Development of the Coulomb excitation technique at INFN LNL and HIL Warsaw

Status and perspectives

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French−Italian−Polish Collaborations on Nuclear Structure and Reactions
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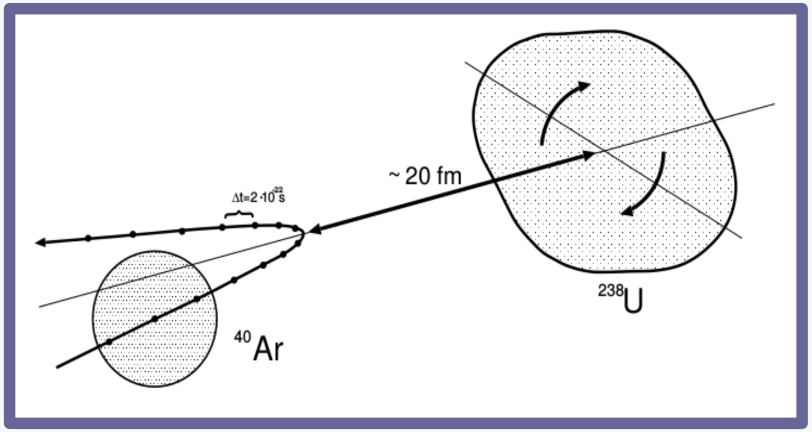
Coulomb excitation

- Pure electromagnetic interaction between the collision partners:

  $$d_{min} = 1.25 * (A_p^{1/3}+A_t^{1/3}) + 5 \text{ fm}$$

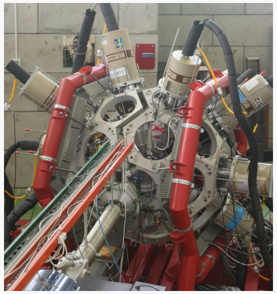
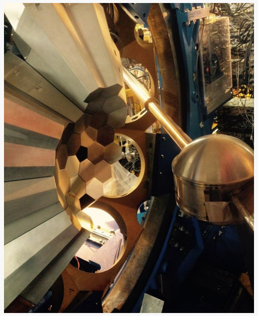
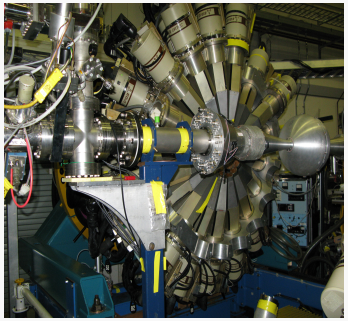
  when the distance of closest approach is saved, nuclear interaction can be neglected (*Cline's empirical criterion*)
- The excitation process depends on:

  E_{beam}, Z of projectile and target nuclei, $\theta_{scattering}$
- projectile and target excitation in the same time
- normal and inverse kinematics
- low-energy and high-energy Coulomb excitation (different conditions)

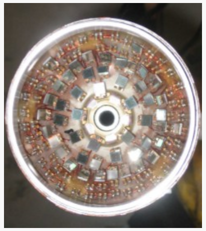


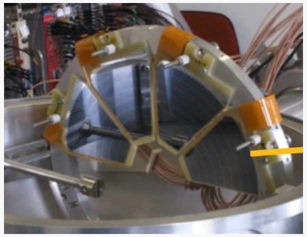
SETUP

- γ-ray detectors (HPGe, scintillation detectors) – to measure γ-ray intensities following Coulomb excitation process


- particle detector - to detect the scattered projectiles and/or recoiling target nuclei (silicon (segmented/PIN diodes), plastic, solar cells, PPAC, MCP,...)





SETUP – why particle detectors?

- to properly describe the **excitation** process (COULEX depends on θ)
- to **identify** the projectile and target nuclei - simultaneous detection of scattered projectiles and recoils, especially important in the RIB experiments
- to provide a clean **trigger** for selecting the events of interest - to select of the real Coulomb excitation events (especially when reaction channels are opened)
- to perform **Doppler correction, the event-by-event kinematics reconstruction**

Coulomb excitation - reorientation effect

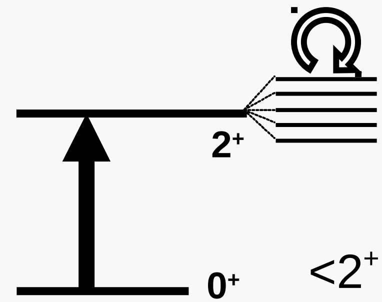
- Relative signs of matrix elements → the <u>quadrupole moment</u> – direct distinguish between prolate and oblate shape

  $Q_s > 0$ prolate

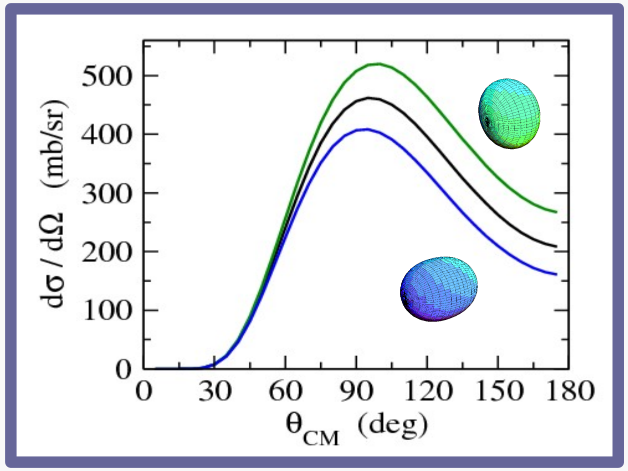
  $Q_s = 0$ spherical

  $Q_s < 0$ oblate

- second step excitation through the magnetic substates - influence of the quadrupole moment of the excited state on its excitation cross-section
- strong dependence on both scattering angle and beam energy
- subdivision of the data set into angular ranges – higher sensitivity



$\langle 2^+||E2||2^+\rangle \sim Q_s$



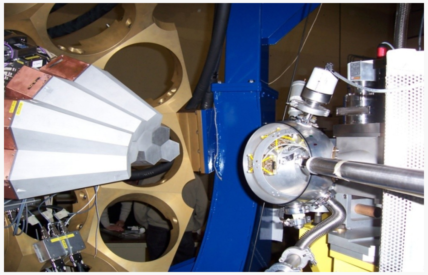
Coulomb excitation - information

- Measured gamma yields
- Particle and gamma geometry
- Additional spectroscopic information (if known)

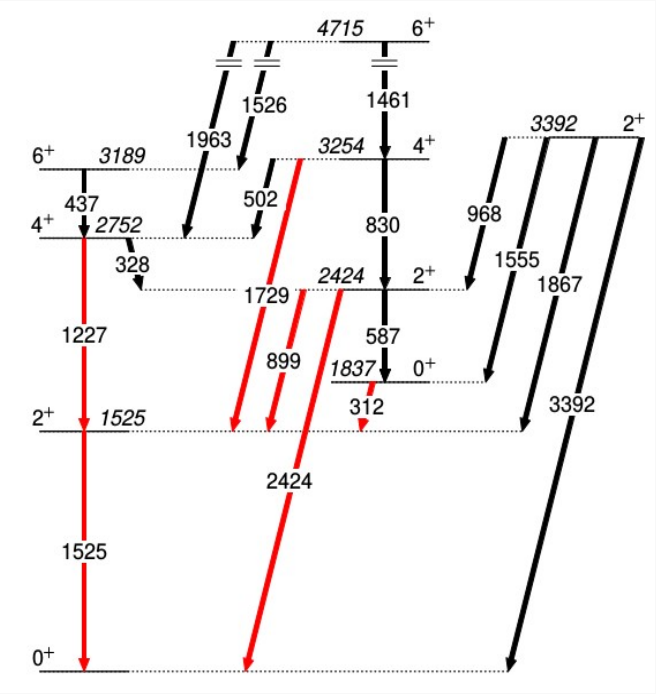
- the set of matrix elements with their relative signs and total correlated errors
- B(Eλ), B(Mλ), quadrupole moments can be determined (collectivity)
- Nuclear shapes (Quadrupole Sum Rules method)

Coulomb excitation of the SD band in ^{42}Ca

- beam: ^{42}Ca, 170 MeV, 1pnA, TANDEM XTU, INFN LNL
- targets:
  ^{208}Pb, 1 mg/cm^2 ,
  ^{197}Au, 1 mg/cm^2
- DANTE: 3 MCP detectors, θ range 100°-144°
- AGATA: 3 clusters



- Spokespersons: P.Napiorkowski (HIL Warsaw), A.Maj (IFJ Krakow), F. Azaiez (IPN Orsay), J.J.Valiente Dobon (INFN LNL)



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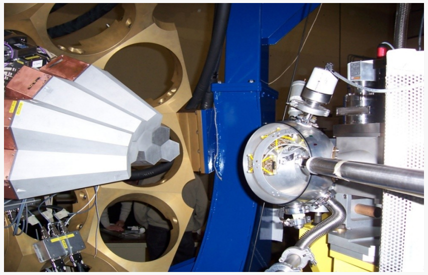

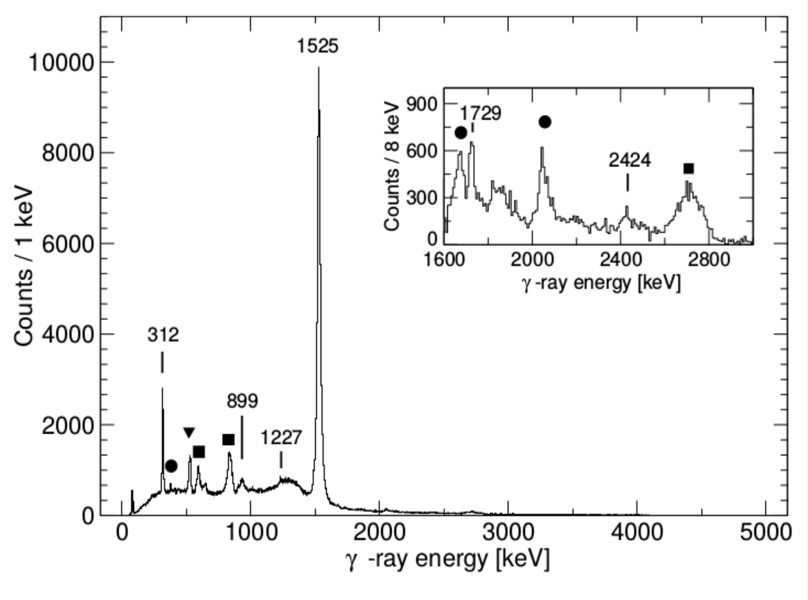

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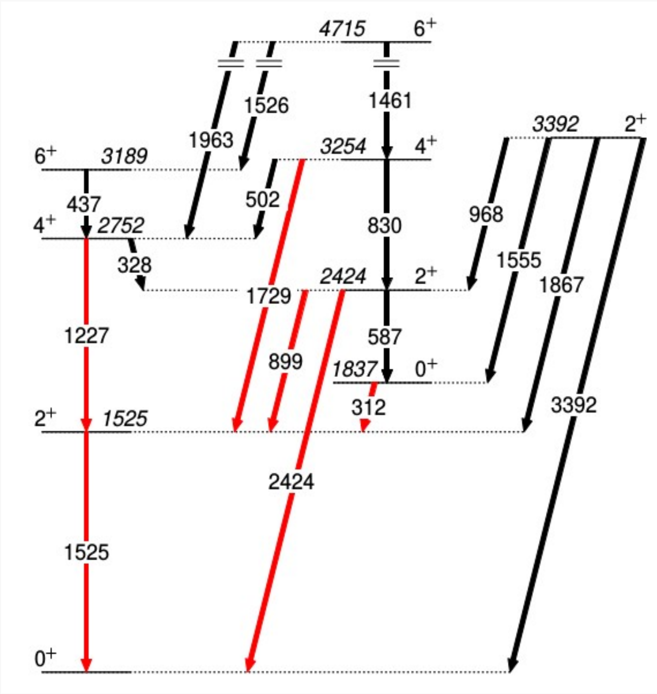
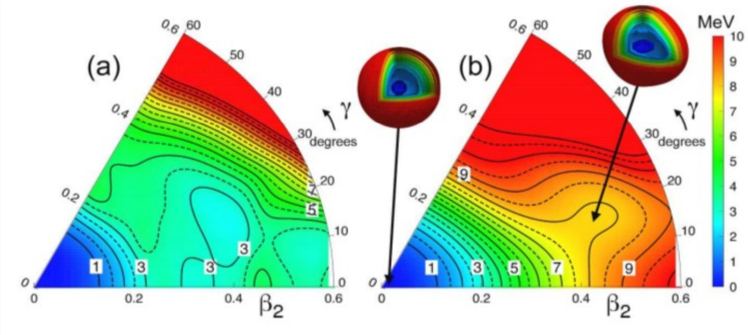


state	$\langle Q^2\rangle_{exp}$	$\langle Q^2\rangle_{SM}$	$\sigma(Q^2)_{SM}$	$\langle Q^2\rangle_{BMF}$	$\sigma(Q^2)_{BMF}$
0_1^+	500 (20)	240	470	100	250
2_1^+	900 (100)	250	490	100	310
0_2^+	1300 (230)	1200	500	1900	520
2_2^+	1400 (250)	1130	500	1900	300

state	$\langle\cos(3\delta)\rangle_{exp}$	$\langle\cos(3\delta)\rangle_{SM}$	$\langle\cos(3\delta)\rangle_{BMF}$
0_1^+	0.06 (10)	0.34	0.34
0_2^+	0.79 (13)	0.67	0.49

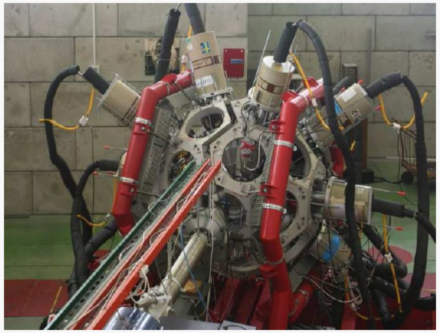


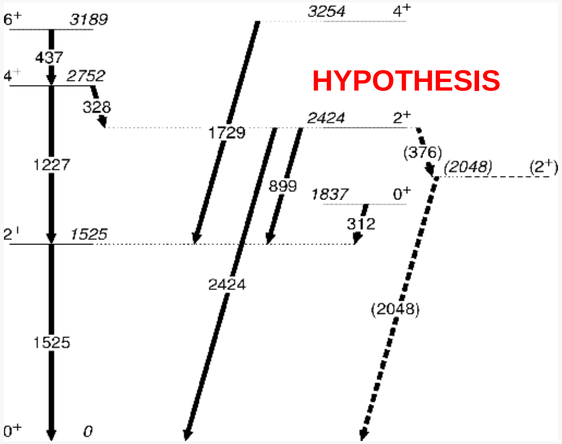
→ LSSM (F. Nowacki, H. Naidja - Strasbourg)
→ BMF (T. Rodriguez - Madrid)

(Submitted to PRL)

^{42}Ca experiment, HIL Warsaw

- Complementary run, strange effects in COULEX observed - possible new level at 2048 keV - low-spin level scheme of ^{42}Ca needed revision
- Reaction: ^{12}C(^{32}S,2p)^{42}Ca, 76 MeV
- EAGLE array: 16 HPGe in ACS, Gammapool
- beam-time: 4 days





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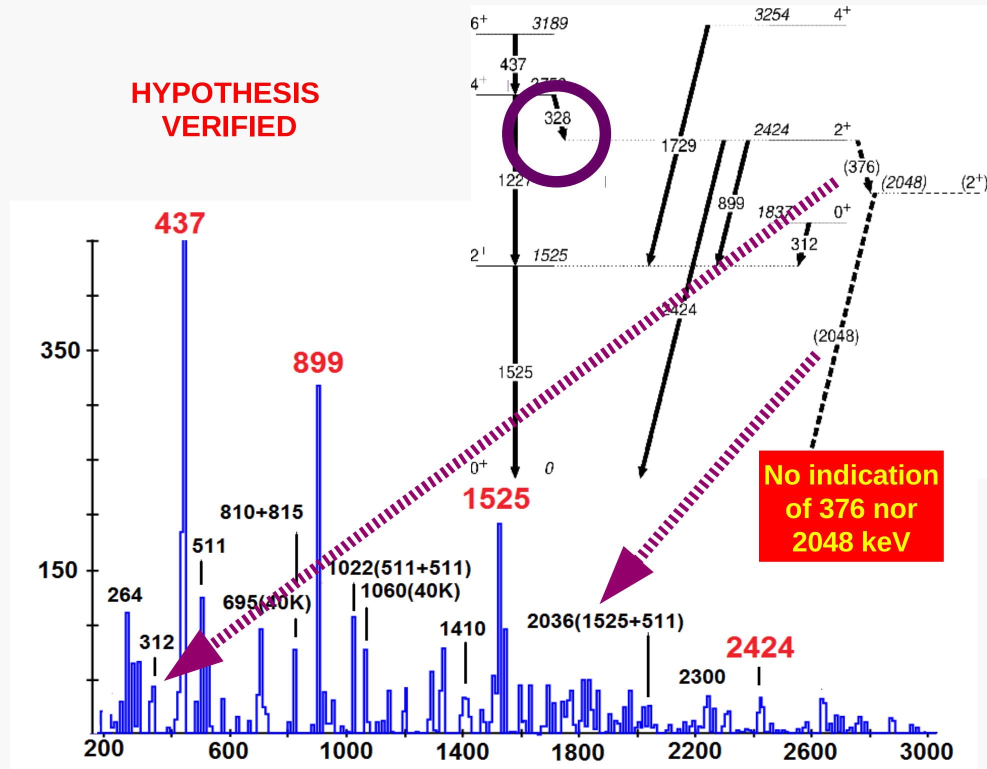
HYPOTHESIS VERIFIED



COULEX at HIL Warsaw

- long tradition, expertise, worldwide collaboration
- COULEX Schools (TU Darmstadt 2011, CERN 2016)
- GOSIA code development (T. Czosnyka, P. Napiorkowski), dedicated workshops (Warsaw, 2008 and 2013), recently also JACOB (genetic algorithm)
- development of particle detector systems (CUDAC, “Munich” pin-diodes chamber, CD detector, CVD diamond detectors)
- Research program:

  - continuation of COULEX of SD structures in A~40 region (UIOslo, IPN Orsay, INFN LNL)

  - octupole deformation in rare-earth nuclei (CEA Saclay)

  - electromagnetic structure of A~100, (^{104}Pd, ^{110}Cd, ^{107}Ag) (KU Leuven - CEA Saclay)

  - COULEX of odd nuclei - ^{45}Sc to be submitted at HIL (INFN LNL)

Exotic beams experiments – SPES project at LNL

- new possibilities for experimental studies of **neutron-rich** nuclei in Italy - RI beams from SPES (Selective Production of Exotic Species) – opportunity for a development of the **Coulomb excitation** technique
- SPES 2010 International Workshop, 15-17.11.2010, INFN LNL (LOIs)
- SPES ONE-DAY WORKSHOP: "Coulomb Excitation with RIBs", 27-28.09.2012, INFN Firenze
- Proposed LoI for SPES, physics cases (selected):

- *Coulomb-excitation measurements in nuclei around ^{132}Sn – ^{135}Sb, $^{126,128}Cd$* (INFN Firenze, INFN Napoli, CEA Saclay)

- *Search for Exotic-Octupole deformation effects in n-rich Ce-Xe-Ba Nuclei* (University of Oslo, INFN LNL)

- *Proton-neutron balance of quadrupole-collective states of even-even n-rich Isotopes* (TU Darmstadt)

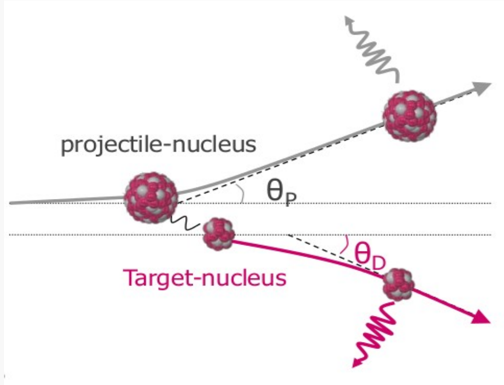
- *Shape coexistence in Kr isotopes towards N = 60* (INFN LNL)

- *Spectroscopy studies around ^{78}Ni and beyond N=50 via transfer and Coulomb excitation reactions* (INFN LNL)

Exotic beams experiments – SPES project at LNL

- energies suitable for Coulomb excitation (2-5 MeV/A)
- beam intensities rather low: particle detectors at forward angles to maximize the statistics - **projectile and recoil identification needed**

Development of the particle detector to be used at LNL needed

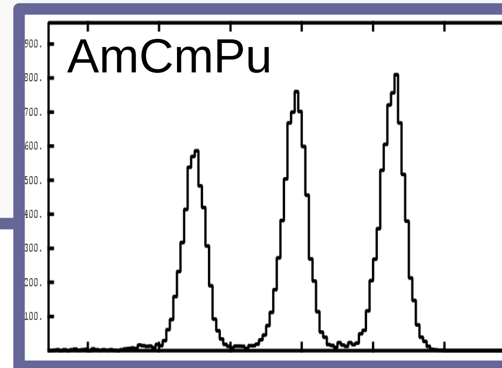


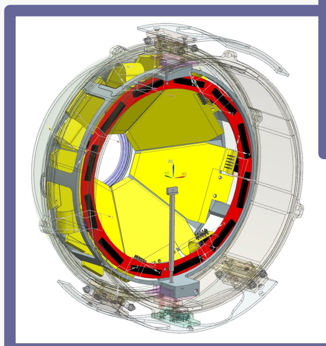
SPIDER - Silicon PIe DetectoR (INFN Firenze – INFN Legnaro)

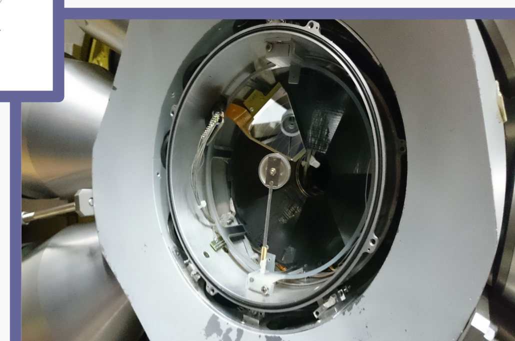
- 300 µm thick silicon segmented detector – GARFIELD@LNL Ring Counter array segments
- Independent sectors segmented in 8 strips in the junction side, the rear surface (ohmic side) consists of a unique electrode
- Guard ring between strips
- First in-beam test of SPIDER at LABEC - INFN Firenze - population of the first 2^+ level in ^{110}Pd using the reaction ^{110}Pd(p,p')^{110}Pd* @5MeV
- Second in-beam test at LABEC - INFN Firenze with the ^{7}Li beam (COULEX with ^{27}Al target)

SPIDER – tests in GALILEO chamber

- “Cone-like” configuration – **7 sectors** suitable for the existing GALILEO reaction chamber, backward angles – max diameter: 200 mm, depth: 45 mm, distance of 80 mm from the target, angles between **124-169°**
- Existing EUCLIDES electronics system (power supply, preamplifiers, DAQ) can be used
- Existing GALILEO configuration of 25 HPGe, future 40 HPGe, triple clusters, (+$LaBr_3$)
- Possible usage with other ancillary devices (solar cells, plunger)
- **Commissioning in-beam run at LNL in July 2016**







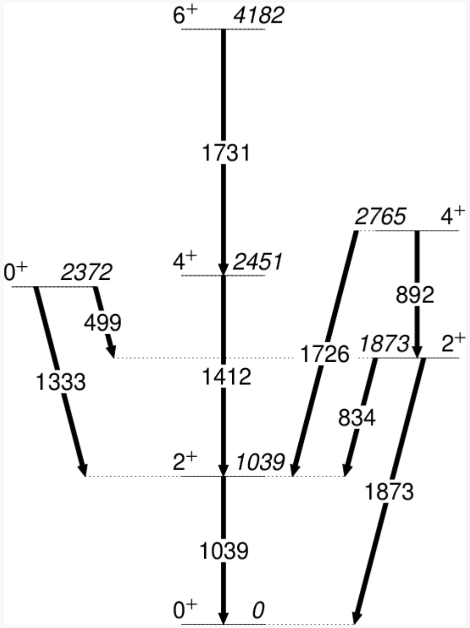
SPIDER – commissioning run

- ^{66}Zn continuous beam from TANDEM accelerator, 4 days accepted, E=240 MeV, I=1pnA
- Target: ^{208}Pb, 1 mg/cm^2
- GALILEO (25 HPGe) + SPIDER (7 segmented detectors)
- Goals:

→ **B(E2;$2_1^+ \rightarrow 0_1^+$) and $Q_s(2_1^+)$**

→ in addition: collectivity of $4_1^+ \rightarrow 2_1^+$ transition

→ in addition: structure of 0_2^+ and 2_2^+ states



COULEX of ^{66}Zn, B(E2,$2_1 \rightarrow 0_1$), $Q_s(2_1)$

- Previous COULEX experiment at TOKAI/JAERI, Japan:

  → GEMINI array, 12 HPGe+ACS, 13cm from the target

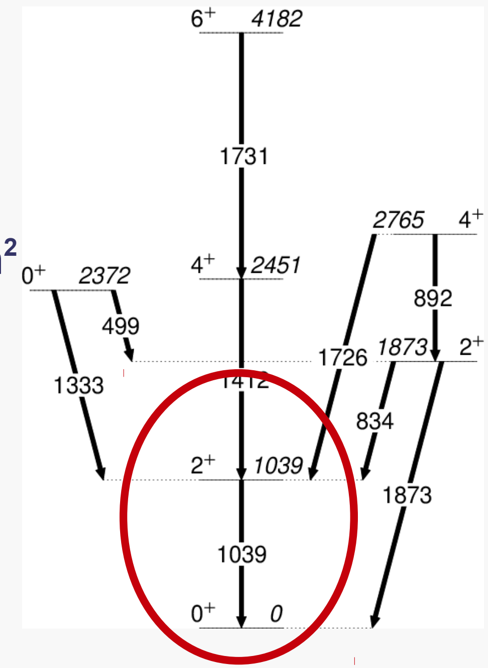
  → LUNA array, position-sensitive Si telescopes, 30% of the solid angle, mostly forward

  → 1.3 mg/cm^2 natPb target, 66h of 5nA ^{66}Zn beam

- Measured **B(E2,$2_1^+ \rightarrow 0_1^+$)=288(18) e^{2}fm^4** and **$Q_s(2_1^+)$=+24(8) efm^2** (slightly triaxial/oblate)

M. Koizumi et al, Eur. Phys. J. A 18, 87–92 (2003)

	Experimental	
	present	NDS
$B(E2; 2_1^+ \rightarrow 0_1^+)$	288 (18)	284 (11)
$B(E2; 2_2^+ \rightarrow 0_1^+)$	0.06 (28)	0.05 (2)
$B(E2; 2_2^+ \rightarrow 2_1^+)$	650 (228)	5700 (220)
$B(E2; 4_1^+ \rightarrow 2_1^+)$	278 (11)	560 (130)
$Q(2_1^+)$	+24 (8)	



COULEX with stable beams, perspective

Selected projects with GALILEO+SPIDER setup:

- Coulomb excitation of ^{12}C (INFN LNL – iThemba Labs)
- The nuclear structure evolution along the stable Xe isotopic chain (INFN Firenze)
- SD bands in A~40 region (Ca, Ar, Ti isotopes) (INFN LNL – HIL Warsaw)

SPIDER – collaboration

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Summary and outlook

- Perspective of COULEX with stable beams at INFN LNL (ALPI,PIAVE,TANDEM XTU facilities)
- Future RIB from SPES
- Development of a new heavy ion detector, SPIDER
- Strong collaboration

Thank you