

Investigation of Octupole Correlations in $^{144,145}\text{Ba}$ using the Recoil Distance Doppler-shift Technique

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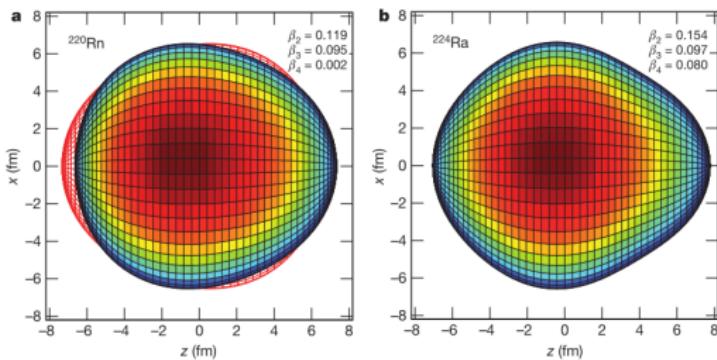
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Octupole correlations in the atomic nucleus

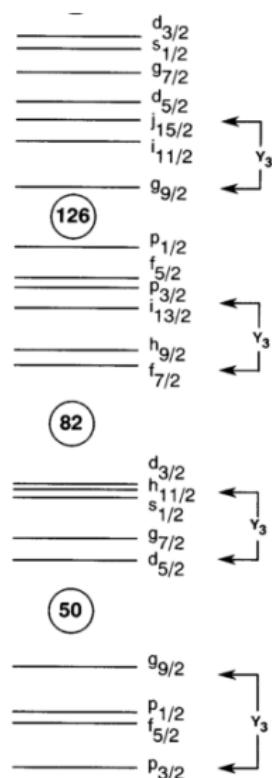
Long-range octupole-octupole interaction,
strength depends on:

- ▶ $r^3Y_3 \bullet r^3Y_3$ ME between SP states with
 $\Delta j = \Delta l = 3\hbar$
- ▶ ΔE between these states

Most pronounced for N,Z = 56,88,134



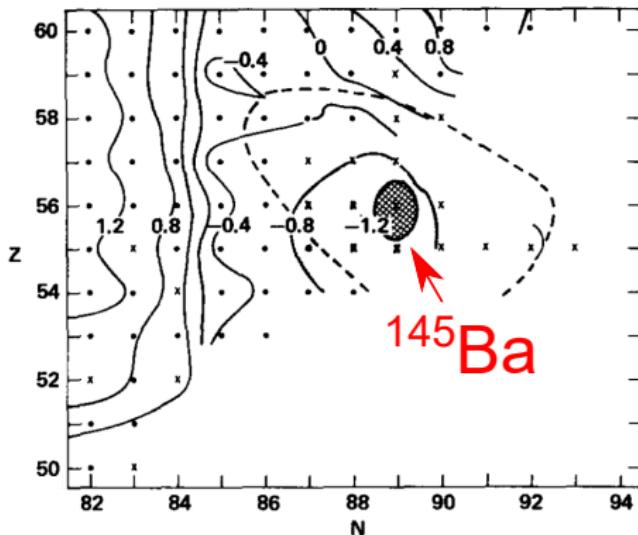
(taken from Gaffney *et al.* Nature 497, 199 (2013))



Octupole correlations in neutron-rich Ba isotopes

Evidence for octupole correlations around $Z \approx 56, N \approx 88, 90$

- **Ground-state masses reveal anomaly around ^{145}Ba**

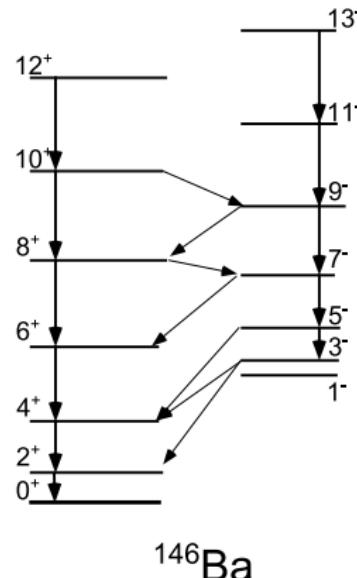
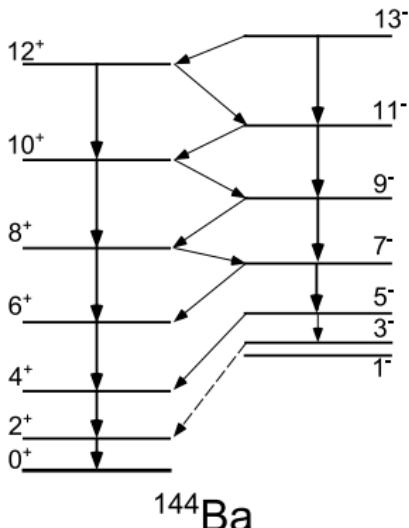


Mass discrepancy exp-calc (Möller-Nix) (MeV)
(taken from Leander PL B **152**, 284 (1985)).

Octupole correlations in neutron-rich Ba isotopes

Evidence for octupole correlations around $Z \approx 56$, $N \approx 88, 90$

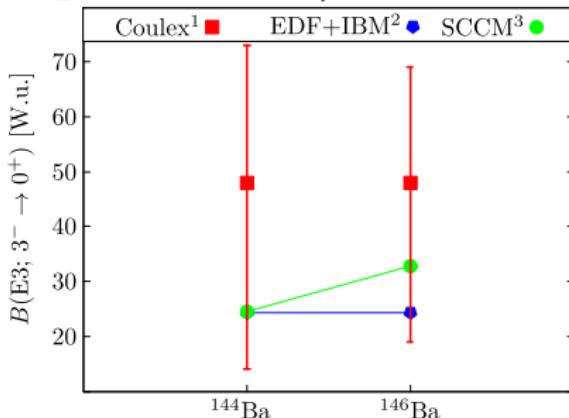
- ▶ Ground-state masses reveal anomaly around ^{145}Ba
- ▶ **Alternating parity sequence above $6\hbar$ in $^{144,146}\text{Ba}$**



Octupole correlations in neutron-rich Ba isotopes

Evidence for octupole correlations around $Z \approx 56$, $N \approx 88, 90$

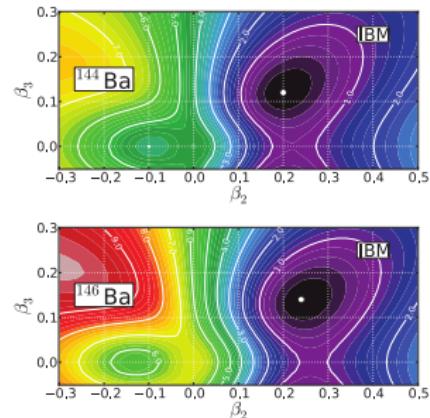
- ▶ Ground-state masses reveal anomaly around ^{145}Ba
- ▶ Alternating parity sequence above $7\hbar$, e.g. in $^{144,146}\text{Ba}$
- ▶ Enhanced $B(\text{E}3; 3^- \rightarrow 0^+)$ values in $^{144,146}\text{Ba}$ (but large error bars)



¹ Bucher *et al.* PRL **118**, 1520504 (2017),
PRL **116**, 112503 (2016)

² Nomura *et al.* PRC **89**, 024312 (2012)

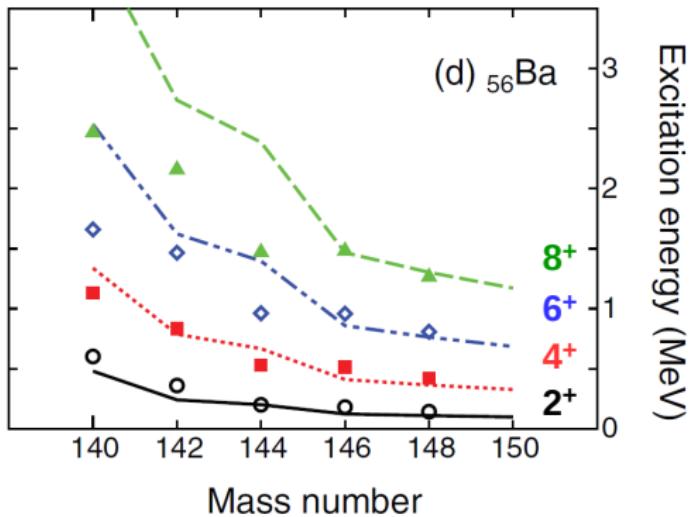
³ Bucher *et al.* PRC **89**, 024312 (2012) and Bernard *et al.* PRC **93**, 061302(R) (2016)



PRC **89**, 024312 (2012)

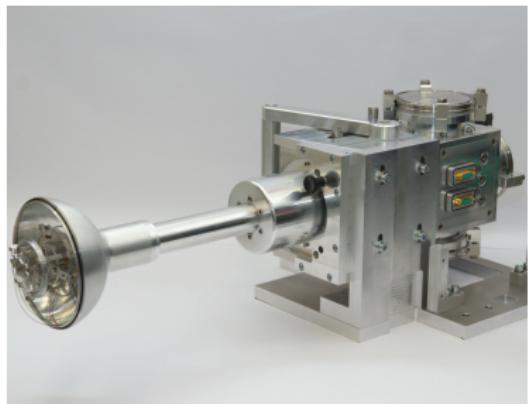
Octupole correlations in neutron-rich Ba isotopes

But: both EDF and SCCM calculations do not reproduce level scheme ^{144}Ba reasonably



Proposed experiment

Determination of level lifetimes in $^{144,145}\text{Ba}$ using the RDDS technique

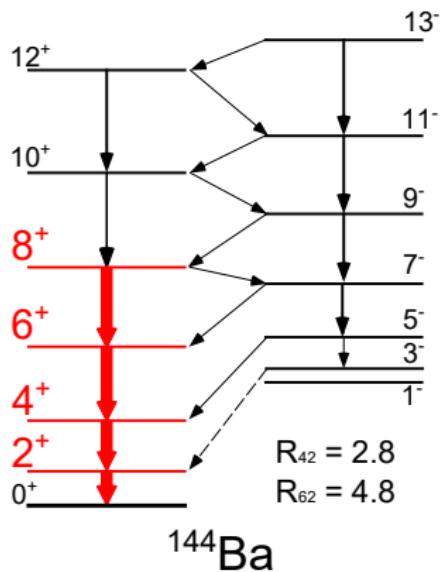


- ▶ Sensitivity to $\tau \approx 0.5 - 500 \text{ ps}$
- ▶ Establish plunger measurements at ISOLDE
- ▶ Population by ^7Li induced ICF¹
(Fusion of $^{144}\text{Cs} + t$)

Which quantities are proposed to be measured?

¹ Bottoni *et al.* PRC **92**, 024322 (2015)

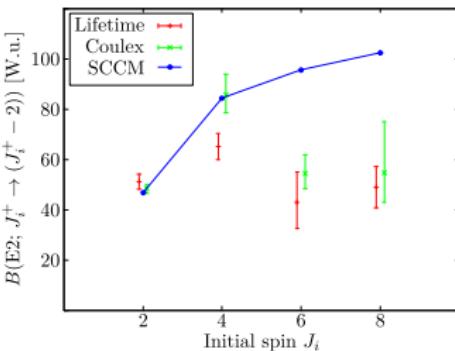
Transition strengths in ^{144}Ba



¹ Bucher PRL **116**, 112503 (2016)

² Biswas PRC **71**, 011301 (2005)

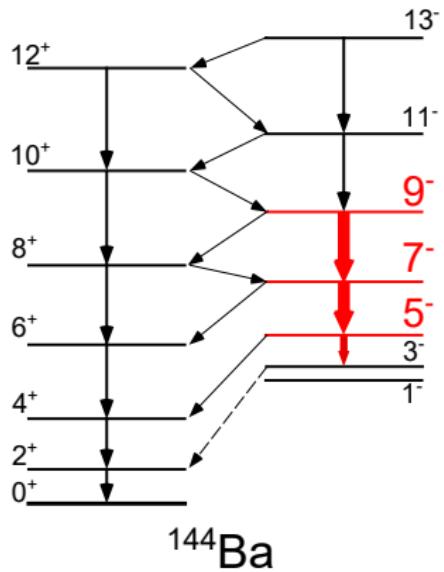
- ▶ $B(\text{E}2)$'s in yrast band (parity +)
 - ▶ Coulomb excitation¹
 - ▶ RDDS (fission source)²



Aim:

- ▶ Classify collective pattern
- ▶ Reduce uncertainties:
 $\tau(4_1^+) = 49(7)$ ps (PRC 41, R2469(R) (1990))
 $\tau(4_1^+) = 71(6)$ ps (PRC 71, 011301 (2005))

Transition strengths in ^{144}Ba



- ▶ $B(\text{E}2)$'s in yrast band (parity +)
- ▶ **$B(\text{E}2)$'s in yrast band (parity -)**
 - ▶ RDDS¹ + branching ratios

Results:

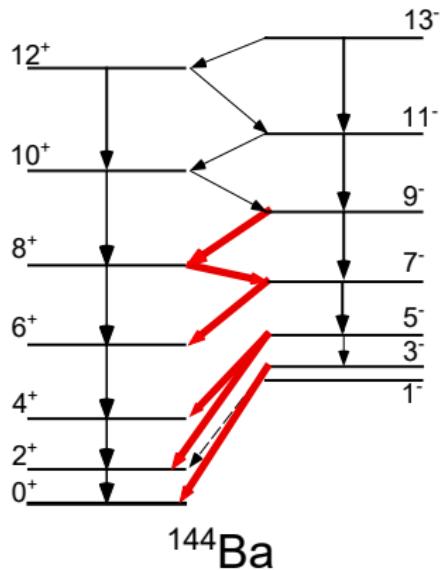
- $B(\text{E}2; 9^- \rightarrow 7^-) = 39(12) \text{ W.u}$
- $B(\text{E}2; 7^- \rightarrow 5^-) = 195(47) \text{ W.u.}$
 \rightarrow unexpected drop $B(\text{E}2, 9_1^- \rightarrow 7_1^-)!$

Aim:

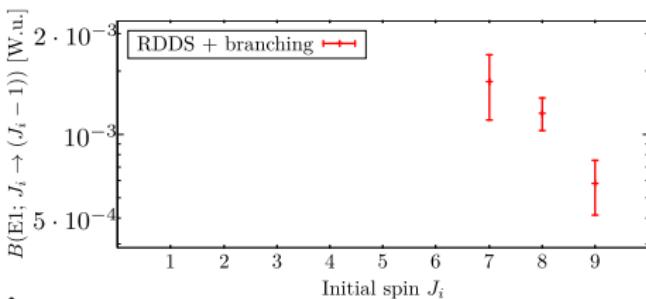
- ▷ Quantify collectivity in $\pi = -$ band
- ▷ Evaluate $B(\text{E}2; 5^- \rightarrow 3^-)$

¹ Biswas PRC **71**, 011301 (2005)

Transition strengths in ^{144}Ba



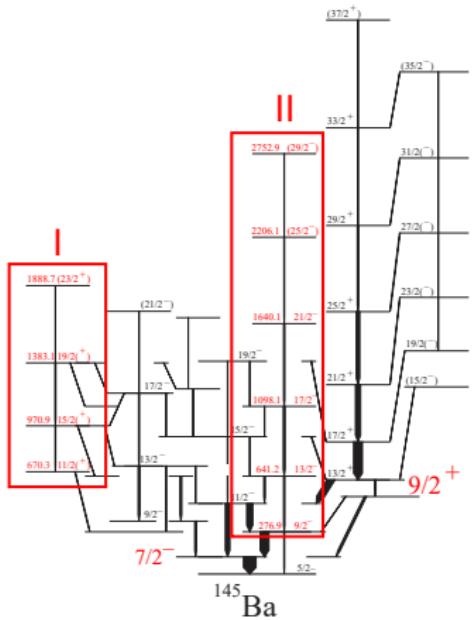
- ▶ $B(\text{E}2)$'s in yrast band (parity +)
- ▶ $B(\text{E}2)$'s in yrast band (parity -)
- ▶ **$B(\text{E}1)$'s and $B(\text{E}3)$'s**
→ unexpected drop of $B(E1, 9_1^- \rightarrow 8_1^+)$!



Aim:

- ▶ Limits for $B(\text{E}3)$ (branching)
- ▶ $\tau(5^-)$, $\tau(3^-)$ and $\tau(1^-)$ (?)

Octupole correlations in ^{145}Ba



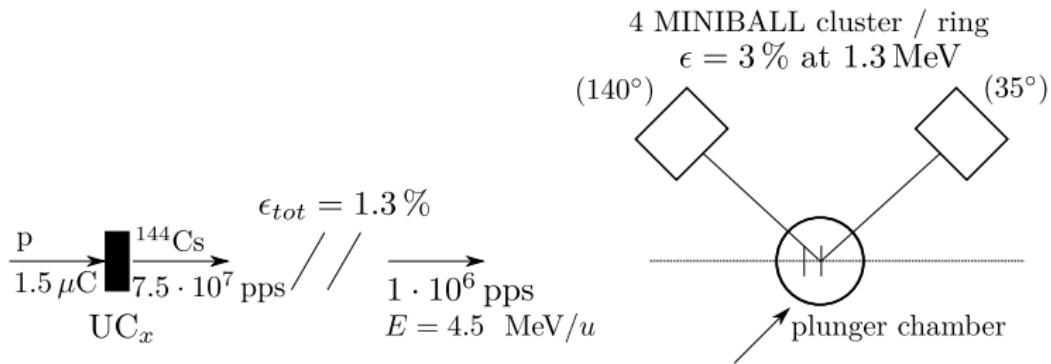
- ▶ No parity doublet to the gs ($5/2^-$)
- ▶ Level scheme hints for symmetric gs shape ¹
 - ▷ Octupole vibrations (coupled to reflection symmetric gs?)
- ▶ So far:
 - Only $\tau(7/2^{(-)})$
 - rel. strengths from branching

Aim:

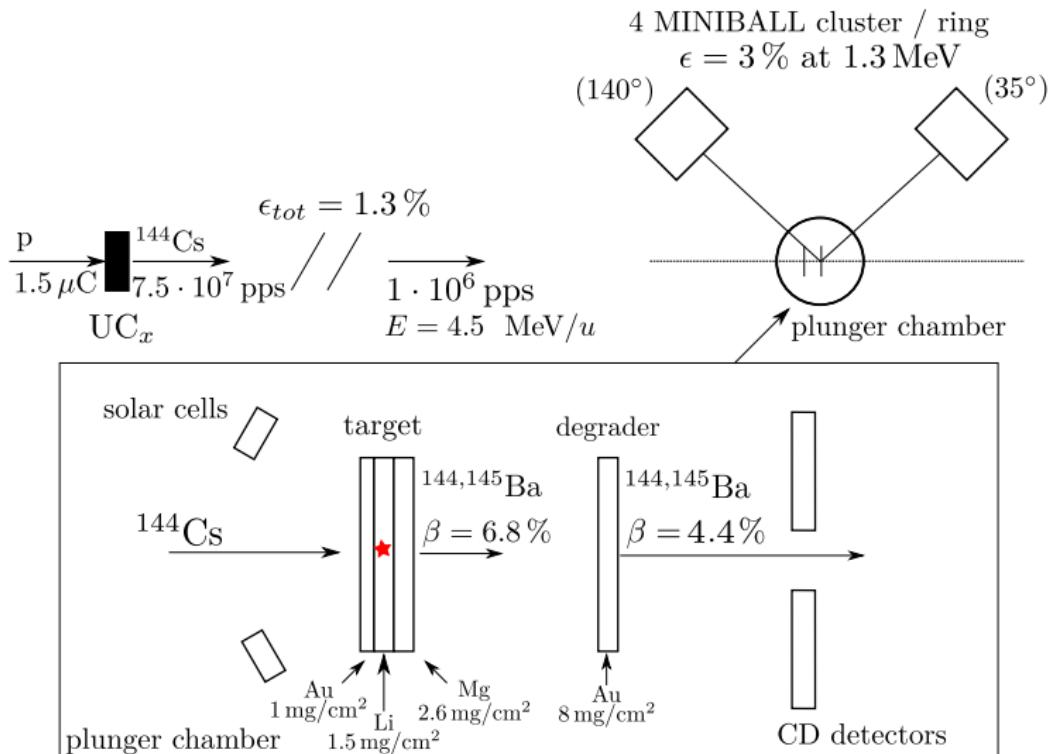
- ▷ Measure transition strengths between lowest states for first time
→ deduce structure: lowest states reflection symmetric?

¹PRC **86**, 044324 (2012)

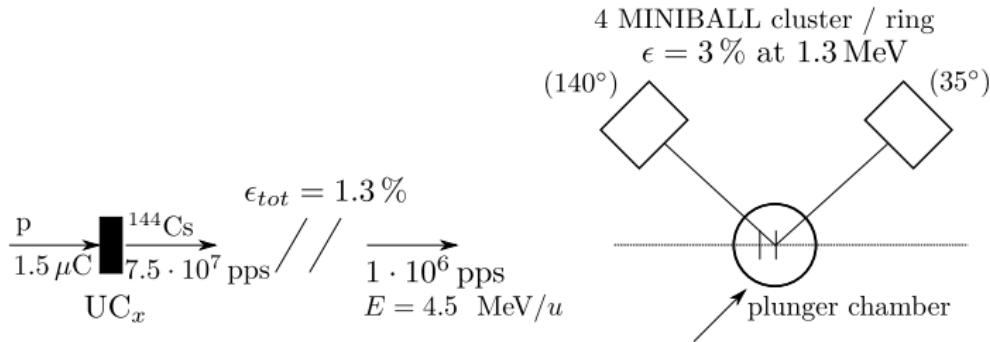
Experimental setup



Experimental setup



Yield estimate



Estimates:

- ▶ Incomplete $^{144}\text{Cs}-t$ fusion cross section: $\sim 50 \text{ mb}$
- ▶ γ -ray yield for $2^+ \rightarrow 0^+$ in ^{144}Ba : $1.0 \cdot 10^4 \gamma$'s in 8hrs
- ▶ In total: 15 shifts
 - ▶ Target-only data: 24 hrs (Three shifts)
 - ▶ Measurement of six foil separations à 16 hrs \rightarrow 12 shifts

Expected γ -ray yields

Transition	E_γ [keV]	Rel. intensity [%]	yield in 16hrs
$2^+ \rightarrow 0^+$	199	100	$\sim 2.0 \cdot 10^4$
$4^+ \rightarrow 2^+$	331	76	$\sim 1.1 \cdot 10^4$
$6^+ \rightarrow 4^+$	431	48	$\sim 6.0 \cdot 10^3$
$5^- \rightarrow 4^+$	509	2.4	$\sim 2.5 \cdot 10^2$
$5^- \rightarrow 3^-$	200	2.7	$\sim 5.1 \cdot 10^2$
$3^- \rightarrow 4^+$	309	6.4	$\sim 1.0 \cdot 10^3$
$3^- \rightarrow 2^+$	640	0.93	$\sim 0.8 \cdot 10^2$
$1^- \rightarrow 2^+$	560	2.5	$\sim 2.6 \cdot 10^2$
$1^- \rightarrow 0^+$	759	2.6	$\sim 2.4 \cdot 10^2$

Conclusion: experimental aims

^{144}Ba

- ▶ Clarify nature of yrast structure, remove ambiguities
- ▶ Enable a comparison of $\pi = +$ and $\pi = -$ bands
- ▶ Evaluate $B(\text{E}1)$ strength, from $1^-, 5^-$ for first time
- ▶ General: Reduction of uncertainties
- ▶ Observe $3^- \rightarrow 0_1^+$, $5^- \rightarrow 2_1^+$, $7^- \rightarrow 4_1^+$ $E3$ transitions in ^{144}Ba (or at least determine upper limits)

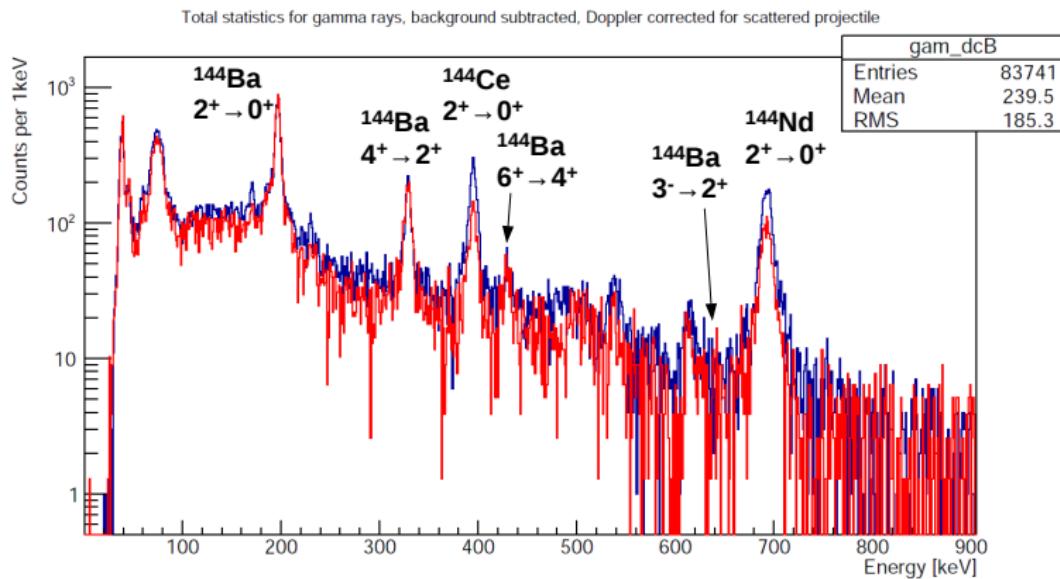
^{145}Ba

- ▶ Measure level lifetimes in ^{145}Ba for the first time:
structural information so far only from level scheme:
 \rightarrow g.s. reflection symmetric?
 \rightarrow existence of octupole correlations?

Online analysis experiment IS533 (M. Scheck et al.)

- ▶ $3_1^- \rightarrow 2_1^+ \approx 50$ counts in “few” days.
- ▶ no hint for 1^- state

Backup - Spectrum of exp. IS 533



Backup - β -decay of ^{144}Ce

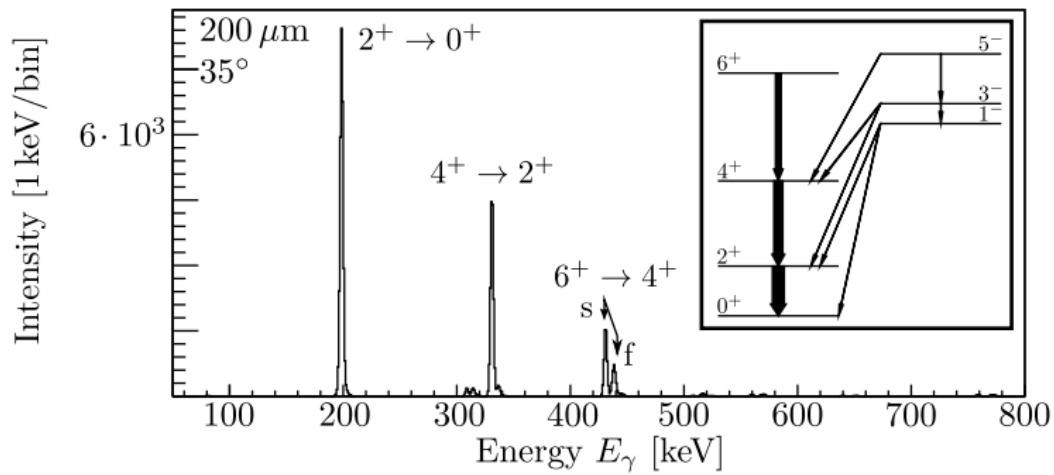
Problematic: ^{144}Ce ($T_{1/2} = 289$ days)

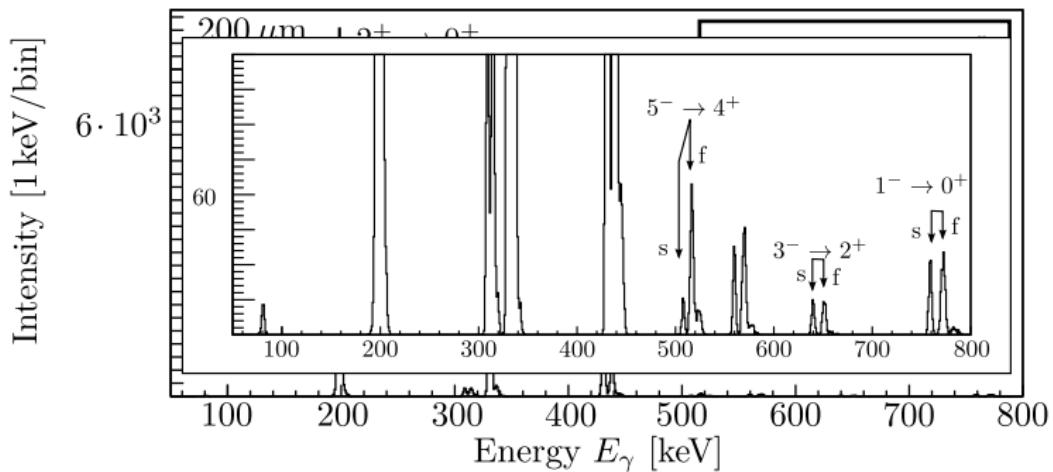
Note: It will be implanted somewhere (CD, shielding foil, beam dump)

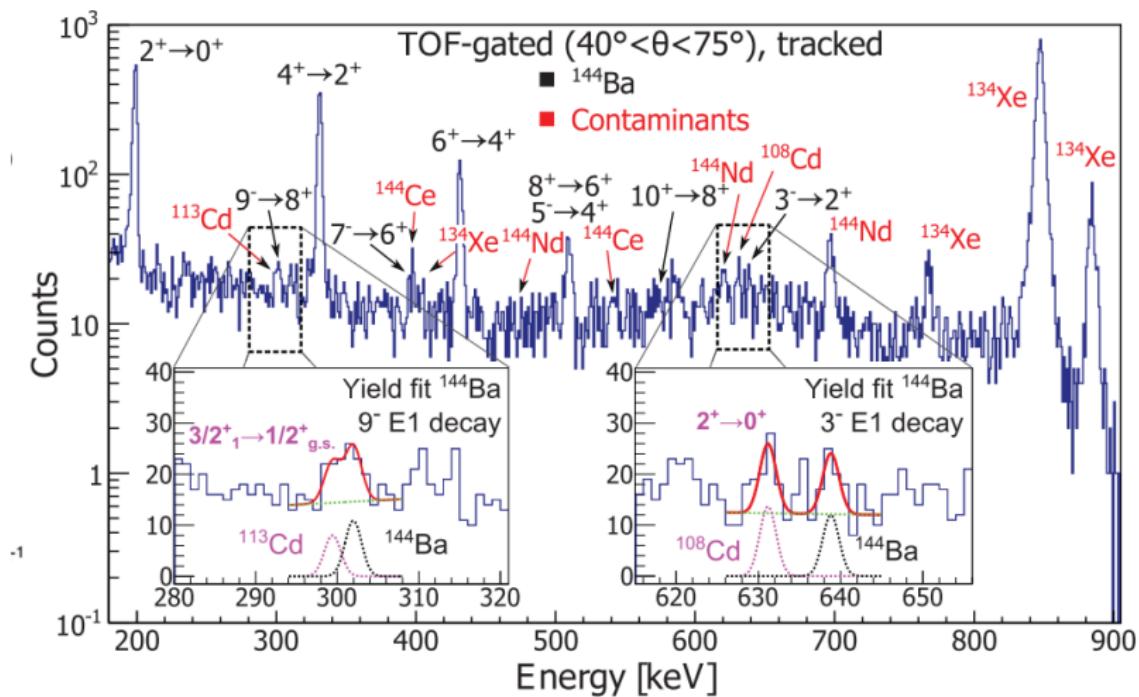
Bright side:

- ▶ Low specific activity
- ▶ Low Q-value for β^- (319keV)
- ▶ Highest γ -ray with $E = 133$ keV (11 %), all others at lower energies (or converted)

General approach: use shielding foils

Simulated spectra ^{144}Ba 

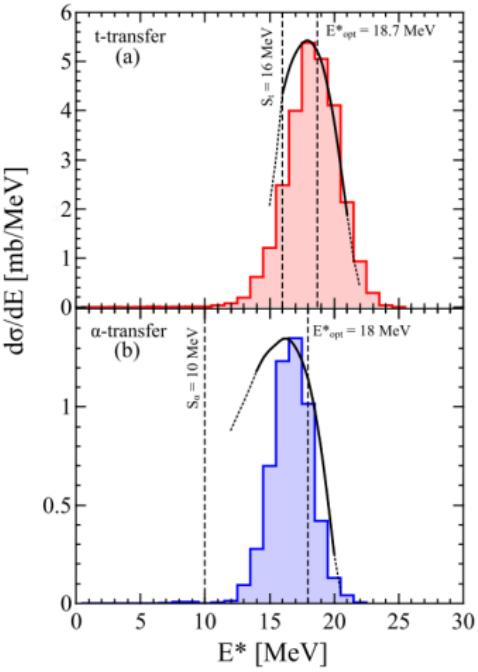
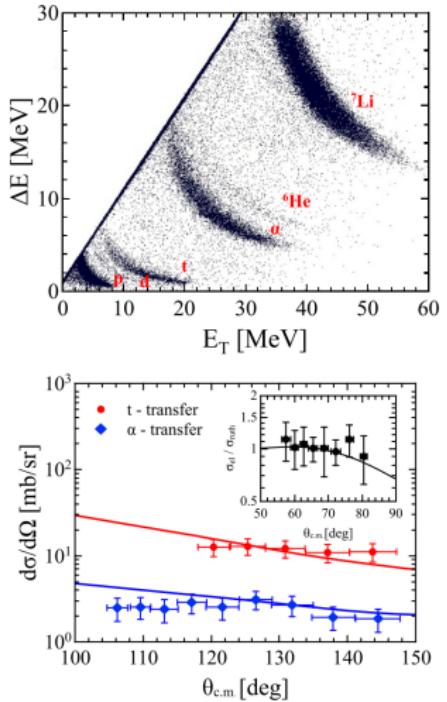
Simulated spectra ^{144}Ba 

Backup - Recent $B(\text{E}3)$ measurement in ^{144}Ba 

Backup - Li induced breakup

	This proposal	INTC-P-419	PRC 92, 0244322
Beam $^A Z$	^{144}Cs	^{132}Sn	^{98}Rb
Compound	^{147}Ba	^{135}Sb	^{101}Sr
Mid-target E [MeV/u]	3.9	3.5	2.48
Intensity	$1 \cdot 10^6$	$8.5 \cdot 10^5$	$2 \cdot 10^4$
Q_{gs} value $^A Z + t$	9.5	5.6	13.6
Q_{op} value	-7.7	-5.3	-5.1
Excitation E E_{op} [MeV]	17.2	10.9	18.9
S_n [MeV]	5.5	3.7	3.8
S_{2n} [MeV]	9.3	6.8	9.2
S_{3n} [MeV]	15.2	12.5	13.4

Backup - Li induced breakup



Source: Bottoni et al., PRC **92**, 024322 (2015)

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Abstract

We propose to exploit the unique capability of ISOLDE to provide intense post-accelerated ^{144}Ba ion beams from the REX facility to enable the Coulomb excitation of the first 3^- state in this nucleus. By measuring the γ -ray yields of the E1 decay connecting the 3^- and 2^+ states using the MINIBALL array, we can obtain the interesting $\langle 3^- | \text{E3} | 0^+ \rangle$ transition matrix element. The result will give quantitative information about octupole correlations in this nucleus. We require 27 shifts to fulfil the aims of the experiment.

Backup - Expected γ -ray yield (simulation)

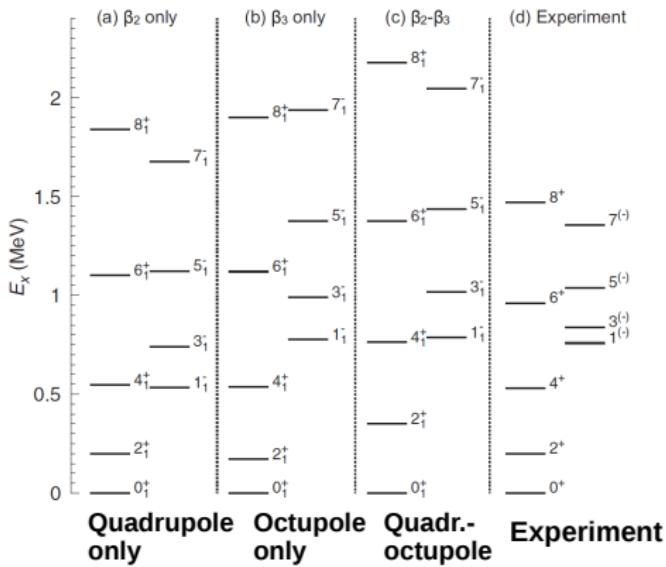
Transition	E_γ [keV]	Rel. intensity [%]	yield in 16hrs
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$6^+ \rightarrow 4^+$	431	48	$\sim 7.9 \cdot 10^3$
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$5^- \rightarrow 3^-$	200	2.7	$\sim 6.8 \cdot 10^2$
$3^- \rightarrow 4^+$	309	6.4	$\sim 1.3 \cdot 10^3$
$3^- \rightarrow 1^-$	80	0.14	$\sim 5.0 \cdot 10^1$
$3^- \rightarrow 2^+$	640	0.93	$\sim 1.1 \cdot 10^2$
$1^- \rightarrow 2^+$	560	2.5	$\sim 3.5 \cdot 10^2$
$1^- \rightarrow 0^+$	759	2.6	$\sim 3.2 \cdot 10^2$

Experimental transition strengths in ^{144}Ba

	Biswas PRC 71, 011301	Mach PRC 41, R2469	Krücken PRC 64, 017305	Bucher PRL 116, 112503
B(E2; $2^+ \rightarrow 0^+$)	51(3)	48.2(20)	-	$48.4^{+1.6}_{-2.0}$
B(E2; $4^+ \rightarrow 2^+$)	65.1(52)	54.9(70)	-	$85.7^{+8.2}_{-7.3}$
B(E2; $6^+ \rightarrow 4^+$)	56.1(71)	-	$42.9^{+12}_{-10.4}$	$54.4^{+7.5}_{-6.0}$
B(E2; $8^+ \rightarrow 6^+$)	48.9(82)	-	-	$54.8^{+20.1}_{-11.8}$
B(E2; $9^- \rightarrow 7^-$)	39(12)	-	-	-
B(E2; $7^- \rightarrow 5^-$)	384(141)	-	195(47)	-
B(E1; $7^- \rightarrow 6^+$)	$1.77(61) \cdot 10^{-3}$	-	$9.0(19) \cdot 10^{-4}$	-
B(E1; $9^- \rightarrow 8^+$)	$5.8(17) \cdot 10^{-4}$			
B(E1; $1^- \rightarrow 0^+$)	$> 2.9 \cdot 10^{-5}$			
B(E3; $3^- \rightarrow 0^+$)	-	-	-	48^{+25}_{-34}
B(E3; $5^- \rightarrow 2^+$)	-	-	-	< 106
B(E3; $7^- \rightarrow 4^+$)	-	-	-	< 189

Octupole correlations in neutron-rich Ba isotopes

But: both EDF and SCCM calculations do not reproduce level scheme ^{144}Ba reasonably



Conclusion

Aim: Measurement of precise level lifetimes in $^{144,145}\text{Ba}$

- ▶ Increase precision of transition strengths from 3^- , 7^- , 9^- states and between yrast states, remove ambiguities.
- ▶ Determine transition strengths from 1^- , 5^- states from level lifetimes in ^{144}Ba for the first time
- ▶ Observe $3^- \rightarrow 0_1^+$, $5^- \rightarrow 2_1^+$, $7^- \rightarrow 4_1^+$ $E3$ transitions in ^{144}Ba (or at least determine upper limits)
- ▶ Learn about octupole collectivity of ^{144}Ba as theoretical approaches are not able to give a sufficient description.
- ▶ Measure level lifetimes in ^{145}Ba for the first time:
structural information so far only from level scheme:
 \rightarrow g.s. reflection symmetric?
 \rightarrow existence of octupole correlations?