Isospin influence on Fragments production in
$^{78}$Kr + $^{40}$Ca and $^{86}$Kr + $^{48}$Ca collisions at 10 MeV/nucleon

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Outlook

Physics Case

Experimental Method

Main Results
  Reaction Mechanisms
  Fragment Kinematical Features and Charge Distributions
  Reaction Cross Sections
  Comparisons with theoretical models

Conclusions and Perspectives
Physics Case

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

Low energy regime $E < 15 \text{ MeV/A}$ is dominated by Compound Nucleus de-excitation processes in competition with binary processes (DIC, Quasi-Fission)
**Physics Case**

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

Low energy regime $E < 15 \text{ MeV/A}$ is dominated by Compound Nucleus de-excitations in competition with binary processes (DIC, Quasi-Fission).

The isospin is expected to play a crucial role in the reaction dynamics:

**N/Z ratio** can influence:
- Fragments formation
- Reaction mechanisms
- Competition among the different decay channels of the CN
ISODEC Experiment

in the LEA/COLLIGA framework

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

E/A=10 MeV/A

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in the LEA/COLLIGA framework

\( ^{78,86}\text{Kr} + ^{40,48}\text{Ca} \rightarrow ^{118,134}\text{Ba} \)

\( E/A=10 \text{ MeV/A} \)


Comparison with

\( ^{78,82}\text{Kr} + ^{40}\text{Ca} \rightarrow ^{118,122}\text{Ba} \)  INDRA detector at GANIL

\( E/A=5.5 \text{ MeV/A} \)  \( E^* \approx 100 \text{ MeV} \)

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

Composite systems with higher \( E^* \rightarrow \) effects on decay

Larger domain of \( N/Z \), maximum with stable beam
Experimental Method

Key observables: cross sections, multiplicities, angular and energy distributions of different reaction products

Good isotopic resolution, low energy threshold, high angular resolution and acceptance

CHIMERA device
operating at INFN-LNS
Experimental Method

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**CHIMERA device**
operating at INFN-LNS

First measurement with pulse shape discrimination in Silicon detector

Fundamental in this energy regime
Main Results

Reaction Mechanisms

Inclusive events: mass distributions at different angles

Different processes (n-poor)
Main Results

Reaction Mechanisms

Inclusive events: mass distributions at different angles

Different processes (n-poor)
- fusion evaporation channel
  \( A \approx 100 \) very forward angles
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Different processes (n-poor)

- fusion evaporation channel
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- fusion-fission channel
  \( A \approx 40-90 \) wider theta range
Main Results

Reaction Mechanisms

Inclusive events: mass distributions at different angles

Different processes (n-poor)

- fusion evaporation channel
  \( A \approx 100 \) very forward angles

- fusion-fission channel
  \( A \approx 40-90 \) wider theta range

- third component
  \( A \approx 80 \) forward angle

kind of binary mechanism, not completely relaxed in mass -> DIC
DIC mechanism typically observed in plot $\text{TKE} - \theta_{\text{cm}}$

TKE reconstructed from fragment kinematical characteristics
DIC mechanism typically observed in plot TKE – $\theta_{cm}$

TKE reconstructed from fragment kinematical characteristics

Dynamical mechanism with $\text{TKE} > 150 \text{ MeV}$ and small $\theta_{cm}$
DIC mechanism typically observed in plot TKE – $\theta_{cm}$

TKE reconstructed from fragment kinematical characteristics

Dynamical mechanism with TKE > 150 MeV and small $\theta_{cm}$

Relaxed process with TKE ~ 85 MeV for any angle

Value in agreement with a compilation of C. Beck et al. on fission energy release

Analogue results for n-rich system, with DIC even more present
Further information from **Complete Events**

\[ M \geq 2 \quad 0.8 \, M_{CN} \leq M_{tot} \leq 1.1 \, M_{CN} \quad 0.6 \leq \frac{p_{tot}}{p_{beam}} \leq 1 \]

**Correlation between sizes of the two biggest fragments**
Further information from Complete Events

\[ M \geq 2 \quad 0.8 \ M_{\text{CN}} \leq M_{\text{tot}} \leq 1.1 \ M_{\text{CN}} \quad 0.6 \leq p_{\text{tot}}/p_{\text{beam}} \leq 1 \]

Correlation between sizes of the two biggest fragments

Evaporation

Fission Like

ER production seems to be slightly more pronounced in n-poor
Further information from Complete Events

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Correlation between fragment mass and parallel velocity

\[ V_{CN} \quad V_{P} \]
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Correlation between fragment mass and parallel velocity

ER production seems to be enhanced in the n-poor system

Mostly Binary Decay is present in both systems
Fragment Kinematical Features and Charge Distributions

Back to Inclusive normalized data

Average velocities in CM frame for fission fragments (n-poor)

Independent from emission angle and decreasing with Z

\(-\) equilibrated process

Good agreement with Viola-Hinde systematic for fission

Regular behavior slightly disregarded for \(Z>30\), maybe due to the dynamical mechanism contribution
Angular distributions of fragments in CM frame (n-poor)

$1/\sin\theta$ behavior, expected for a production via a long lived system $\rightarrow$ fission like mechanism from equilibrated source
Main Results

Angular distributions of fragments in CM frame (n-poor)

1/\sin \theta \text{ behavior, expected for a production via a long lived system } \rightarrow \text{ fission like mechanism from equilibrated source}

Z > 28 stronger contribution at smaller angles, confirming a not fully equilibrated binary mechanism
Integration of $1/\sin \theta$ angular distribution gives production cross sections for each $Z$. 

![Graph showing production cross sections for different nuclei](image)
Integration of $1/\sin\theta$ angular distribution gives production cross sections for each $Z$

Strong even-odd staggering effect $\rightarrow$ preference for even value of $Z$ the atomic number, because of the larger binding

Staggering more pronounced for the neutron poor system, in particular for $Z \leq 10$

Fragments production globally favored for $n$-poor
Integration of $1/\sin \theta$ angular distribution gives production cross sections for each $Z$

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Charge distribution asymmetric with respect to $Z_{CN}/2=28$

Possible contamination of DIC for heavier fragments even with $1/\sin \theta$ behaviour -> process not fully relaxed in mass
Selection of complete events to get rid of very dissipative binary collisions (TLF not detected)

Cross sections normalized to value for $Z = 18$

**DIC process influence on fragment production starting from $Z > 26$ - 28**
Comparison for n-poor system at 5 MeV/A for Z < 30

Larger cross section at higher energy

Difference decreasing with increasing of Z
Comparison for n-poor system at 5 MeV/A for Z < 30

Larger cross section at higher energy

Difference decreasing with increasing of Z

Lower energy -> favored decay mode is evaporation

Higher energy -> fusion-fission channel prevails on, with a stronger production of fragments
Main Results

**Reaction Cross sections**

Process cross sections deduced from $\sigma(z)$
- Fusion Evaporation - ER: $Z > 41/45$ subtracting FL for heavy fragments
- Fission Like - FL: $Z = 3 - 28/26$ -> corrected for DIC
- Reaction: elastic scattering (quarter point recipe)

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Fusion Evaporation similar in the two systems
Fission Like more present for n-rich systems

Fusion reaction cross sections ($\sigma_{\text{ER}} + \sigma_{\text{FL}}$) in good agreement with a recent systematic study of Eudes et al.
**Main Results**

**Reaction Cross sections**

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**Difference $\sigma_{Reac} - \sigma_{Fus}$ probably due to the DIC, more pronounced for the n-rich system**

**Difference in $\sigma_{FL}$ between n-rich and n-poor higher than in the low energy case, with only 4n difference rather than 16n**
**Comparison with Models**

**Di Nuclear System - JINR Dubna & INP Tashkent**

Dynamical evolution of the composite system is considered

Nucleon exchange drives towards compact configurations:
- CN decaying by evaporation or fission
- DiNuclear system leading to QF

Decay process is then traced until all fragments become cold
Comparison with Models

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S.A. Kalandarov et al. PRC 93 (2016) 024613

Staggering is reproduced

Cross sections are slightly under estimated
Comparison with Models

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Nucleon exchange drives towards compact configurations:
- CN decaying by evaporation of fission
- DiNuclear system leading to QF

Most of the fragments comes from the quasi-fission process, strongly affected by the $J_{\text{max}}$

Underestimation indicates fusion and quasi-fission events also at $b$ larger than in the model
GEMINI++

Statistical model code considering fusion, CN formation, evaporation, fission and sequential binary-decay
GEMINI++

Statistical model code considering fusion, CN formation, evaporation, fission and sequential binary decay

$J_{\text{max}}$ and level density parameter used for DNS

Lower fragments yield, probably due to absence in the model of quasi fission, incomplete fusion, pre-equilibrium
Conclusions and Perspectives

ISODEC Experiment $^{86}\text{Kr} + ^{40,48}\text{Ca} \rightarrow ^{118,134}\text{Ba}$ $E/A=10$ MeV/A

CHIMERA detector at LNS-INFN Catania - LEA/COLLIGA

N/Z ratio and energy effects on reaction mechanisms

Contributions from different reaction mechanisms ER FL DIC

Kinematical characteristics typical of an energy equilibrated system
Charge distributions

Staggering in cross sections

DIC effects $Z>28-30$

More fragments for n-poor and at higher $E$

Process cross sections

Evaporation comparable

Fission more present for n-poor

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Comparison with models

Underestimation of the sigma larger $b$ should contribute

DNS seems to works better

$\rightarrow$ important contribution of quasi-fission events
Further analysis to be done:

- Study of three fragments events and in particular Projectile like Fragment fission, already analyzed at higher energy

- Analysis of Deep Inelastic Contribution as a function of $N/Z$

- Analysis of LCP energy spectra in coincidence with ER and FF

  -> secondary decay, source characteristics (Z. Xiao)

- Refinement of theoretical calculations: comparison with a microscopic transport models to see relation among different mechanisms as a function of impact parameter, possible effect of N/Z ($E_{sym}$)

- Further GEMINI++ calculations for particle energy spectra in order to have information on “a” parameter (P. St-Onge)
Isospin dependence of compound nucleus formation and decay

E. De Filippo INFN Catania - J. D. Frankland GANIL - S. Pirrone INFN Catania
G. Politi Università and INFN Catania - P. Russotto INFN LNS

Study of isospin effects on the reaction mechanisms with RIB delivered by SPES at LNS

- compound nucleus formation and decay
- competition between Statistical and Dynamical Fission

Interest in the intermediate mass: Kr, Cs, Sn beams on Ca Ni Sn
-> broad domain in n/p ratio in entrance and compound system

In particular
- $^{88-94}\text{Kr}$ with $10^5 - 10^7$ pps @ $E/A = 10 - 12$ MeV/A
Thank you all for the attention