Studies of Pear-Shaped Nuclei

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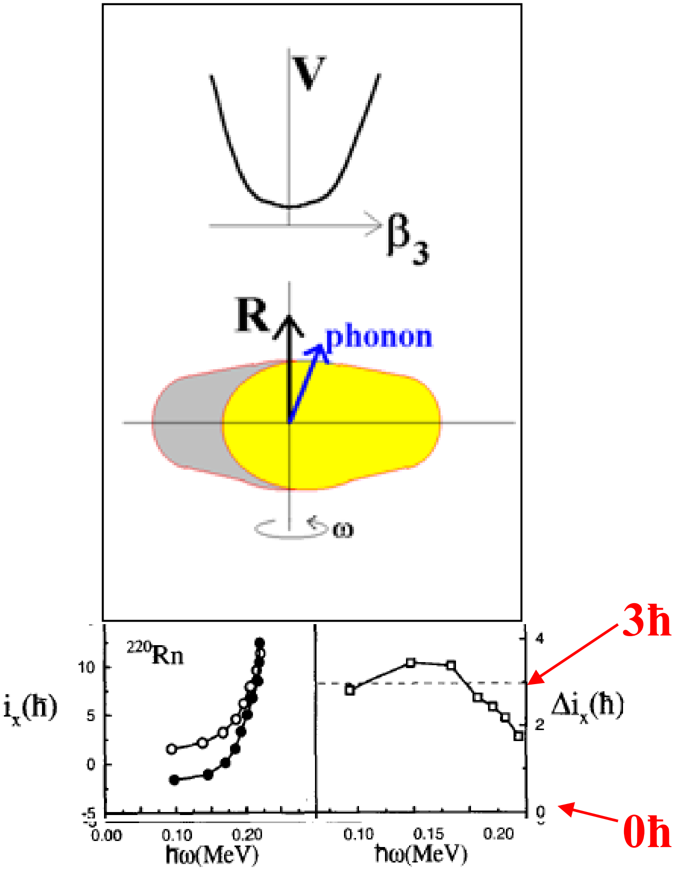
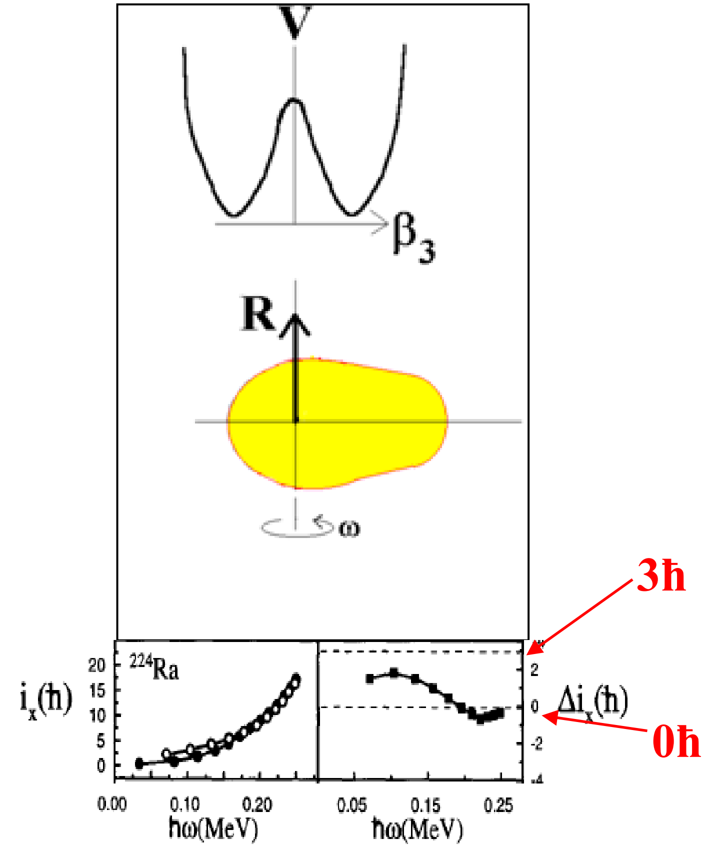
Introduction
Rotations
Eλ moments
Future prospects

Rotating octupole shapes



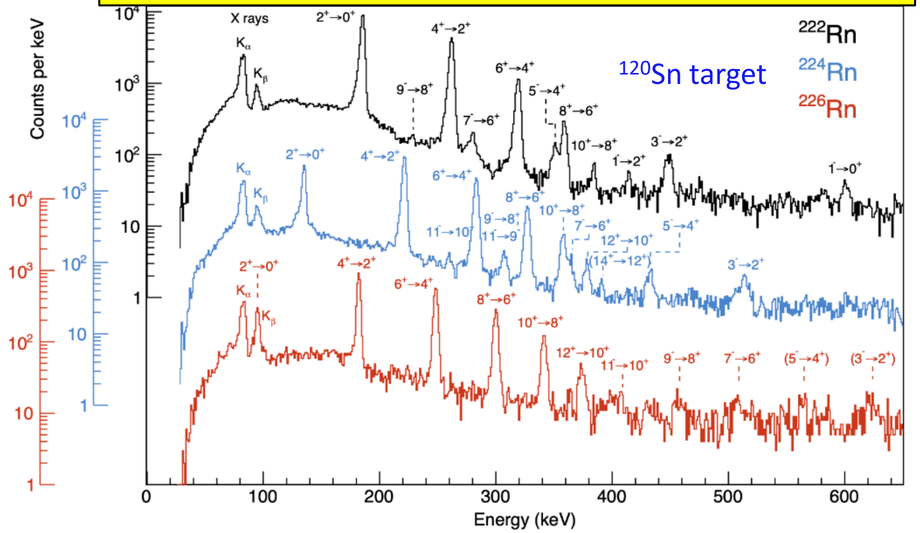
Octupole vibrational



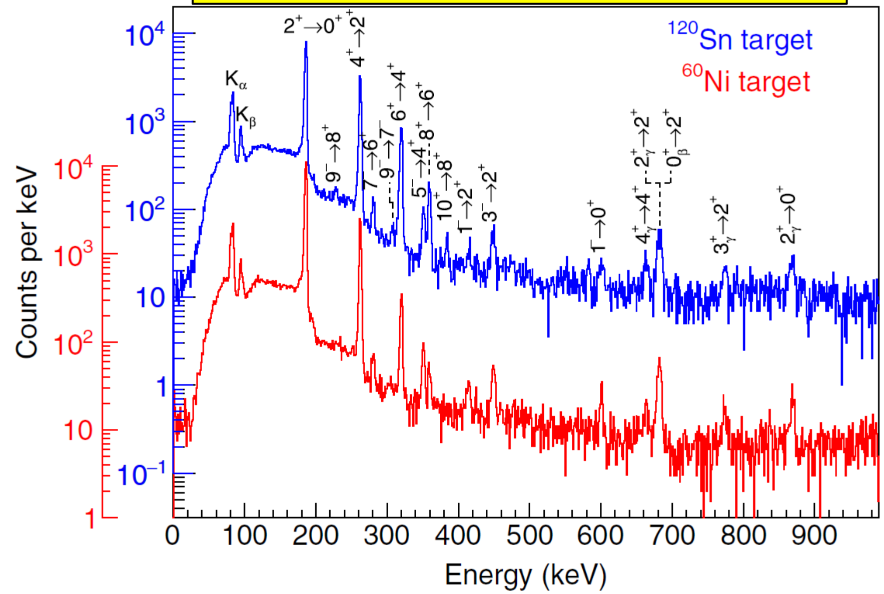
Octupole deformed

Coulex of Rn, Ra using HIE-ISOLDE & Miniball

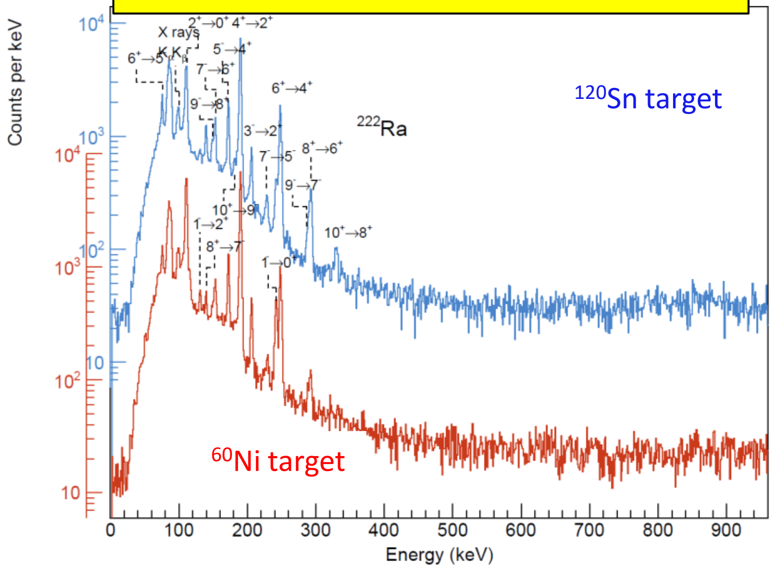
10^5 **^{224}Rn,** 10^3 **^{226}Rn** ions/s 5.08 MeV/u



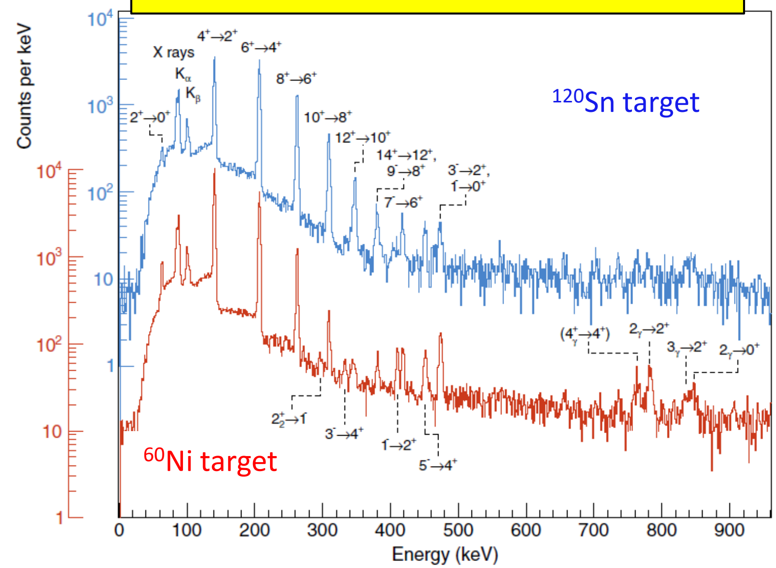
6x10^5 **^{222}Rn** ions/s 4.23 MeV/u



2x10^5 **^{222}Ra** ions/s 4.31 MeV/u

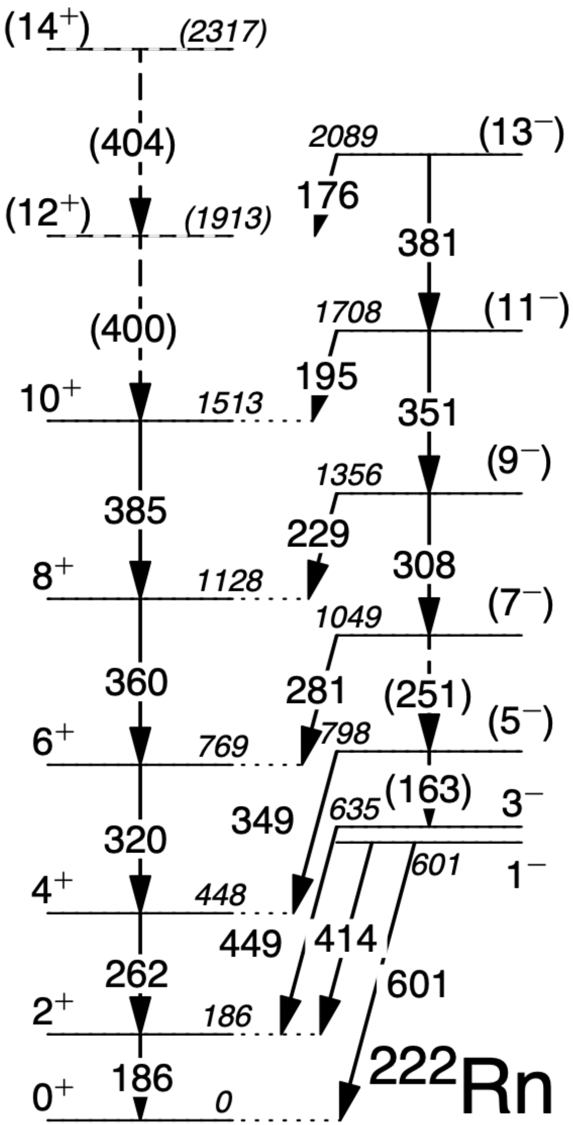


~10^5 **^{228}Ra** ions/s 4.31 MeV/u

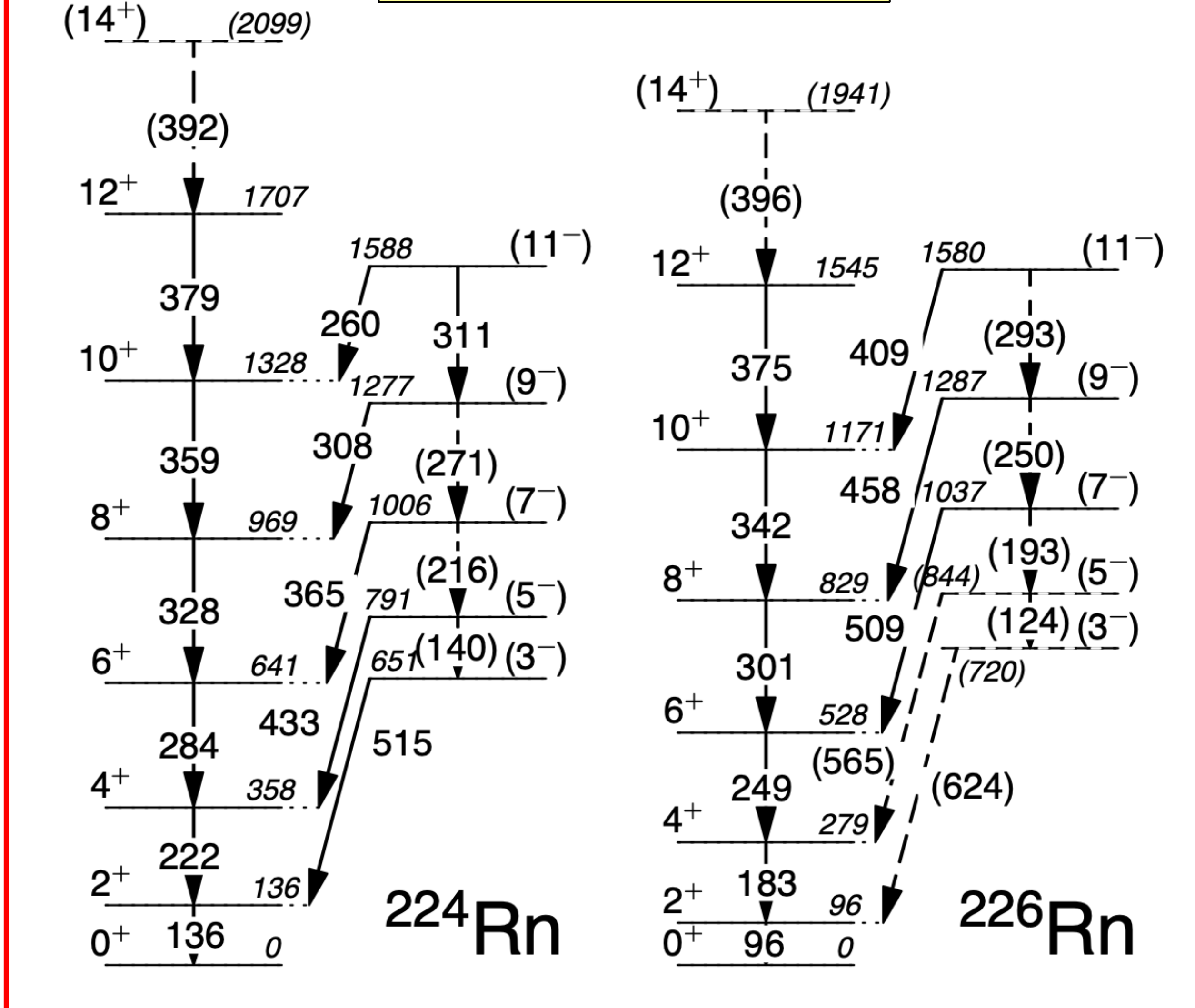


Level schemes Rn

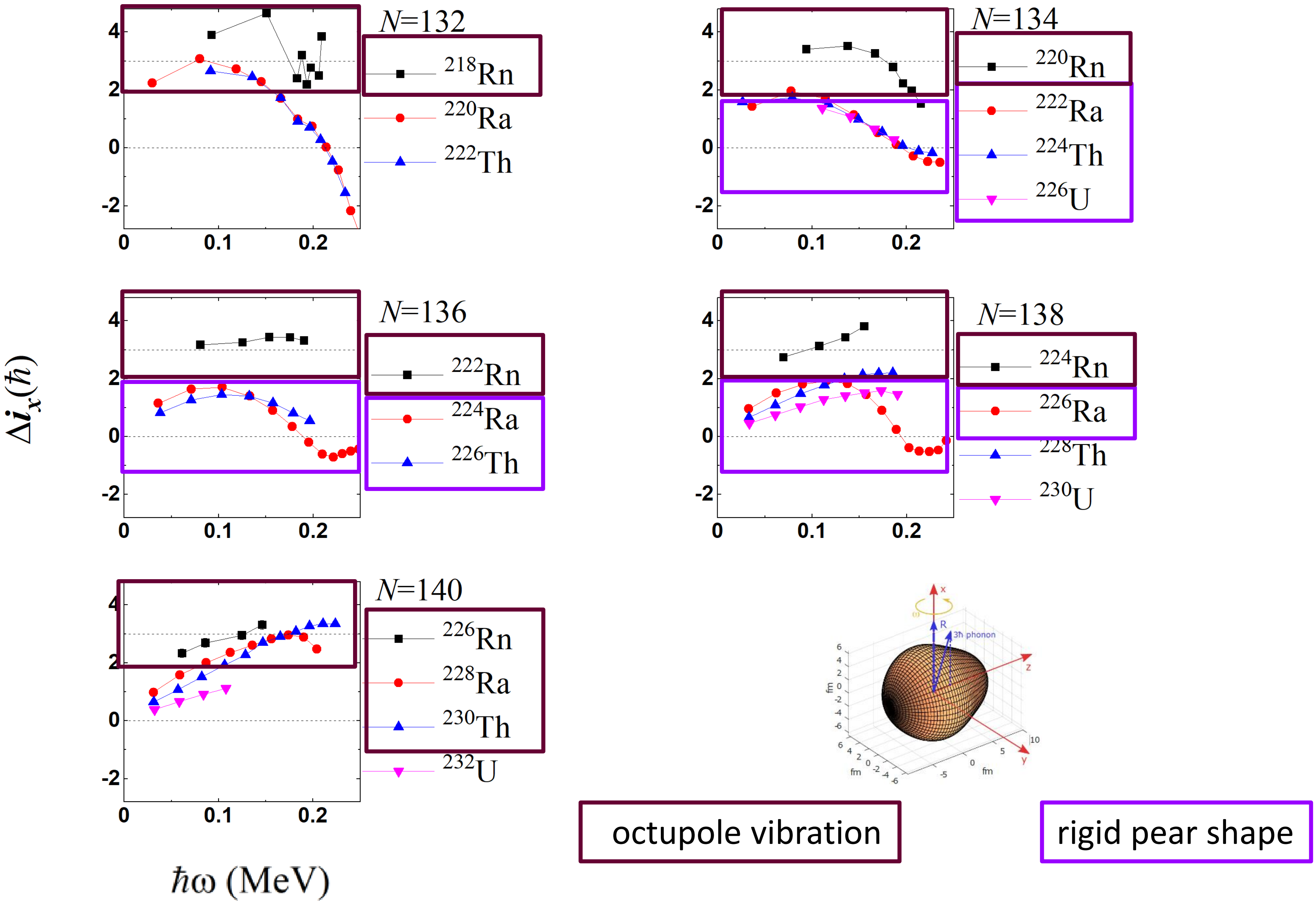
JFC Cocks et al
PRL 78 (1997) 2920



PA Butler et al.
Nat. Comm. 10 (2019) 2473,
Nat Comm. Add. 11 (2020) 3560

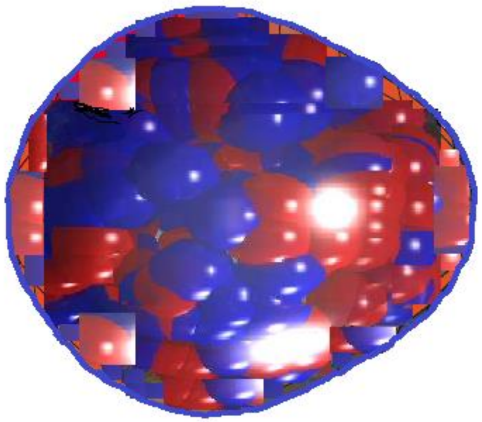


Rotating pear shapes



E3 moments

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

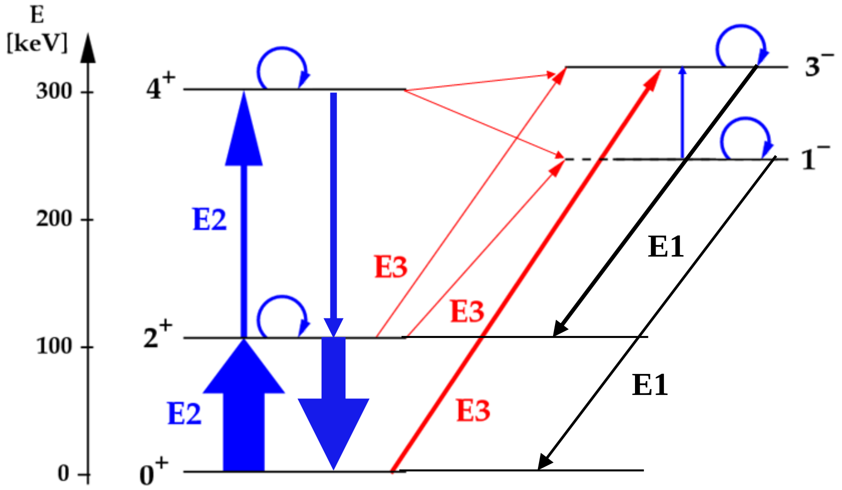


$$\overline{\beta}_3 = f(\beta_3, ...)$$

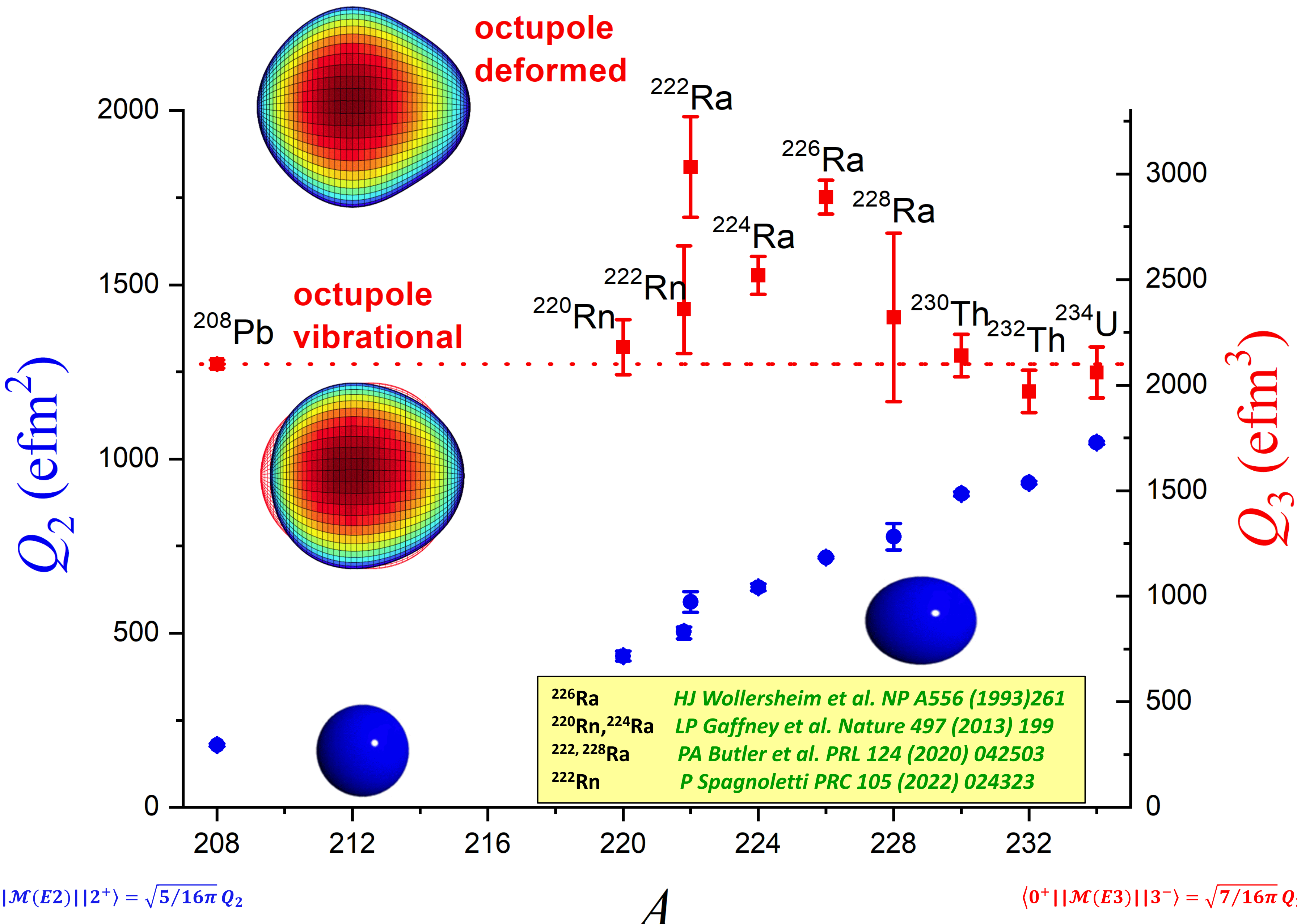
$$B(E3; I_i \to I_f) = \frac{7}{16\pi} < I_i 030 | I_f 0 >^2 Q_3^2$$

$B(E3; 0^+ \to 3^-)$ ~ **30 – 50** single particle units for β_3 ~ 0.1

$B(E1)$ ~ **$10^{-(2-3)}$** single particle units



E2 and E3 moments



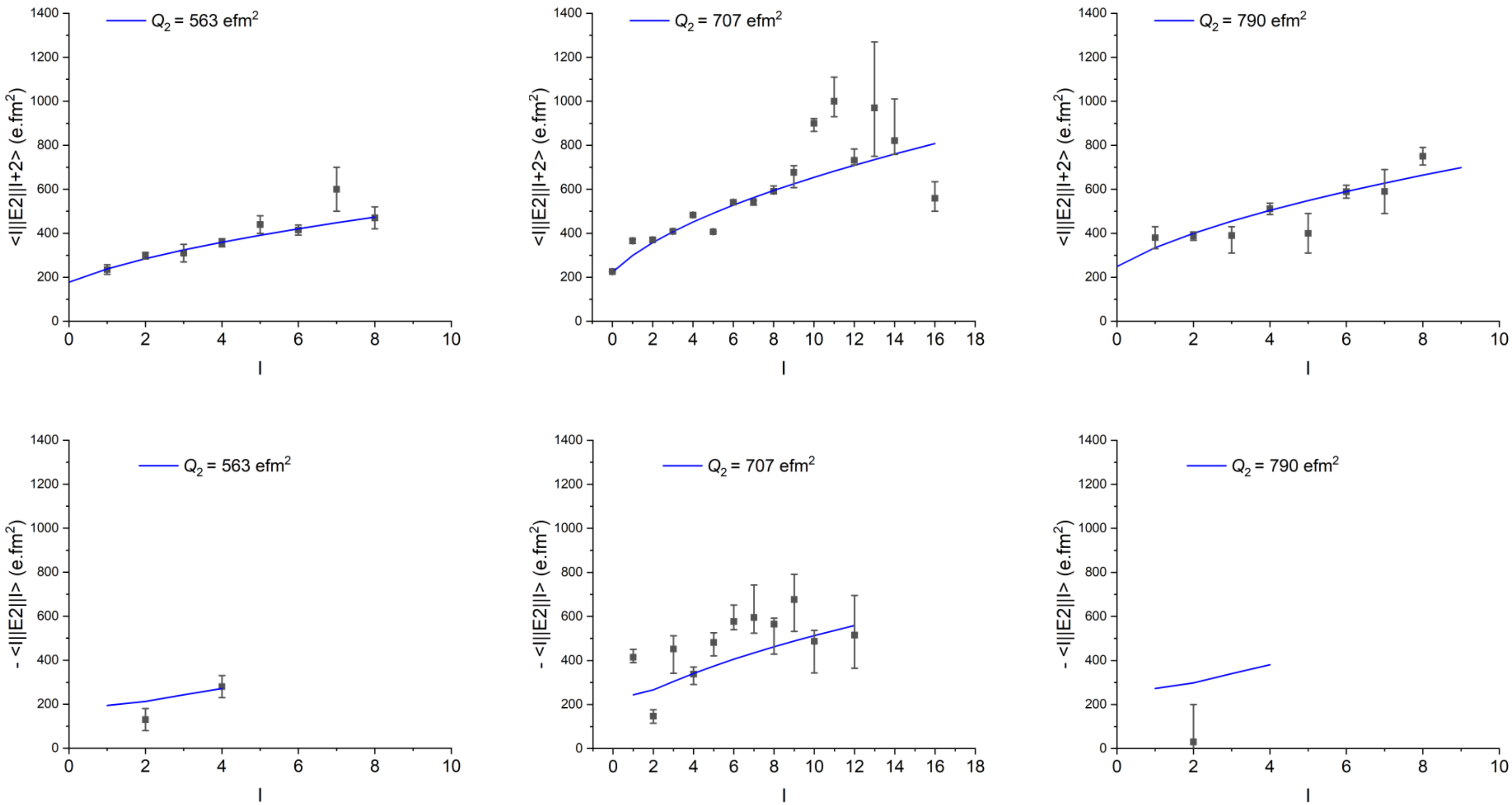
$\langle 0^+ || \mathcal{M}(E2) || 2^+ \rangle = \sqrt{5/16\pi}\, Q_2$

$\langle 0^+ || \mathcal{M}(E3) || 3^- \rangle = \sqrt{7/16\pi}\, Q_3$

Behaviour of Q_2 with I_i, I_f

See also ^{220,222}Rn, ^{224}Ra

^{222}Ra ^{226}Ra ^{228}Ra

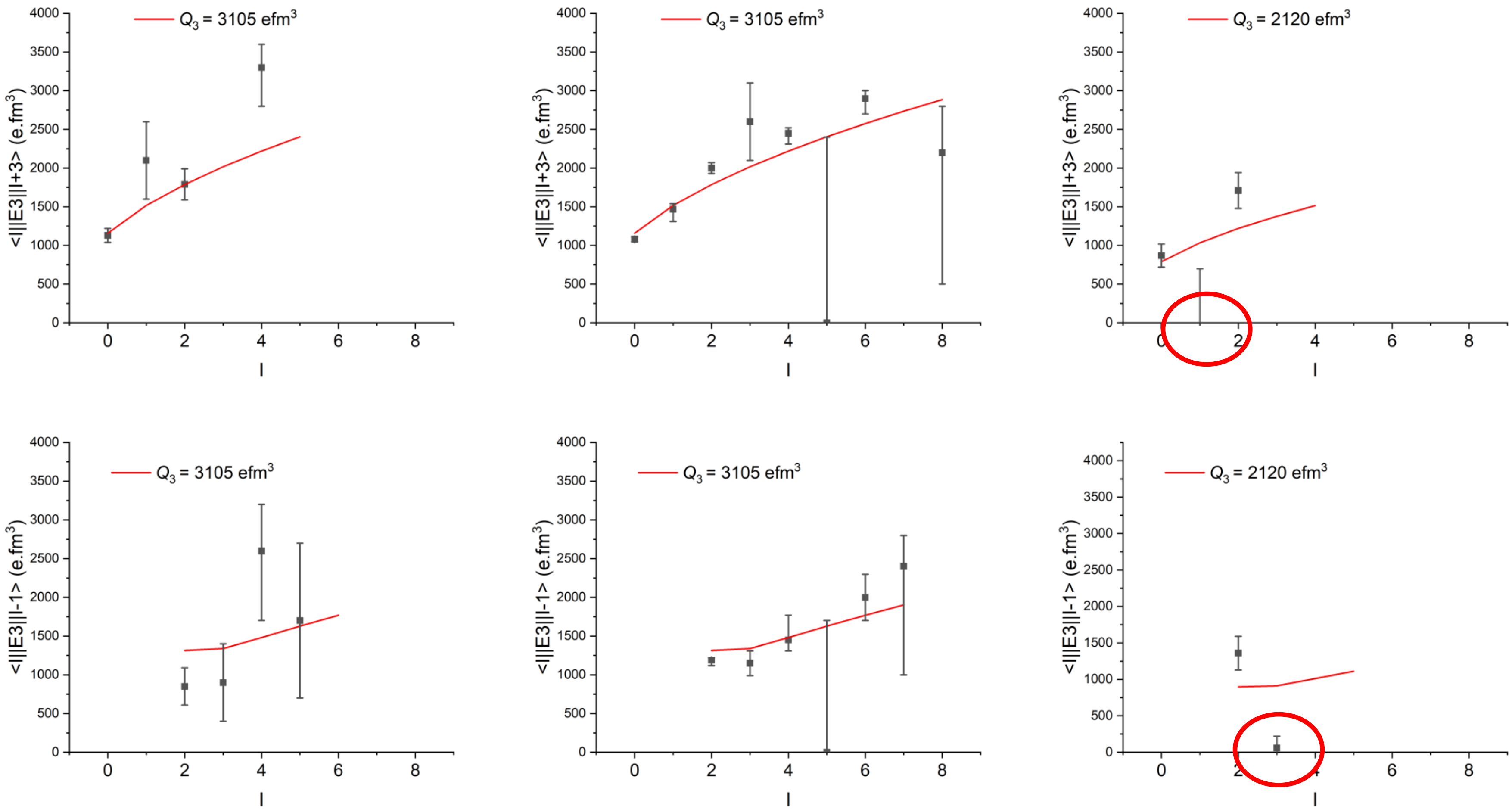


$$\langle I_i||\mathcal{M}(E2)||I_f\rangle = \sqrt{5/16\pi}\,(2I_i+1)(I_i020|I_f0)Q_2$$

Behaviour of Q_3 with I_i, I_f

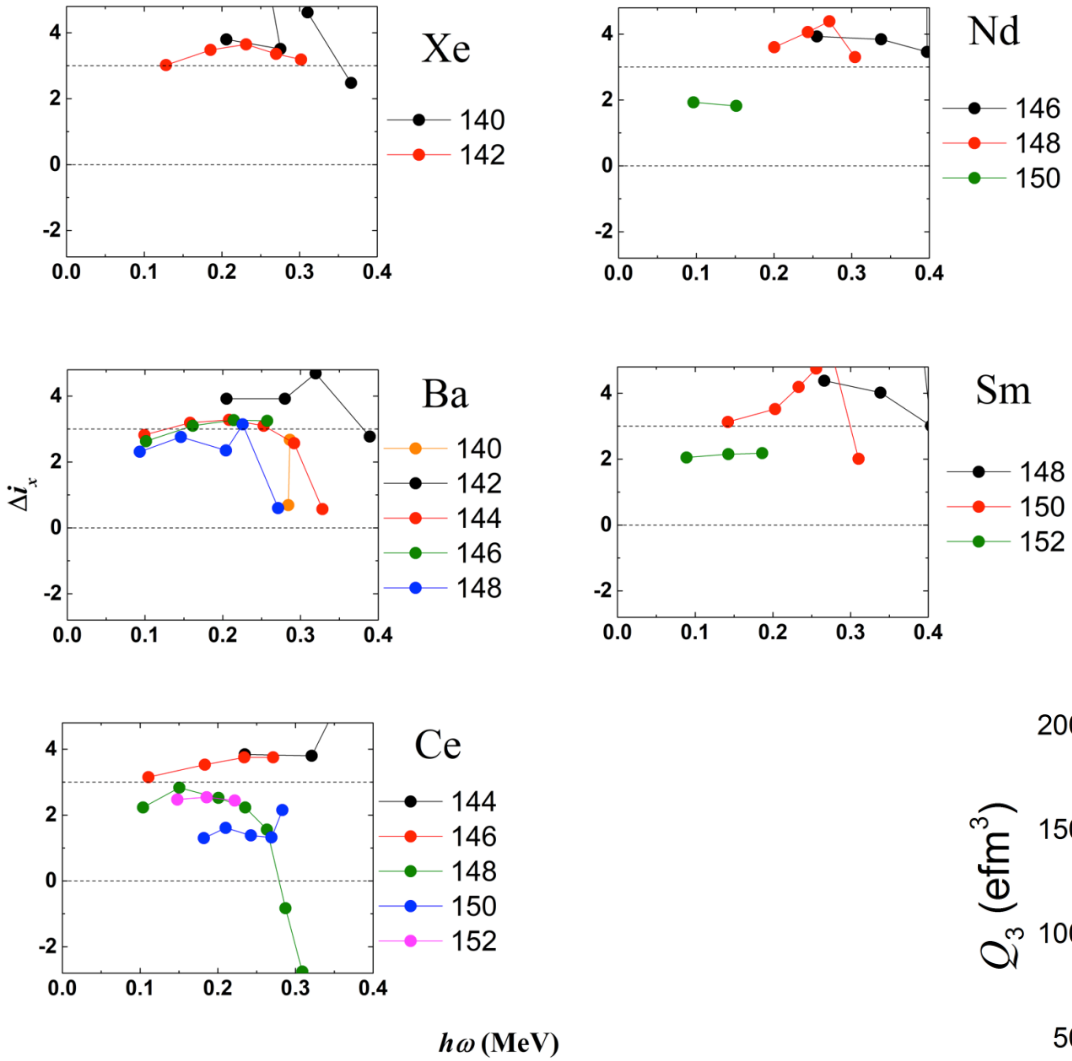
See also ^{220,222}Rn, ^{224}Ra; and Q_1

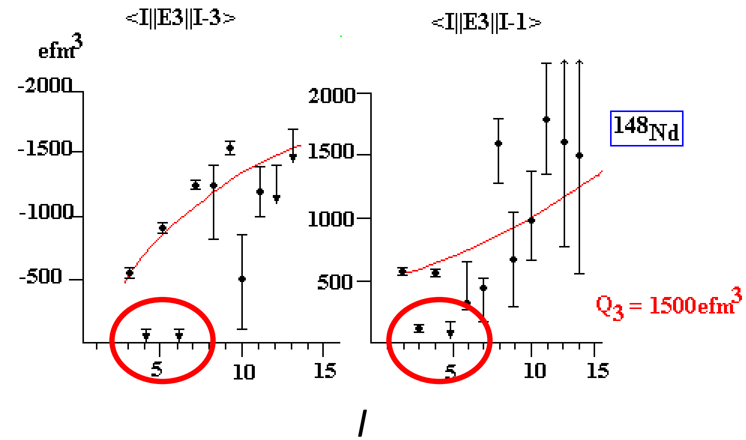
^{222}Ra $\qquad$ ^{226}Ra $\qquad$ ^{228}Ra

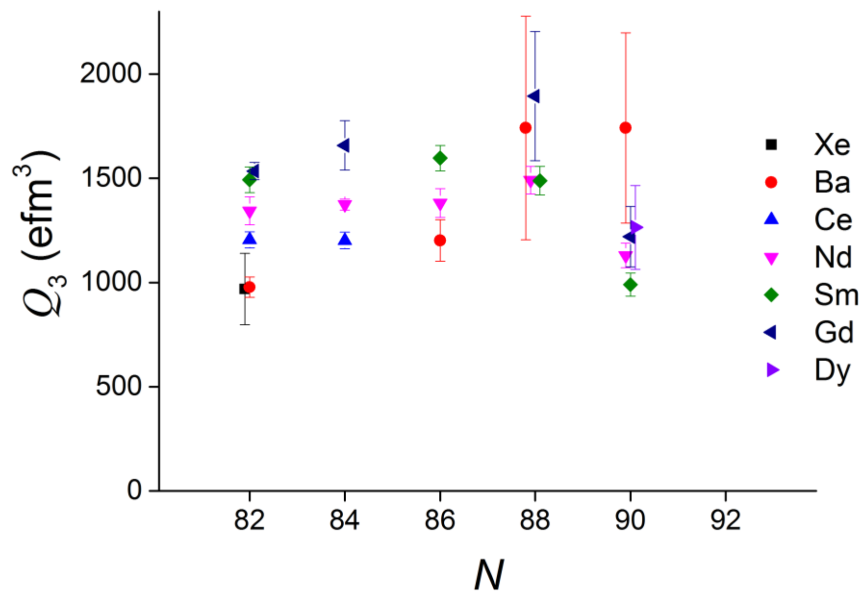


$$\langle I_i||\mathcal{M}(E3)||I_f\rangle = \sqrt{7/16\pi}\,(2I_i+1)(I_i030|I_f0)Q_3$$

lanthanides

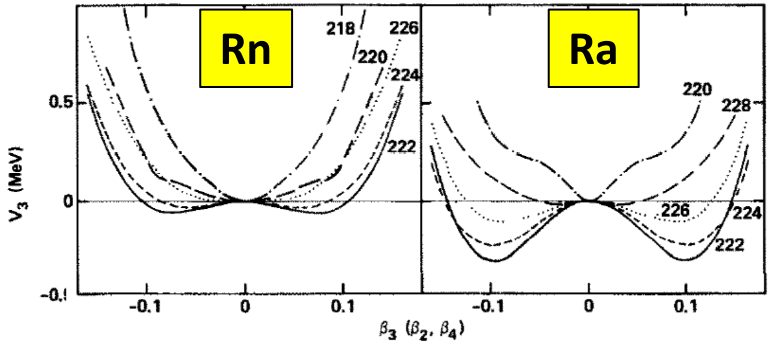




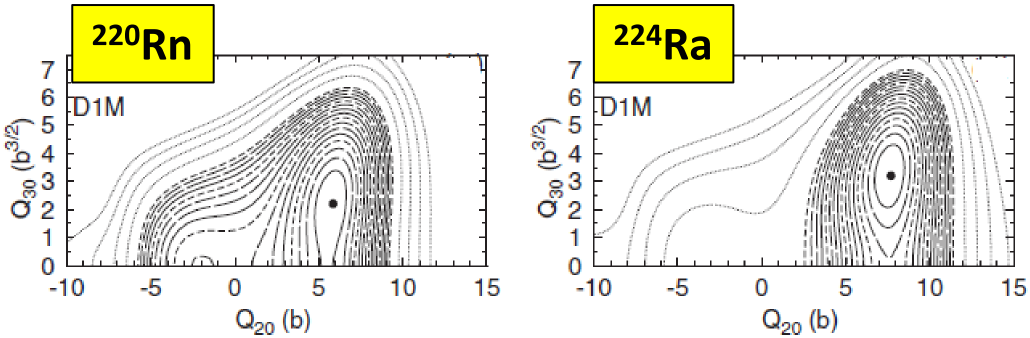


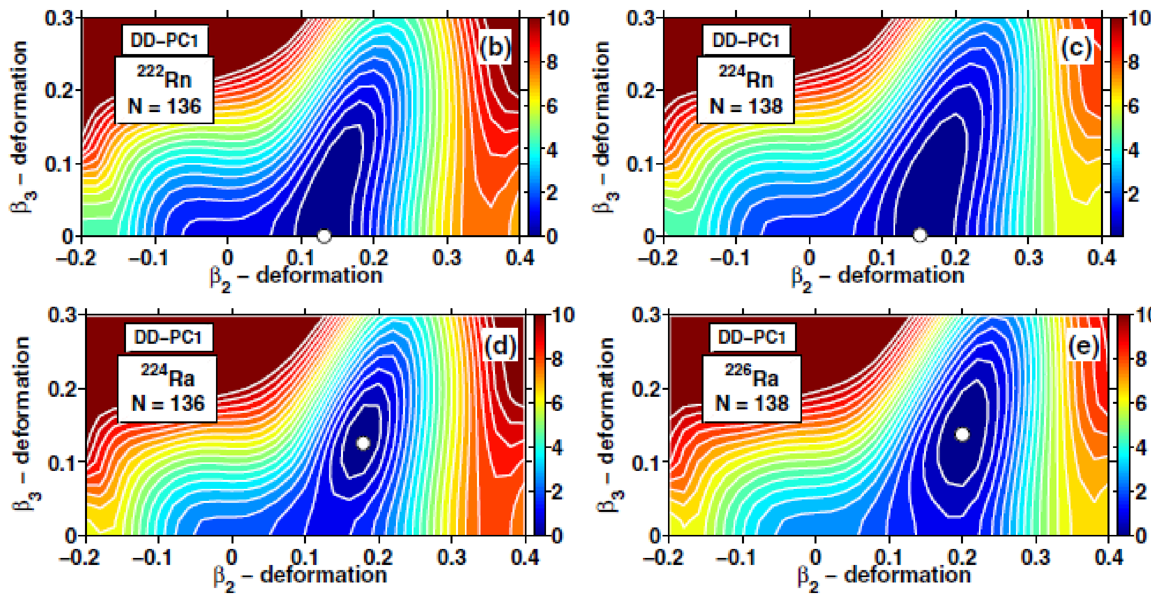
Calculated nuclear shapes: radon & radium

Nazarewicz et al. Strut. WS (MaMi)
NP A429 (1984) 269



Robledo & Butler HFB Gogny (D1M2d)
PRC 88 (2013) 051302



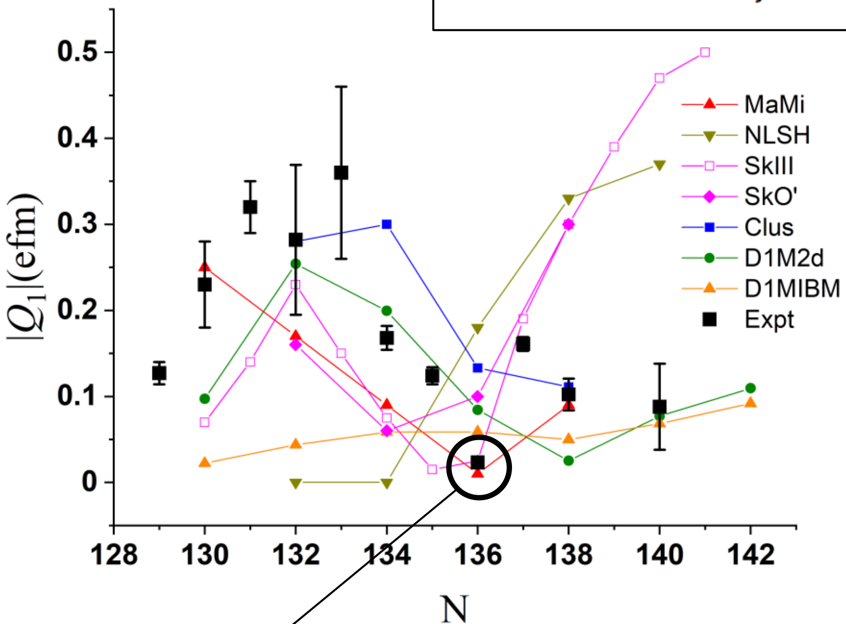


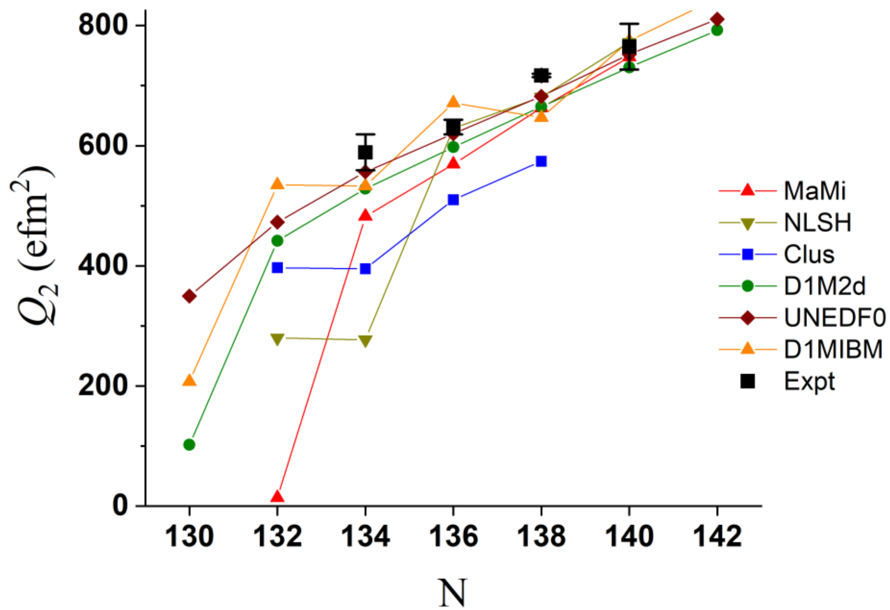
Agbemava et al. Rel. HFB
PRC 93 (2016) 044304

Radium predicted to have a more rigid pear shape than radon

Expt v. theory for electric moments: radium

$$< I_i \parallel \mathcal{M}(E\lambda) \parallel I_f >= (2I_i + 1)^{\frac{1}{2}} (I_i 0 \lambda 0 | I_f) Q_\lambda a_\lambda$$





Very small E1 observed for ^{224}Ra

From E1/E2 branching ratios:

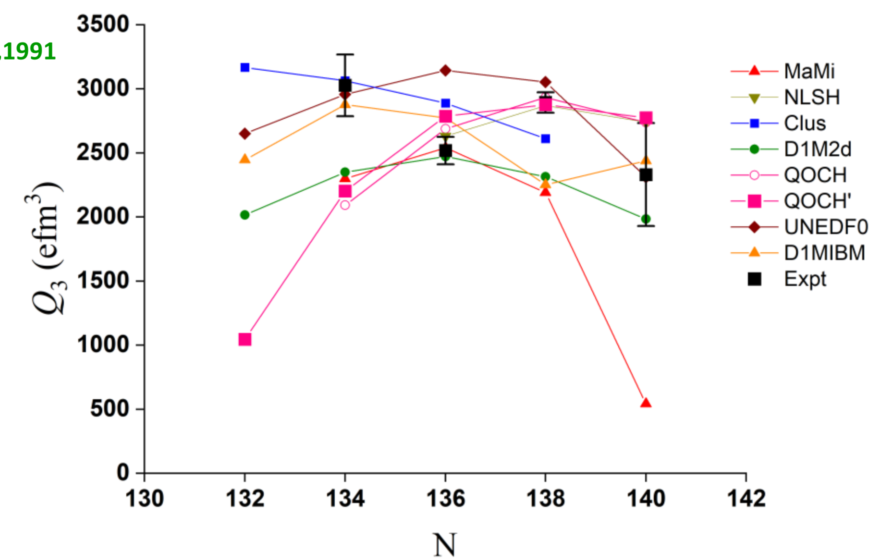
Poynter et al. PLB 232 (1989) 447

Cocks et al. NPA 645 (1999) 61

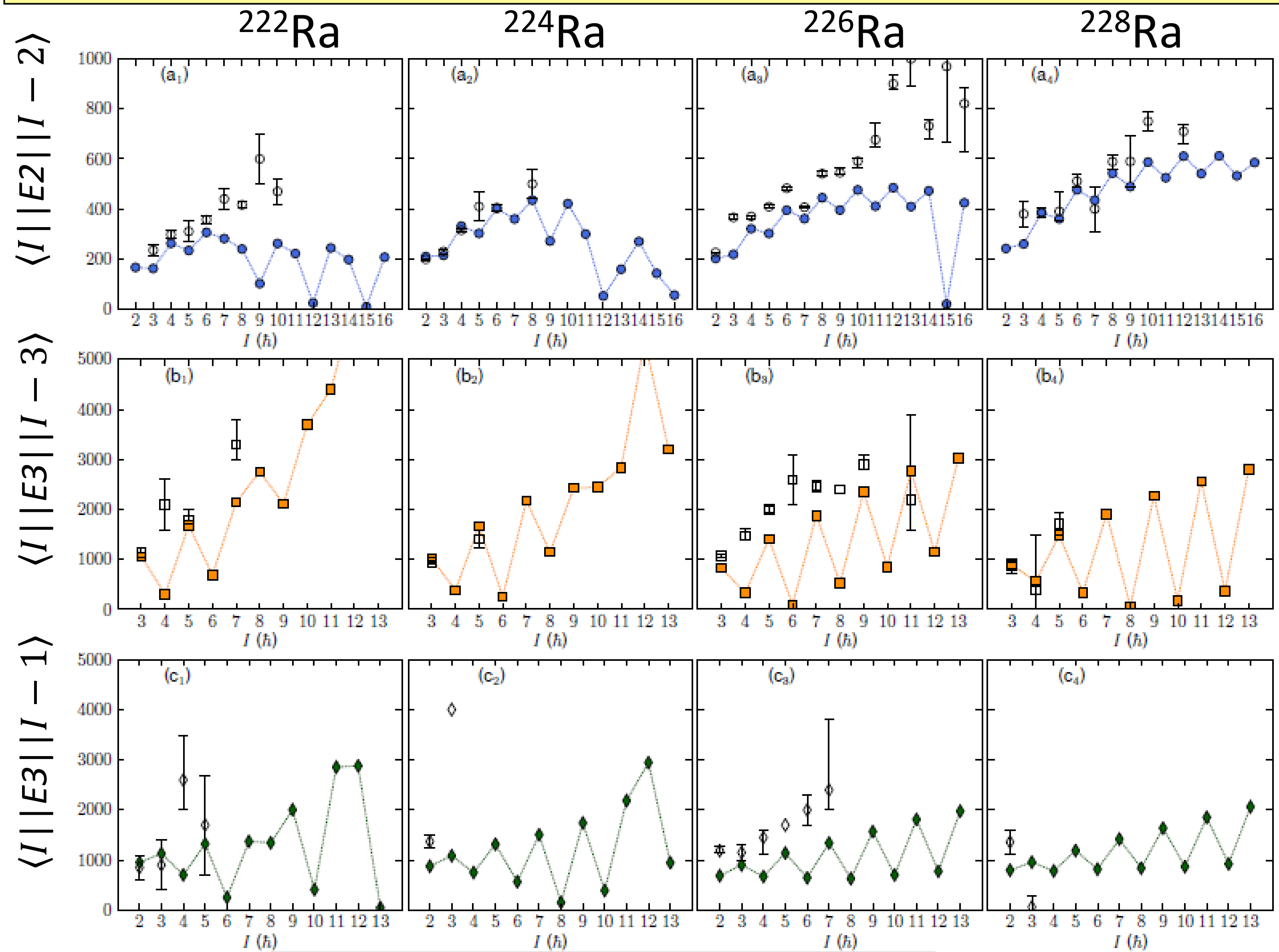
Absolute measurement of E1

LP Gaffney et al. Nature 497 (2013) 199

MaMi	Nazarewicz 1984,1991
NLSH	Rutz 1993
SkIII	Tsvetlov 2002
SkO'	Engel 2003
Clus	Shneidman 2003
D1M2d	Robledo 2013
QOCH	Sun 2019
QOCH'	Zhang 2019
UNEDF0	Cao 2020
D1MIBM	Nomura 2020



Expt v. theory for spin dependence of E2 and E3s



K Nomura et al. HFB Gogny + *sdf* IBM (D1MIBM)
PRC 102, 064326 (2020)

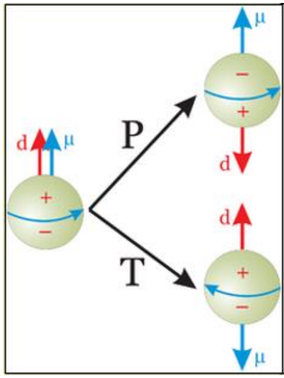
See Kosuke's talk Wed am

Octupole enhanced atomic EDM moment

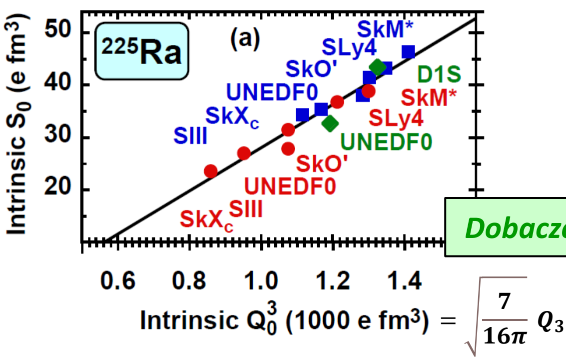
CP violation in nuclear force

Schiff moment: $$S = -2\frac{J}{J+1}\beta_2\beta_3^2 Z A^{2/3}\frac{\langle \hat{V}_{PT}\rangle}{\Delta E}$$

energy splitting of parity doublet
in odd-A nucleus



Measured in $^{220,222}Rn$, $^{222\text{-}228}Ra$
(but not odd-A nuclei)



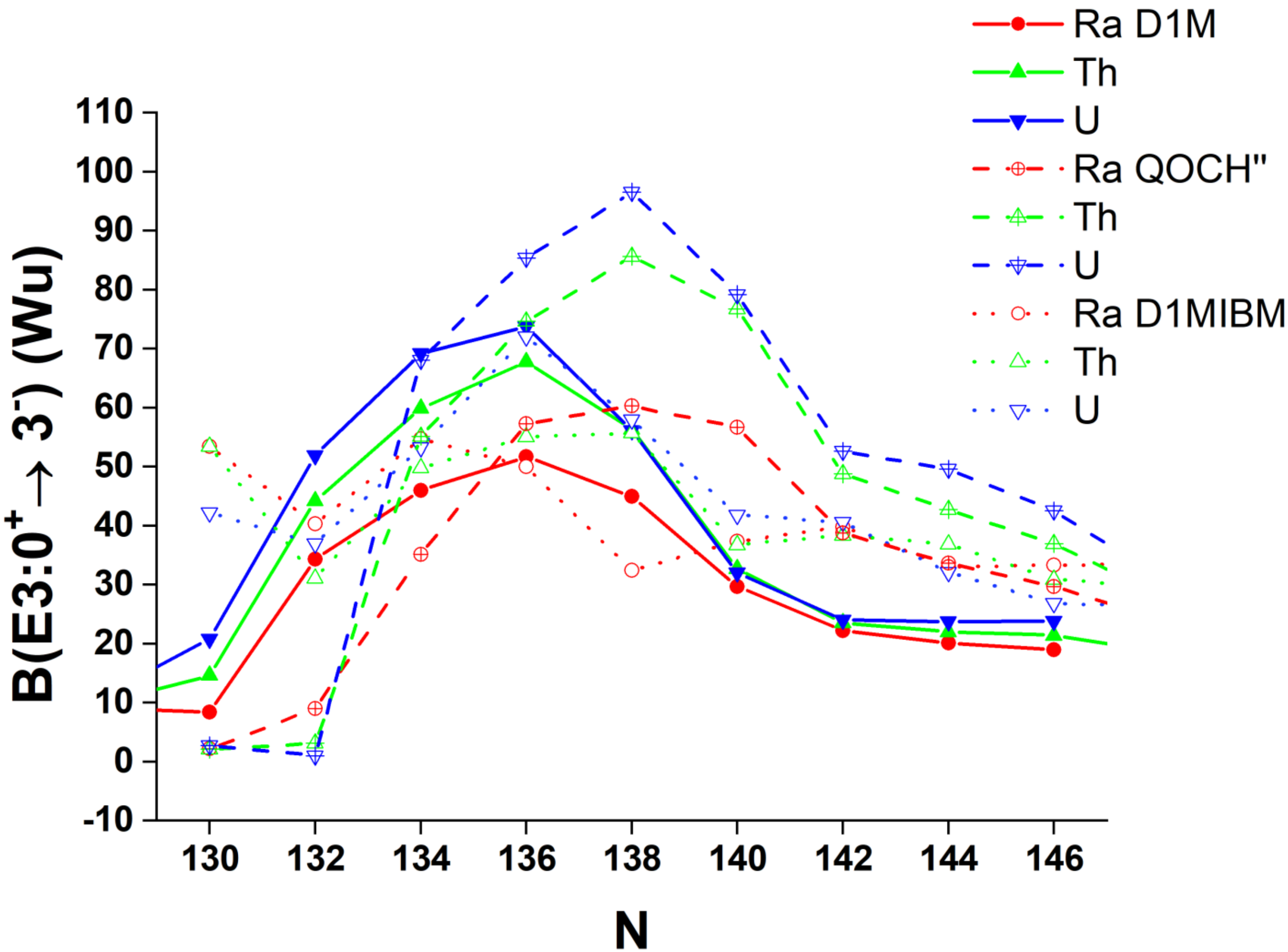
Dobaczewski et al. PRL 121 (2018) 232501

Measured in $^{223,225}Ra$ (~ 50 keV)
ΔE smaller in Ra than in Rn

EDM (^{225}Ra) ~ 100-1000 x EDM (^{199}Hg)
EDM (^{229}Pa) ~ 1000 x EDM (^{225}Ra) ???

Latest (ANL/MSU) ^{225}Ra limit = 10^6 x ^{199}Hg limit

Future prospects



Robledo & Bertsch
PRC 84, 054302 (2011)

Xia et al.
PRC 96, 054303 (2017)

Nomura et al.
PRC 103, 044311 (2021)

Estimated re-accelerated intensity of ^{228}U from FRIB: 3.5.10^5 /s (LoI endorsed)
Possibility to extract UF_x from ISOLDE (LoI endorsed)

Summary

We can classify the rotational behaviour of Rn-U isotopes with N=132-138 as octupole vibrational or as having static octupole deformation.

This is consistent with the observed behaviour of the E3 moments, suggesting that ^{222,224,226}Ra are pear-shaped.

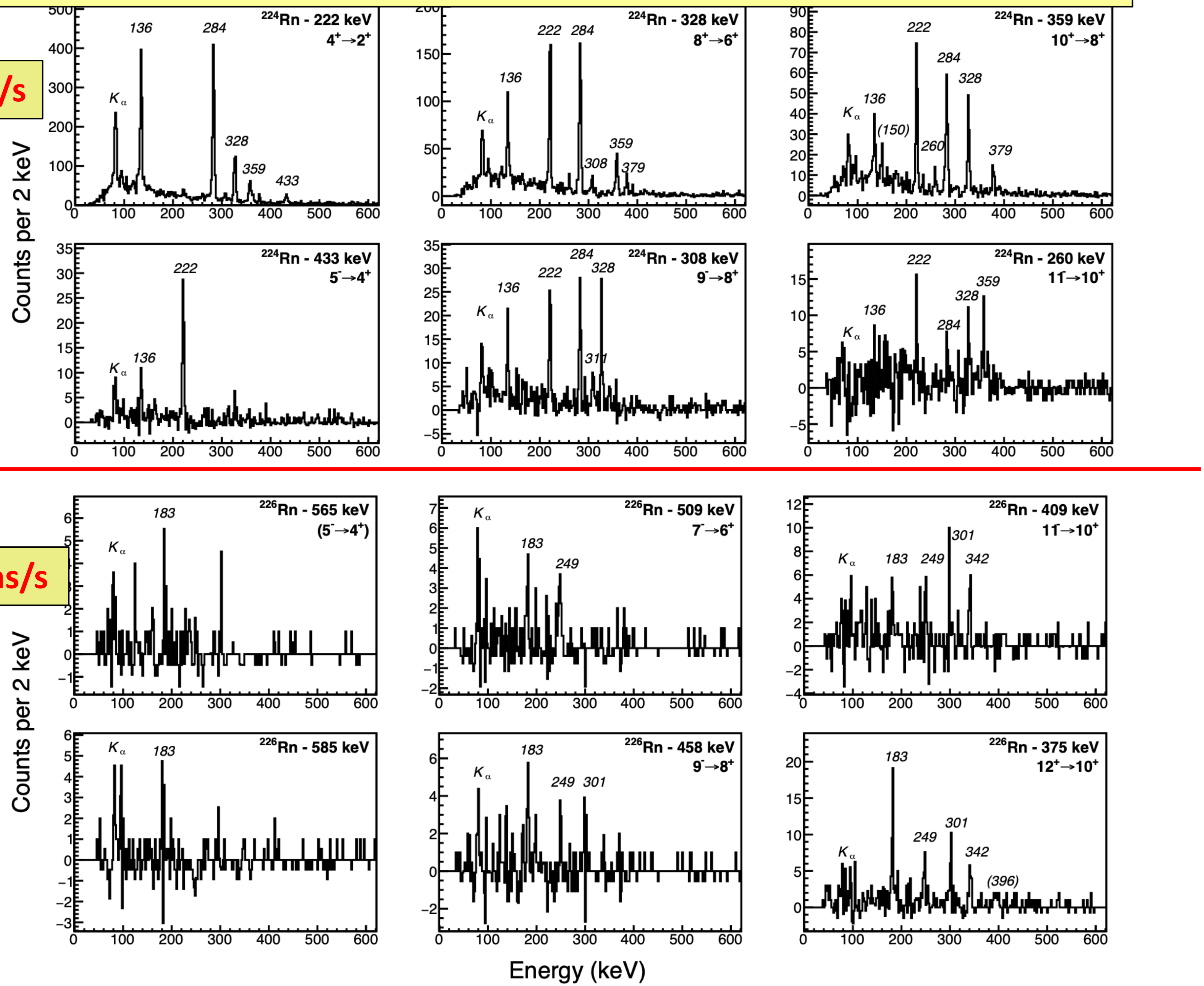
Expect higher B(E3) values for U isotopes.

University of Liverpool
CERN
U. of the West of Scotland
University of the Western Cape
TRIUMF
University of Lund
University of Michigan
INFN Legnaro
KU Leuven
University of Guelph
University of Cologne
TU Darmstadt
HIL, University of Warsaw
University of Jyvaskyla
Helsinki Institute of Physics
University of Oslo
University of York
JINR Dubna
CSIC Madrid
CEA Saclay

γ-γ spectra: gates on transitions in ^{224,226}Rn

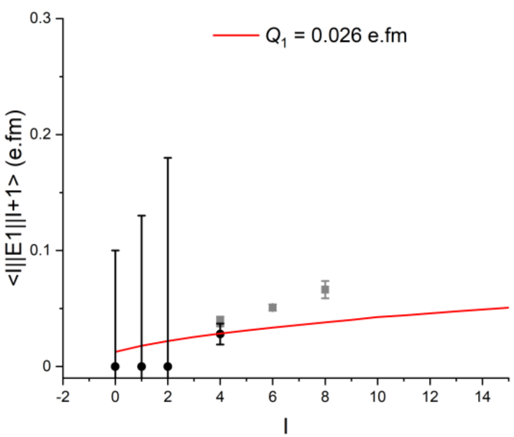
10^5 ^{224}Rn ions/s

2×10^3 ^{226}Rn ions/s

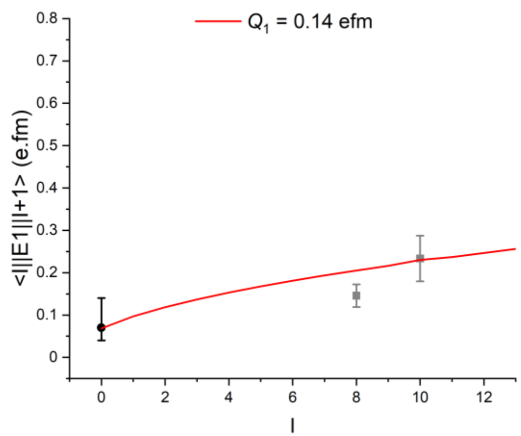


Behaviour of Q_1 with I_i, I_f

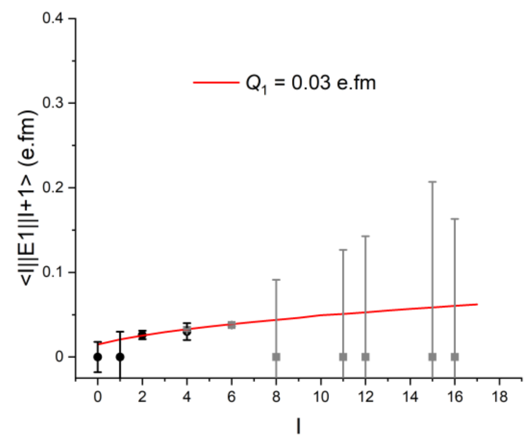
^{220}Rn



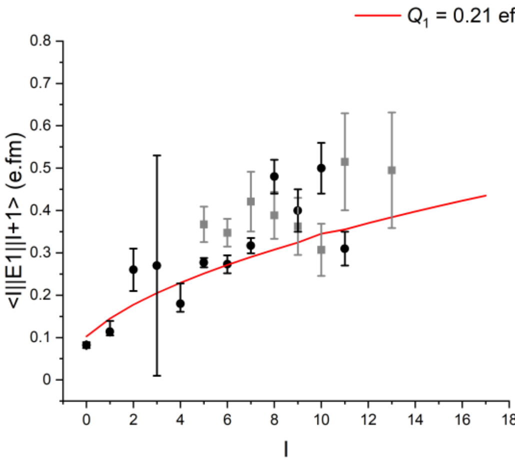
^{222}Rn



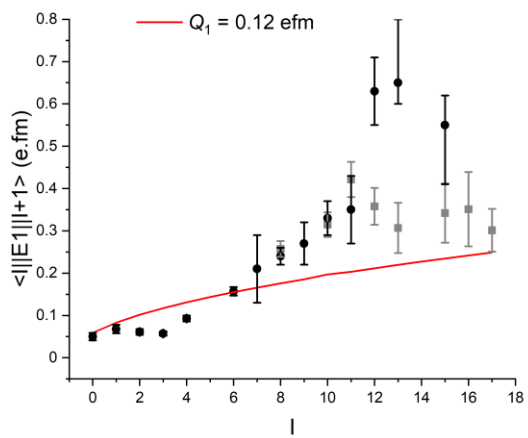
^{224}Ra



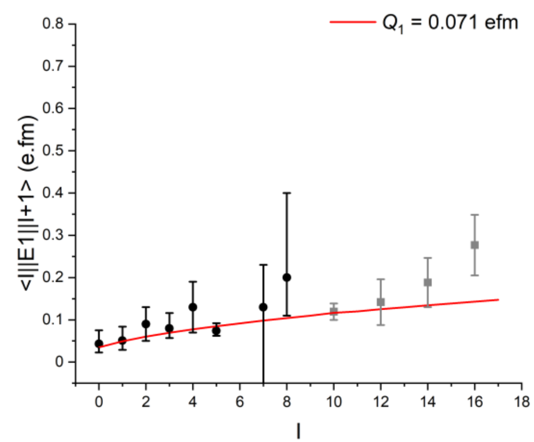
^{222}Ra



^{226}Ra



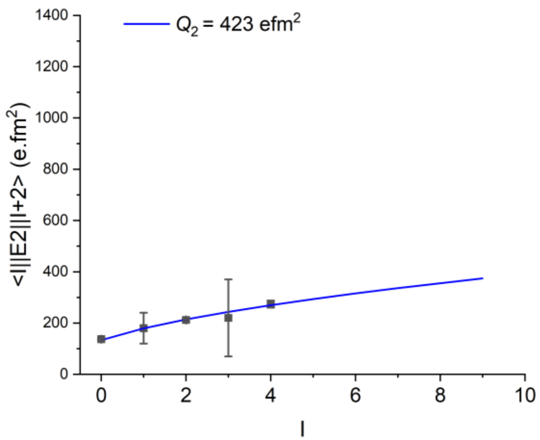
^{228}Ra

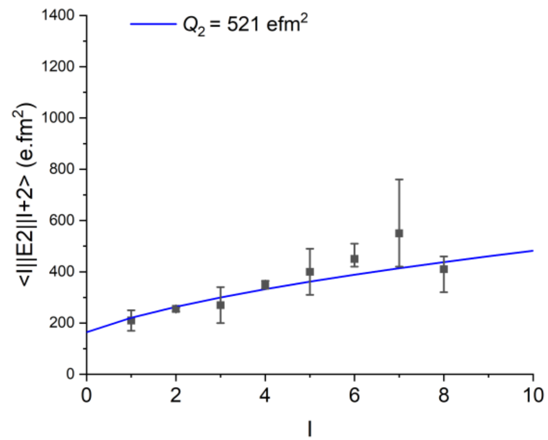


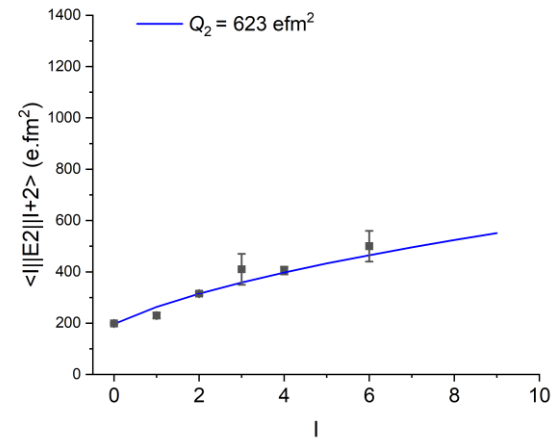
$$\langle I_i||\mathcal{M}(E1)||I_f\rangle = \sqrt{3/4\pi\,(2I_i+1)}\,(I_i010|I_f0)Q_1$$

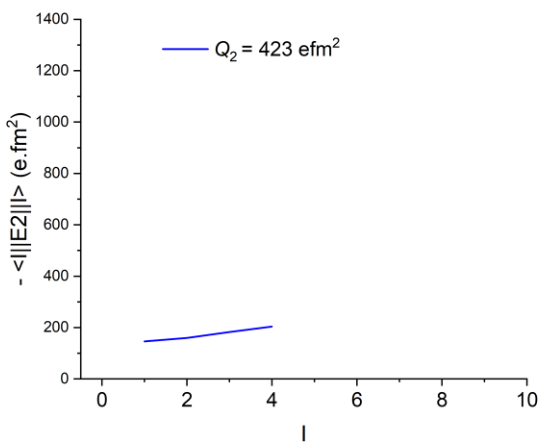
Behaviour of Q_2 with I_i, I_f

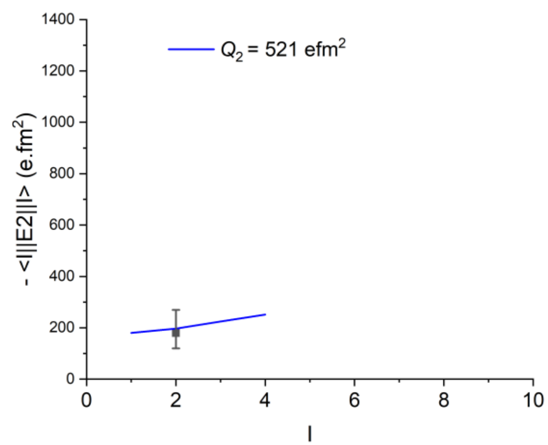
^{220}Rn ^{222}Rn ^{224}Ra

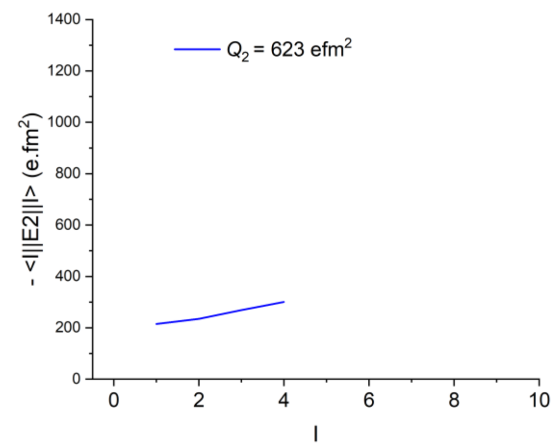








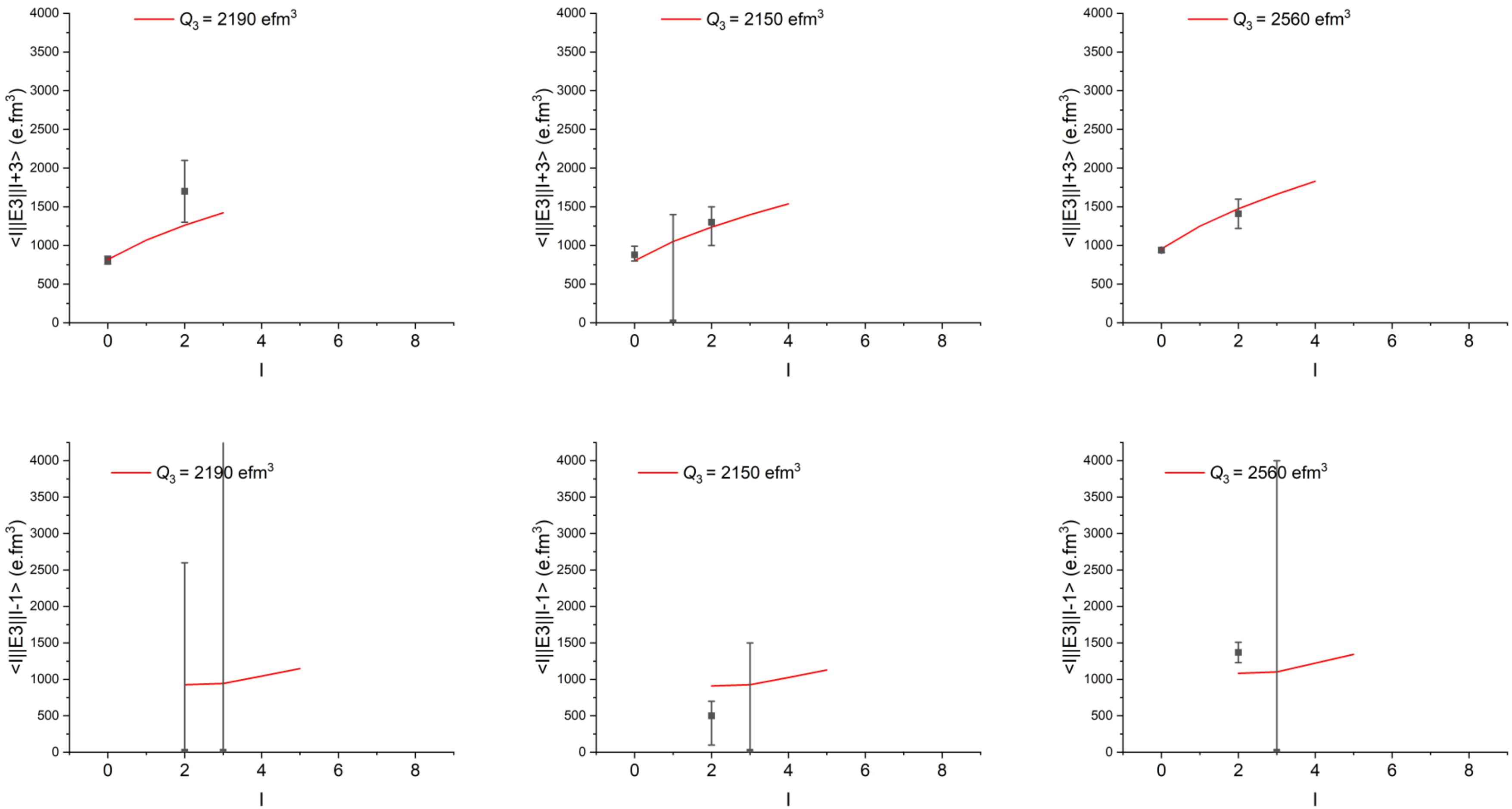




$$\langle I_i||\mathcal{M}(E2)||I_f\rangle = \sqrt{5/16\pi\,(2I_i+1)}\,(I_i020|I_f0)Q_2$$

Behaviour of Q_3 with I_i, I_f

^{220}Rn ^{222}Rn ^{224}Ra



$$\langle I_i||\mathcal{M}(E3)||I_f\rangle = \sqrt{7/16\pi\,(2I_i+1)}\,(I_i 030|I_f 0)\,Q_3$$