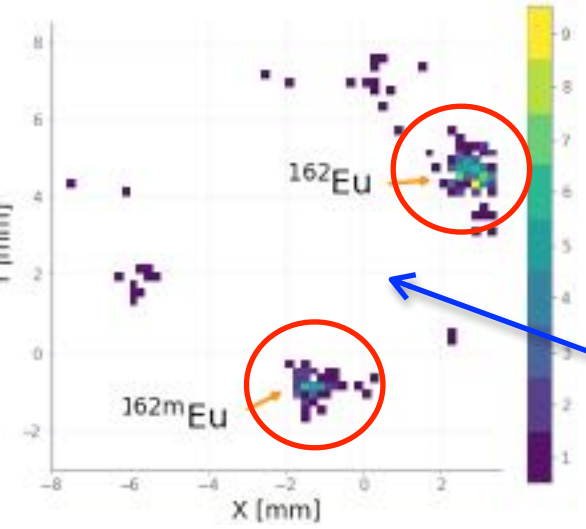
PHYSICAL REVIEW LETTERS 120, 262701 (2018)

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]

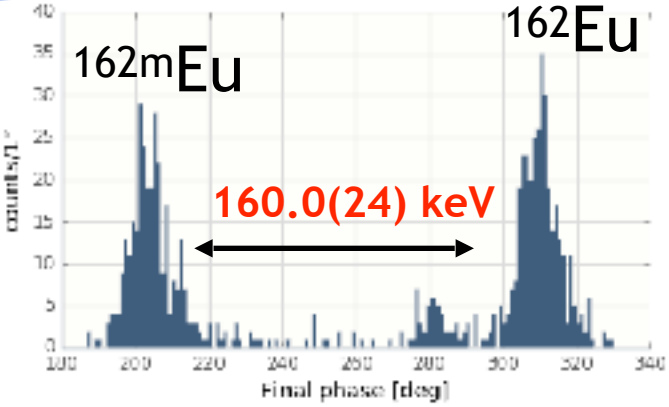
Isotope	Reference	ME_{AME}(keV)	$r - \nu_{ref}/\nu_r$	ME_{JYFL}(keV)	ME_{AME20}(keV)	$\Delta ME_{JYFL-AME20}$(keV)
^{150}Nd	^{136}Xe	86429.159(7)	1.147 366 924(19)	60210(2)	60470(200)	260(200)
^{158}Nd	^{136}Xe	-86429.159(7)	1.162 132 772(290)	-53897(37)	-54060(200) //	160(200) //
^{158}Pm	^{158}Gd	-70689.5(12)	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(38)	58658(4)	58700(40)	42(40)
^{160}Tm	^{158}Dy	-66381.2(8)	1.000 055 633(23)	-58420(4)	-58480(70)	60(70)
^{164}Gd	^{162}Dy	-66381.2(8)	1.000 034 135(22)	-61200(4)[c]	-61314(8)	114(9)
^{161}Gd	^{171}Yb	59306.810(13)	0.959 046 522(14)	59691(3)	59770(100)#	79(100)#
^{165}Gd	^{171}Yb	-59306.810(13)	1.068 459 243(23)[b]	-56522(4)	-56650(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)

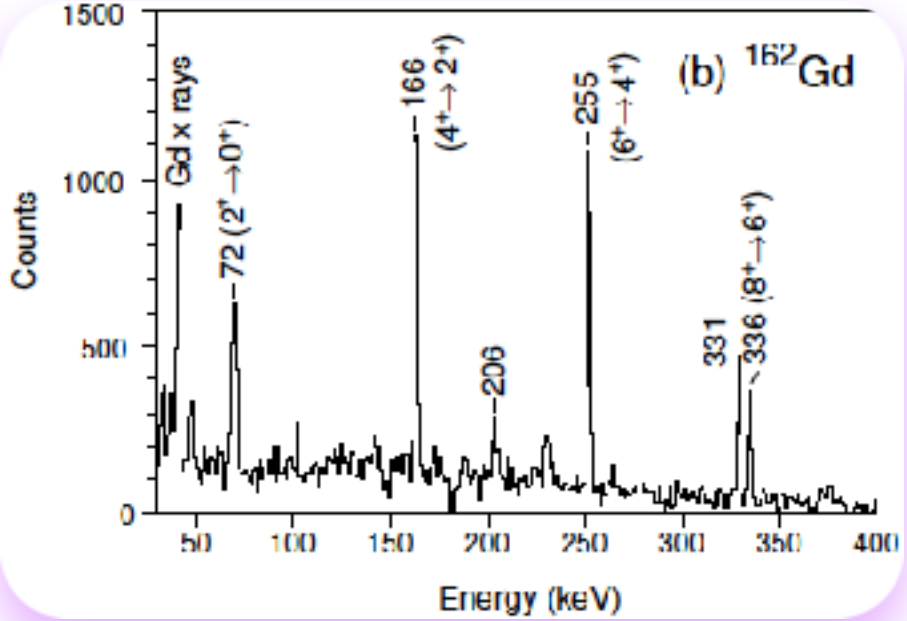


phase-imaging ion-cyclotron-resonance technique

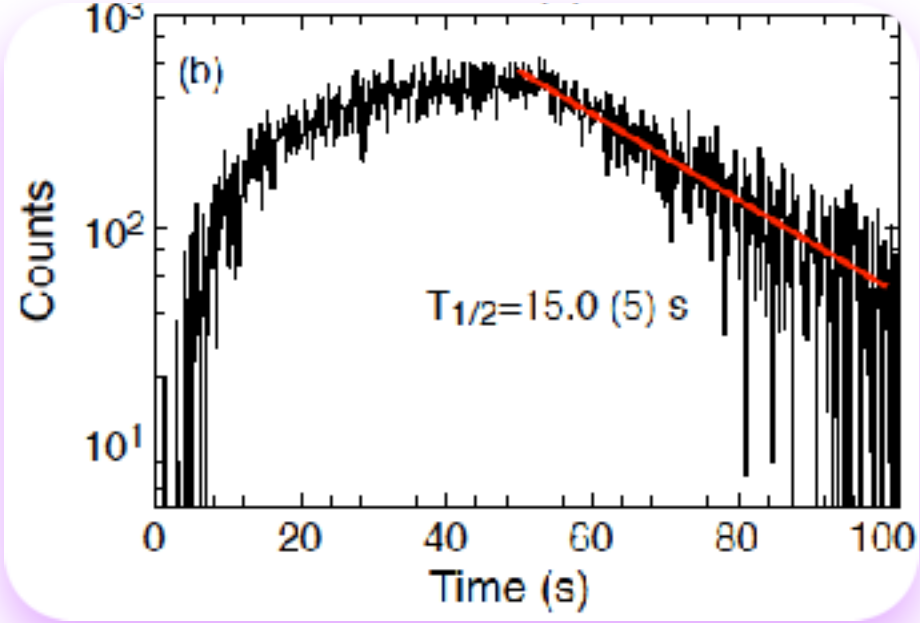
D.J. Hartley et al. PRL120 182502 2018

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

β-γ-γ coincidences



β-γ-t coincidences



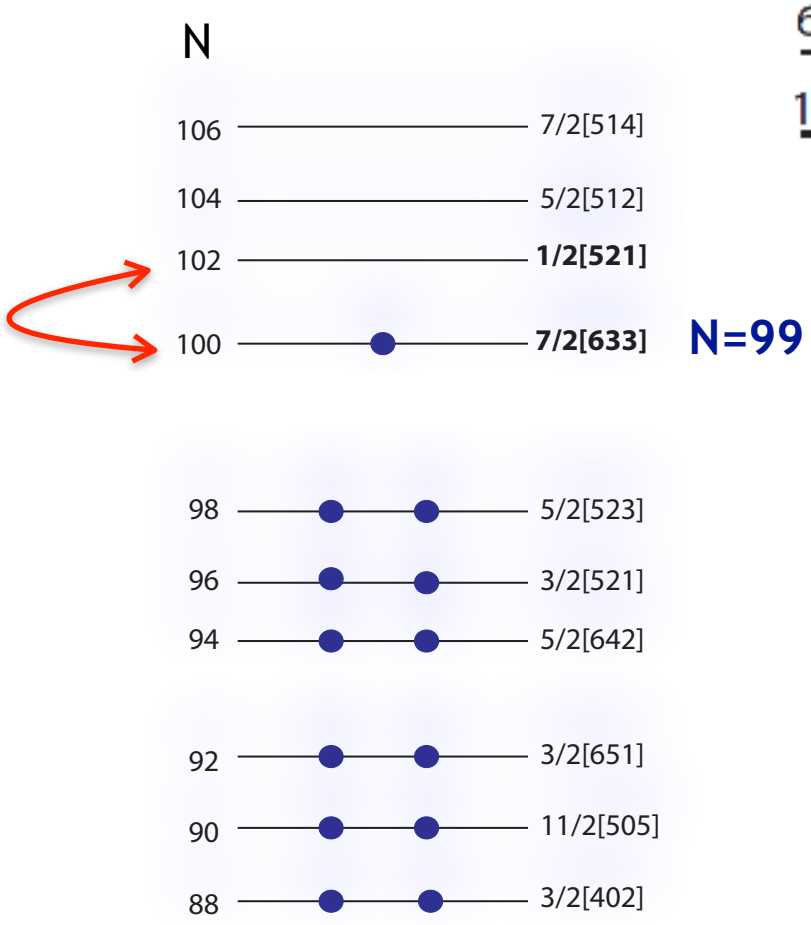
- high-spin β-decaying state - feeding of the $I^{\pi}=8+$ of the $K^{\pi}=0+$ band - inconsistent with the expected **π5/2[413] ν1/2[521]** configuration that would imply **$I^{\pi}=3-$** for the parent (^{162}Eu)

Compared to:

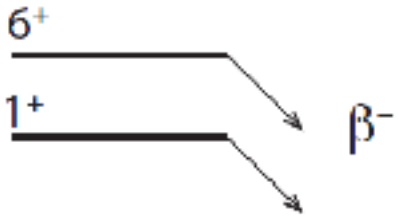
- 11.8 (14) s J. Wu *et al.*
- 10.6 (1) s Greenwood *et al.*

D.J. Hartley et al. PRL120 182502 2018

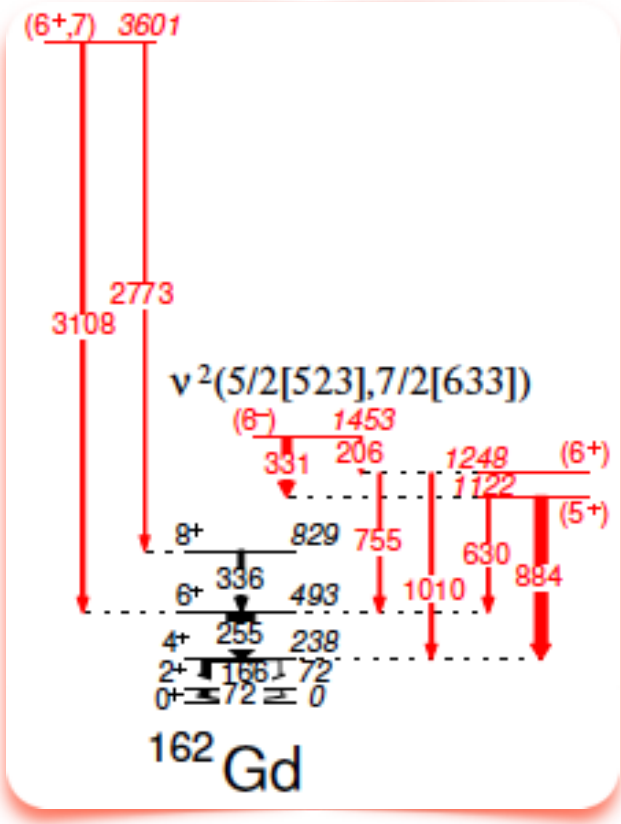
Studies of ^{162}Eu (N=99) cont.



N=99



π5/2[413] ν7/2[633]

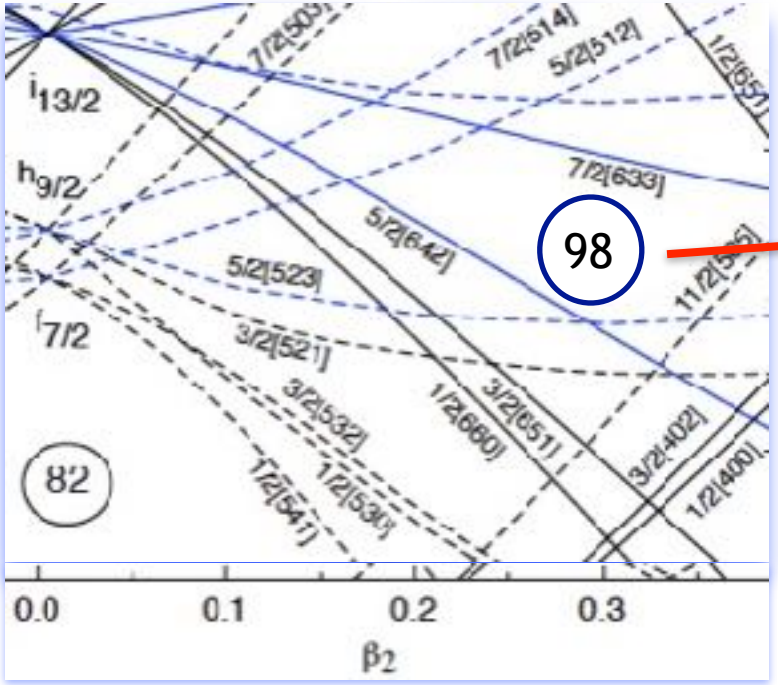


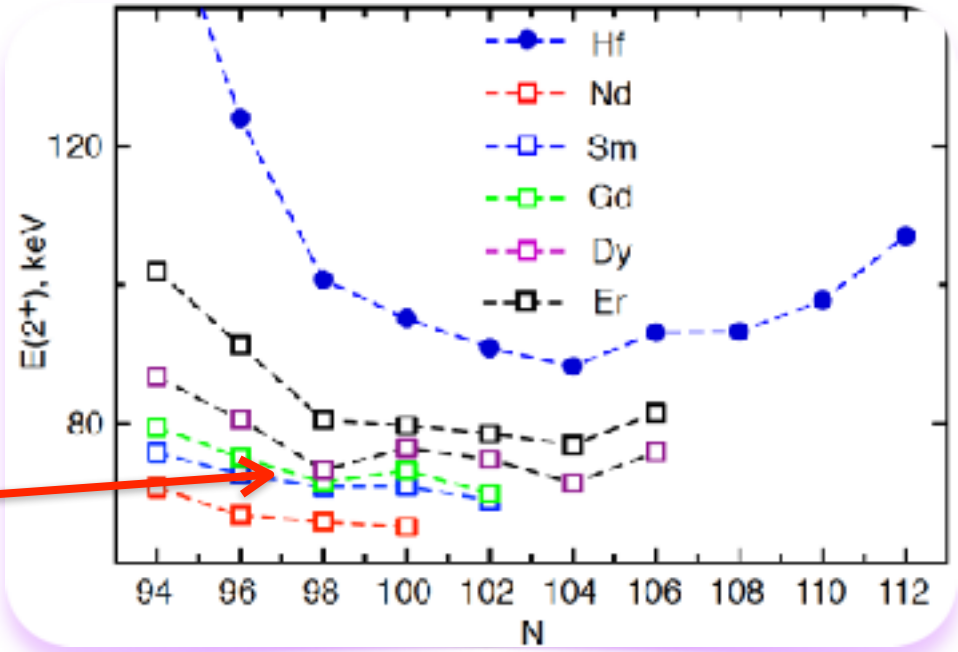
deviations from WS, Nilsson & folded-Yukawa ordering of the 1/2[521] and 7/2[633] neutron orbitals

D.J. Hartley et al. PRL120 182502 2018

Sub-shell gap at N=98 and β_2~0.3

Patel *et al.*, PRL**113** (2014) 262502 proposed a gap at N=100, but there is no evidence for its existence





- evidences from high-spin and transfer reaction studies that N-98 deformed sub-shell gap exists in other regions of the nuclear chart

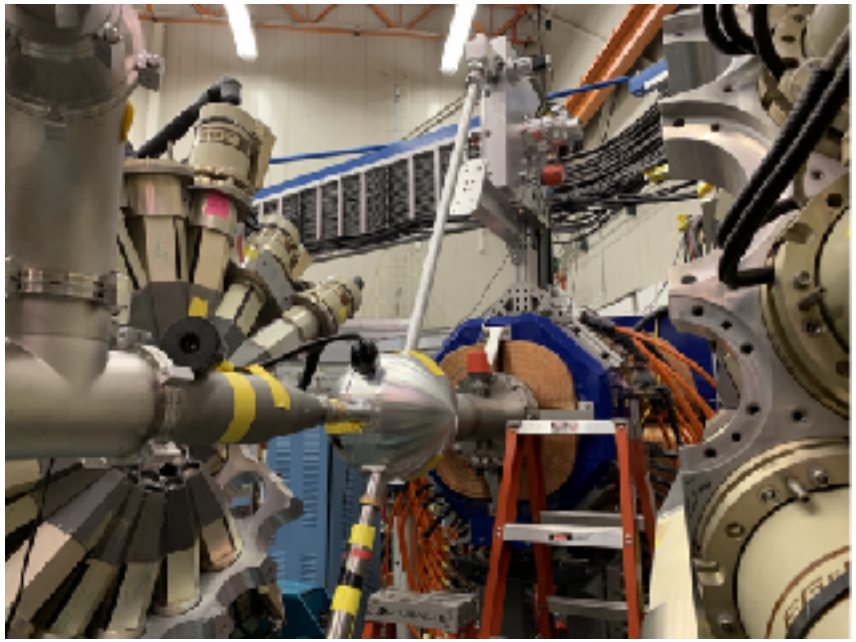
D.J. Hartley et al. PRL120 182502 2018

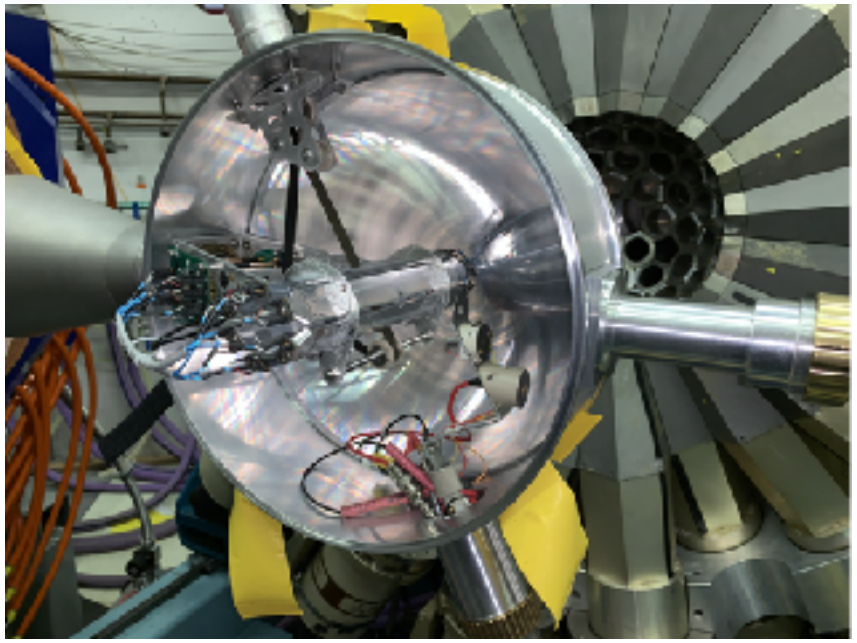
D.G. Burke & G. Lovhoiden, NP A750 (2005) 185
H.J. Jensen et al., Z. Phys. A359 (1997) 127
Md. Asgar et al. PRC95 (2017) 031304(R)

New Development

Decay spectroscopy with Gammasphere

new Decay Data Station at Gammasphere - commissioned December 17-22, 2018
target chamber (WUSL), tape station (LSU) and ß- particle detector arrays (ANL)



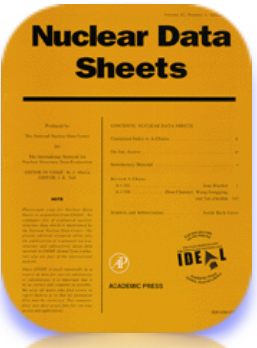


- flexible selection of different growth & decay cycles
- increased sensitivity for fast-decaying nuclei (down to 100 of ms); resolving isomers

- **HEART** - Hexagonal Array for Triggering
  - ✓ 6 EJ-204 plastic scint. & 12 SiPM
  - ✓ ε_{β}=75 (2)% from ß-γ singles & coin.
- powerful γ-γ-ß-t coincidence device

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

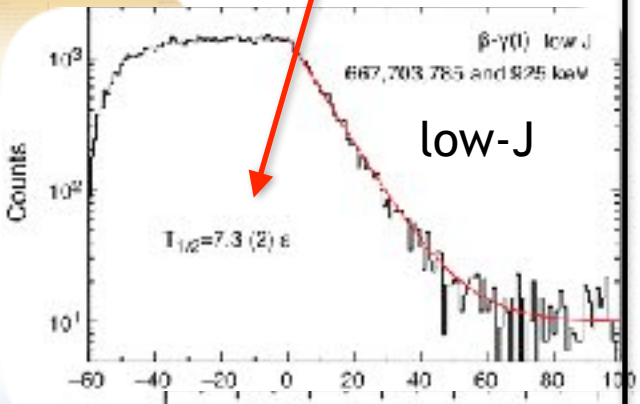
$(1^-,2^-)$ 0.0+X

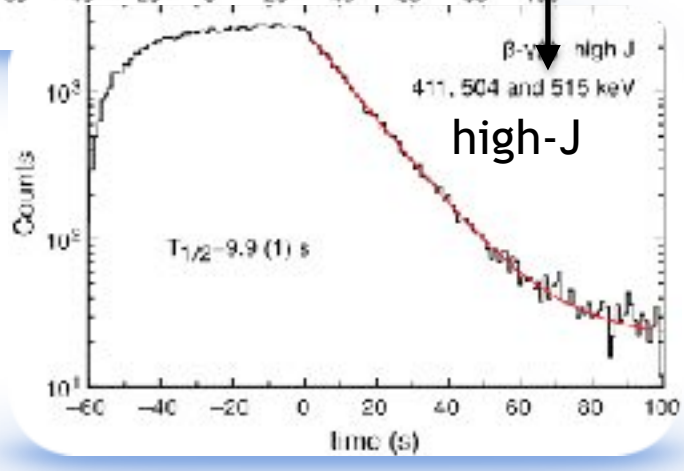
(5^-) 0.0

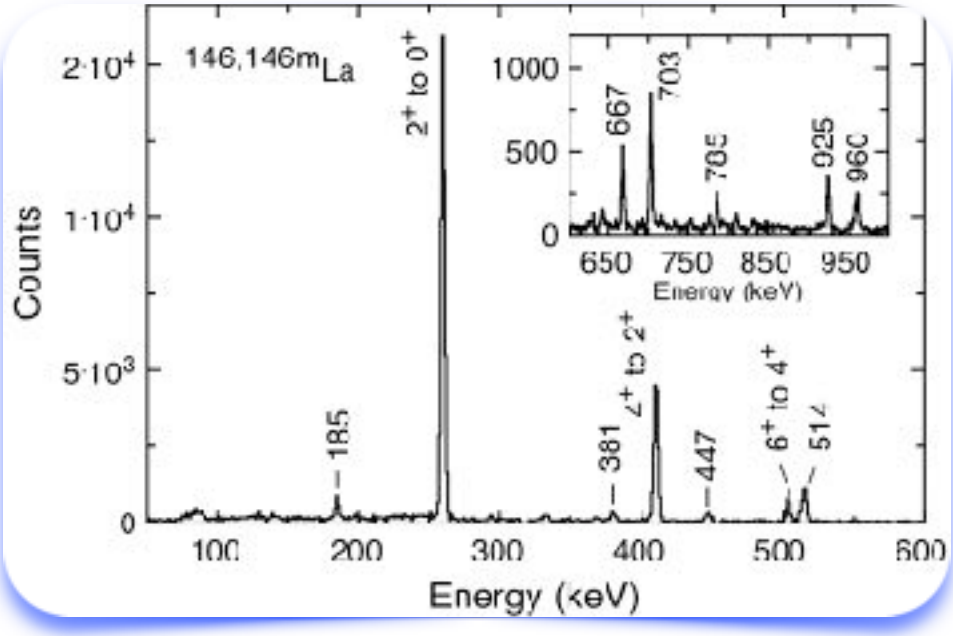
π5/2+[413] ν1/2[530]

π5/2+[413] ν5/2[523]

Nilsson assignment

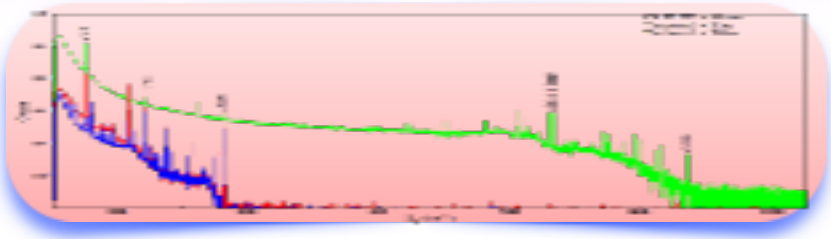


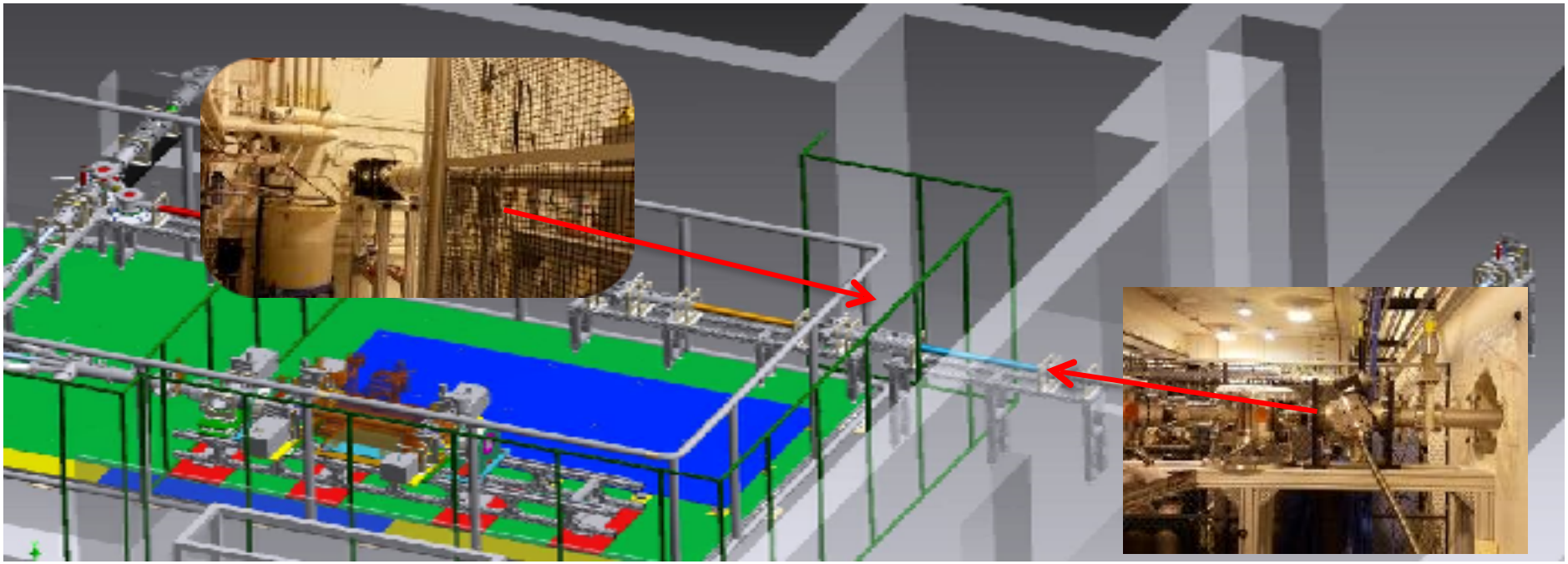




New LE CARIBU experimental area

- ANL tandem was removed in March 2019
- services in place and first beam line installed
- new experiments expected to start this summer





Outlook & Conclusions

- direct mass measurements in conjunction with detailed ß-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

- 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 workshop planed in ANL later in the fall