Relativistic Projectile Coulomb Excitation to the Yrast and Non-yrast 2^+ States of ^{134}Ce and ^{136}Nd

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and
Johannes Gutenberg-Universität Mainz

for the RISING collaboration

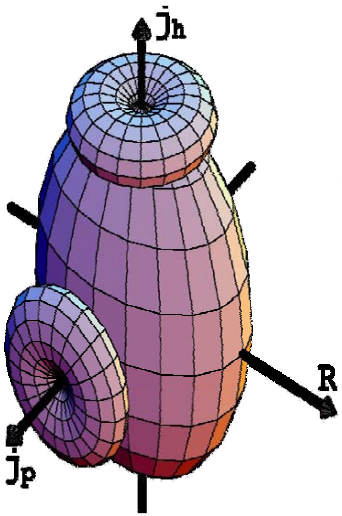
Physics motivation

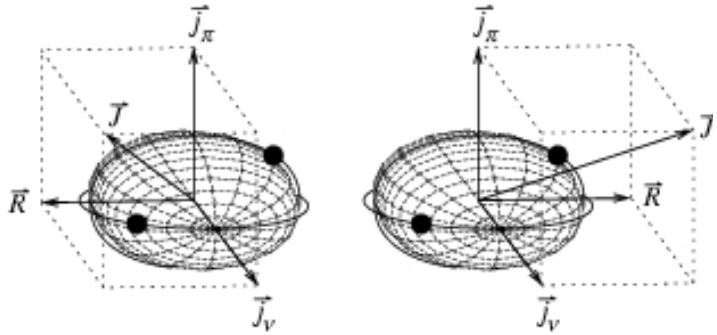
- Nuclear phase transition around A~130

Spherical ⟷ **Prolate**

(A~100) (A~150)

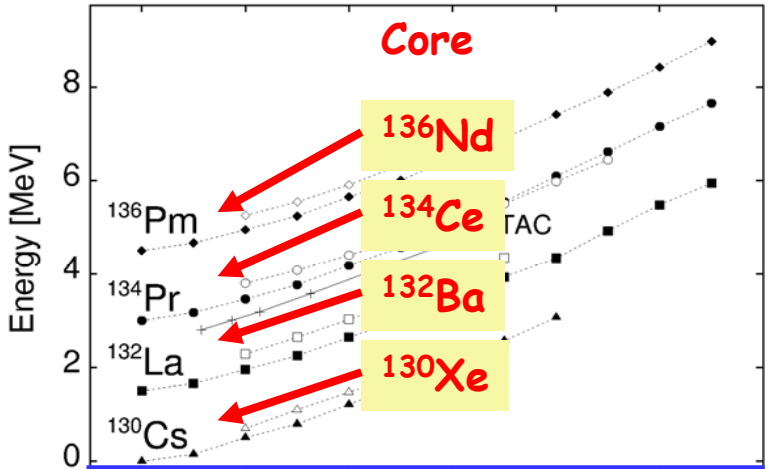
Triaxial shape, γ-softness





- Left-handed and Right-handed structures: identical
- Chiral twin-bands

K. Starosta, et.al.



Are these core nuclei triaxial or γ-soft?

Physics motivation

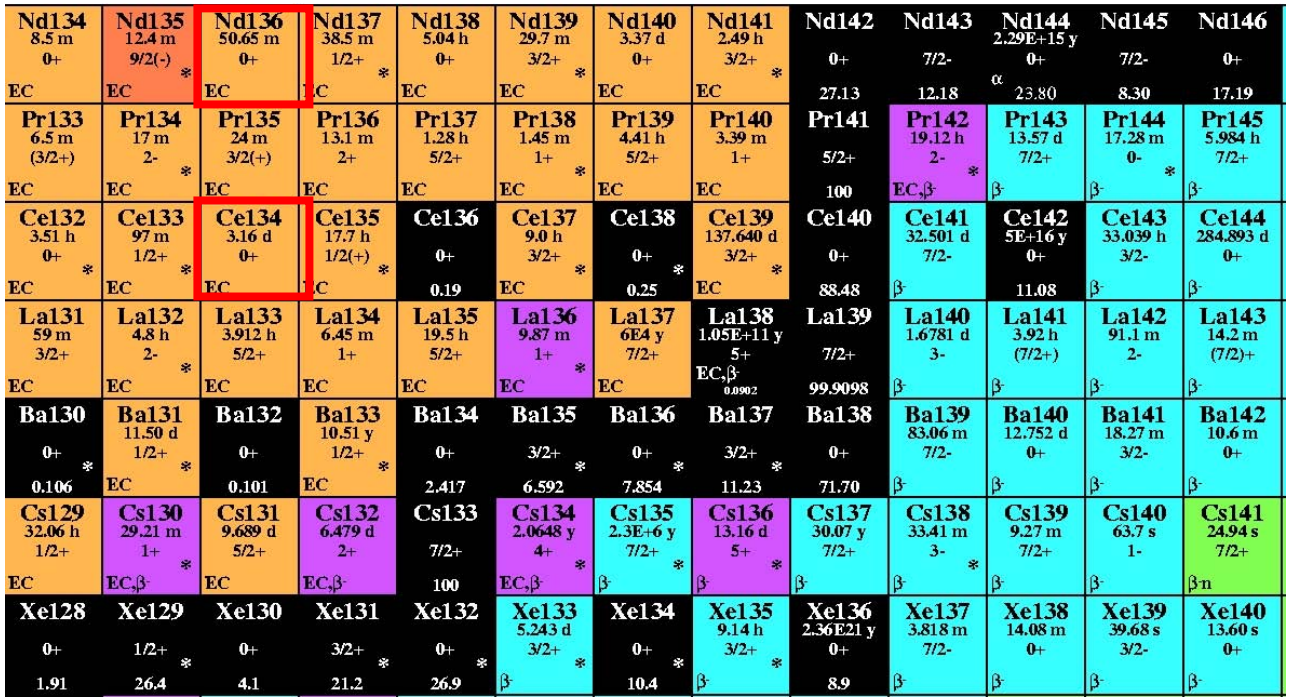
- **Triaxiality and γ-softness play a role in chiral structures**

- **Indication of triaxiality and γ-softness near the ground state**
  - Lower 2^+_2 energy and large $B(E2;2^+_2 \rightarrow 0^+)$
    - **γ-softness**
  - Lower 2^+_2 energy than 4^+_1 and large $B(E2;2^+_2 \rightarrow 2^+_1)$
    - **Triaxiality**

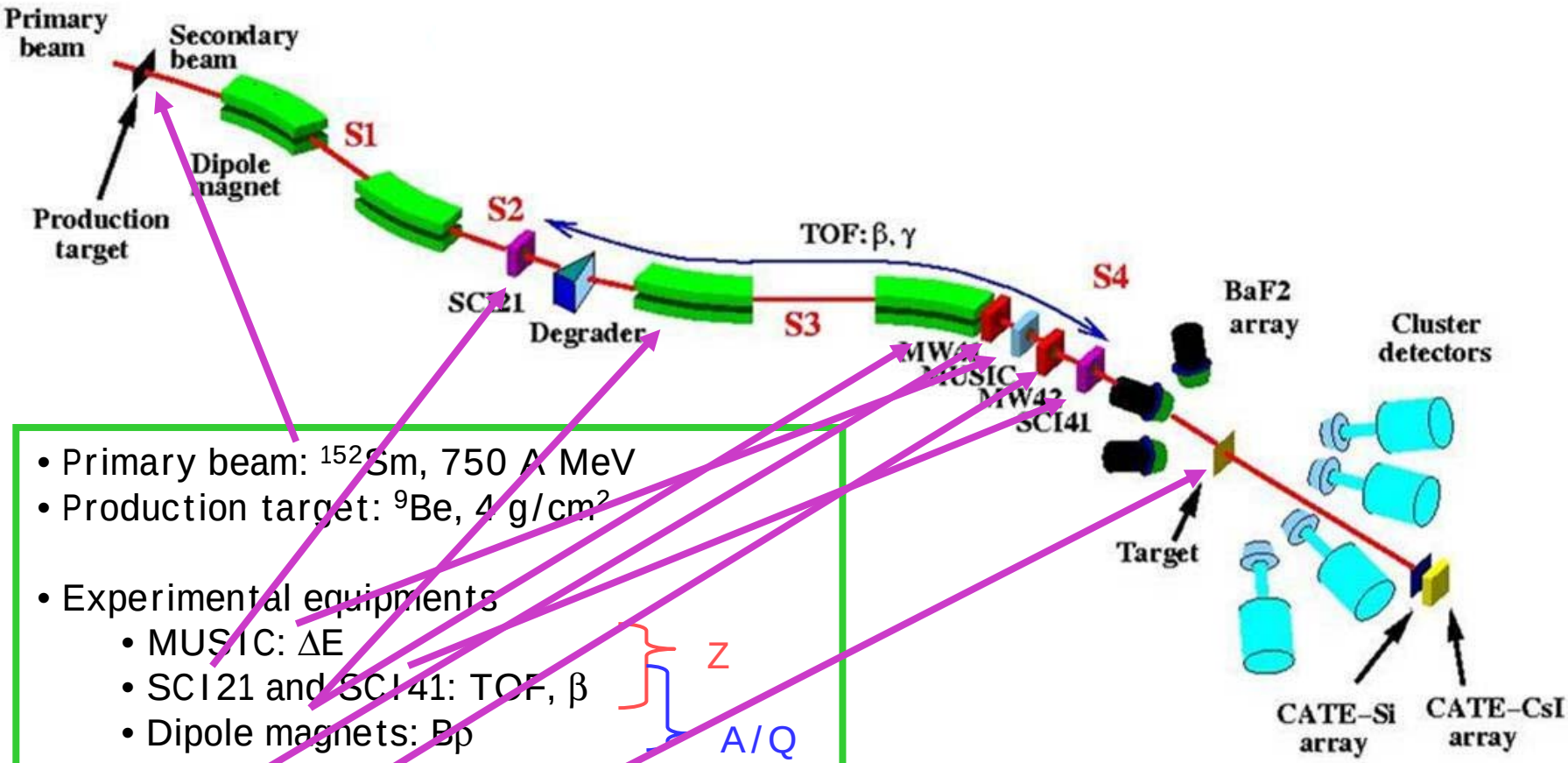
- **Large scale microscopic Monte Carlo Shell Model Calculation is available**
  - Reproduced nuclear properties of neutron rich Ba isotopes

Goal of the experiment

- To measure B(E2) of transitions depopulating 2^+_1 and 2^+_2 states in ^{134}Ce and ^{136}Nd
- Relativistic Coulomb excitation of secondary ^{134}Ce and ^{136}Nd projectiles with FRS at GSI
- γ-ray measurements with RISING Ge detector array



Fragment separator



- Primary beam: ^{152}Sm, 750 A MeV
- Production target: ^{9}Be, 4 g/cm^2

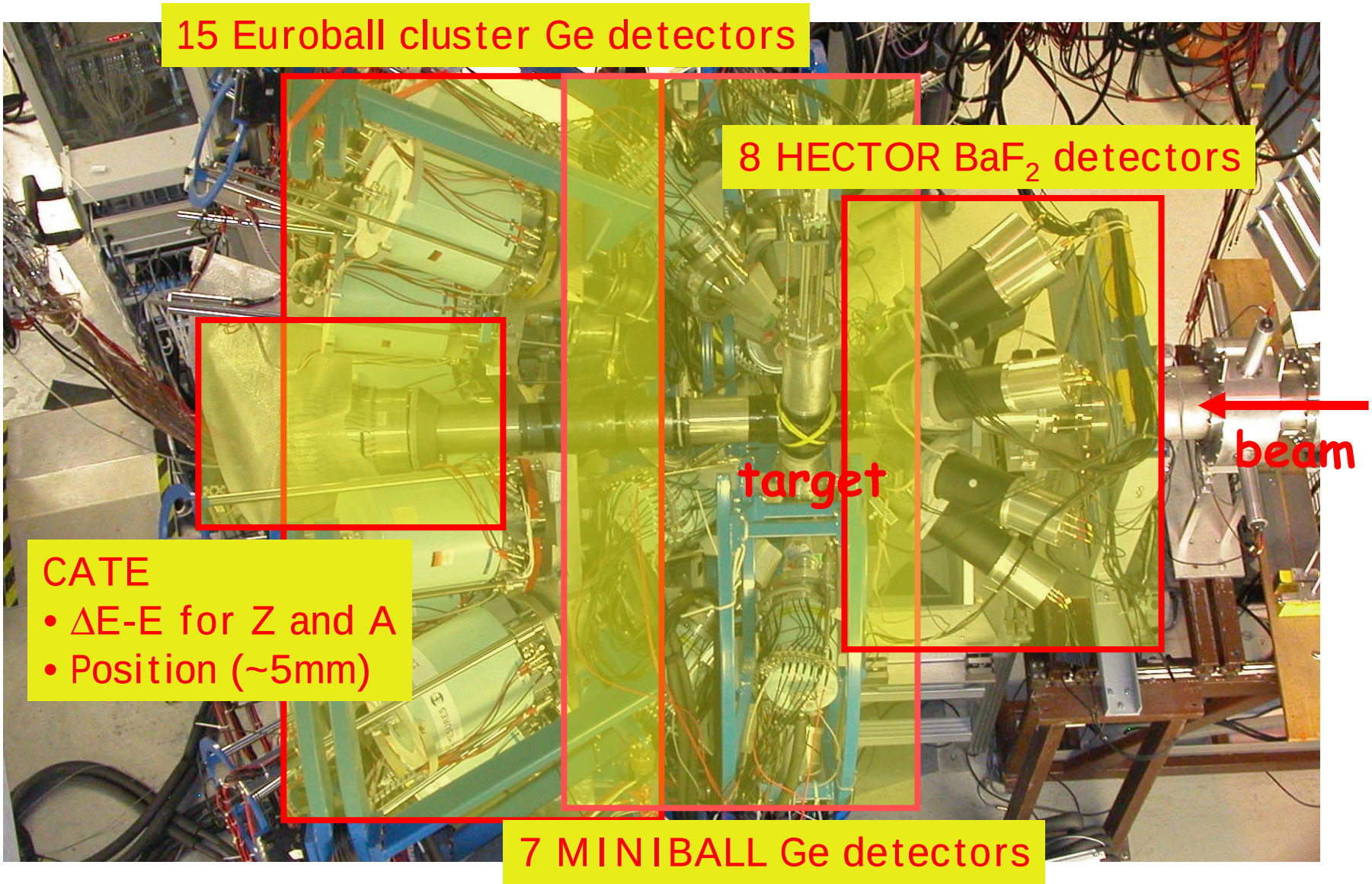
- Experimental equipments
  - MUSIC: ΔE
  - SCI21 and SCI41: TOF, β
  - Dipole magnets: Bρ
  - MW41, MW42 and target-Si: tracking

Z

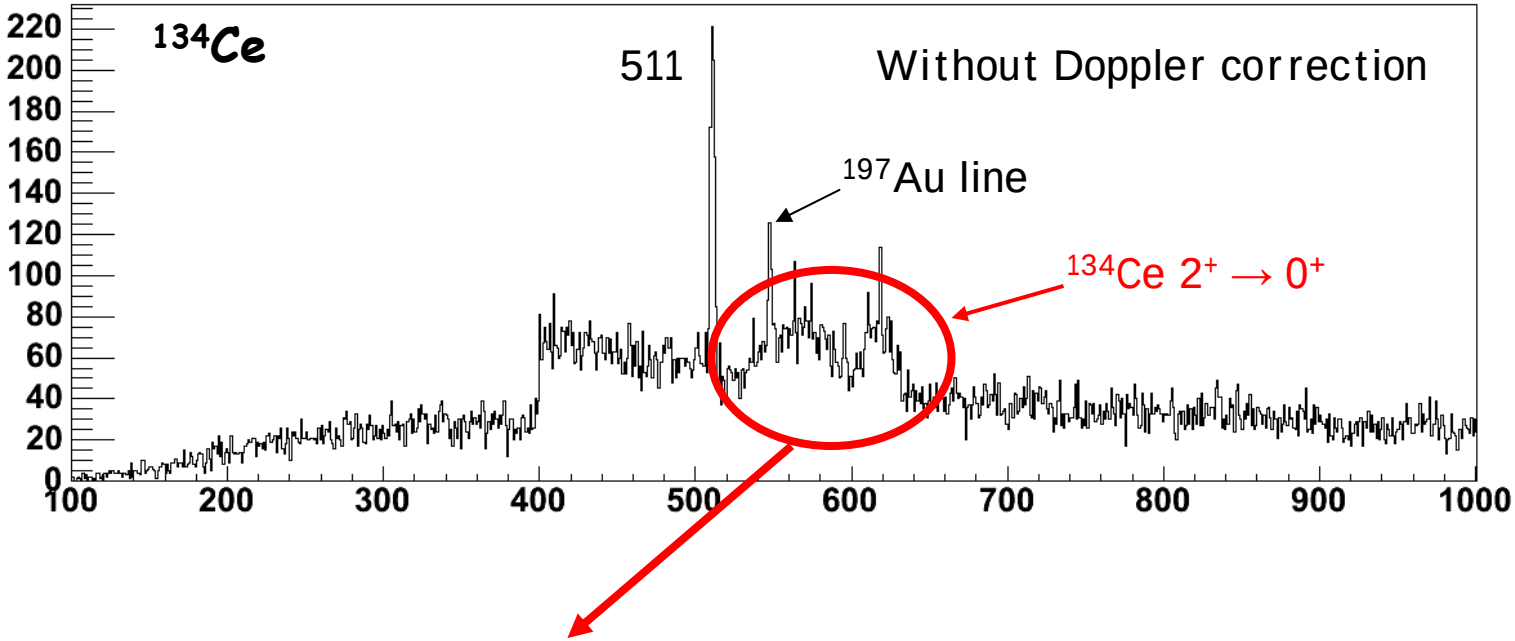
A/Q

Secondary beams
- ^{134}Ce and ^{136}Nd at 126 A MeV
- 3 k Hz

RISING setup at the final focal plane



Doppler shift correction

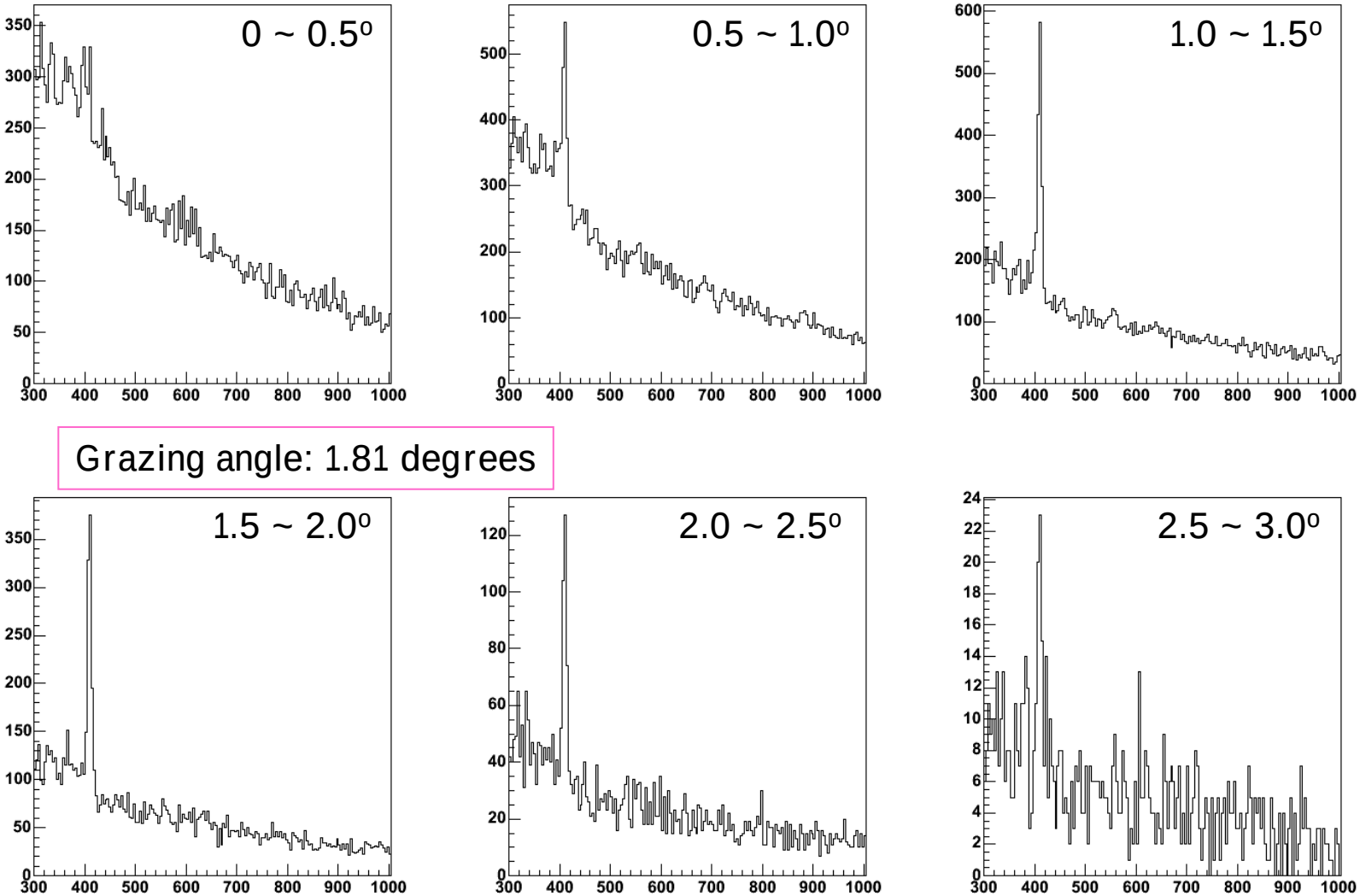


Event by event Doppler shift correction

- Velocity calculation with TOF
- Angle measurement with tracking

Selection of Coulomb excitation events: scattering angle

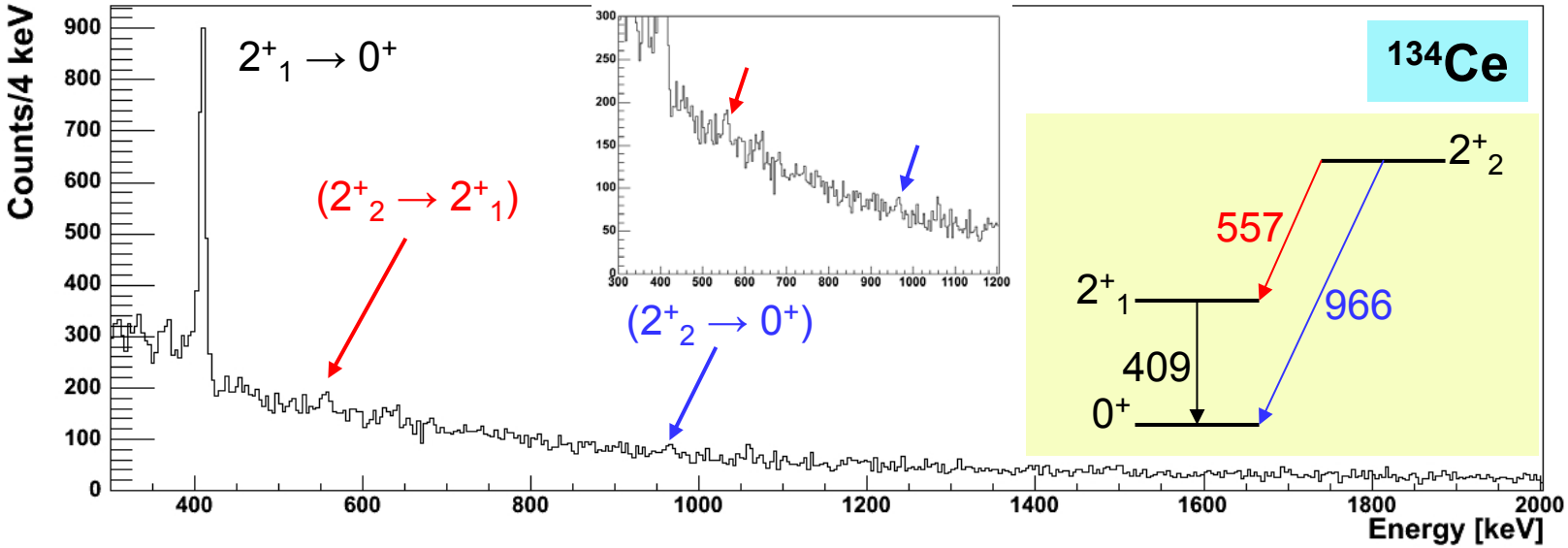
^{134}Ce on ^{197}Au at 126 A MeV

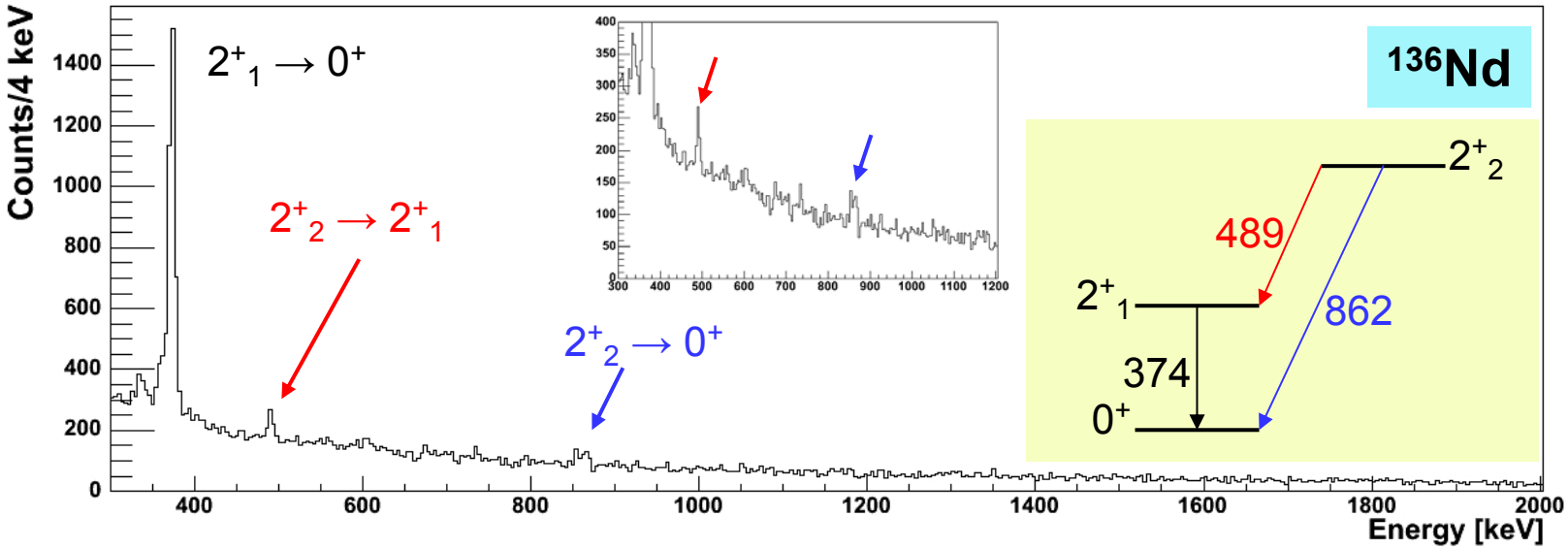


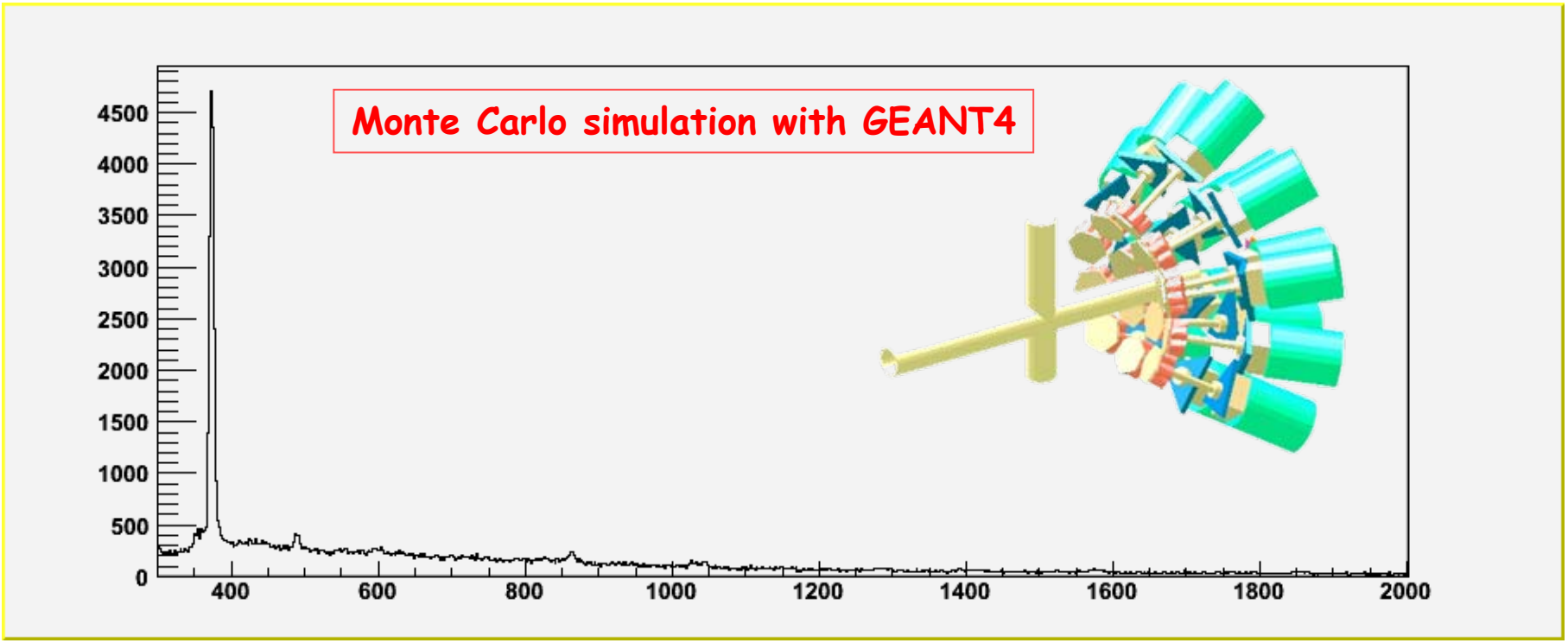
Grazing angle: 1.81 degrees

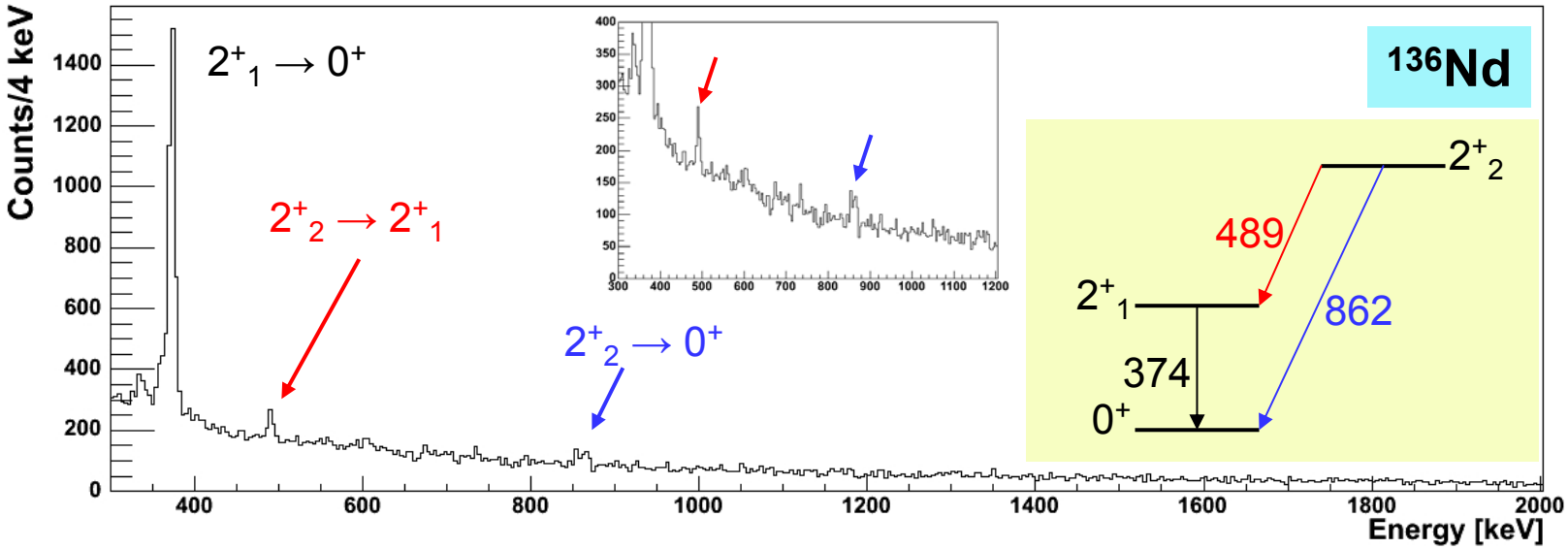
Cut with 0.8 ~ 1.8 degrees is optimum

Gamma-ray spectra



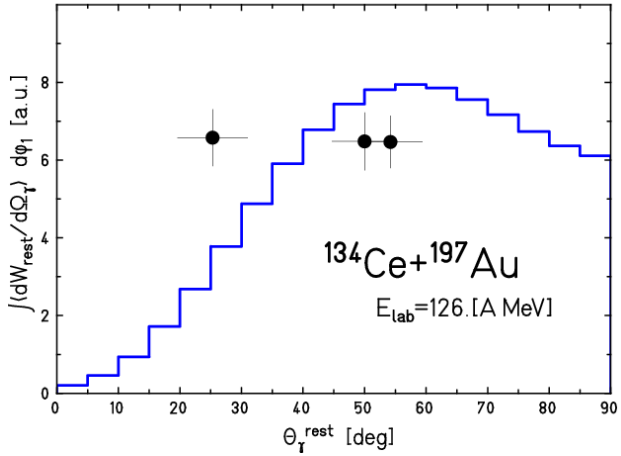


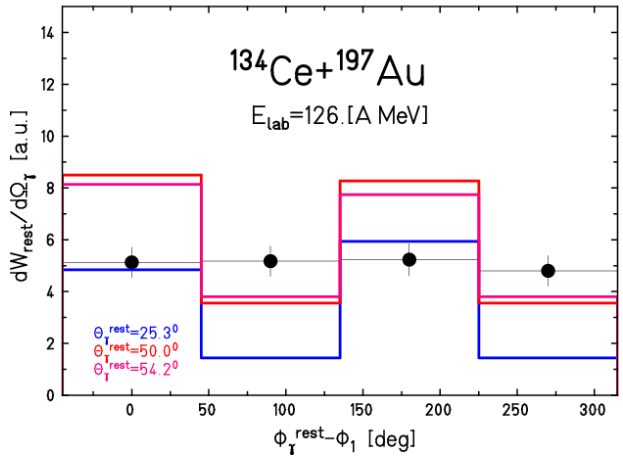

Monte Carlo simulation with GEANT4
4500
4000
3500
3000
2500
2000
1500
1000
500
0
400
600
800
1000
1200
1400
1600
1800
2000


Counts/4 keV
Energy [keV]
$2^+_1 \rightarrow 0^+$
$2^+_2 \rightarrow 2^+_1$
$2^+_2 \rightarrow 0^+$
^{136}Nd
2^+_2
489
2^+_1
862
374
0^+

Particle-γ angular correlation

- **Correlation on θ**
  - Rising-wise sorting at the rest frame
  - Isotropic 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
  - Isotropic distribution observed
  - Can not reproduced by calculations with alignments





Surprisingly, no (or very small) alignment was observed

Deducing B(E2)

	^{134}Ce on ^{197}Au at 126 A MeV			^{136}Nd on ^{197}Au at 126 A MeV		
	E_γ [keV]	N_γ	ε [%]	E_γ [keV]	N_γ	ε [%]
$2^+_1 \rightarrow 0^+$	409	1713±101	1.98±0.06	374	3039±130	1.98±0.06
$2^+_2 \rightarrow 0^+$	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_{pro} 1895843±1377		DAQ livetime [%] 77	N_{pro} 1986411±1409		DAQ livetime [%] 79

- **Known value: ^{134}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.

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

- Complete measurements for ^{136}Nd
- 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 ^{197}Au Coulomb excitation used for cross-checking

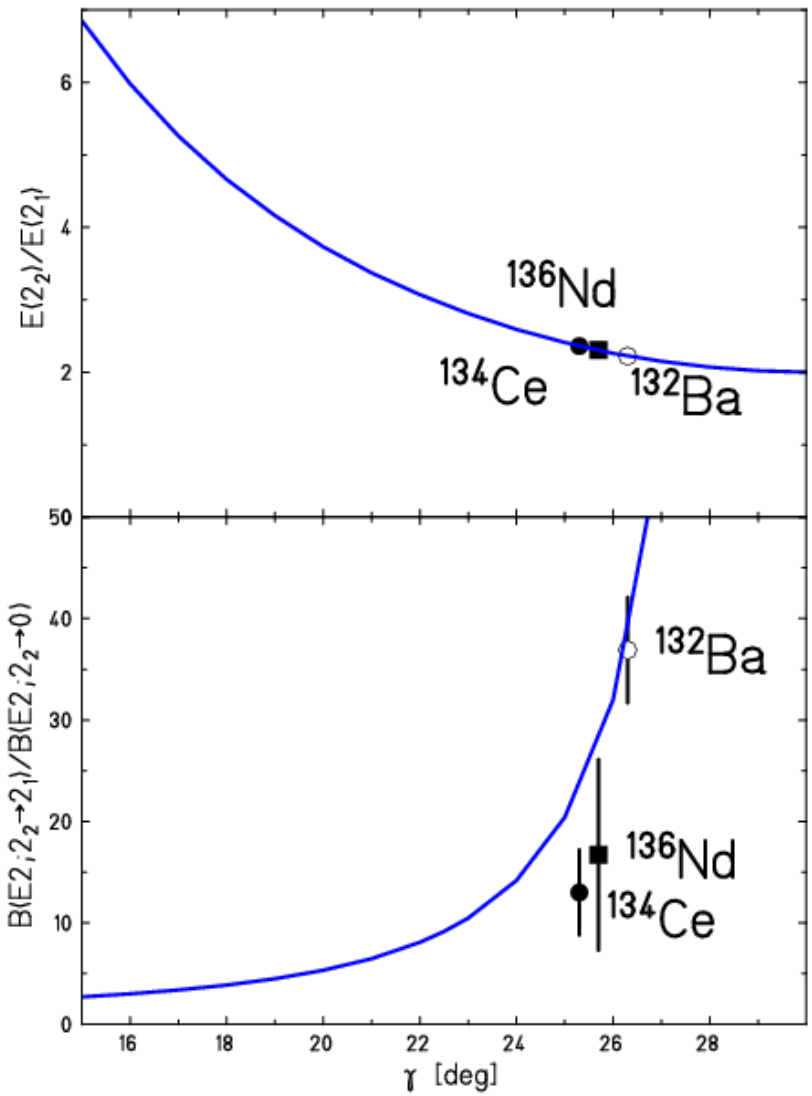
Comparison to the theoretical calculations

- **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^+_2 states

Asymmetric Rotor Model (ARM) for ^{132}Ba, ^{134}Ce and ^{136}Nd



$$\frac{E(2_2^+)}{E(2_1^+)} = \frac{3+\sqrt{9-8\cdot\sin^2(3\gamma)}}{3-\sqrt{9-8\cdot\sin^2(3\gamma)}}$$

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

- ^{134}Ce: from the known branching ratio
- ^{136}Nd: from this experiment

Asymmetric Rotor Model (ARM) for ^{132}Ba, ^{134}Ce and ^{136}Nd

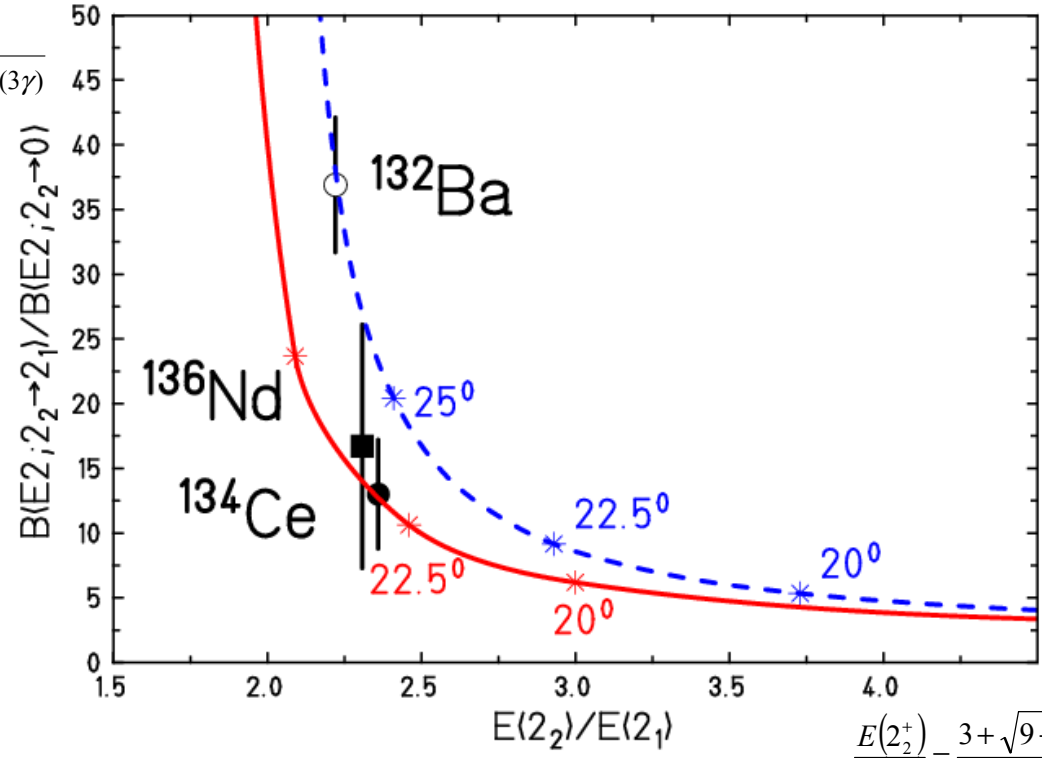
- **γ-rigid ARM**

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

- **γ-soft ARM with μ=0.5**

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

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



$$\frac{E(2_2^+)}{E(2_1^+)} = \frac{3+\sqrt{9-8\cdot\sin^2(3\gamma)}}{3-\sqrt{9-8\cdot\sin^2(3\gamma)}}$$

Summary

- Relativistic projectile Coulomb excitation with RI-beams of ^{134}Ce and ^{136}Nd to 2^+_1 and 2^+_2 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

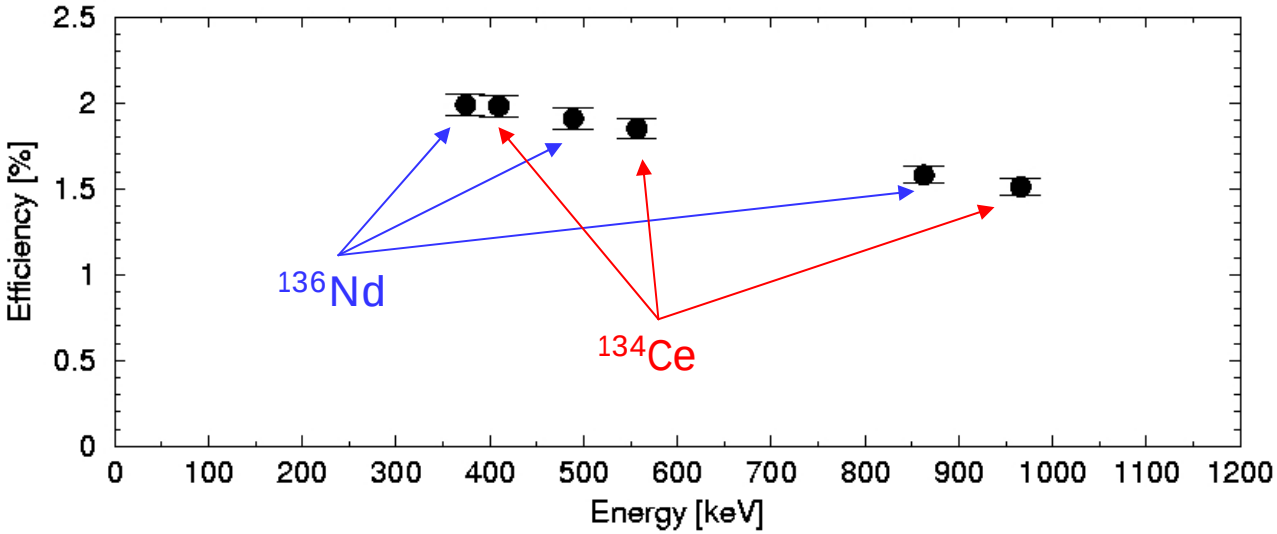
Deducing B(E2)

	^{134}Ce+^{197}Au at 126 A MeV			^{136}Nd+^{197}Au at 126 A MeV		
Transitions	E_γ [keV]	N_γ	ε [%] ($\beta = 0.42$)	E_γ [keV]	N_γ	ε [%] ($\beta = 0.42$)
$2_1^+ \rightarrow 0^+$	409.2	1713 ± 101	1.98 ± 0.06	373.7	3039 ± 130	1.99 ± 0.06
$2_2^+ \rightarrow 0^+$	965.7		1.51 ± 0.05	862.4	156 ± 49	1.58 ± 0.05
$2_2^+ \rightarrow 2_1^+$	556.6	< 149	1.85 ± 0.06	488.6	183 ± 56	1.91 ± 0.06
^{197}Au transitions	E_γ [keV]	N_γ	ε [%] ($\beta = 0.0$)	E_γ [keV]	N_γ	ε [%] ($\beta = 0.0$)
$7/2^+ \rightarrow 3/2^+$	547.5	130 ± 41	0.97 ± 0.03	547.5	171 ± 44	0.97 ± 0.03
	N_{pro}		DAQ livetime [%]	N_{pro}		DAQ livetime [%]
	1895843 ± 1377		77	1986411 ± 1409		79

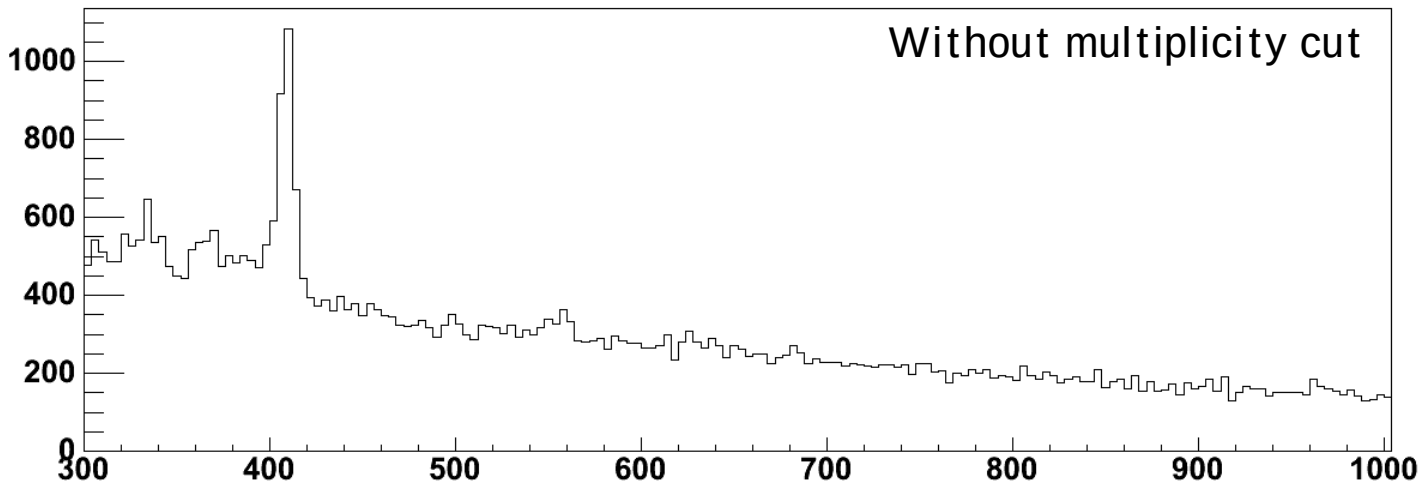
- **Known value: ^{134}Ce $2^+_1 \rightarrow 0^+$ B(E2), 52 (5) W.u.; reference**
- **Absolute efficiency with Lorentz boost with β=0.42 and DAQ livetime taken into account**
- **Isotropic distribution at the rest frame assumed**
- **Gamma-ray intensities normalized by particle numbers on the target**

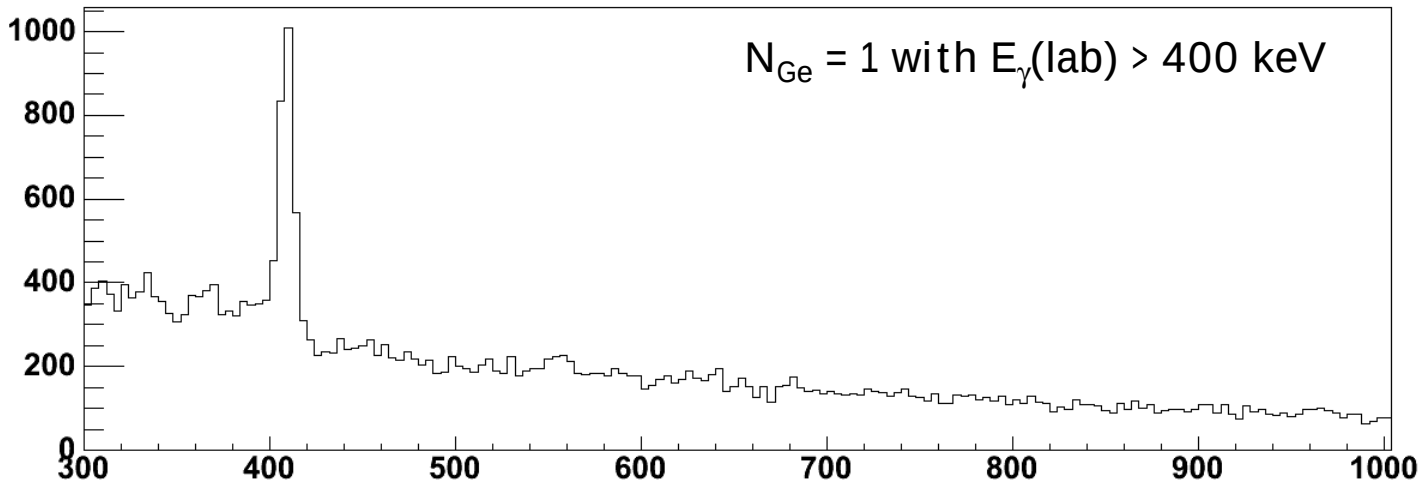
Absolute efficiency calibration

- **γ-γ coincidence measurement with ^{60}Co γ-ray source**
  - Absolute efficiency for 1.173 and 1.333 MeV γ-rays
  - Calibration with an assumption of isotropic γ-γ angular correlation
    - Actual γ-γ angular correlation gives difference of 1 % in the calibration
      → systematic error
- **Relative efficiency calibration (energy dependence) with ^{152}Eu γ-ray source**
- **Lorentz-boost to the rest frame**

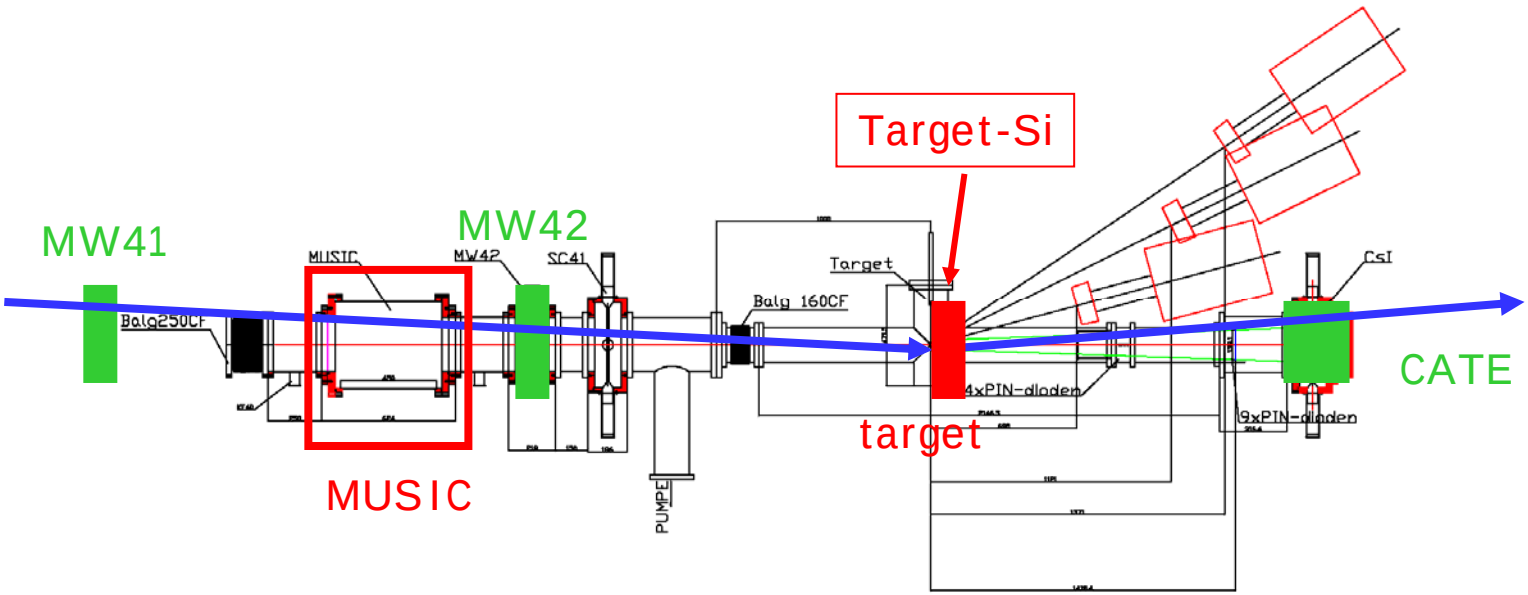


Selection of Coulomb excitation events: γ-multiplicity





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 ^{132}Ba, ^{134}Ce and ^{136}Nd

- **Very naive calculations**

- **For transitions from 2^+_1**
  - ^{132}Ba: $\beta = 0.19$
  - ^{134}Ce: $\beta = 0.20$
  - ^{136}Nd: $\beta = 0.24$

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

$$Q_0 = \frac{3\cdot Z\cdot R^2\cdot\beta}{\sqrt{5\pi}}$$

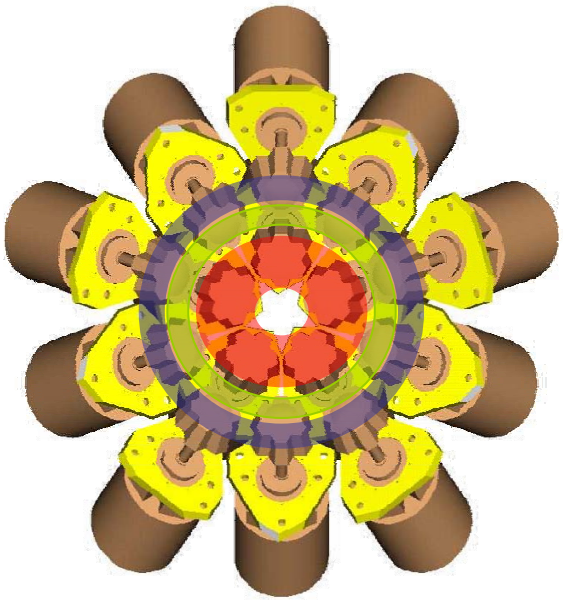
- **For transitions from 2^+_2**

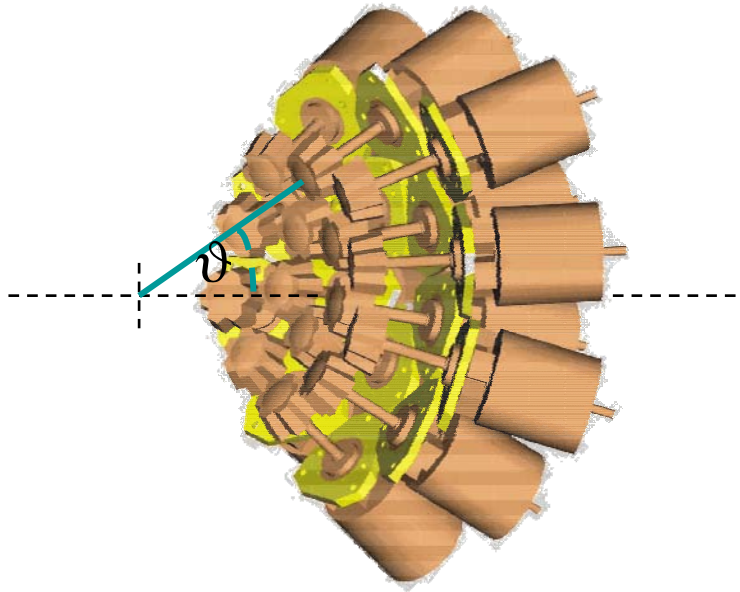
$$B(E2;2_2^+ \to 0^+) = \frac{e^2 Q_0^2}{16\cdot\pi}\cdot\frac{1}{2}\cdot\left[1-\frac{3-2\cdot\sin^2(3\gamma)}{\sqrt{9-8\cdot\sin^2(3\gamma)}}\right]$$

$$B(E2;2_2^+ \to 2_1^+) = \frac{e^2 Q_0^2}{16\cdot\pi}\cdot\frac{10}{7}\cdot\frac{\sin^2(3\gamma)}{\sqrt{9-8\cdot\sin^2(3\gamma)}}$$

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

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	33.0°	~720 mm
Ring #3	5	36.0°	~720 mm mm