

# Pear-shaped nuclei

*Peter Butler*

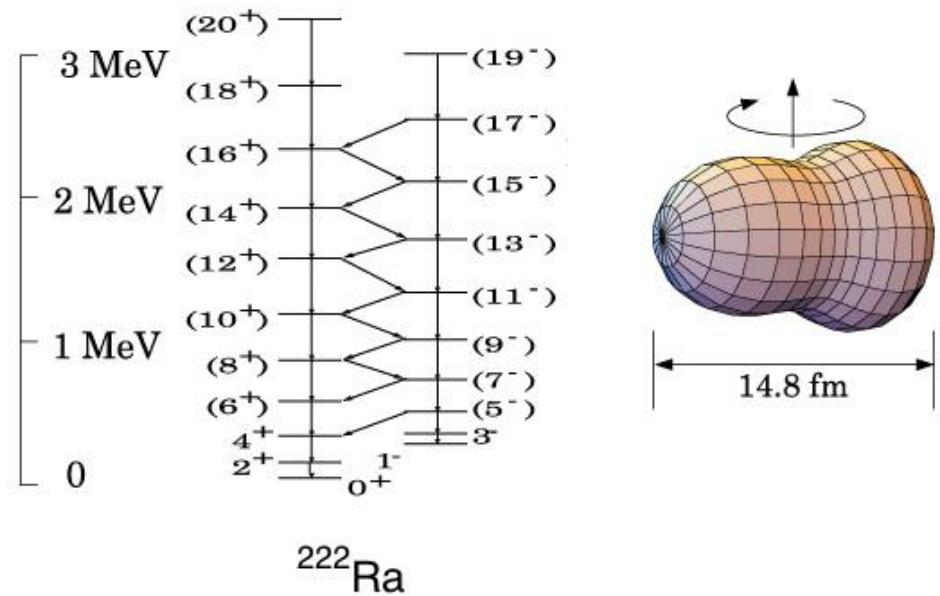
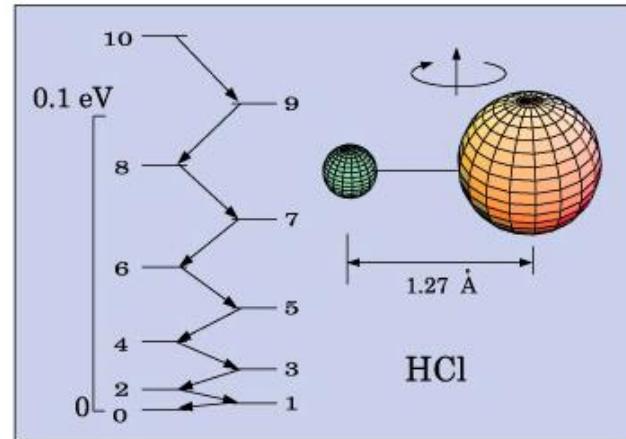
*University of Liverpool*

**Generalised octupole shapes  
Rotating even-even nuclei  
Odd electric moments  
Odd-mass nuclei & EDMs**

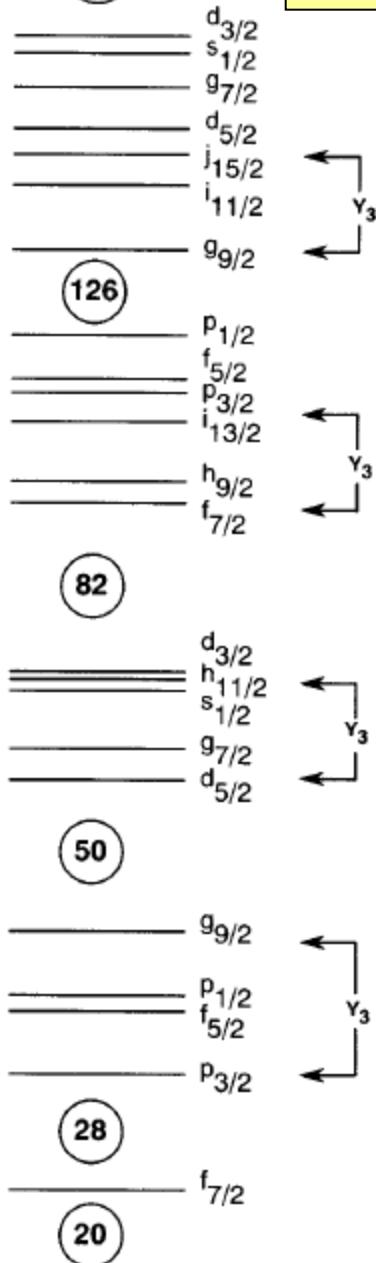
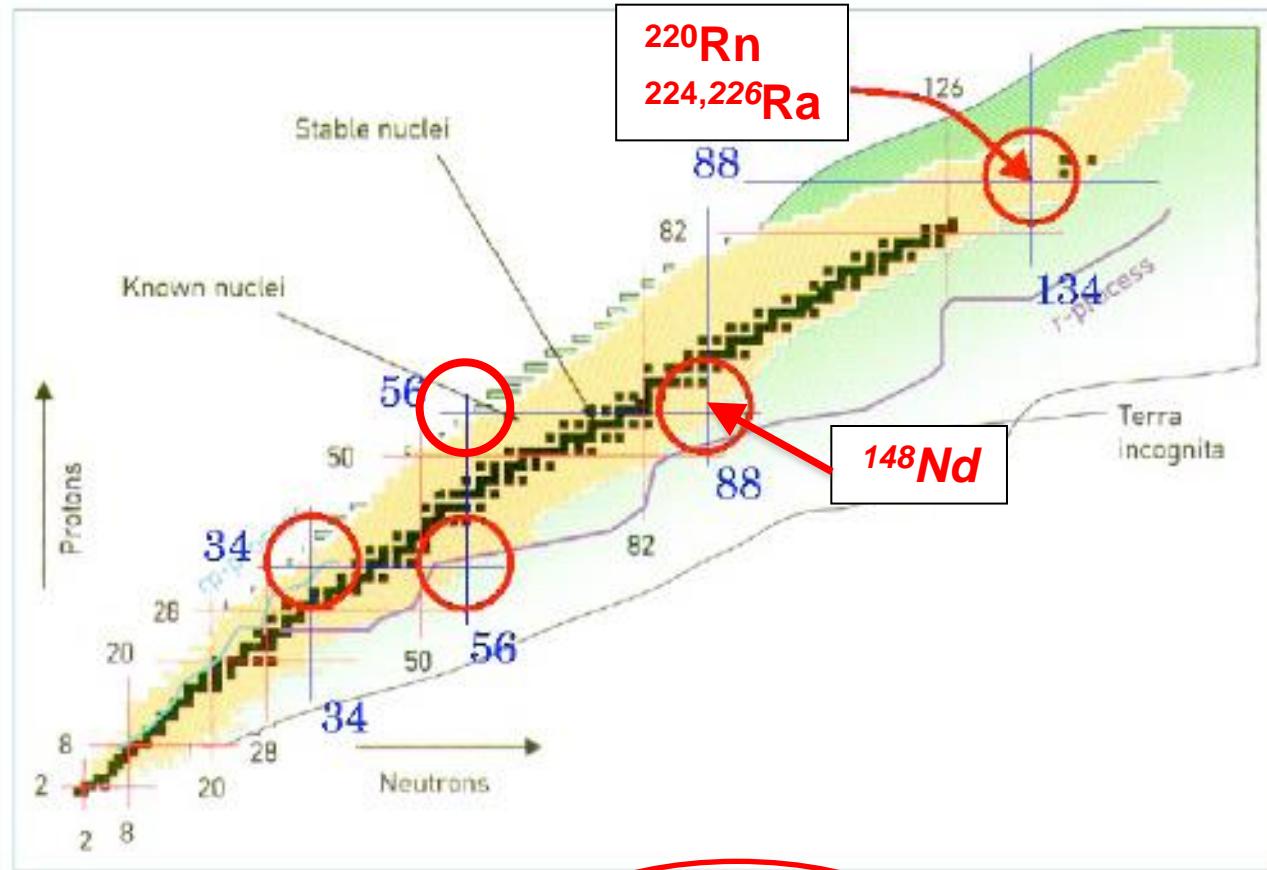
# Reflection Asymmetric Shapes

$$R(\Omega) = c(\alpha) R_0 \left[ 1 + \sum_{\lambda=2}^{\lambda_{\max}} \sum_{\mu=-\lambda}^{+\lambda} \alpha_{\lambda\mu} Y_{\lambda\mu}^*(\Omega) \right]$$

If  $\alpha_{\lambda\mu}$  is non-zero for odd  $\lambda$  then the nuclear shape becomes reflection-asymmetric, or pear-shaped.



# Regions of Enhanced Octupole Correlations

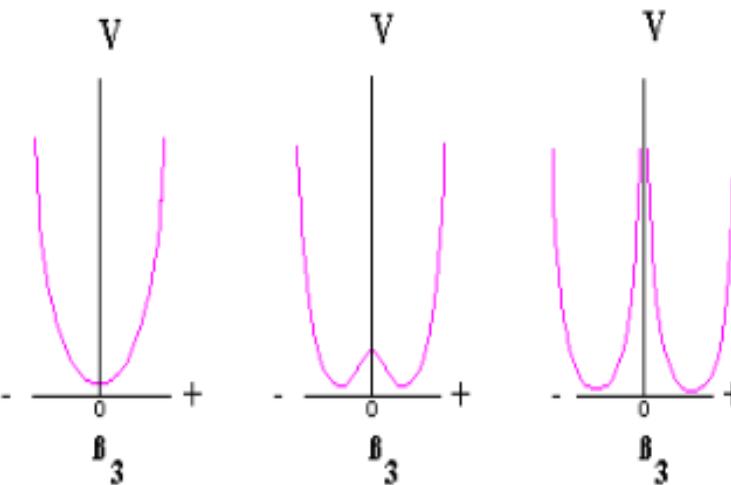
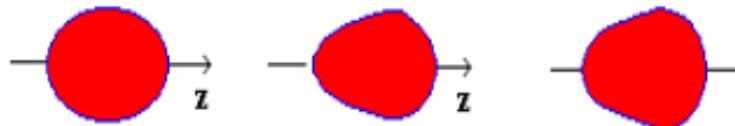
**134****88****56****34**

$$H = \sum_j e_j c_j^+ c_j - \frac{1}{2} \sum_{\lambda} \kappa_{\lambda} \sum_{\mu=-\lambda}^{+\lambda} Q_{\lambda\mu}^+ \cdot Q_{\lambda\mu} + H_{\text{pair}}$$

long range multipole-multipole force

# Octupole Collectivity

Soft Octupole      Static Deformation      Rigid Deformation



even-even

$4^+$	$3^-$
$2^+$	$1^-$
$0^+$	

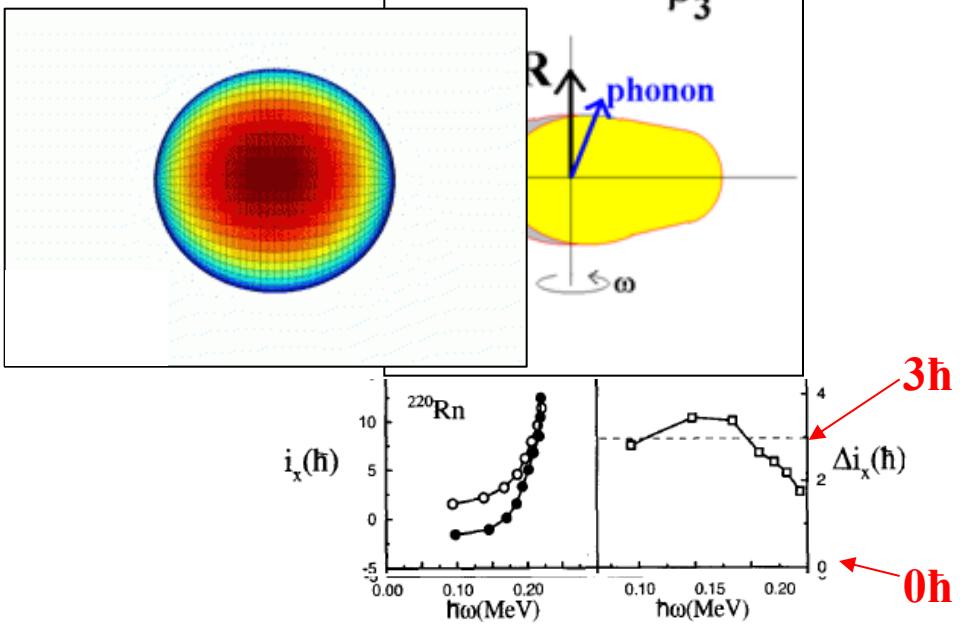
odd-A

$11/2^+$	$9/2^-$
$9/2^+$	$7/2^-$
$7/2^+$	$5/2^-$
$5/2^+$	

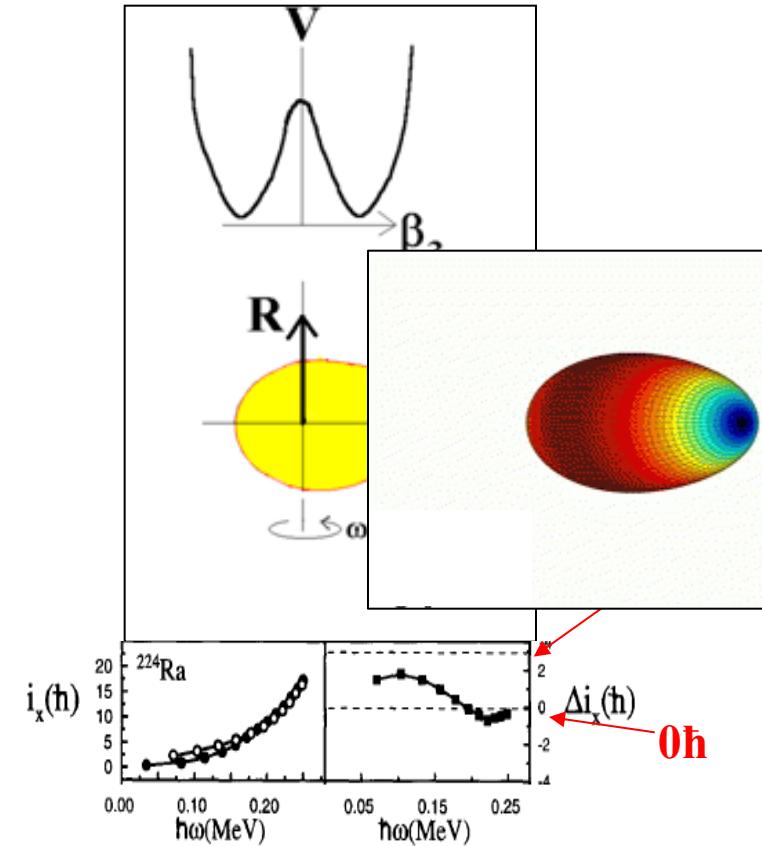
$11/2^+$	$9/2^-$
$9/2^+$	$7/2^-$
$7/2^+$	$5/2^-$
$5/2^+$	

$11/2^\pm$	$9/2^\pm$
$9/2^\pm$	$7/2^\pm$
$7/2^\pm$	$5/2^\pm$
$5/2^\pm$	

# Rotating octupole shapes

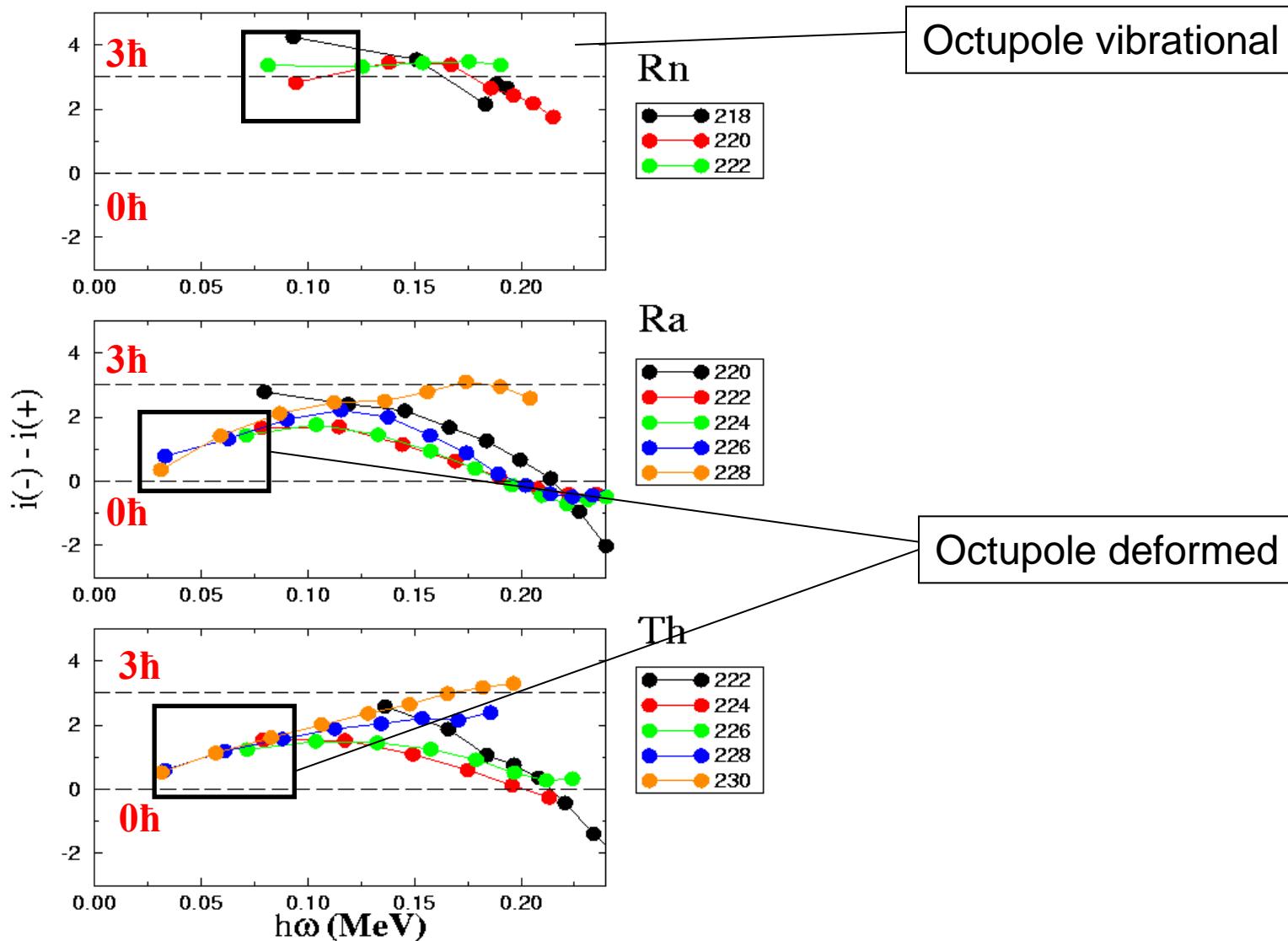


Octupole vibrational



Octupole deformed

# Actual Behaviour (near the ground state)



JFC Cocks et al PRL 78 (1997) 2920, Nucl. Phys. A645 (1999) 61

## Electric moments

E $\lambda$  moment       $Q_{nm} = \langle \psi_n | \hat{Q} | \psi_m \rangle$

Since the E $\lambda$  operator is an odd function of  $\mathbf{r}$  if  $\lambda$  is odd,  
the moment is:

Zero for diagonal matrix elements (***unless P, T are violated, see later***)

Non-zero for transition matrix elements if  $\psi_n$  has opposite parity to  $\psi_m$

# Electric dipole transitions

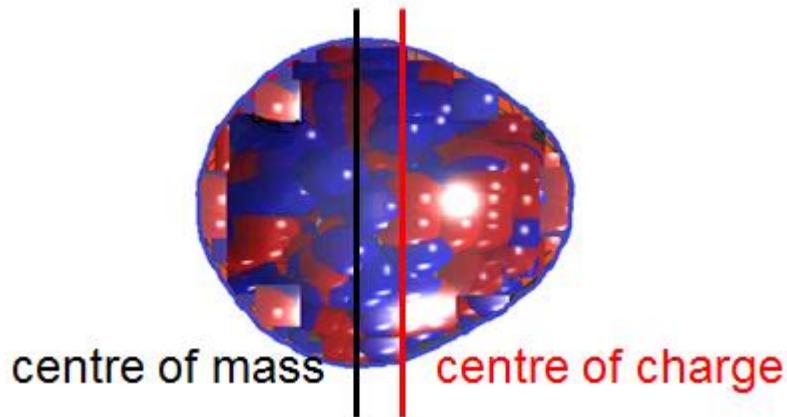
$$B(E1) = \frac{3}{4\pi} (I_i 010 | I_f 0)^2 Q_1^2$$

$$Q_1 = e \frac{N}{A} <Z_p> - e \frac{Z}{A} <Z_n>$$

Macroscopic contribution to E1 moment

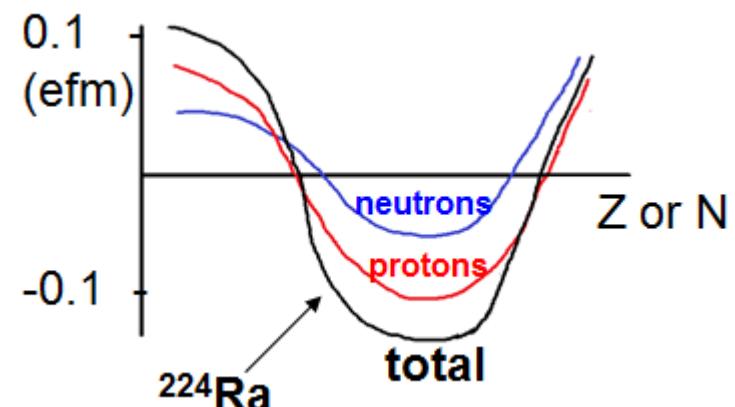
=  $a A Z$  (charge) –  $b (N-Z)$  (neutron skin)

= 0.1 efm for  $^{224}\text{Ra}$

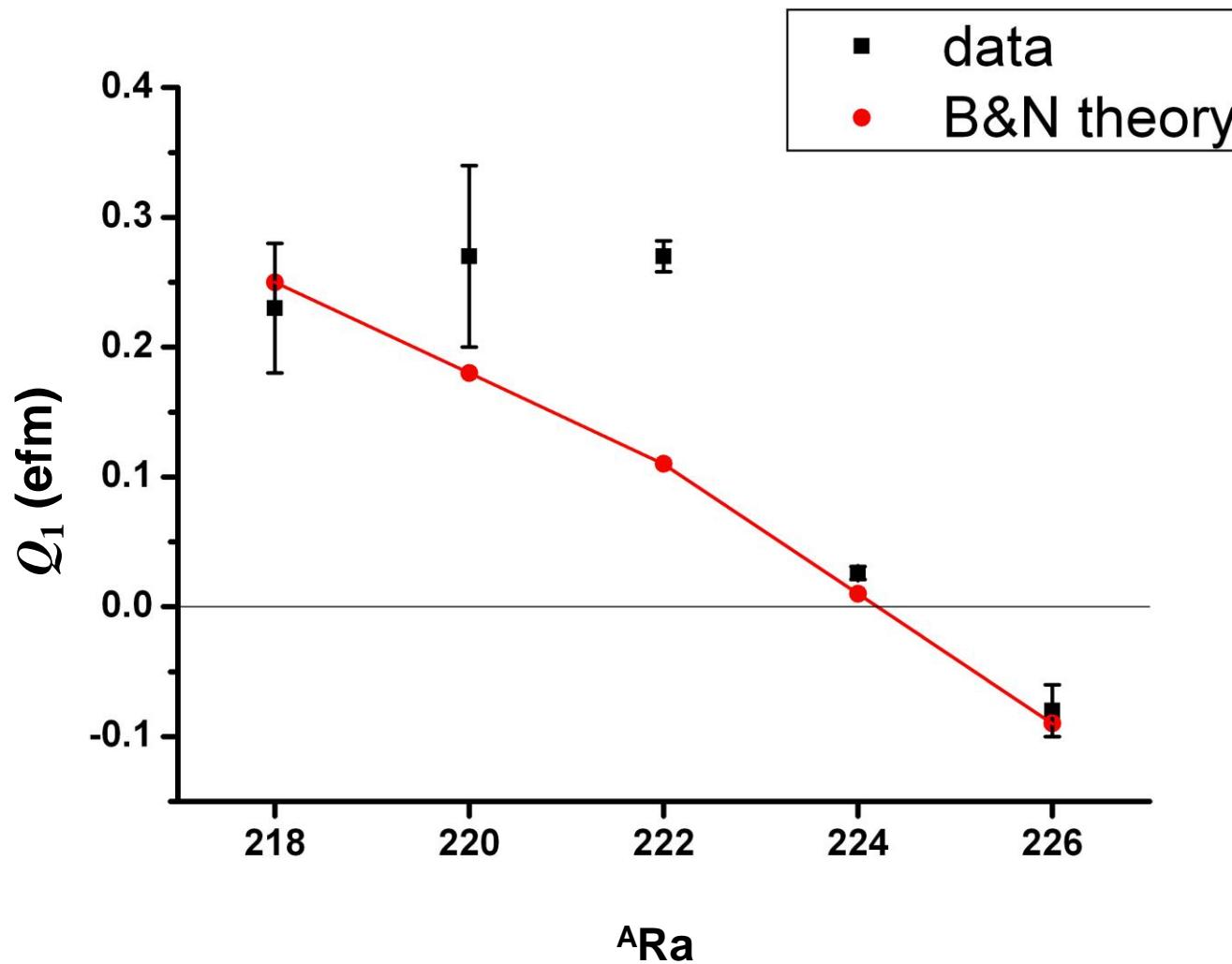


Microscopic contribution to E1 moment

= **-0.1 efm for  $^{224}\text{Ra}$**



# Experimental E1 moments in octupole nuclei



## B(E3) transitions

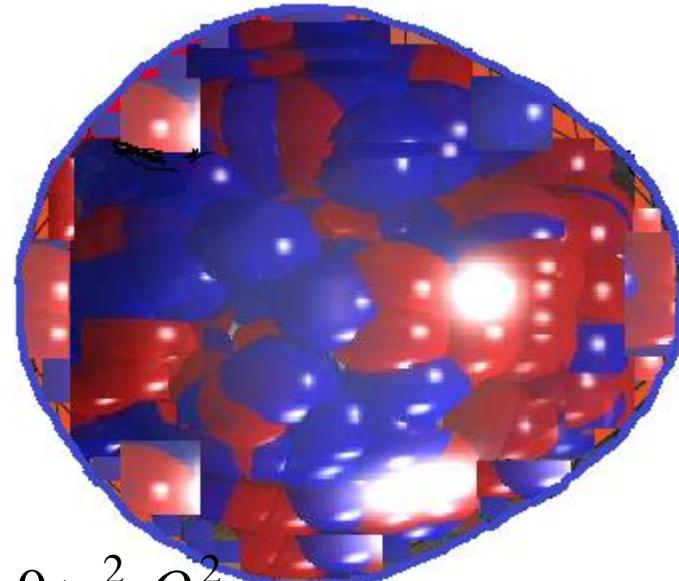
$$Q_3 = \frac{3}{\sqrt{7\pi}} ZeR_0^3 \bar{\beta}_3$$

$$\bar{\beta}_3 = f(\beta_3, \dots)$$

$$B(E3; I_i \rightarrow I_f) = \frac{7}{16\pi} \langle I_i 030 | I_f 0 \rangle^2 Q_3^2$$

$B(E3; 0^+ \rightarrow 3^-) \sim 30 - 50$  single particle units for  $\beta_3 \sim 0.1$

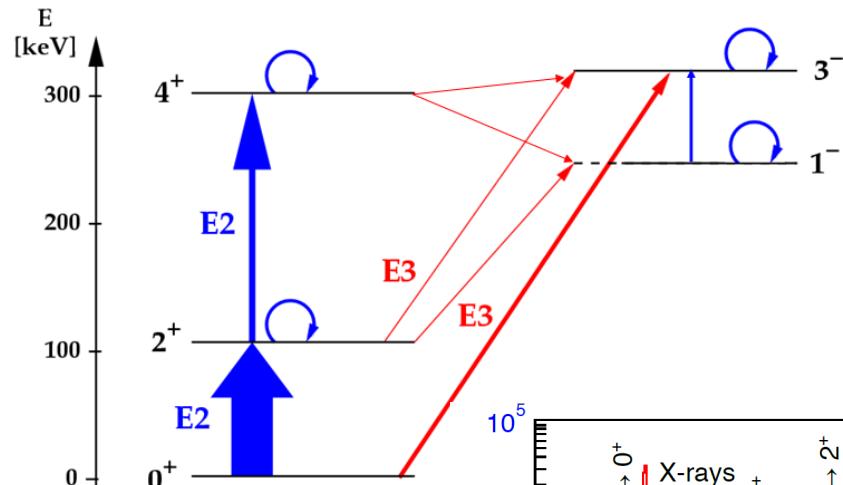
To study the “best” candidates for octupole shapes, we excite either radioactive targets (e.g.  $^{226}\text{Ra}$ , 1600y) or use radioactive beams



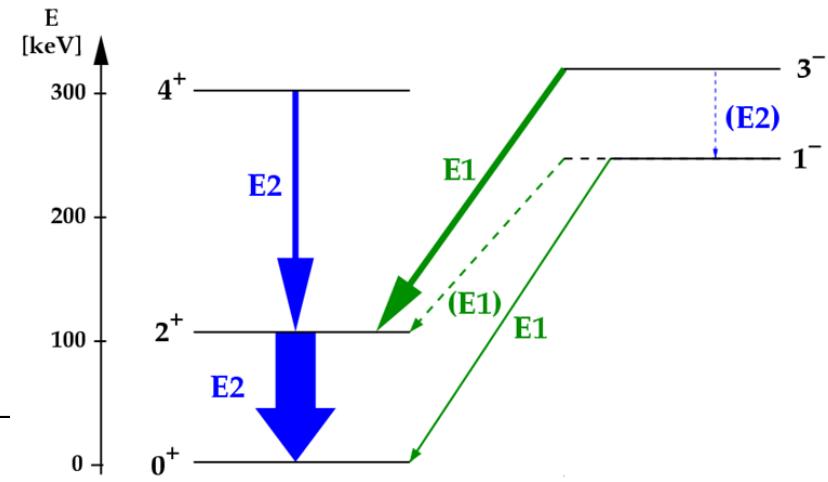
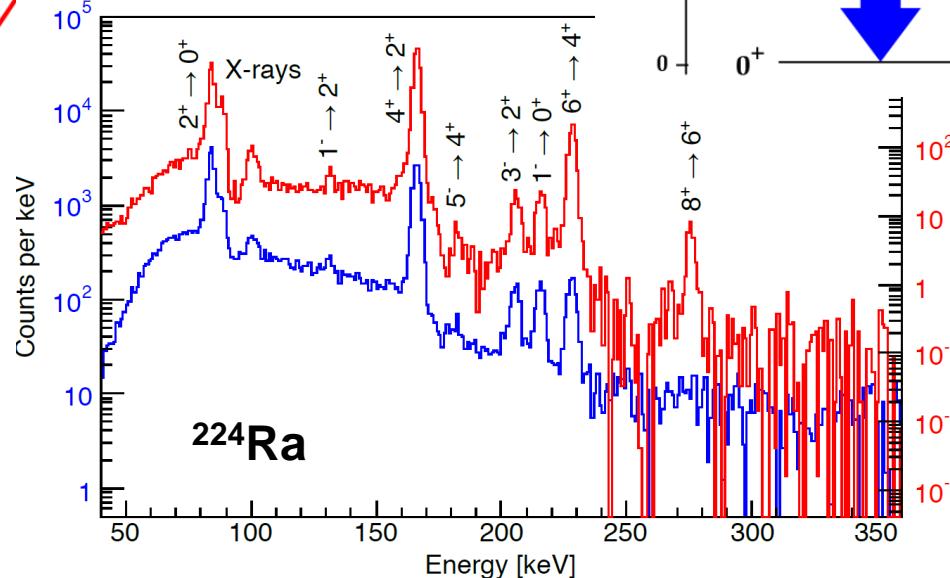
# Coulomb excitation and $\gamma$ -ray decay

$$\frac{\sigma(E3)}{\sigma(E2)} \approx \left( \frac{R_0}{a} \right)^2 \frac{B(E3)}{B(E2)} f \approx 10^{-2}$$

$$\frac{\lambda(E3)}{\lambda(E2)} \approx \left( \frac{\omega}{c} R_0 \right)^2 \frac{B(E3)}{B(E2)} f \approx 10^{-4}$$



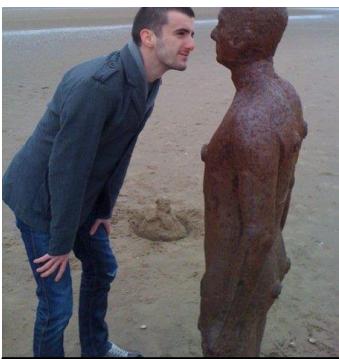
$^{60}\text{Ni}$  target  
 $^{120}\text{Sn}$  target



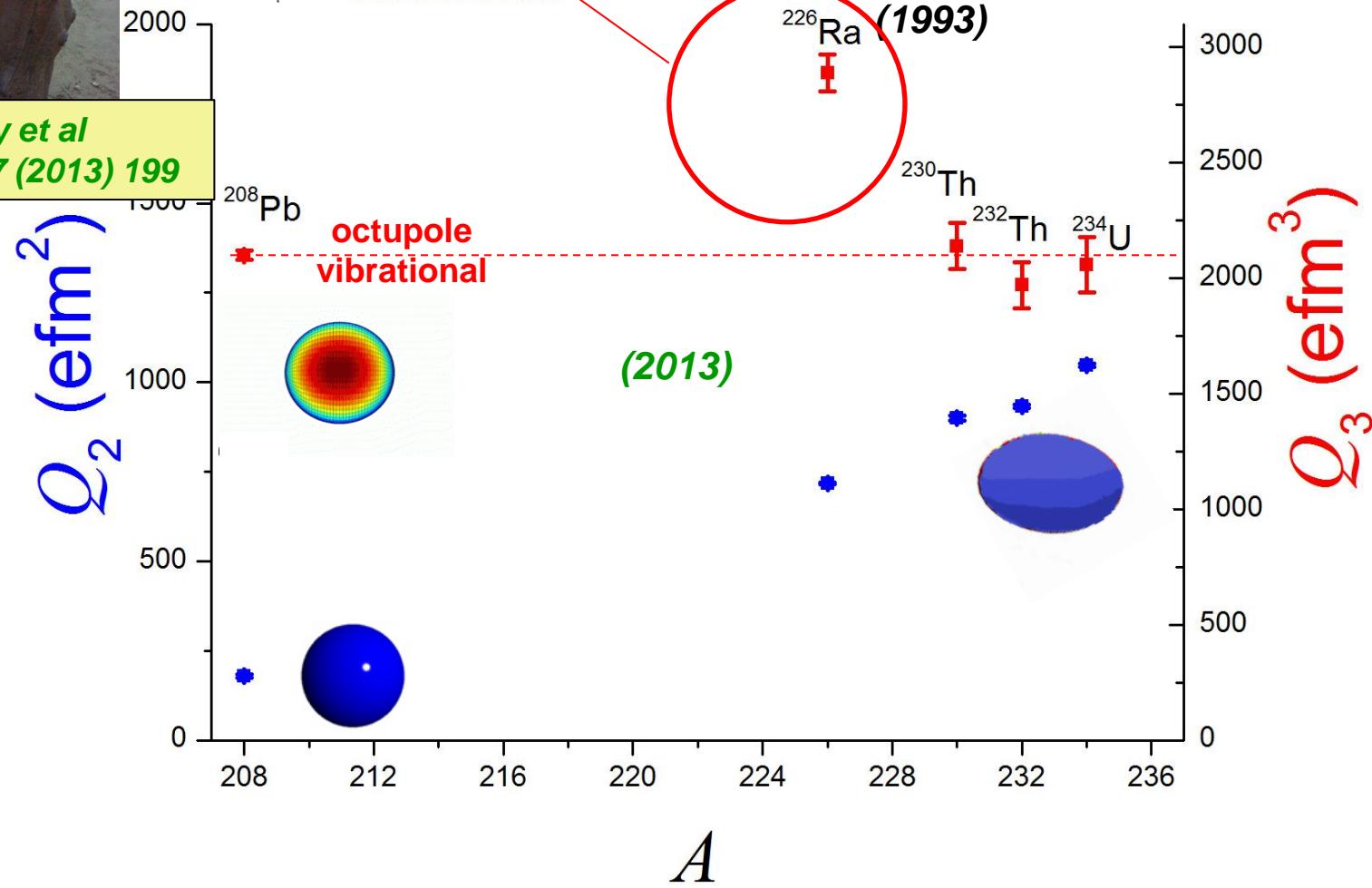
REX-ISOLDE

Spectrum taken  
with MINIBALL

# E2 and E3 moments in “octupole” mass region



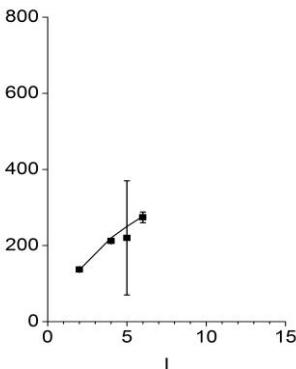
LP Gaffney et al  
Nature 497 (2013) 199



$A$

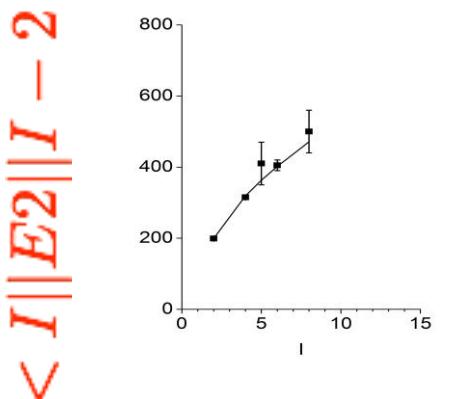
# Rotating charged pear-shape

**$^{220}\text{Rn}$**

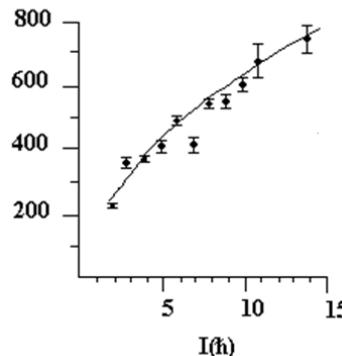


*LP Gaffney et al,  
Nature 497 (2013) 199*

**$^{224}\text{Ra}$**

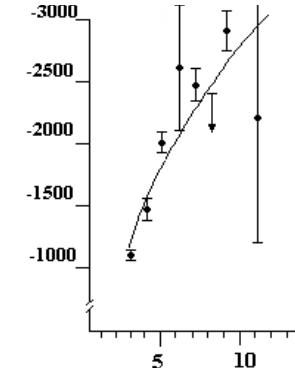
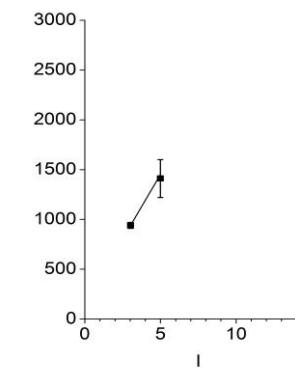
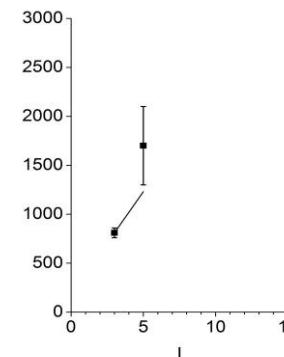


**$^{226}\text{Ra}$**



*HJ Wollersheim et al.,  
NP A556 (1993) 261*

$\langle I || E2 || I - 2 \rangle$

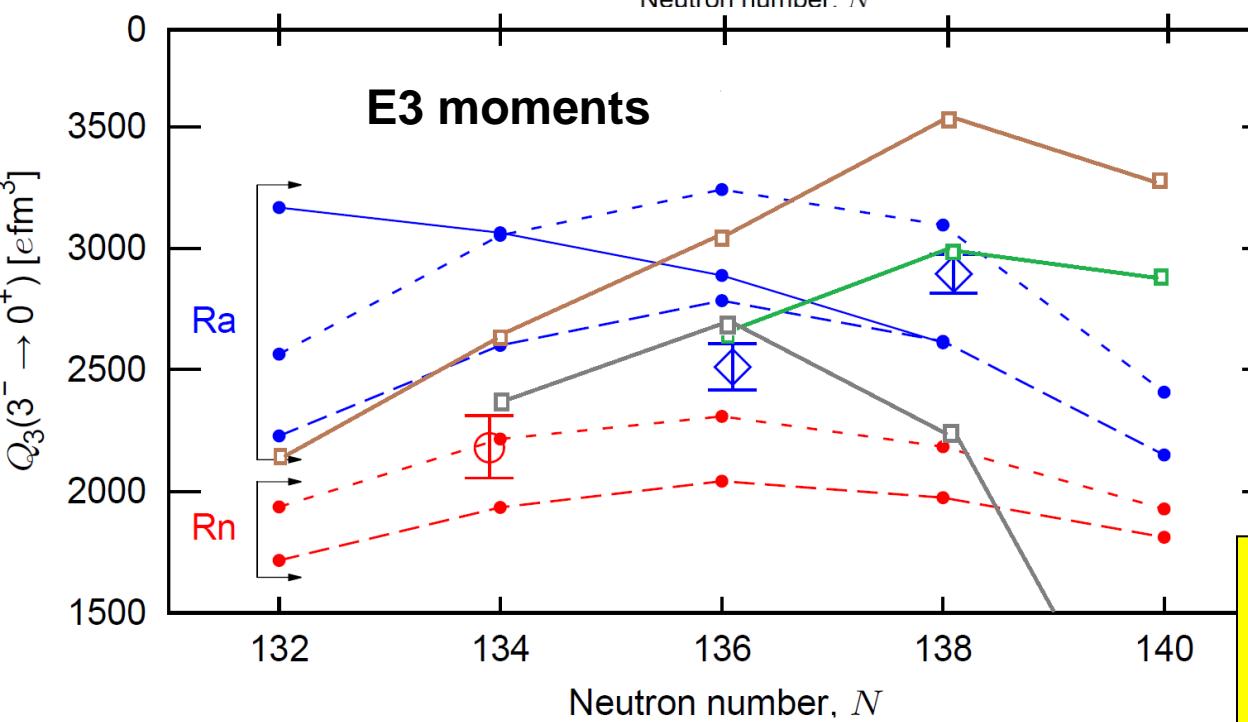
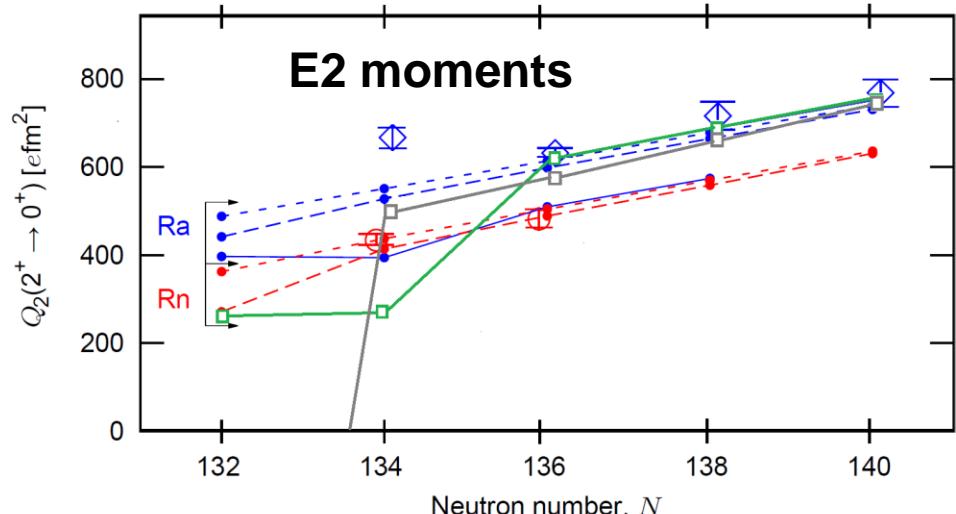


$\langle I || E3 || I - 1 \rangle$



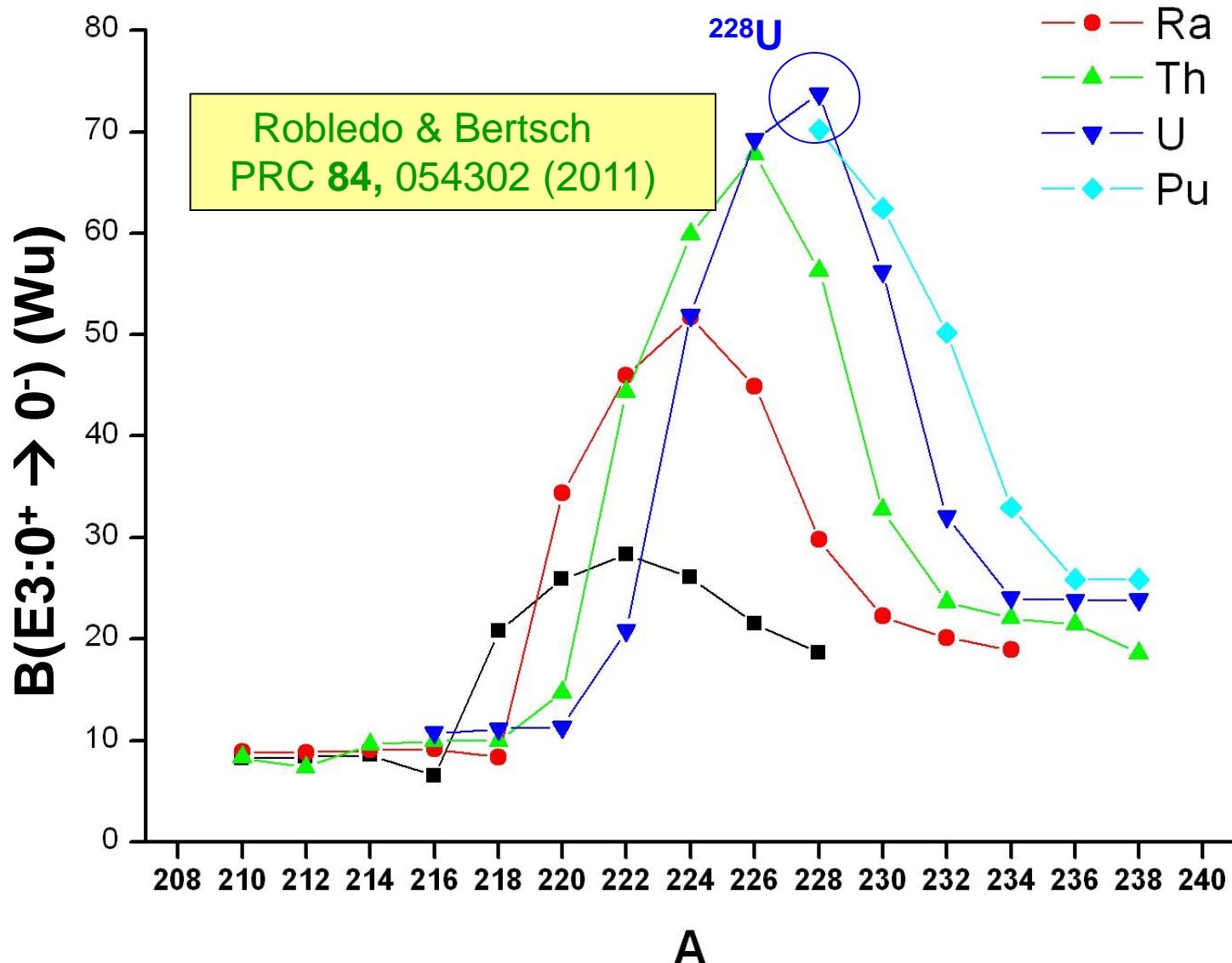
E2 matrix elements [e·fm<sup>2</sup>]

# Comparison with theory



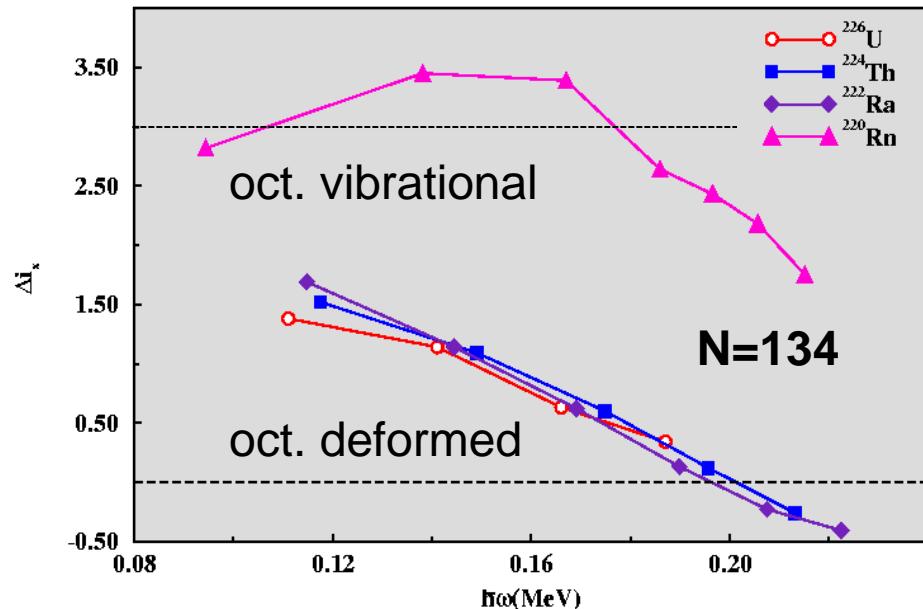
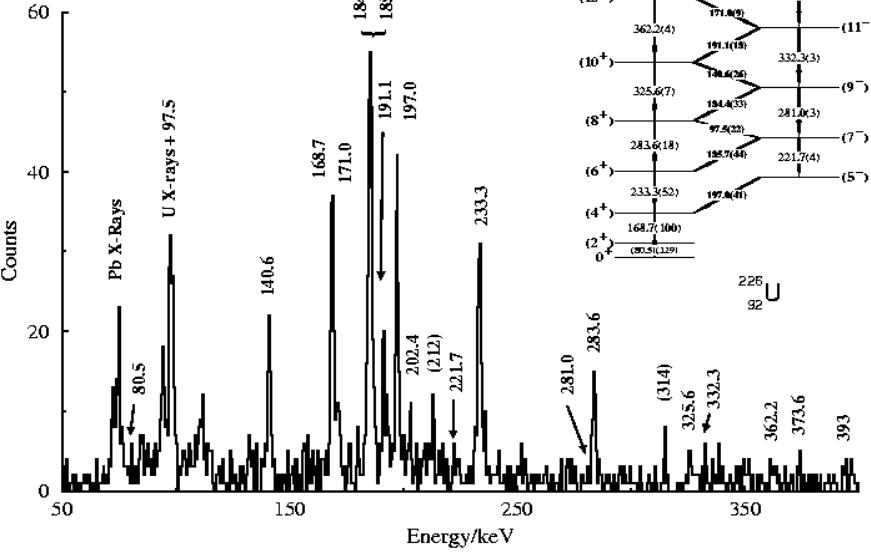
1. Shneidman et al PRC 67 (2003) 014313
2. Robledo & Bertsch PRC 84 (2011) 054302
3. Rutz et al. NP A590 (1995) 680
4. Engel et al. PRC 68 (2003) 025501
5. Nazarewicz et al NP A429 (1984) 269

# The largest B(E3)s



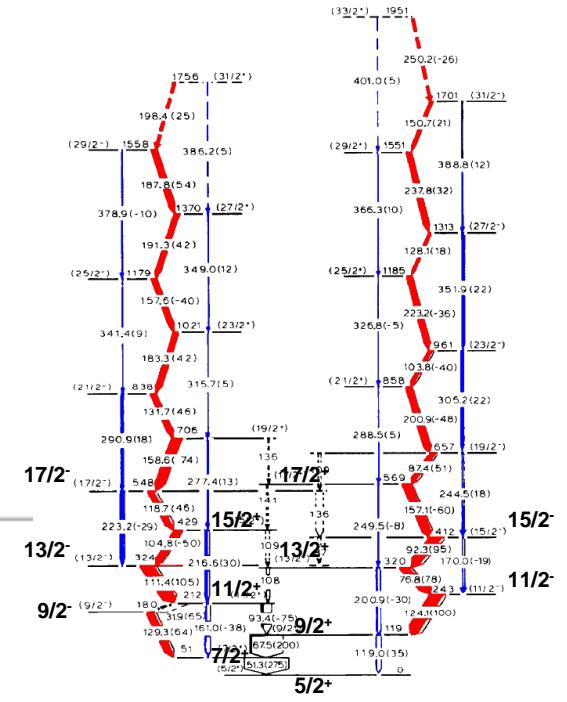
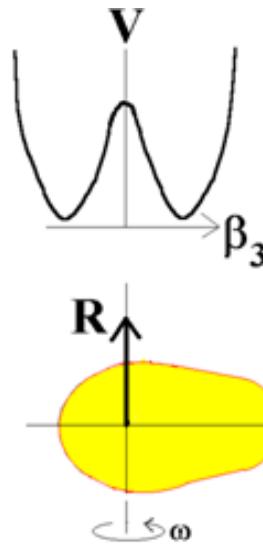
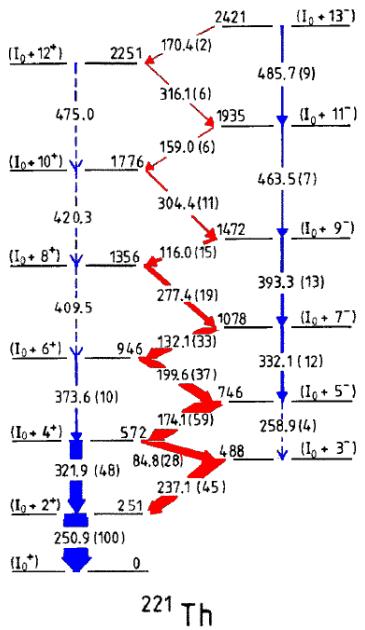
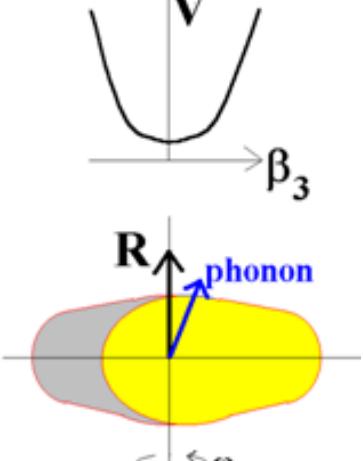
# Prospects for measuring $^{226,228}\text{U}$

$^{226}\text{U}$



PT Greenlees et al J. Phys. G: Nucl. Part. Phys. 24 (1998) L63

# Octupole collectivity in odd-mass nuclei



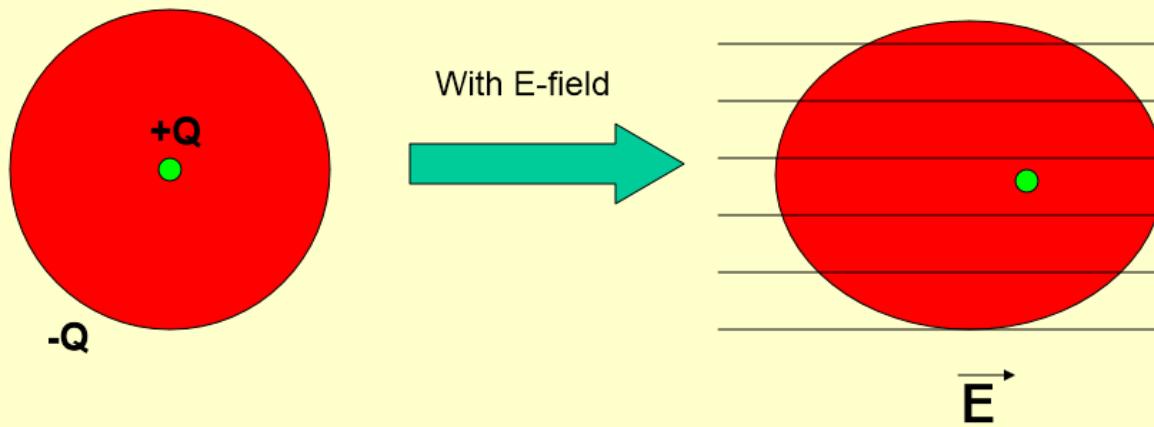
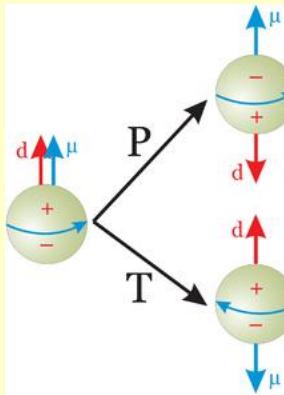
Smaller octupole correlations  
Large parity splitting

Large octupole correlations  
Small parity splitting  $\sim 50$  keV

*M Dahlinger et al* Nucl. Phys. A484 (1988) 337

# Neutron and Atomic EDM moment

Static Electric Dipole Moment implies CP-violation



**Schiff Theorem:** neutral atomic system of point particles in electric field readjusts itself to give zero E field at all charges.

**BUT:** finite size **and shape** of nucleus breaks the symmetry

# Octupole enhanced atomic EDM moment

See Next Talk!!

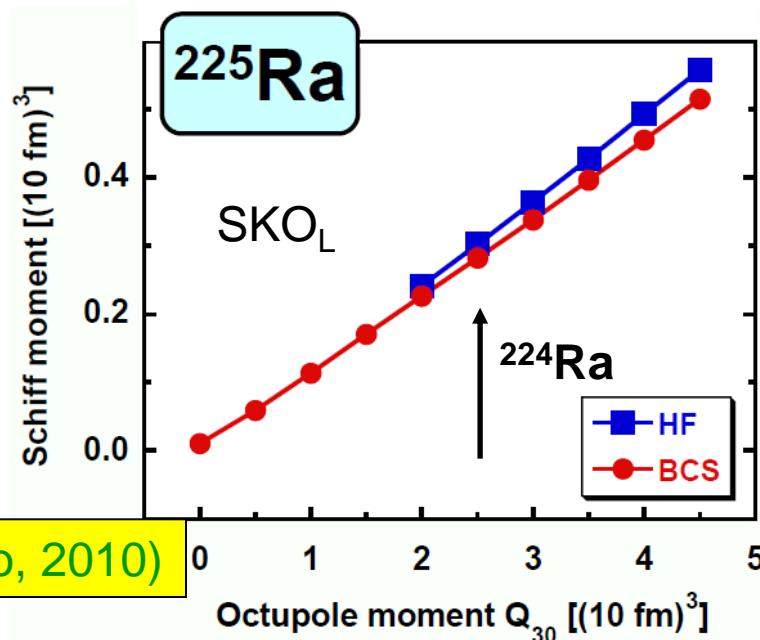
V Spevak, N Auerbach, and VV Flambaum  
PR C 56 (1997) 1357

related to  $Q_3$  P,T-violating n-n interaction

Schiff moment: 
$$S = -2 \frac{J}{J+1} \frac{\langle \hat{S}_z \rangle \langle \hat{V}_{PT} \rangle}{\Delta E}$$

energy splitting of parity doublet

Schiff moment enhanced by ~ 3 orders of magnitude in pear-shaped nuclei



J Dobaczewski (Trento, 2010)

# Summary

Strong circumstantial evidence that some nuclei are pear-shaped



Odd mass octupole-deformed nuclei offer greatly increased sensitivity for EDM searches

CERN-ISOLDE  
Technische Universität Darmstadt  
University of Edinburgh  
**GANIL**  
University of Jyväskylä  
Universität zu Köln  
**KU Leuven**  
Laboratory Lawrence Livermore NL  
University of Liverpool

University of Lund  
Universidad Autónoma de Madrid  
University of Michigan  
Ludwig-Maximilians-Universität and  
Technische Universität München  
**SCK CEN**  
University of Rochester  
University of Warsaw, Heavy Ion Lab  
University of York

## NewStatesman

"Last year's discovery has left the scientists there a little deflated because the Higgs has turned out to be a boring, just-as-they-predicted kind of particle. The nucleus of the radium atom, on the other hand, is much more interesting."