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

Status and perspectives

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Coulomb excitation

- Pure electromagnetic interaction between the collision partners:
  \[ d_{\text{min}} = 1.25 \times (A_p^{1/3} + A_t^{1/3}) + 5 \text{ fm} \]
  when the distance of closest approach is saved, nuclear interaction can be neglected (Cline's empirical criterion)
- The excitation process depends on:
  \( E_{\text{beam}}, \ Z \) of projectile and target nuclei, \( \theta_{\text{scattering}} \)
- 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 $\theta$)
- 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 quadrupole moment – 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

\[ <2^+||E2||2^+> \sim Q_s \]
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
- $B(E\lambda), B(M\lambda)$, 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, $\theta$ 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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Joint LIA COLL-AGAIN, COPIGAL and POLITA Workshop,
French–Italian–Polish Collaborations on Nuclear Structure and Reactions
Catania, 26-29.04.2016

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

(Submitted to PRL)
**42^{\text{Ca}} experiment, HIL Warsaw**

- Complementary run, strange effects in COULEX observed - possible new level at 2048 keV - low-spin level scheme of $^{42}\text{Ca}$ needed revision
- Reaction: $^{12}\text{C}(^{32}\text{S},2p)^{42}\text{Ca}$, 76 MeV
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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, \(^{104}\text{Pd},^{110}\text{Cd},^{107}\text{Ag}\) (KU Leuven - CEA Saclay)
  - COULEX of odd nuclei - \(^{45}\text{Sc}\) to be submitted at HIL (INFN LNL)

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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)


• 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
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 $^{110}\text{Pd}$ using the reaction $^{110}\text{Pd}(p,p')^{110}\text{Pd}^*$ @5MeV

Second in-beam test at LABEC - INFN Firenze with the $^7\text{Li}$ beam (COULEX with $^{27}\text{Al}$ 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

- $^{66}\text{Zn}$ continuous beam from TANDEM accelerator, 4 days accepted, $E=240 \text{ MeV}, I=1\text{pnA}$
- Target: $^{208}\text{Pb}, 1 \text{ mg/cm}^2$
- GALILEO (25 HPGe) + SPIDER (7 segmented detectors)
- Goals:
  - $\text{B}(E2; 2^+_1 \rightarrow 0^+_1)$ 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

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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)

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

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