First direct observation of enhanced octupole collectivity in ^{144,146}Ba

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Brian Bucher

Lawrence Livermore National Laboratory

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Collaborators

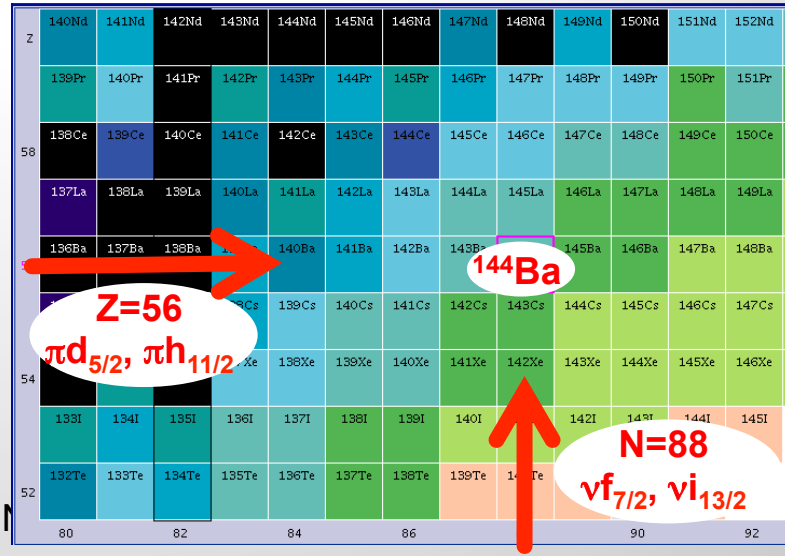
Lawrence Livermore National Lab
B. Bucher, **C.Y. Wu**, M.Q. Buckner
Argonne National Lab
S. Zhu, **R.V.F. Janssens**, M. Albers, A.D. Ayangeakaa, M.P. Carpenter, J.A. Clark, H.M. David, C.R. Hoffman, B.P. Kay, F.G. Kondev, A. Korichi, T. Lauritsen, R.C. Pardo, G. Savard, D. Seweryniak
Lawrence Berkeley National Lab
C.M. Campbell, M. Cromaz, A.O. Macchiavelli, A. Wiens
University of Maryland
C.J. Chiara, J. Harker
University of Rochester
D. Cline, **A.B. Hayes**
Ohio University
H.L. Crawford, A. Richard
Florida State University
M. Riley
University of Notre Dame
M.K. Smith
University of Liverpool
P.A. Butler
University of the West of Scotland
E.T. Gregor, M. Scheck

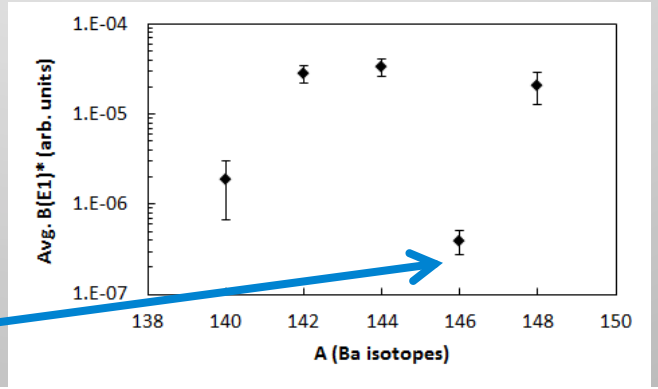
Background

- Experimental & theoretical indications that ^{144,146}Ba are among the most octupole-enhanced isotopes
- Octupole enhancement due to $\Delta J,\Delta l=3$ orbitals near the Fermi surface at Z~56,N~88
- How does octupole collectivity evolve with Z,N?
  - Improve nuclear models
  - Atomic EDM search

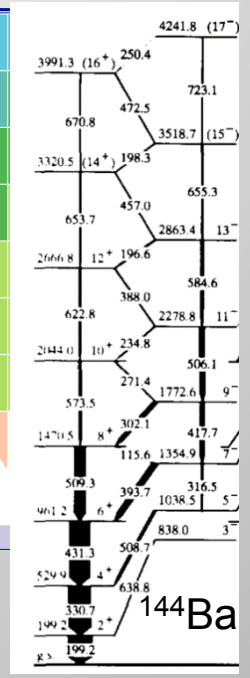
Coulomb Excitation is only unambiguous measure of E3 strength!

E3 quenched or shell occupancy effect?





Data taken from NNDC

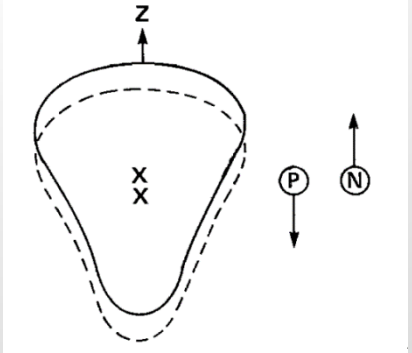


Urban et al., NPA 613:107 (1997)

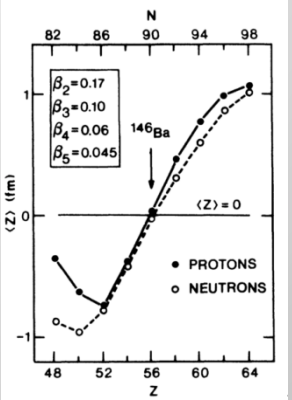
* Spin-averaged B(E1)/B(E2) multiplied by B(E2;2→0), ^{148}Ba B(E2) estimated from systematics

Theory: E1 behavior due to shell structure

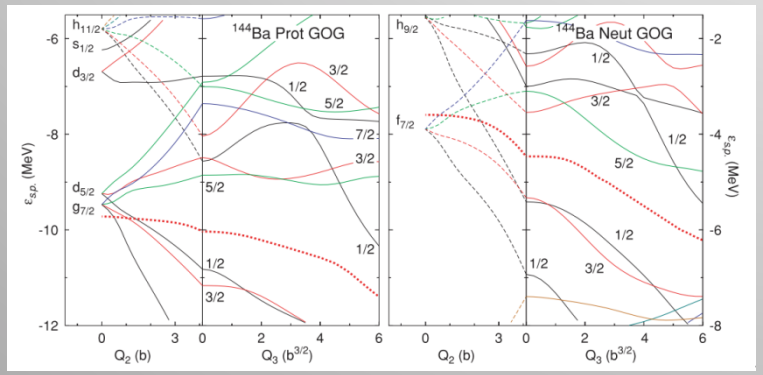
- First described in macroscopic-microscopic calculations as shell correction
- Later reproduced in self-consistent mean-field models
- Consistent with octupole-deformed nuclear potential



Leander *et al.* NPA **453**, 58 (1986)

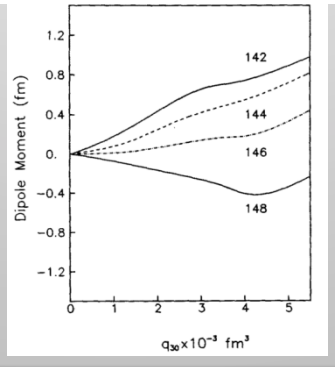


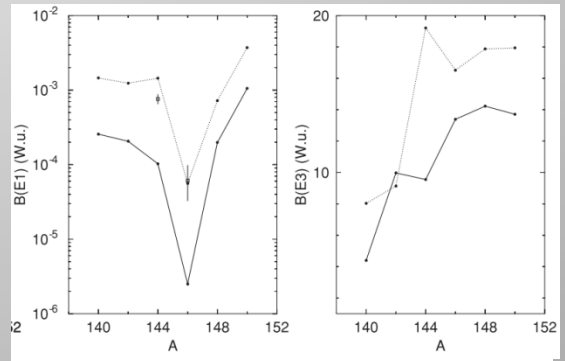
Mach, Nazarewicz *et al.*
PRC **41**, R2469 (1990)



Robledo *et al.* PRC **81**:034315 (2010)

D vs. oct. def. $^{142\text{-}148}$Ba





Robledo *et al.* PRC **81**:034315 (2010)

Egido & Robledo, NPA **518**:475 (1990)

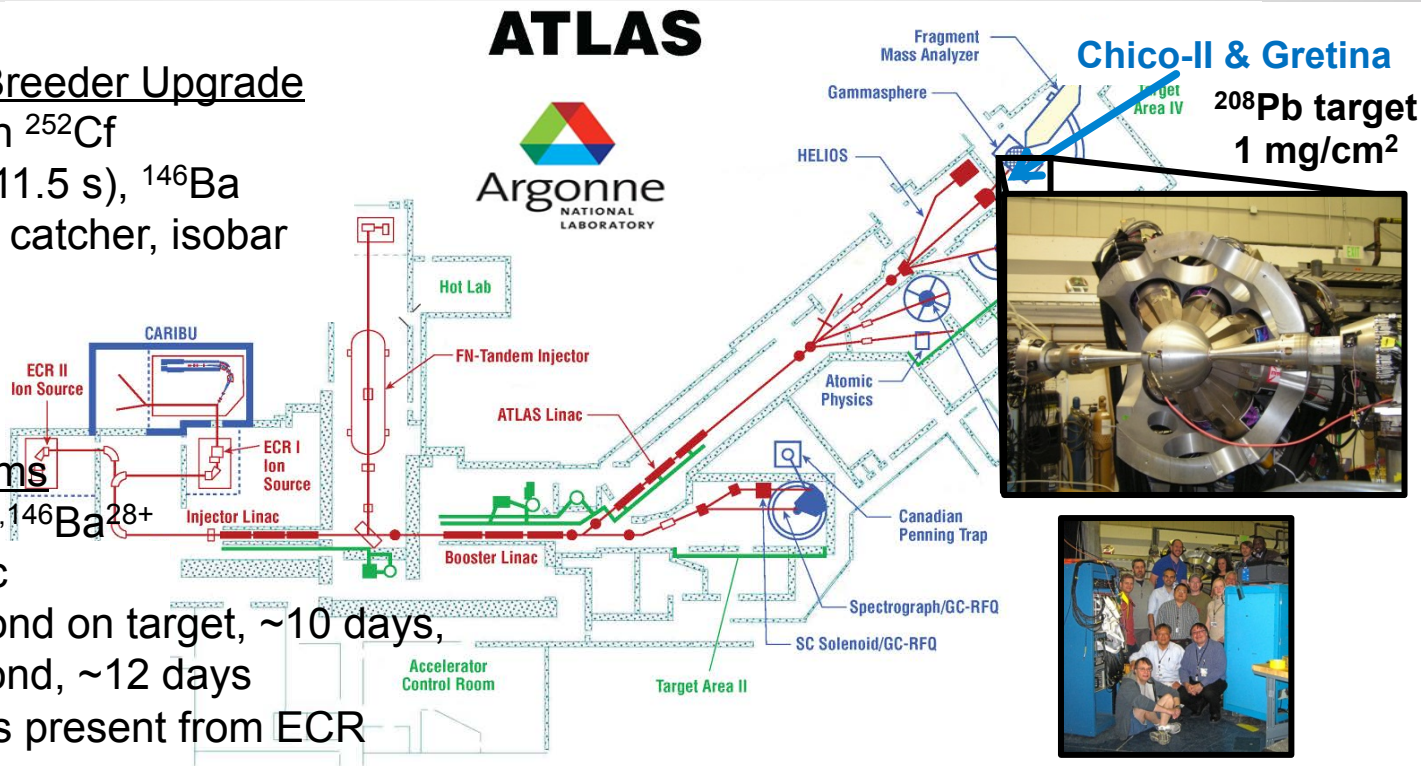
Production of radioactive barium beams from CARIBU

CAlifornium Rare Ion Breeder Upgrade

- Spontaneous fission ^{252}Cf
- Extract ^{144}Ba ($T_{1/2}$=11.5 s), ^{146}Ba ($T_{1/2}$=2.2 s): He gas catcher, isobar separator

650 MeV $^{144,146}Ba$ Beams

- ECR Ion source: $^{144,146}Ba^{28+}$
- Accelerated by linac
- 8000 ^{144}Ba per second on target, ~10 days, 3000 ^{146}Ba per second, ~12 days
- Stable contaminants present from ECR

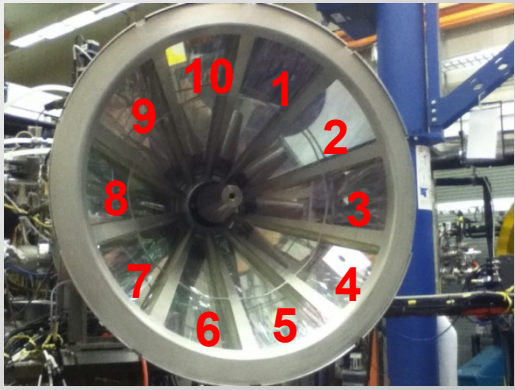


Coulomb Excitation with Chico-II / Gretina

Compact Heavy-Ion COunter

- Parallel-plate avalanche counter (20 total)
- Angular coverage is 69% of 4π
- Good intrinsic spatial & temporal resolution (1σ): θ (0.66°), φ (1.05°), Δt (0.51 ns)
- Provides particle ID and Doppler correction for GRETINA

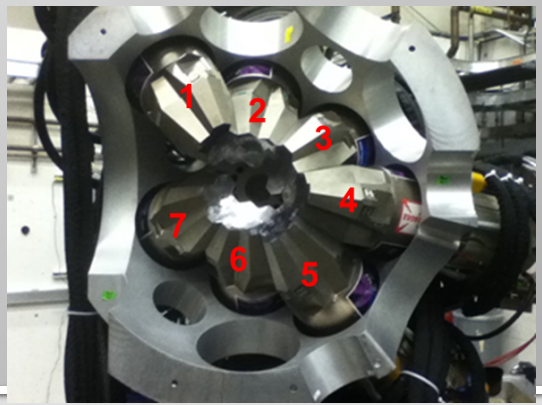
(Half of CHICO)



0.9 μm thick Mylar window

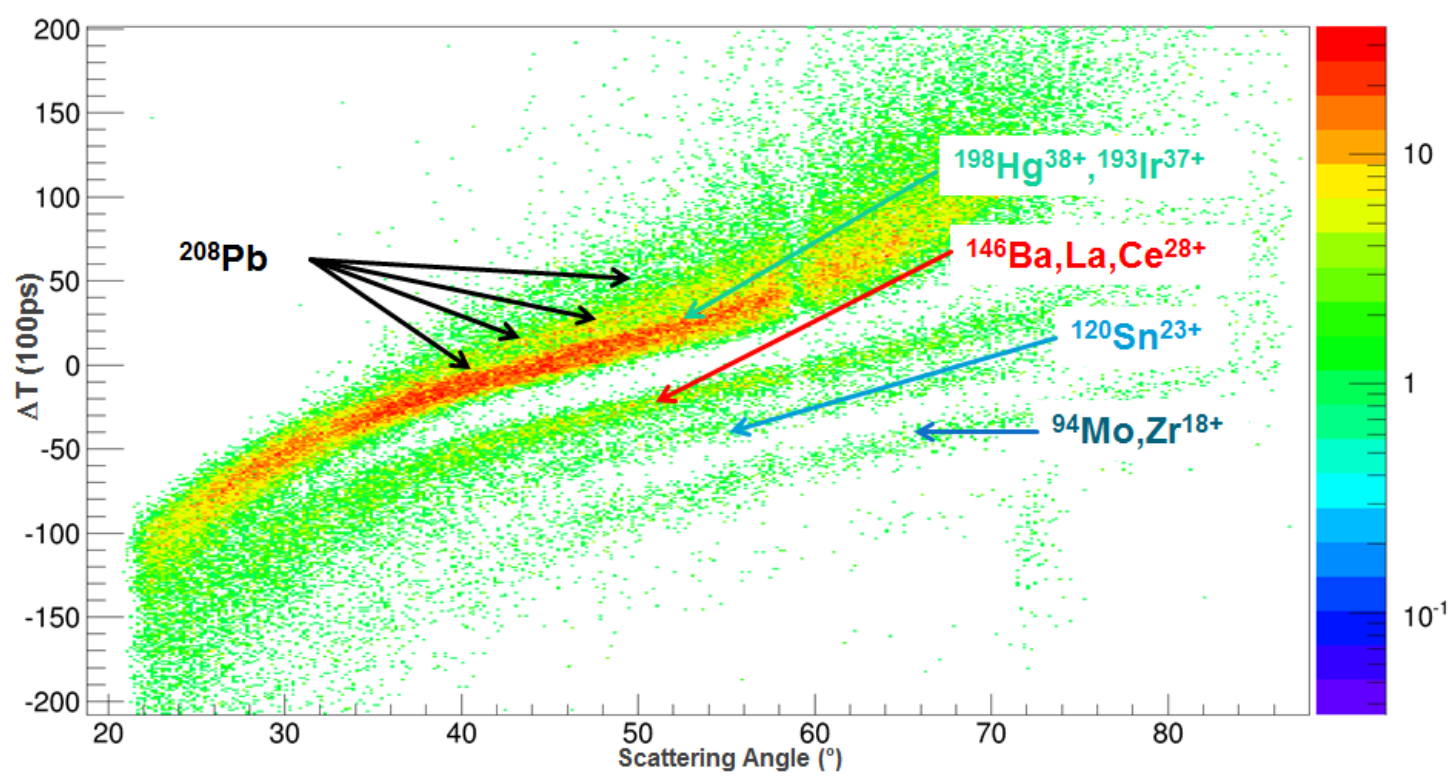
Gamma-Ray Energy Tracking In-beam Nuclear Array

- Segmented Ge γ-ray tracking array
- 1π angular coverage
- Position resolution 2mm
- 7 clusters each with 4 segmented Ge detectors



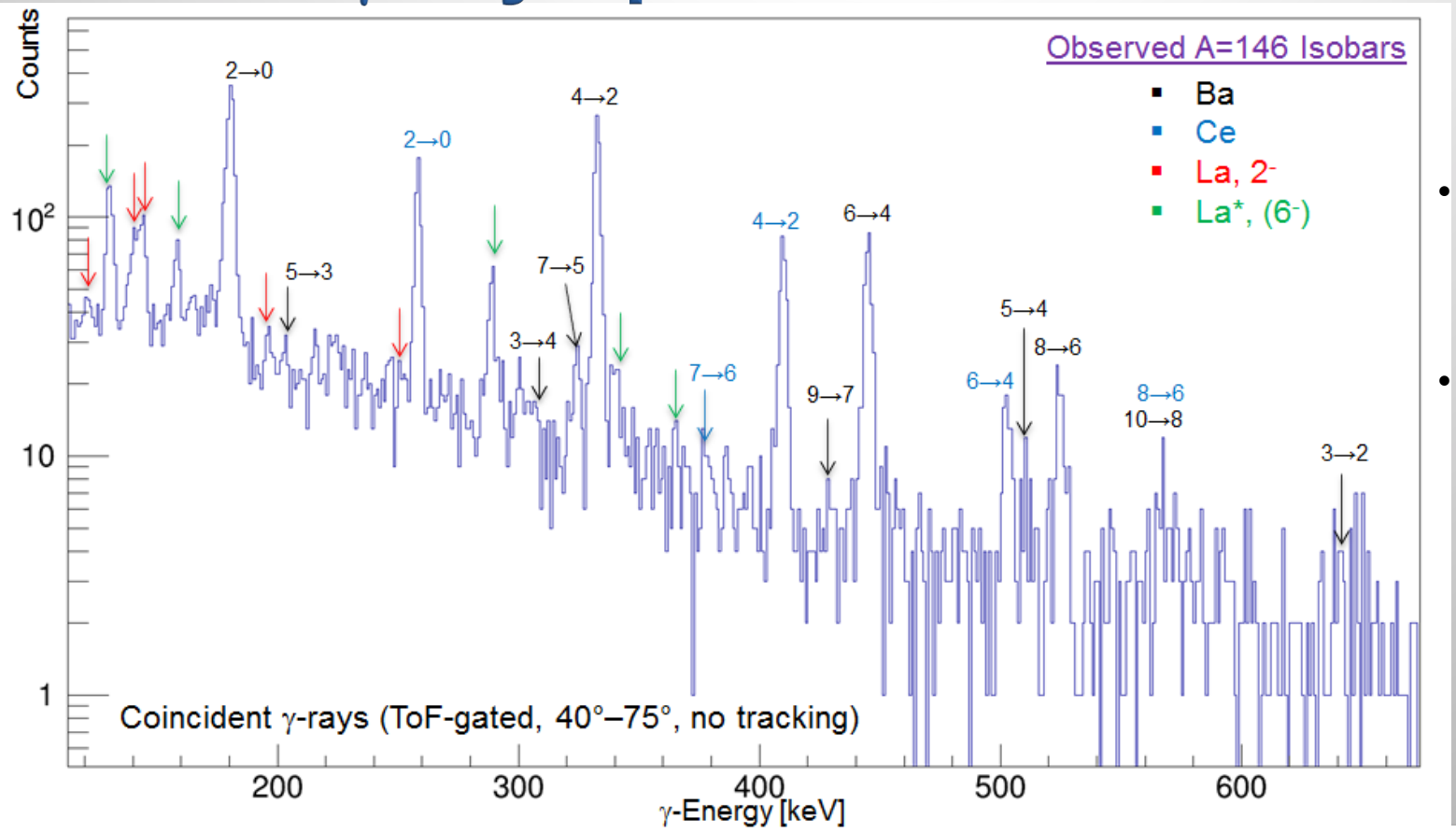
New ^{146}Ba ($t_{1/2}$=2.2 s) Results
3000 pps on target, 12 days

Beam intensity based on β-delayed γ-rays from beam dump



Lower intensity, but cleaner beam than ^{144}Ba measurement

^{146}Ba γ-ray spectrum

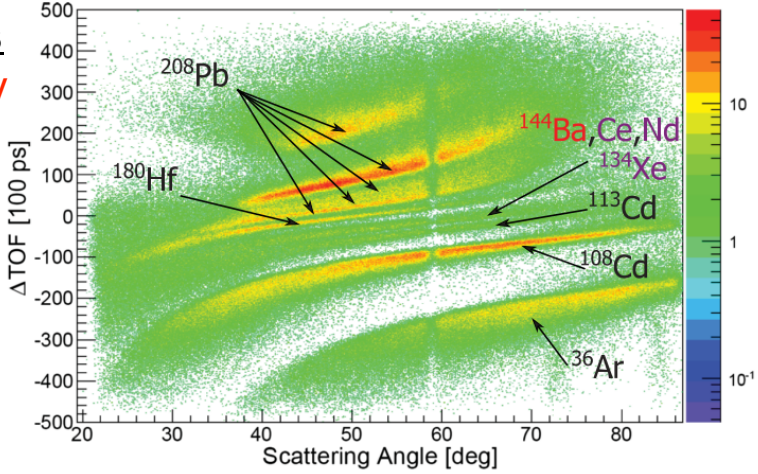


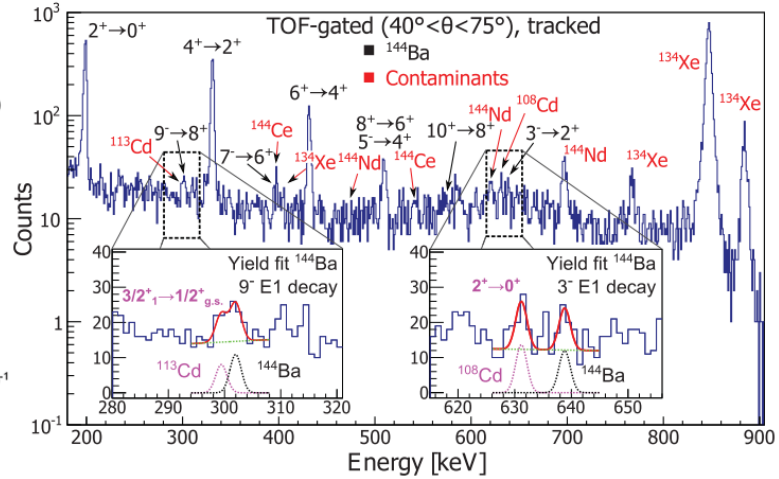
- Negative-parity (odd-spin) levels excited by E3
- Decay yields provide measurement of E3 excitation probability!

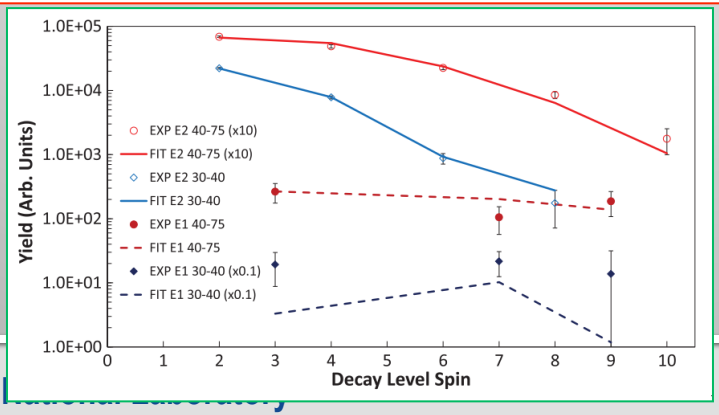
Direct Evidence of Octupole Deformation in Neutron-Rich ^{144}Ba

Earlier ^{144}Ba results

- Precision hurt by stable beam contaminants
- Good fit to experimental yields
- New E2 & **E3** matrix elements obtained



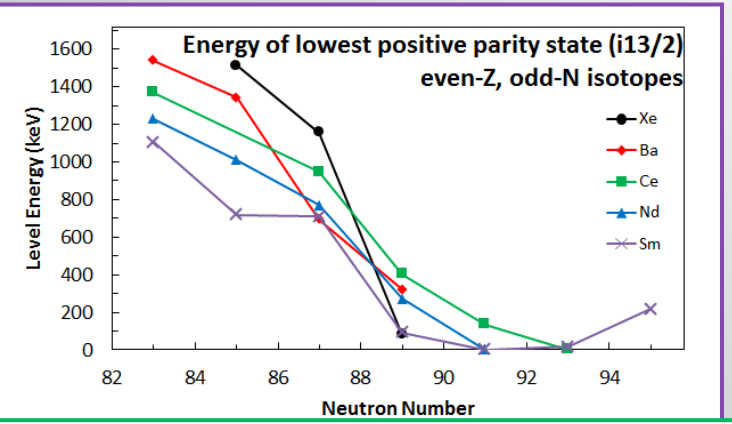


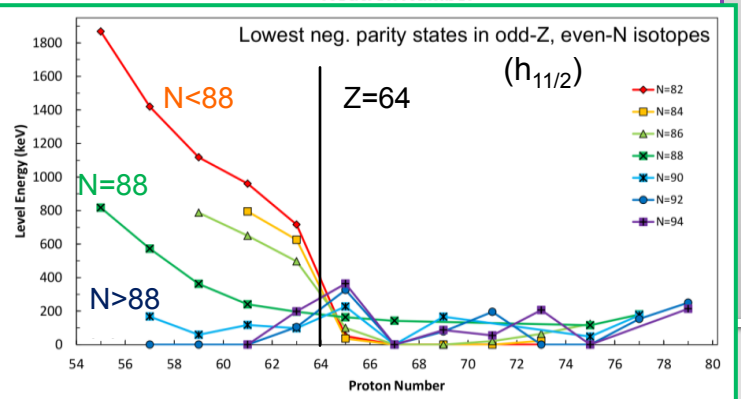


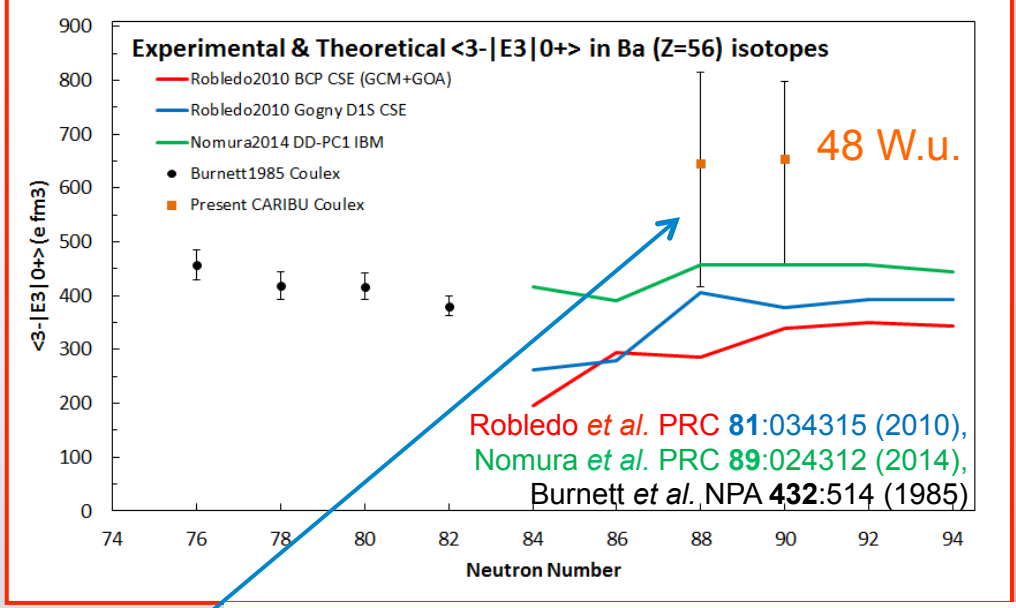
$I_i^\pi \to I_f^\pi$	$E\lambda$	$\langle I_f^\pi \Vert \mathcal{M}(E\lambda) \Vert I_i^\pi \rangle$
$0^+ \to 2^+$	$E2$	$1.042(^{+17}_{-22})$
$2^+ \to 4^+$	$E2$	$1.860(^{+86}_{-81})$
$4^+ \to 6^+$	$E2$	$1.78(^{+12}_{-10})$
$6^+ \to 8^+$	$E2$	$2.04(^{+35}_{-23})$
$0^+ \to 3^-$	$E3$	$0.65(^{+17}_{-23})$
$2^+ \to 5^-$	$E3$	< 1.2
$4^+ \to 7^-$	$E3$	< 1.6

New E3 matrix element in ^{146}Ba with theoretical and experimental comparisons

Data from NNDC

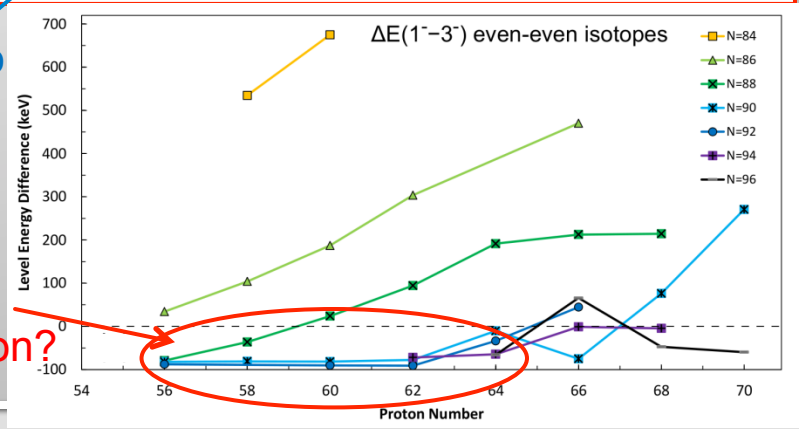






Enhancement due to stronger $\pi h_{11/2}$-$d_{5/2}$ and $\nu i_{13/2}$-$f_{7/2}$ couplings

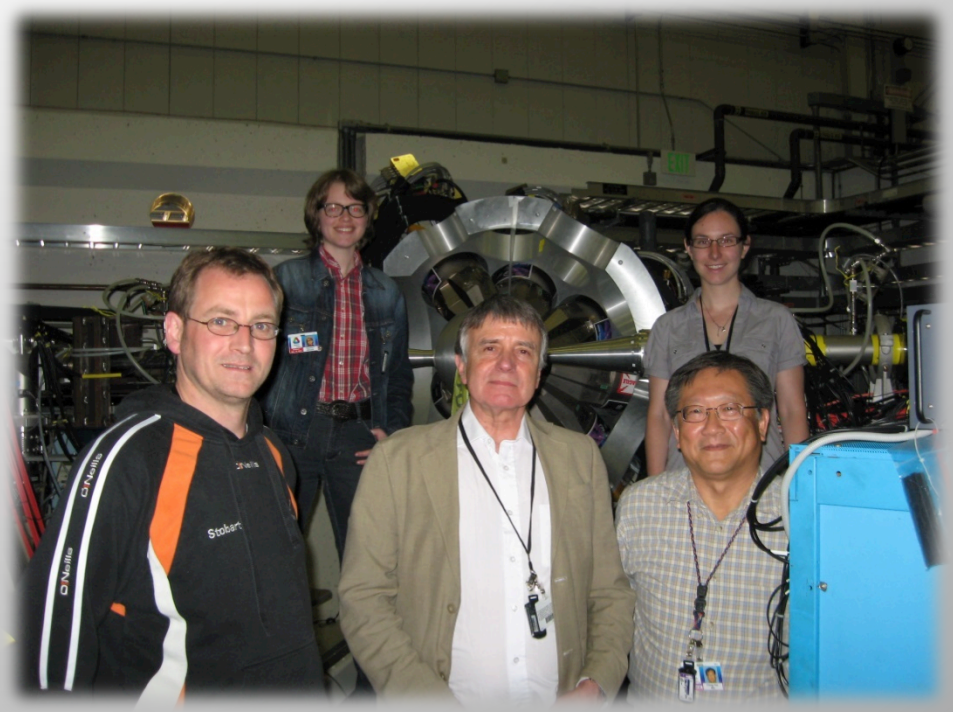
Region of stable octupole deformation?



Conclusions

- First direct E3 measurements in octupole-deformed(?) lanthanide region using R.I. beams from CARIBU and CHICO2-GRETINA setup
- New results provide (qualitative) support for theory, but identify needed quantitative improvement on E1 and E3 strengths
- For quantitative improvement, effective interactions must accurately account for isospin-dependent forces influencing shell dynamics

THANK YOU!



Coulomb Excitation Analysis

Experimental Input

- 16 Yields, 2 angles (our experiment)
- 6 Lifetimes, 9 Branching Ratios (previous data sets)

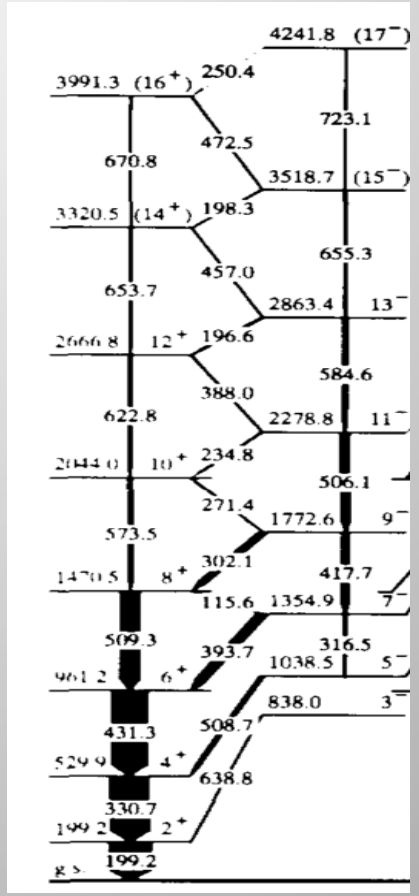
GOSIA
Semiclassical Coulex Least-Squares Search Code

minimization

70 Matrix Elements (E1,E2,E3 up to 15-)

Rigid Rotor Assumption (K=0) D0,Q2,Q3

6 Free Parameters (1-E1, 4-E2, 1-E3)

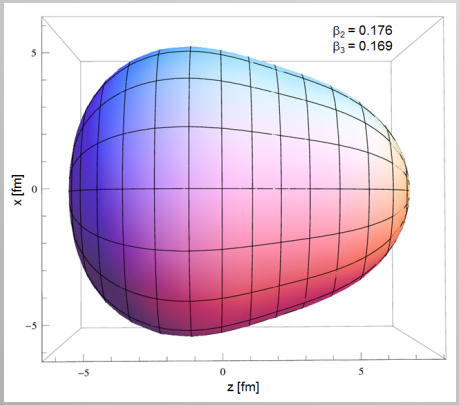


Urban et al., NPA 613:107 (1997)

E3 results compared to theory:

- Measured $\langle 3^- \| E3 \| 0^+ \rangle = 6.5(^{+16}_{-23}) \times 10^2$ $e\,fm^3$
- Largest calculated values ~1σ less than measured value

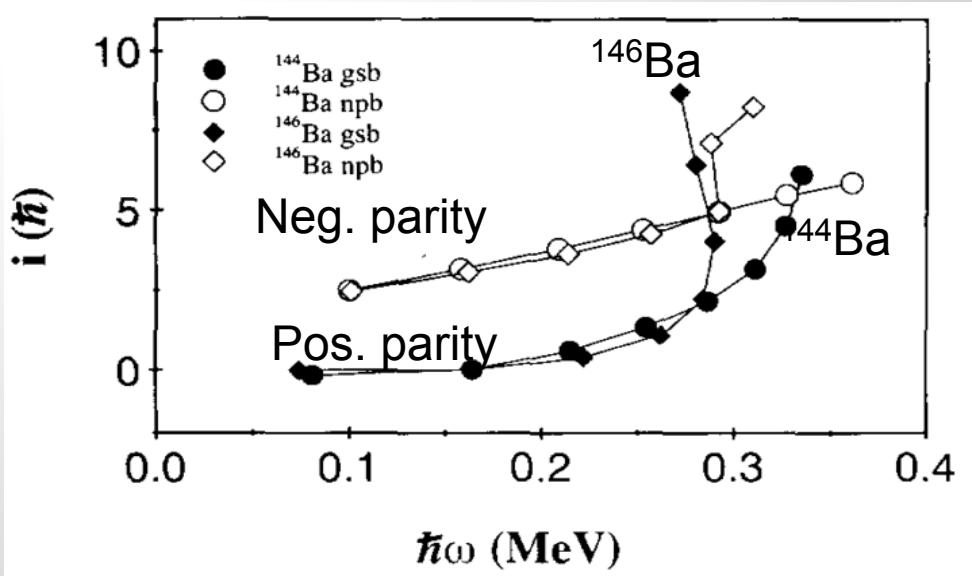
B(E3;$3^- \rightarrow 0^+$) (W.u.)	Reference
48(+25/-34)	This measurement
24	Nomura *et al.* PRC **89**:024312 (2014)
20	Egido & Robledo NPA **518**:475 (1990)
19	Robledo *et al.* PRC **81**:034315 (2010) Gogny
10	Robledo *et al.* PRC **81**:034315 (2010) BCP
5	Egido & Robledo NPA **524**:65 (1991)

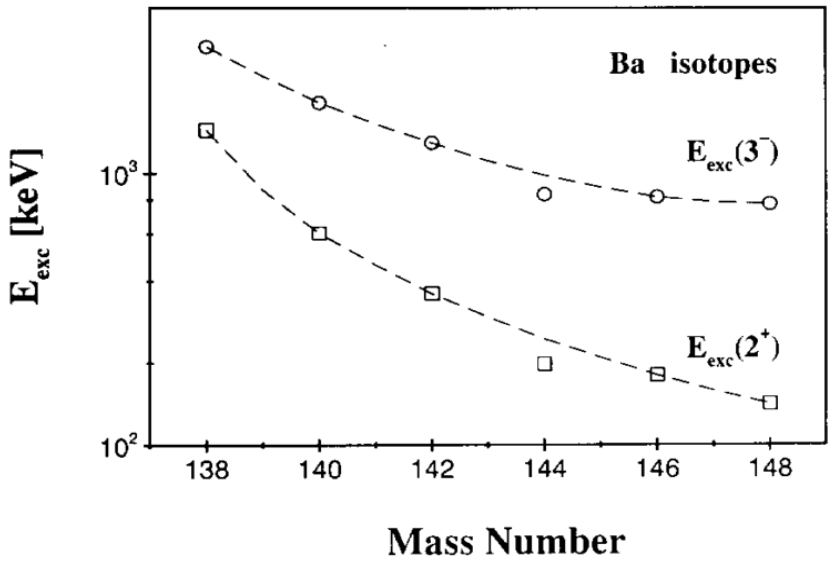


^{144}Ba shape using present β_2,β_3 results

$\lvert\beta_3\rvert$	Reference
0.17(+4/-6)	This measurement
0.13	Moller *et al.* ANDT **59**:185 (1995)
0.12	Nomura *et al.* PRC **89**:024312 (2014)
0.12	Zhang *et al.* CPC **34**:1094 (2010)
0.11	Wang *et al.* PRC **92**:024303 (2015)
0.093	Sobiczewski *et al.* NPA **485**:16 (1988)
0.068	Nazarewicz *et al.* NPA **429**:269 (1984)

Urban *et al.* 1997:
Octupole correlations weakened in ^{146}Ba; strongest in ^{144}Ba





Alignment should happen gradually with rotation in octupole-deformed potential (like in ^{144}Ba)

Urban *et al.* NPA 613:107 (1997)

Results from Minimization

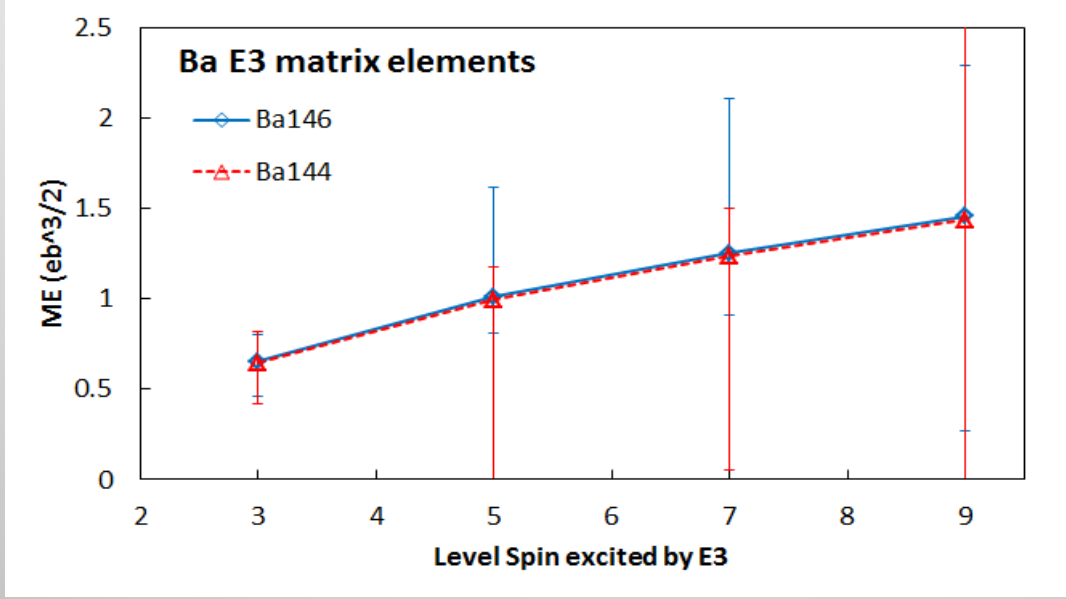
TABLE I. E2 and E3 matrix elements $(e \cdot b^{\lambda/2})$

$I_i^\pi \rightarrow I_f^\pi$	$E\lambda$	$\langle I_f^\pi \| M(E\lambda) \| I_i^\pi \rangle$
$0^+ \rightarrow 2^+$	$E2$	$1.042(^{+17}_{-22})$
$2^+ \rightarrow 4^+$	$E2$	$1.860(^{+86}_{-81})$
$4^+ \rightarrow 6^+$	$E2$	$1.78(^{+12}_{-10})$
$6^+ \rightarrow 8^+$	$E2$	$2.04(^{+35}_{-23})$
$0^+ \rightarrow 3^-$	$E3$	$0.65(^{+17}_{-23})$
$2^+ \rightarrow 5^-$	$E3$	< 1.2
$4^+ \rightarrow 7^-$	$E3$	< 1.6

B(E2)↓=48.5(+1.6/-2.1) W.u.

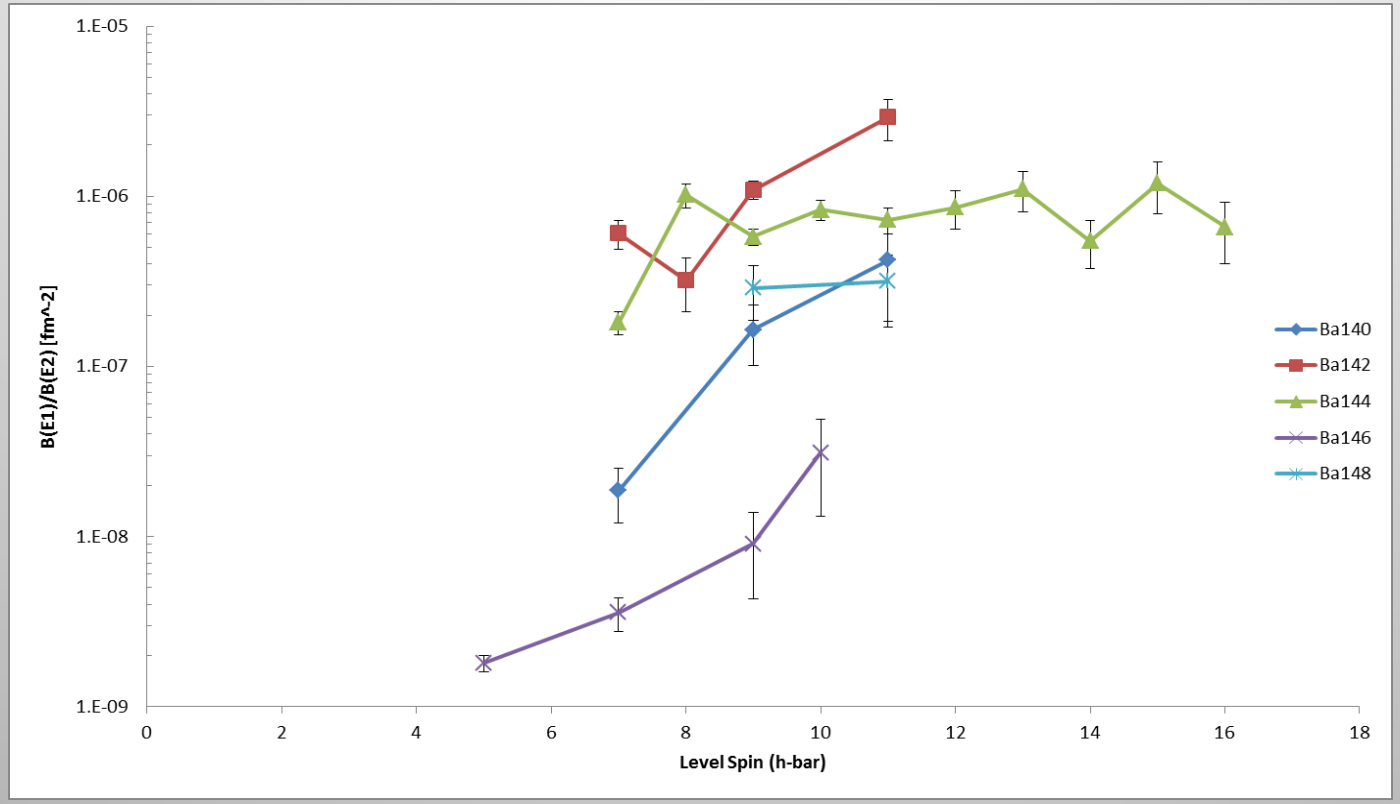
B(E3)↓=48(+25/-34) W.u.

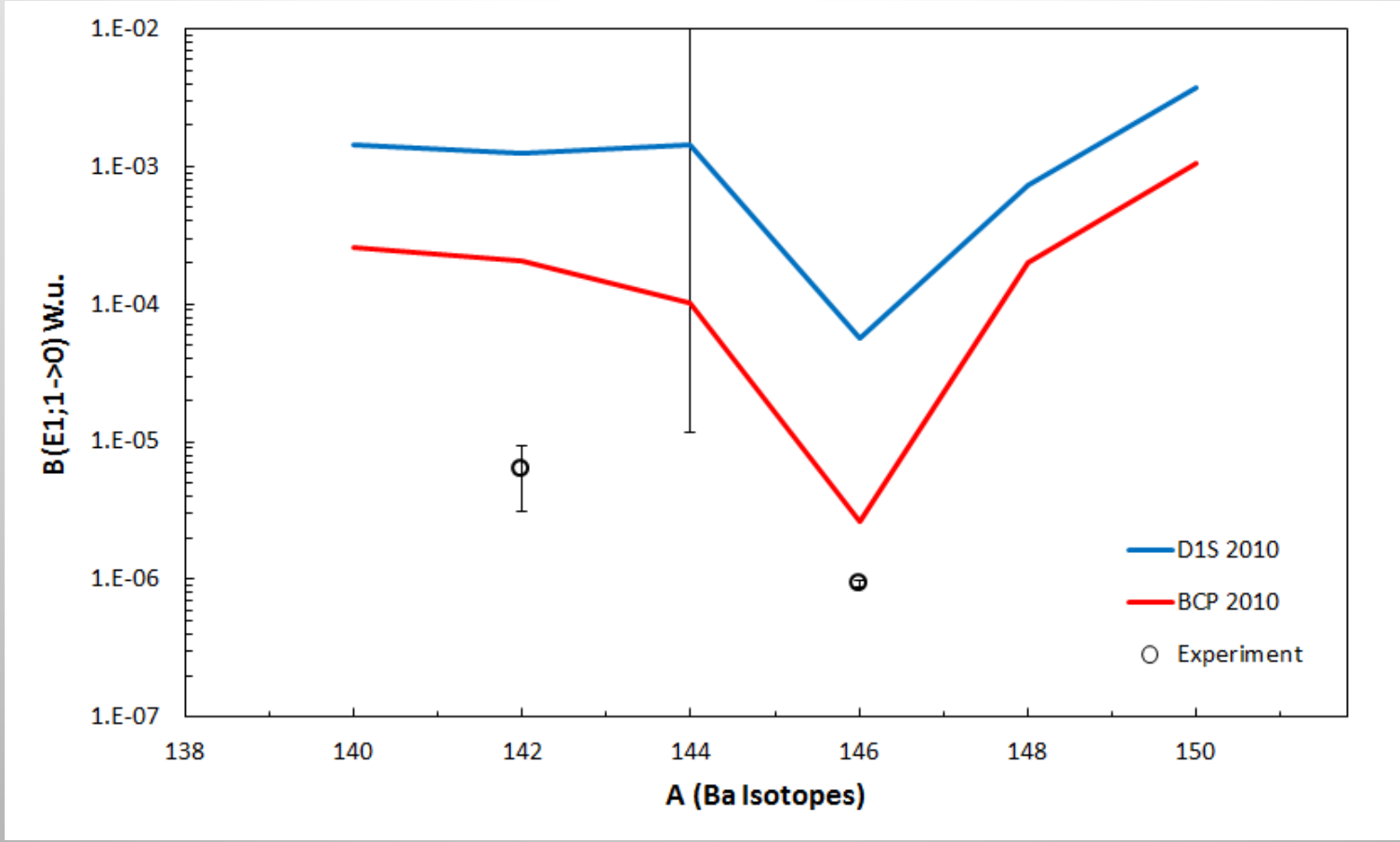
^{146}Ba E3 matrix elements compared to ^{144}Ba



- B(E3;3→0) = 48 W.u. (same as ^{144}Ba, smaller uncertainty)
- Measurements obtained for $2^+ \rightarrow 5^-$ & $4^+ \rightarrow 7^-$ MEs (instead of upper limits)

Note: B(E2,2→0) = 60 W.u. compared with 48 W.u. in ^{144}Ba


1.E-05
1.E-06
1.E-07
1.E-08
1.E-09
B(E1)/B(E2) [fm^-2]
0
2
4
6
8
10
12
14
16
18
Level Spin (h-bar)
Ba140
Ba142
Ba144
Ba146
Ba148

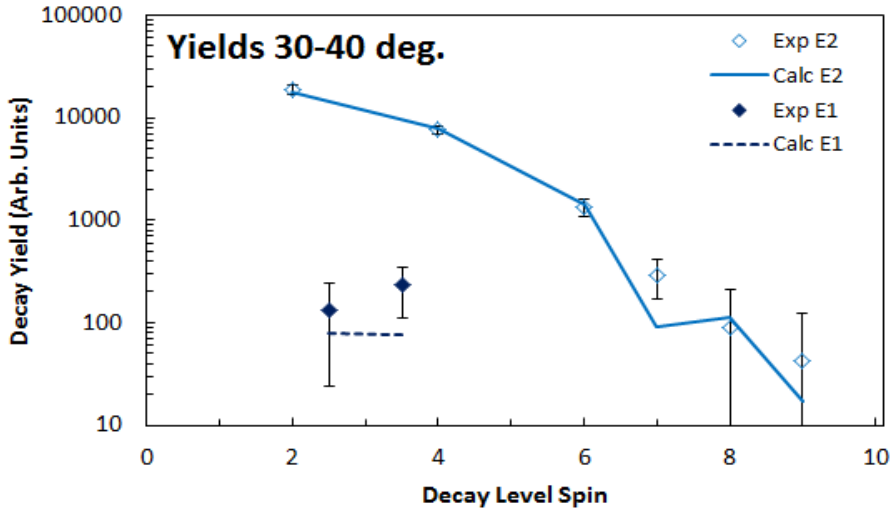


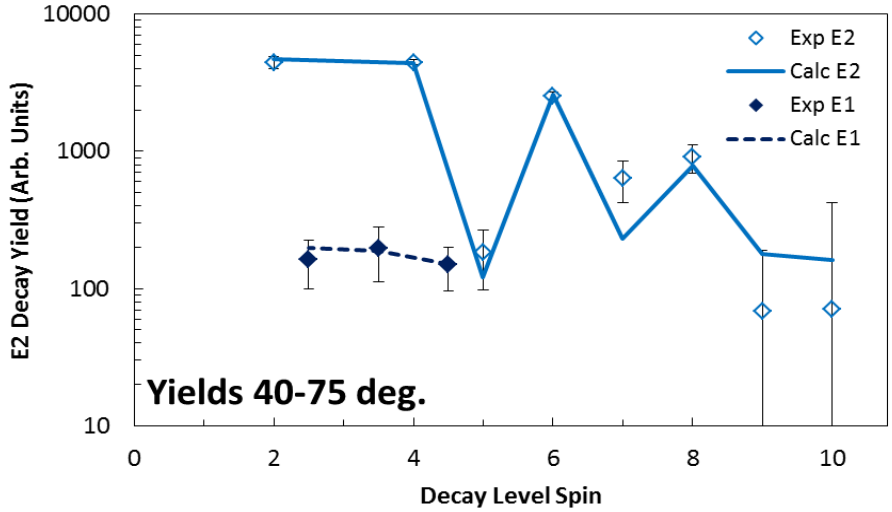
Theory: Robledo *et al.* PRC **81**:034315 (2010)

^{146}Ba Fit Results

Smaller angles →

Larger angles ↘





Note: E2/E1 ratio is much larger in ^{146}Ba

Ground-state β_3 deformation: atomic EDM search

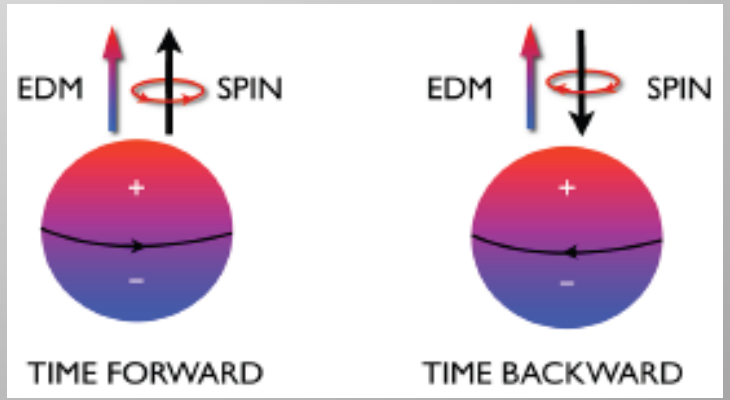
- Nuclear Schiff moment expected to be largest contribution to atomic EDM for diamagnetic atoms
- Are Schiff moments larger in lanthanide region?

Compare parameters between ^{224}Ra and Ba measurements: ^{144}Ba is 64% larger, ^{146}Ba 84% larger (numerator only)

***Reaching for the Horizon* (2015 Long Range Plan), p. 73**

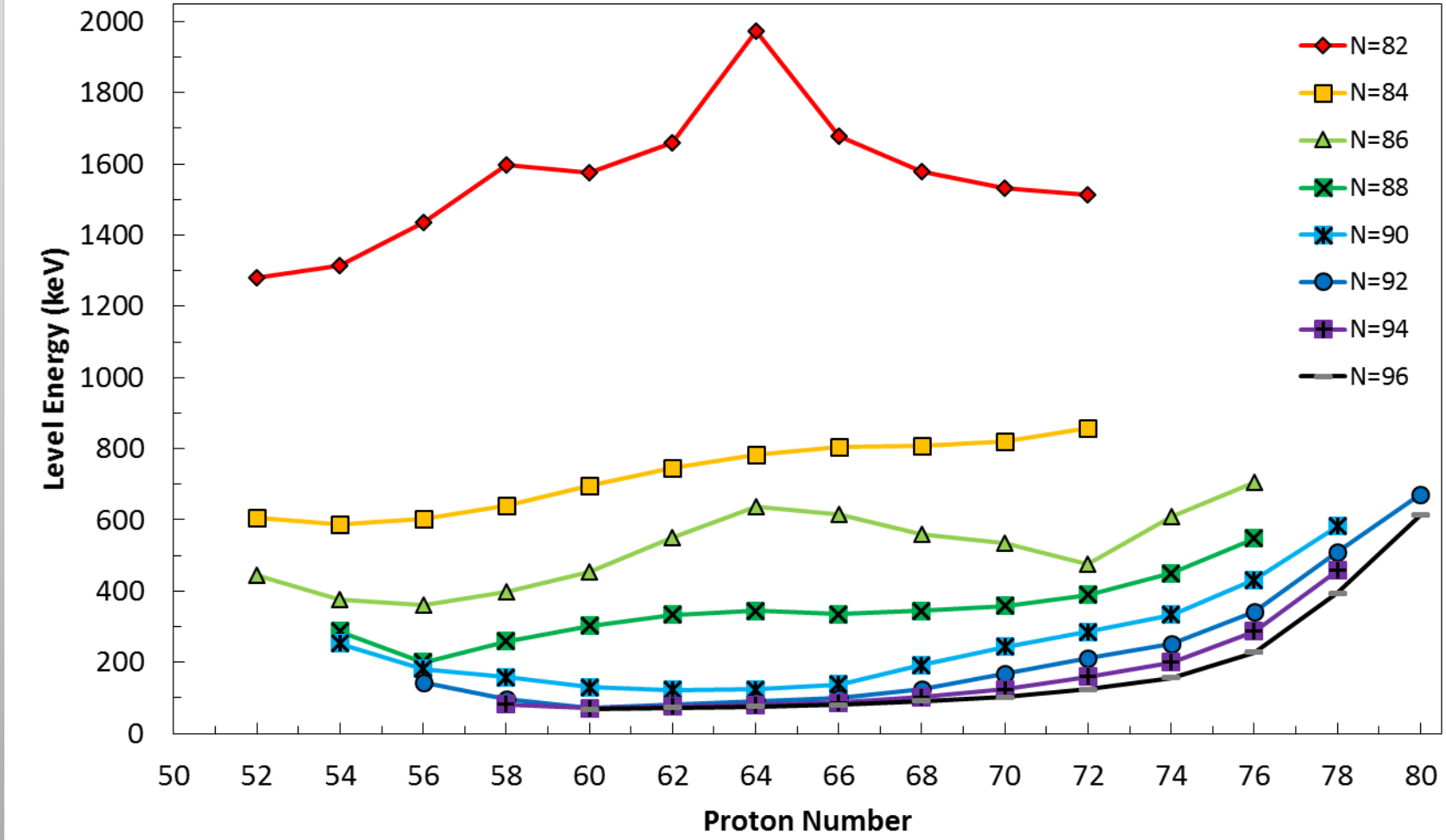
$$S \propto \beta\downarrow 2\ \beta\downarrow 3\ \downarrow\uparrow 2\ ZA\uparrow 2/3\ /|E\uparrow + -E\uparrow - |$$

(lab frame)



Spevak, Auerbach, & Flambaum, PRC **56**: 1357 (1997)

Need more data from reaccelerated RI beam experiments!


Level Energy (keV)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
50
52
54
56
58
60
62
64
66
68
70
72
74
76
78
80
Proton Number
N=82
N=84
N=86
N=88
N=90
N=92
N=94
N=96