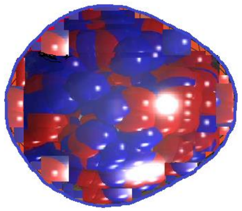
Pear-shaped nuclei and CP-violation

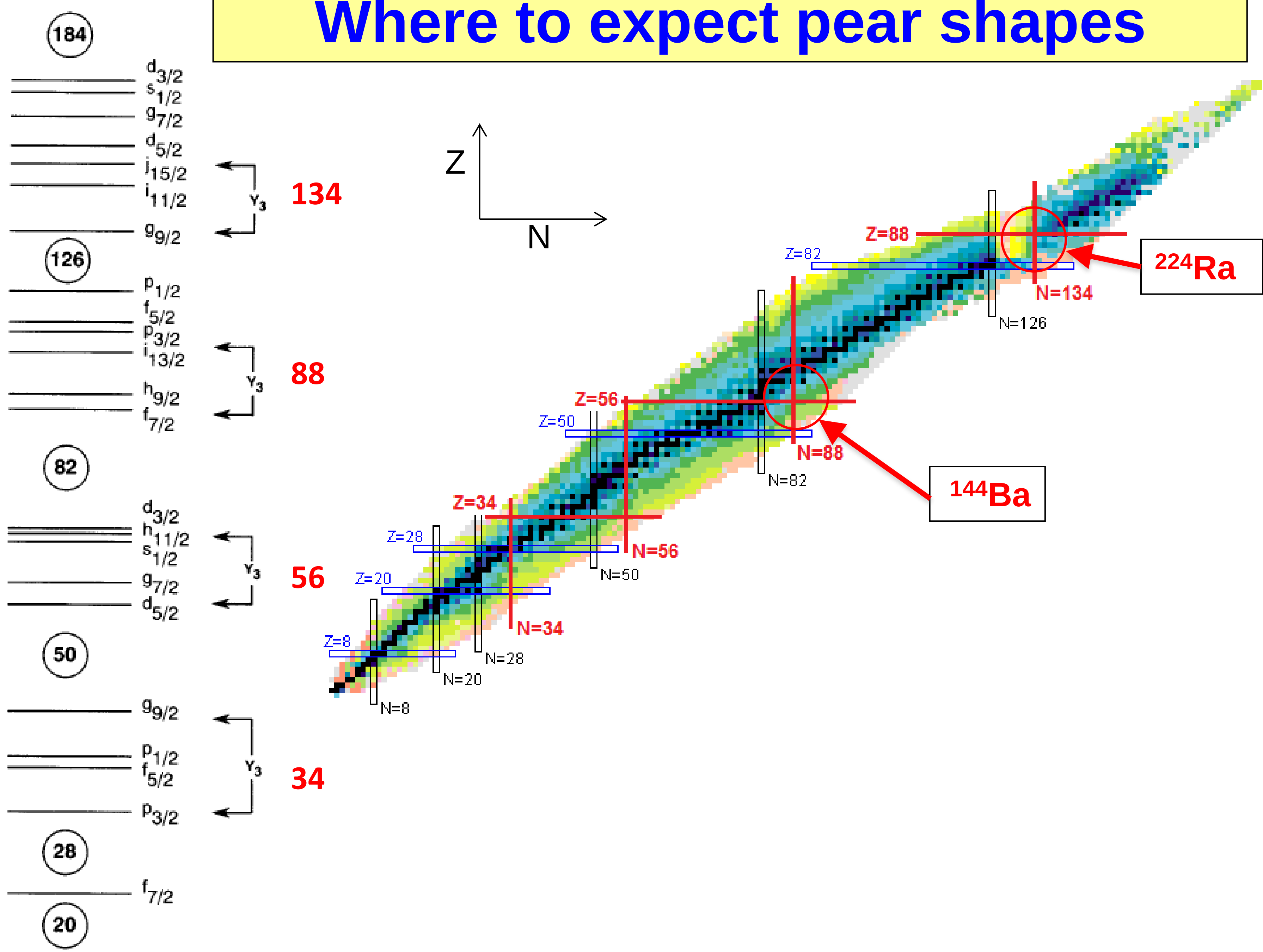


Peter Butler

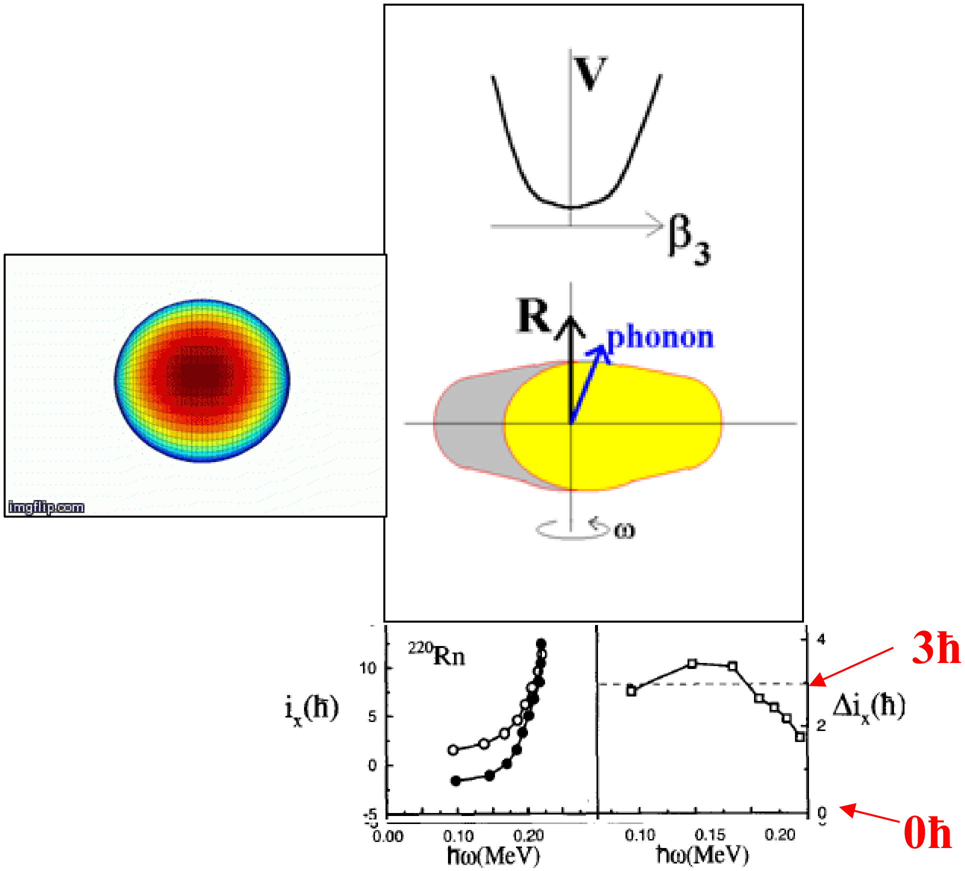
Department of Physics

University of Liverpool

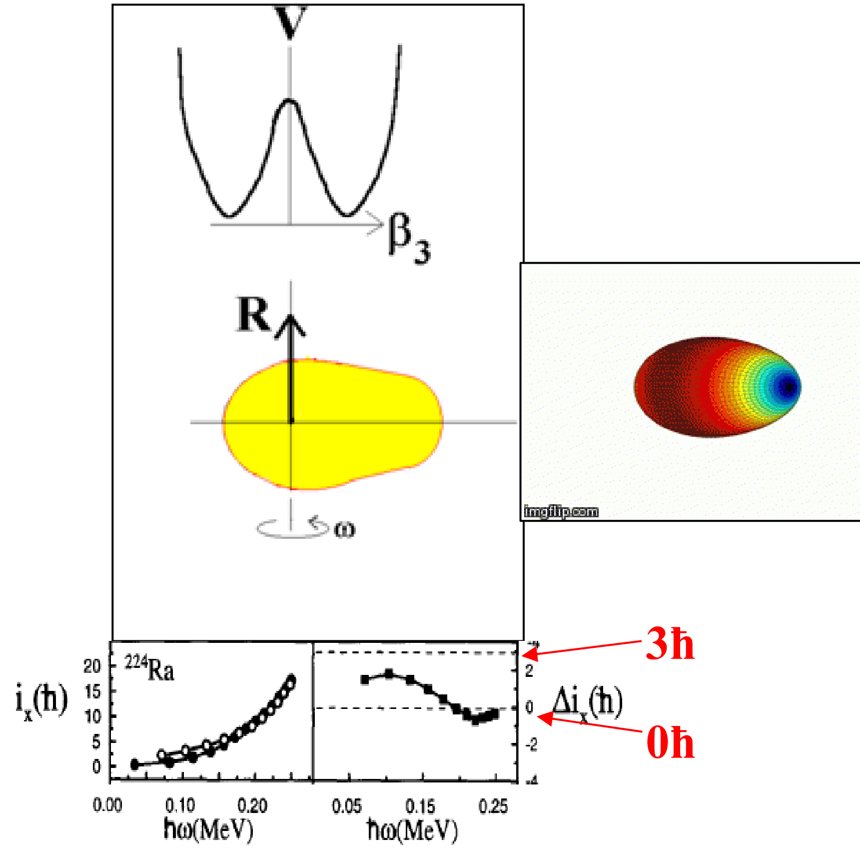
Where to expect pear shapes



Rotating pear shapes

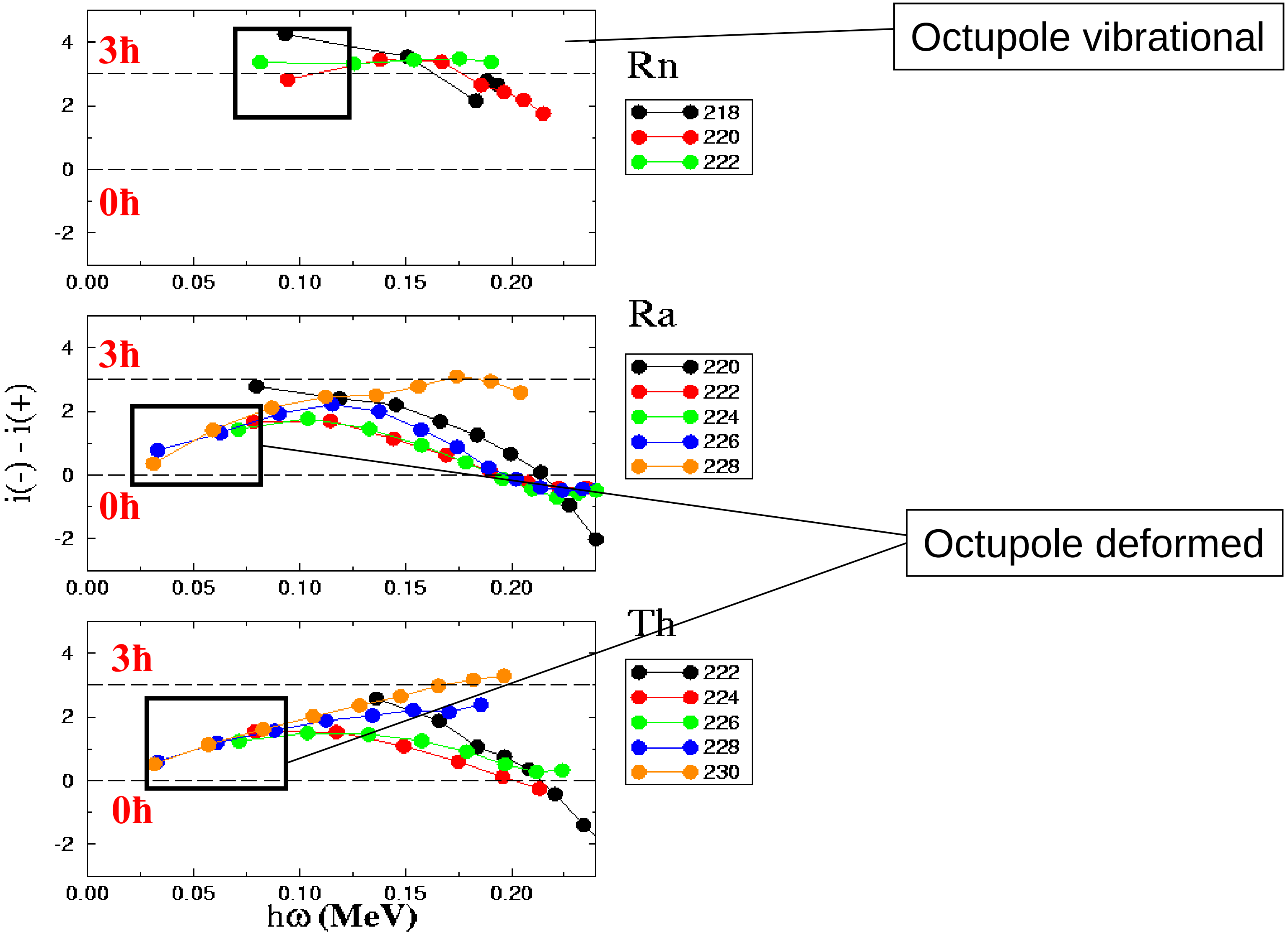


Octupole vibrational



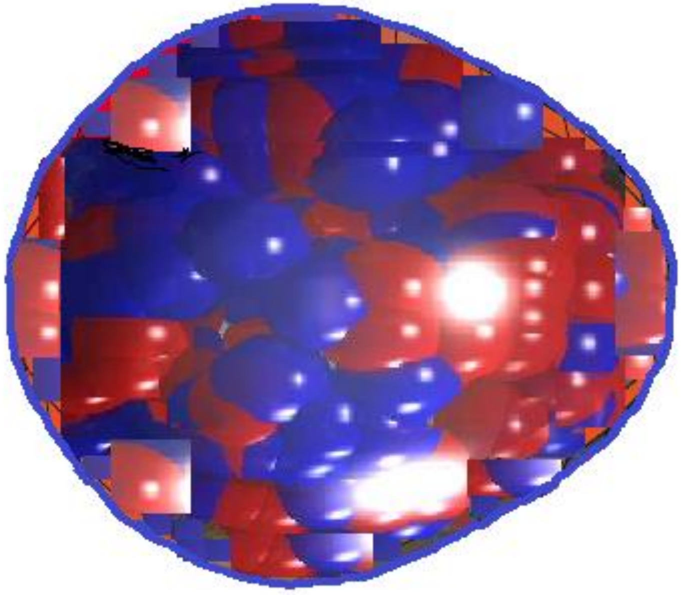
Octupole deformed

Alignment of octupole bands: actinides



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

Electric octupole transitions



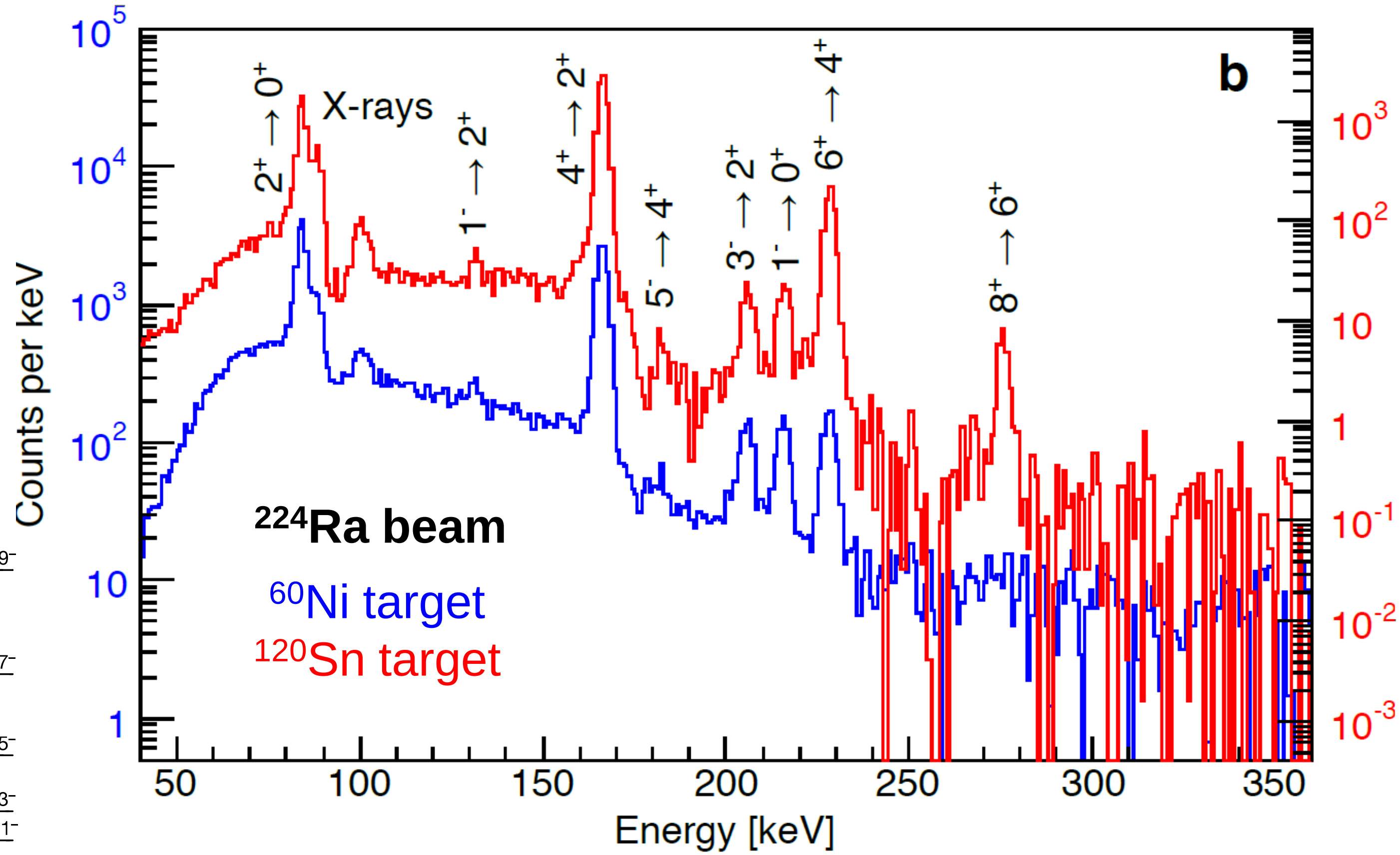
$$Q_3 = \frac{3}{\sqrt{7\pi}} ZeR_0^3 \overline{\beta}_3$$

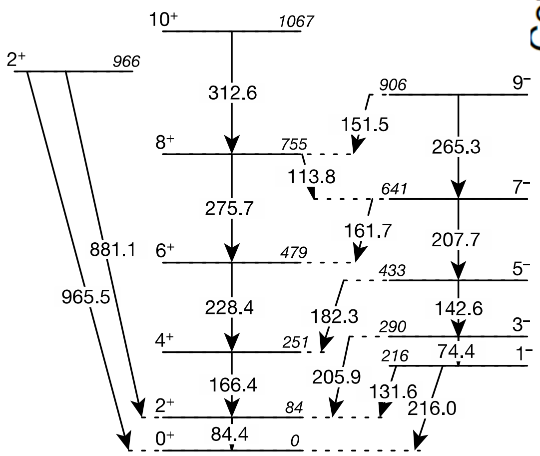
E3 transition moment ~ **50** single particle units for β_3 ~ 0.1

Strong indication of octupole deformation

Coulomb excitation of ^{224}Ra beam

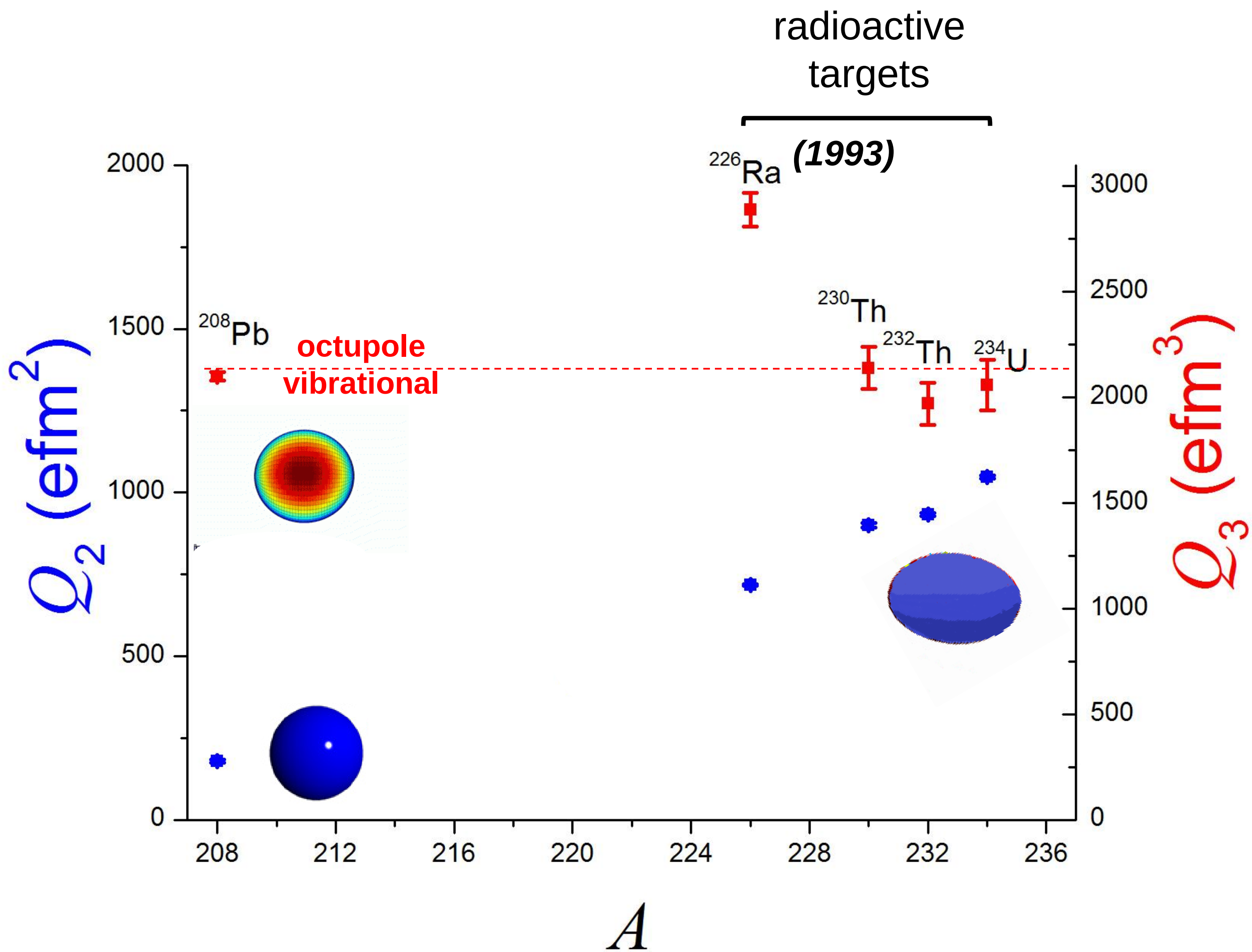
γ-ray spectrum taken
with MINIBALL & REX-ISOLDE



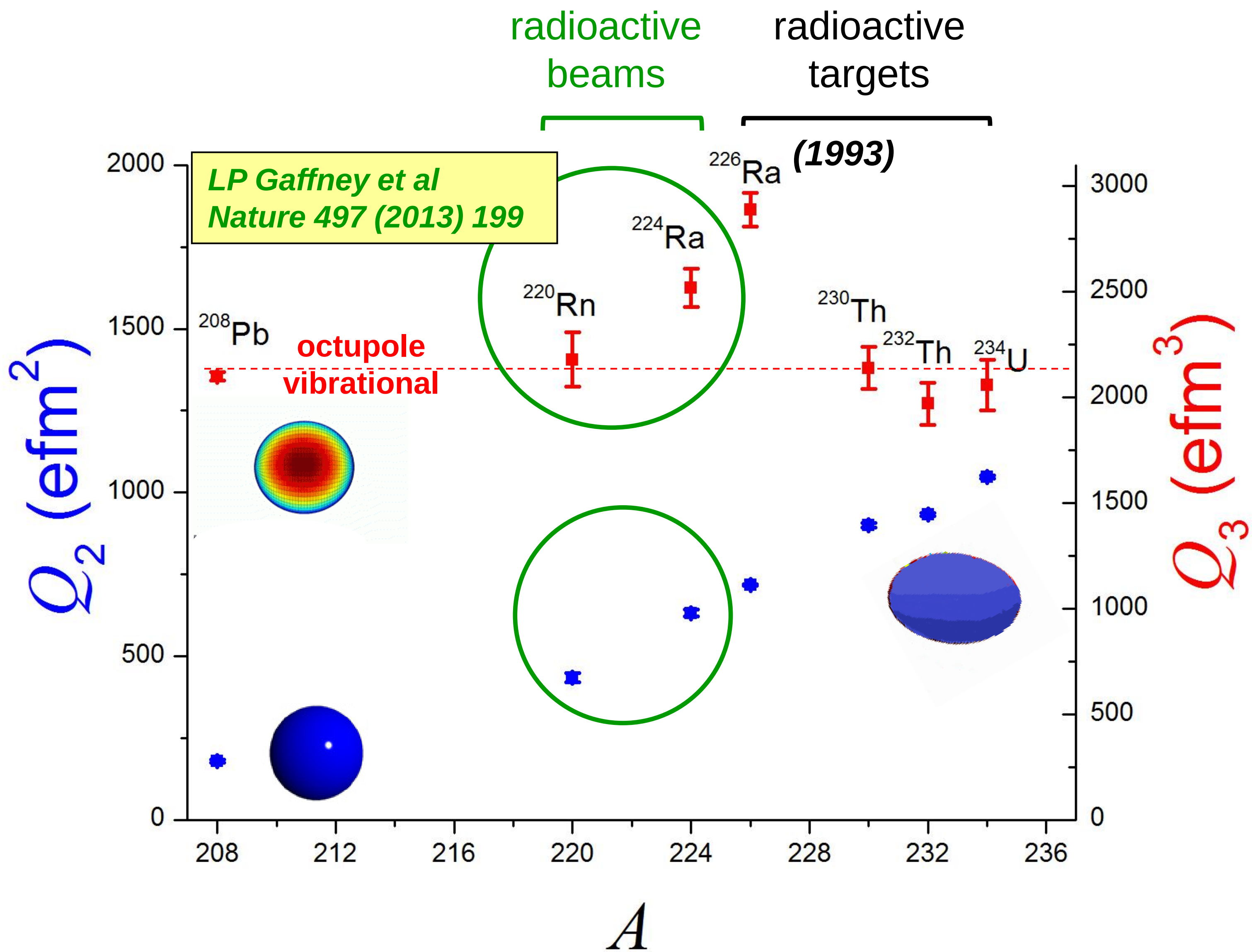


224Ra

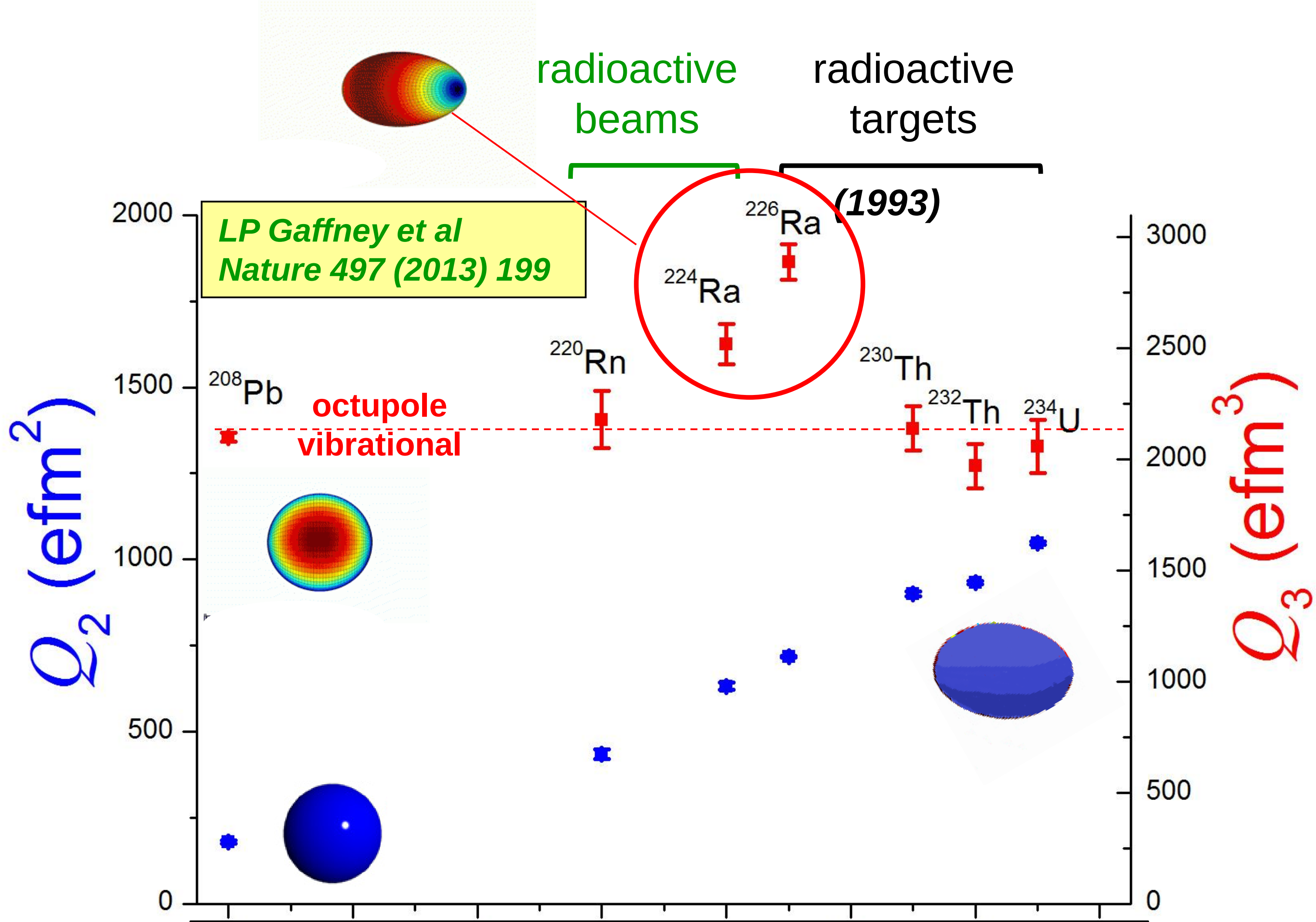
E2 and E3 moments for heavy nuclei



E2 and E3 moments for heavy nuclei



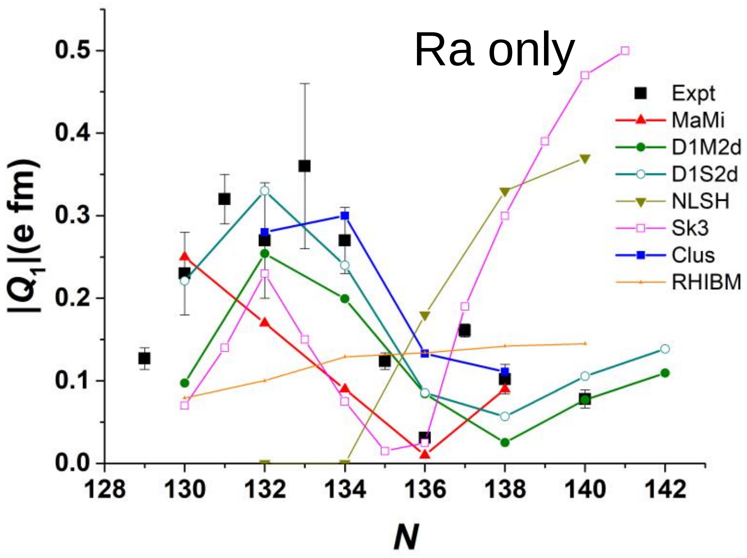
E2 and E3 moments for heavy nuclei

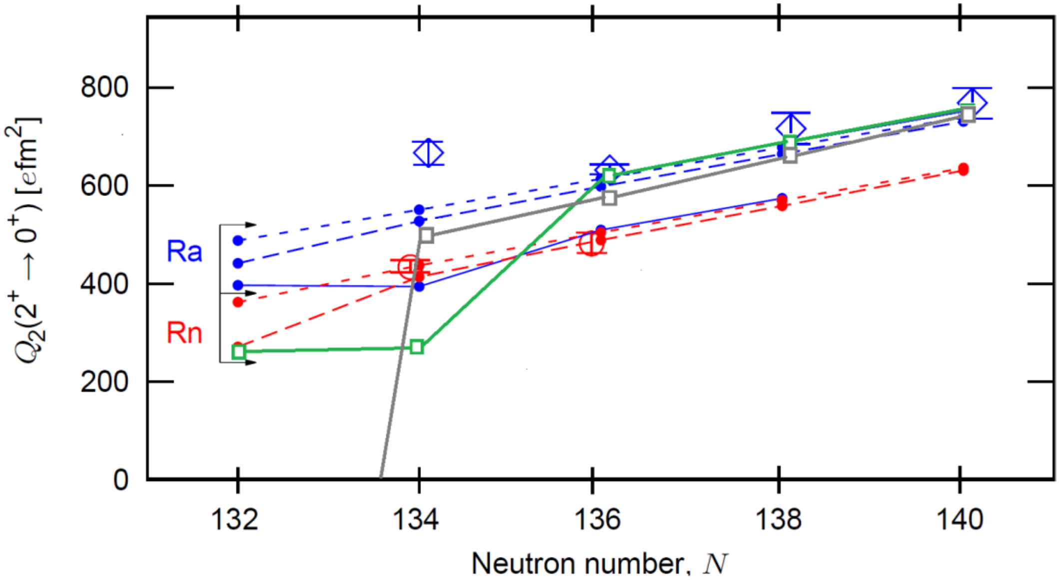


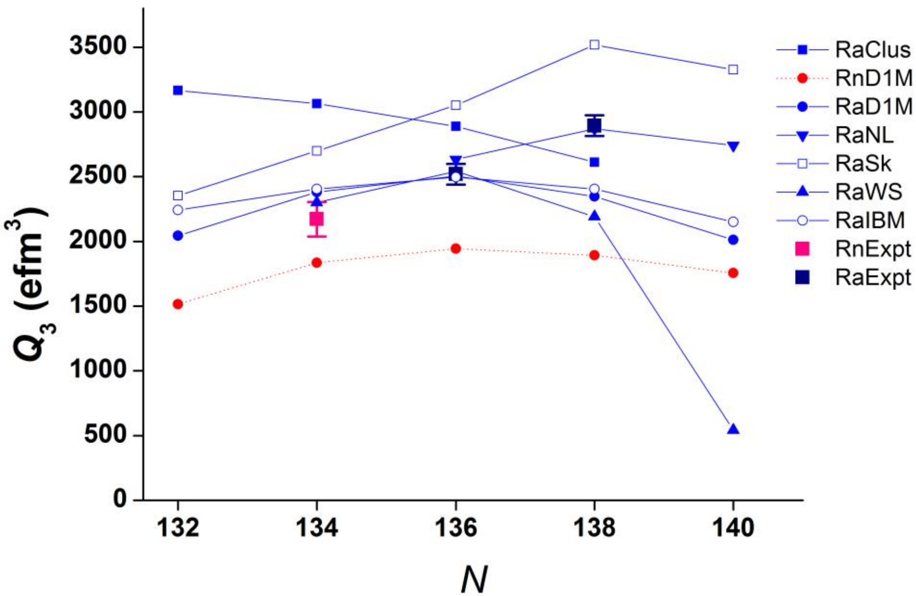
NewStatesman

The Higgs boson was small beer. Exploring the properties of the fruit-shaped nucleus could finally reveal the reason for our existence.

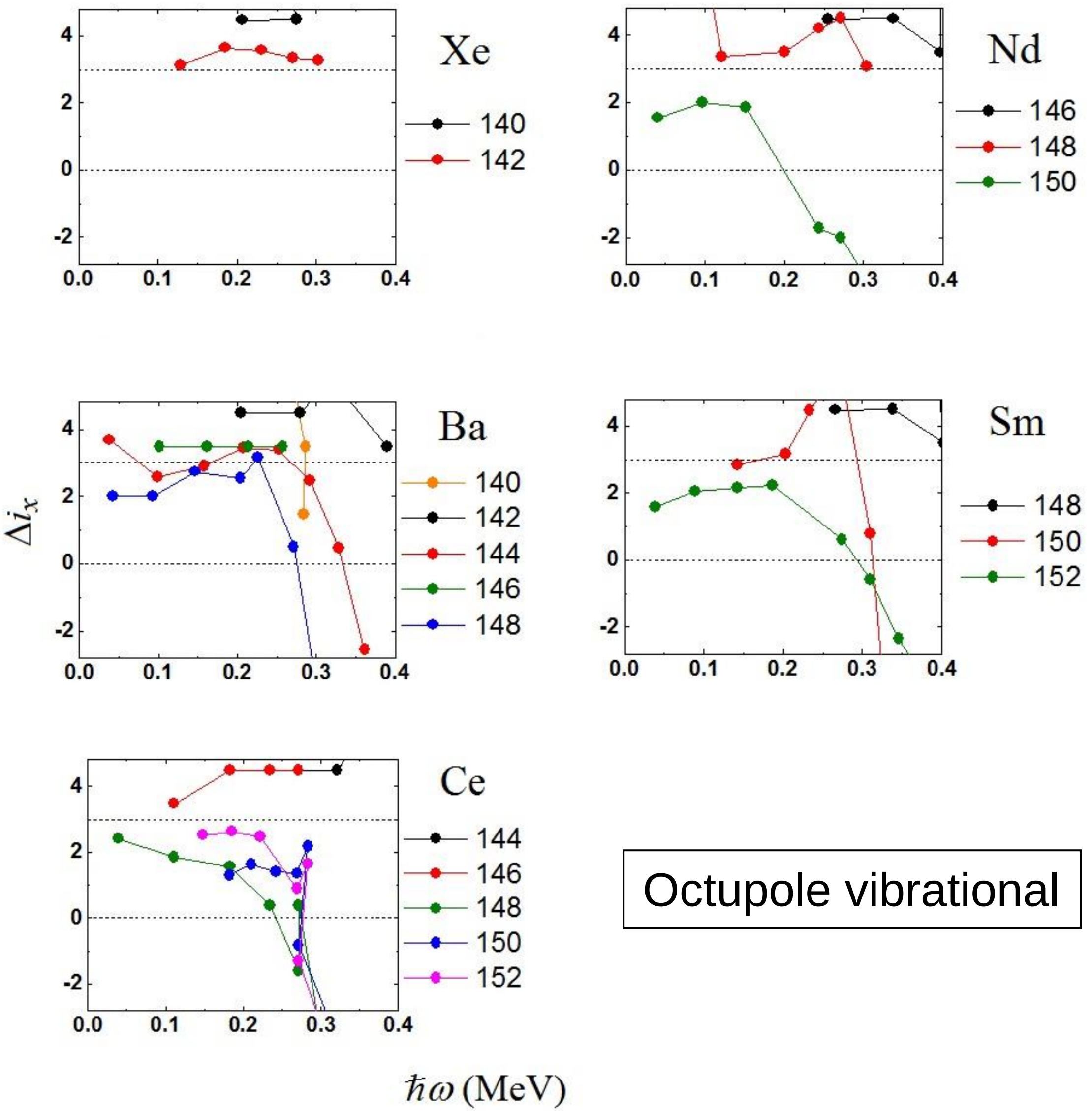
Comparison with theory



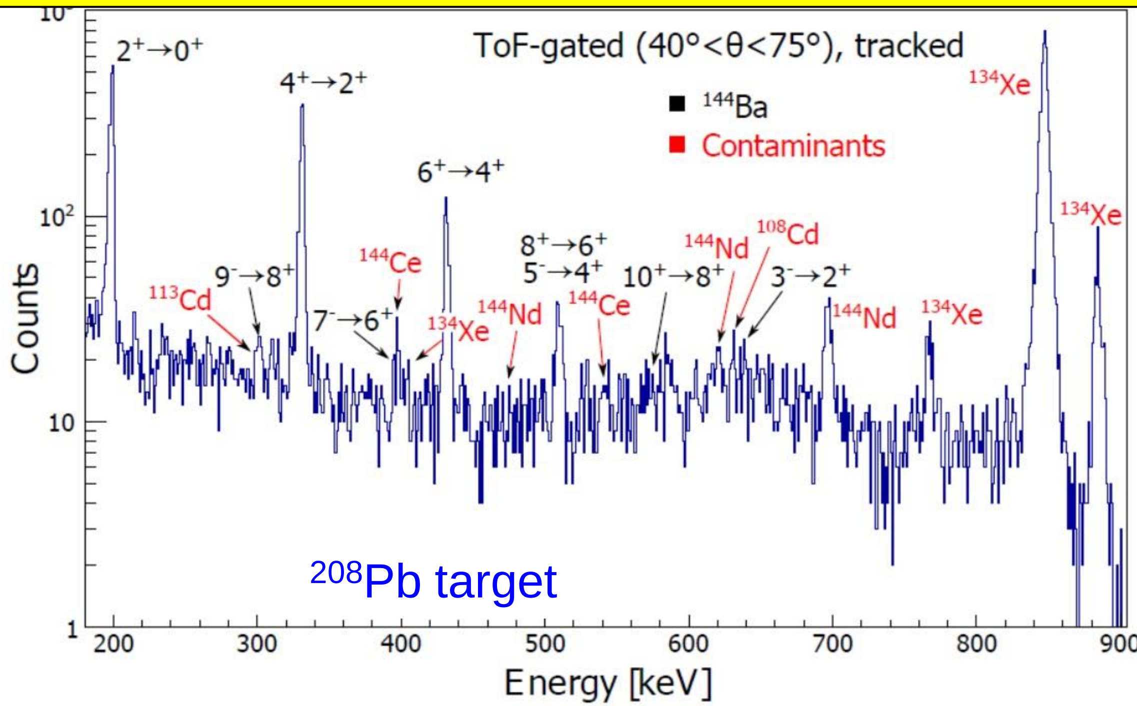




Alignment of octupole bands: lanthanides



Octupole moments in Z>50, N~88 region: ^{144}Ba

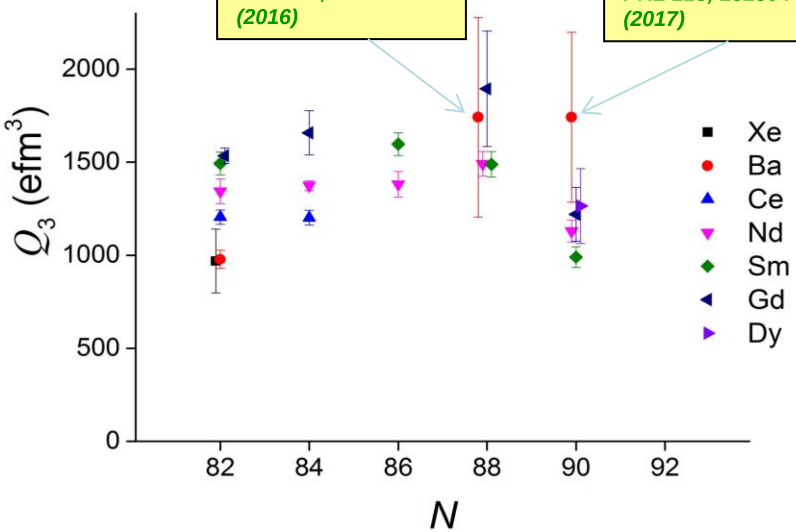


CARIBU
Argonne National Lab.

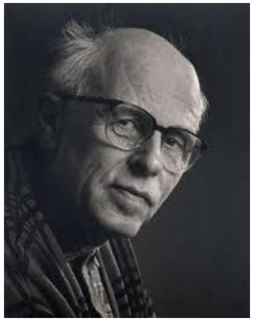
8x10^3 /s 4.5 MeV.A ^{144}Ba

B Bucher et al. PRL 116, 112503 (2016)

B Bucher et al. PRL 118, 152504 (2017)



Matter – Antimatter Difference in the Universe



A. Sakharov

Sakharov conditions require CP symmetry violation.

CP violation is observed in electro-weak interaction (e.g. neutral kaons) while *as yet* there is no evidence for sizeable CP violation in strong interaction. Everything is, so far, as predicted by Standard Model.

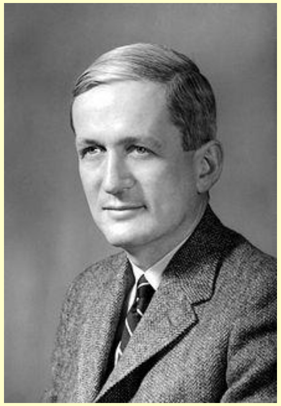
Excess baryons/ photons in the Universe is 6×10^{-10} ; SM predicts 10^{-18}

Need to go "Beyond the Standard Model" (BSM), or …

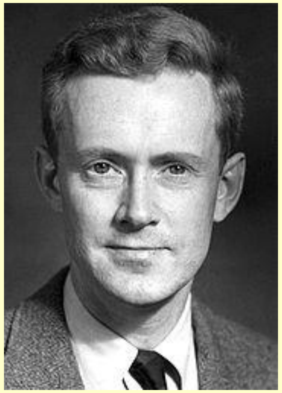
CP violation in the lepton sector is not known, could also account for matter-antimatter difference (e.g. NOvA experiment is measuring CP phase)

Neutron and Atomic EDM moment

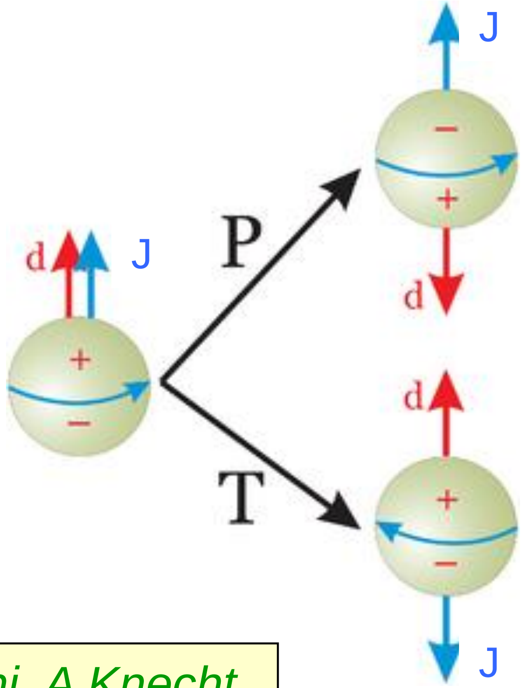
Static Electric Dipole Moment implies CP-violation



N. Ramsey



E. Purcell

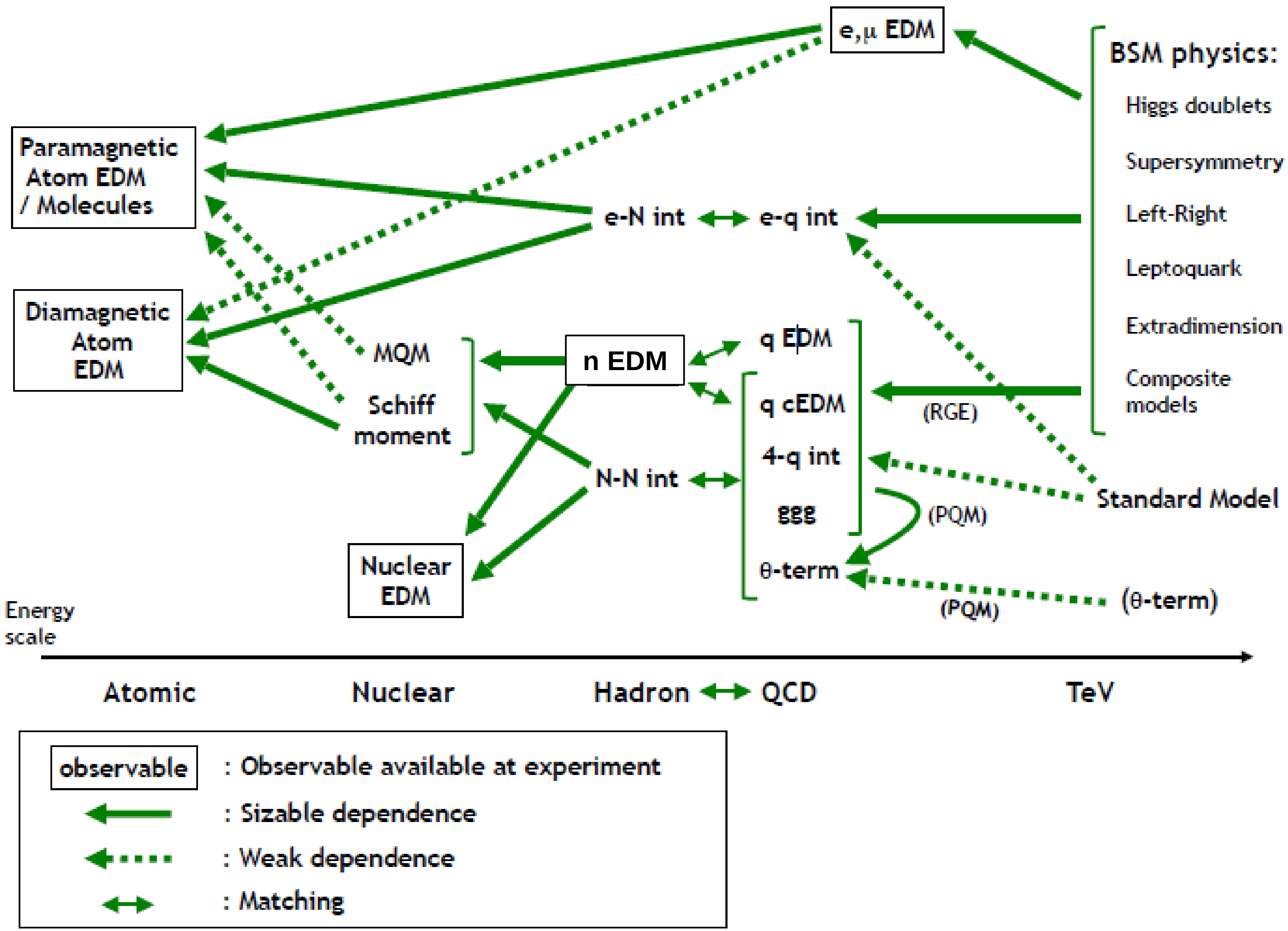


Parity violation

Time reversal invariance violation ➔ CP violation

See also talk by M Viviani, A Knecht

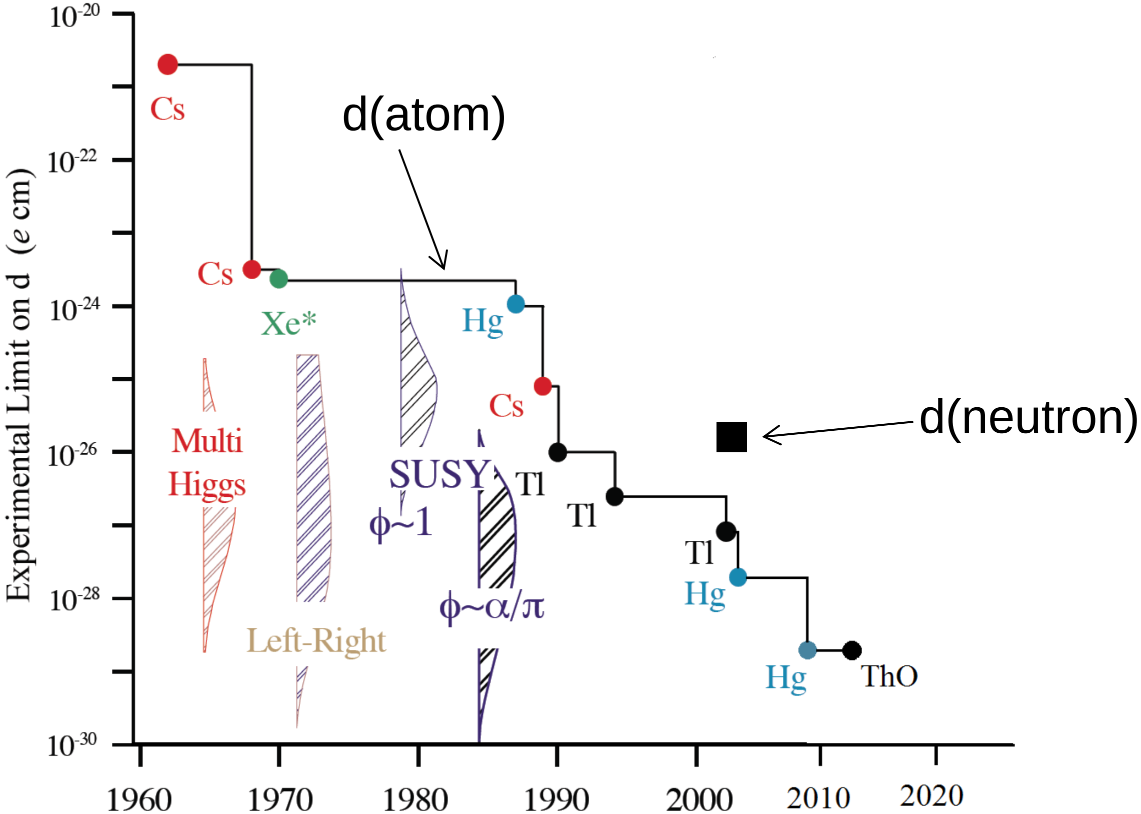
Dependence of atomic EDMs on CP-violating processes

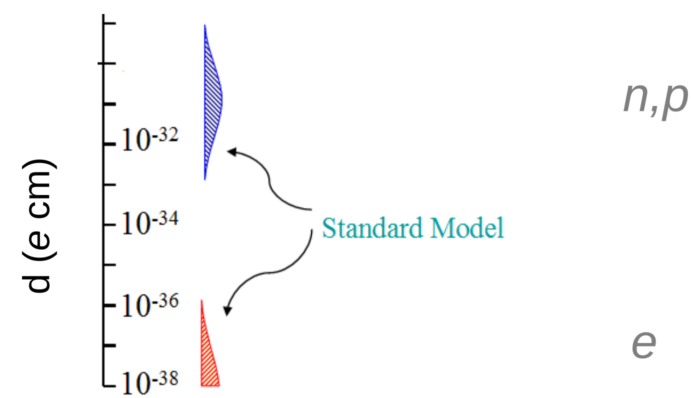


N Yamanaka et al.
Eur. Phys. J. A ***53*** *(2017) 54*

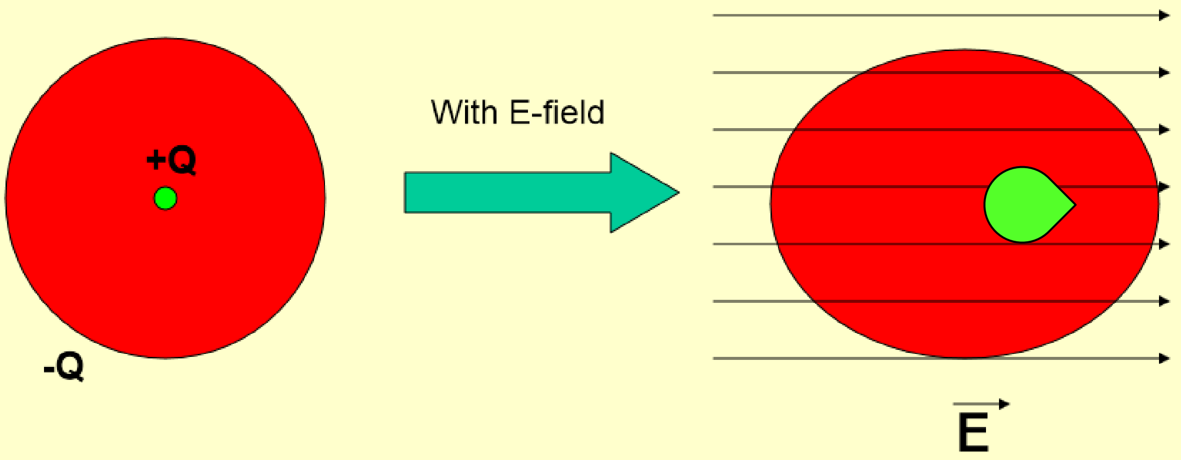
Experimental limits on EDMs

In many cases provides best test of extensions of the Standard Model that violate CP symmetry.





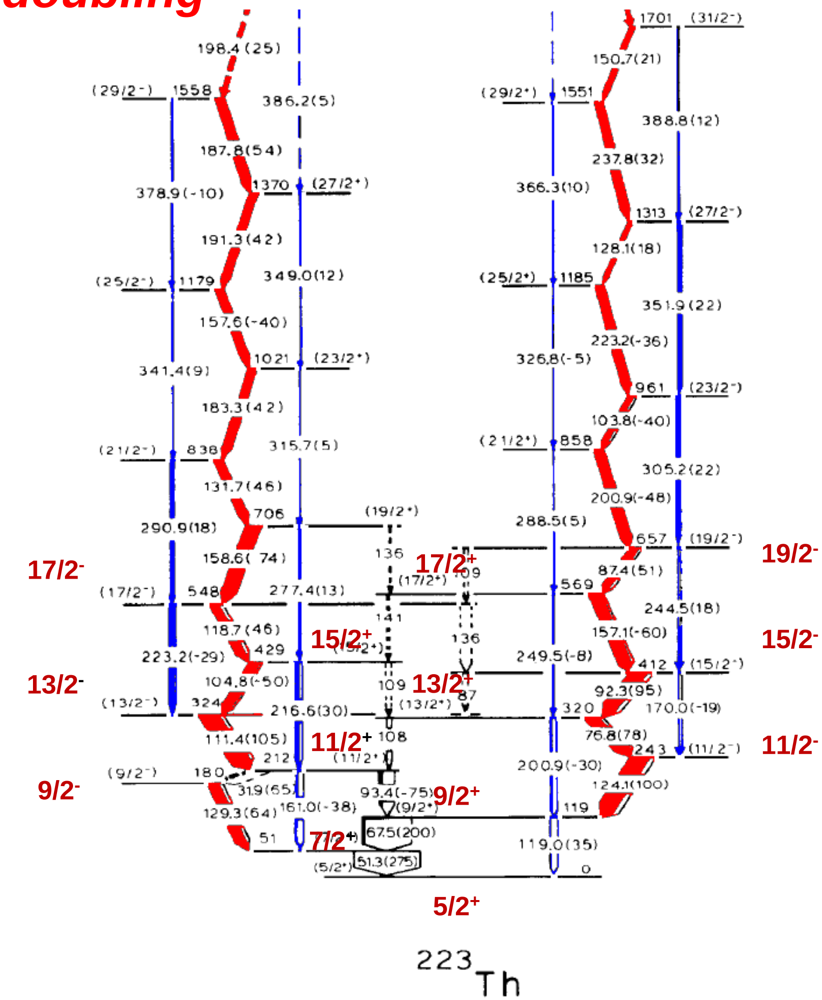
Schiff moment (atom)



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

Odd-mass nuclei with pear shapes

J = K$^{\pm}$, K+1$^{\pm}$, K+2$^{\pm}$ ***parity doubling***



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

Small parity splitting ~ 50 keV: see also ^{223}Ra, ^{225}Ra, ^{223}Ac, ^{225}Ac, ^{227}Ac and ^{227}Th

Octupole enhanced atomic EDM moment

related to Q_3

P,T-violating n-n interaction,etc

Schiff moment:

$$S = -2 \frac{J}{J+1} \frac{< \hat{S}_z >< \hat{V}_{PT} >}{\Delta E}$$

energy splitting of parity doublet

See, e.g.
WC Haxton & EM Henley
PRL **51** (1983) 1937
VV Flaumbaum & VG Zelevinsky
PRC **68** (2003) 035502
J Dobaczewski & J Engel
PRL **94** (2005) 232502
J Ellis, JS Lee & A Pilaftsis
JHEP **02** (2011) 045

Measured in ^{220}Rn, ^{224,226}Ra
(but not odd-A nuclei)

Measured in ^{223,225}Ra
(but not odd-A Rn)

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

See also talk by F Recchia

2016 EDM Limits

Prog. Part. Nuc. Phy. 71 (2013) 21; PHYSICAL REVIEW C 94, 025501 (2016) , Phys. Rev. Lett. 116, 161601 (2016)

System	Best Limit (2σ) 10^{-28} e*cm	SM estimate 10^{-28} e*cm	Method (Location)
Electron	0.9	$\sim 10^{-10}$	cold ThO beam (Harvard/Yale)
Neutron	300	$\sim 10^{-4}$	UCN in bottle (ILL)
Nuclear	0.074	$\sim 10^{-7}$	Hg atoms in vapor cell (Washington-Seattle)

Nuclear	Best Limit (2σ) 10^{-28} e*cm	Long Term Goal	Goal on "Hg scale"	Method (Location)
Hg-199	0.074	0.010	0.010	Hg atoms in vapor cell (Washington-Seattle)
Xe-129	66	0.001	0.010	Xe/He gas mixture cell (Michigan)
Ra-225	140000	1.000	0.001	Ra atoms in a laser trap (Argonne)

Future Octupole EDM programme

^{225}Ra, ^{229}Pa?
[Argonne/MSU, Groningen]

ΔE ~ 50 keV
Q_3 known for ^{224,226}Ra

^{223}Rn
[TRIUMF]

ΔE not known
Q_3 known for ^{220}Rn

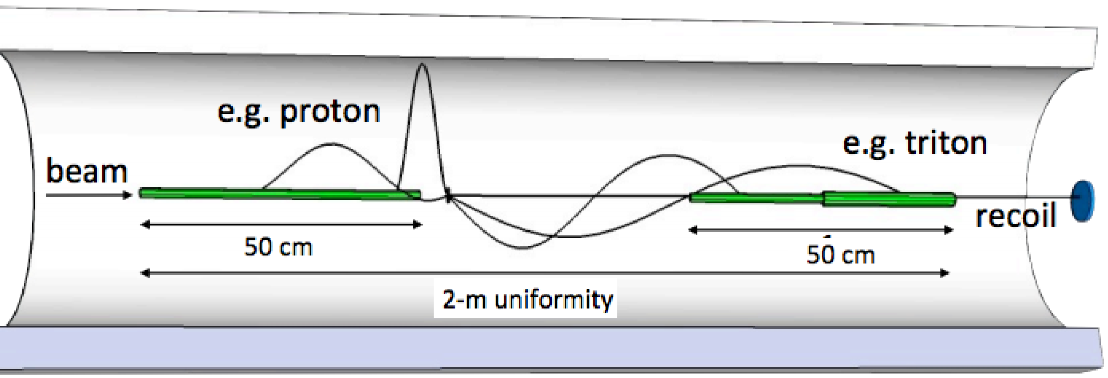
Nuclear Spectroscopy:

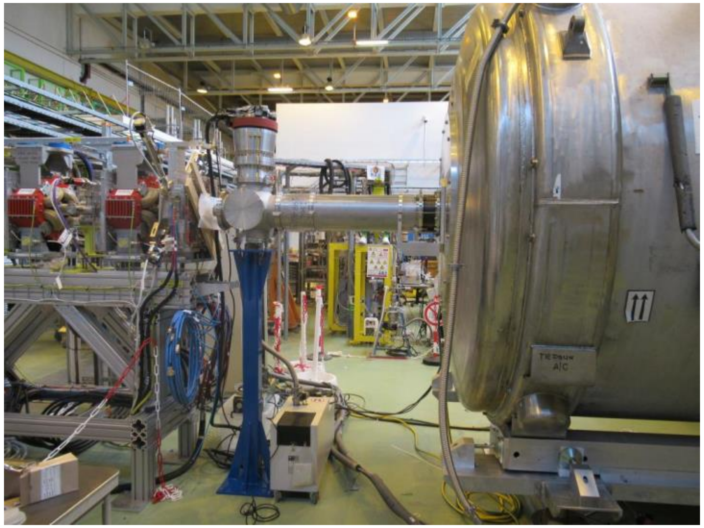
^{222,228}Ra - B(E3)s HIE-ISOLDE + MINIBALL

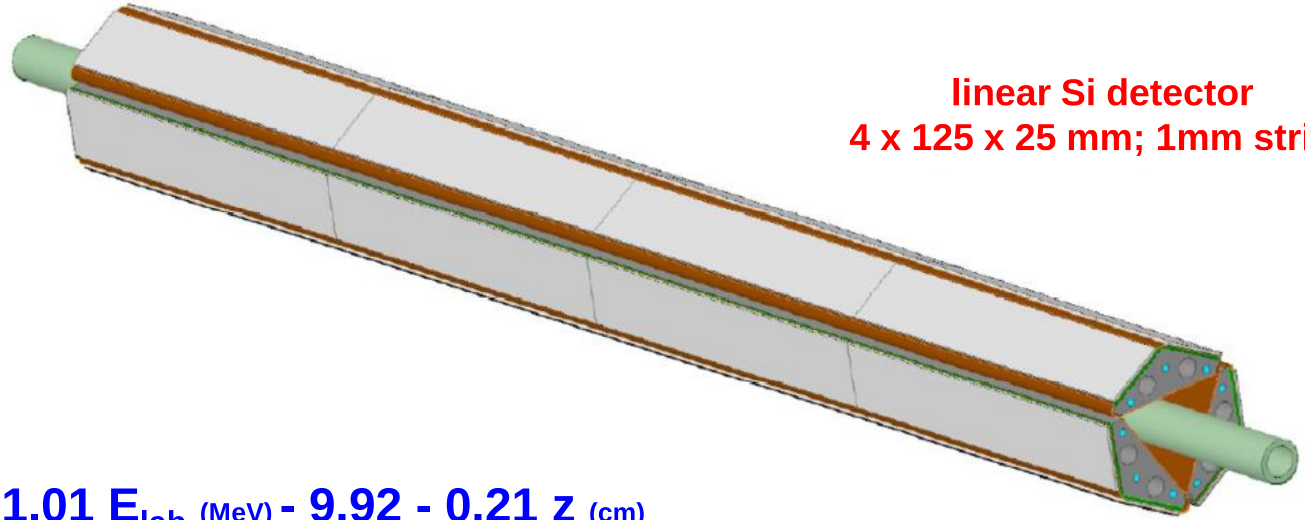
^{221,222,224,226}Rn - parity doublets in odd-A Rn?+ SPEDE

^{225}Ra- B(E3)s – *challenging* HIE-ISOLDE + ISS

Isol Solenoidal Spectrometer







linear Si detector
4 x 125 x 25 mm; 1mm strips

Q-value = 1.01 E_{lab} (MeV) - 9.92 - 0.21 z (cm)
for 10 MeV/u ^{132}Sn(d,p)

See also talk by D Santonocito

Measuring odd-A nuclei: ^{225}Ra parity doublet

$$\frac{d\sigma}{d\Omega} = \beta_\ell^2 |< I_A \ell K 0 | I_B >|^2 \sigma_{\mathrm{DWUCK}}$$

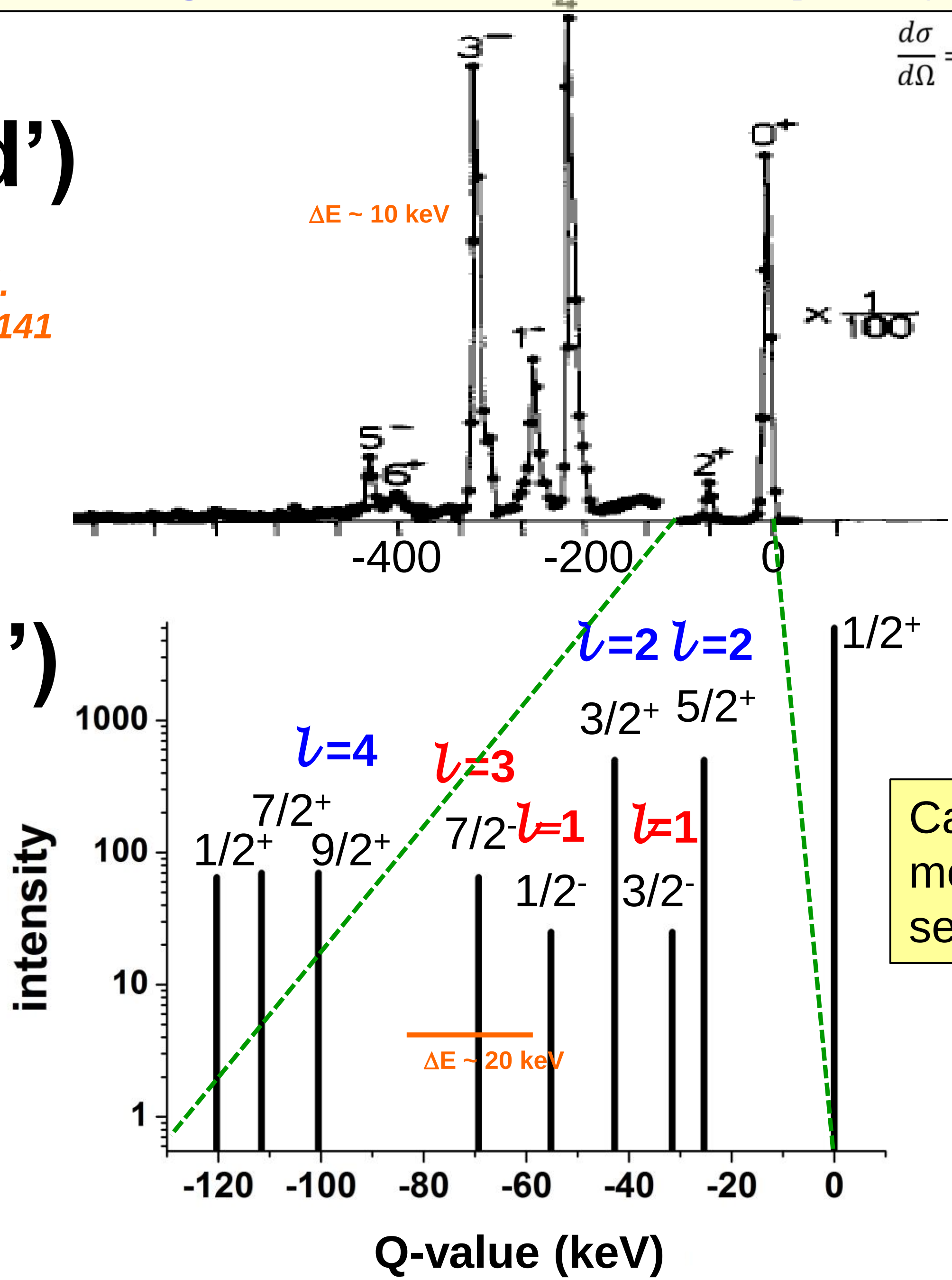
^{226}Ra(d,d')

actual data

Thorsteinsen et al.
Phys. Scr. 42 (1990) 141

^{225}Ra(d,d')

2023



Can also re-measure ^{144,146}Ba separation > 80 keV

Summary

Strong circumstantial evidence that some nuclei are pear-shaped

Best evidence comes from behaviour of energy levels and B(E3)s. Wide discrepancy of theories for this quantity.

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

Programme to extend B(E3) measurements in Rn, Ra and look for parity doubling in heavy Rn isotopes.