Study and comparison of the decay modes of the systems formed in the reactions $^{78}\text{Kr}+^{40}\text{Ca}$ and $^{86}\text{Kr}+^{48}\text{Ca}$ at 10 AMeV

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Outline

- The Physics
- The Experimental Method
- First Results
- Conclusions and Perspectives
The Physics

Decay modes of Compound Nuclei with different N/Z

Heavy-ion induced reactions with stable and radioactive beams are ideal to explore the response of nuclei under different stress.

Energy domain $E < 15 \text{ MeV} / \text{A}$ is dominated by fusion processes that can be very complex and largely influenced by different parameters:
- angular momentum, dynamical effect $\rightarrow$ quasi-fission
- structure and N/Z of the system

CN decay modes populate the whole mass (charge) range from evaporated light particles up to the symmetric fission, with the intermediate-mass fragments (IMF) in between.
Various theoretical models have been developed to explain the complex aspects of formation and disintegration mode and to describe the thermal and collective properties that rule the competition between CN decay modes.

- fundamental nuclear ingredients such as the level density, the fission barriers, the nuclear viscosity

N/Z degree of freedom is expected to play a crucial role on these phenomena:

- the level-density parameter is related to the effective mass, a property of the effective nucleon-nucleon interaction that is sensitive to the neutron-proton composition of the nuclei
- the fission barriers depend strongly on the symmetry energy
Example: study of the system $^{78,82}$Kr + $^{40}$Ca at 5.5 MeV/A

Exclusive measurements allow a precise characterization of the different mechanisms originating all the reaction products.

The data with different N/Z give new insights on the influence of the neutron content on decay mechanism.

The ER cross-section and fission like component are higher for neutron poor system.

There is a strong odd-even staggering in fragment yields, slightly dependent on N/Z ratio of the system.

Comparison with models shows signals of a competition between fusion-fission and quasi-fission processes.

G. Ademard et al. PRC 83 (2011) 054619
The Physics

ISODEC experiment proposed by an international collaboration, in the framework of the LEA-Colliga (GANIL,LNS,LNL), spokes

**J.P. Wieleczko GANIL, S. Pirrone INFN-CT**

**M. La Commara Univ. & INFN-Na, G. Politi Univ. & INFN-CT**

\[ ^{78,86}\text{Kr} + ^{40,48}\text{Ca} \rightarrow ^{118,134}\text{Ba}^* \]

\[ E_{\text{Lab}} = 10 \text{ MeV/A} \quad E^* \approx 250 \text{ MeV} \]

Composite system with higher energy and temperature with respect to the previous ones

- Energy influence on staggering effect
- T influence on decay mechanism

Study of staggering with fragment isotopic identification (Z-A)

Larger domain of N/Z (max with stable beam)

comparison with theoretical models for the study of N/Z influence on formation and decay of compound nuclei

The Experimental Method

First Results

Conclusions and Perspectives

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The Experimental Method

Two systems with different characteristics, studied at the INFN - LNS Catania

<table>
<thead>
<tr>
<th></th>
<th>$^{78}\text{Kr} + ^{40}\text{Ca} \rightarrow ^{118}\text{Ba}$</th>
<th>$^{86}\text{Kr} + ^{48}\text{Ca} \rightarrow ^{134}\text{Ba}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E^*(\text{MeV})$</td>
<td>215</td>
<td>270</td>
</tr>
<tr>
<td>$V_B (\text{MeV})$</td>
<td>90</td>
<td>87</td>
</tr>
<tr>
<td>$E_{\text{CM}}/V_B$</td>
<td>2.9</td>
<td>3.5</td>
</tr>
<tr>
<td>$(N/Z)_{\text{tot}}$</td>
<td>1.11</td>
<td>1.39</td>
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System well above Coulomb barrier

Formation of compound nuclei with evaporation/fission

Quasi fission process

Beginning of Multifragmentation phenomenon?
Experimental observables

- Detection of FF-ER, IMF, LCP

- Fragment Isotopic Distribution $3 < Z < 12$
  $E = 8 \div 20 \text{ MeV/A}$ $4^\circ < \theta < 30^\circ$

- Charge identification of FF ($Z < 25$) Tagging of ER ($Z < 50$)

- Energy spectra and angular distribution of reaction products
  FF - ER $E > 2 \text{ MeV/A}$ $4^\circ < \theta < 30^\circ$
  LCP $E > 2 \text{ MeV/A}$ $4^\circ < \theta < 170^\circ$

- Absolute cross section of different decay modes

- Relative velocity and angular correlation $\rightarrow$ time scale

- Coincidence between ER-LCP, FF-LCP, IMF-LCP for reaction mechanism characterization
Experiment performed at INFN-LNS in Catania – ITALY

Beams of $^{78,86}$Kr delivered by Superconducting Cyclotron (i ~ 1 nA) impinging on 1 mg/cm$^2$ $^{40,48}$Ca targets realized by INFN-LNL target service
**CHIMERA device at INFN-LNS in Catania – ITALY**

4π device

1192 Telescopes

Si (300µm) - CsI(Tl)/PD

Forward part 1°<θ<30°

688 modules

9 Rings  100<d<350 cm

Backward part  30°<θ<176°

504 modules

Sphere R=40 cm

Precise measurement of  E, TOF, Velocity, θ/φ

Dedicated electronics and data acquisition for low threshold (~MeV) and high dynamical range
CHIMERA device at INFN-LNS in Catania – ITALY
Identification methods:

Si

CsI(Tl)

E-TOF

A=15

PSD in CsI

H.I.  \(^6\)He  \(^4\)He  \(^3\)He  \(t\)  \(d\)  \(p\)  \(d\)  \(t\)

Csl Slow Low Gain

\(\Delta E/E < 1\%\)

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Identification methods:

E-TOF

A=15

Si

CsI(Tl)

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Identification methods:

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Pulse Shape Discrimination is fundamental in this energy domain for the two stage telescope of CHIMERA

Example of charge identification of reaction products
First Results

Experiment performed in 2010, good performances even at this lower energy with PSD in silicon, data reduction in progress
First Results

Energy spectra in the CM frame for fragments at $\theta = 10^\circ-13^\circ$ for $n$-rich system

Asymmetric shape probably due to contributions of different mass of the same $Z$ $\rightarrow$ indication of isotopic distribution

To be checked and compared with $n$-poor system
Different isotopic composition and relative enrichment for the same Z in the two systems

Mass distribution of different Z for n-rich and n-poor, $\theta = 10^\circ - 13^\circ$
Different isotopic composition and relative enrichment for the same Z in the two systems

Mass distribution of different Z for n-rich and n-poor, $\theta = 10^\circ - 13^\circ$

n-poor\n
n-rich\n
Different yields for the two values of N/Z of entrance channel
Charge Yield for IMF (3 < Z < 12) of n-poor and n-rich, \( \theta = 10^\circ-13^\circ \)

The IMF yield exhibits a strong odd-even staggering, that is more pronounced for the n-poor system
The odd-even effects have been observed in various data sets in a large range of beam energy, sometimes related to N/Z -> staggering decreases for n-rich systems

Ex: $^{40,48}$Ca + $^{40,48}$Ca
at 25 MeV/A with
CHIMERA device
Z and N distributions

*I. lombardo et al.*
*PRC C 84 (2010) 024613*

They can be qualitatively explained by considering the influence of nuclear pairing forces on the last steps of disintegration chain

They can be related also to symmetry energy term by means of some theoretical models

More complex scenario have also been proposed

To be studied also by looking at the isotopic composition
Conclusions and Perspectives

Experiment performed at LNS to study isospin effects on composite system formation and decay modes

Experimental observables and reaction product characteristics

\[ \rightarrow \text{CHIMERA device with optimization at lower energy} \]

Energy spectra in CM frame for some of the fragments

Mass distribution of light fragments different according to the entrance channel

Odd/even effects present in fragment yields, with different amplitude according to N/Z of the system
Data analysis are in progress

Energy spectra for n-npoor

Isotopic distributions for all fragments

Angular distributions

Absolute cross sections calculations

Comparisons with theoretical model predictions to provide important indications on the isospin influence on the reaction mechanism and fragments production

Possible extension to higher value of N/Z

-> use of radioactive beams

LOI presented at SPES2010 to use radioactive beams at INFN-LNL, Kr, Sr, Sn + Ca, Ni - large range of N/Z in entrance channel and compound nuclei: $^{88-92}\text{Kr E/A} = 12 \text{ MeV}$
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