LOW ENERGY COULOMB EXCITATION OF SPES RIB

A. NANNINI

INFN - SEZIONE DI FIRENZE - ITALY

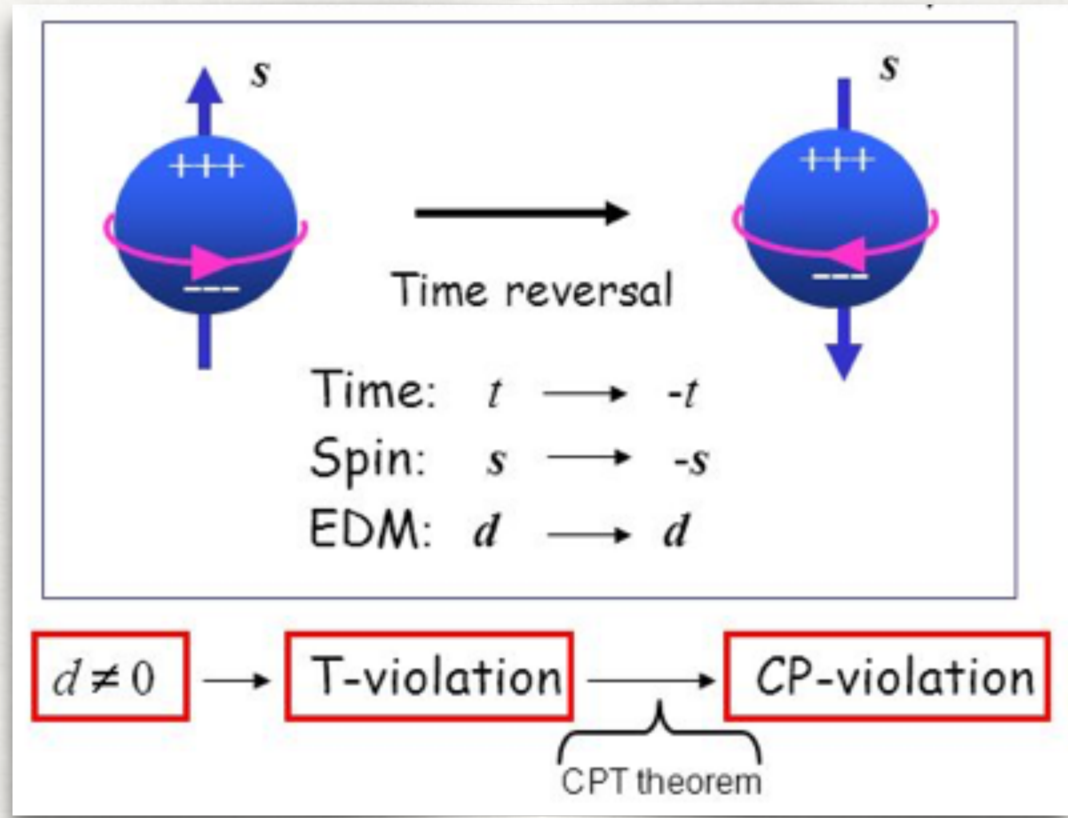
SPES-NUSPRASEN WORKSHOP
PISA, FEBRAUARY 2 2018

BRIEF SUMMARY ON EDM AND PEAR-SHAPED NUCLEI

- The existence of permanent atomic EDM implies CP violation beyond the standard model.

- Any measurable electric-dipole moment is expected to be enhanced in octupole deformed nuclei.

- Experimental campaign to study the octupole collectivity in radioactive nuclei.



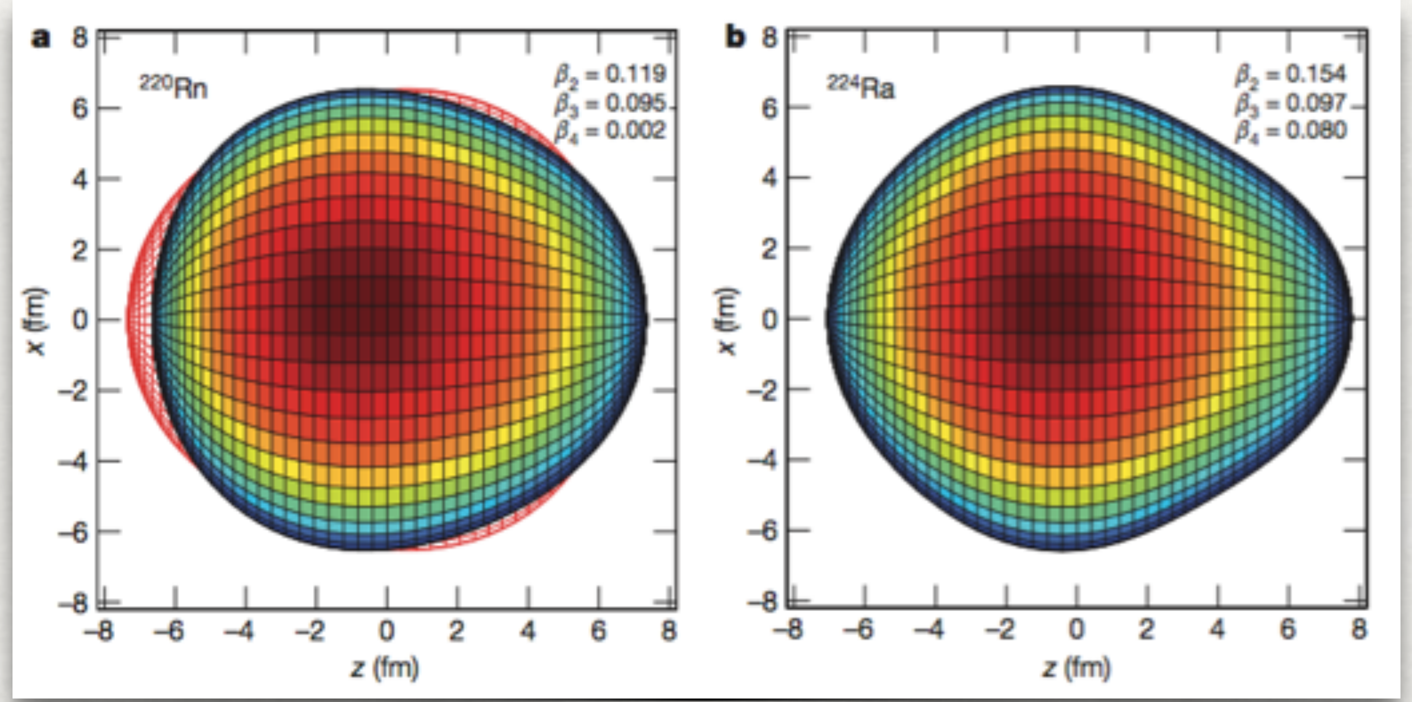
- The E3 moment provides direct evidence for enhanced octupole correlations and, for deformed nuclei, can be related to the intrinsic octupole deformation parameter.

BRIEF SUMMARY ON EDM AND PEAR-SHAPED NUCLEI

- Direct experimental determination of the electric octupole moment requires the use of the Coulomb Excitation of short-lived radioactive beams.

- The E3 transition strengths in ^{220}Rn and ^{224}Ra have been recently measured via Coulomb Excitation of radioactive beams.

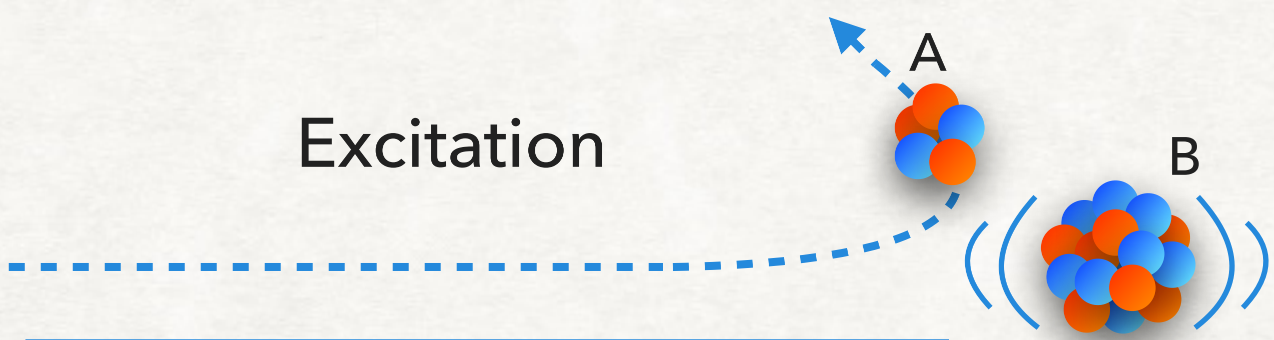
LP Gaffney et al
Nature 497 (2013) 199



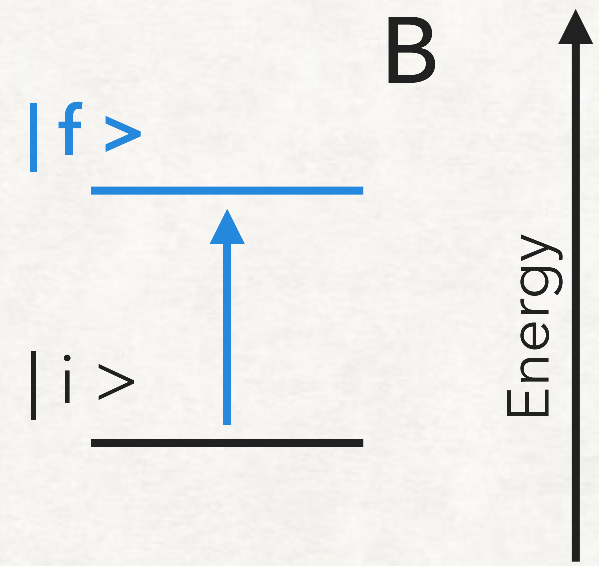
Graphical representation of the shape of ^{220}Rn and ^{224}Ra

COULOMB EXCITATION

- Beam energy < **Safe energy** (~ 5 MeV/A)

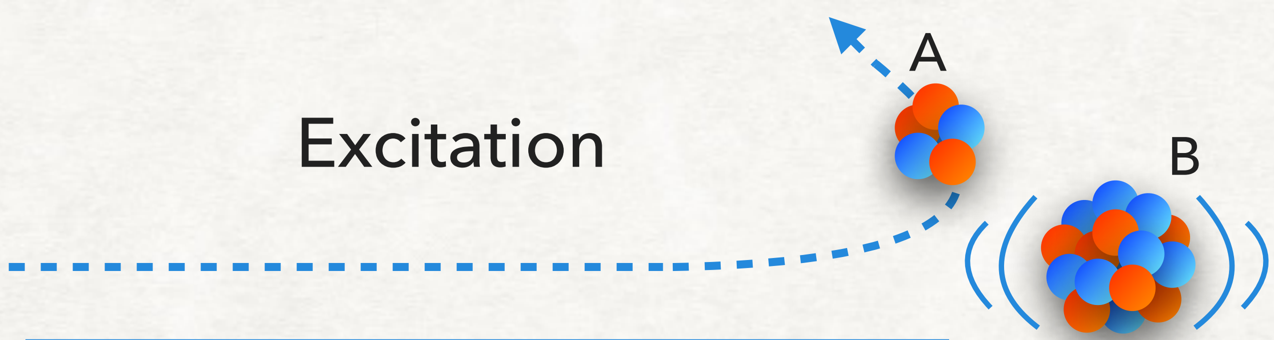


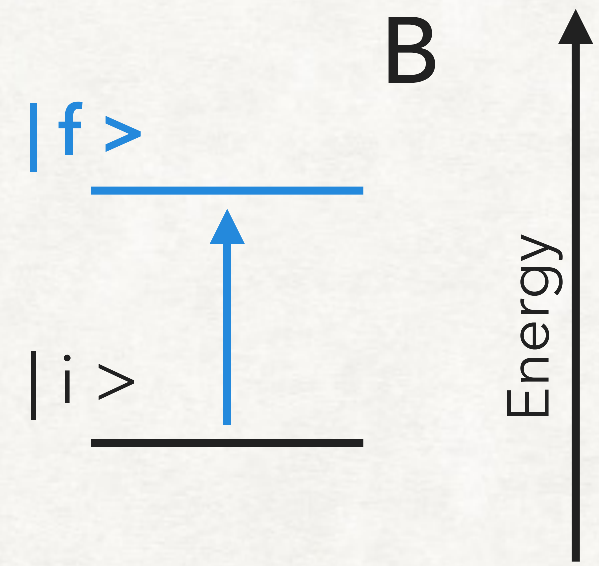
$$\frac{d\sigma_{clx}}{d\Omega} = \frac{d\sigma_{Ruth}}{d\Omega} \cdot P\left(i \longrightarrow f\right)$$



COULOMB EXCITATION

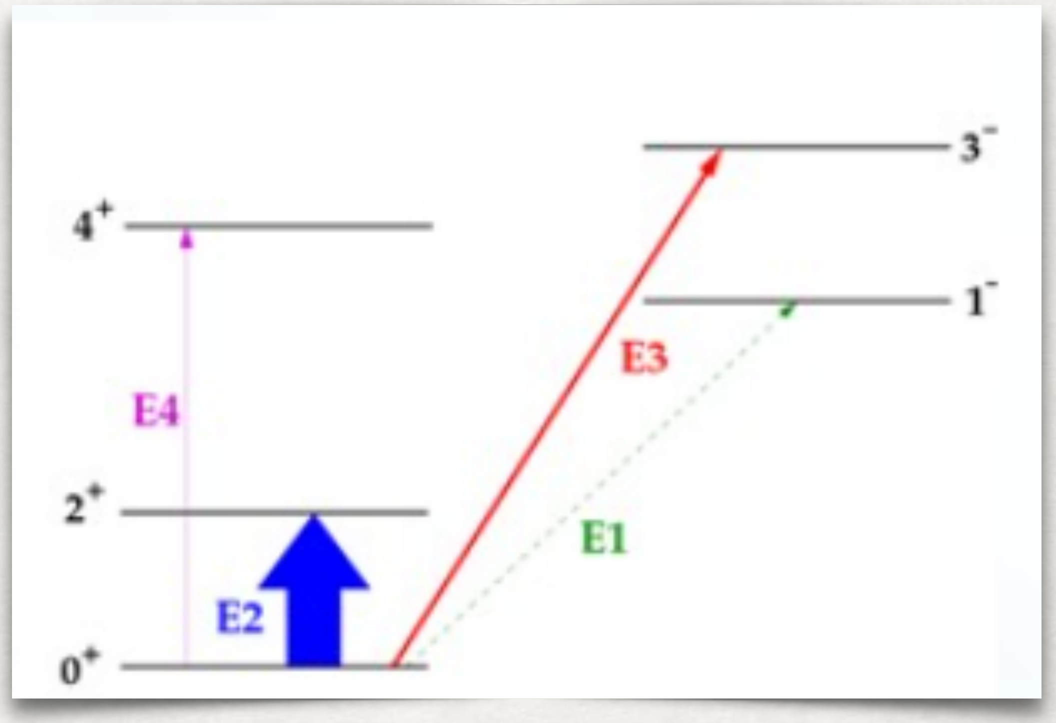
- Beam energy < **Safe energy** (~ 5 MeV/A)





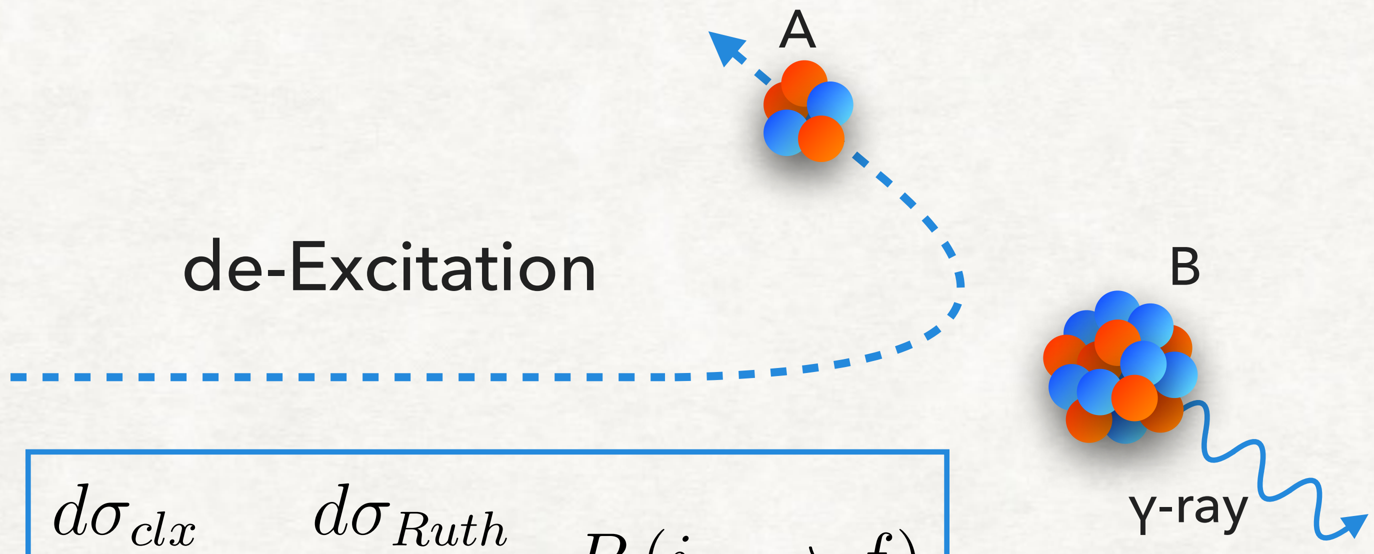
$$\frac{d\sigma_{clx}}{d\Omega} = \frac{d\sigma_{Ruth}}{d\Omega} \cdot P\,(i \longrightarrow f)$$

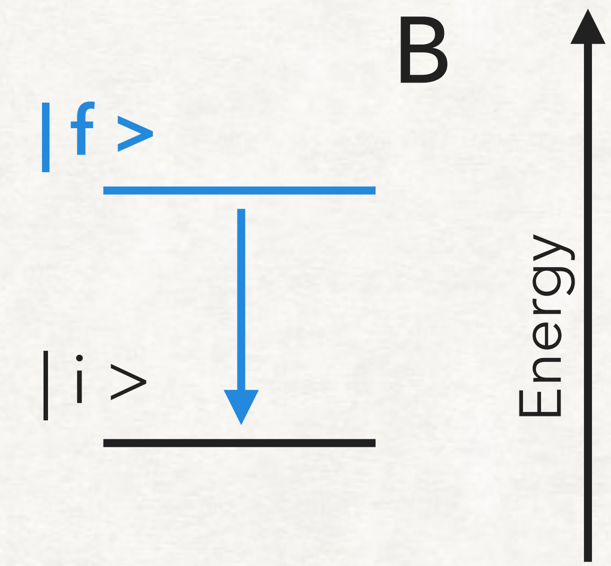
- Negative parity levels are excited predominantly through E3 transitions



COULOMB EXCITATION

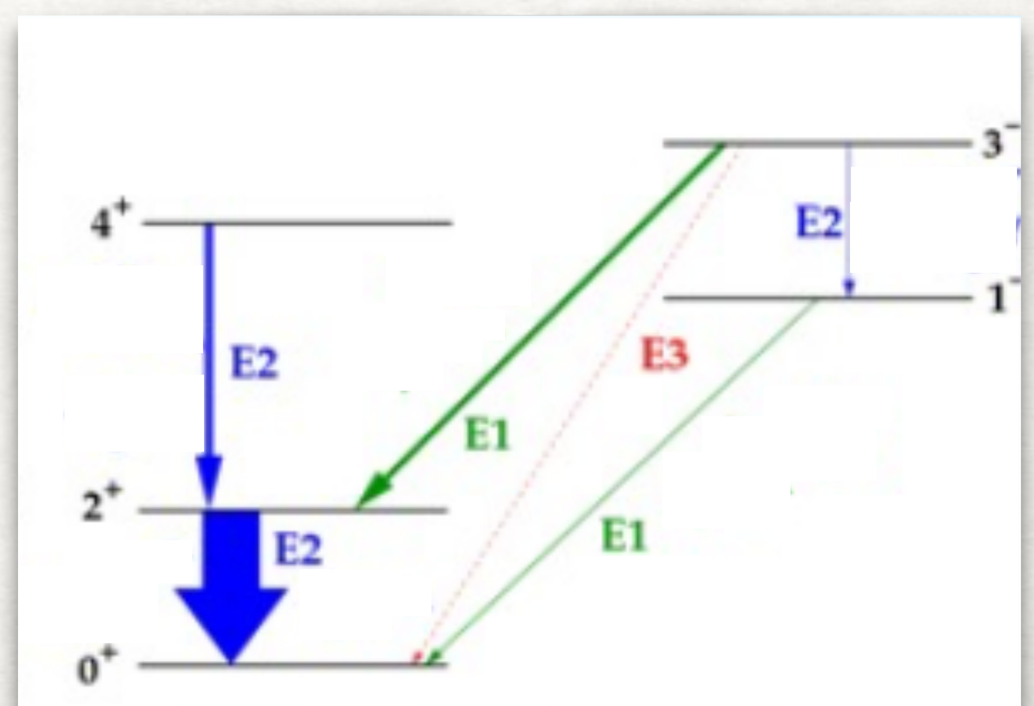
- Beam energy < **Safe energy** (~ 5 MeV/A)





$$\frac{d\sigma_{clx}}{d\Omega} = \frac{d\sigma_{Ruth}}{d\Omega} \cdot P\,(i \longrightarrow f)$$

- Negative parity levels are excited predominantly through E3 transitions
- Their decay yields provide a measurement of the corresponding E3 matrix elements.



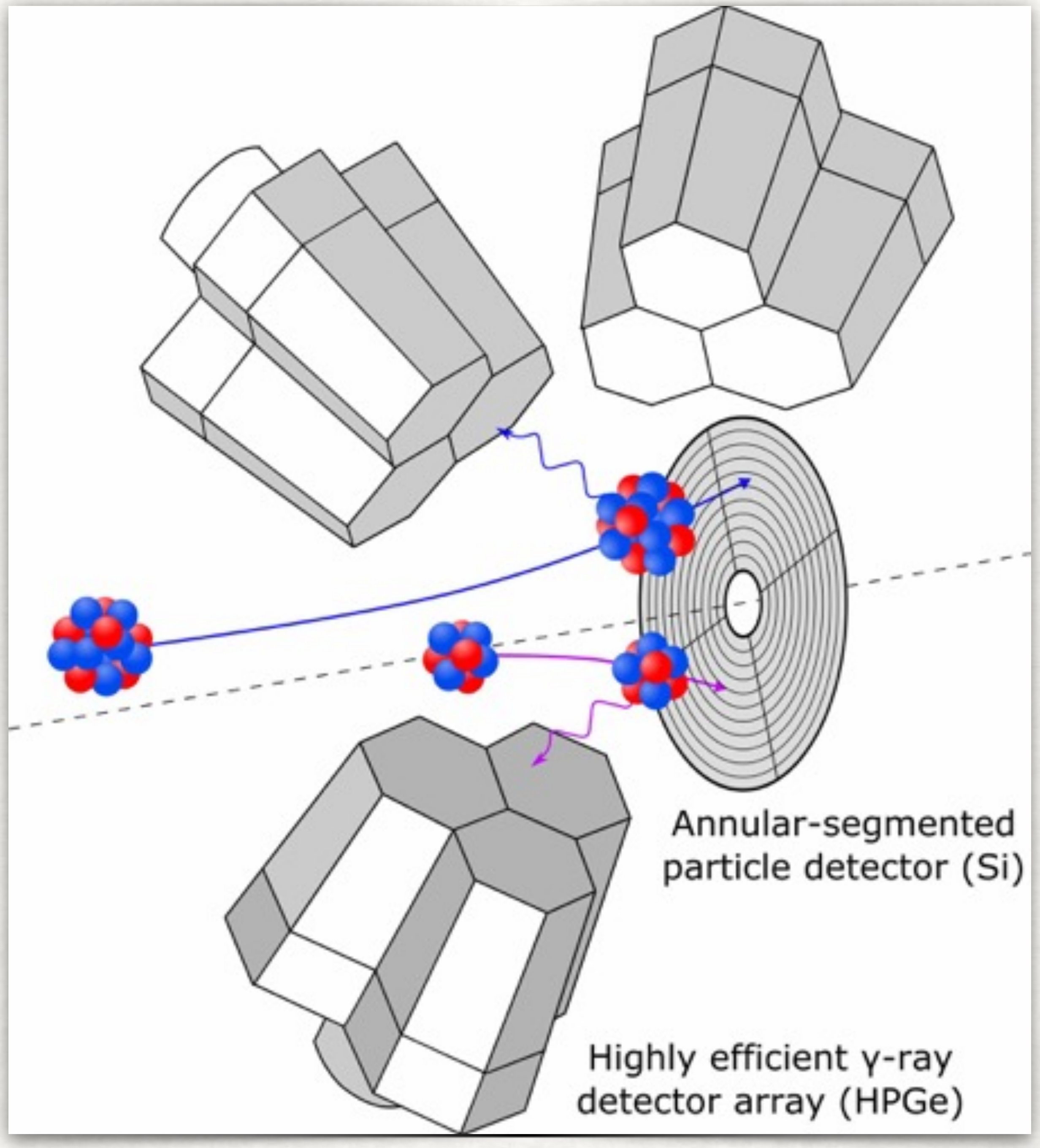
COULOMB EXCITATION

Gamma detector:

- To measure γ-ray yields

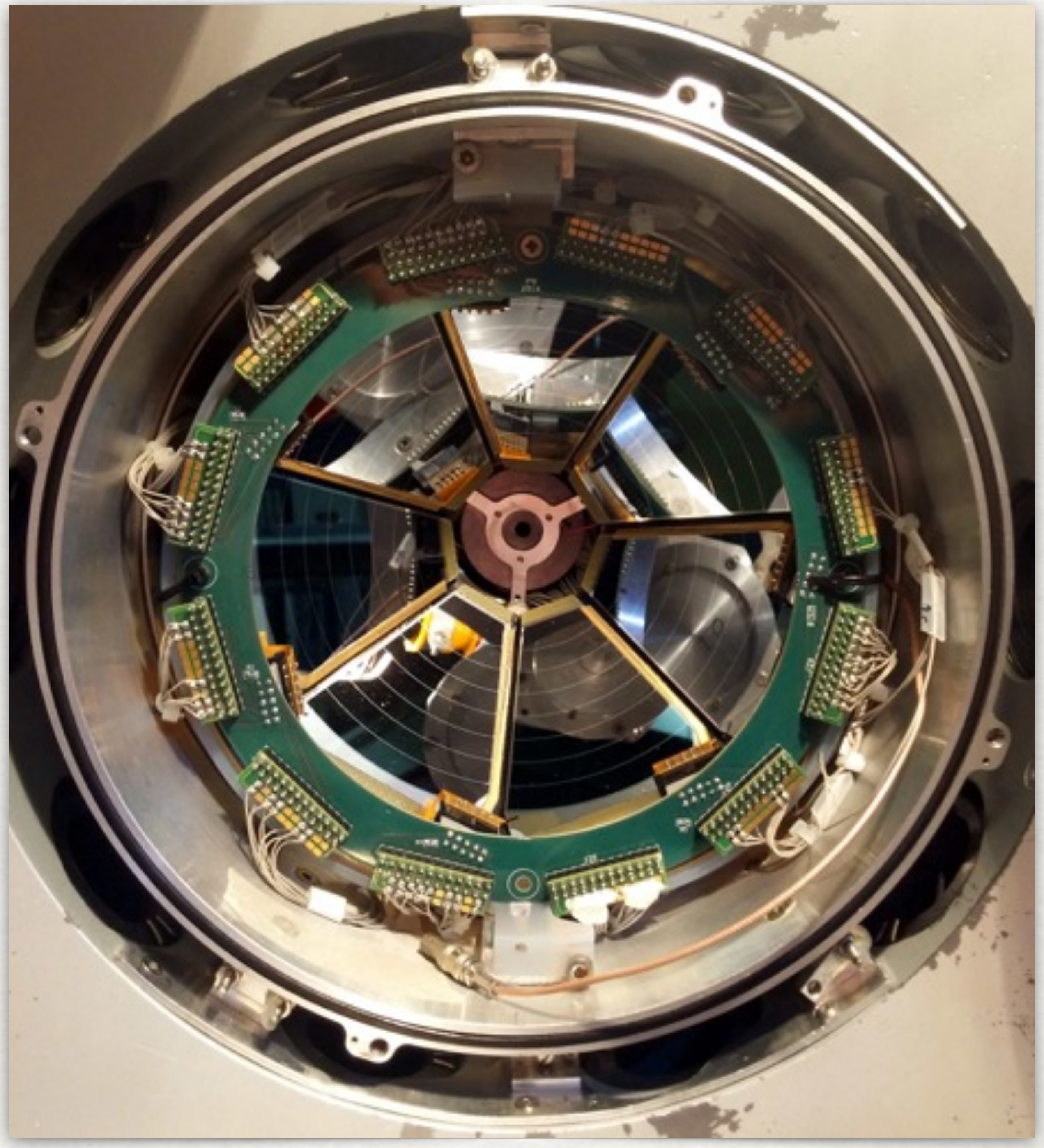
Particle detector:

- To select Coulomb excitation events
- To distinguish between projectile and target
- To select the scattering angle
- To perform the Doppler correction



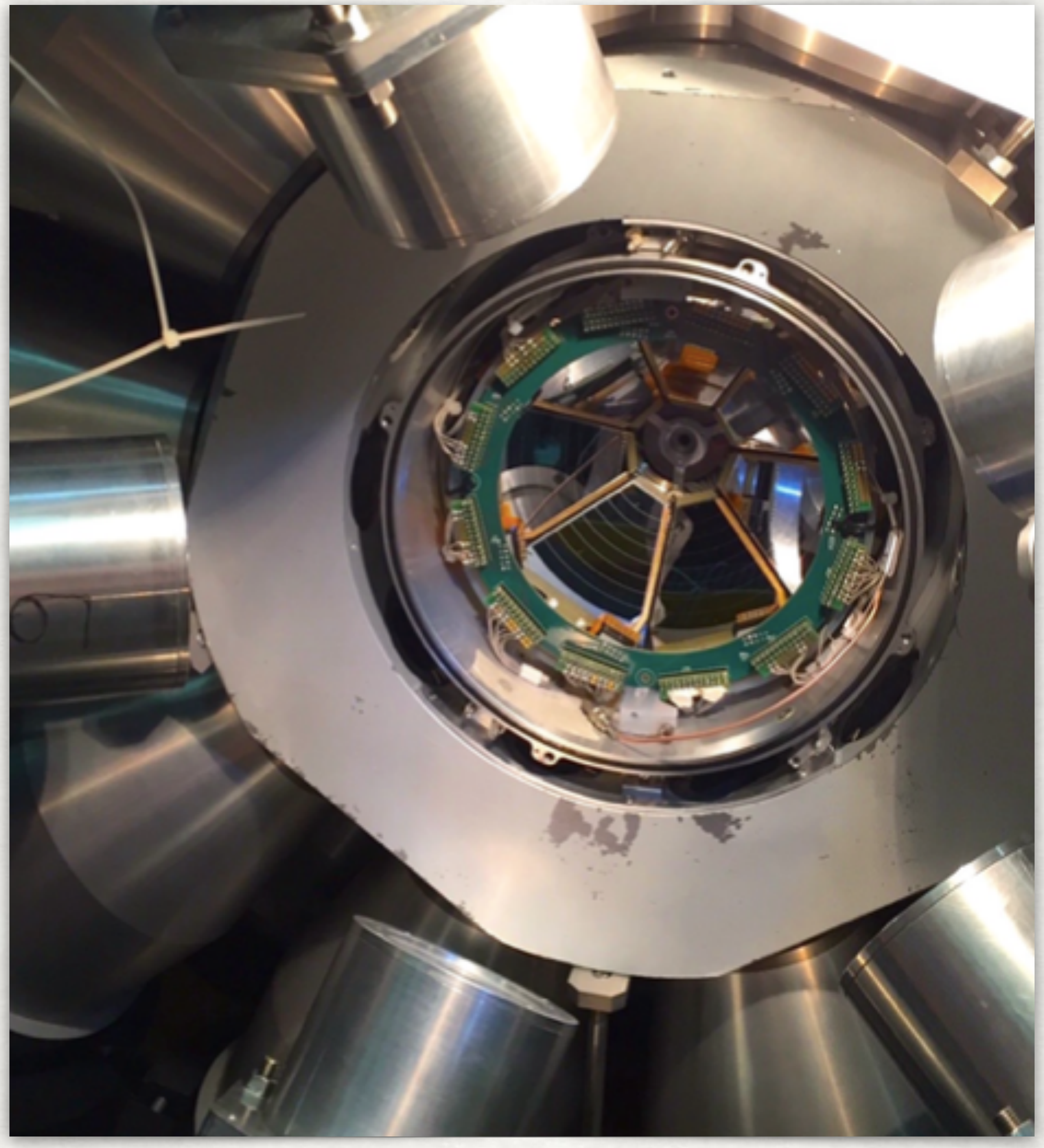
SPIDER: A SILICON PIE DETECTOR FOR HEAVY IONS

- Up to 8 independent sectors, 8 annular strips + guard ring
- Detector thickness ~300 μm, dead layers ~ 50 nm in the junction (front) side and ~ 350 nm in the ohmic (rear) side
- Cone configuration (7 sectors) at backward angles: 8.5 cm from the target $\Delta\Theta = 37.4°$, $\Omega/4\pi = 17.3\%$

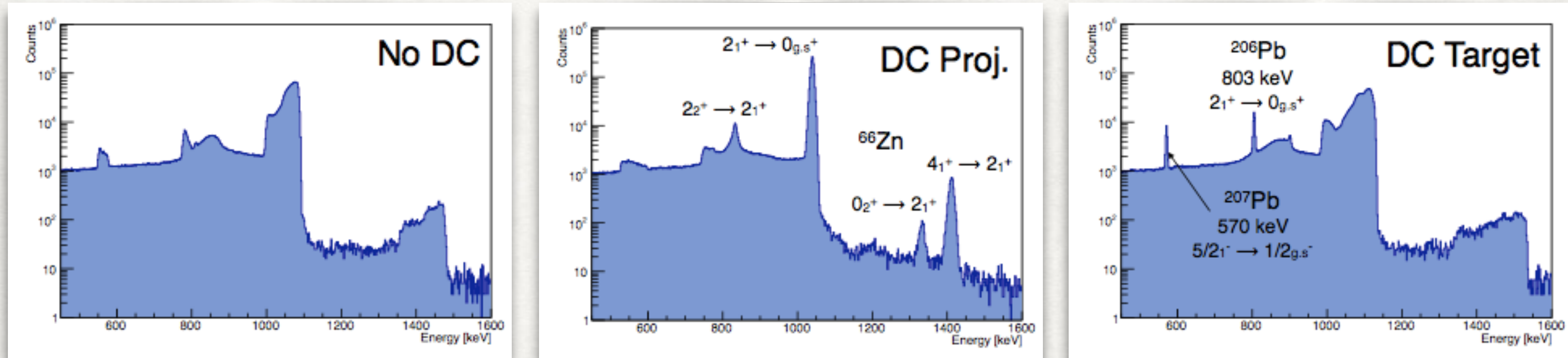


FIRST EXPERIMENT: COULEX OF 66ZN

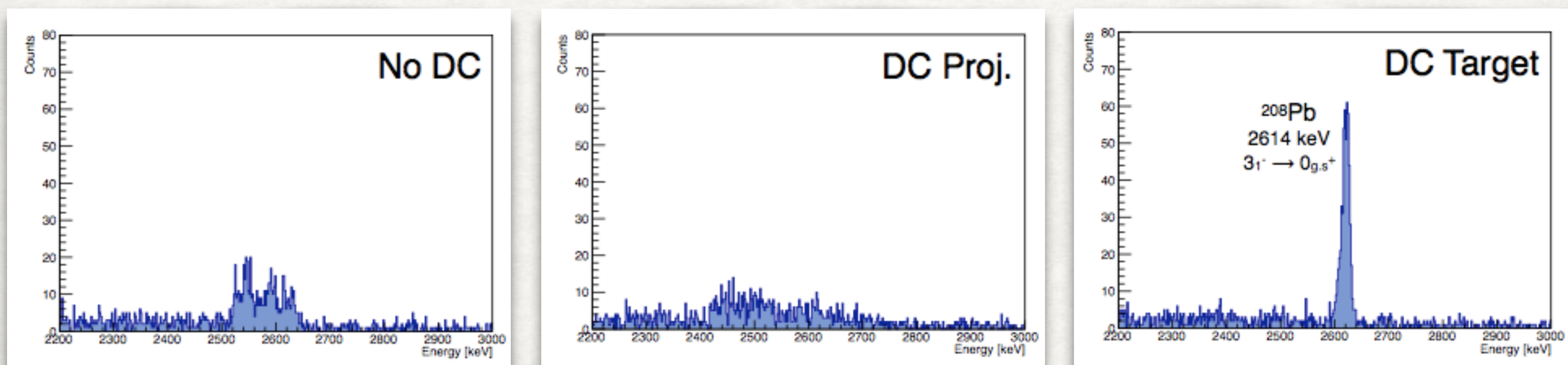
- SPIDER coupled to the GALILEO array (25 HPGe Compton suppressed detectors)
- Coulomb excitation of 66Zn
- Beam: 66Zn (240 MeV, 1-1.5 pnA)
- Target: 1 mg/cm2 of 208Pb
- 4 days of measurement
- SPIDER at backward angles (from 124 to 161 degrees)



DOPPLER CORRECTION OF GAMMA SPECTRA



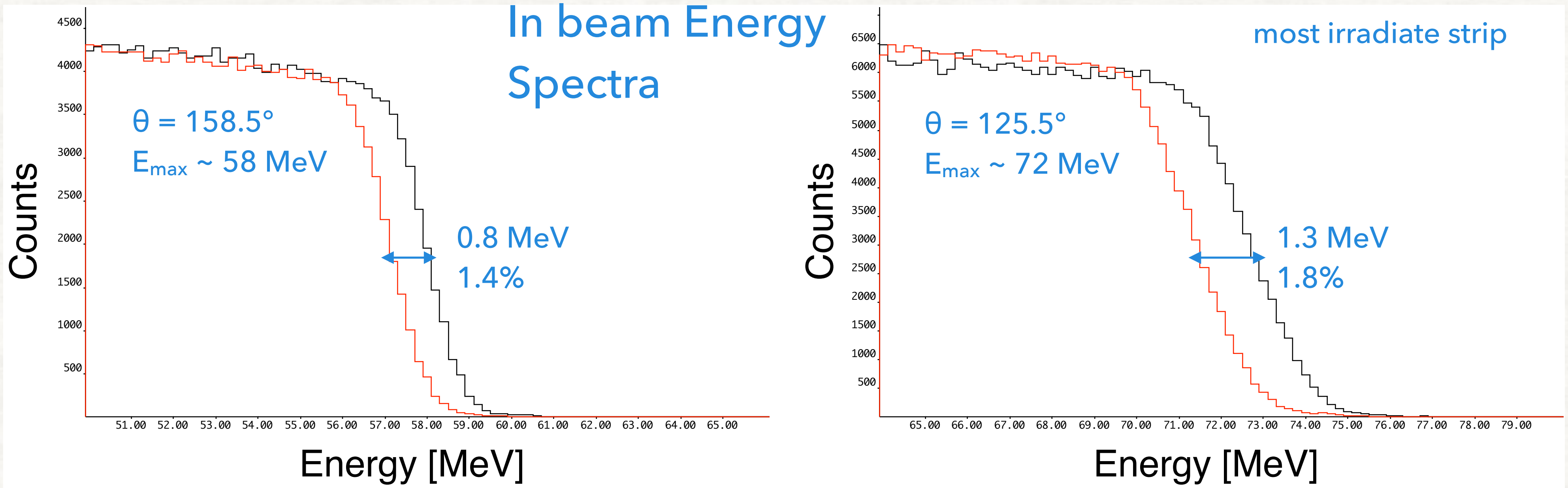
- FWHM for the 21+ —> 01+ transition = 11.3 keV

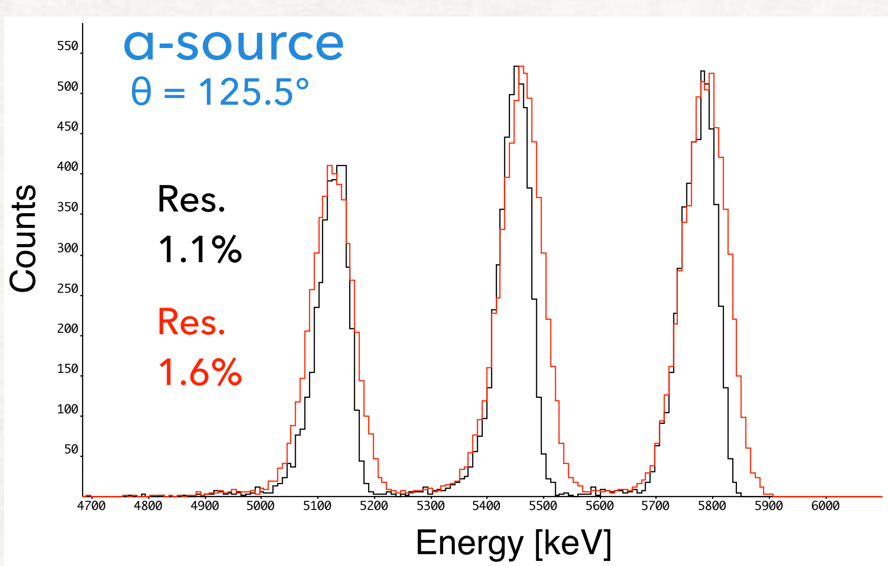


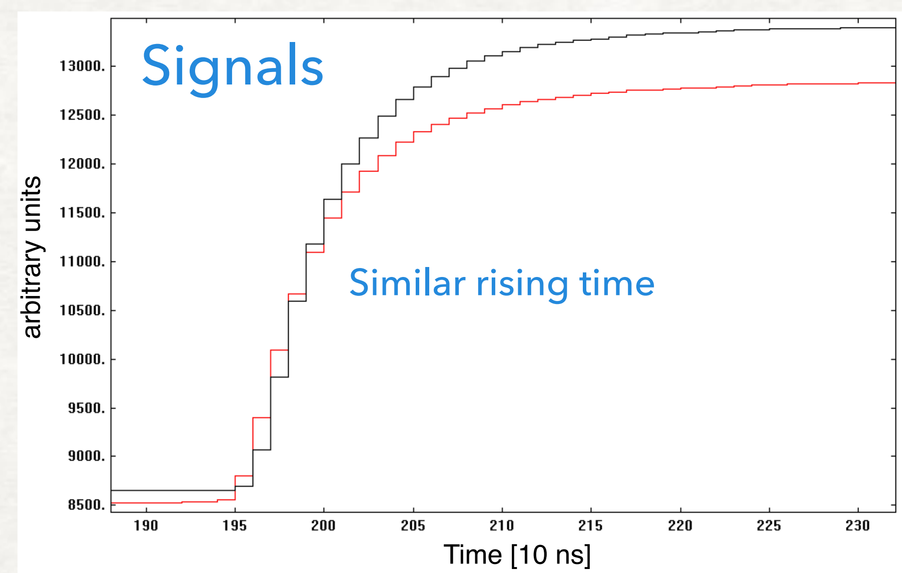
RADIATION DAMAGE

- Visible effects:

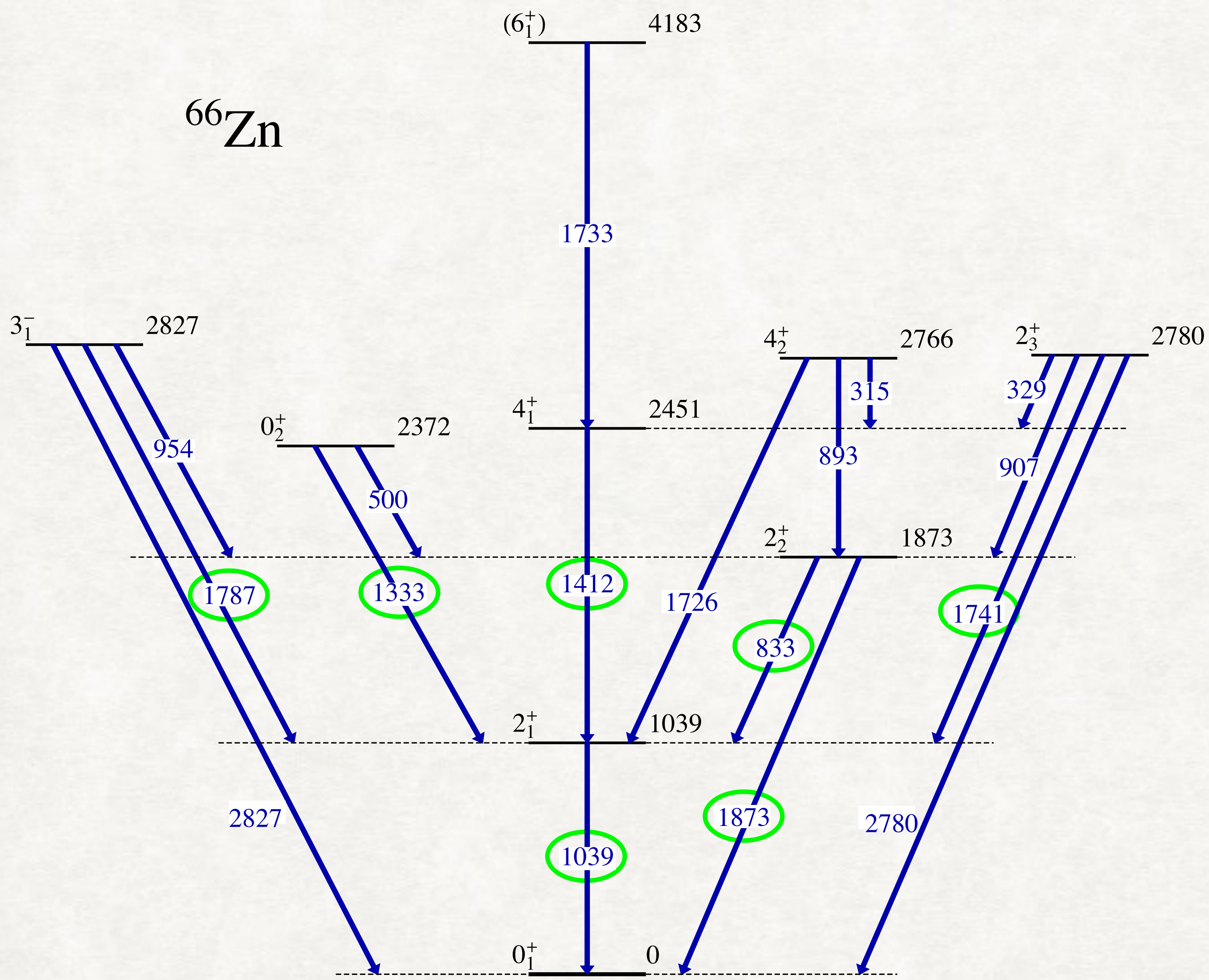
black -> before the experiment **red -> after the experiment**







GOSIA ANALYSIS

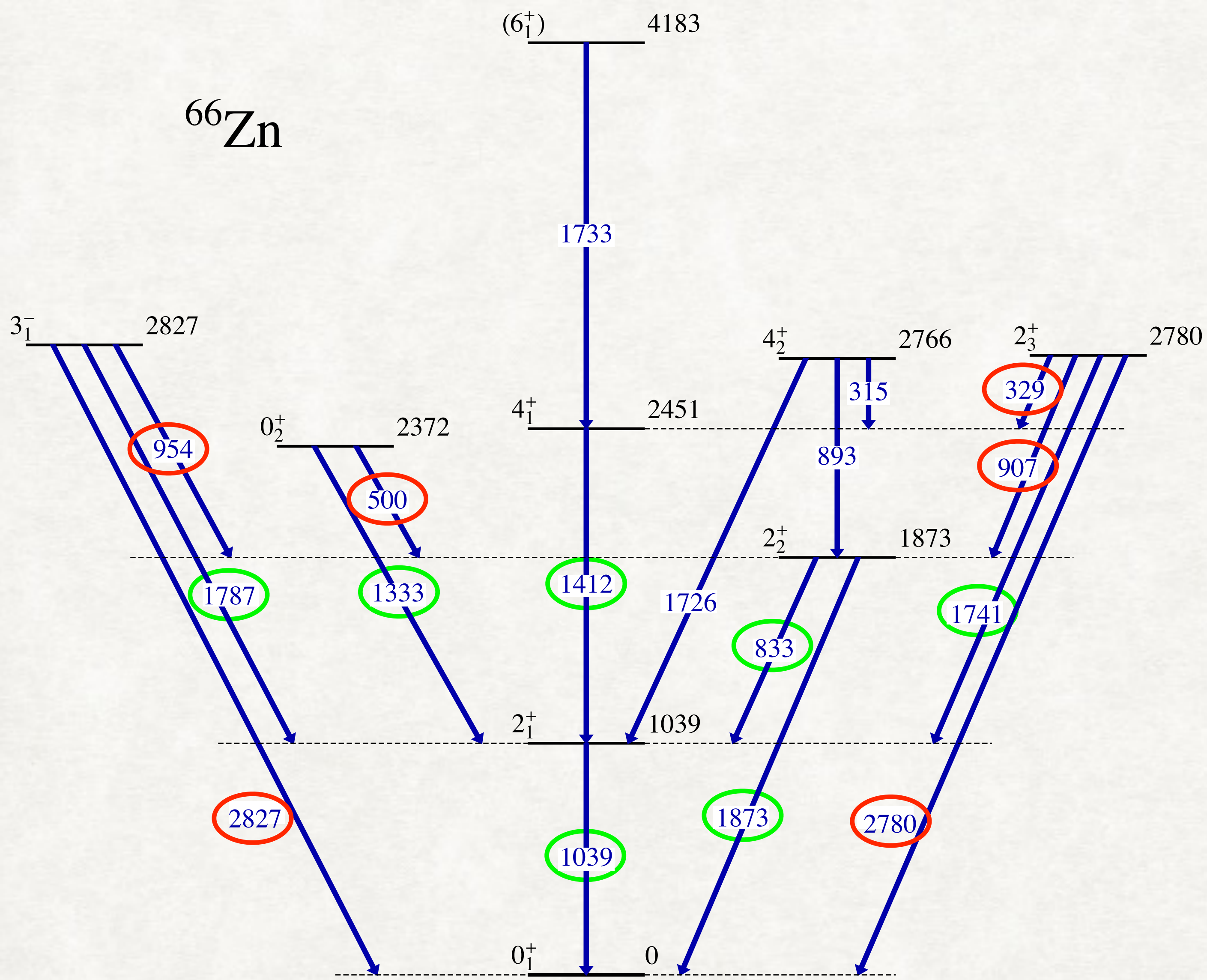


16 Matrix Elements:

- **9 B(E2), 2 B(E1), 1 B(E3), 2 B(M1)**
- **$Q_s(2_1^+)$, $Q_s(2_2^+)$**

- B(E2) values from observed transitions in gamma spectra
- $Q_s(2_1^+)$
- Deformation (**β**, **γ**) of the ground state

GOSIA ANALYSIS



16 Matrix Elements:

- **9 B(E2), 2 B(E1), 1 B(E3), 2 B(M1)**
- **$Q_s(2_1^+)$, $Q_s(2_2^+)$**

- B(E2) values from observed transitions in gamma spectra
- $Q_s(2_1^+)$
- Deformation (**β**, **γ**) of the ground state

B(E2) values, $Q_s(2_2^+)$, deformation (**β**, **γ**) of the 0_2^+ state obtained from known lifetimes, mixing and branching ratios.

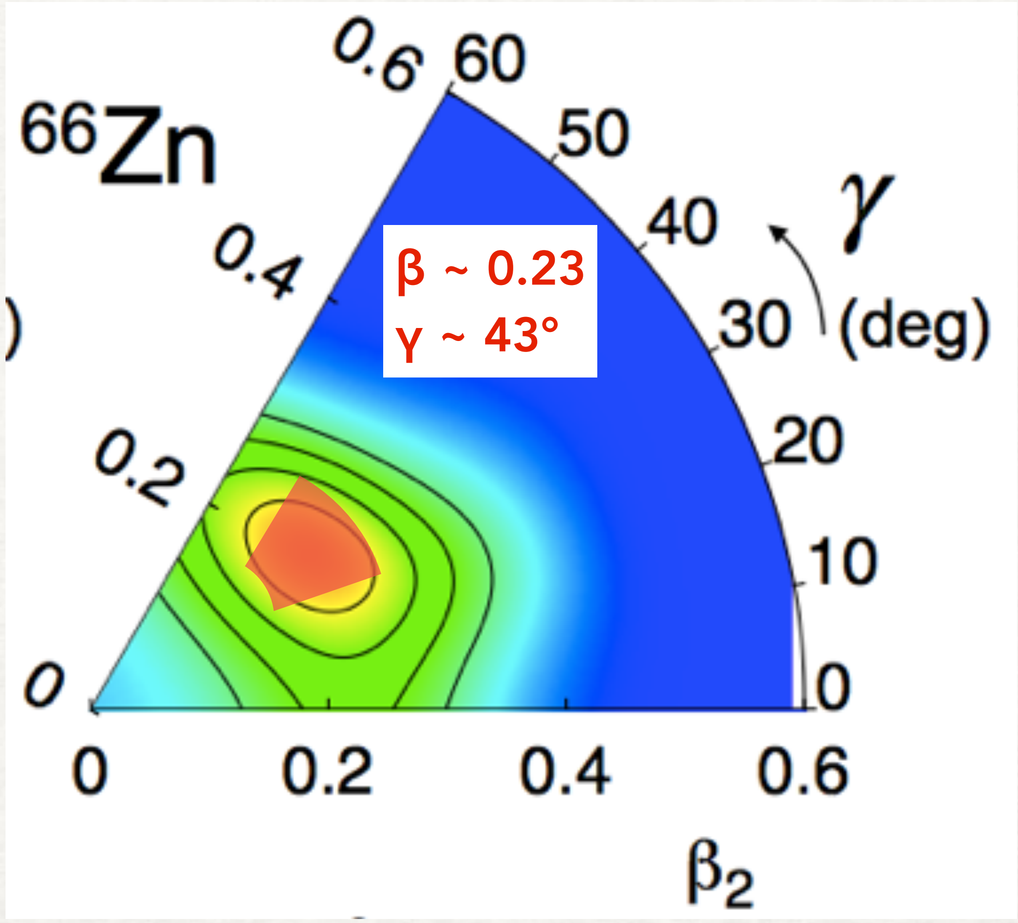
DEFORMATION OF 0^+ STATES

- **Preliminary results:**

- 0_1^+: $\langle\beta\rangle \sim 0.23$, $\langle\gamma\rangle \sim 43°$

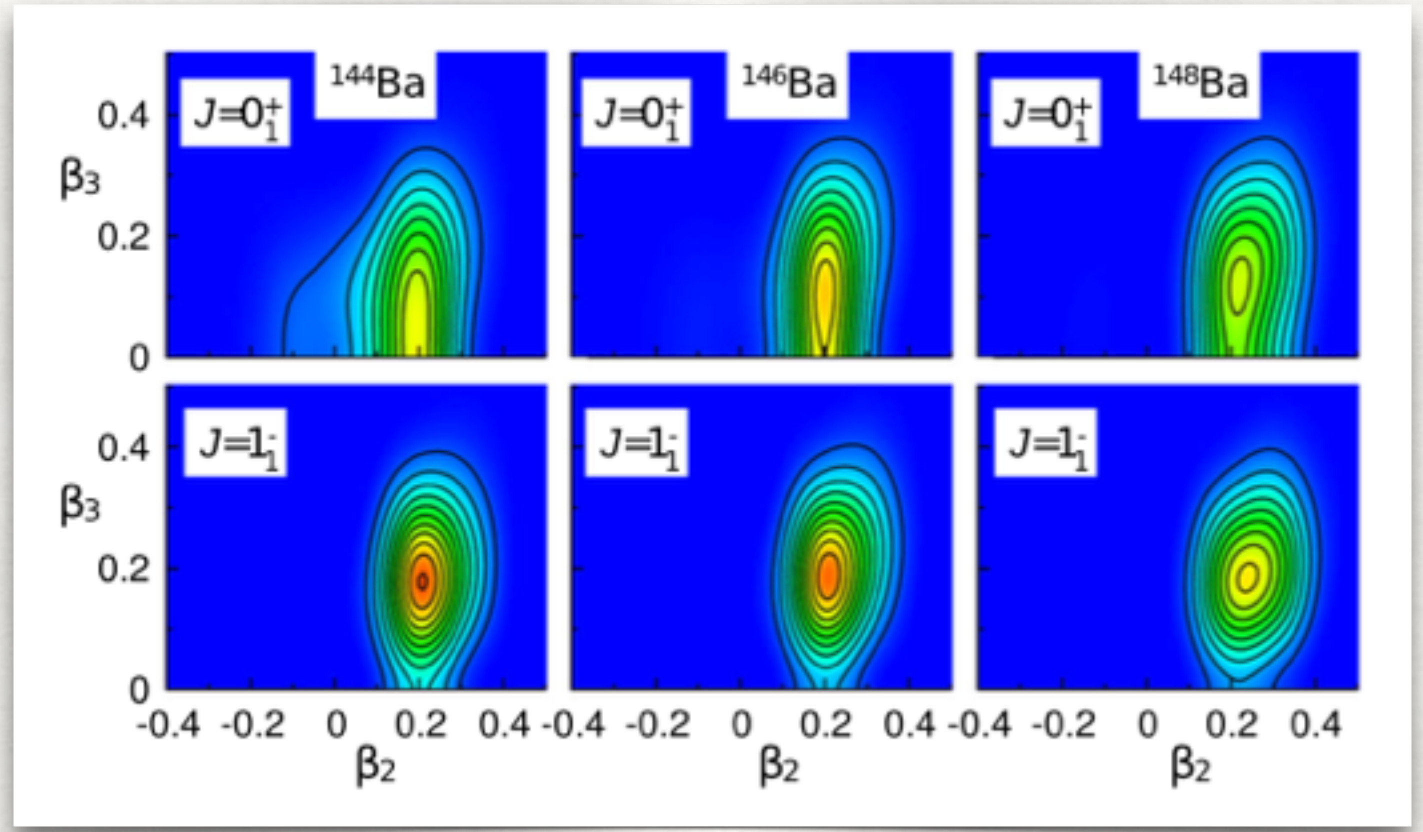
- 0_2^+: $\langle\beta\rangle \sim 0.055$

- Comparison with BMF calculations for the collective wave function for the ground state. (T. Rodriguez, private communication)



COULEX OF OCTUPOLE DEFORMED NUCLEI AT SPES

- Strong octupole correlations are expected in the region centered around neutron-rich Ba nuclei (Z=56,N~88)
- Low-lying negative parity states have been found experimentally
- Calculate collective amplitudes of 1^- and 0^+ overlap



COULEX OF OCTUPOLE DEFORMED NUCLEI AT SPES

- First Coulomb Excitation measurements performed at Argonne on $^{144,146}Ba$ [B. Butcher et al., PRL 116 (2016) - PRL 118 (2017)]

- The case of ^{144}Ba taken as an example

- E3 transition strength higher than model predictions (but significant uncertainties on the measurement)

- Further experiments would be helpful to disentangle the actual amount of octupole correlation in ^{144}Ba

- Gain of two order of magnitude in the beam intensity (according to the beam SPES tables)

COULEX OF ^{144}BA AT SPES

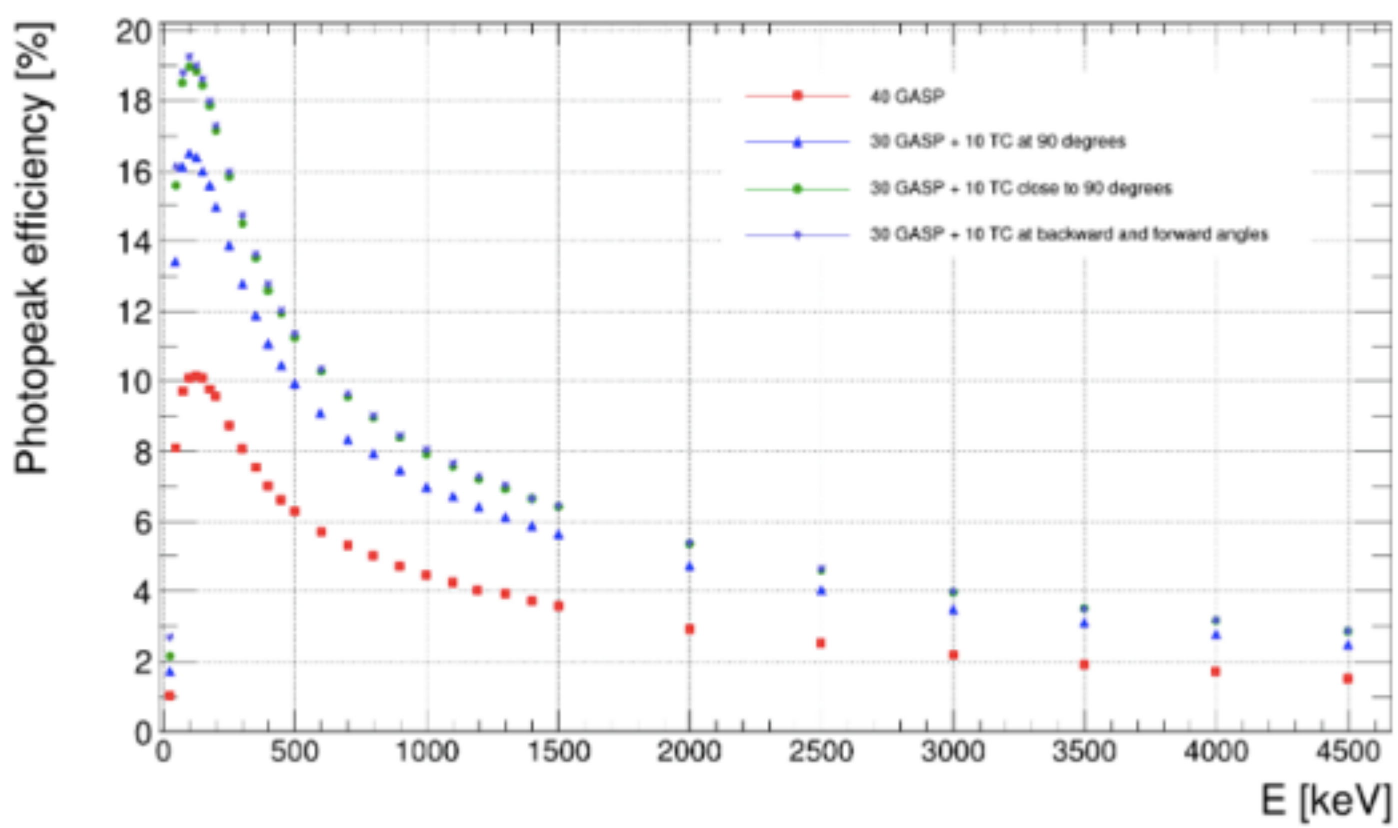
GOSIA SIMULATION

- Level scheme from nndc http://www.nndc.bnl.gov/ensdf
- Absolute values of the transition matrix elements from symmetry-conserving configuration-mixing calculations [R. N. Bernard et al. PRC93 (2016)].
- 4π GALILEO array
- Beam: ^{144}Ba (580 MeV, $1.14 \cdot 10^6$ pps)
- Target: 1 mg/cm2 of ^{208}Pb
- 4 days of measurement
- Particle detector at backward angles (from 30 to 75)

COULEX OF ^{144}BA AT SPES

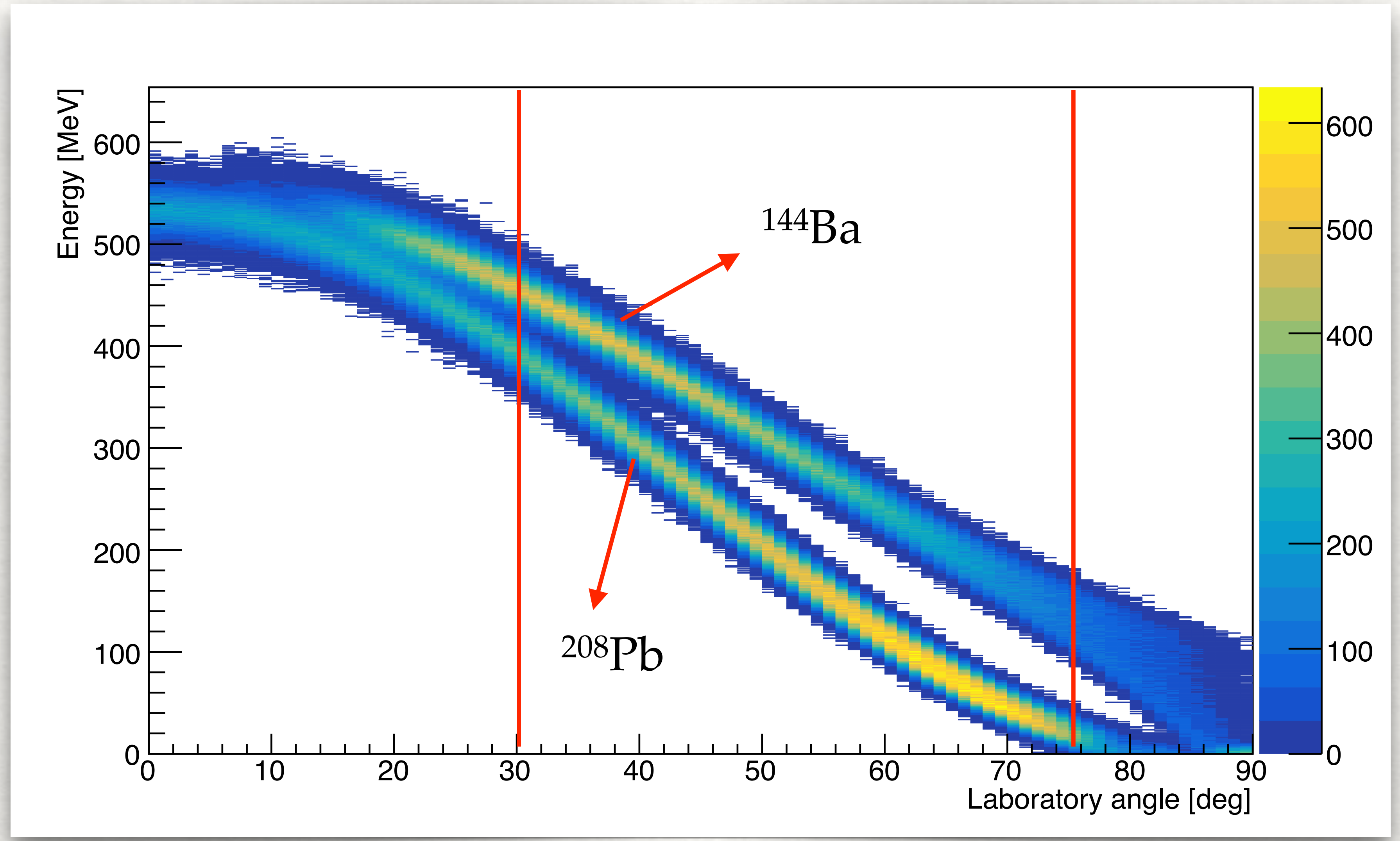
GAMMA DETECTORS

- The 4π GALILEO array: 30 gamma-ray Ge detectors with anti-Compton shields and 10 triple cluster Ge detectors realized with the capsules of the previous EUROBALL array



A. Goasduf

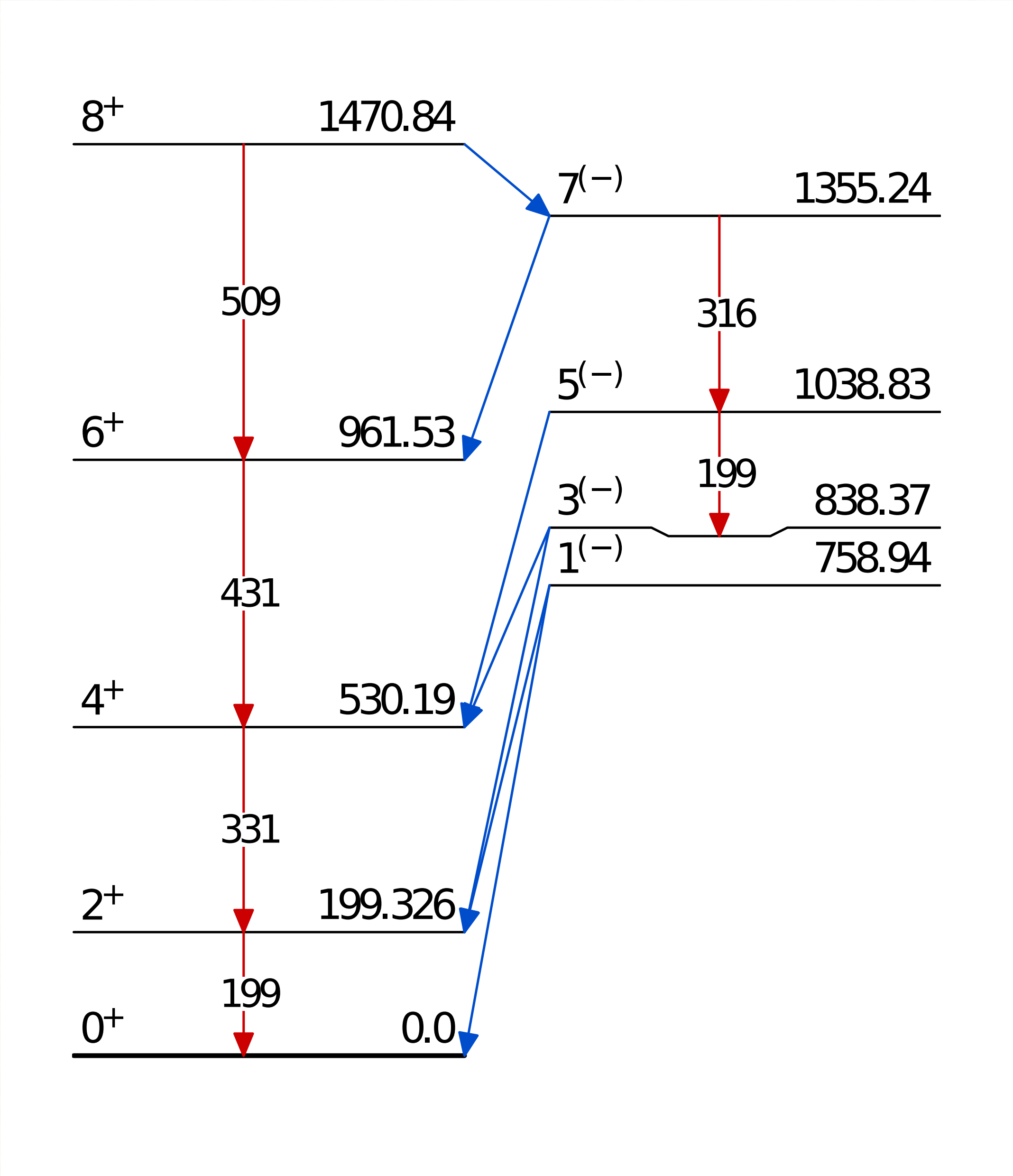
COULEX OF ^{144}BA AT SPES



Reaction kinematics calculated taking into account the energy loss in the target

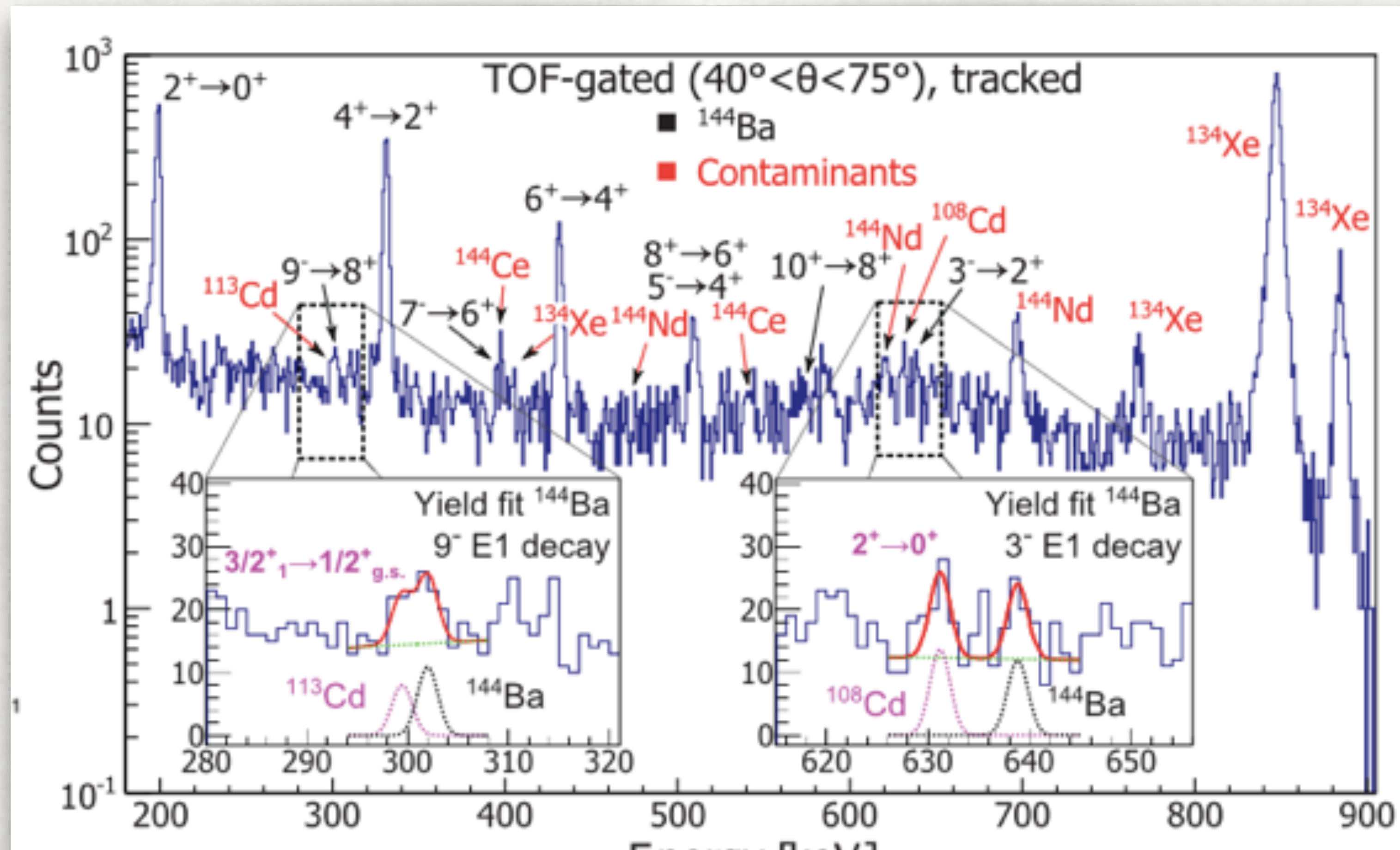
COULEX OF ^{144}BA AT SPES

Transition	Energy [keV	Counts
8+ -> 6+	509	2.31E+04
7- -> 4+	825	1.19E+03
5- -> 2+	840	3.99E+03
6+ -> 4+	432	1.16E+05
6+ -> 3-	124	2.73E-05
3- -> 0+	838	2.98E-02
3- -> 2+	639	2.93E+03
3- -> 4+	308	8.17E+02
3- -> 1-	79	9.57E-02
1- -> 0+	759	9.89E+02
4- -> 2+	331	4.79E+05
2+ -> 0+	199	1.24E+06



COULEX OF ^{144}BA AT SPES

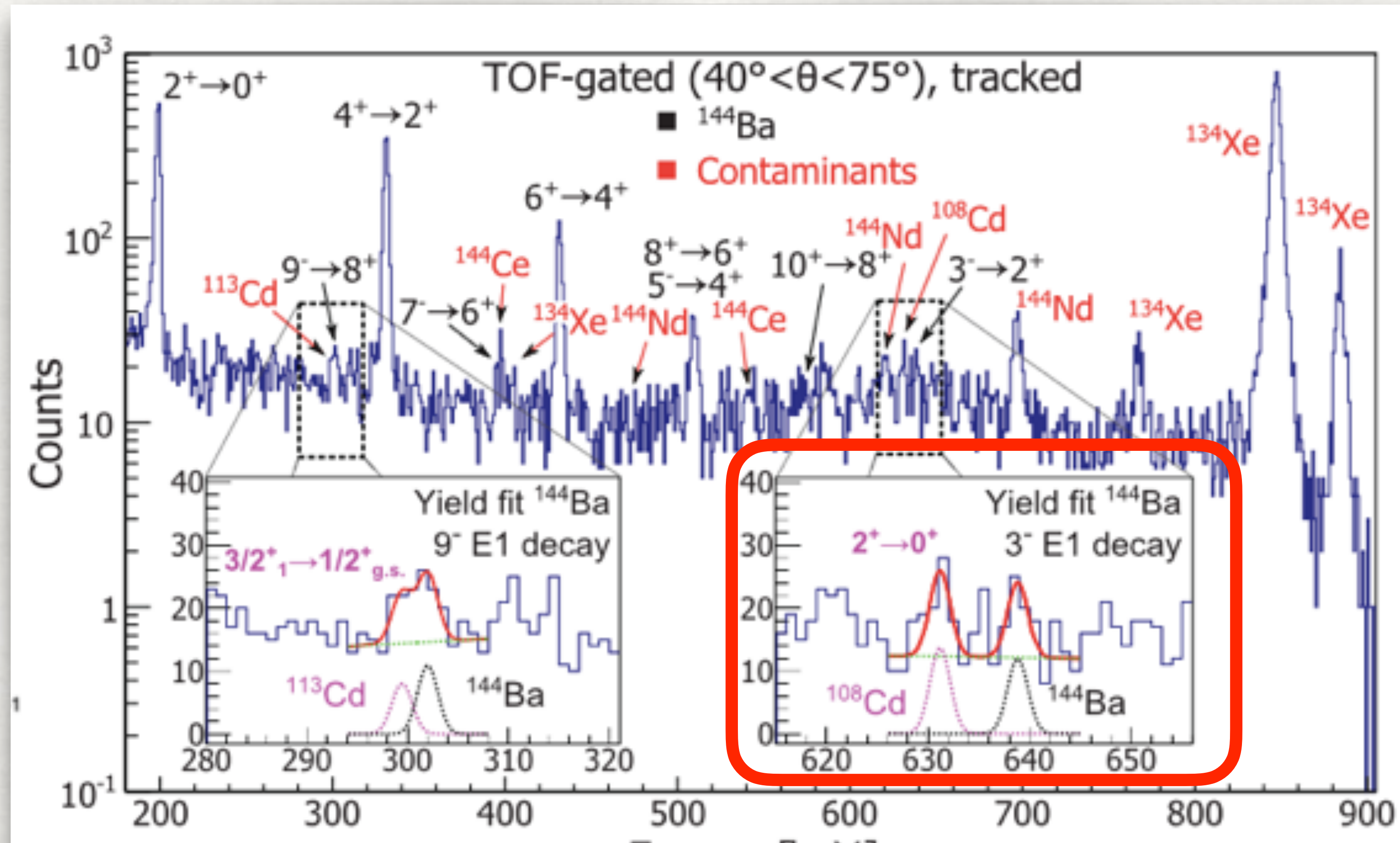
Transition	Energy [keV	Counts
8+ -> 6+	509	2.31E+04
7- -> 4+	825	1.19E+03
5- -> 2+	840	3.99E+03
6+ -> 4+	432	1.16E+05
6+ -> 3-	124	2.73E-05
3- -> 0+	838	2.98E-02
3- -> 2+	639	2.93E+03
3- -> 4+	308	8.17E+02
3- -> 1-	79	9.57E-02
1- -> 0+	759	9.89E+02
4- -> 2+	331	4.79E+05
2+ -> 0+	199	1.24E+06



B. Butcher et al., PRL 116 (2016)

COULEX OF ^{144}BA AT SPES

Transition	Energy [keV	Counts
8+ -> 6+	509	2.31E+04
7- -> 4+	825	1.19E+03
5- -> 2+	840	3.99E+03
6+ -> 4+	432	1.16E+05
6+ -> 3-	124	2.73E-05
3- -> 0+	838	2.98E-02
3- -> 2+	639	2.93E+03
3- -> 4+	308	8.17E+02
3- -> 1-	79	9.57E-02
1- -> 0+	759	9.89E+02
4- -> 2+	331	4.79E+05
2+ -> 0+	199	1.24E+06



B. Butcher et al., PRL 116 (2016)

CONCLUSION

- identification of octupole deformed nuclei important for the search of atomic EDM
- Coulomb excitation is the best tool to measure E3 transition strength
- the experimental set-up implemented at LNL paves the way to Coulomb excitation measurements of SPES beam

THANK YOU FOR THE ATTENTION

A. Nannini[2], M. Rocchini[1,2], K. Hadyńska-Klek[3], J. J. Valiente-Dobón[3], A. Goasduff[4,5], D. Testov[4,5], M. Zielińska[6], P. Cocconi[3], M. Chiari[1,2], D. Mengoni[4,5,] M. Ottanelli[2], A. Perego[1,2], L. Ramina[5], D. Rosso[3], M. Siciliano[3,4] and P. Sona[1]

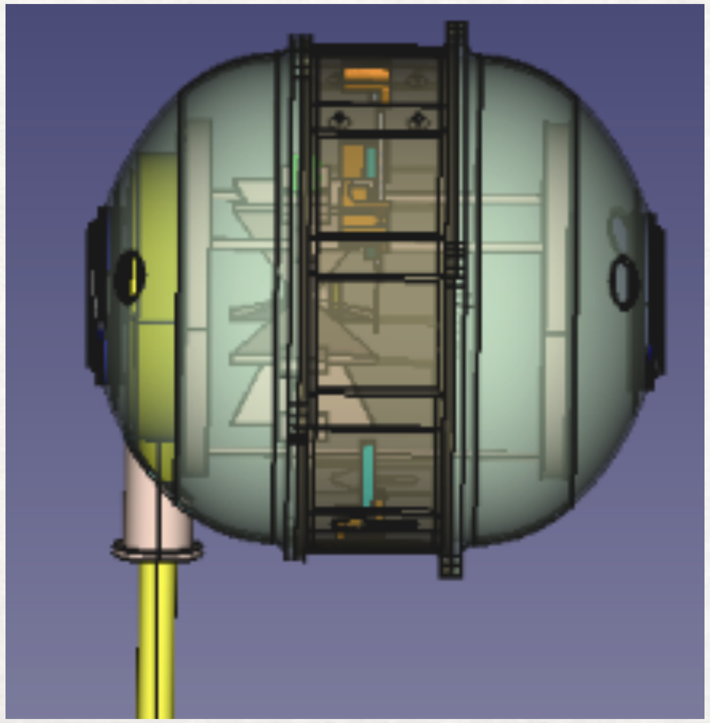
[1] Dipartimento di Fisica e Astronomia, Università degli Studi di Firenze, Firenze, Italy, [2] INFN, Sezione di Firenze, Firenze, Italy, [3] INFN, Laboratori Nazionali di Legnaro, Legnaro (Padova), Italy, [4] Dipartimento di Fisica e Astronomia, Università degli Studi di Padova, Padova, Italy, [5] INFN, Sezione di Padova, Padova, Italy, [6] CEA Saclay, IRFU/SPhN, France.

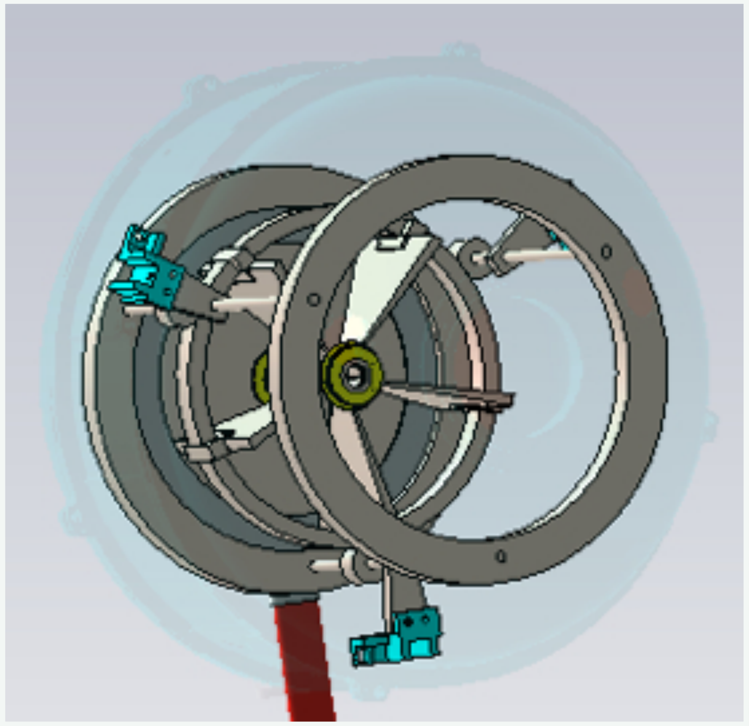
SETUP FOR IN-BEAM CONVERSION ELECTRONS AND GAMMA-RAYS COINCIDENCES AT LNL

- to reduce the δ electron background the Si(Li) is mounted at backward angles
  non standard annular Si(Li) and central hole in the absorber

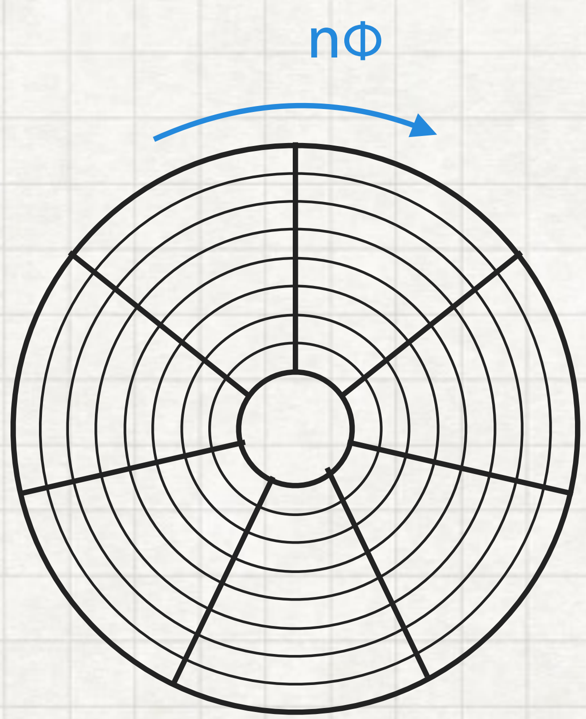
- to have a wide energy acceptance window without moving the MoS
  large size of the magnetic lenses and of the Si(Li) detector

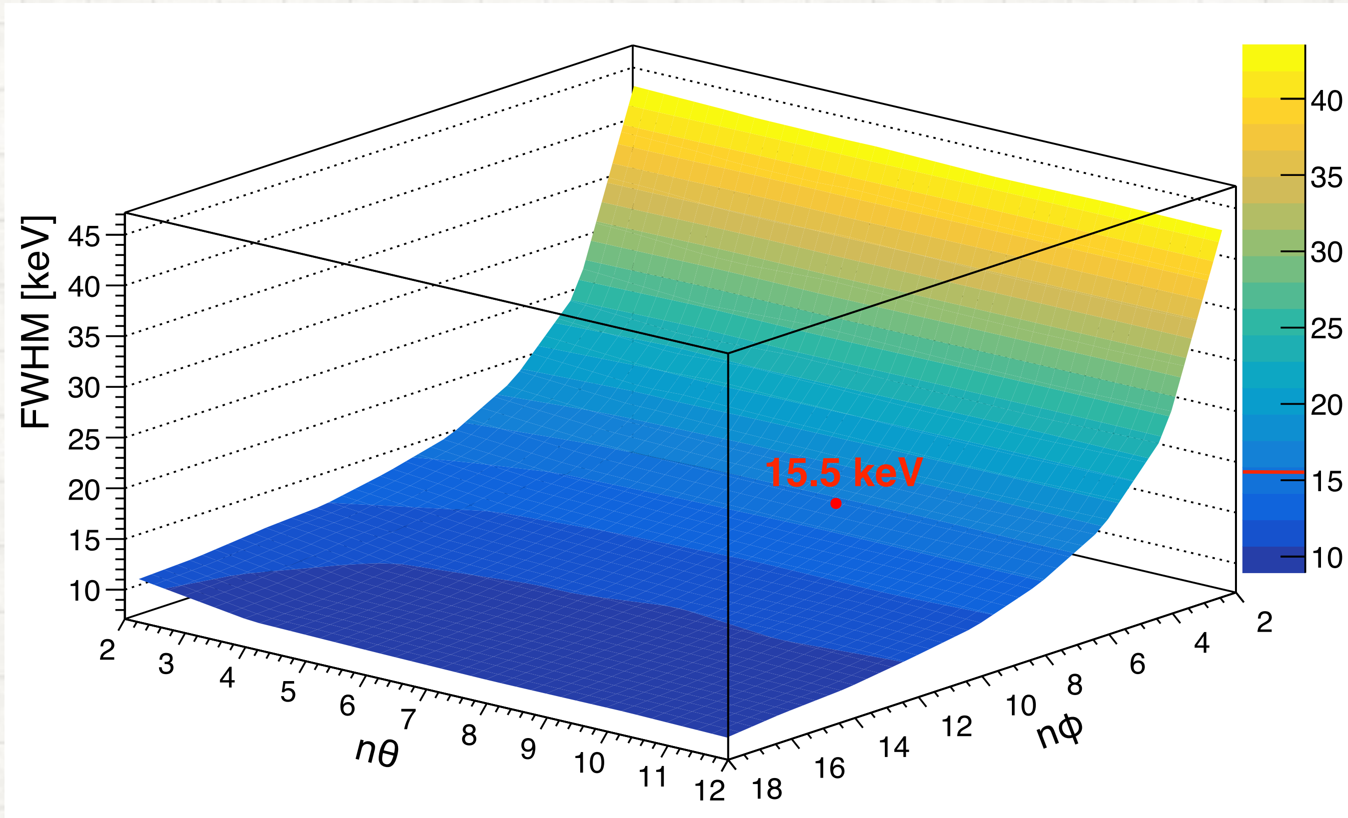
- to correct the electron energy spectra for relativistic kinematics effects
  non standard highly segmented Si(Li) detector





- Simulation:
    - γ-rays at 1335 keV emitted by ^{60}Ni nuclei scattered on a 1 mg/cm^2 ^{208}Pb target (β ~ 5%)
    - GALILEO 25 HPGe, SPIDER cone-configuration at backward angles
    - From nΦ = 7 (present configuration) to nΦ = 14 –> FWHM decreasing of 30%

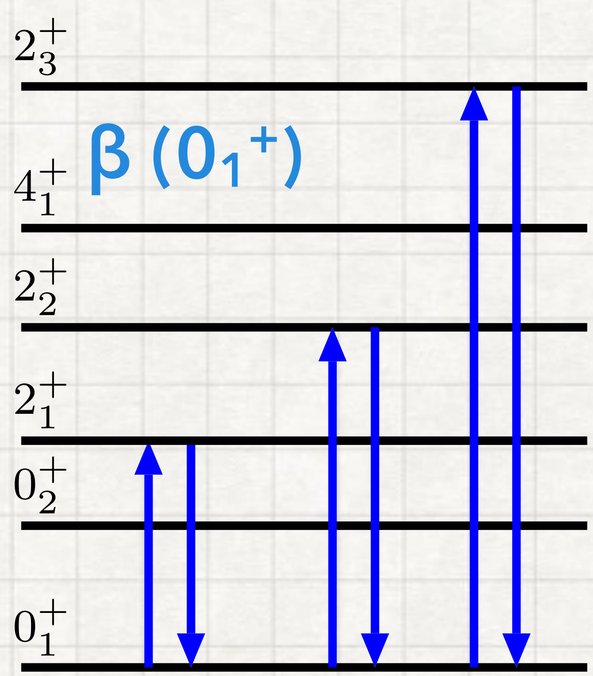


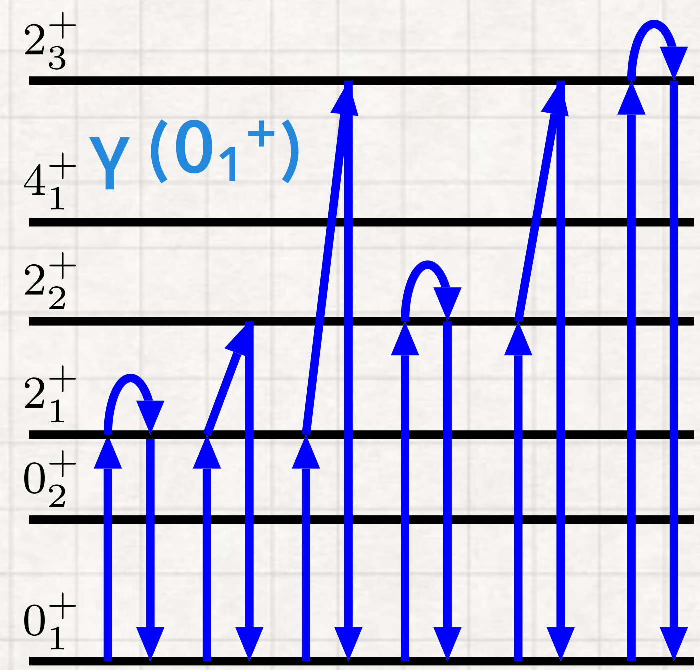


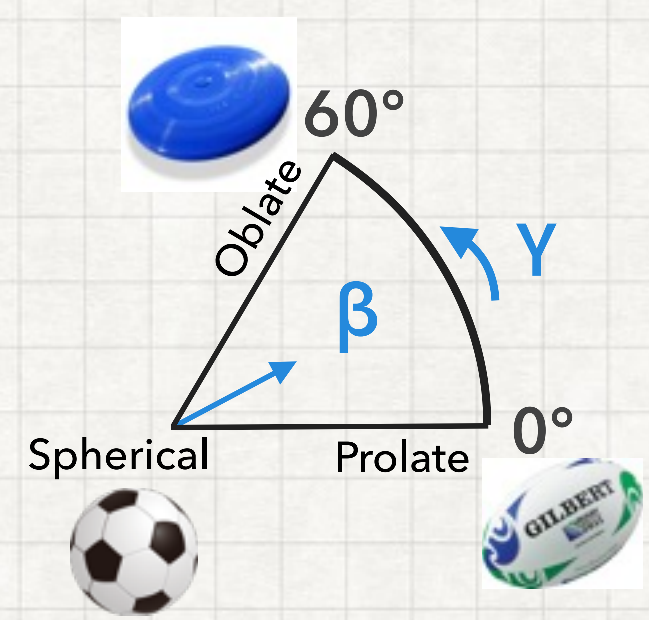
Quadrupole sum rule (K. Kumar, Phys. Rev. Lett. 28 (1972) 249) to obtain Nuclear Shape from matrix elements

$$\left\langle \beta^2 \right\rangle = \frac{\sqrt{5}}{q_0^2 \sqrt{2I_i+1}} \sum_t \langle i \,||E2||\, t\rangle \langle t \,||E2||\, i\rangle \begin{Bmatrix} 2 & 2 & 0 \\ I_i & I_i & I_t \end{Bmatrix} \qquad (4)$$

$$\left\langle \beta^3 \cos(\gamma) \right\rangle = \frac{\sqrt{35}}{q_0^3 \sqrt{2}} \frac{1}{\sqrt{2I_i+1}} \sum_{tu} \langle i \,||E2||\, t\rangle \langle t \,||E2||\, u\rangle \langle u \,||E2||\, i\rangle \begin{Bmatrix} 2 & 2 & 2 \\ I_i & I_t & I_u \end{Bmatrix}$$







OUTLINE

- atomic EDM and nuclear deformation
- octupole strength and coulomb excitation
- coulomb excitation at LNL: present status
- coulomb excitation at SPES: the octupole deformed 144Ba
- conclusion