COULOMB EXCITATION AT LNL WITH THE SPIDER ARRAY
Coulomb Excitation

Low-energy Coulomb excitation is a simple and precise tool to measure excitation probabilities and provide insight on the collectivity of nuclear excitations and in particular on nuclear shapes.
Cross-sections give a measure of the matrix elements of the e.m. operators

\[
\frac{d\sigma_{\text{clx}}}{d\Omega} = \frac{d\sigma_{\text{Ruth}}}{d\Omega} \cdot P(i \rightarrow f)
\]
cross-sections give a measure of the matrix elements of the e.m. operators
\[
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diagonal matrix elements (spectroscopic quadrupole moments) give a measure of charge distribution
\[
Q_s(J) = \sqrt{\frac{16\pi}{5}} \frac{\langle JJ20|JJ\rangle}{\sqrt{2J+1}} \frac{\langle J||E2||J\rangle}{2J+1}
\]
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diagonal matrix elements (spectroscopic quadrupole moments) give a measure of charge distribution

\[
Q_s (J) = \sqrt{\frac{16\pi}{5}} \frac{\langle JJ20|JJ\rangle}{\sqrt{2J+1}} \langle J || E2 || J \rangle
\]

complete set of E2 matrix elements brings information on shape parameters via the quadrupole sum rules
COULOMB EXCITATION MEASUREMENTS

- germanium detectors to detect γ-rays
- Doppler correction of γ-ray spectra
- inverse kinematics: excitation of a heavy projectile on a light target (typically $^{12}$C)
COULOMB EXCITATION MEASUREMENTS

- germanium detectors to detect $\gamma$-rays

- segmented particle detector to detect the scattered projectiles and/or recoiling target nuclei
  - to select Coulomb Excitation events
  - to determine scattering angle and reconstruct the kinematics of the reaction
  - to perform Doppler correction
Available beams (official LNL list):  

Many possibilities for Coulex with stable beams
SPIDER Silicon PlE DETector

- 8 independent sectors, 8 strips + guard ring
- Detector thickness ~ 300 μm
- FWHM ~ 21 keV for α-particles @ ~ 5.5 MeV
- Modularity: with GALILEO cone configuration (7 sectors) at backward angles \( \Delta \Theta \sim 38^\circ, \frac{\Omega}{4\pi} \sim 17\%

<table>
<thead>
<tr>
<th>Strip</th>
<th>( \theta_{\text{min}} ) [deg]</th>
<th>( \theta_{\text{mean}} ) [deg]</th>
<th>( \theta_{\text{max}} ) [deg]</th>
<th>( \Delta \theta ) [deg]</th>
<th>( \Omega ) [srad]</th>
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<td>125.4</td>
<td>127.5</td>
<td>4.0</td>
<td>0.046</td>
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<td>129.6</td>
<td>131.8</td>
<td>4.3</td>
<td>0.046</td>
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<tr>
<td>5</td>
<td>131.8</td>
<td>134.0</td>
<td>136.4</td>
<td>4.6</td>
<td>0.045</td>
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<td>138.7</td>
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<td>156.3</td>
<td>5.1</td>
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<tr>
<td>0</td>
<td>156.3</td>
<td>158.8</td>
<td>161.3</td>
<td>5.1</td>
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</tr>
<tr>
<td>Tot</td>
<td>123.5</td>
<td>142.4</td>
<td>161.3</td>
<td>37.8</td>
<td>2.2</td>
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DOPPLER CORRECTION OF GAMMA SPECTRA

Simulated FWHM @ 1332 keV as a function of the polar ($n\theta$) and azimuthal ($n\varphi$) segmentation

- annular particle detector at 8.5 cm from the target with $\Delta \Theta = 35^\circ$
- $^{60}\text{Ni}$ nuclei scattered on a 1 mg/cm$^2$ $^{208}\text{Pb}$ target
DOPPLER CORRECTION OF GAMMA SPECTRA

FWHM@1200 ~11 keV
THE SPIDER - GALILEO SETUP

GALILEO

LaBr$_3$:Ce

SPIDER
Event structure:
- Detector id 1
  - Energy
  - Timestamp
  - Time
- Detector id 2
  - ...

Selected events:
- One or more particles
- One or more gammas
- Particles gammas coincidences

Data analysis:
- Particle and gamma singles spectra
- Gamma-Gamma
- Particle-Gamma
- Particles-Gamma-Gamma
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ACQUISITION SYSTEM
6 experiments approved in the last three years, 4 already performed

- **58Ni (approved)**
  - SP: M. Rocchini, A. Nannini, K. Hadynska-Klek

- **116Sn (performed)**
  - SP: M. Siciliano, A. Illana, M. Saxena

- **66Zn (performed)**
  - SP: K. Hadynska-Klek, M. Rocchini

- **94Zr (performed)**
  - SP: D. Doherty, M. Rocchini, M. Zielinska

- **96Zr (approved)**
  - SP: D. Doherty, N. Marchini, M. Zielinska

- **130Xe (performed)**
  - SP: A. Nannini, P. Napiorkowski, M. Rocchini

- **116Sn (performed)**
  - SP: K. Hadynska-Klek, M. Rocchini

- **66Zn (performed)**
  - SP: K. Hadynska-Klek, M. Rocchini

- **58Ni (approved)**
  - SP: M. Rocchini, A. Nannini, K. Hadynska-Klek
6 experiments approved in the last three years, 4 already performed

**Shapes of 0+ States and Collectivity in $^{130}$Xe for Studies of $^{130}$Te ββ-decay**

Spokesperson(s): A. Nannini, P. Napiorkowski, M. Rocchini

On-line data sorting partial statistics
First Experiment: Collectivity of $^{66}$Zn
Spokespersons: M. Rocchini, K. Hadynska-Klek

- Commissioning: $B(E2; 2^+_1 \rightarrow 0^+_1)$ and $Q(2^+_1)$ known with high precision.
- New physics:
  - Shape of $0^+_2$? $B(E2)$ value unknown
  - Is the $2^+_2$ high-collective or not? Discrepant values for its lifetime
  - Is the $4^+_1$ collective or not? Discrepant values for the $B(E2; 4^+_1 \rightarrow 2^+_1)$
- Beam: $^{66}$Zn (240 MeV, 1 — 1.5 pnA)
- Target: 1 mg/cm$^2$ of $^{208}$Pb
First Experiment: Collectivity of $^{66}$Zn
Spokespersons: M. Rocchini, K. Hadynska-Klek

- Data already available in the literature confirmed, sufficient precision to distinguish between discrepant values achieved

<table>
<thead>
<tr>
<th></th>
<th>Present</th>
<th>NDS</th>
<th>M. Koizumi et al., 2003</th>
<th>K. Moschner et al., 2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B(E2; 2_1^+ \rightarrow 0_1^+)$ [W.u.]</td>
<td>17.5(10)</td>
<td>17.5(4)</td>
<td>18.2(11)</td>
<td>17.4(3)</td>
</tr>
<tr>
<td>$Q_s(2_1^+)$ [efm$^2$]</td>
<td>+24(9)</td>
<td>+24(8)</td>
<td>+24(8)</td>
<td></td>
</tr>
<tr>
<td>$B(E2; 4_1^+ \rightarrow 2_1^+)$ [W.u.]</td>
<td>8.1(12)</td>
<td>18(3)</td>
<td>17.5(7)</td>
<td>8.4(15)</td>
</tr>
<tr>
<td>$B(E2; 2_2^+ \rightarrow 2_1^+)$ [W.u.]</td>
<td>35(13)</td>
<td>330(130)</td>
<td>41(14)</td>
<td></td>
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</tbody>
</table>

- First measurement of $B(E2)$ values from $0_2^+$: $B(E2; 0_2^+ \rightarrow 2_1^+) = 3.1(11)$ W.u., $B(E2; 0_2^+ \rightarrow 2_2^+) = 1.6(6)$ W.u. ($\tau = 3.9(13)$ ps)

- First measurement of shape parameters for the $0_1^+$: $\langle \beta \rangle = 0.224(6)$, $\langle \gamma \rangle = 45^\circ(5^\circ)$
Probing collectivity and configuration coexistence in $^{94}$Zr
Spokespersons: D. Doherty, M. Rocchini, M. Zielinska

- Recent state-of-the-art Monte Carlo shell model calculations* predict shape coexistence in Zr isotopes.
  *T. Togashi et al., PRL 117, 17252 (2016).

- Observation* of a strong $2^+_2 \rightarrow 0^+_2$ transition (19 W.u.) suggests a deformed band built on $0^+_2$

- Beam: $^{94}$Zr (370 MeV, 1 — 1.5 pnA)
- Target: 1 mg/cm$^2$ of $^{208}$Pb
- Six 3”X3” LaBr$_3$:Ce used for the first time in COULEX @LNL
Probing collectivity and configuration coexistence in $^{94}$Zr

Spokespersons: D. Doherty, M. Rocchini, M. Zielinska

- Random-background-subtracted $\gamma$-$\gamma$ coincidence spectrum gated on the 382 keV
  
  *A. Chakraborty et al., PRL 110, 022504 (2013).*

- Random-background-subtracted $\gamma$-$\gamma$-particle coincidence spectrum gated on the 382 keV
Shape Coexistence in the Tin isotopic chain: Coulomb Excitation measurement of $^{116}\text{Sn}$
Spokespersons: M. Saxena, M. Siciliano, A. Illana

- The semi-magic Sn isotopes represent a good case to study shape coexistence
- Within Sn isotopes $^{116}\text{Sn}$ intriguing position $Z=50$, $N=66$
- Discrepant values for the $2_{1}^{+}$ quadrupole moments in the literature

- Beam: $^{58}\text{Ni}$ @ 180 MeV 4 pnA, continuous
- Target: $^{116}\text{Sn}$ 1 mg/cm$^2$ $^{12}\text{C}$ backing
- Setup: GALILEO (25 HPGe) 6 LaBr$_3$ SPIDER

- **Target excitation**: kinematics reconstruction needed
Workshop at the INFN Legnaro National Laboratories (25-26 March 2019)

Five LoI for Coulex with AGATA - SPIDER presented

Why AGATA?

- Better Energy resolution
- Better Efficiency
- Higher granularity

better Doppler correction for peak identification
To increase sensitivity to Qs and EM signs → Use of an additional forward angles particle detector f.i. four ring of SiPM
SPES - BEAMS

$p (40 \text{ MeV}) + ^{238}\text{U}$

200 $\mu$A

Cs, Ba, ...
VERY intense, pure

Sn, Sb, Te
VERY intense, pure

Ga, Ge ...
intense, pure

Rb, Sr, ...
VERY intense, pure

200 $\mu$A (pps)  5 $\mu$A DAY0

$> 10^{11}$  - $10^{10}$
$10^{10} - 10^{11}$  - $10^{10}$
$10^{9} - 10^{10}$  - $10^{9}$
$10^{8} - 10^{9}$  - $10^{8}$
$10^{7} - 10^{8}$  - $10^{7}$
$10^{6} - 10^{7}$  - $10^{6}$
$10^{5} - 10^{6}$  - $10^{5}$
$10^{4} - 10^{5}$  - $10^{4}$
$10^{3} - 10^{4}$  - $10^{3}$
$10^{2} - 10^{3}$  - $10^{2}$
$10^{1} - 10^{2}$  - $10^{1}$
$< 10$  - $< 10$
SPES International Workshop: 47 Letter of Intents

- Ground States Properties
- Nuclear Moments
- Direct Reaction with ActiveTarget
- Direct Reaction with Si Detectors
- Multinucleon Transfer
- Coulomb Excitation
- Collective excitation
- Fusion
- Super Heavy
- Dynamics
SUMMARY AND OUTLOOK

- Coulomb Excitation @LNL with stable beams is on-going
- Near future 2nd phase GALILEO 30 GASP detectors + 10 triple cluster
- Future: AGATA
- Far future: Coulex @LNL with SPES radioactive beams
THANK YOU FOR THE ATTENTION

A. N¹, M. Rocchini¹, K. Hadymska-Klek², N. Marchini¹,³, D.T. Doherty⁴, M. Zielinska⁵, M. Siciliano⁵, A. Illana⁶, M. Saxena², D. Bazzacco⁷,⁸, G. Benzoni⁹, F. Camera⁹,¹⁰, A. Goasduff⁷,⁸, P.R. John¹¹, M. Komorowska², M. Matejska-Minda²,¹², D. Mengoni⁷,⁸, P. Napiorkowski², D.R. Napoli⁶, M. Ottanelli¹, F. Recchia⁷,⁸, P. Sona¹, D. Testov⁷,⁸ and J.J. Valiente-Dobon⁶,

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GALILEO 1st Phase

- 25 HPGe Compton-suppressed detectors (GASP type)
- FWHM (@1332.5 keV) < 2.4 keV
- Efficiency (@1332.5 keV) = 2.1%
- Complete digital DAQ (takes advantage of the developments made for AGATA):
  - Trigger-less mode
  - Typical operational rate ~ 20 kHz/det
  - Common clock synchronization
\[ \langle \beta^2 \rangle = \frac{\sqrt{5}}{q_0^2 \sqrt{2I_1} + 1} \sum_t \langle i \| E2 \| t \rangle \langle t \| E2 \| i \rangle \begin{pmatrix} 2 & 2 & 0 \\ I_i & I_i & I_t \end{pmatrix} \]

\[ \langle \beta^3 \cos(\gamma) \rangle = \frac{\sqrt{35}}{q_0^3 \sqrt{2} \sqrt{2I_1} + 1} \sum_{tu} \langle i \| E2 \| t \rangle \langle t \| E2 \| u \rangle \langle u \| E2 \| i \rangle \begin{pmatrix} 2 & 2 & 2 \\ I_i & I_t & I_u \end{pmatrix} \]
Example: first $2^+$ state in an even-even target nucleus

\[ P \left( 0_1^+ \rightarrow 2_1^+ \right) = F(\theta, E_P) B(E2) \left[ 1 + 1.32 \frac{A_P}{Z_T} \frac{\Delta E}{1 + A_{P/A_T}} Q_s(2^+) K(\theta, E_P) \right] \]

Access to: transition probabilities and spectroscopic quadrupole moments in a model independent way