Light Charged-Particle emission and the Giant Dipole Resonance in highly excited Ce nucleus formed in reactions with different mass entrance channels.

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  1) Light Charged Particle emission mechanism
  2) Pre-equilibrium particle multiplicities and energy loss
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- GDR width as a function of the temperature
- Conclusions
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Physics motivation

- Study of the Light Charged Particle emission mechanism depending on the mass entrance channel (reaction asymmetry) at high excitation energies (150-200 MeV). In particular, study of the LCP emission mechanism in the Compound Nucleus formed with the same excitation energy in the symmetric and asymmetric nuclear reactions.
- Study of the damping mechanism of the GDR as a function of nuclear temperature in the region of 2<T=4 MeV.
### Systems studied

<table>
<thead>
<tr>
<th>System</th>
<th>$E_{\text{Beam}}$ (MeV)</th>
<th>$E_{\text{Beam}}$ (MeV/u)</th>
<th>$E^*$ (MeV)</th>
<th>$v_{CN}$ (cm/ns)</th>
<th>$v_B$ (cm/ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{64}\text{Ni}+^{68}\text{Zn}$</td>
<td>400</td>
<td>6.25</td>
<td>151</td>
<td>1.69</td>
<td>3.48</td>
</tr>
<tr>
<td>$^{64}\text{Ni}+^{68}\text{Zn}$</td>
<td>500</td>
<td>7.61</td>
<td>203</td>
<td>1.88</td>
<td>3.89</td>
</tr>
<tr>
<td>$^{16}\text{O}+^{116}\text{Sn}$</td>
<td>250</td>
<td>15.63</td>
<td>206</td>
<td>0.67</td>
<td>5.49</td>
</tr>
<tr>
<td>$^{64}\text{Ni}+^{68}\text{Zn}$</td>
<td>300</td>
<td>4.69</td>
<td>100</td>
<td>1.46</td>
<td>3.01</td>
</tr>
<tr>
<td>$^{16}\text{O}+^{116}\text{Sn}$</td>
<td>130</td>
<td>8.13</td>
<td>100</td>
<td>0.48</td>
<td>3.96</td>
</tr>
</tbody>
</table>
HECTOR: 8 large BaF$_2$ crystals used for the detection of high energy $\gamma$-rays.

**GARFIELD**: Double stage $\gamma$-E (CsI(Tl)-MSGC) telescopes
In the experiment the angular coverage was 30°-90° in $\gamma$ and 2p in $f$
Charge resolution from Z=1 to Z=28
Typical energy resolution for CsI(Tl) crystal is 3.0% for 5.5 MeV $\alpha$
Identification threshold is 0.9 MeV/u

**PSPPAC**: used for the Evaporation Residues detection covering the angular range 4°-12°.
Time resolution is 800 ps
Detection efficiency is around 100% for Z>10
The active area is 20X20 cm$^2$
**Analysis strategy**

**Study of the LCP spectra**

**Moving fit analysis on multiple angles**

( parameter: $N_1, N_2, T_1, T_2, V_c, a_2,$ and $v_s$ )

**Comparison with statistical code**

in centre of mass system as a prove that only evaporative mechanism is present.

\[
\begin{align*}
\frac{d^2N_2}{d\Omega dE}_{C.M} &= \frac{N_2}{2(\pi T_2 e^{\frac{(E-V_c)}{T_2}})} \\
\frac{d^2N_1}{d\Omega dE}_{C.M} &= \frac{N_1}{4\pi T_1^2} (E - V_c)^e^{-\frac{(E-V_c)}{T_1}} (1 + \alpha_2 P_2 (\cos \theta))
\end{align*}
\]

$N_1, e T_1$ evaporated particles and temperature

$N_2, e T_2$ pre-equilibrium particles and temperature

$V_c$, coulomb barrier; $P_2$, Legendre polynome

\[
\begin{align*}
\frac{d^2N}{d\Omega dE}_{lab} &= \frac{E_{lab}}{E} \left( \frac{d^2N}{d\Omega dE}_{C.M} \right)
\end{align*}
\]

\[
E' = E_{lab} - 2\sqrt{\frac{1}{2}mv_s^2 E_{lab}} \cos \theta_{lab} + \frac{1}{2}mv_s^2
\]

$\theta_{lab}$ angle of emission in the laboratory system

$v_s$ source velocity

**Reference**


**After the correct characterization of the emitting source, it is possible to study the behaviour of the resonance width as a function of the temperature**

**CRUCIAL!!**
Particle spectra

400 MeV$^{64}$Ni + $^{68}$Zn

Moving source fit analysis (only evaporative contribution)

Alpha particles spectra in the centre of mass. In pink – PACE simulations.
Particle spectra

Moving source fit analysis (only evaporative contribution)

500 MeV $^{64}$Ni + $^{68}$Zn

Alpha particles spectra in the centre of mass. In pink – PACE simulations.
Particle spectra

500 MeV $^{64}$Ni + $^{68}$Zn

Possible correction: Simulated pre-equilibrium source

Upper limit of pre-equilibrium

$$E_{loss} = (E_k + E_b)_{n} M_{n}^{PE} + (E_k + E_b)_{p} M_{p}^{PE} + (E_k + E_b)_{\alpha} M_{\alpha}^{PE}$$

TOT. $(6.3 \pm 3.2)$ MeV
$(3.1 \pm 1.6)$

Exp. Data
Evap. Fit
Pre-eq. simulation
Total fit
**Particle spectra**

**250 MeV \(^{16}\text{O} + ^{116}\text{Sn}\)**

Moving source fit analysis (yellow → Ev., black → Pre-eq., red → sum)

Alpha particles spectra in the centre of mass. In pink – PACE simulations.

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**Multiple Energies (°)**

- Black → \(\theta = 74.6°\)
- Red → \(\theta = 60.05°\)
- Green → \(\theta = 46.9°\)
- Blue → \(\theta = 34.7°\)
Particle spectra

Possible correction:
A third source emission to simulate break-up of projectile

<table>
<thead>
<tr>
<th>( \frac{N_3}{N_1 + N_2} )</th>
<th>( V_e ) (MeV)</th>
<th>( T_3 ) (MeV)</th>
<th>( \frac{v_s}{\sqrt{v_{beam}}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>3.4</td>
<td>8.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Particle spectra

400 MeV $^{64}$Ni + $^{68}$Zn

Moving source fit analysis (only evaporative contribution)

Protons spectra in the centre of mass. In violet – PACE simulations.

- Black $\Rightarrow 74.6^\circ$
- Red $\Rightarrow 60.05^\circ$
- Green $\Rightarrow 46.9^\circ$
- Blue $\Rightarrow 34.7^\circ$

Singles (X50)

Double Coinc.

Triple Coinc.
Particle spectra

250 MeV $^{16}$O + $^{116}$Sn

Moving source fit analysis (yellow $\rightarrow$ Ev, black $\rightarrow$ Pre-eq, red $\rightarrow$ sum)

Protons spectra in the centre of mass. In pink – PACE simulations.

Moving Source Pt 250 MeV O+Sn – proton sector 13

DISTRIBUTION PROTONI

Black $\rightarrow$ $\theta = 74.6^\circ$
Red $\rightarrow$ $\theta = 60.05^\circ$
Green $\rightarrow$ $\theta = 46.9^\circ$
Blue $\rightarrow$ $\theta = 34.7^\circ$

Singles (X50)

Double Coinc.

Triple Coinc.
Particle multiplicities and energy loss

Pre-equilibrium proton and alpha multiplicities obtained in our analyses follow the general trend observed from other experimental data. The CN E* is reduced by $\sim 17\%$, $\Delta M$, $\Delta Z \leq 1$.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>LCP</th>
<th>Mevap.</th>
<th>Mpre-eq.</th>
<th>Mtot</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{16}\text{O}+^{116}\text{Sn}$ 250 MeV</td>
<td>p</td>
<td>0.83±0.08</td>
<td>0.25±0.03</td>
<td>1.08±0.09</td>
</tr>
<tr>
<td>$^{16}\text{O}+^{116}\text{Sn}$ 250 MeV</td>
<td>a</td>
<td>0.17±0.02</td>
<td>0.22±0.02</td>
<td>0.39±0.03</td>
</tr>
<tr>
<td>$^{64}\text{Ni}+^{68}\text{Zn}$ 400 MeV</td>
<td>p</td>
<td>0.48±0.05</td>
<td>0</td>
<td>0.48±0.05</td>
</tr>
<tr>
<td>$^{64}\text{Ni}+^{68}\text{Zn}$ 400 MeV</td>
<td>a</td>
<td>0.47±0.05</td>
<td>0</td>
<td>0.47±0.05</td>
</tr>
<tr>
<td>$^{64}\text{Ni}+^{68}\text{Zn}$ 500 MeV</td>
<td>a</td>
<td>0.42±0.05</td>
<td>0.04</td>
<td>0.46±0.05</td>
</tr>
</tbody>
</table>

$E_{\text{loss}} = (E_k + E_b)_{\text{eq}} \left| M_{\nu}^{\text{PE}} + (E_k + E_b)_{\text{pre-eq}} \right| M_{\nu}^{\text{PE}} + (E_k + E_b)_{\text{eq}} \right| M_{\nu}^{\text{PE}}$

$E_k$ average kinetic energy
$E_b$ binding energy
$M_{\nu}^{\text{PE}}$ pre-equilibrium multiplicity
SYMMETRICAL REACTIONS

<table>
<thead>
<tr>
<th>E_{beam} (MeV)</th>
<th>E^* (MeV)</th>
<th>GDR pos (MeV)</th>
<th>GDR width (MeV)</th>
<th>T (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>200</td>
<td>13.6</td>
<td>14.1</td>
<td>3.69±0.15</td>
</tr>
<tr>
<td>400</td>
<td>150</td>
<td>14.0</td>
<td>12.4</td>
<td>2.79±0.10</td>
</tr>
<tr>
<td>300</td>
<td>100</td>
<td>14.0</td>
<td>7.9</td>
<td>1.83±0.05</td>
</tr>
</tbody>
</table>
No saturation of the $\gamma_{\text{GDR}}$ up to 4 MeV

TFM model fits very well the experimental data

Correction for the uncertainty ($\gamma \pm t$) in the lifetime of the CN is needed for temperature $> 2$ MeV

WAITING THE RESULT OF THE ASYMMETRIC REACTIONS!!
The mechanism of the LCP emission was studied for the same Compound Nucleus and E* for the symmetric and asymmetric reactions.

In the symmetric case the LCP emission could be fully characterized as an evaporative (statistical) process. In the asymmetric case a sufficient LCP yield is devoted to the pre-equilibrium process.

Experimentally obtained pre-equilibrium particle multiplicities and energy loss are follow the systematic of J. Cabrera et al., PRC 68(2003)034613.

The analysis of the GDR width as a function of the temperature for the symmetric mass reactions follow a trend well described by the TFM with the correction for the uncertainty in the lifetime of the CN.
Outlook

- Analysis for the last two reactions and for the emitted light fragments (Z>2) has to be completed.
- The GDR analysis for the asymmetric reactions has to be completed.
- New experiments are needed in order to understand the pre-equilibrium emission dependence on the projectile energy.
Participants

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