

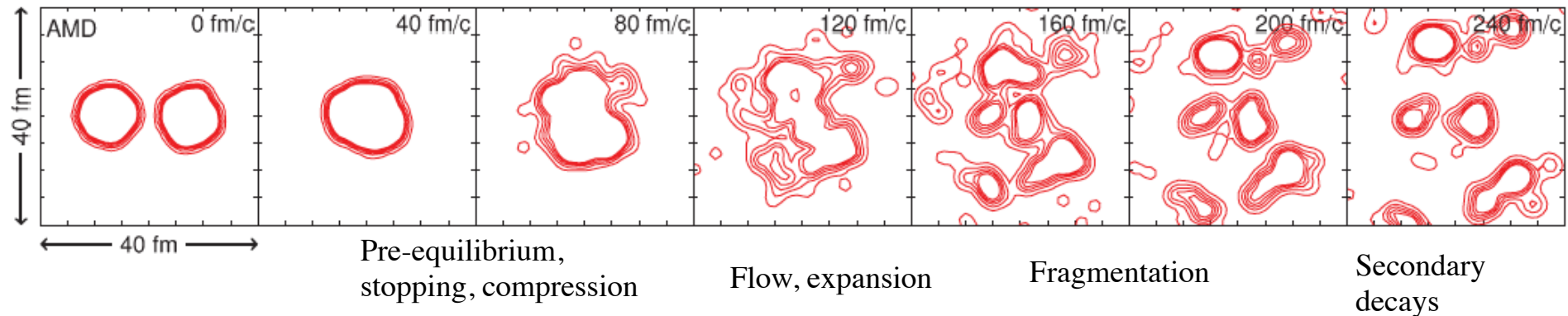
In-medium dynamics in nuclear structure

A. Chbihi (GANIL) & G. Verde (IPNO / INFN-CT)

- Reaction dynamics
- Medium effects on nuclear binding energies (based on generalized RMF approach)
- Isotopic distribution analysis in term of RMF
- Experimental signals of BEC
- Investigation of Hoyle state of ^{12}C
- Experimental perspectives: FAZIA-MUST2@LISE
- Conclusions

Time evolution of HIC at intermediate energies

M. Colonna, A. Ono and J. Rizzo PRC82, 054613 (2010) Typical event of Xe+Sn @ $E/A = 50$ MeV



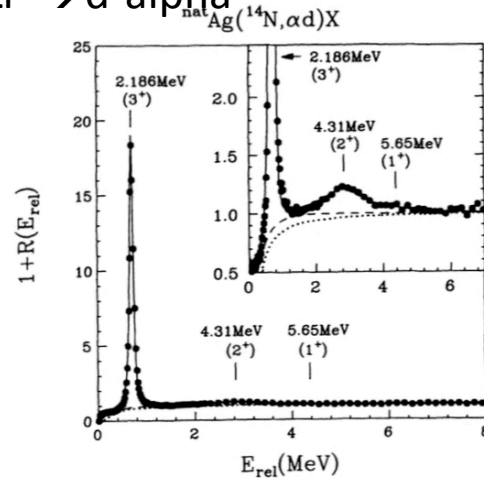
- HIC produce very exotic nuclei during different stages of the reaction
 - ✧ Light clusters dynamically produced at early stage of the reaction
 - ✧ Light clusters at late secondary decay stages as evaporation from excited frag at unbound states.
- HIC scan densities and temperatures comparable to those expected on the neutrinosphere in core collapse supernovae
- What is the effect on in-medium dynamics on the structure properties of nuclei?

Special role of alpha particle and their clustering

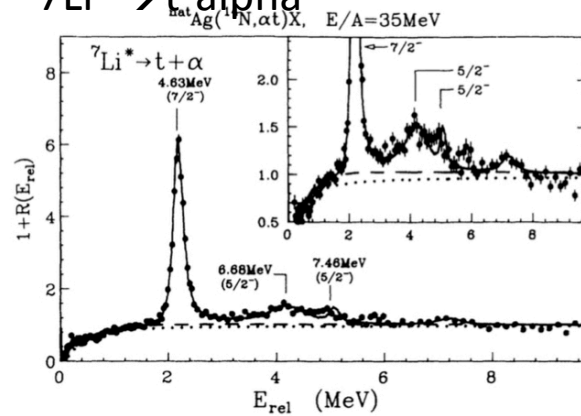
Reconstruction of invariant mass spectra:

Peaks \rightarrow decay of unstable states

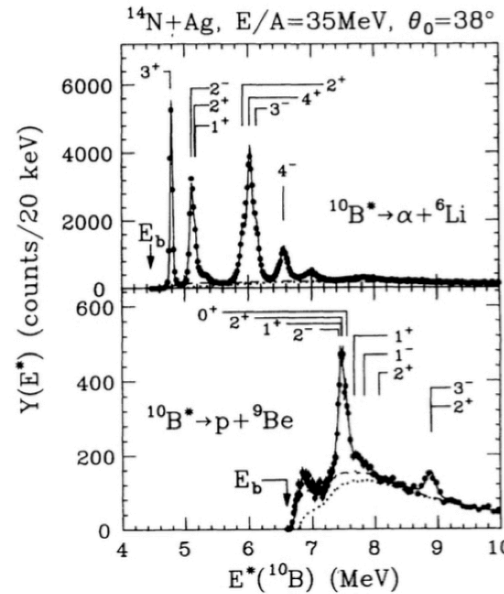
$6\text{Li}^* \rightarrow \text{d-alpha}$



$7\text{Li}^* \rightarrow \text{t-alpha}$

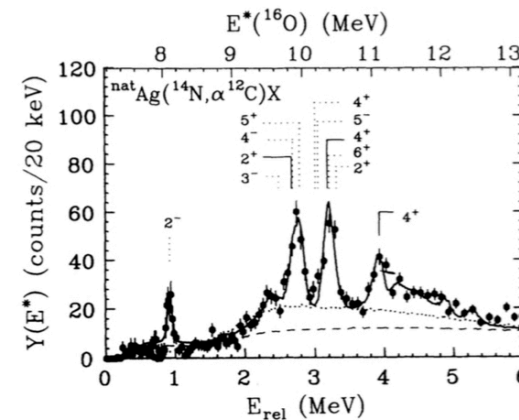


$14\text{N}+\text{Ag}$ @ $E/A=35$ MeV



$10\text{B}^* \rightarrow \text{alpha-Li}$

$10\text{B}^* \rightarrow \text{p}+9\text{Be}$



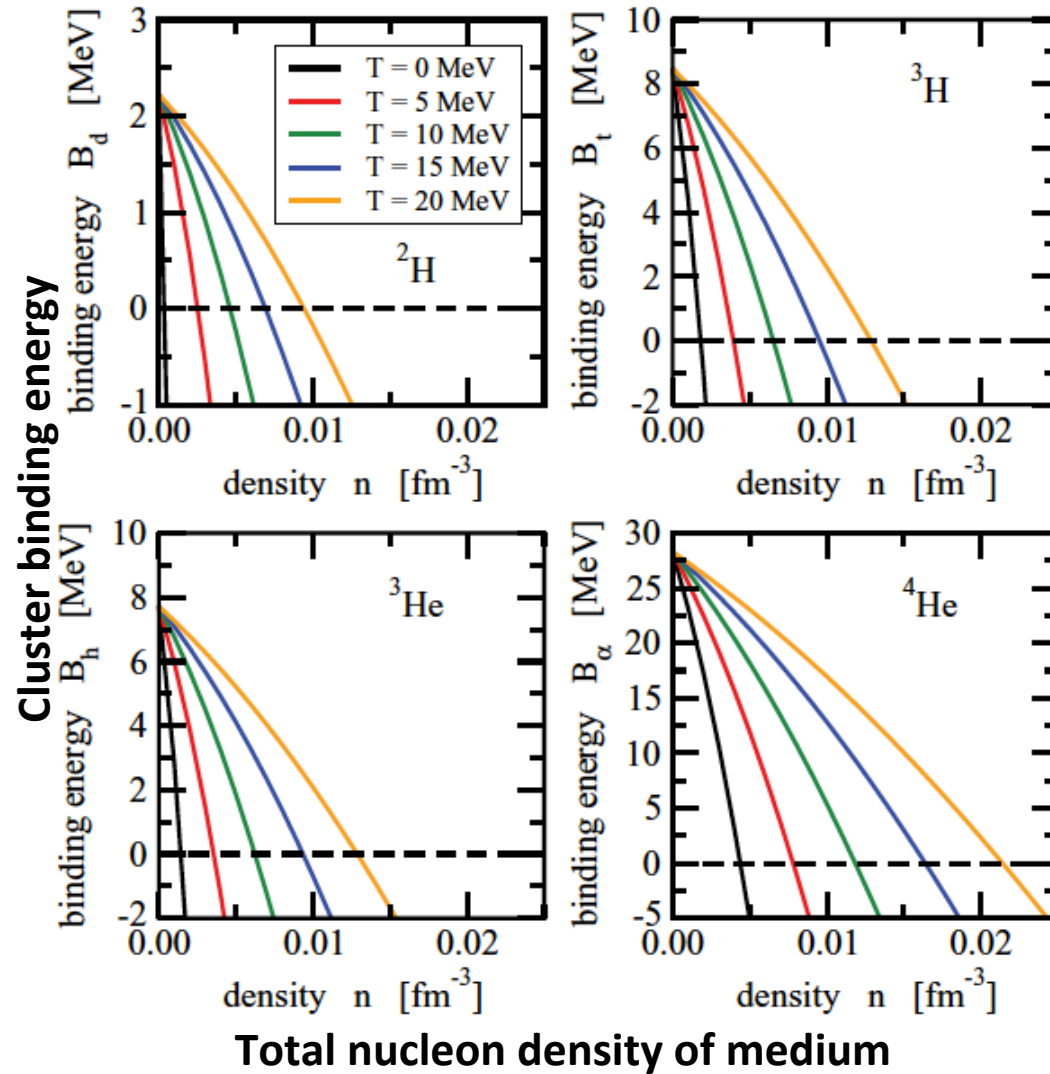
The temperatures of the emitting sources are extracted from relative population of particle-unstable states.

Is structure of these nuclei modified by the medium ?

T.K. Nayak et al., PRC45, 132, 1992

Predictions of in-medium effect on cluster BE

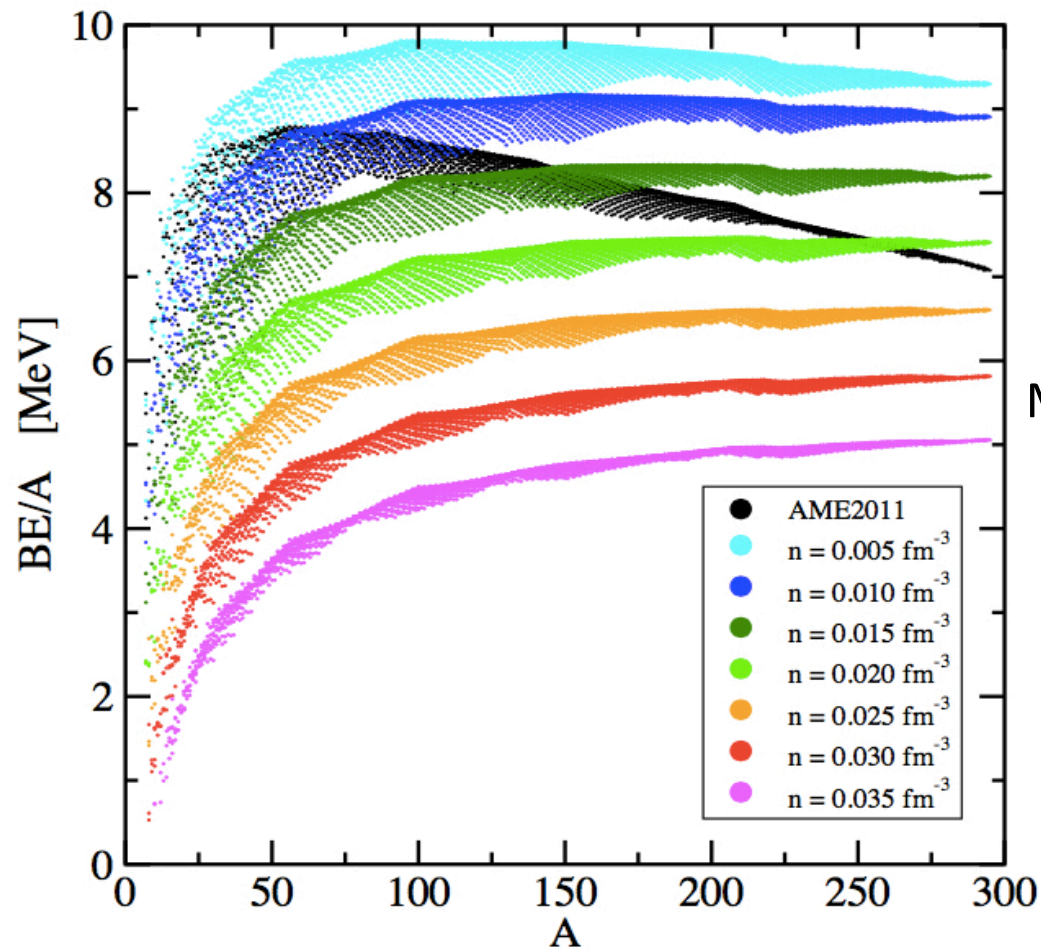
Based on Quantum Statistical and Generalized RMF approaches



- $n \rightarrow 0$, $B_i = \text{experimental } B$
- For the density where cluster becomes unbound, $n(B_i \leq 0)$, density increases with increasing T .
- **modification of cluster properties with change of nuclear medium**

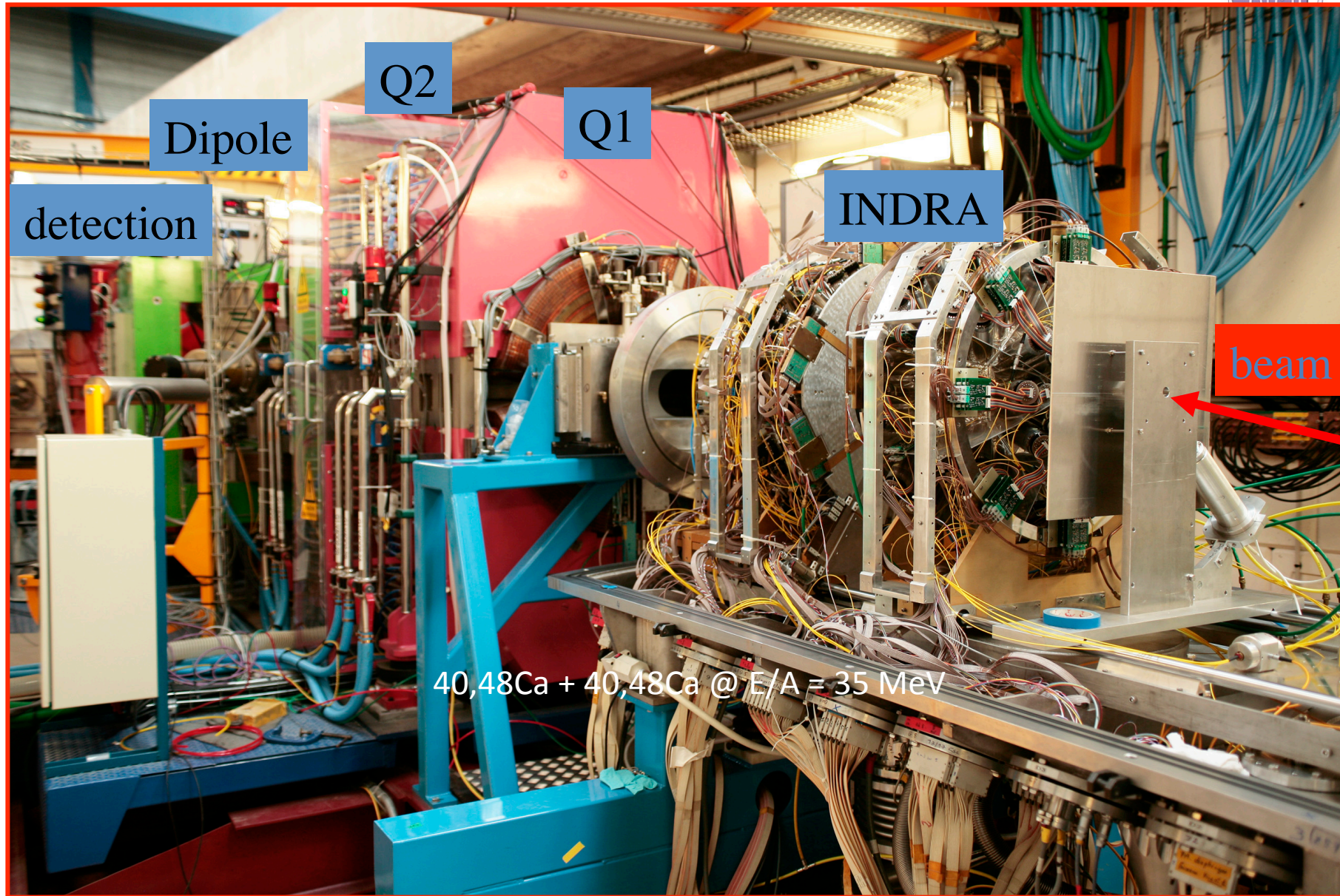
S. Typel et al., PRC81, 015803 (2010)

Predictions of in-medium effect on heavier fragment BE



Modification of BE with densities

S. Typel et al., J of Phys., Conf. Series 420, 012078



$40,48\text{Ca} + 40,48\text{Ca} @ E/A = 35 \text{ MeV}$

VAMOS

PLF (E503) or residues (E494s)

High Isotopic Resolution

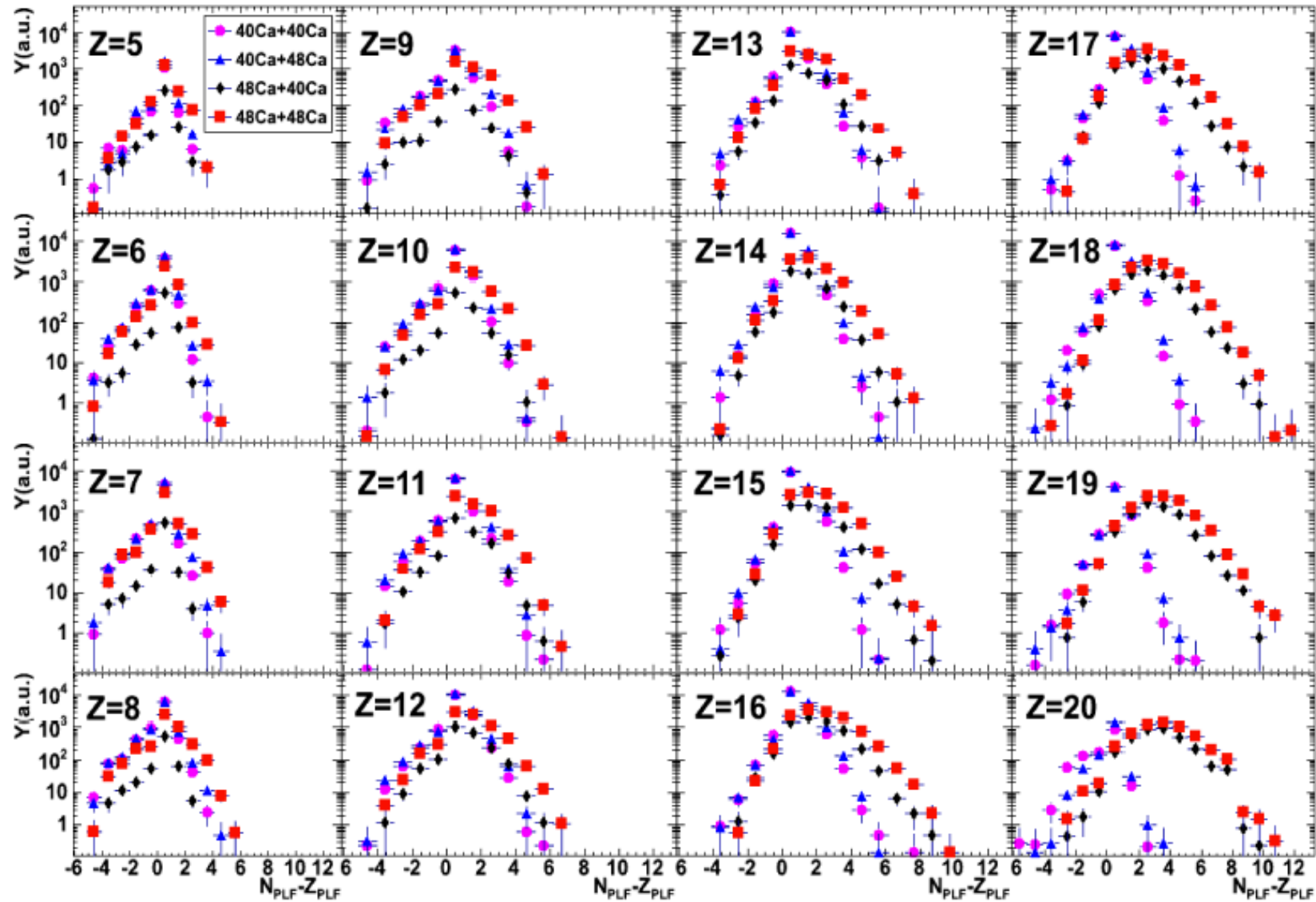
INDRA

beam

*INDRA in coincidence LCP /IMF
event characterization
(b , excitation energy)*

Isotopic distributions of the PLF

For $^{40,48}\text{Ca} + ^{40,48}\text{Ca}$ @ $E/A = 35$ MeV



Constraints on the Generalized RMF

Collaboration with Stefan Typel

Step 1:

- Input density and temperature
- Fit the experimental isotopic distributions
- Result : Density vs temperature distributions for different asymmetric nuclei
not only, the density dependence of E_{sym} can be extracted

Step 2:

- Experimental characterization of nuclear medium will be shown by G. Verde on Friday (femtoscscopy)

Work in collaboration with S. Typel (GSI)



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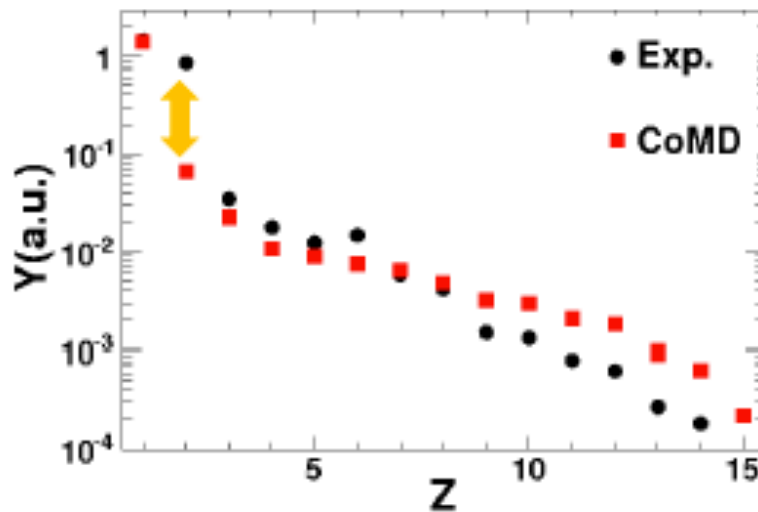
Signals of Bose Einstein condensation and Fermi quenching in the decay of hot nuclear systems



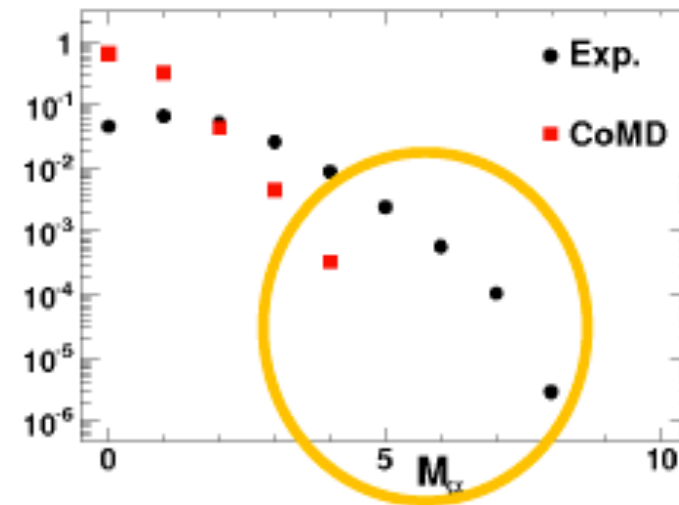
P. Marini ^{a,*,1}, H. Zheng ^{b,c}, M. Boisjoli ^{a,d}, G. Verde ^{e,f}, A. Chbihi ^a, P. Napolitani ^e, G. Ademard ^e, L. Augey ^g, C. Bhattacharya ^h, B. Borderie ^e, R. Bougault ^g, J.D. Frankland ^a, Q. Fable ^a, E. Galichet ^{e,i}, D. Gruyer ^a, S. Kundu ^h, M. La Commara ^{j,k}, I. Lombardo ^{j,k}, O. Lopez ^g, G. Mukherjee ^h, M. Parlog ^{g,l}, M.F. Rivet ^{e,2}, E. Rosato ^{j,k,2}, R. Roy ^d, G. Spadaccini ^{j,k}, M. Vigilante ^{j,k}, P.C. Wigg ^m, A. Bonasera ^{b,c}
(INDRA Collaboration)

Comparison to CoMD

40Ca + 40Ca @ E/A = 35 MeV
 Charge distribution



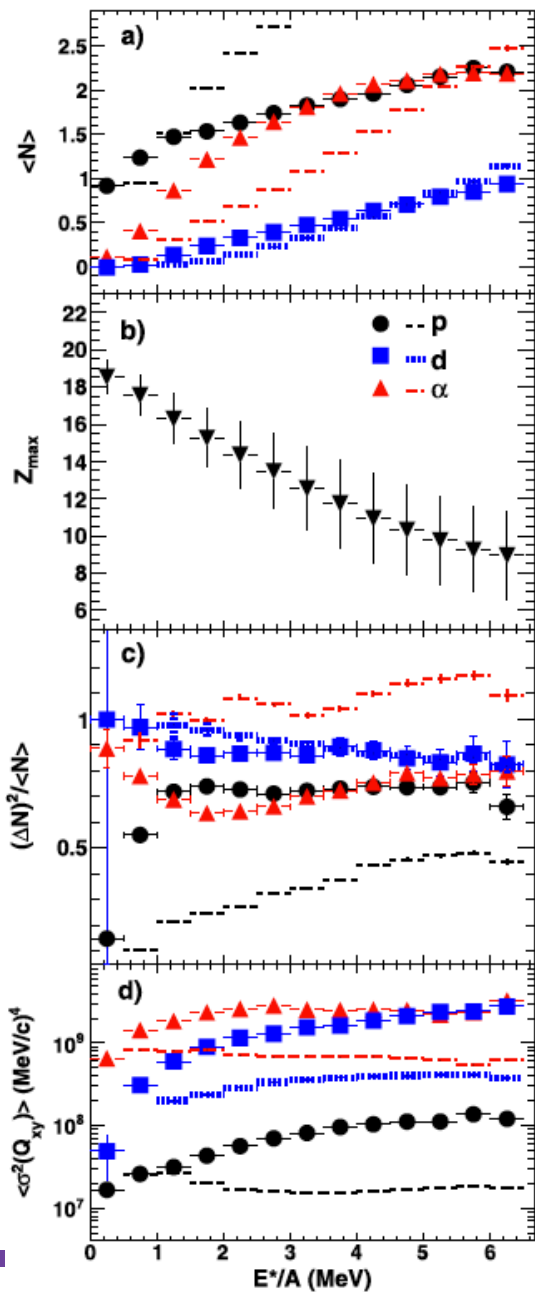
Alpha multiplicity distribution



Cluster formation : Alpha production is underestimated

Do and when bosonic properties dominate over the fermionic properties ?

Observables



multiplicity

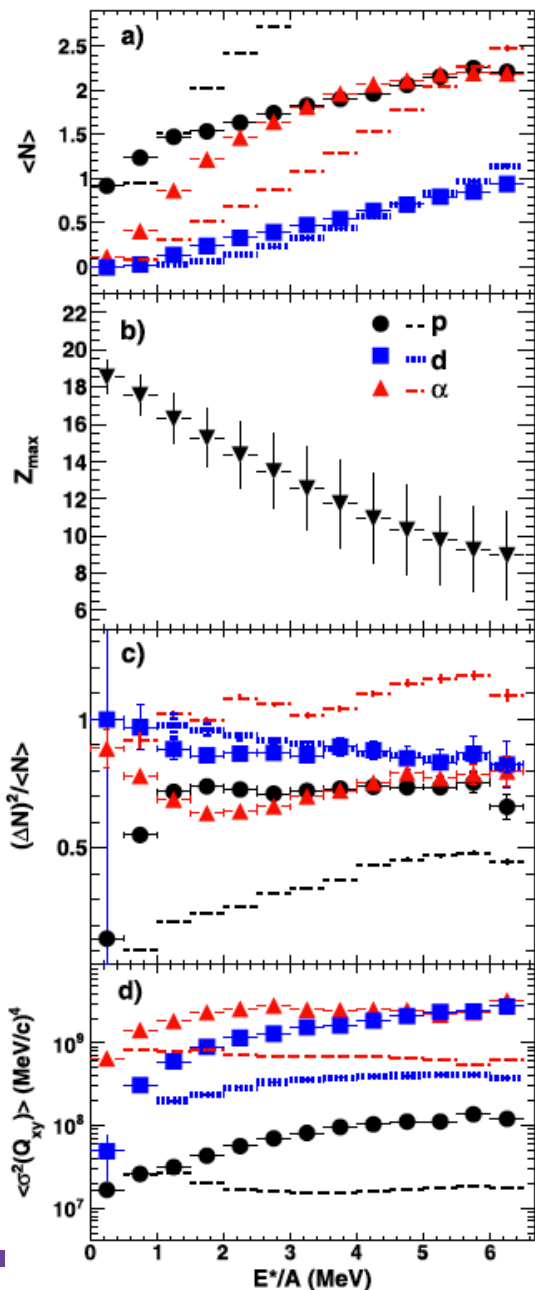
- p
- d
- ▲ α

Z_{\max}

Multiplicity fluctuation

Quadrupole moment fluctuation

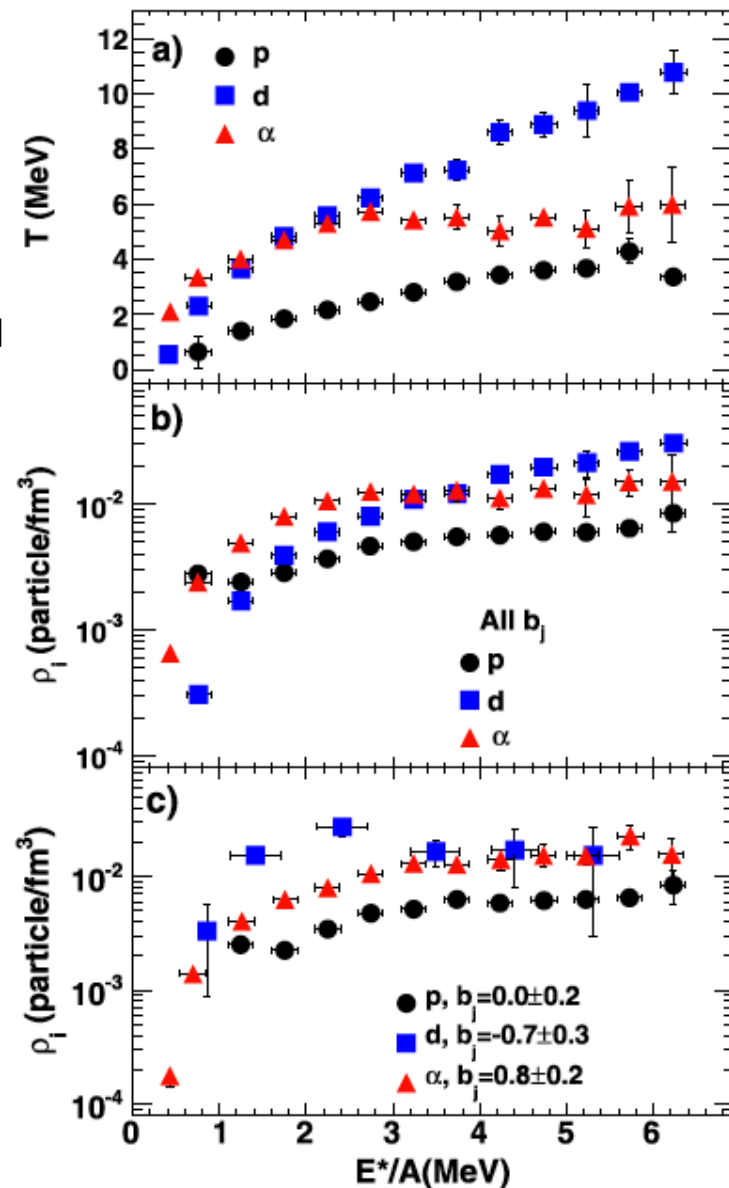
Observables



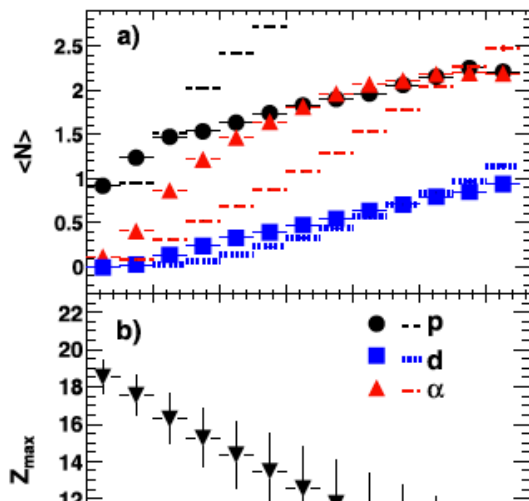
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From Quantum-fluctuation analysis technique
 Local densities of bosons and fermions were extracted

$$\begin{cases}
 \langle N \rangle_i = f_1(T_i, \rho_i, \mu_i) \\
 (\Delta N_i)^2 / \langle N \rangle_i = f_2(T_i, \rho_i, \mu_i) \\
 \sigma^2(Q_{xy})_i = f_3(T_i, \rho_i, \mu_i)
 \end{cases}$$

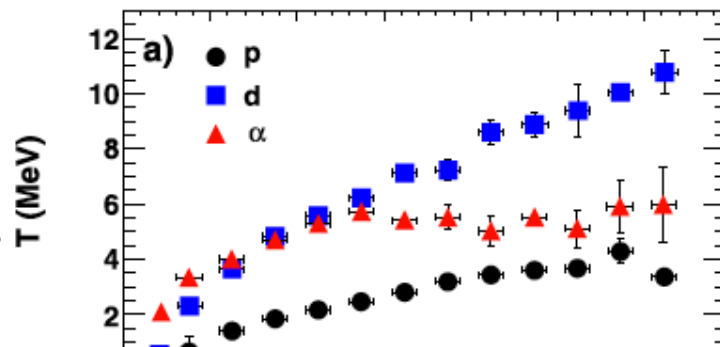


Observables



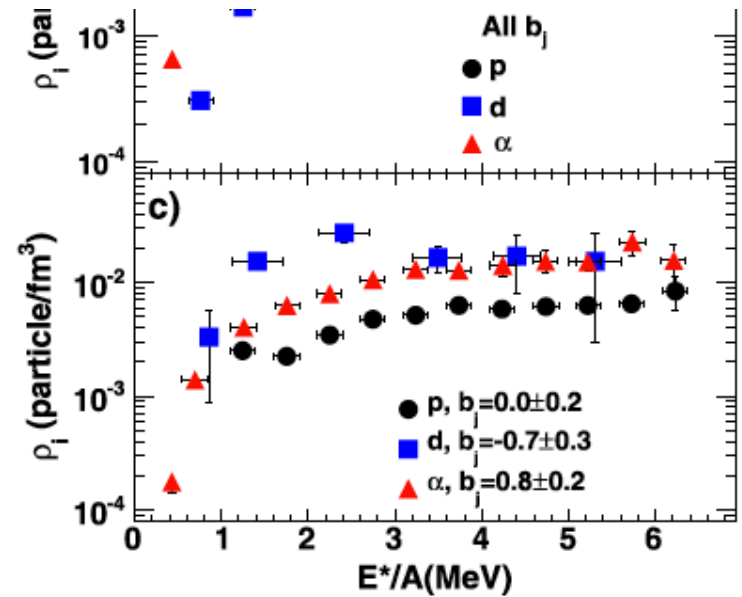
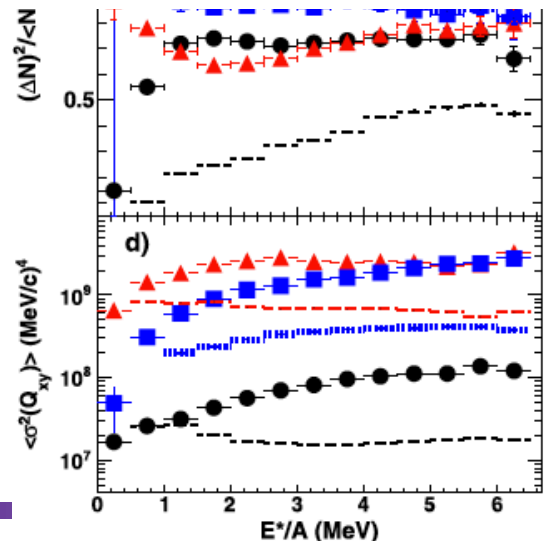
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Quantum-fluctuation analysis technique
 Local densities of bosons and



$\rho_{\text{fermions}} < \rho_{\text{bosons}}$ independently of the presence of fermions in the event

Possible BEC persisting in presence of fermions



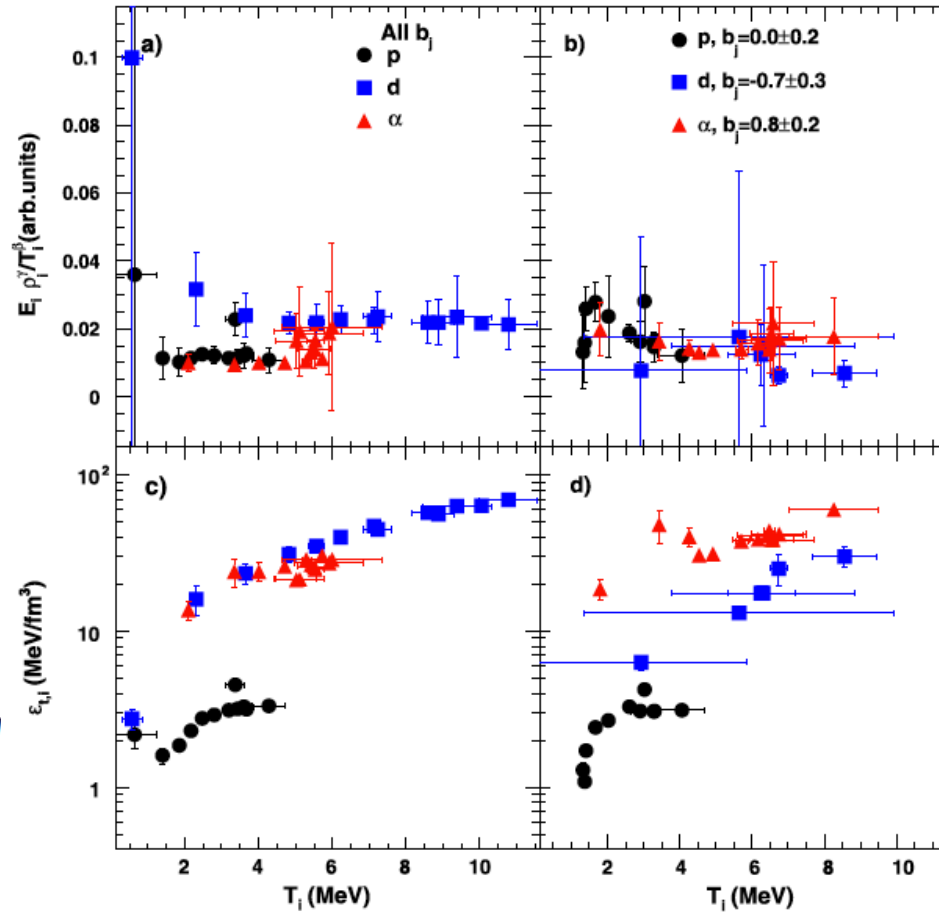
Other signal of BEC

Energy per particle

$$E_i = A_i E^* / A_{QP}$$

Ideal Fermi gas : $E_i \propto T_i^2 / \rho_i^{2/3}$

Ideal Bose gas : $E_i \propto T_i^{5/2} / \rho_i$



Energy density

$$\varepsilon_{t,i} = (E^* + m_i) / V$$

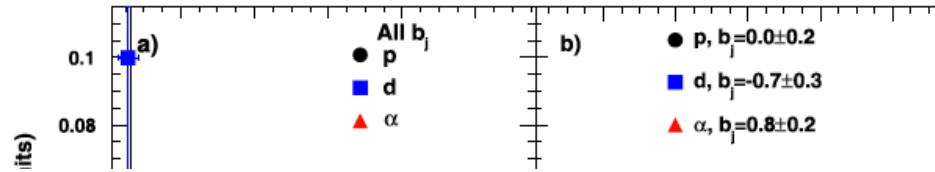
Other signals of BEC

Energy per particle

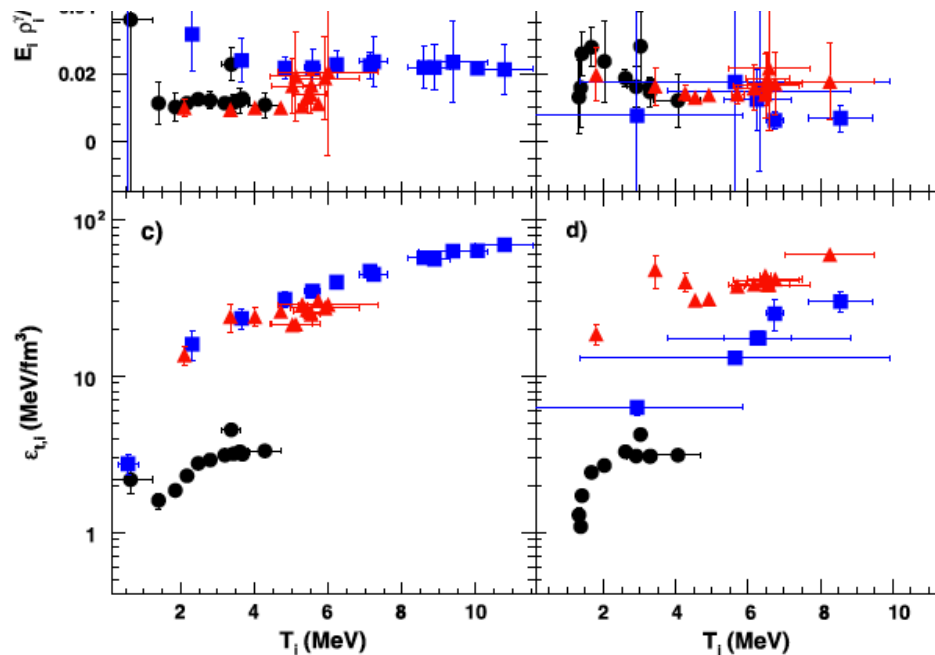
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Ideal Fermi gas : $E_i \propto T_i^2 / \rho_i^{2/3}$

Ideal Bose gas : $E_i \propto T_i^{5/2} / \rho_i$



Different quantum behavior to the density profile



Energy density

$$\epsilon_{t,i} = (E^* + m_i) / V$$

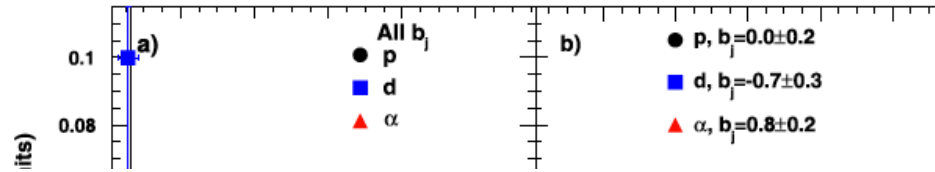
Other signals of BEC

Energy per particle

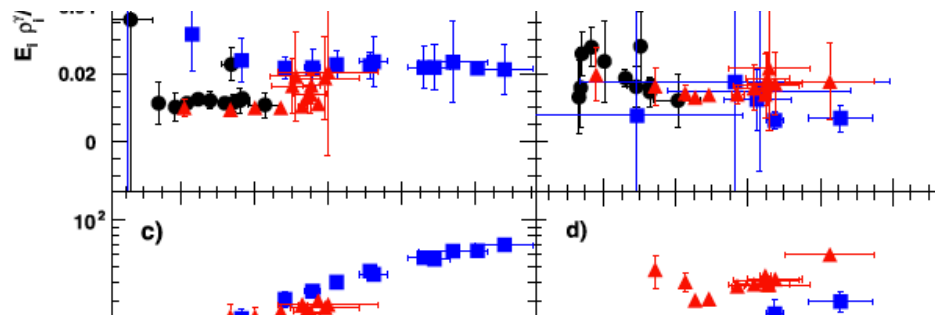
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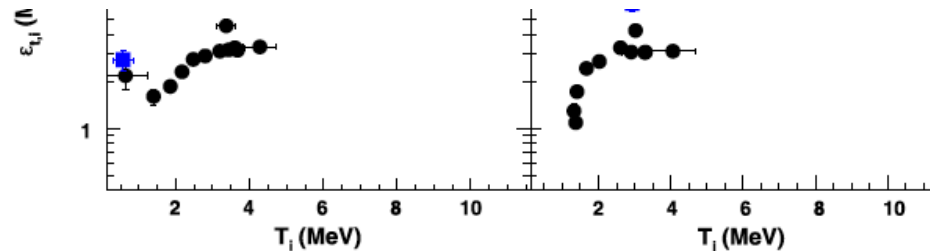


Different quantum behavior to the density profile



Energy **For bosons: high concentration of energy in small volume**

$$\epsilon_{t,i} = (E^* + m_i) / V$$



Direct vs Sequential decay mechanisms of Hoyle state

laboratoire commun CEA/DSM  CNRS/IN2P3

PhD Thesis: Lucia Quattrocchi

Direct vs Sequential decay mechanisms of Hoyle state

PhD Thesis: Lucia Quattrocchi

MONTECARLO SIMULATIONS

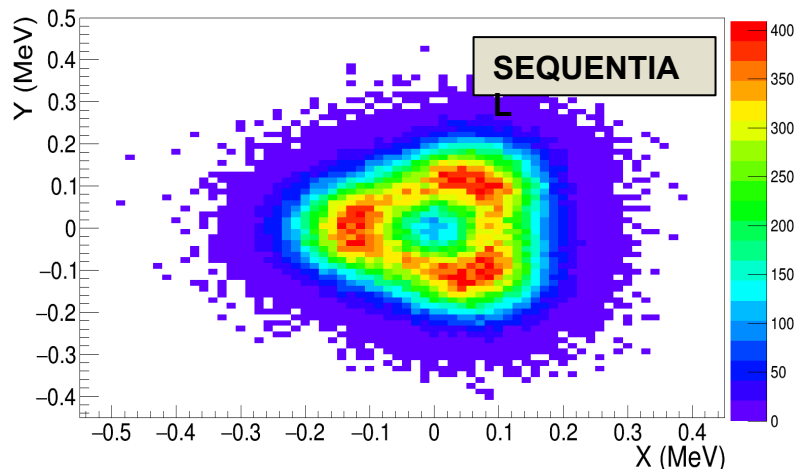
laboratoire de physique nucléaire CNRS/IN2P3

Dalitz parameter

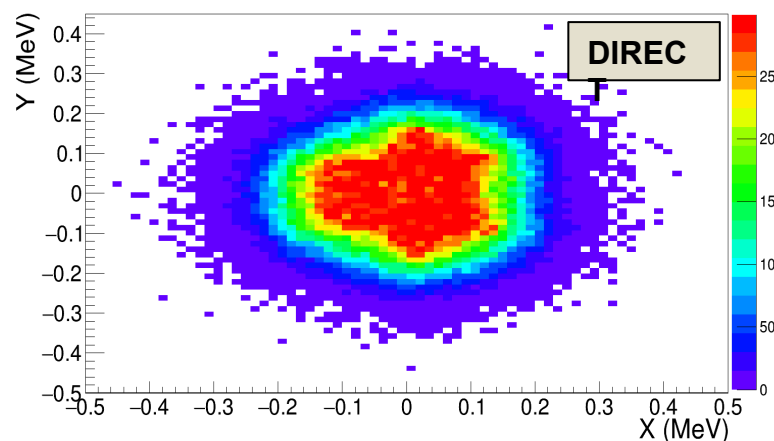
$$x = \sqrt{3}(E_{1CM} - E_{2CM})/3$$

$$y = (2E_{3CM} - E_{1CM} - E_{2CM})/3$$

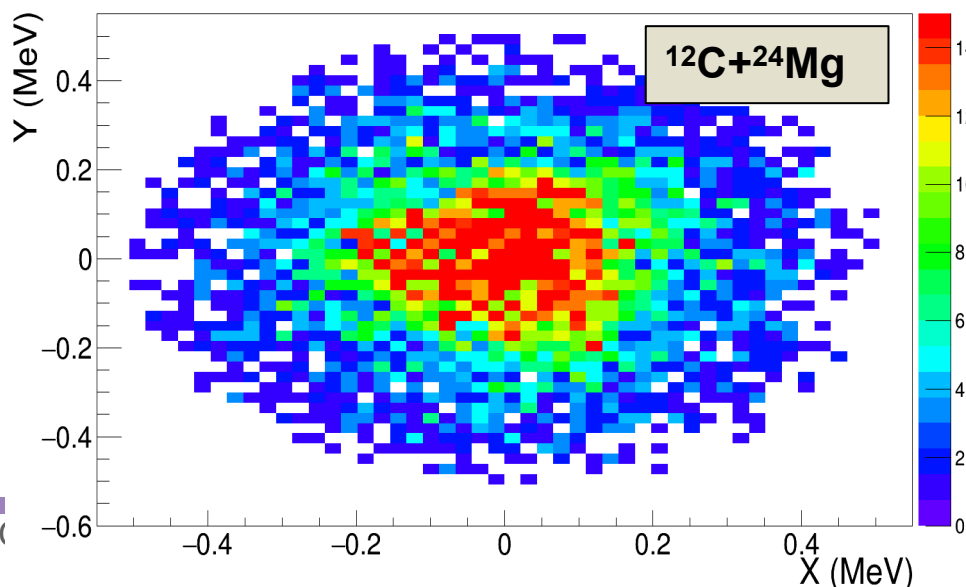
$^{12}\text{C}^* \rightarrow \alpha + ^8\text{Be} \rightarrow 3\alpha$



$^{12}\text{C}^* \rightarrow 3\alpha$



EXPERIMENTAL DATA



The comparison between experimental and simulated data evidences the contribution of a direct mechanism component in decay of the Hoyle state!!

the Hoyle state; component in decay of a direct mechanism

Direct vs Sequential decay mechanisms of ^{12}C resonances

MONTECARLO SIMULATIONS

laboratoire de physique nucléaire CNRS/IN2P3

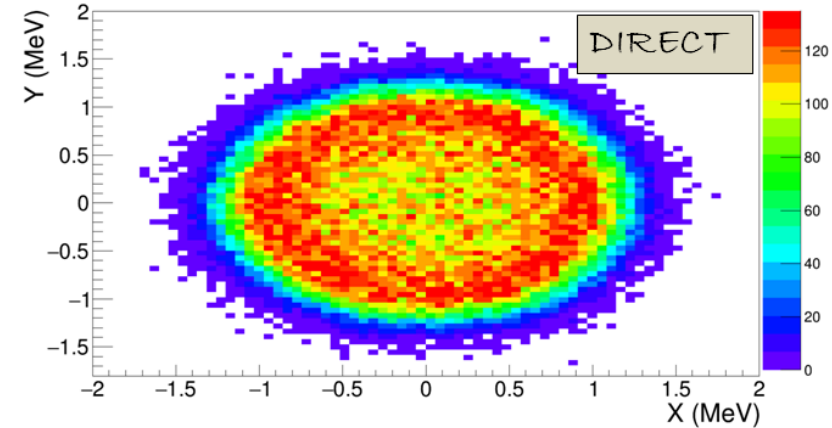
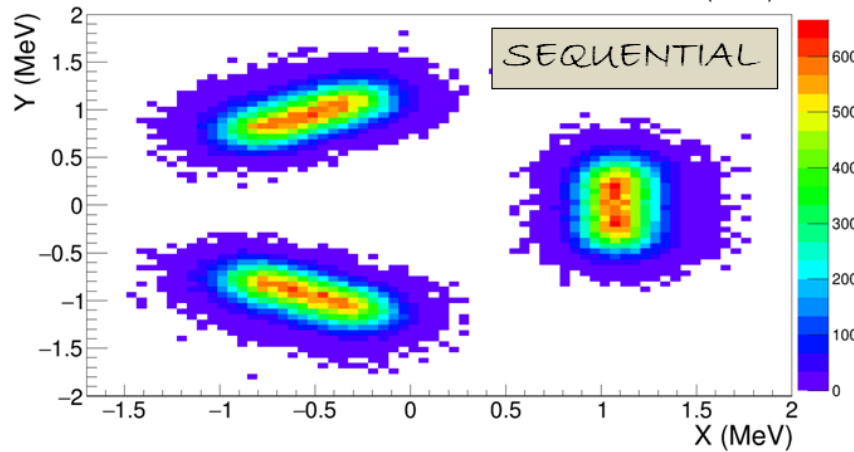
Dalitz parameter

$$x = \sqrt{3}(E_{1CM} - E_{2CM})/3$$

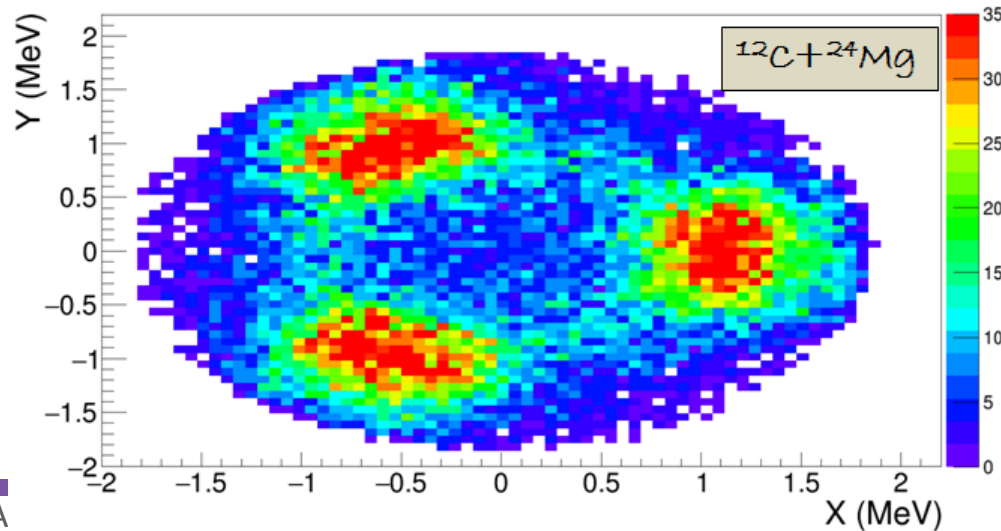
$$y = (2E_{3CM} - E_{1CM} - E_{2CM})/3$$

$^{12}\text{C}^*(9.64 \text{ MeV}) \rightarrow \alpha + ^8\text{Be} \rightarrow 3\alpha$

$^{12}\text{C}^*(9.64 \text{ MeV}) \rightarrow 3\alpha$



EXPERIMENTAL DATA



Dominance of sequential mechanism but direct one is not excluded

EXCJNq6q

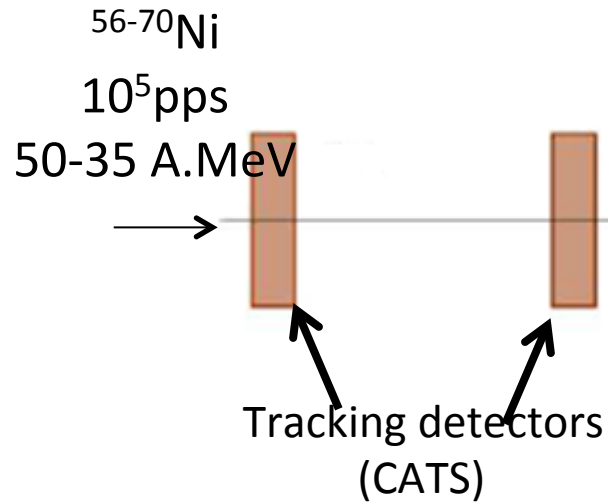
UJ6CUNU2UW D0E 0U6CE 0U6 12 10E

Dynamics and particle-particle correlation studies @ LISE

GANIL
FAZIA/ 12 blocks (192)
2°-14°

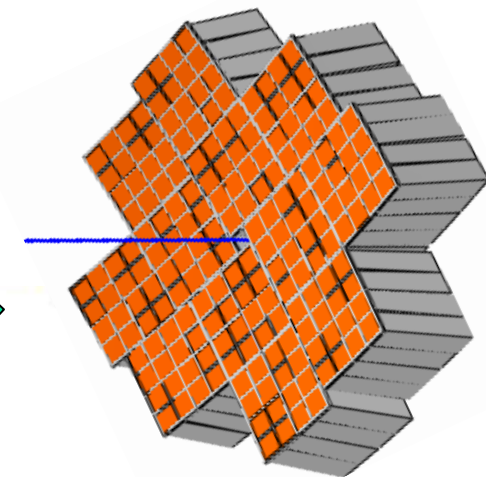
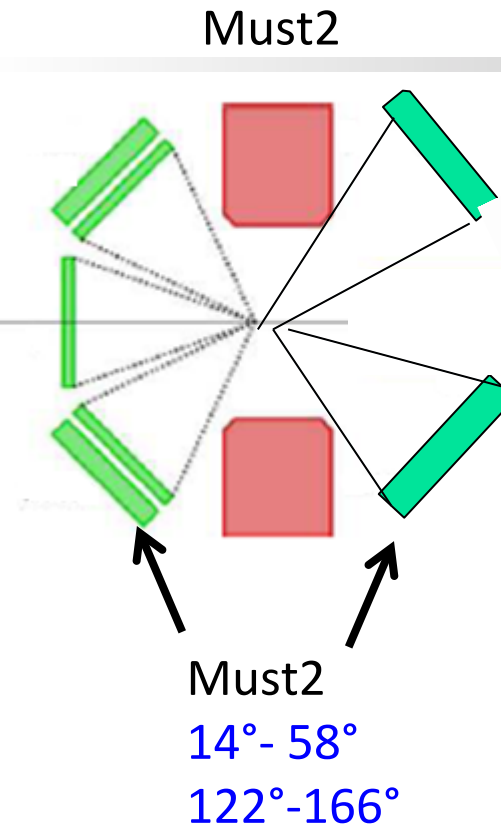
3

Exotic beam from LISE



$$\delta = (N-Z)/A = 0.2, \text{ for } ^{70}\text{Ni}$$

$$\delta = 0.0 \text{ for } ^{56}\text{Ni}$$



- Fazia 2°-14° : isotopic distributions of the PLF in coinc with LCP in Fazia and Must2 provide the primary isotopic distribution $\rightarrow E_{\text{sym}}$.
- Must2 14°- 58° and 122°-166° (it covers the MR region (90° CM)) :
 - ✓ correlation function for space-time characterization of sources
 - ✓ estimation of the density around the projectile and MR
 - ✓ In-medium short-lived nuclei as well as out-of-medium

Perspectives

- Experimental program at LNS4 FAZIA blocks
 - Two experiments accepted will be scheduled in 2016
- FAZIA-INDRA at GANIL : 2017, for experiments in 2018
- FAZIA-LISE 2018-2019

Collaboration France – Italy - Poland

CHIMERA-INDRA

INDRA-VAMOS

FAZIA

LNL GARFIELD

Organization of IWM-EC2016

Organized by CHIMERA-INDRA
 Collaborations
 Every two years

IWM-EC 2016
 9th – 12th May 2016, GANIL, (Caen) France

INTERNATIONAL WORKSHOP ON MULTI FACETS OF EOS AND CLUSTERING

TOPICS

- dynamics & structure in heavy-ion collisions with stable & radioactive beams
- Correlations & clustering phenomena
- isospin effects in nuclear reactions
- isospin & other probes in Nuclear Equation Of State
- nuclear thermodynamics with isospin degree of freedom
- New experimental tools and detection techniques

INVITED SPEAKERS

- Bernardo Boreime**
IPN ORSAY, FRANCE
- Giuseppe Cardella**
INFN SEZIONE DI CATANIA, ITALY
- Przem. Danielewicz**
MSU EAST LANSING, USA
- Franco Fabbri**
IN2P3 PARIS, FRANCE
- Sylvie Hudan**
INDIANA UNIVERSITY BLOOMINGTON, USA
- Stéphane Le Pape**
LPC CAEN, FRANCE
- Thomas Egidio**
GSI DARMSTADT, GERMANY
- Andrey Lebedev**
GANIL CAEN, FRANCE
- William Lovelace**
MSU EAST LANSING, USA
- Roberta Giusi**
TOHOKU UNIVERSITY, JAPAN
- Paolo Pochini**
INFN SEZIONE DI CATANIA, ITALY
- Stefano Spavola / Massimo De Santis**
INFN - LNL LEGNARO, ITALY

SCIENTIFIC COMMITTEE

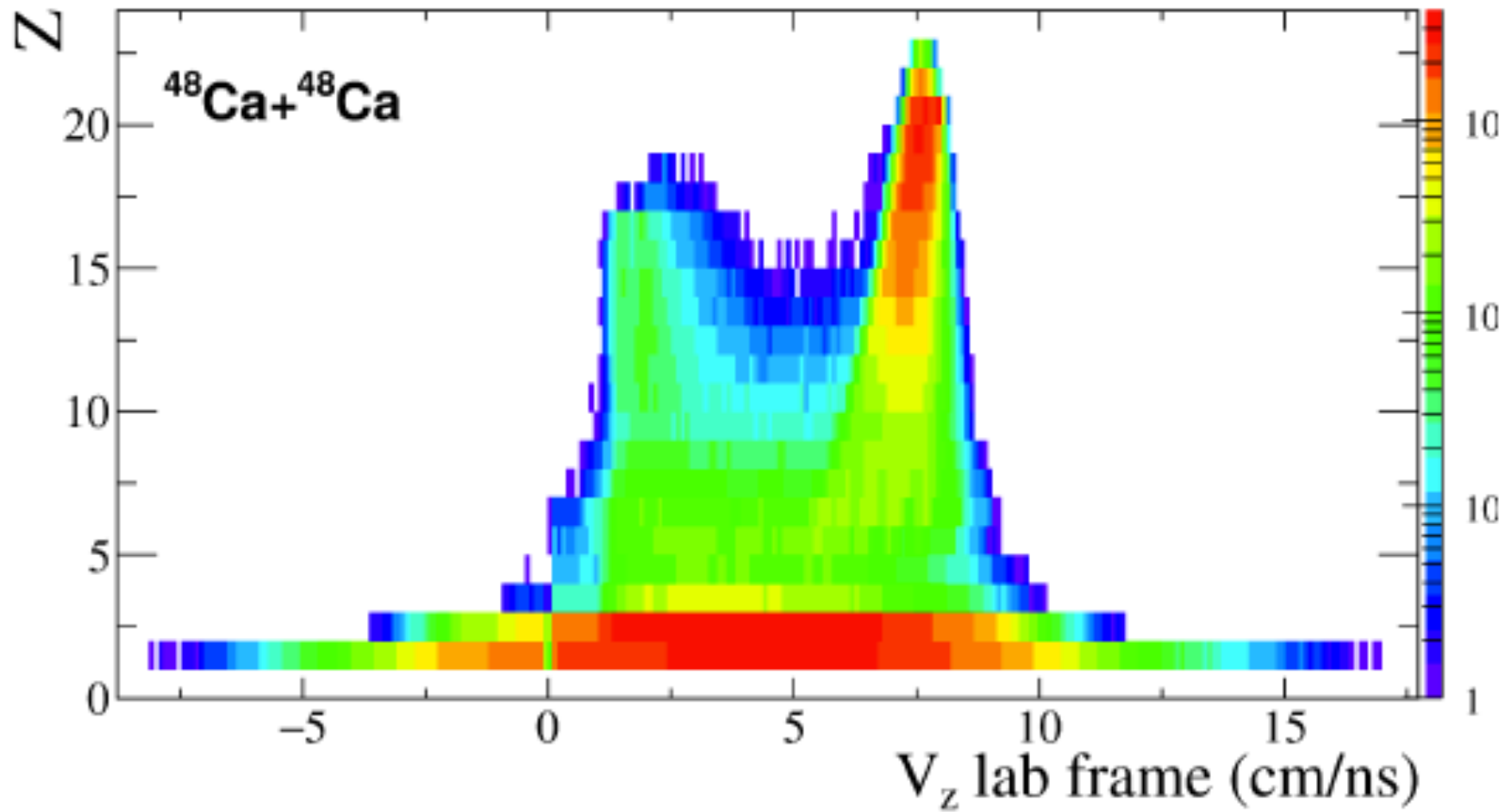
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- Protopopescu Cyprien**
GANIL CAEN, FRANCE
- Environ Laper**
LPC CAEN, FRANCE
- Wang Peng**
TOHOKU UNIVERSITY, JAPAN
- Saba Pradhan**
INFN SEZIONE DI CATANIA, ITALY
- Federico Ricci**
UNIVERSITÀ DI CATANIA & INFN LABORATORI NAZIONALI DEL SUD, ITALY
- Paolo Ruggiero**
INFN SEZIONE DI CATANIA, ITALY
- Protopopescu Theodor**
GSI DARMSTADT, GERMANY
- Giuseppe Verde**
IPN ORSAY & INFN SEZIONE DI CATANIA, ITALY
- Sherry Yennello**
TEXAS A&M UNIVERSITY, USA

LOCAL ORGANIZATION & CONFERENCE SECRETARIAT

- Abdelouahad Chbihi
- Sabrina Lecerf-Rossard
- Marie-Laure Abavent
- Laurent Fortin

CONTACT: iwec2016@ganil.fr
[HTTP://PROSPIC.GANIL.ORG/COLLOQUIA/2016/IWEC2016](http://prospic.ganil.org/colloquia/2016/iwec2016)

Logos at the bottom: CNRS IN2P3, CaenIamer, INFN, GANIL, ENSICAEN, Université de Caen, LPC CAEN, cea, IPN



Temperatures and mean partial densities

Method: quantum fluctuation analysis technique

H. Zheng et al., Nucl. Phys. A 892 (2012) 43; PLB 696 (2011) 178;
PRC 86 (2012) 027602

Ingredients :

- Fermions follow the Fermi statistics and bosons the Bose statistics
- Coulomb repulsion is accounted for

$$\longrightarrow \left\{ \begin{array}{l} \langle N \rangle_i = f_1 (T_i, \rho_i, \mu_i) \\ (\Delta N_i)^2 / \langle N \rangle_i = f_2 (T_i, \rho_i, \mu_i) \\ \sigma^2(Q_{xy})_i = f_3 (T_i, \rho_i, \mu_i) \end{array} \right. \quad \longrightarrow \quad (T_i, \rho_i) \text{ for each particle species } i \text{ from experimental data}$$

T : temperature

ρ : mean partial density

μ : chemical potential