Vaporization event properties to constrain low-density warm matter

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Simulating the Supernova Neutrinosphere with Heavy Ion Collisions
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Vaporization?

- When the system experience high excitation, it explodes in light particles without going through the spinodal region (instability region).
- It can be seen as the asymptotic gas phase of the liquid-gas first order phase transition in nuclei.

- Theoretical prediction: if heated sufficiently, nuclear matter "vaporizes" into nucleons & isotopes of H and He (A<5)

Bondorf et al., PLB162, 30(1985)
Vaporization & phase diagram

Low-density nuclear gas at high temperature

Temperature

Ar+Ni collisions

Density

ONSET OF MULTIFRAG.

FREE GAS

VAPORIZATION

Nuclear Thermodynamics with INDRA

INDRA20ans

15/10/2013
Experimental evidence of vaporization

  - Au+Au system in central collisions
  - Poor reproduction using molecular dynamics calculation

- Experimental observation by the INDRA collaboration
  - 36Ar+58Ni system in central and peripheral collisions
  - Characterization of its properties using QSM (NSE) model
    - Reproduction of cluster yields and mean kinetic energies
    - Check of equilibrium assumption looking at variances
Thermal and chemical equilibrium for vaporizing sources

- clusters up to 6He
- Grand canonical ensemble
- Excited states up to Ne is included
- At E*=18.5 MeV/A, density fixed at \( \rho_0/3 \) to reproduce alpha-proton ratio

Comparison with the predictions of a model describing the properties of a quantum weakly-interacting gas of nuclear species in thermal and chemical equilibrium

From theoretical side

- Low density warm nuclear matter has a renewed interest coming from the need in the description of neutrino sphere region during the core-collapse supernovae (Topical Volume EPJA 50 (2014))
- Data in the subsaturation (rho<rho0) densities region and finite temperature (T<20 MeV) are needed to constrain new developments and approaches in this topic:
  - “In-medium“ nuclear data shift
  - Non homogeneous matter, Gas-Clusters interaction, Surface effects ...
  - Isovector part of the symmetry energy
- The mixing of clusters in a nucleon gas is a particular state which is be reached in HIC, specially in vaporization
  - Yields of bound clusters are the straightforward observables in NSE models which can be extracted in experimental data

see Ad. Raduta, S. Typel talks
Vaporization process in the framework of neutrino sphere calculation

- Evolution with excitation energy of the composition of cluster yields
- Final clusters produced by one source, event by event properties, statistical ensemble
- Good reproduction using QSM which assume thermodynamical equilibrium in grand canonical ensemble.
- Give sense to the definition of temperature, density
- Further comparison with available models can be done
58Ni+58Ni collisions studied with INDRA@GANIL

- Beam energies: 32, 40, 52, 64, 74, 82, 90 MeV/A
- Focus on the Quasi-Projectile vaporization in light charge particles from proton up to Be isotopes.
- Focus on the forward hemisphere and keep only events with clusters up to Be
2D velocity space for 58Ni+58Ni@90MeV/A

Only the forward hemisphere is used where full isotopic resolution is achieved

Transverse direction

H isotopes

CM velocity

Beam direction
2D velocity space for 58Ni+58Ni@90MeV/A

Transverse direction

He isotopes

Beam direction
2D velocity space for 58Ni+58Ni@90MeV/A

Transverse direction

Li isotopes

Beam direction
2D velocity space for 58Ni+58Ni@90MeV/A

Transverse direction

Be isotopes

Beam direction
Calorimetry and event sorting

- We kept only events where total detected charge (Ztot) is greater than 90% of the Ni: 
  \[ Z_{\text{tot}} \geq 0.90 \times 28 \]

- To sort events, we choose the excitation energy \( E^* \) obtained by calorimetry (energy balance):
  \[ Q_s + E^* = \text{Sum} \left( E_k + Q \right)_{\text{charged}} + Mn(En+Qn) \]

- Concerning the undetected neutrons:
  - As all charged products are isotopically resolved, the neutron multiplicity (Mn) is deduced directly by the mean of mass conservation:
    \[ Mn = \frac{58}{28} \times Z_{\text{tot}} - A_{\text{tot}} \]
  - The estimation is made using the Fermi gas relation between temperature and excitation energy: \( E^*/A = aT^2 \) (\( a = 1/10 \) MeV\(^{-1}\))
  - We assume volume emission in the Boltzmann statistics: \( En = 3/2T \)

- For the “temperature-addict”, using calorimetry, temperature is obtained for free
58Ni+58Ni: cross section of vaporization events

Measured cross section = 137 mb (not corrected from efficiency)

Red dashed line is the envelope deduced using all beam energies
Green line is the available CM energy
58Ni+58Ni: output of the calorimetry
Temperature, Neutron Yield and densities "à la" Albergo

Compared obtained values with those extracted from other experimental analyse

\[ T_{\text{HHe}} = 14.3 \text{ MeV} \left( \log \left[ 1.59 \frac{Y_\alpha Y_d}{Y_t Y_h} \right] \right)^{-1/2} \]

\[ Y_n = Y_p \frac{Y_t}{Y_h} f_\delta(T) \]

\[ f_\delta(T) = \exp \left[ \frac{(E_h - E_t)}{T} \right] \left[ \frac{(m_n m_h)}{(m_p m_t)} \right]^{3/2} \]

\[ n_p = 0.62 \times 10^{36} T^{3/2} \exp\left[ -19.8/T \right] \frac{Y_\alpha}{Y_t} \]

\[ n_n = 0.62 \times 10^{36} T^{3/2} \exp\left[ -20.6/T \right] \frac{Y_\alpha}{Y_h} \]

\[ n_B = \left( n_p/Y_p \right) \sum_i A_i Y_i \]

J.B. Natowitz et al, PRL 104 (2010)
S. Kowalski et al, PRC 75 (2007)
G. Röpke et al, PRC 88 (2013) (modified to take into account nuclear data shift)
- Density values for nucleon gas are around \( \rho_0/20 \).
- Baryonic denity between \( \rho_0/2 \) and \( \rho_0/3 \) compatible with Freeze-Out density used in QSM.
- Isotopic ratio temperature is lower.
- For the estimation of neutron yields, it is constant on an excitation energy range of 20MeV/A, which is quite surprising ...
Mixing of clusters in a nuclear gas

- $A \geq 2$ (bound clusters) + $A=1$ gas (neutron and proton)
- What the percentage of nucleons in each part?
- Linear dependence with $E^*$

![Graphs showing linear dependence with $E^*$ for different energies](image)


Yields of bound clusters

\[ \frac{N_i}{N_{\text{tot}}} \]

\[ E^* \text{ (MeV/A)} \]

FIG. 15. (Color online) Comparison of α-particle fractions in symmetric nuclear matter as a function of the density at four temperatures for the virial expansion (black dashed-dotted lines), NSE (green dotted lines), the EoS of Shen et al. [29] (blue dashed lines), the generalized RMF model (red solid lines), and the QS approach (orange dashed lines). Note the different scales on the x axes.
Putting all yields together

Very similar trends for the vaporization of the two sources (factor of 2 in size)
Putting all yields together

H and He isotopes

Li and Be isotopes
Conclusions

- Vaporization observed in 58Ni, 2 times heavier than 36Ar
- Significant cross section
- Isotopic yields up to Be
- Very promising data for comparison with NSE models
- Check the equilibrium assumption, density and temperature from the models
- Constrain the symmetry energy (isovector part)
(Near) future

Loi INDRA-FAZIA@GANIL for 2016

N/Z dependence of the dynamics in dissipative collisions, from evaporation towards vaporization

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(for the FAZIA Collaboration)
Figure 2: **On the left:** FAZIA demonstrator coupled to INDRA multidetector; **on the right:** Response of the FAZIA demonstrator located at 80 cm from the target, inside INDRA. Only angular range from 14 to 27° of INDRA is presented in this figure.
No limit in the size of the cluster for the definition and characterization of isotopic yields

One of experiment in this LoI addresses:

- The study of vaporization in the reaction \(^{40,48}\text{Ca} + ^{40}\text{Ca}\) up to 88 MeV/A
- Exclusif information on cluster yields on all the accessible subsaturation densities
- Explore the continuous path between multifragmentation and vaporization and focus on neutron rich source
Probing the decay mechanism of hot nuclei by Coulomb chronometry

Particle identification in Si-Si

$^{40}\text{Ar} + ^{112}\text{Sn} @ 35 \text{ MeV/amu}$

$\theta \gtrsim \theta_{\text{grazing}}$
Vaporization in 36Ar, 40,48Ca and 58Ni

Exclusif high quality data will be available in a large range in:

- Mass $A < 60$
- Temperature $T < 20$ MeV
- Sub saturation density until $\rho_0/4$
- Charge Asymmetry $N/Z$ up to 1.4

To be done with INDRA-FAZIA

Already done with INDRA
Thank you for your attention
Probing the decay mechanism of hot nuclei by Coulomb chronometry

**Charged particle identification used in INDRA**

**ΔE-ΔE-E telescopes**

- 1\(^{st}\) stage: ΔE(Chlo)-E(Si) with low threshold
- 2\(^{nd}\) stage: ΔE(Si)-E(Csl) with good resolution
- 3\(^{rd}\) stage: Csl fast-slow

**Ionisation chamber**

- Silicon
- Csl light
- Csl fast
- Csl slow

4 Cesium Iodide
(5-14 cm)

4 Silicon detectors
(300 μm)

1 Ionisation Chamber
(C3F8, 30 Torr, 5 cm)
- Maxwellian fit on kinetic energy spectra of all clusters
  - Good reproduction on all $E^*$
  - No barrier needed
  - Volume emission
Energy spectra of clusters

$^{58}\text{Ni} + ^{58}\text{Ni}$ @ 90 MeV/A - $E^* = 10$ MeV/A

- 4He
- 3He
- 2H
- 3H

Ek (MeV)