High-Resolution Study of Low-Spin States in ^{240}Pu

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**Supported by the Bonn-Cologne Graduate School of Physics and Astronomy*

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Bonn-Cologne Graduate School of Physics and Astronomy

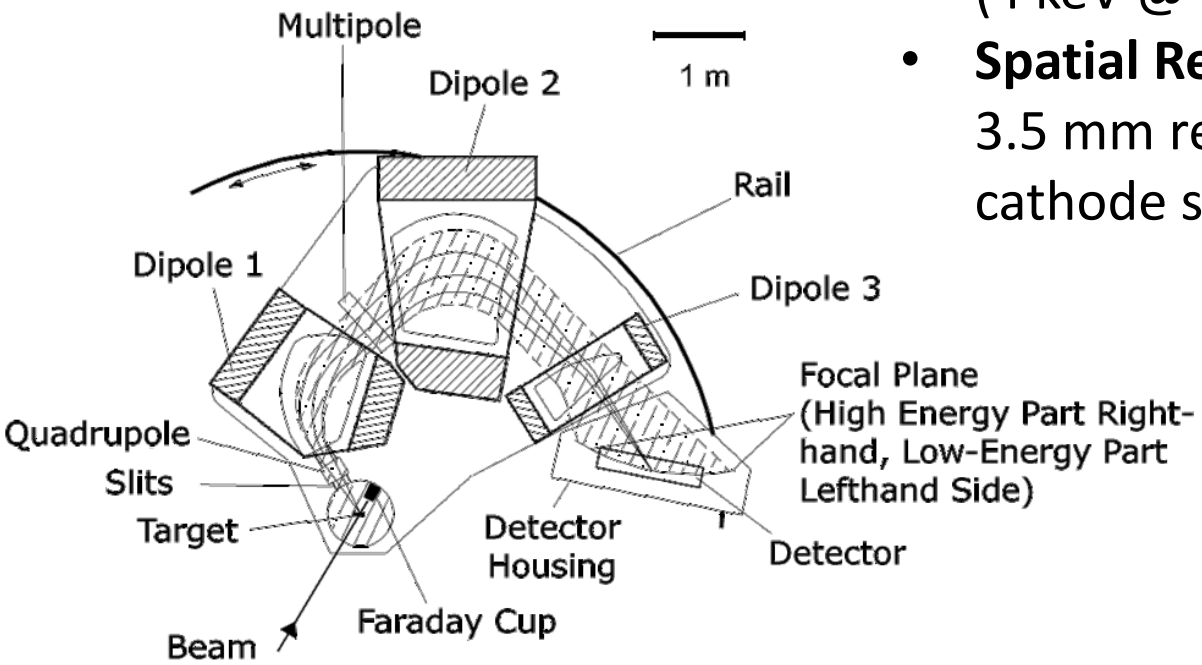
Outline

- **Experimental Setup:** ^{242}Pu(p,t)^{240}Pu @ Q3D, MLL Munich
- **Motivation**
  - (p,t) reactions: selective study of low-spin states
  - The nature of the first excited 0^+ states in the actinides
- **The special case of ^{240}Pu?**
- **Summary and Outlook**

Experimental Setup

Experiment: two-neutron transfer reaction (p,t) to populate low-spin states in ^{240}Pu (E_p= 24 MeV)

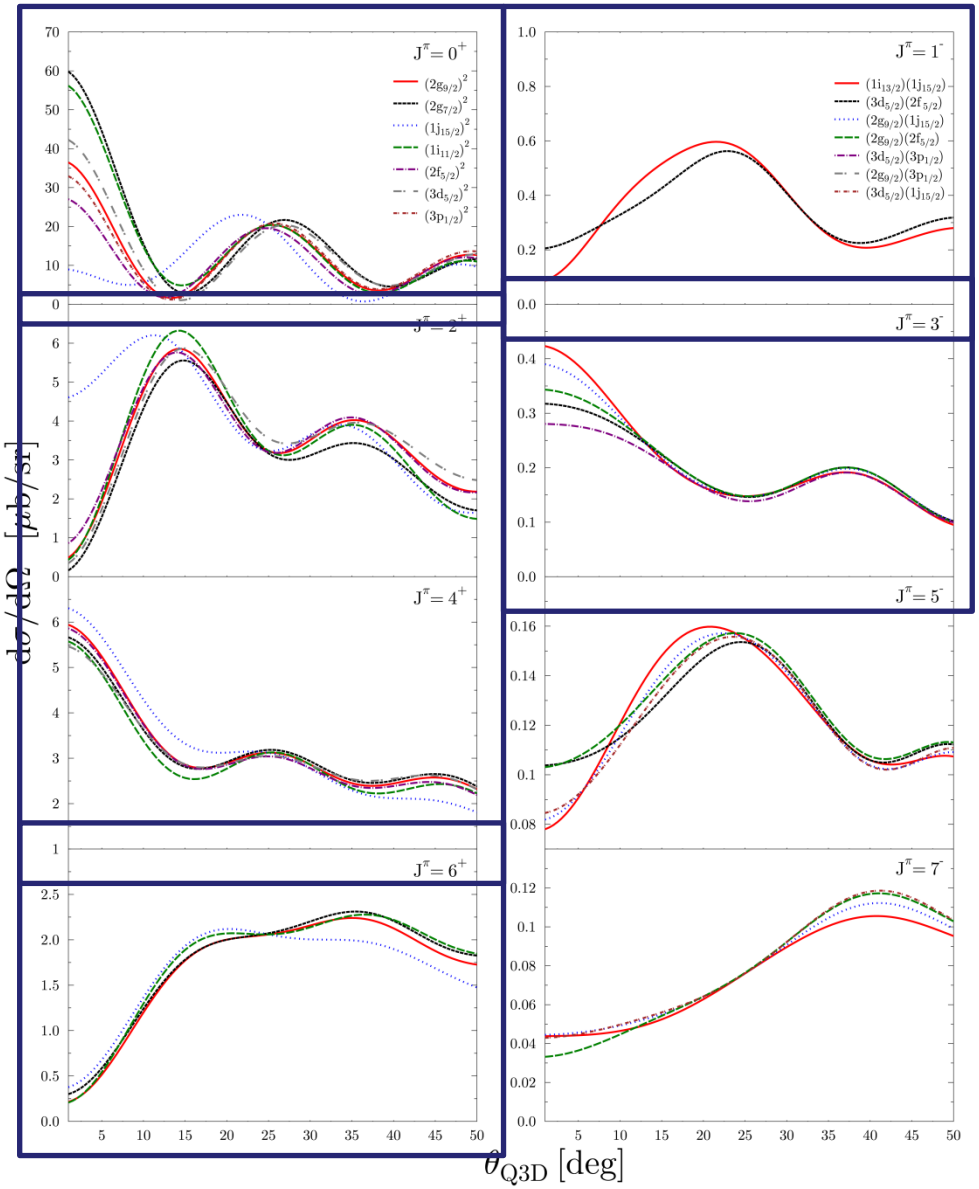
Q3D @ MLL, Munich



- **Energy Resolution:**
  $\Delta E/E = 2 \times 10^{-4}$
  (4 keV @ E_t= 20 MeV)
- **Spatial Resolution:**
  3.5 mm repetition length, 255 cathode strips (length: 1 m)

Target:
120 μg/cm^2 ^{242}Pu(99.93%, $T_{1/2}$= 3.75 x 10^5 a) on a 25 μg/cm^2 carbon backing (provided by Oak Ridge National Laboratory)

Motivation



- **High-resolution (p,t) studies @ Q3D, Munich**

→ Sensitive reaction to study L=0 transfers (i.e. 0^+ states in even-even nuclei) and very selective at forward angles

D.A. Meyer *et al.*, PRC **74** (2006) 044309;
H.-F. Wirth *et al.*, PRC **69** (2004) 044310

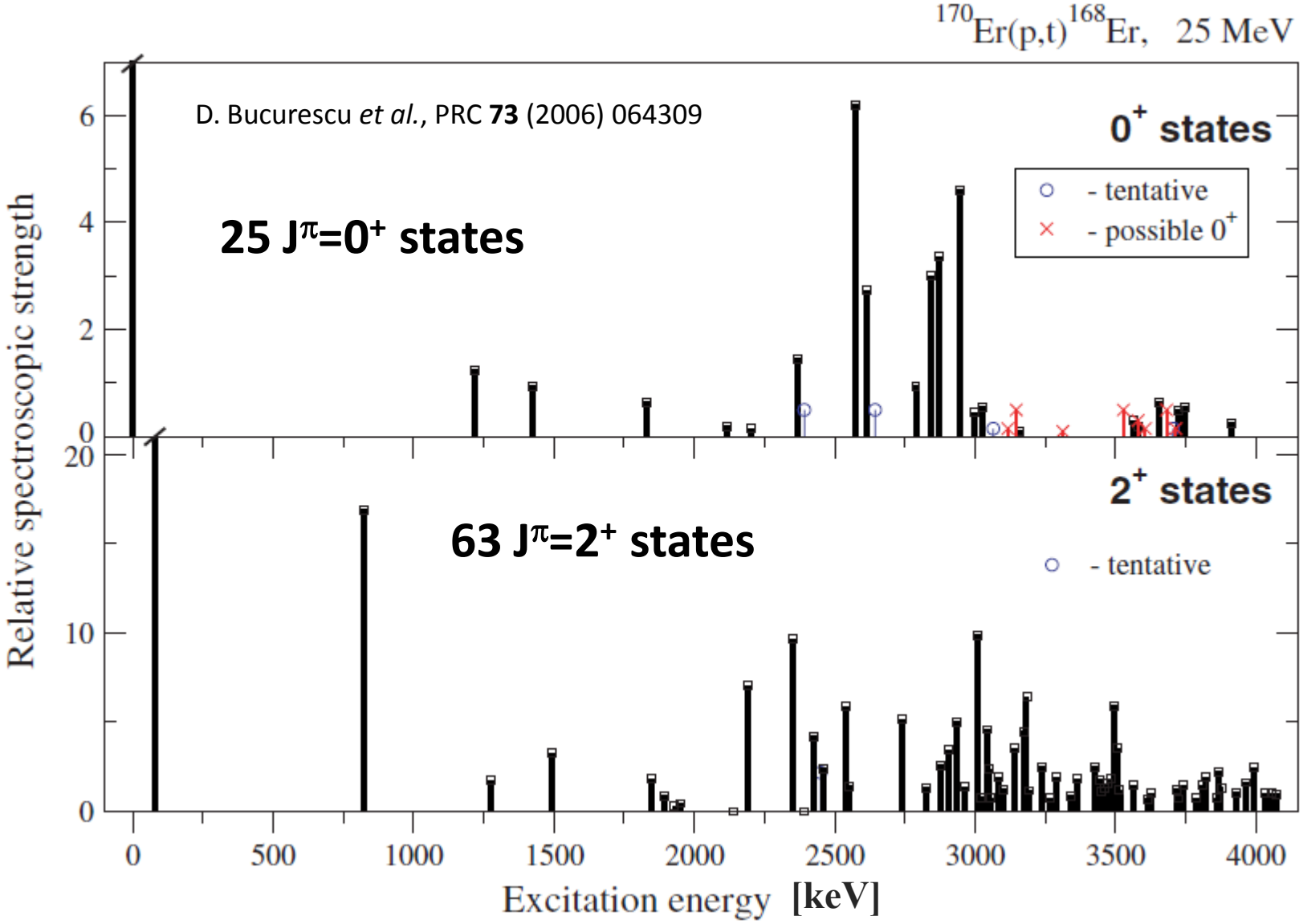
→ Strong L=2,3,4 transfers

D. Bucurescu *et al.*, PRC **73** (2006) 064309;
A.I. Levon *et al.*, PRC **79** (2009) 014318

→ Unambiguous triton selection via *dE/E* and nearly background-free spectra allow for identification of less probable L-transfers (e.g. L=1,6 transfers) and weakly excited states

A.I. Levon *et al.*, PRC **79** (2009) 014318

Motivation


^{170}Er(p,t)^{168}Er, 25 MeV
D. Bucurescu *et al.*, PRC **73** (2006) 064309
0$^+$ states
- tentative
- possible 0$^+$
25 J$^\pi$=0$^+$ states
2$^+$ states
63 J$^\pi$=2$^+$ states
- tentative
Relative spectroscopic strength
Excitation energy [keV]

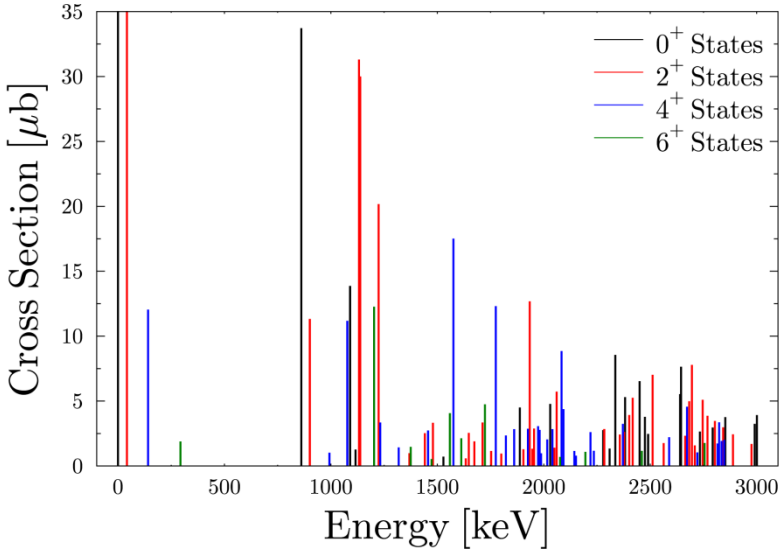
Motivation

High-resolution (p,t) experiments

Stringent tests of nuclear structure, nuclear reaction, and statistical models with a single reaction

^{242}Pu(p,t)^{240}Pu @ E_p= 24 MeV

Population of 209 states up to 3.1 MeV



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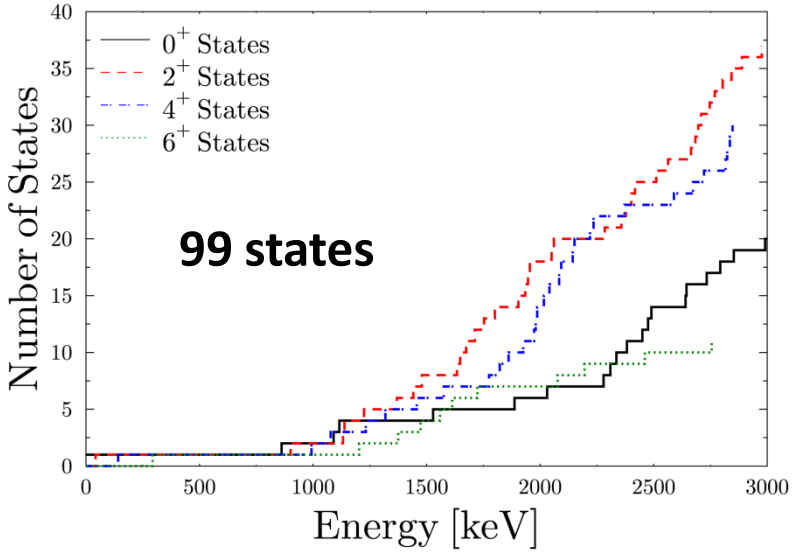
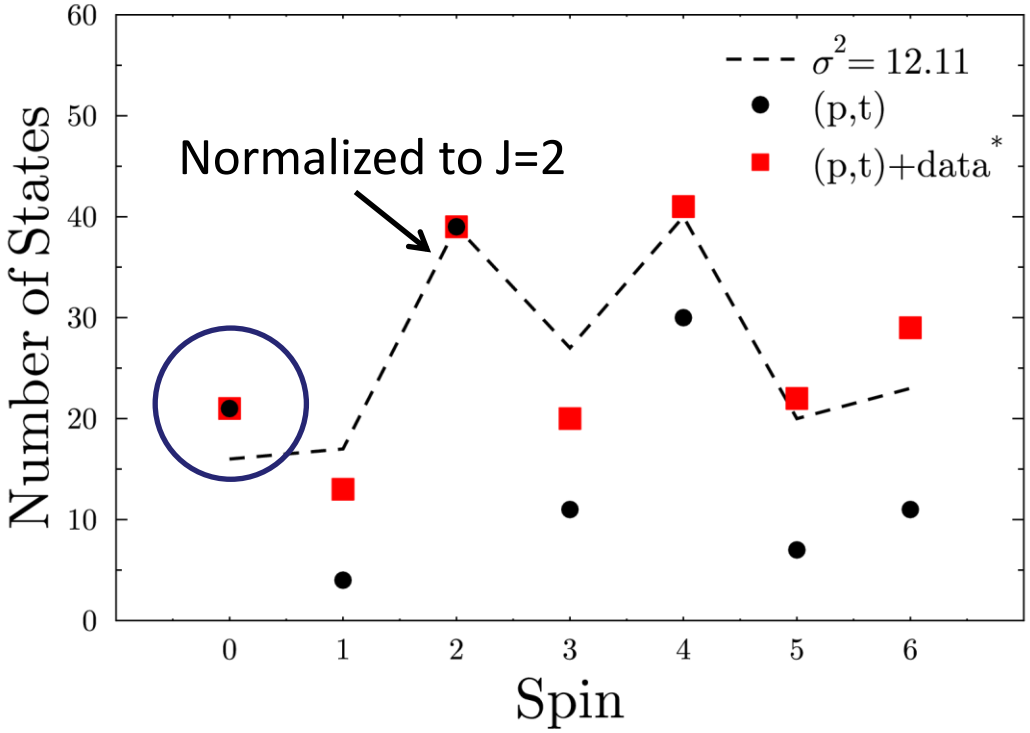


Number of States $f(J,\sigma)$

Spin Distribution up to 3 MeV in ^{240}Pu:

$$f(J,\sigma) = e^{-J^2/2\sigma^2} - e^{-(J+1)^2/2\sigma^2} \approx \frac{2J+1}{2\sigma^2} e^{-J(J+1)/2\sigma^2}$$

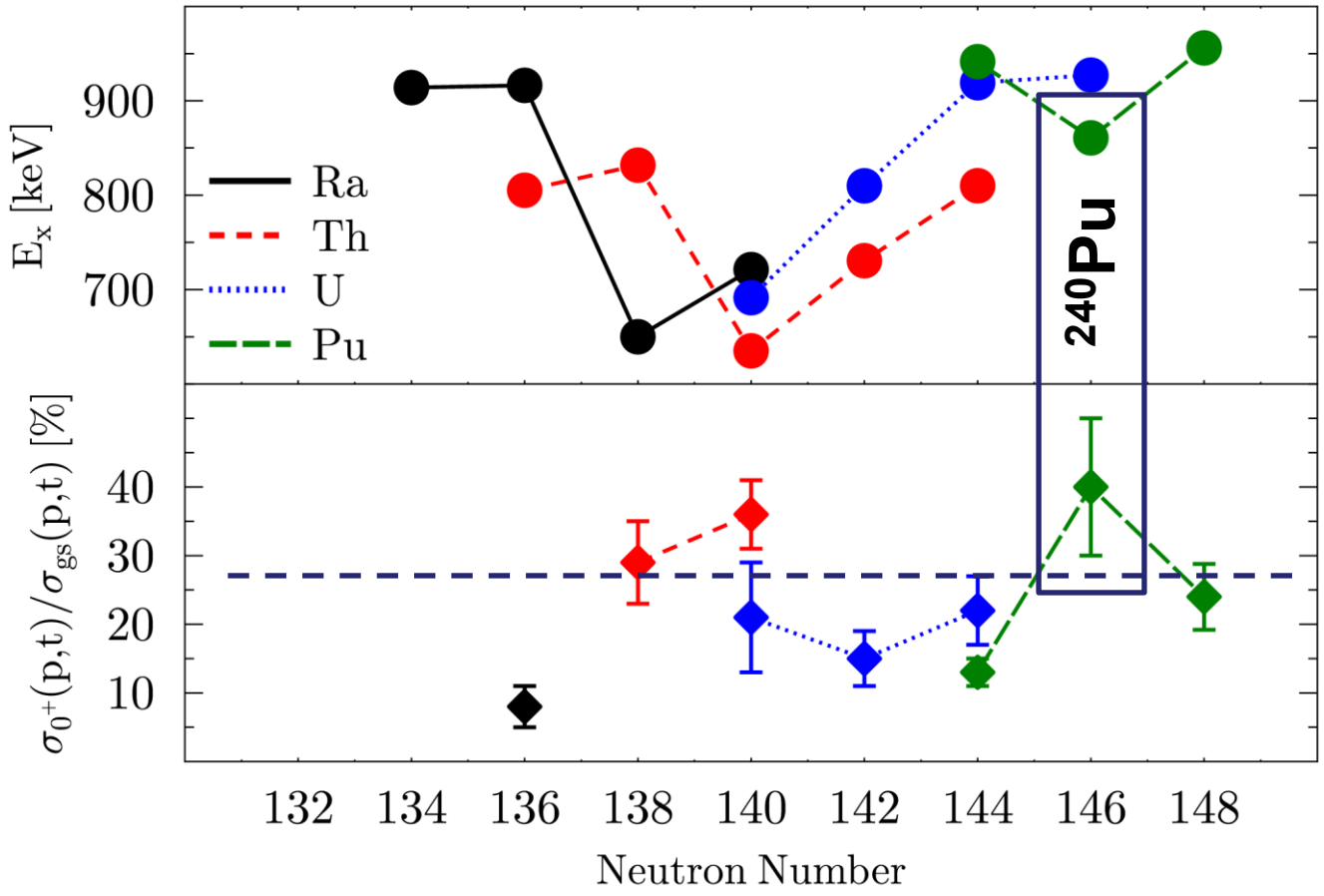


$$f_{ee}(J,\sigma) = f(J,\sigma)(1+x)$$

$$x = \begin{cases} +0.227(14), & \text{for even spin values,} \\ -0.227(14), & \text{for odd spin values,} \\ +1.02(9), & \text{for zero spin levels.} \end{cases}$$

T. von Egidy and D. Bucurescu, PRC **78** (2008) 051301(R)
* B.J. Quiter *et al.*, PRC **86** (2012) 034307

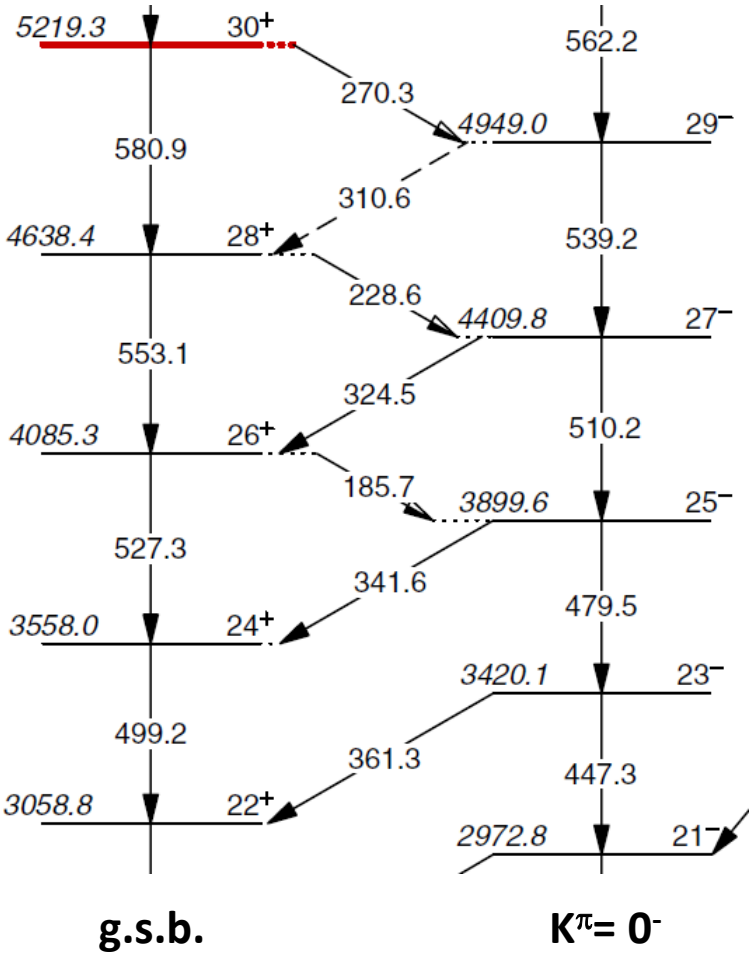
First Excited 0^+ States in the Actinides



J.V. Maher *et al.*, PRL **25** (1970), 302;
J.V. Maher *et al.*, PRC **5** (1972), 1380;
A.M. Friedman *et al.*, PRC **9** (1974) 760

Octupole Correlations in ^{240}Pu

^{240}Pu @ Gammasphere, Argonne National Laboratory

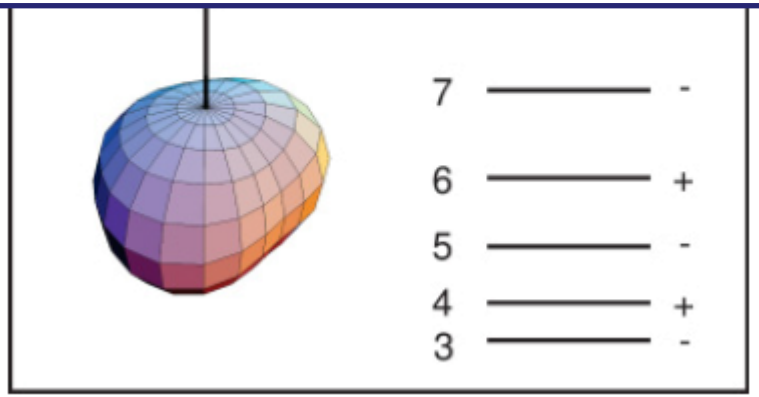


X. Wang *et al.*, PRL **102** (2009) 122501

Experiment:

- Build-up of an alternating-parity band at $J \geq 20$
- Induced intrinsic dipole moment $D_0 = 0.2$ e fm (e.g. light Th-Isotopes 0.2 – 0.3 e fm)

Octupole deformation might set in at high spin



S. Frauendorf, PRC **77** (2008) 021304(R)

Octupole Correlations in ^{240}Pu

ARTICLE

doi:10.1038/nature12073

Studies of pear-shaped nuclei using accelerated radioactive beams

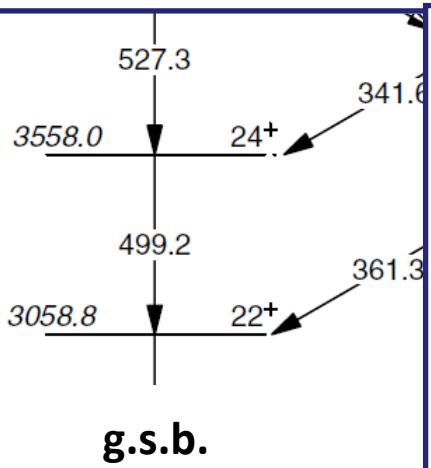
L. P. Gaffney[1], P. A. Butler[1], M. Scheck[1,2], A. B. Hayes[3], F. Wenander[4], M. Albers[5], B. Bastin[6], C. Bauer[2], A. Blazhev[5], S. Bönig[2], N. Bree[7], J. Cederkäll[8], T. Chupp[9], D. Cline[3], T. E. Cocolios[4], T. Davinson[10], H. De Witte[7], J. Diriken[7,11], T. Grahn[12], A. Herzan[12], M. Huyse[7], D. G. Jenkins[13], D. T. Joss[1], N. Kesteloot[7,11], J. Konki[12], M. Kowalczyk[14], Th. Kröll[2], E. Kwan[15], R. Lutter[16], K. Moschner[5], P. Napiorkowski[14], J. Pakarinen[4,12], M. Pfeiffer[5], D. Radeck[5], P. Reiter[5], K. Reynders[7], S. V. Rigby[1], L. M. Robledo[17], M. Rudigier[5], S. Sambi[7], M. Seidlitz[5], B. Siebeck[5], T. Stora[4], P. Thoele[5], P. Van Duppen[7], M. J. Vermeulen[13], M. von Schmid[2], D. Voulot[4], N. Warr[5], K. Wimmer[18], K. Wrzosek-Lipska[7,14], C. Y. Wu[15] & M. Zielinska[14,19]

...rnating-parity

...lipole moment

...light Th-

...e fm)



X. Wang *et al.*, PRL **102** (2

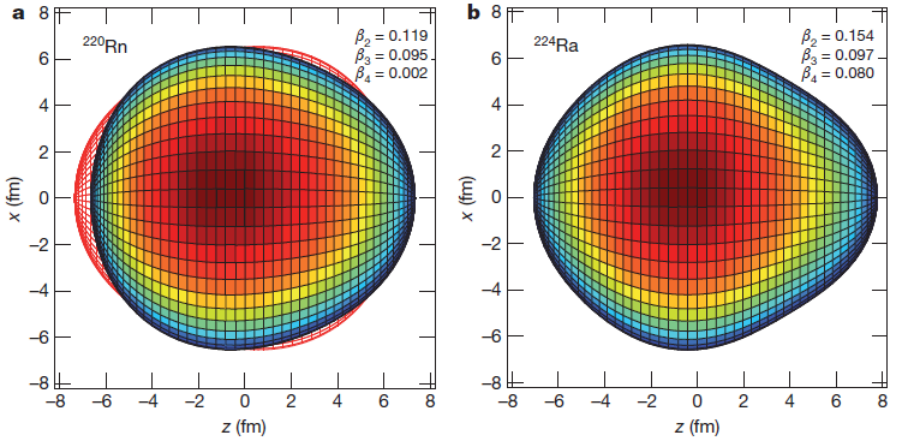
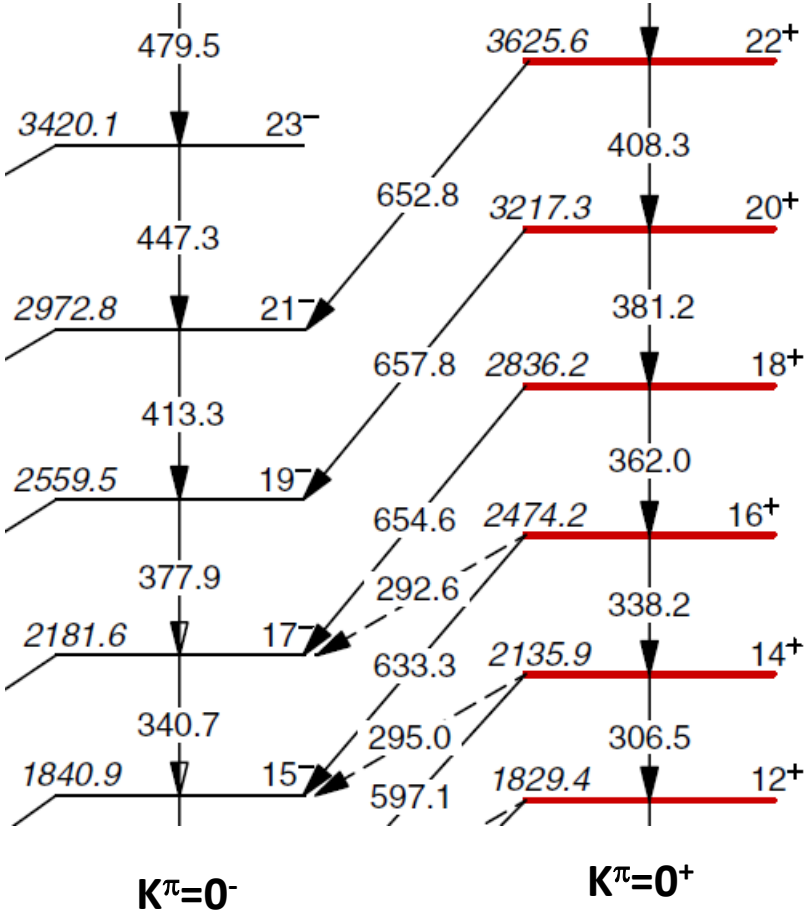


Figure 4 | Graphical representation of the shapes of ^{220}Rn and ^{224}Ra. a, ^{220}Rn; b, ^{224}Ra. Panel a depicts vibrational motion about symmetry between the surface shown and the red outline, whereas b depicts static deformation in the intrinsic frame. Theoretical values of β_4 are taken from ref. 10. The colour scale, blue to red, represents the y-values of the surface. The nuclear shape does not change under rotation about the z axis.

Octupole Correlations in ^{240}Pu

^{240}Pu @ Gammasphere, Argonne National Laboratory



X. Wang *et al.*, PRL **102** (2009) 122501

Experiment:

- Observation of an additional $K^\pi = 0^+$ rotational band up to highest spins
  - → Exclusive decay to $K^\pi = 0^-$ one-octupole phonon band
  - → Enhanced *E1* transitions of ~ 2 mW.u.

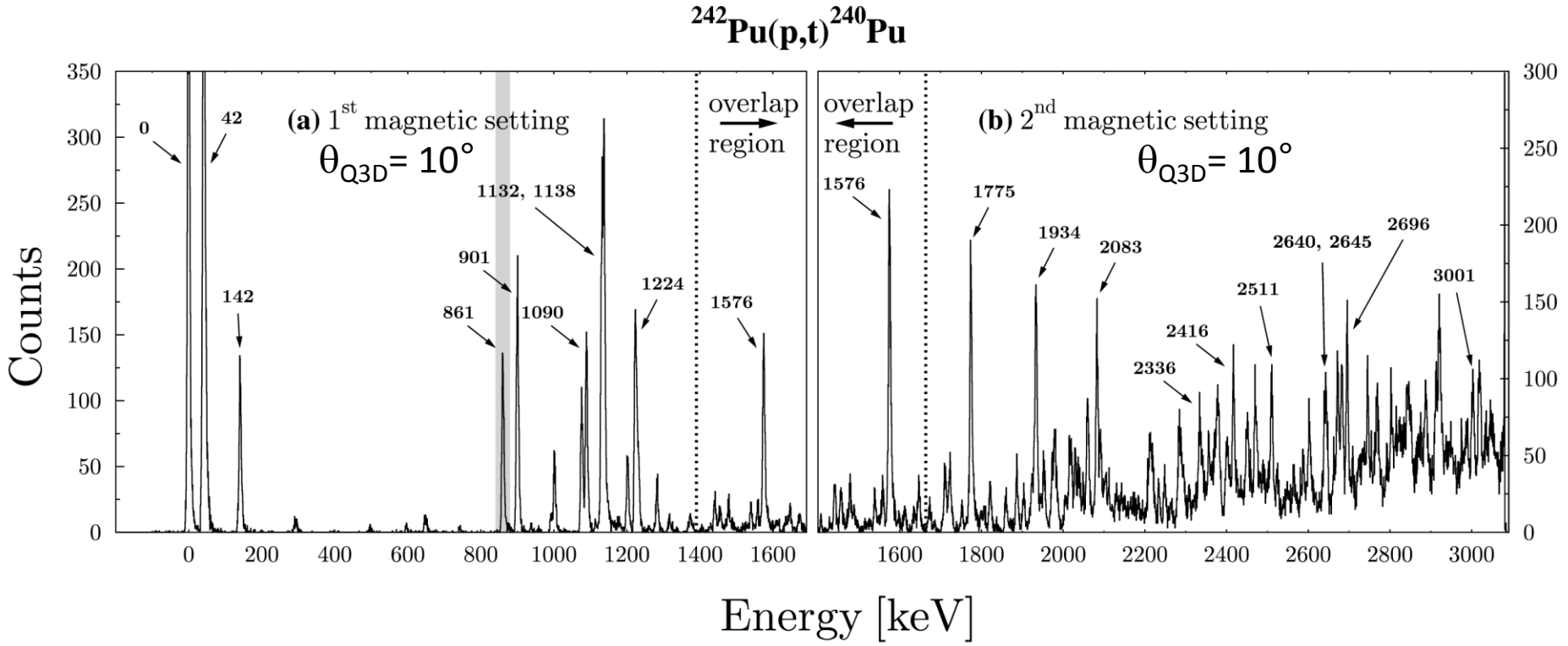
- **Theory:** $K^\pi = 0_2^+$ is double-octupole phonon band

$$\left(3^- \otimes 3^-\right)_{0^+}$$

Excited States in ^{242}Pu(p,t)^{240}Pu

2 magnetic settings of Q3D to cover the focal plane of 1.8 m

→ Excitation energies up to 3 MeV could be measured

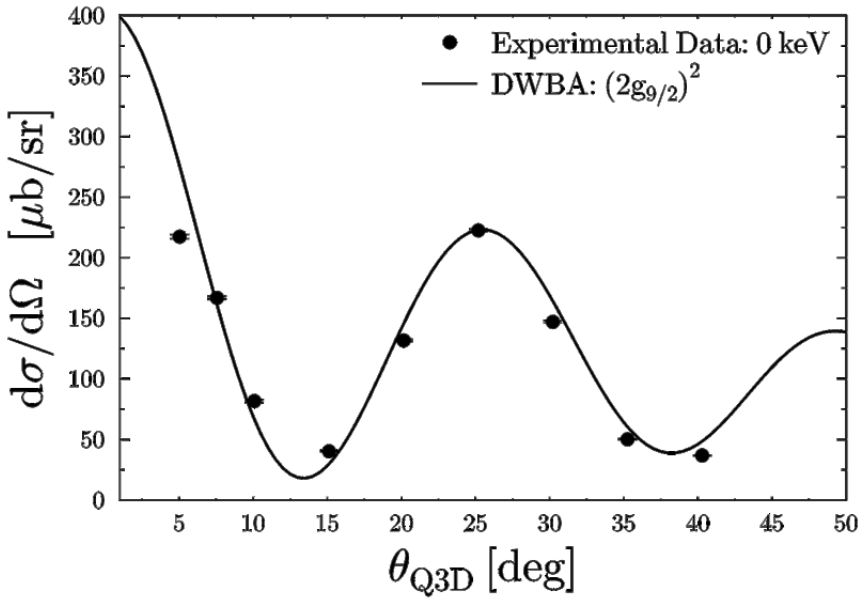


Angular Distribution of 0^+ States

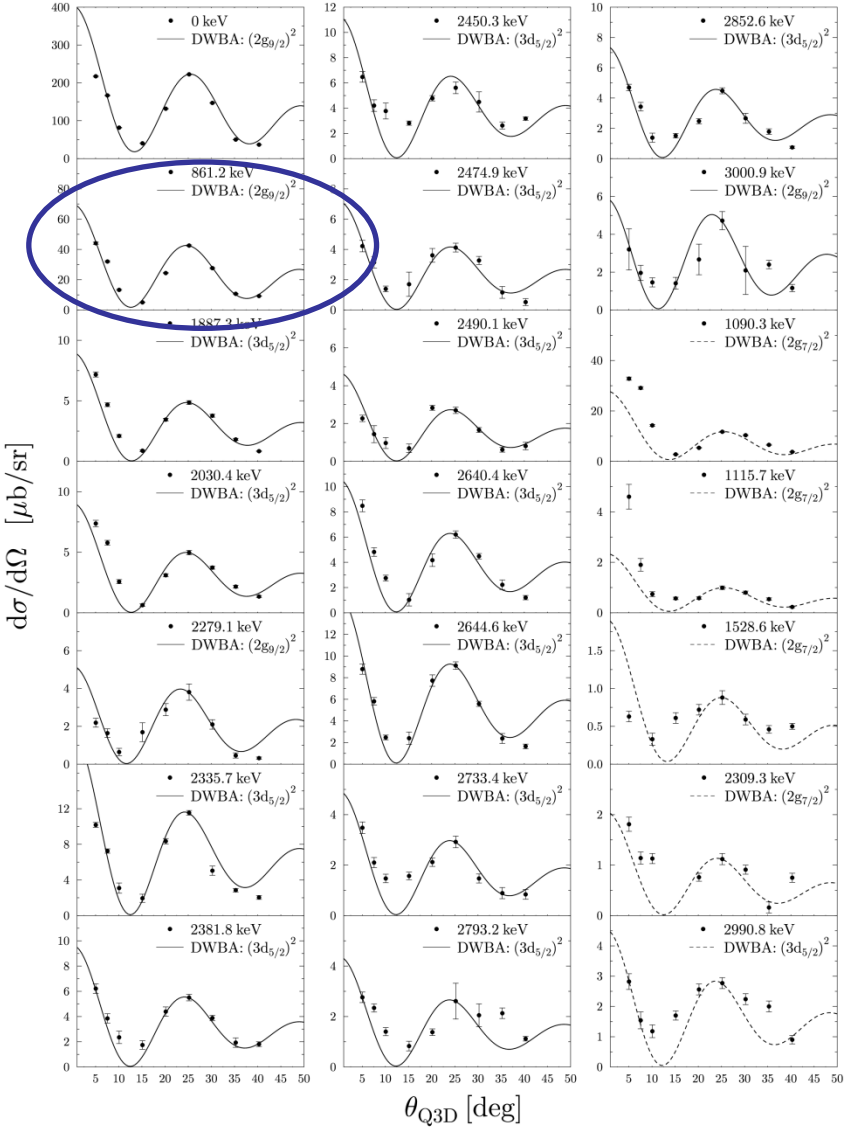
Angular Distribution of the $K^\pi = 0^+$ ground state of ^{240}Pu

Experiment: Q3D angles (θ_{Q3D}): 5° - 40°

Theory: Distorted Wave Born Approximation (DWBA) fit to data



Angular Distribution of 0^+ States

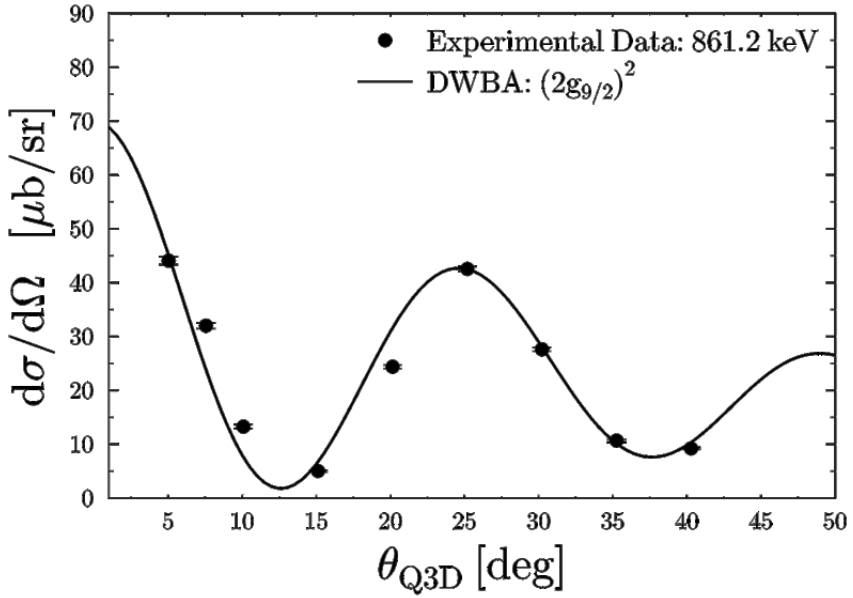


- **21 $J^\pi=0^+$ states observed**
  - 16 firmly assigned (solid lines)
  - 5 tentatively assigned (dashed lines)

$\rightarrow$ 17 newly assigned 0^+ states up to 3 MeV

(p,t) observables of the proposed double-octupole state @ 861.2 keV?

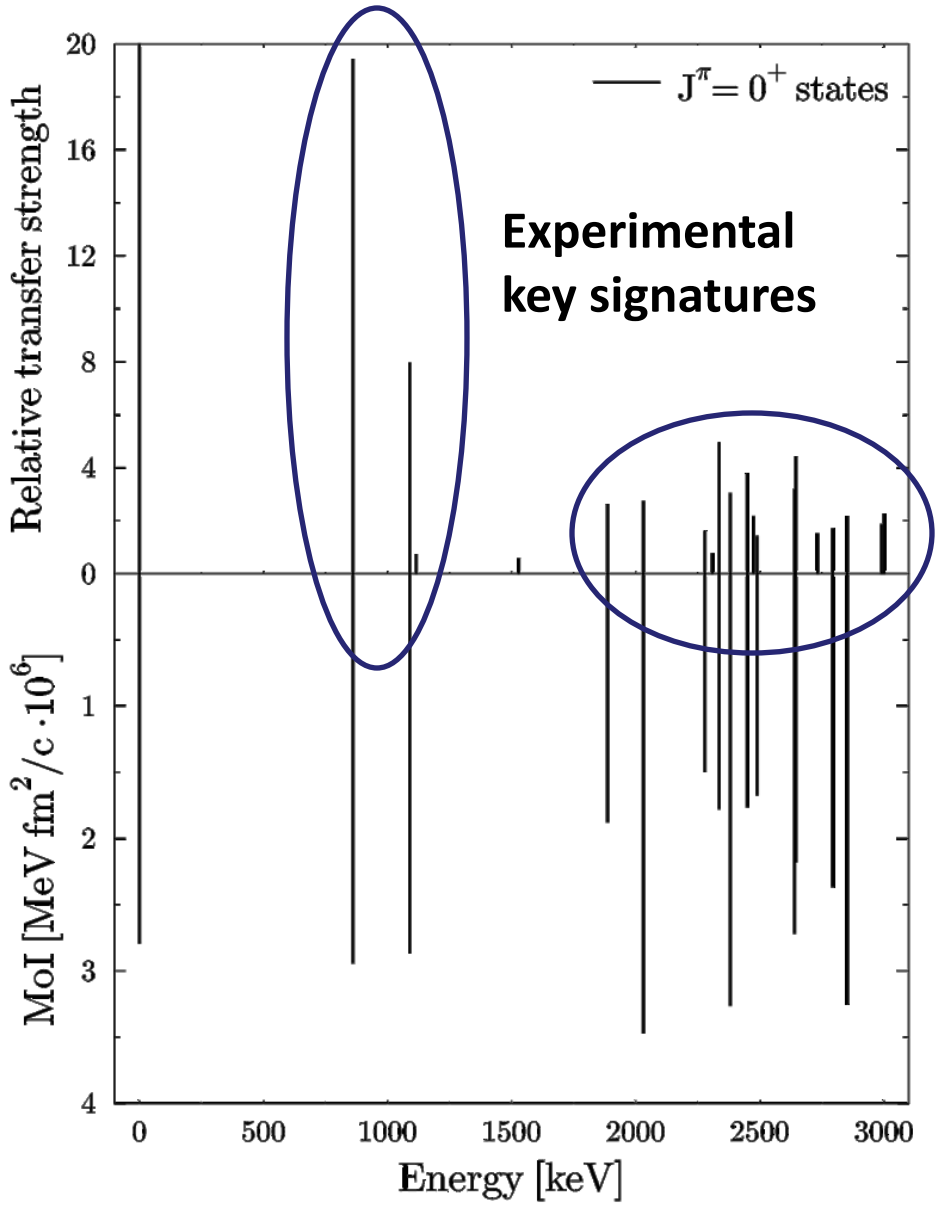
$K^{\pi} = 0^{+}$ @ 861.2 keV



$K^{\pi} = 0^{+}$ @ 861.2 keV

- Shape reflects positive-parity L=0 transfer

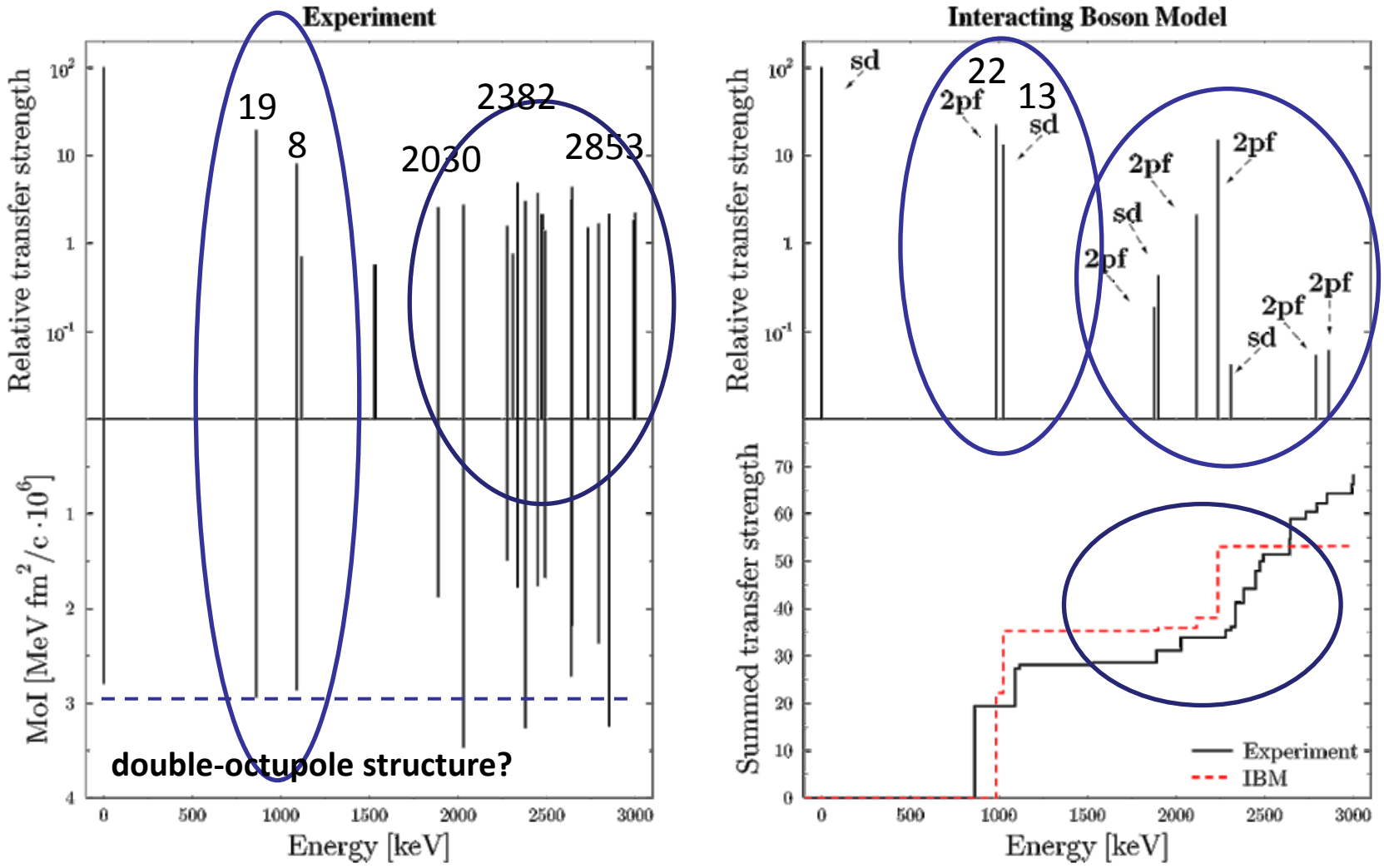
$K^{\pi}= 0^{+}$ @ 861.2 keV



$K^{\pi}= 0^{+}$ @ 861.2 keV

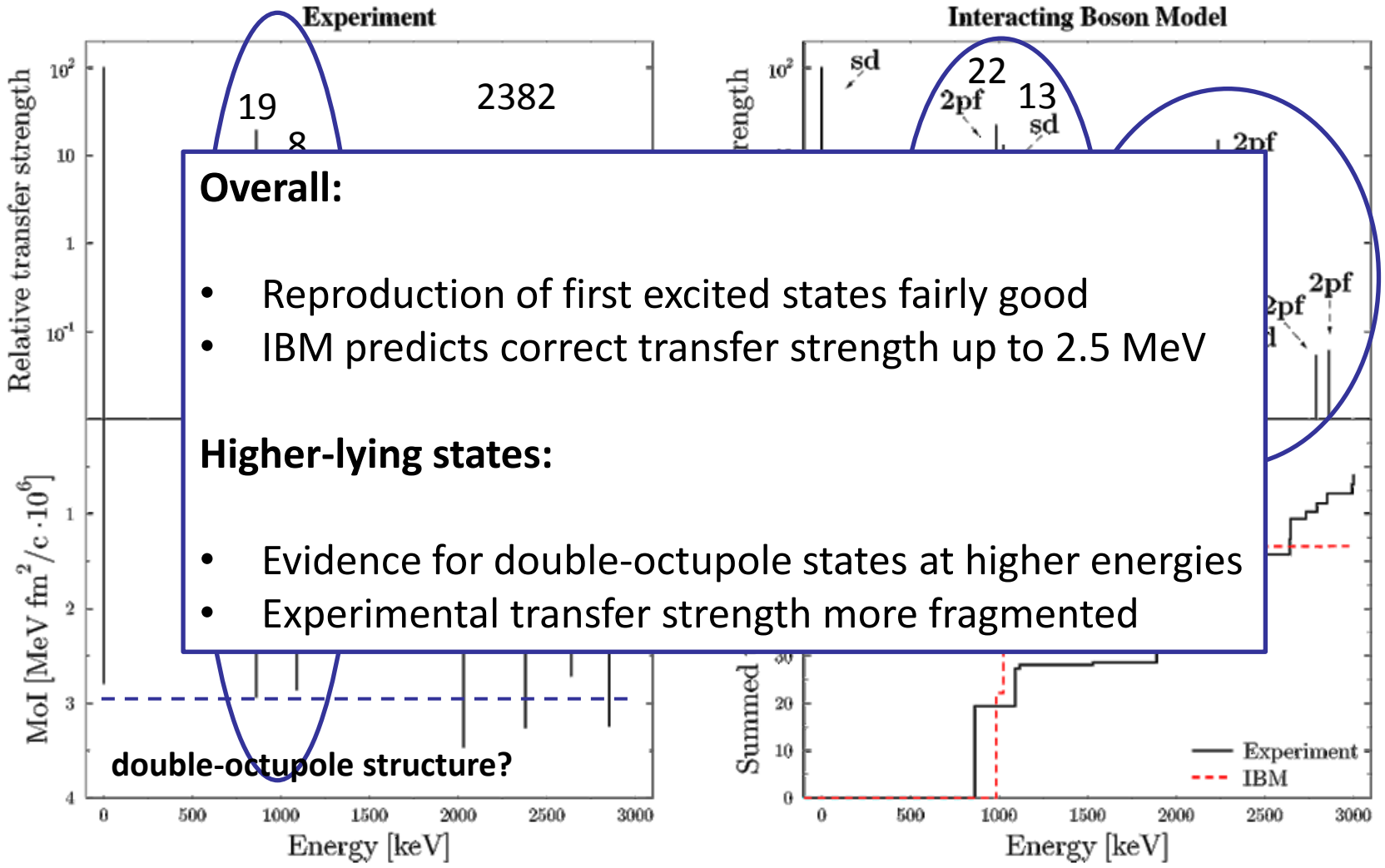
- Shape reflects positive-parity L=0 transfer
- **Relative transfer strength**
  19.39(2)% of gs strength
  (33.69(3) μb and 173.75(7) μb)
- **Moment of inertia**
  2.93(2) x 10^6 MeV fm^2/c
  → located between g.s.b. (*2.77(2) x 10^6 MeV fm^2/c*) and one-octupole phonon projections (e.g. *K*= 1: *3.19(11) x 10^6 MeV fm^2/c*)

spdf – IBM Calculations



spdf-IBM parameters adopted from N.V. Zamfir and D. Kusnezov, PRC **67** (2003) 014305

spdf – IBM Calculations



Overall:

- Reproduction of first excited states fairly good
- IBM predicts correct transfer strength up to 2.5 MeV

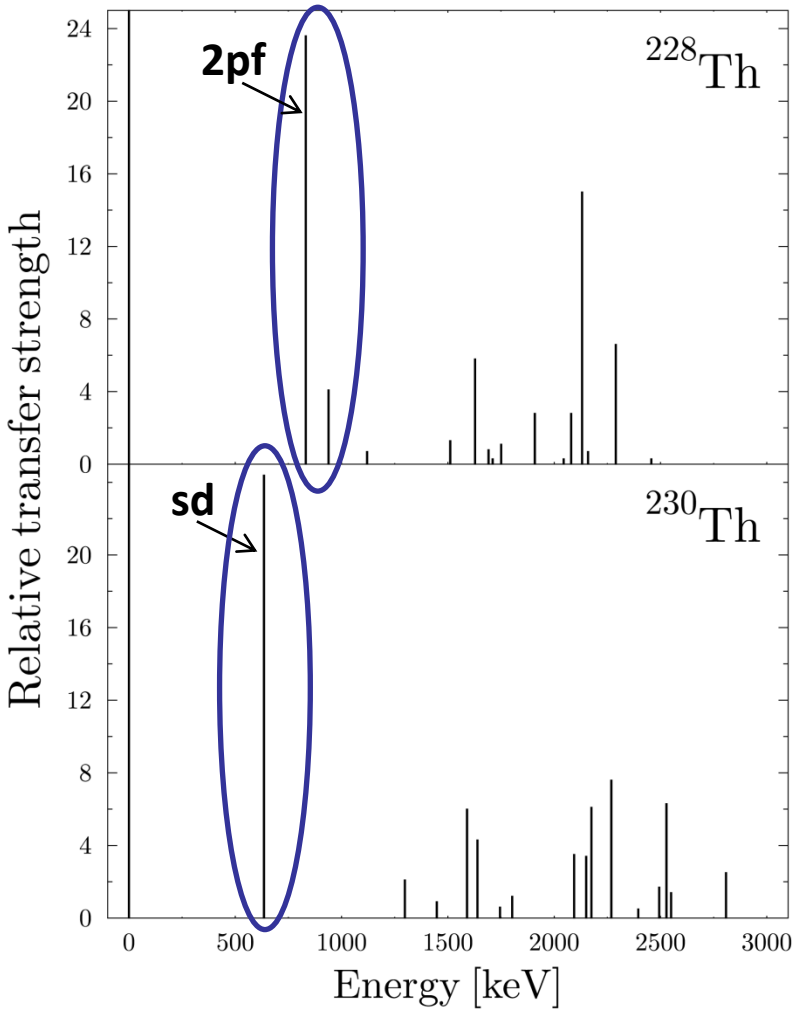
Higher-lying states:

- Evidence for double-octupole states at higher energies
- Experimental transfer strength more fragmented

spdf-IBM parameters adopted from N.V. Zamfir and D. Kusnezov, PRC **67** (2003) 014305

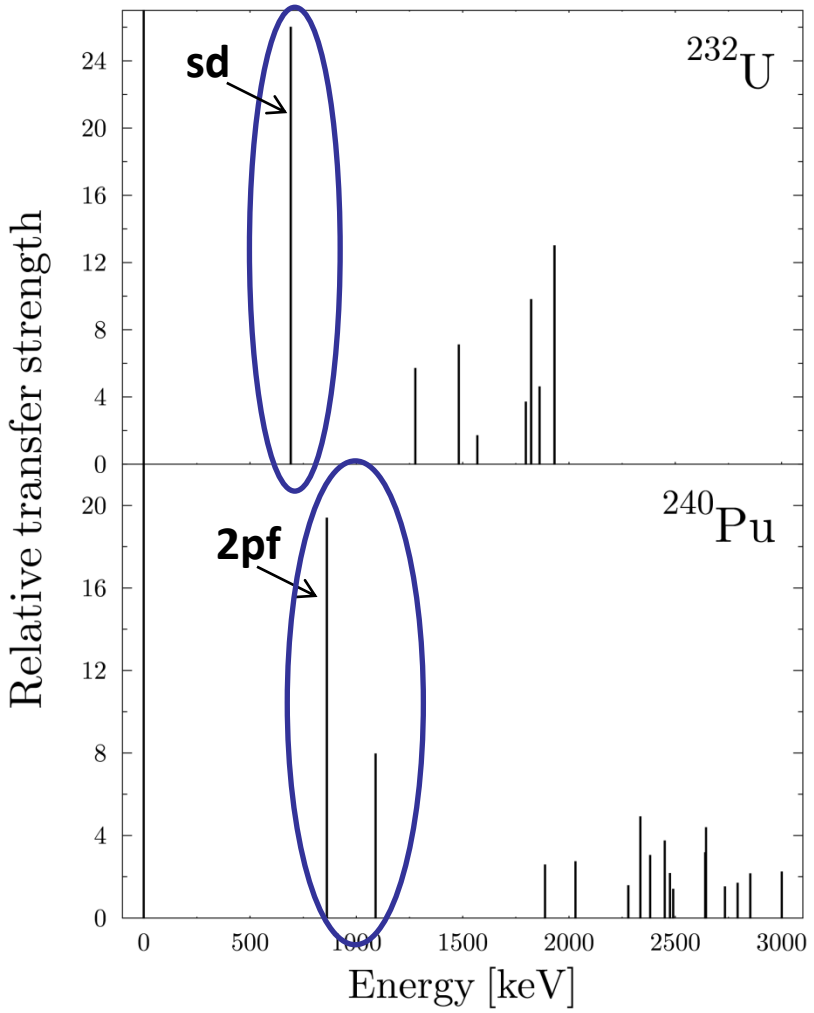
Experiment - The Actinides: 0^+ States

A.I. Levon *et al.*, private communication (2012)



A.I. Levon *et al.*, PRC **79** (2009) 014318

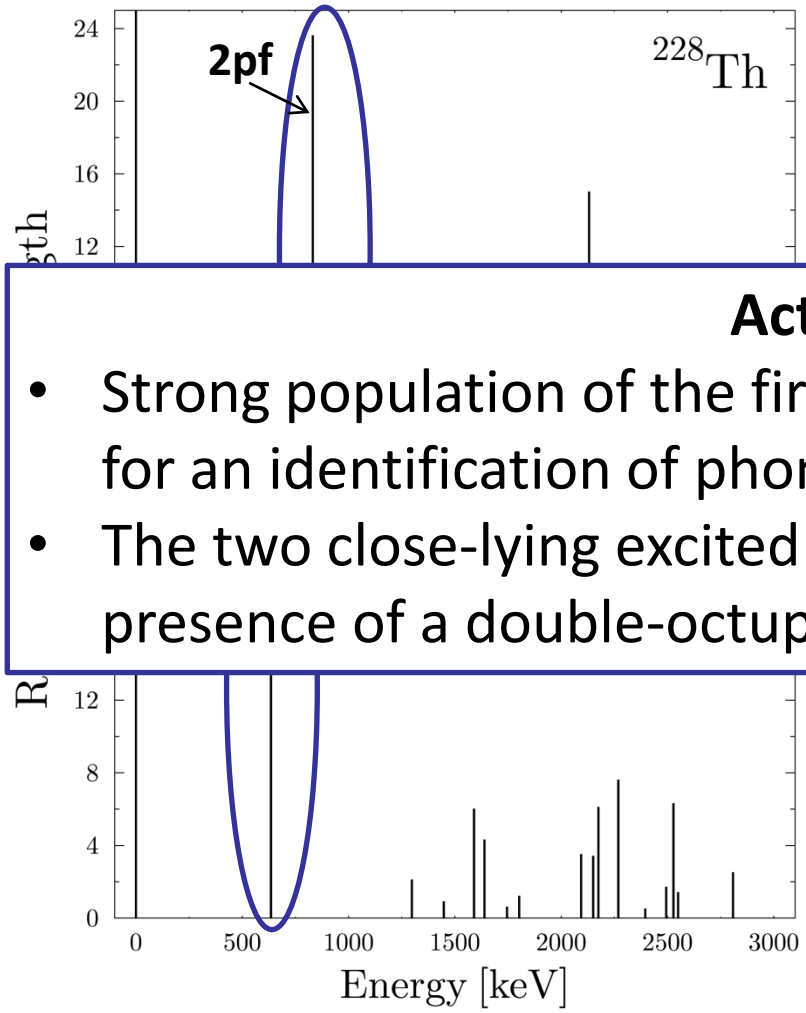
H.-F. Wirth *et al.*, PRC **69** (2004) 044310



M. Spieker *et al.*, present study (2013)

Experiment - The Actinides: 0^+ States

A.I. Levon *et al.*, private communication (2012)



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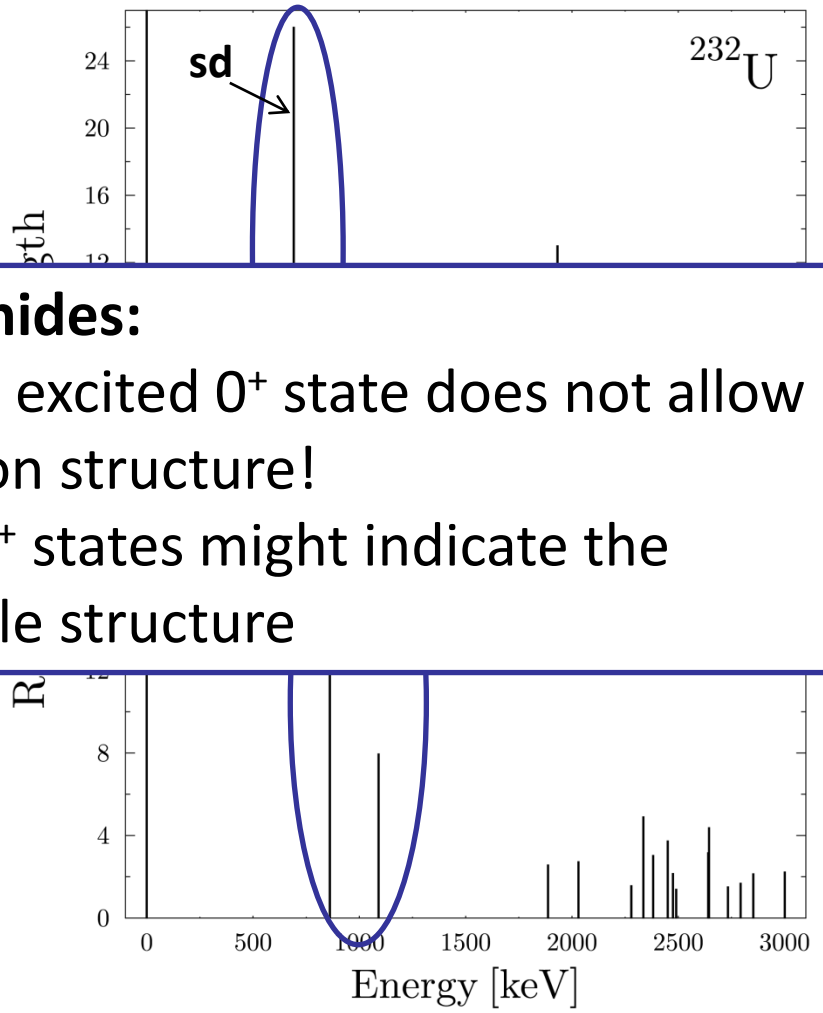
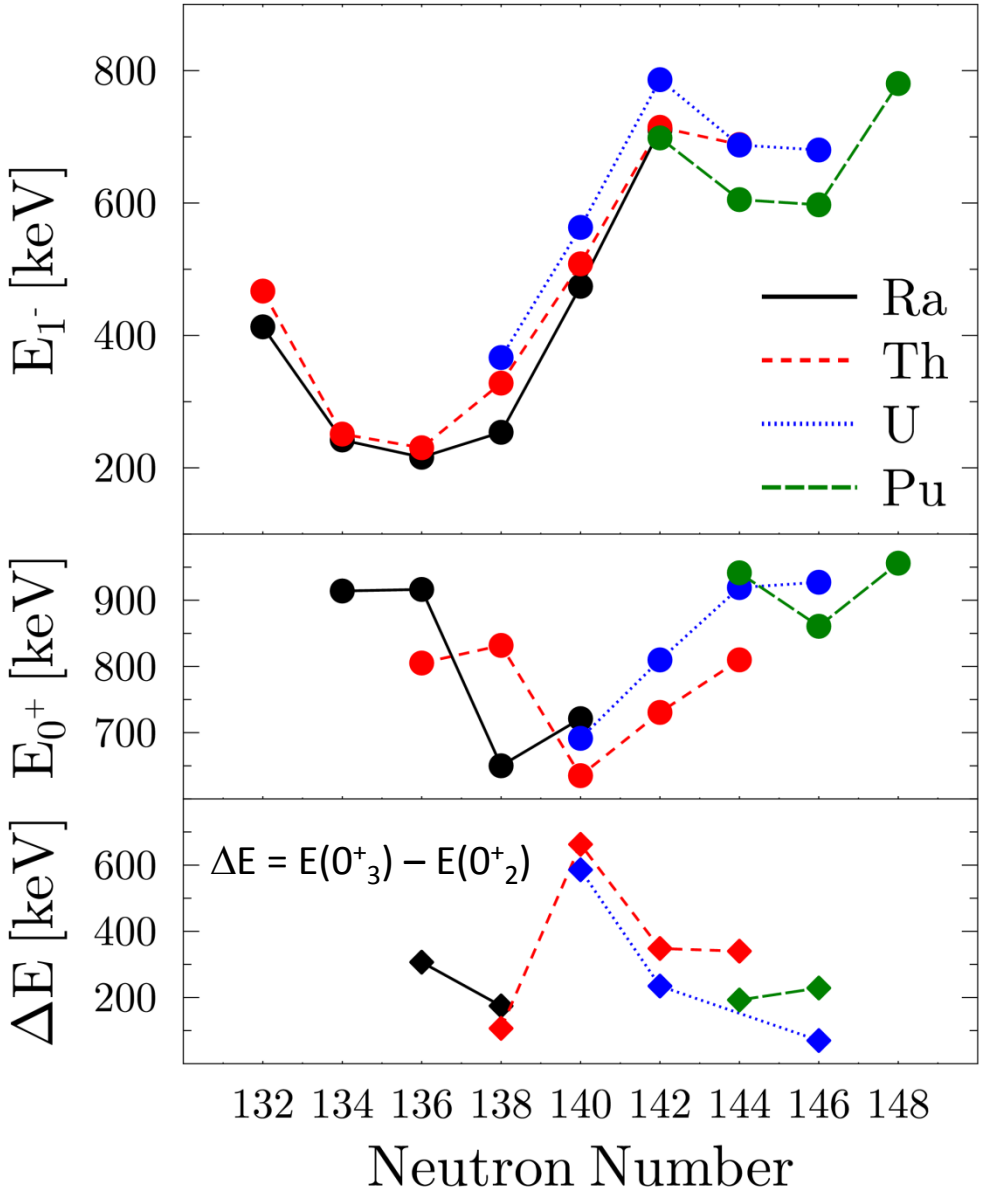


M. Spieker *et al.*, present study (2013)

Actinides:

- Strong population of the first excited 0^+ state does not allow for an identification of phonon structure!
- The two close-lying excited 0^+ states might indicate the presence of a double-octupole structure

Double-Octupole 0^+ States in the Actinides?



- Enhanced octupole correlations ↔ Minimum energy of first 1^- state

  → $^{222\text{-}226}$Ra, $^{224\text{-}226}$Th, ^{236,238}U, and ^{238,240}Pu

- Comparably large E_x in these nuclei

- Minimum ΔE ($0^+_3 - 0^+_2$) @ minimum energy of 1^- state

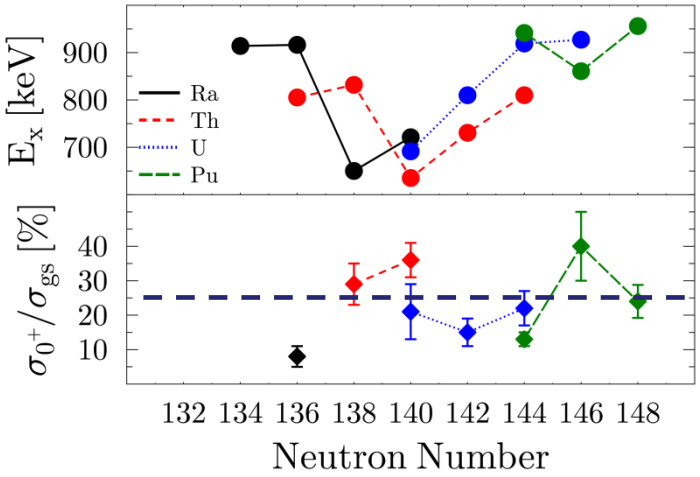
  → Another $(3^- \otimes 3^-)_{0^+}$ candidate proposed in ^{238}U by S. Zhu *et al.*

S. Zhu *et al.*, PRC **81** (2010) 041306(R)

Summary & Outlook

Summary

- **High-resolution (p,t) study of ^{240}Pu** @ Q3D, MLL Munich
  → Population of low-spin states up to 3 MeV
- **21 $J^{\pi}= 0^{+}$ states observed**
  → 17 $J^{\pi}= 0^{+}$ states newly assigned
  → 14 $K^{\pi}= 0^{+}$ rotational bands
- **Double-octupole phonon structure**
  → Structure of state @ 861.2 keV further supported
- **0^{+}_{2} states in the actinides**
  → Strong excitation does not allow for identification of phonon structures!
  → Excitation mechanisms ↔ structure of the state?



J.V. Maher *et al.*, PRL **25** (1970), 302;
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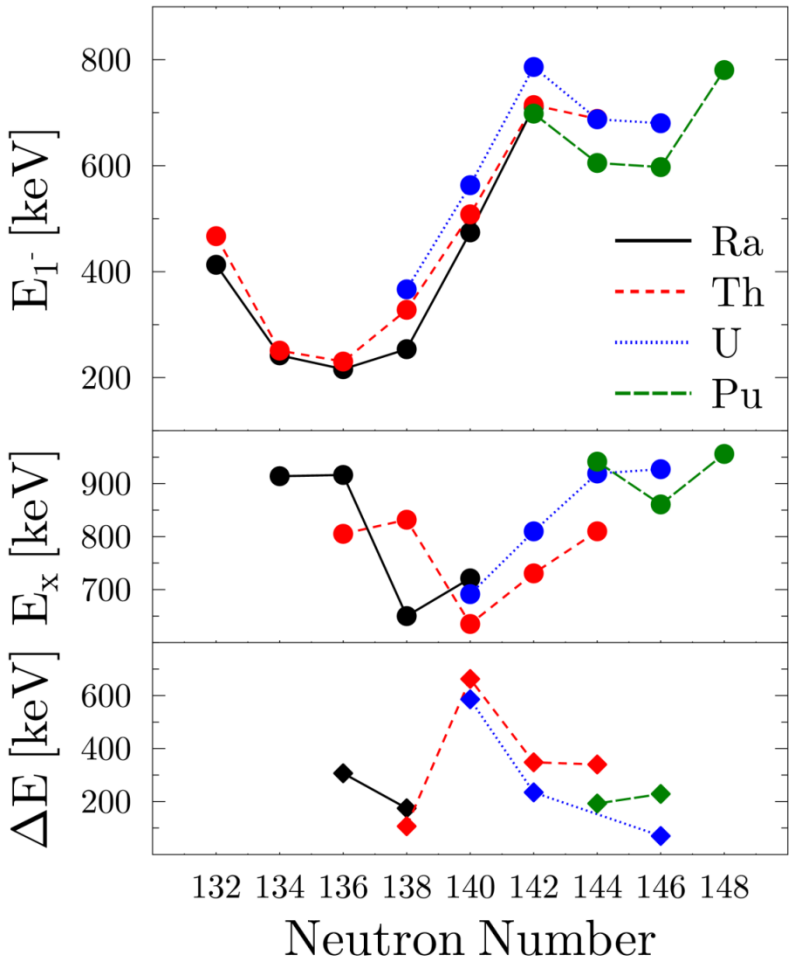
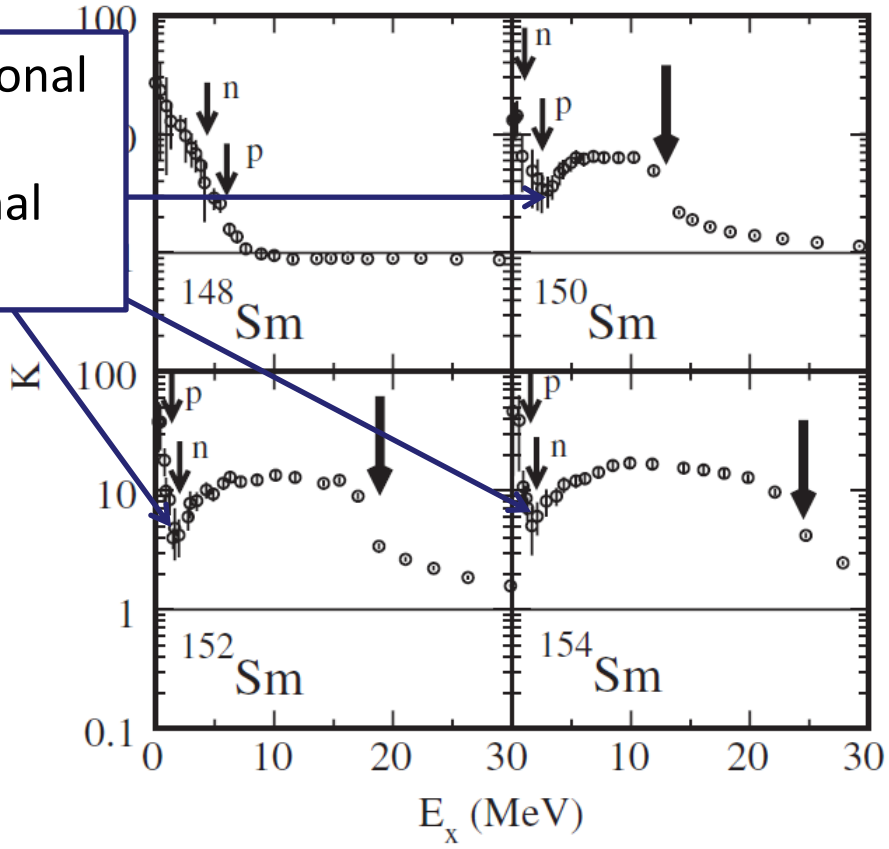


Summary & Outlook

Damping of vibrational collectivity / Effect of rotational collectivity



C. Özen , Y. Alhassid, and H. Hakada, PRL **110** (2013) 042502

Summary & Outlook

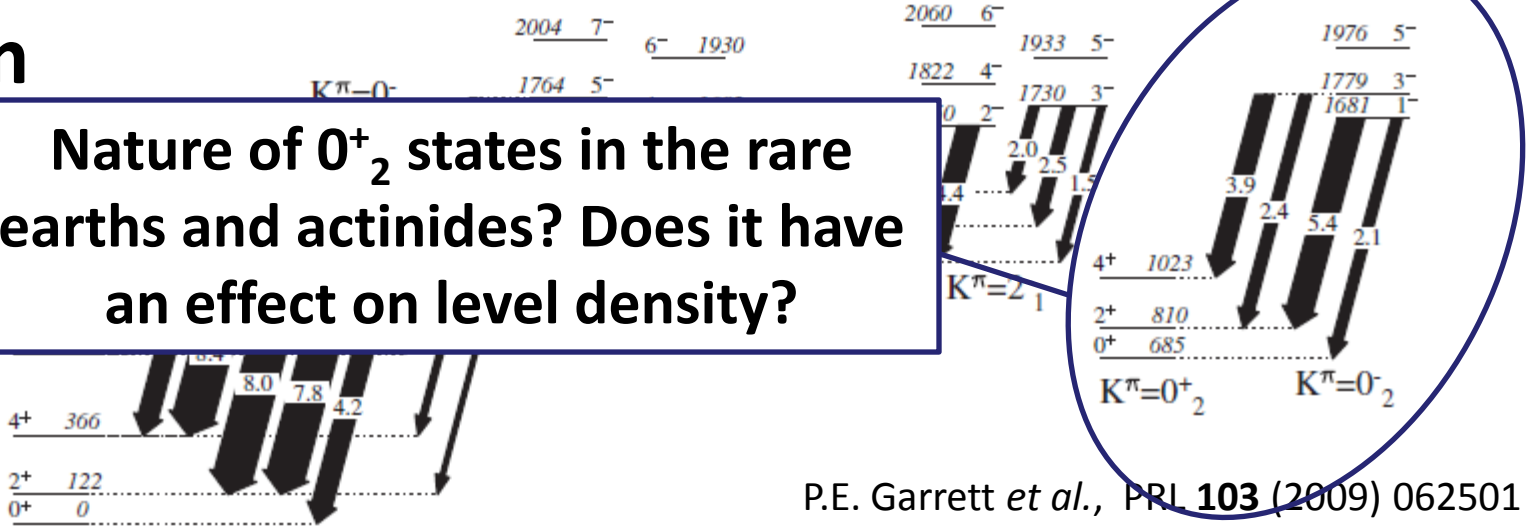
PHYSICAL REVIEW C **87**, 044333 (2013)

Octupole correlations in the structure of 0_2^+ bands in the $N = 88$ nuclei ^{150}Sm and ^{152}Gd

S. P. Bvumbi,[1,*] J. F. Sharpey-Schafer,[2,*] P. M. Jones,[3,†] S. M. Mullins,[4] B. M. Nyakó,[5] K. Juhász,[6,‡] R. A. Bark,[4] L. Bianco,[7] D. M. Cullen,[3,§] D. Curien,[8] P. E. Garrett,[7] P. T. Greenlees,[3] J. Hirvonen,[3] U. Jakobsson,[3] J. Kau,[4] F. Komati,[4] R. Julin,[3] S. Juutinen,[3] S. Ketelhut,[3,‖] A. Korichi,[9] E. A. Lawrie,[4] J. J. Lawrie,[4] M. Leino,[3] T. E. Madiba,[2] S. N. T. Majola,[4] P. Maine,[2]

^{152}Sm

Nature of 0^+_2 states in the rare earths and actinides? Does it have an effect on level density?



P.E. Garrett *et al.*, PRL **103** (2009) 062501

PRL **103,** 062501 (2009) PHYSICAL REVIEW LETTERS week ending 7 AUGUST 2009

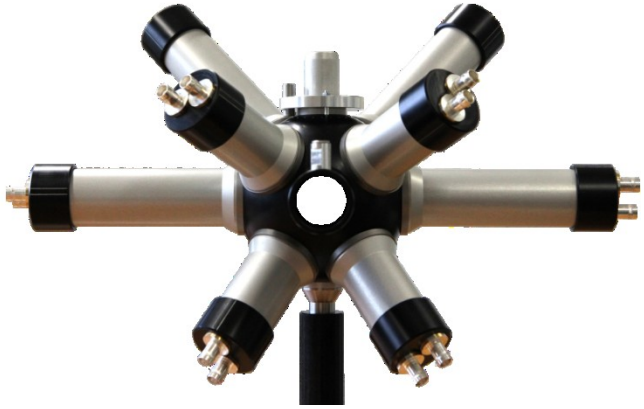
New Features of Shape Coexistence in ^{152}Sm

P. E. Garrett,[1] W. D. Kulp,[2] J. L. Wood,[2] D. Bandyopadhyay,[3] S. Choudry,[3] D. Dashdorj,[4] S. R. Lesher,[3] M. T. McEllistrem,[3] M. Mynk,[3] J. N. Orce,[3] and S. W. Yates[3]

Summary & Outlook

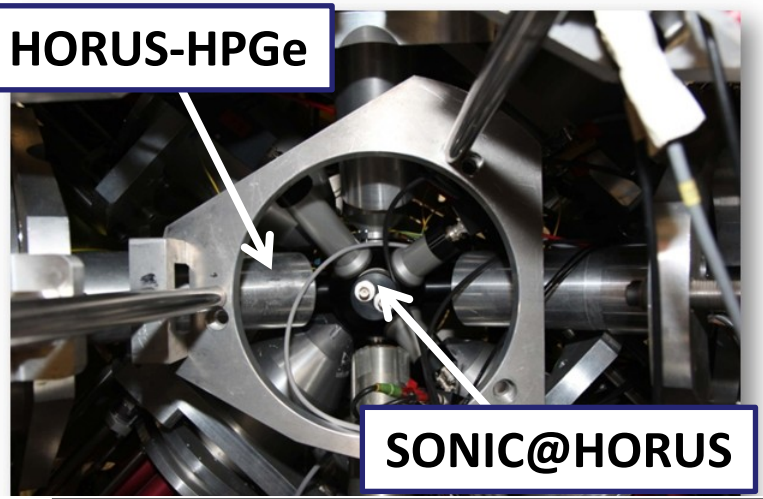
Outlook

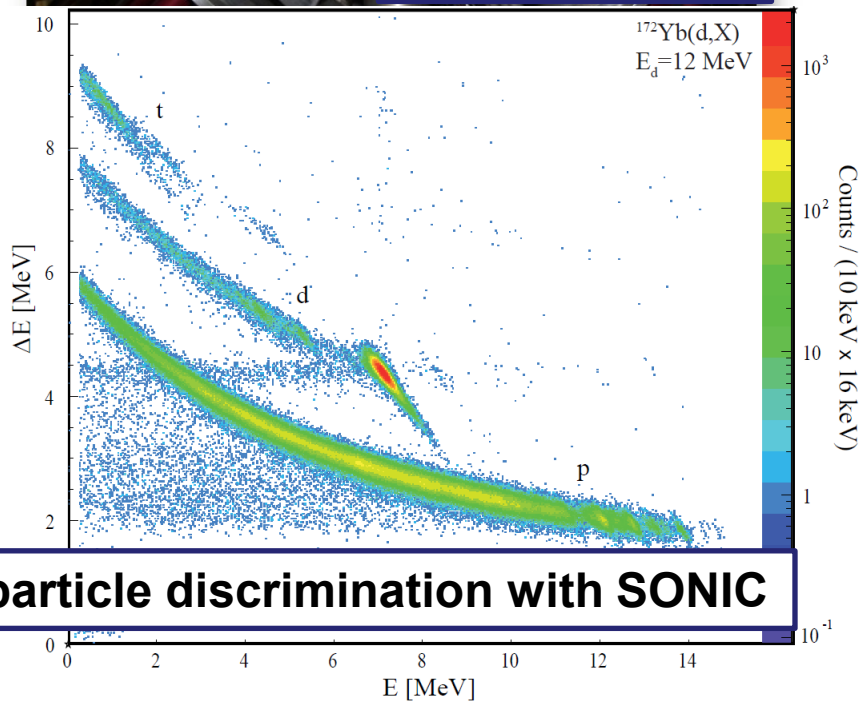
- **Further (p,t) studies in the actinides (e.g. ^{224}Ra, ^{236}U)**
- **(p,tγ) experiments with SONIC@HORUS, Cologne**



→ Decay of 0^+ states?

→ Collective or non-collective nature?





particle discrimination with SONIC