



## Relativistic Projectile Coulomb Excitation to the Yrast and Non-yrast 2<sup>+</sup> States of <sup>134</sup>Ce and <sup>136</sup>Nd

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for the RISING collaboration



## **Physics motivation**

Nuclear phase transition around A~130



## Physics motivation

- Triaxiality and γ-softness play a role in chiral structures
- Indication of triaxiality and γ-softness near the ground state
  - Lower  $2_{2}^{+}$  energy and large B(E2; $2_{2}^{+} \rightarrow 0^{+}$ ) •  $\gamma$ -softness
  - Lower  $2_{2}^{+}$  energy than  $4_{1}^{+}$  and large B(E2;  $2_{2}^{+} \rightarrow 2_{1}^{+}$ ) • Triaxiality

Large scale microscopic Monte Carlo Shell Model Calculation is available

Reproduced nuclear properties of neutron rich Ba isotopes

## Goal of the experiment

- To measure B(E2) of transitions depopulating 2<sup>+</sup><sub>1</sub> and 2<sup>+</sup><sub>2</sub> states in <sup>134</sup>Ce and <sup>136</sup>Nd
- Relativistic Coulomb excitation of secondary <sup>134</sup>Ce and <sup>136</sup>Nd projectiles with FRS at GSI
- $\textcircled{\sc s} \gamma\text{-ray}$  measurements with RISING Ge detector

array

Nd134 8.5 m	Nd135 12.4 m	Nd136 50.65 m	Nd137 38.5 m	Nd138 5.04 h	Nd139 29.7 m	Nd140 3.37 d	Nd141 2.49 h	Nd142	Nd143	Nd144 2.29E+15 y	Nd145	Nd146
0+	9/2(-)	0+	1/2+	0+	3/2+	0+	3/2+	0+	7/2-	0+	7/2-	0+
EC	EC	EC	i c 🌷	EC	EC	EC	EC	27.13	12.18	α 23.80	8.30	17.19
Pr133	Pr134	Pr135	Pr136	Pr137	Pr138	Pr139	Pr140	Pr141	Pr142	Pr143	Pr144	Pr145
(3/2+)	2-	3/2(+)	2+	5/2+	1.45 m 1+	4.41 fi 5/2+	3.39 m 1+	5/2+	19.12 ft 2-	7/2+	0-	5.984 fi 7/2+
EC	EC *	EC	EC	EC	EC *	EC	EC	100	ΈC,β *	β-	β-	β-
Ce132	Ce133	Ce134	Ce135	Ce136	Ce137	Ce138	Ce139	Ce140	Ce141	Ce142	Ce143	Ce144
3.51 h 0+	97 m 1/2+	3.16 d 0+	17.7 h 1/2(+)	0+	9.0 h 3/2+	0+	137.640 d 3/2+	0+	32.501 d 7/2-	5E+16 y 0+	33.039 h 3/2-	284.893 d 0+
* EC	* EC	EC	c *	0.19	* EC	<b>0.2</b> 5	* EC	88.48	β-	11.08	β-	β≓
La131	La132	La133	La134	La135	La136	La137	La138	La139	La140	La141	La142	La143
59 m 3/2+	4.8 h 2-	3.912 h 5/2+	6.45 m 1+	19.5 h 5/2+	9.87 m 1+	6E4 y 7/2+	1.05E+11 y 5+	7/2+	1.6781 d 3-	3.92 h (7/2+)	91.1 m 2-	14.2  m (7/2)+
FC	FC *	FC	FC	FC	*	FC	EC,β	00 0000	R-	R-	R-	R-
Po120	LC	LC	L.C.	E.C.	LC	LC	0.0902	557570570	٣	P	F	P
	Ro131	<b>Bal32</b>	Ba133	Ro134	Ro135	Ba136	Ba137	Ro138	Ba139	Ba140	Ba141	<b>Bal4</b> 2
Da130	Ba131 11.50 d	Ba132	Ba133 10.51 y	Ba134	Ba135	Ba136	Ba137	Ba138	Ba139 83.06 m	Ba140 12.752 d	<b>Ba141</b> 18.27 m	Ba142 10.6 m
0+ *	Ba131 11.50 d 1/2+	Ba132 0+	Ba133 10.51 y 1/2+	Ba134 0+	Ba135 <sup>3/2+</sup> *	Ba136 0+ *	Ba137 <sup>3/2+</sup> *	Ba138 0+	Ba139 83.06 m 7/2-	Ba140 12.752 d 0+	Ba141 18.27 m 3/2-	Ba142 10.6 m 0+
0+ * 0.106	Ba131 11.50 d 1/2+ EC	Ba132 0+ 0.101	Ba133 10.51 y 1/2+ EC	Ba134 0+ 2.417	Ba135 3/2+ 6.592	Ba136 <sup>0+</sup> 7.854	Ba137 <sup>3/2+</sup> * 11.23	Ba138 0+ 	Ba139 83.06 m 7/2- β-	Ba140 12.752 d 0+ β·	Ba141 18.27 m 3/2- β-	Ba142 10.6 m 0+ β·
0+ 0+ 0.106 Cs129	Ba131 11.50 d 1/2+ * EC Cs130	Ba132 0+ 0.101 Cs131	Ba133 10.51 y 1/2+ * EC Cs132	Ba134 0+ 2.417 Cs133	Ba135 3/2+ * 6.592 Cs134	Ba136 0+ * 7.854 Cs135	Ba137 3/2+ 11.23 Cs136	Ba138 0+ 71.70 Cs137	Ba139 83.06 m 7/2- β- Cs138	Ba140 12.752 d 0+ β <sup>-</sup> Cs139	Ba141 18.27 m 3/2- β <sup>-</sup> Cs140	Ba142 10.6 m 0+ β- Cs141
0+ * 0.106 Cs129 32.06 h 1/2+	Ba131 11.50 d 1/2+ * EC Cs130 29.21 m 1+	Ba132 0+ 0.101 Cs131 9.689 d 5/2+	Ba1 33 10.51 y 1/2+ * EC Cs1 32 6.479 d 2+	Ba134 0+ 2.417 Cs133 7/2+	Ba135 <sup>3/2+</sup> * 6.592 Cs134 2.0648 y 4+	Ba136 0+ * 7.854 Cs135 2.3E+6 y 7/2+	Ba137 3/2+ * 11.23 Cs136 13.16 d 5+	Ba138 0+ 71.70 Cs137 30.07 y 7/2+	Ba139 83.06 m 7/2- β- Cs138 33.41 m 3-	Ba140 12.752 d 0+ β· Cs139 9.27 m 7/2+	Ba141 18.27 m 3/2- β- Cs140 63.7 s 1-	Ba142 10.6 m 0+ β- Cs141 24.94 s 7/2+
0+ * 0.106 Cs129 32.06 h 1/2+	Ba131 11.50 d 1/2+ EC Cs130 29.21 m 1+ FC 6-	Ba132 0+ 0.101 Cs131 9.689 d 5/2+	Ba133 10.51 y 1/2+ EC Cs132 6.479 d 2+ EC B-	Ba134 0+ 2.417 Cs133 7/2+	Ba135 3/2+ * 6.592 Cs134 2.0648 y 4+ * FC 8-	Ba136 0+ * 7.854 Cs135 2.3E+6 y 7/2+ *	Ba137 3/2+ * 11.23 Cs136 13.16 d 5+ *	Ba138 0+ 71.70 Cs137 30.07 y 7/2+	Ba139 83.06 m 7/2- β- Cs138 33.41 m 3- *	Ba140 12.752 d 0+ β <sup>-</sup> Cs139 9.27 m 7/2+ β <sup>-</sup>	Ba141 18.27 m 3/2- β- Cs140 63.7 s 1- β-	Ba142 10.6 m 0+ β- Cs141 24.94 s 7/2+
0+ 0.106 Cs129 32.06 h 1/2+ EC V \$ 138	Ba131 11.50 d 1/2+ * EC Cs130 29.21 m 1+ * EC,β- V 2120	Ba132 0+ 0.101 Cs131 9.689 d 5/2+ EC	Ba133 10.51 y 1/2+ * EC Cs132 6.479 d 2+ EC,β- Vo123	Ba134 0+ 2.417 Cs133 7/2+ 100 Vo123	Ba135 3/2+ * 6.592 Cs134 2.0648 y 4+ * EC,β Vo122	Ba136 0+ * 7.854 Cs135 2.3E+6 y 7/2+ β <sup>5</sup> Yo124	Ba137 <sup>3/2+</sup> * 11.23 Cs136 13.16 d 5+ β <sup>3</sup> Vo125	Ba138 0+ 71.70 Cs137 30.07 y 7/2+ β <sup>-</sup>	Ba139 83.06 m 7/2- β- Cs138 33.41 m 3- β- Vo127	Ba140 12.752 d 0+ β· Cs139 9.27 m 7/2+ β·	Ba141 18.27 m 3/2- β- Cs140 63.7 s 1- β- Va120	Ba142 10.6 m 0+ β- Cs141 24.94 s 7/2+ βn
0+ 0.106 Cs129 32.06 h 1/2+ EC Xe128	Ba131 11.50 d 1/2+ * EC Cs130 29.21 m 1+ * EC,β <sup>2</sup> Xe129	Ba132 0+ 0.101 Cs131 9.689 d 5/2+ EC Xe130	Ba133 10.51 y 1/2+ * EC Cs132 6.479 d 2+ EC,β <sup>-</sup> Xe131	Ba134 0+ 2.417 Cs133 7/2+ 100 Xe132	Ba135 3/2+ * 6.592 Cs134 2.0648 y 4+ * EC,β <sup>-</sup> Xe133 5.243 d	Ba136 <sup>0+</sup> * 7.854 Cs135 2.3E+6 y 7/2+ * β· Xe134	Ba137 3/2+ * 11.23 Cs136 13.16d 5+ * β Xe135 9.14h	Ba138 0+ 71.70 Cs137 30.07 y 7/2+ β· Xe136 2,36E21 y	Ba139 83.06 m 7/2- β Cs138 33.41 m 3- * β Xe137 3.818 m	Ba140           12.752 d           0+           β           Cs139           9.27 m           7/2+           β           Xe138           14.08 m	Ba141           18.27 m           3/2-           β-           Cs140           63.7 s           1-           β-           Xe139           39.68 s	Ba142           10.6 m           0+           β-           Cs141           24.94 s           7/2+           βn           Xe140           13.60 s
0+ * 0.106 Cs129 32.06 h 1/2+ EC Xe128 0+	Bal31 11.50 d 1/2+ EC Cs130 29.21 m 1+ EC,β <sup>±</sup> Xel29 1/2+ 2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.	Ba132 0+ 0.101 Cs131 9.689 d 5/2+ EC Xe130 0+	Ba133 10.51y 1/2+ * EC C \$132 6.479 d 2+ EC,β· Xe131 3/2+	Ba134 0+ 2.417 Cs133 7/2+ 100 Xe132 0+	Ba135 3/2+ * 6.592 Cs134 2.0648 y 4+ * EC,β <sup>2</sup> Xe133 5.243 d 3/2+ *	Ba136 <sup>0+</sup> * 7.854 Cs135 2.3E+6 y 7/2+ * β- Xe134 <sup>0+</sup> *	Ba137 3/2+ * 11.23 Cs136 d 5+ * β Xe135 9.14h 3/2+ *	Ba138 0+ 71.70 Cs137 30.07 y 7/2+ β· Xe136 2.36E21 y 0+	Ba139 83.06 m 7/2- β- Cs138 33.41 m 3- * β- Xe137 3.818 m 7/2-	Ba140           12.752 d           0+           β-           Cs139           9.27 m           7/2+           β-           Xe138           14.08 m           0+	Ba141         18.27 m           3/2-         β-           Cs140         63.7 s           β-         β-           Xe139         39.68 s           3/2-         3/2-	Ba142         10.6 m           0+         β-           Cs141         24.94 s           7/2+         βn           Xe140         13.60 s           0+         9+

## **Fragment separator**



## **RISING** setup at the final focal plane



## Doppler shift correction





Cut with 0.8 ~ 1.8 degrees is optimum

## Gamma-ray spectra









# Particle- $\gamma$ angular correlation

#### Correlation on θ

- Rising-wise sorting at the rest frame
- I sotropic distribution observed
- Can not reproduced by calculations with alignments
- Efficiency calibration being crucial
- Correlation on φ difference
   between γ-rays and outgoing
   particles, event-by-event
  - Using all Ge-CATE phase space
  - Efficiency calibration cancelled
  - I sotropic distribution observed
  - Can not reproduced by calculations with alignments



Surprisingly, no (or very small) alignment was observed

# Deducing B(E2)

	<sup>134</sup> Ce on <sup>197</sup> Au at 126 A MeV			<sup>136</sup> Nd on <sup>197</sup> Au at 126 A MeV			
	E <sub>γ</sub> [keV]	Nγ	ε [%]	E <sub>γ</sub> [keV]	Nγ	ε [%]	
2 <sup>+</sup> 1→0 <sup>+</sup>	409	1713±101	1.98±0.06	374	3039±130	1.98±0.06	
2 <sup>+</sup> <sub>2</sub> →0 <sup>+</sup>	966		1.51±0.05	862	156±49	1.58±0.05	
$2^{+}_{2} \rightarrow 2^{+}_{1}$	557	<149	1.85±0.05	489	183±56	1.91±0.06	
	N <sub>pro</sub> 1895843±13	DAQ 377	livetime [%] 77	N <sub>pro</sub> 1986411±14	DAQ 09	livetime [%] 79	

- Shown value: <sup>134</sup>Ce  $2_{1}^{+} \rightarrow 0^{+}$  B(E2), 52 (5) W.u.; reference
- Absolute efficiency with Lorentz boost with β=0.42 and DAQ livetime taken into account
- Isotropic distribution at the rest frame assumed
- Gamma-ray intensities normalized by particle numbers on the target

## B(E2) values in W.u.

	<sup>132</sup> Ba	<sup>134</sup> Ce	<sup>136</sup> Nd
$2^{+}_{1} \rightarrow 0^{+}$	43 (4)	52 (5) 77 (26)	<b>80 (11)</b> 97 (27)
<b>2</b> <sup>+</sup> <sub>2</sub> → <b>0</b> <sup>+</sup>	3.9 (4)	< 11	<b>11 (3)</b> 13 (5)
$2^+_2 \rightarrow 2^+_1$	144 (14)	< 140	182 (93)
			219 (124)

- Complete measurements for <sup>136</sup>Nd
- Solve the only upper limit given to  $2^+_2 \rightarrow 0^+$  and  $2^+_2 \rightarrow 0^+$  in  $^{134}Ce$
- B(E2) values with normalization to the target <sup>197</sup>Au Coulomb excitation used for cross-checking

Comparison to the theoretical calculations

Large scale microscopic Monte Carlo Shell Model Calculation

Still in progress by Otsuka of Tokyo University

- Naive Macroscopic Asymmetric Rotor model calculations
  - Experimental information on the transition probability is limited only up to the 2<sup>+</sup><sub>2</sub> states

### Asymmetric Rotor Model (ARM) for <sup>132</sup>Ba, <sup>134</sup>Ce and <sup>136</sup>Nd



## Asymmetric Rotor Model (ARM) for <sup>132</sup>Ba, <sup>134</sup>Ce and <sup>136</sup>Nd

#### γ-rigid ARM

A.S. Davydov and G.F. Filippov, Nucle. Phys. 8, 237 (1958)

#### $\sim$ $\gamma$ -soft ARM with $\mu$ =0.5

A.S. Davydov and A.A. Chaban, Nucle. Phys. 20, 499 (1960)



## Summary

- Relativistic projectile Coulomb excitation with RI-beams of <sup>134</sup>Ce and <sup>136</sup>Nd to 2<sup>+</sup><sub>1</sub> and 2<sup>+</sup><sub>2</sub> with FRS-RISING at GSI
  - The first relativistic Coulomb excitation to non-yrast states
- No alignment observed
- Relative B(E2) measurement normalized to the known B(E2) of  $2^{+}_{1} \rightarrow 0^{+}$  in  $^{134}Ce$
- Data compared to asymmetric rotor model
  - Indication of a triaxial soft rotor
- Microscopic calculations with Monte Carlo Shell Model are in progress

## Backup slides

# Deducing B(E2)

	13	<sup>34</sup> Ce+ <sup>197</sup> Au at 1	26 A MeV	<sup>136</sup> Nd+ <sup>197</sup> Au at 126 A MeV			
Transitions $2^+_1 \rightarrow 0^+$ $2^+_2 \rightarrow 0^+$ $2^+_2 \rightarrow 2^+_1$	${f E}_{\gamma}  [{ m keV}] \ 409.2 \ 965.7 \ 556.6$	$N_{\gamma}$ $1713 \pm 101$ $< 149$	$\varepsilon$ [%] ( $\beta = 0.42$ ) 1.98 ± 0.06 1.51 ± 0.05 1.85 ± 0.06	${f E}_{\gamma}  [{ m keV}] \ 373.7 \ 862.4 \ 488.6$	$N_{\gamma}$ $3039 \pm 130$ $156 \pm 49$ $183 \pm 56$	$\varepsilon$ [%] ( $\beta$ = 0.42) 1.99 ± 0.06 1.58 ± 0.05 1.91 ± 0.06	
$\begin{array}{c}^{197}\text{Au transitions}\\7/2^+ \rightarrow 3/2^+\end{array}$	${f E}_{\gamma} \ [{ m keV}] \ 547.5$	$\begin{array}{c} \mathrm{N}_{\gamma}\\ 130\pm41 \end{array}$	$\varepsilon \ [\%] \ (\beta = 0.0) \ 0.97 \pm 0.03$	${f E}_{\gamma} \ [{ m keV}] \ 547.5$	$\begin{array}{c} \mathrm{N}_{\gamma}\\ 171 \pm 44 \end{array}$	$ \begin{aligned} \varepsilon \; [\%] \; (\beta = 0.0) \\ 0.97 \pm 0.03 \end{aligned} $	
	$N_{pro}$ 1895843 ± 1377		DAQ livetime [%] 77	$\begin{array}{cc} N_{pro} & DAQ \text{ liveti} \\ 1986411 \pm 1409 & 79 \end{array}$		DAQ livetime [%] 79	

- Shown value: <sup>134</sup>Ce  $2_{1}^{+} \rightarrow 0^{+}$  B(E2), 52 (5) W.u.; reference
- Solute efficiency with Lorentz boost with  $\beta$ =0.42 and DAQ livetime taken into account
- Isotropic distribution at the rest frame assumed
- Gamma-ray intensities normalized by particle numbers on the target

## Absolute efficiency calibration

 $\sim \gamma - \gamma$  coincidence measurement with <sup>60</sup>Co  $\gamma$ -ray source

- Absolute efficiency for 1.173 and 1.333 MeV γ-rays
- Calibration with an assumption of isotropic  $\gamma$ - $\gamma$  angular correlation
  - Actual  $\gamma$ - $\gamma$  angular correlation gives difference of 1 % in the calibration  $\rightarrow$  systematic error
- Relative efficiency calibration (energy dependence) with <sup>152</sup>Eu γ-ray source
- Lorentz-boost to the rest frame



# Selection of Coulomb excitation events: $\gamma$ -multiplicity



## Improved particle tracking



- Old tracking method: MW41 MW42 CATE
  - Scattering in MUSIC -> wrong vertex reconstruction

#### New method with target-Si detector

- No affection from MUSIC on the tracking
- Easier vertex reconstruction

## Asymmetric Rotor Model (ARM) for <sup>132</sup>Ba, <sup>134</sup>Ce and <sup>136</sup>Nd

- Very naive calculations
- Solution For transitions from 2<sup>+</sup><sub>1</sub>  $^{132}$ Ba: β = 0.19  $^{134}$ Ce: β = 0.20  $^{136}$ Nd: β = 0.24

$$B(E2;2_1^+ \to 0^+) = \frac{e^2 Q_0^2}{16 \cdot \pi} \cdot \frac{1}{2} \cdot \left[1 + \frac{3 - 2 \cdot \sin^2(3\gamma)}{\sqrt{9 - 8 \cdot \sin^2(3\gamma)}}\right]$$
$$Q_0 = \frac{3 \cdot Z \cdot R^2 \cdot \beta}{\sqrt{5\pi}}$$

For transitions from 2<sup>+</sup><sub>2</sub>

$$B(E2;2_{2}^{+} \to 0^{+}) = \frac{e^{2}Q_{0}^{2}}{16 \cdot \pi} \cdot \frac{1}{2} \cdot \left[1 - \frac{3 - 2 \cdot \sin^{2}(3\gamma)}{\sqrt{9 - 8 \cdot \sin^{2}(3\gamma)}}\right]$$

$$B(E2;2_{2}^{+} \to 2_{1}^{+}) = \frac{e^{2}Q_{0}^{2}}{16 \cdot \pi} \cdot \frac{10}{7} \cdot \frac{\sin^{2}(3\gamma)}{\sqrt{9 - 8 \cdot \sin^{2}(3\gamma)}}$$

$$\frac{B(E2;2_2 \to 2_1)}{B(E2;2_2 \to 0)} = \frac{20}{7} \frac{\sin^2(3\gamma)}{\sqrt{9 - 8\sin^2(3\gamma)} - 3 + 2\sin^2(3\gamma)}}$$

## **EUROBALL cluster detectors**





- 15 Euroball cluster Ge detectors (105 crystals)
- Energy resolution for 1 MeV
   γ-ray with 126 A MeV RI beams: ~2.0 %

	Cluster detector	Angle	Target distance
Ring #1	5	15.9°	~720 mm
Ring #2	5	<b>33.0</b> °	~720 mm
Ring #3	5	36.0°	~720 mm mm