

Structure of Neutron-Rich Nuclei in the A~160 Region via Beta Decay & Mass Measurements

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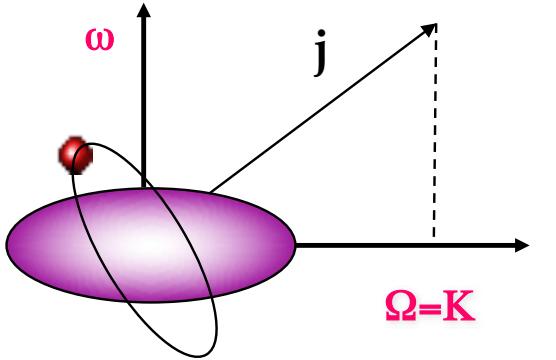
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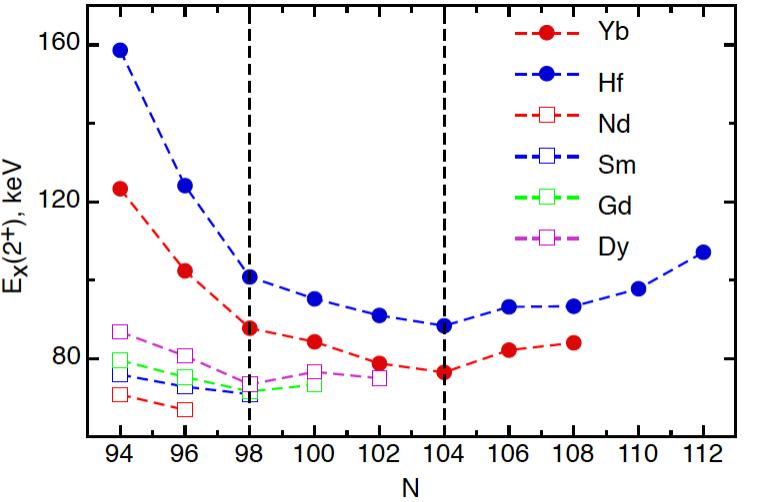
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Motivation



unusual structure behavior near N= 98

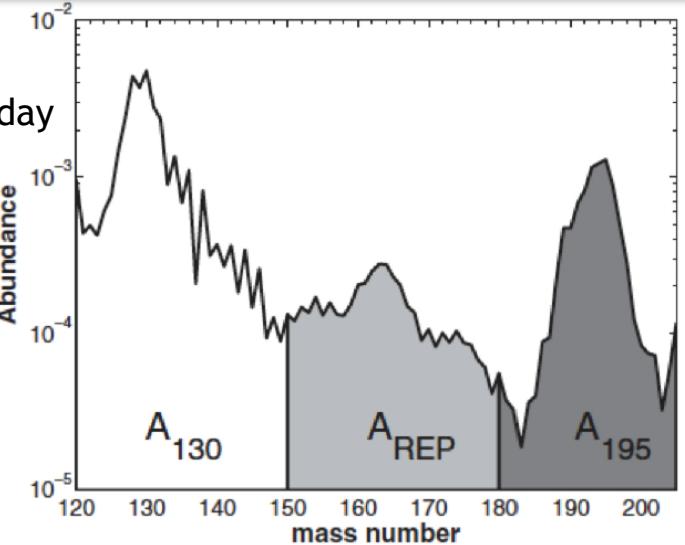


- single-particle structure; size of deformation; pairing and residual interactions

¹⁵⁸ Tb 93	¹⁵⁹ Tb 94	¹⁶⁰ Tb 95	¹⁶¹ Tb 96	¹⁶² Tb 97	¹⁶³ Tb 98	¹⁶⁴ Tb 99	¹⁶⁵ Tb 100	¹⁶⁶ Tb 101
16.9 ± 5.6 from 10.3 14.0 ± 1.1 from 10.1	18.7 ± 3.7 from 10.8 Δ=6948.1 (1.6) β=100%	72.3 ± 3.2+/- Δ=67855.5 (1.8) β=100%	6.89 ± 3.2+/- Δ=67466.6 (1.8) β=100%	7.68 ± 1.1 (-) Δ=65678 (40) β=100%	19.5 ± 3.2+/- Δ=64595 (4) β=100%	3.0 ± 1.5 (+) Δ=62698 (108) β=100%	2.11 ± 3.2+/- Δ=60578 (2008) β=100%	25.1 ± 2.2 (-) Δ=57888 (78) β=100%
¹⁵⁷ Gd 93	¹⁵⁸ Gd 94	¹⁵⁹ Gd 95	¹⁶⁰ Gd 96	¹⁶¹ Gd 97	¹⁶² Gd 98	¹⁶³ Gd 99	¹⁶⁴ Gd 100	¹⁶⁵ Gd 101
48.0 ± 10.5 from 10.1 Δ=5925.1 (1.6) β=100%	51.0 ± 8.0 from 10.0 Δ=78688.9 (1.6) β=100%	18.479 ± 3.2+/- Δ=65568.8 (1.6) β=100%	3.446 ± 5.2+/- Δ=55585.8 (2.6) β=100%	8.4 ± 8.4+/- Δ=64280 (4) β=100%	6.8 ± 7.2+/- Δ=63234 (81) β=100%	4.5 ± 8.4+/- Δ=59770 (2008) β=100%	18.3 ± 1.2+/- Δ=564598 (2008) β=100%	
¹⁵⁶ Eu 93	¹⁵⁷ Eu 94	¹⁵⁸ Eu 95	¹⁵⁹ Eu 96	¹⁶⁰ Eu 97	¹⁶¹ Eu 98	¹⁶² Eu 99	¹⁶³ Eu 100	¹⁶⁴ Eu 101
15.19 ± 8.0+/- Δ=76085 (6) β=100%	15.18 ± 5.2+/- Δ=66458 (4) β=100%	45.9 ± 1.1 (-) Δ=67255 (4) β=100%	18.1 ± 5.2+/- Δ=66843 (4) β=100%	38 ± (1.1-#) Δ=63486 (10) β=100%	26 ± 5.2+/- Δ=63792 (10) β=100%	18.6 ± 5.2+/- Δ=58860 (66) β=100%	7.7 ± 5.2+/- Δ=56640 (78) β=100%	4.2 ± 8.2+/- Δ=533308 (2108) β=100%
¹⁵⁵ Sm 93	¹⁵⁶ Sm 94	¹⁵⁷ Sm 95	¹⁵⁸ Sm 96	¹⁵⁹ Sm 97	¹⁶⁰ Sm 98	¹⁶¹ Sm 99	¹⁶² Sm 100	¹⁶³ Sm 101
7.8 ± 1.5 from 10.3 Δ=5615.5 (1.6) β=100%	22.1 ± 3.0+/- Δ=6036.2 (1.6) β=100%	16.5 ± 5.0+/- Δ=6039.5 (1.6) β=100%	3.1 ± 1.6+/- Δ=6033.1 (1.6) β=100%	13.9 ± (1.1-#) Δ=5620.1 (1.6) β=100%	11.07 ± 1.2+/- Δ=5620.5 (1.6) β=100%	4.8 ± 7.2+/- Δ=56372 (7) β=100%	2.4 ± 8.4+/- Δ=545380 (2008) β=100%	1.8 ± 1.2+/- Δ=587208 (3008) β=100%
¹⁵⁴ Pm 93	¹⁵⁵ Pm 94	¹⁵⁶ Pm 95	¹⁵⁷ Pm 96	¹⁵⁸ Pm 97	¹⁵⁹ Pm 98	¹⁶⁰ Pm 99	¹⁶¹ Pm 100	¹⁶² Pm 101
12.0 ± 1.6+/- from 10.1 Δ=6514.6 (1.6) β=100%	12.0 ± 1.2+/- Δ=64884 (40) β=100%	41.5 ± 5.2+/- Δ=66948 (5) β=100%	2.1 ± 1.0+/- Δ=66344 (4) β=100%	10.56 ± 5.2+/- Δ=62297 (7) β=100%	4.8 ± 8.4+/- Δ=59899 (13) β=100%	1.5 ± 5.2+/- Δ=56554 (10) β=100%	2.0 ± 8.4+/- Δ=53080 (3008) β=7 β=?	7.008 ms 5.2+/- Δ=502408 (3008) β=7 β=?
¹⁵³ Nd 93	¹⁵⁴ Nd 94	¹⁵⁵ Nd 95	¹⁵⁶ Nd 96	¹⁵⁷ Nd 97	¹⁵⁸ Nd 98	¹⁵⁹ Nd 99	¹⁶⁰ Nd 100	¹⁶¹ Nd 101
1.19 ± 0.2+/- from 10.1 Δ=4720.2 (1.7)	31.6 ± 1.2+/- from 10.1 Δ=4720.2 (1.7)	32.2 ± 1.4+/- from 10.1 Δ=45088 (10)	8.9 ± 3.2+/- Δ=42284 (9)	20.16 ± 1.4+/- Δ=40870 (10)	5.0 ± 4.0+/- Δ=56462 (25)	7.008 ms 7.2+/- Δ=549508 (4008) β=100%	3.008 ms 0+ Δ=471308 (4008) β=100%	2.008 ms 1.2+/- Δ=425908 (5008)

understanding the pygmy rare-earth peak depends on nuclear structure input

R. Surman (ND)
plenary talk yesterday



M.R. Mumpower, G.C. McLaughlin, R. Surman, PRC **86**, 035803 (2012)

- basic nuclear data: masses, $T_{1/2}$, Pn
- role of deformation on stellar rates

CARIBU & ANL

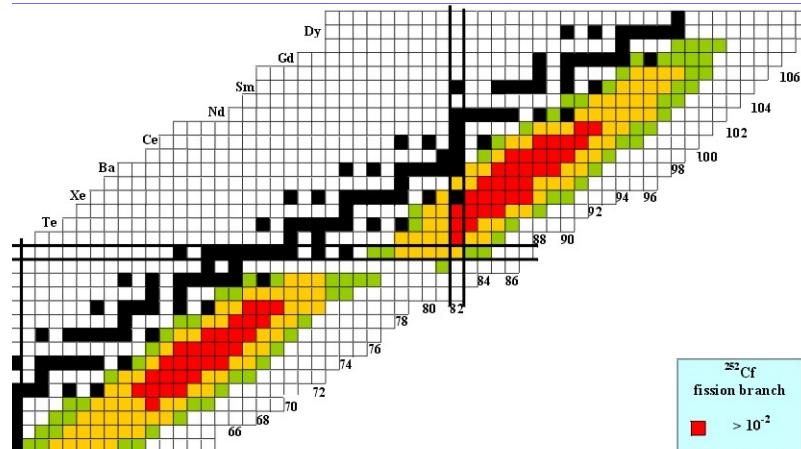
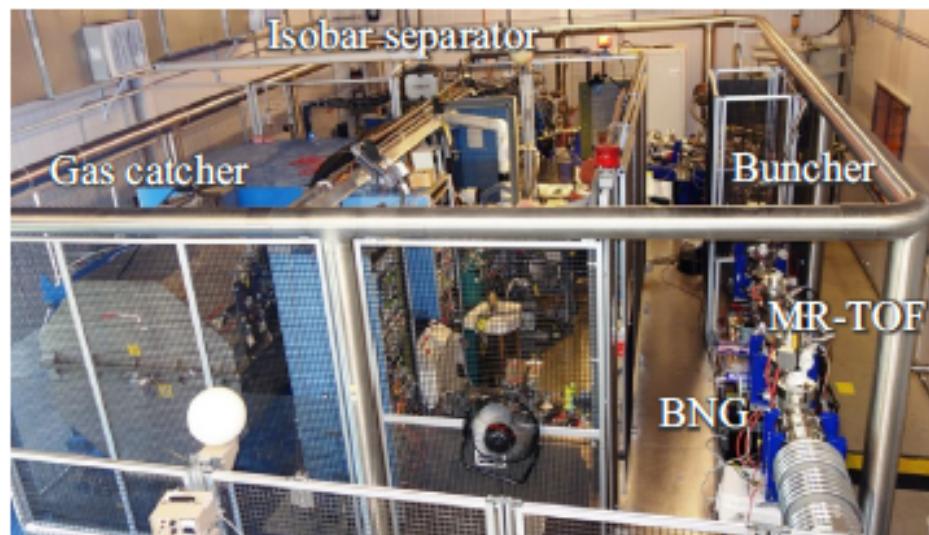
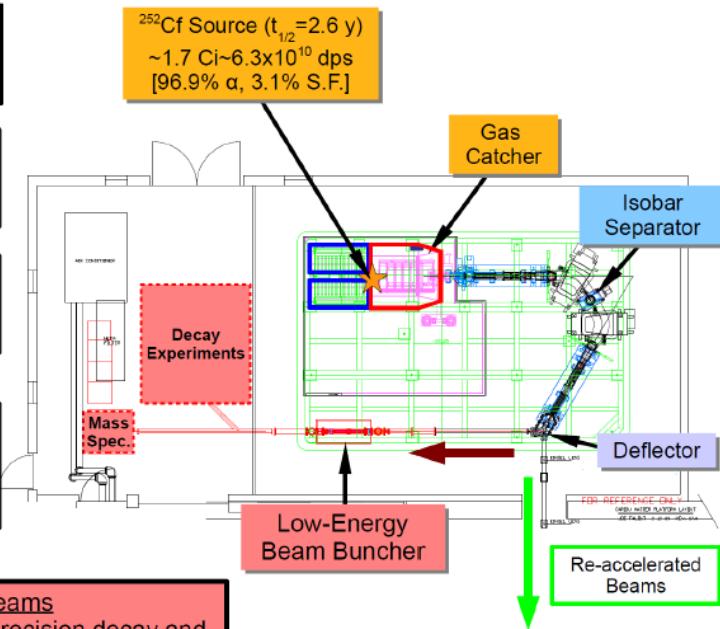
^{252}Cf fission fragments are slowed and focused in a helium-gas catcher

Beams of a desired mass are selected by a 120° magnetic isobar separator

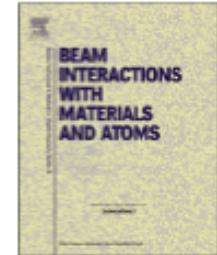
The neutron-rich beams can be deflected to low-energy or re-accelerated beam lines

Re-accelerated beams
Charge bred and injected into ATLAS resulting in energies up to ~ 15 MeV/A

Low Energy Beams
Beams bunched for use in precision decay and mass spectrometry experiments



mass resolving power $R \sim 10000$



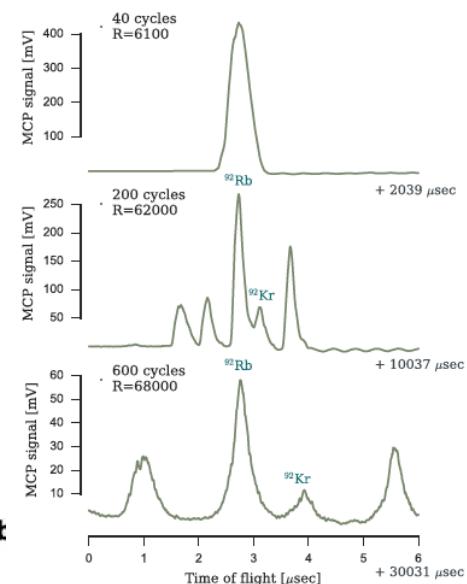
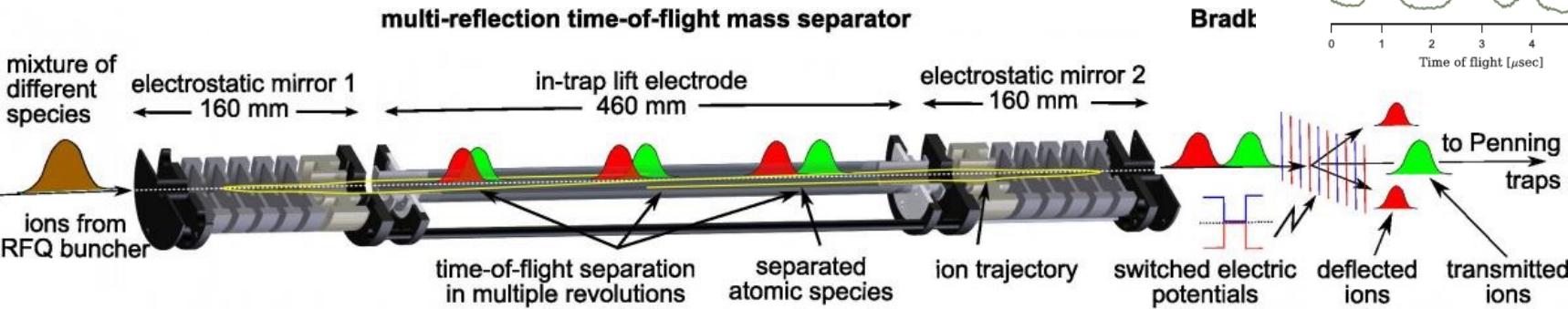
First operation and mass separation with the CARIBU MR-TOF



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

'Fast' isobar separator:

- based on ISOLTRAP/ISOLDE design
- ~ 1.3 m long MR-TOF
- currently mass resolving power, R~50,000 with ~50% transmission in ~15 ms



CARIBU low-energy experimental area

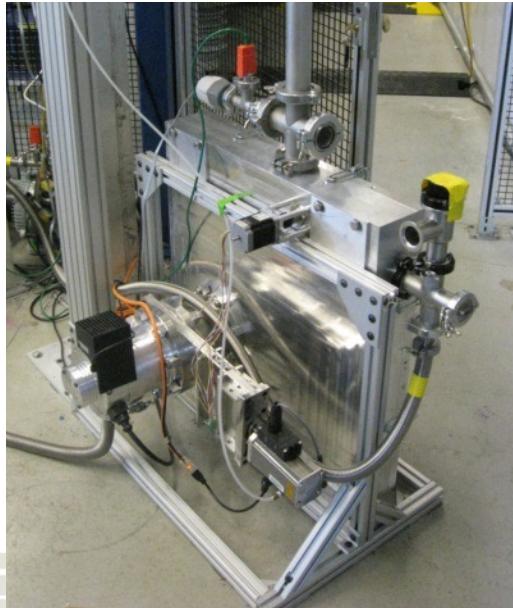
- Delivers 1.5 kV to 10 kV beam to experimental stations
- Pulsed beams with rates from ~ 50 ms to seconds
- Low emittance



CPT



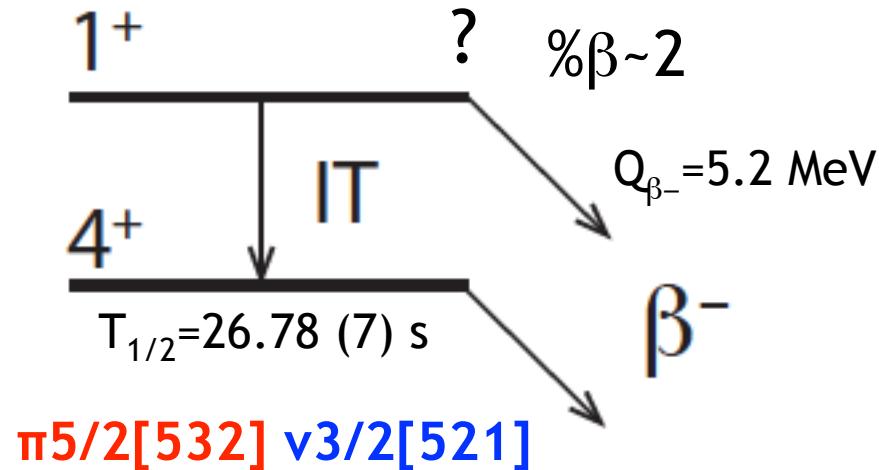
TAPE STATION



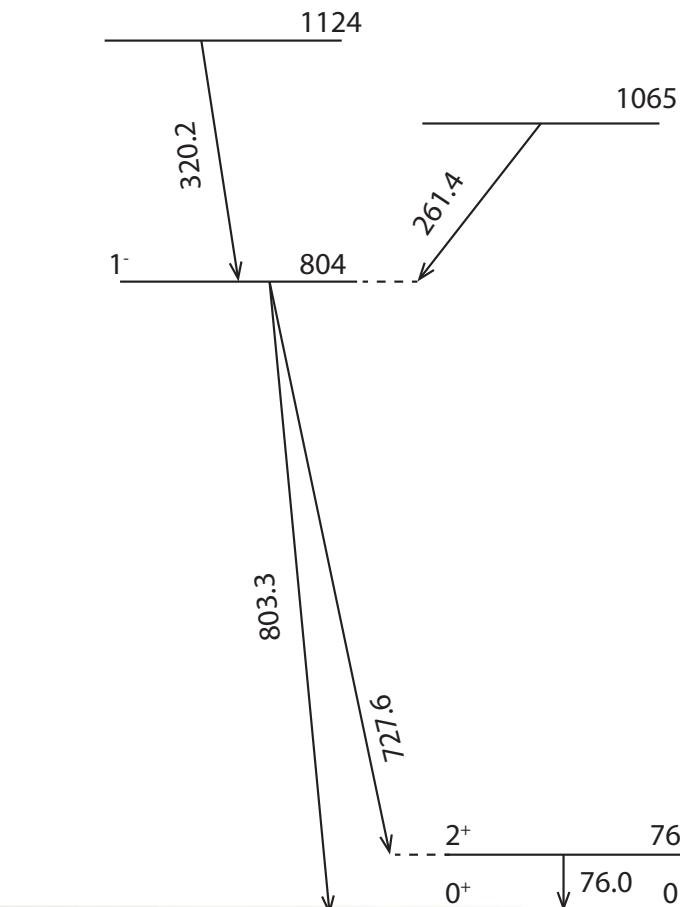
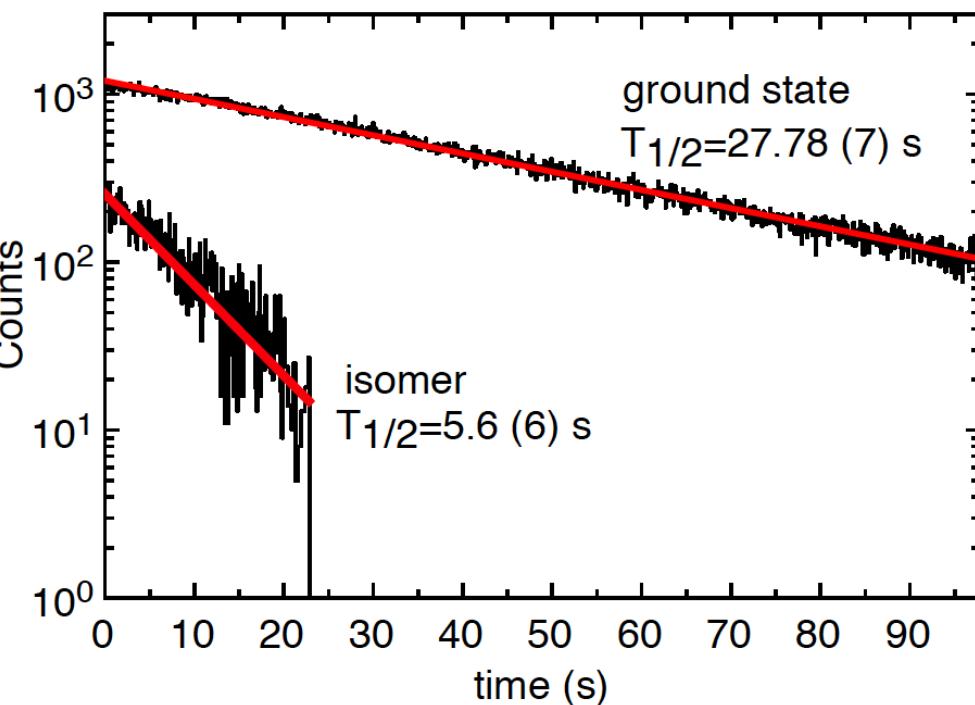
X-ARRAY



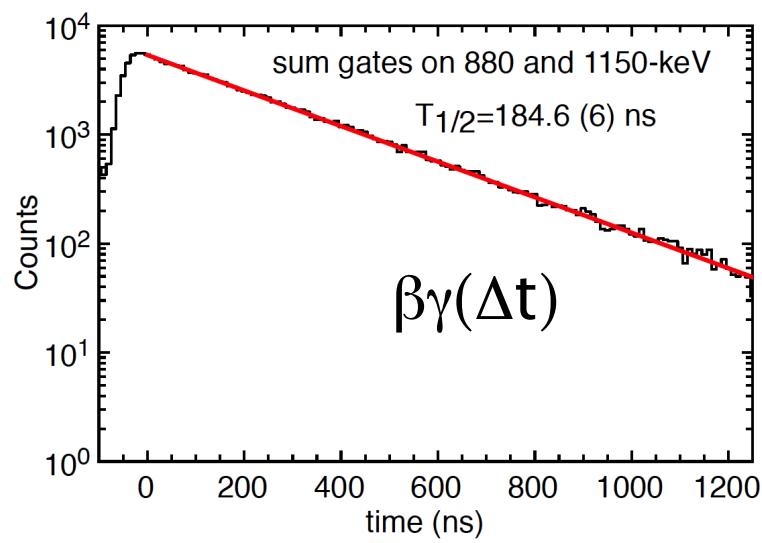
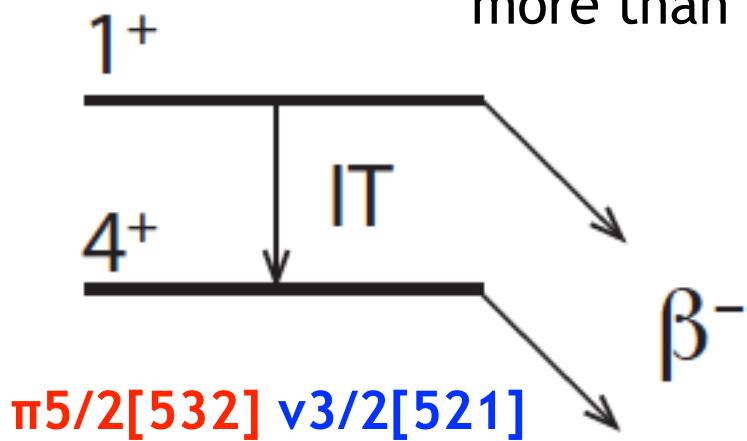
Studies of ^{156}Pm ($N=95$): low-spin isomer



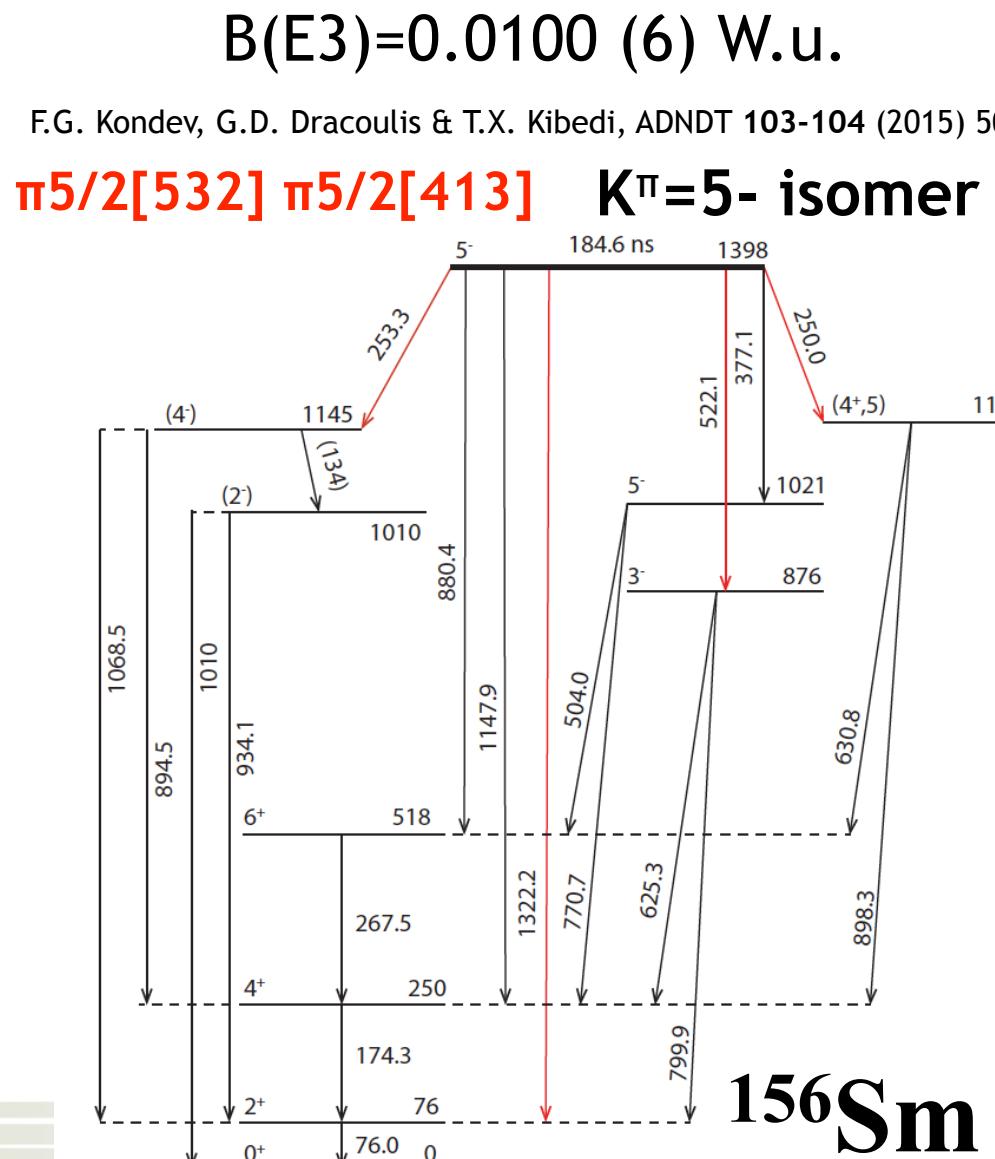
- speculations about the $J\pi$ and the structure of the g.s. and isomer
- unknown $T_{1/2}$ for the isomer



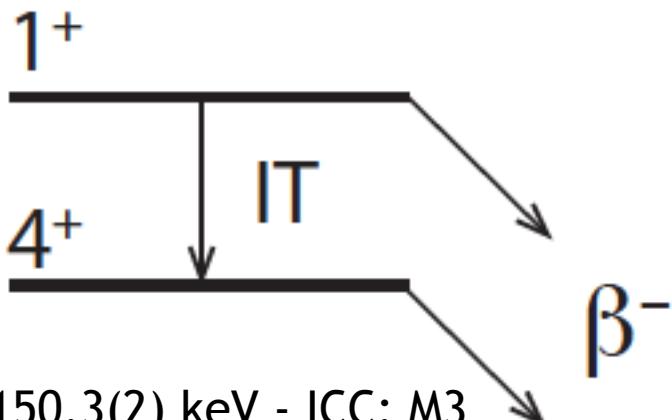
Studies of $^{156}\text{Pm}(\text{N}=95)$: high-K states



... significant differences with the TAGS data of Greenwood ...

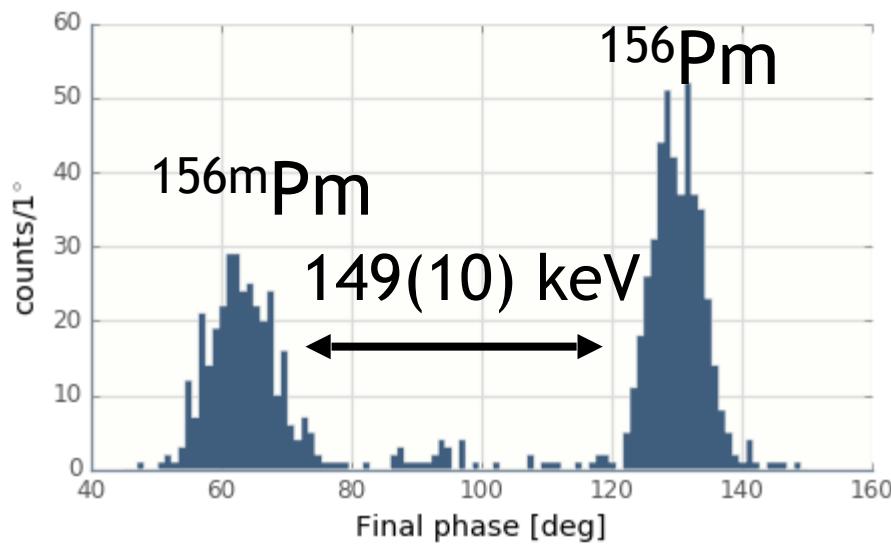


Studies of ^{156}Pm : isomer excitation energy



$\Delta E = 150.3(2)$ keV - ICC: M3

M. Shibata et al., EPJ A31, 171 (2007)

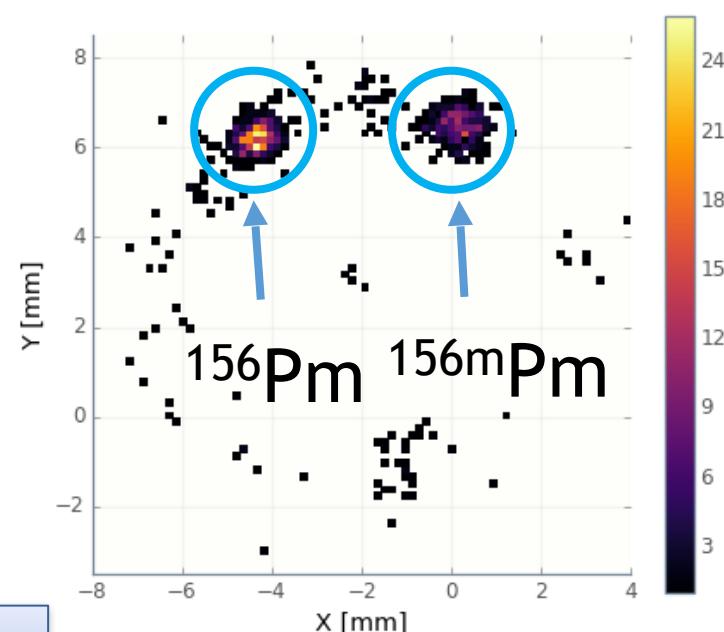


$\pi 5/2[532] \nu 3/2[521]$

$\Delta E_x =$

- 50 keV - δ force
- 118 keV - central force + spin polarization
- 140 keV - + tensor and long-range force

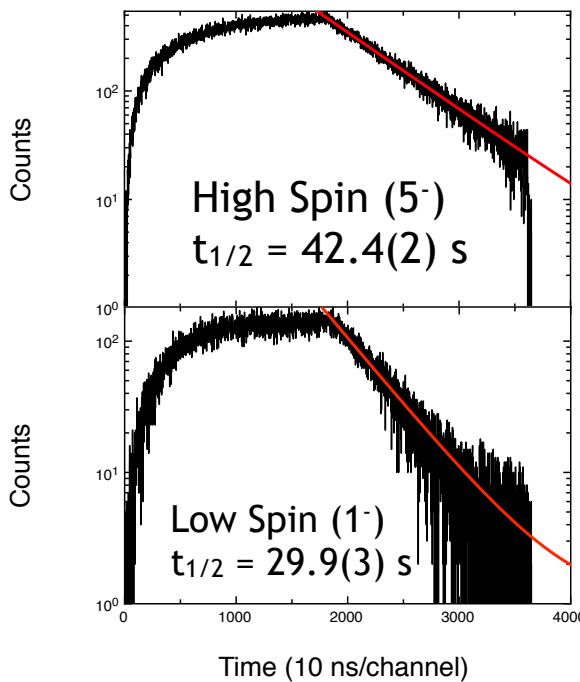
J.P. Boisson et al., Phys. Rep. 26, 99 (1976)



phase-imaging ion-cyclotron-resonance technique

S. Eliseev et al., Phys. Rev. Lett. 110, 082501 (2013)

Studies of ^{160}Eu ($N=97$)

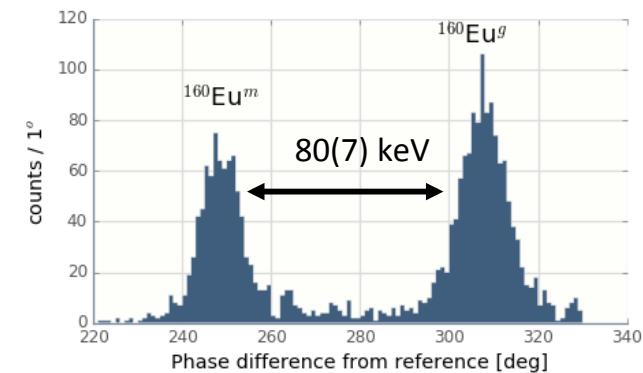
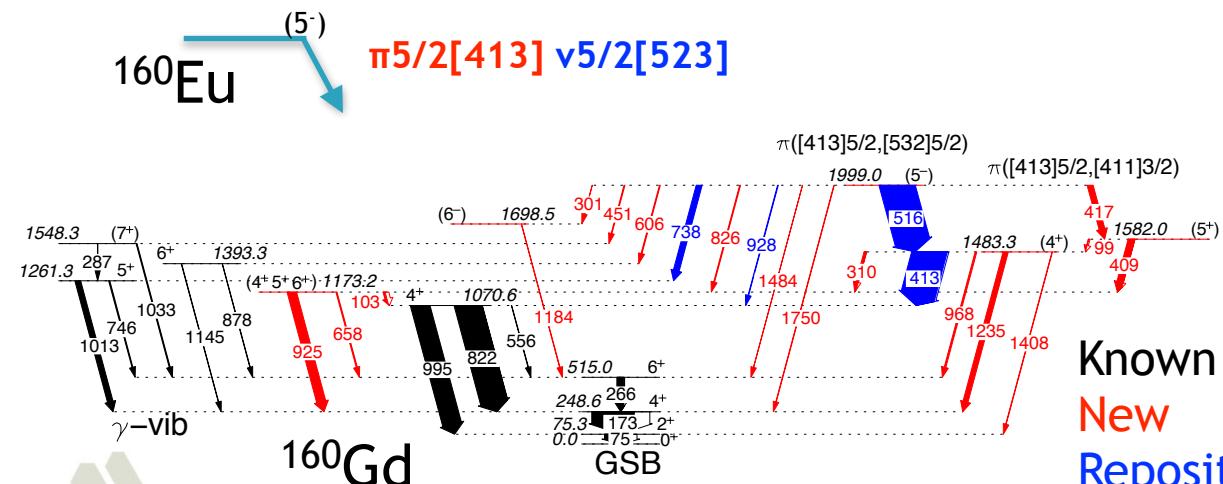


Previous $t_{1/2}$: 31(4) s, 41(4) s, 50(10)s, 53(10)s, assuming a single (low-spin) β -decaying state
Present: lifetimes of γ 's fell into 2 values (2 isomers)

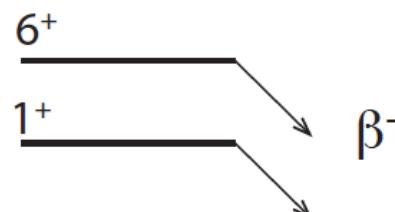
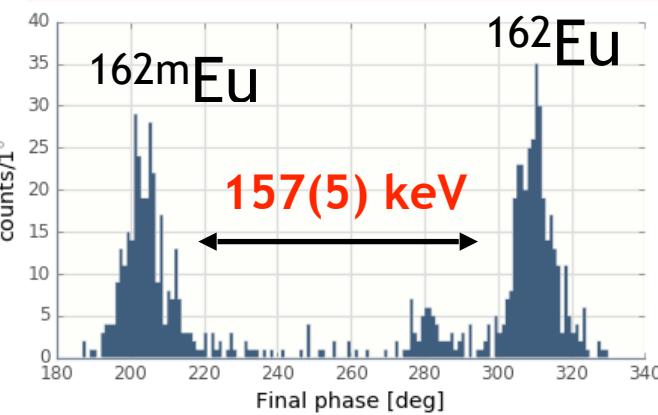
$\pi 5/2[413] \nu 5/2[523] \rightarrow K^\pi = 5^- \& 0^-$

Two different decay schemes proposed for ^{160}Gd , ours differs from both!

1999-keV state most strongly fed by $K^\pi = 5^-$, $t_{1/2}=42$ s isomer; $\log ft \approx 5.0$ -> related configurations



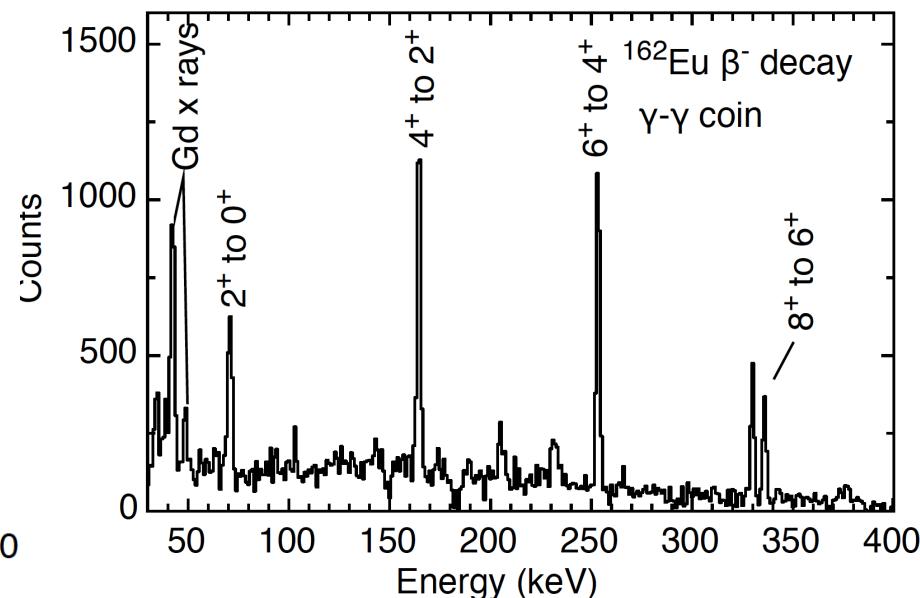
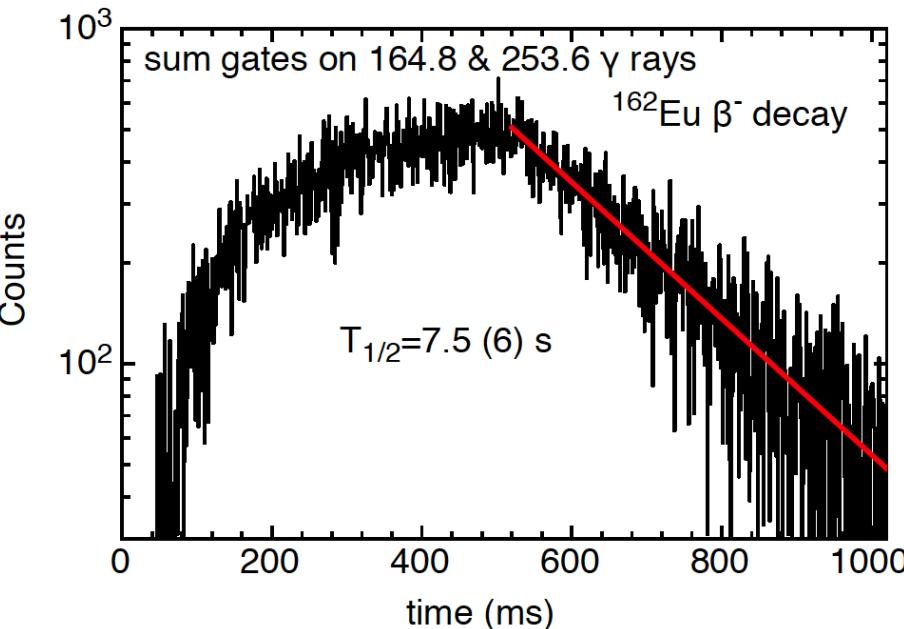
Studies of ^{162}Eu ($N=99$)



$\pi 5/2[413] \nu 7/2[633]$

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

deviations from WS predictions (ordering of the $1/2[521]$ and $7/2[633]$ neutron orbitals):
 $\nu p_{3/2}$ higher compared to $\nu i_{13/2}$



Outlook & Conclusions

- direct mass measurements in conjunction with detailed β -decay studies are powerful tool to elucidate properties of neutron-rich nuclei
- CARIBU produces high-quality LE beams with sufficient yield for detailed spectroscopy - examples on ^{156}Pm , $^{160,162}\text{Eu}$ - decay properties, isomers, excitation energies ...
- limitations - the high background in the LE area - a new beam line has been built and will be operational early next year
- future DIC & MNT using Gammasphere (^{160}Gd beam on ^{154}Sm and ^{164}Dy targets) to look for in-beam structures

Ning Wang and Lu Guo, Phys. Lett. **B 760**, 236 (2016)