Heavy-Ion collisions and the low-density equation of state

“Valid treatment of the correlations and clusterization in low density matter”

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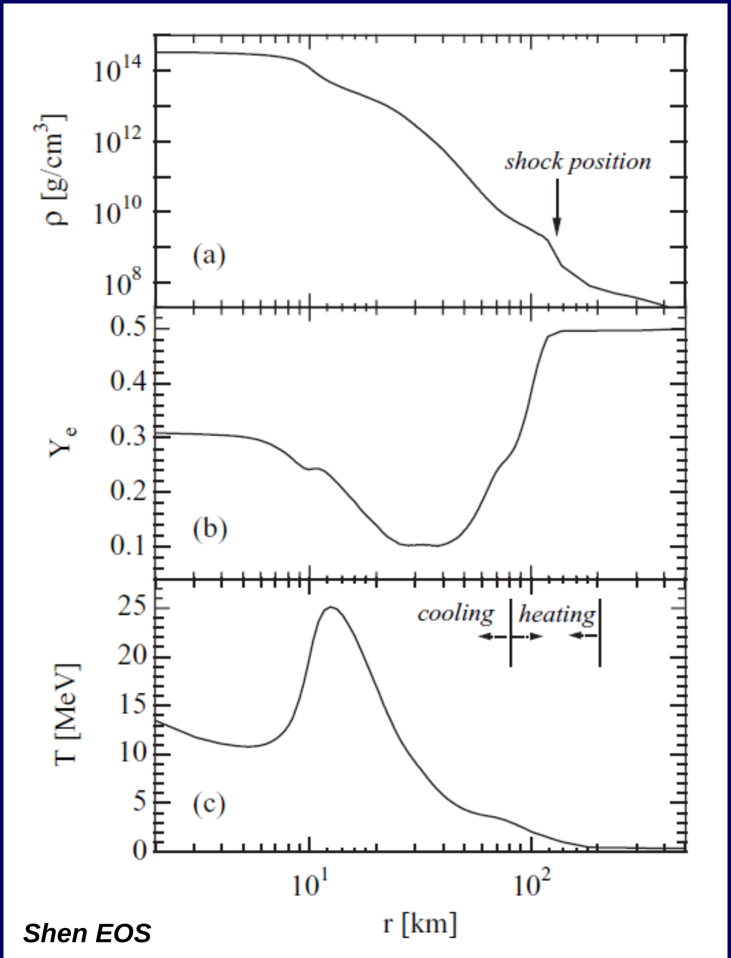
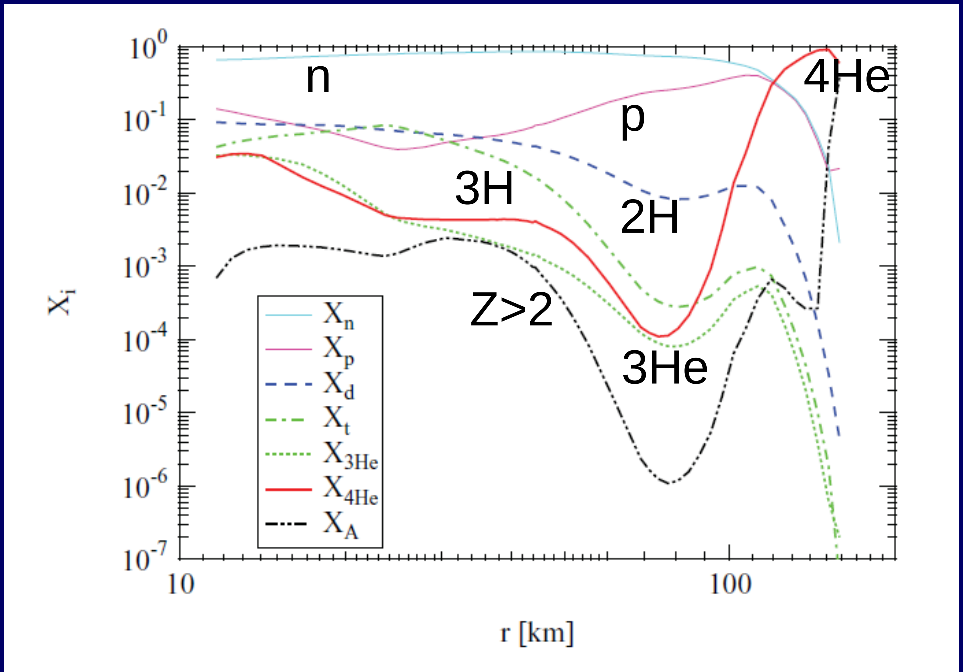
PHC PESSOA France Portugal

Composition of Supernova Core

Numerical simulation of the profile of the supernova core at 150 ms after core bounce as a function of the radius:



Light cluster mass fractions calculated for given profiles of temperature, density and proton fraction:



At low densities the system can minimize its energy by forming light clusters.

K. Sumiyoshi, G. Röpke Phys. Rev. C77, 055804 (2008)

Nuclear issue: in-medium effects

Expected modifications of cluster properties at low densities.
→ In-medium effects

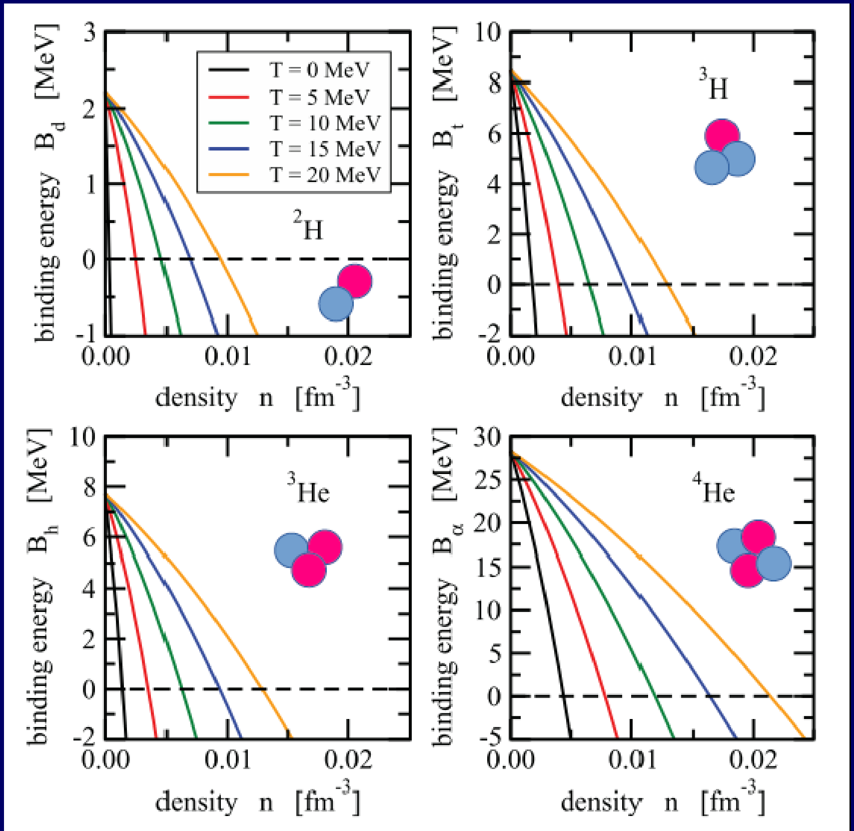


FIG. 1. (Color online) Change of the binding energy $B_i = B_i^0 + \Delta B_i$ of the clusters $i = d, t, h, \alpha$ at rest in symmetric nuclear matter due to the binding energy shift ΔB_i as used in the generalized RMF model as a function of the total nucleon density $n = n_n^{tot} + n_p^{tot}$ of the medium for various temperatures T.

Typel, Phys. Rev. C81 **2010**

Pauli exclusion principle: blocking of states in the medium:

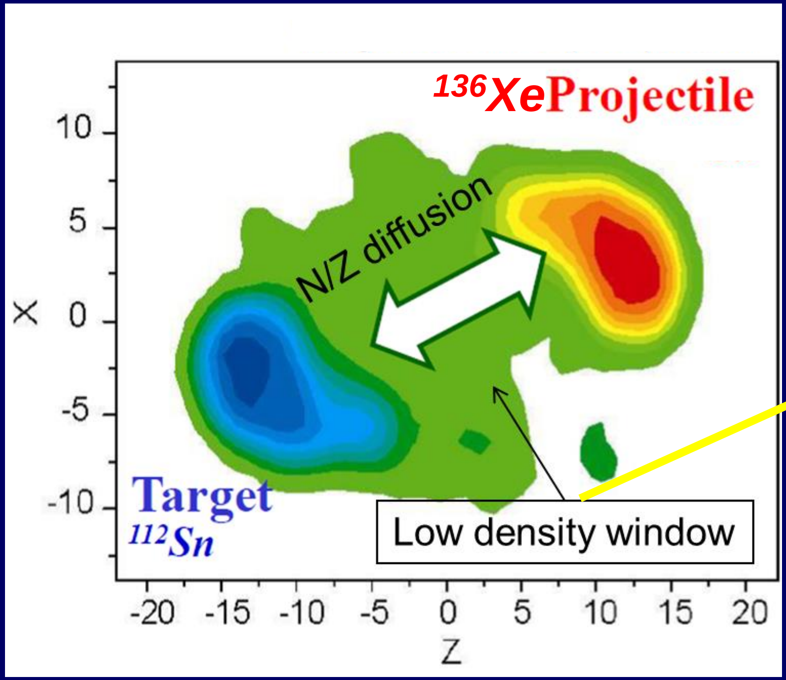
- ***reduction of binding energies***
- ***cluster dissolution at high densities: Mott effect***

Nuclear issue: in-medium effects

The experimental goal is therefore:

- **Measure Mass fractions at low densities and moderate temperatures**
- **Quantify in-medium effects**

How to create low density nucl. Matter
Heavy Ion collisions



STUDY of a Gas composed of light clusters formed in central collisions

INDRA@GANIL
$^{136,124}Xe+^{124,112}Sn$ 32 A MeV

There is

- Temperature & expansion: hot expanding source
- Coulomb effects: corrections to go back to the original velocity spectra at cluster creation time

Treatment of the gas material in a statistical/equilibrium framework

(equilibrium character: R. Bougault et al. PRC 97(2018)024612)

Measurements with INDRA detector:

(Xe+Sn 32 A MeV / GANIL)

Final result for identified clusters

^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{6}He

Gas of protons & neutrons in equilibrium with clusters:

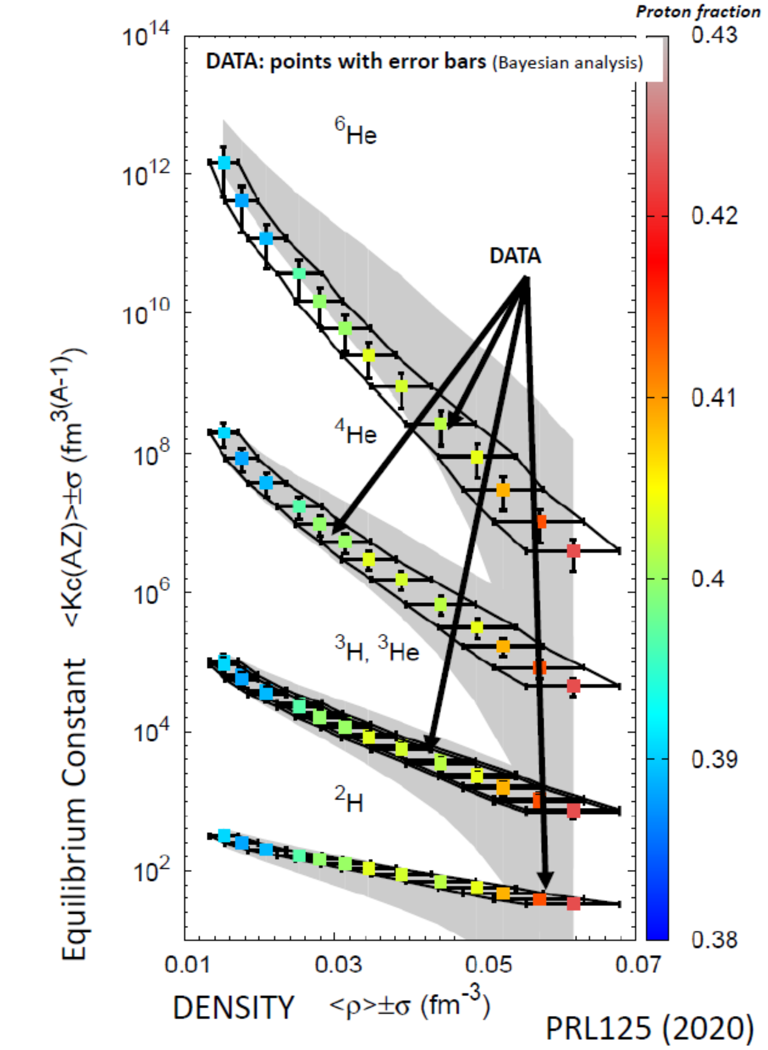
for each cluster, the equilibrium reaction $Z\,{}^{1}_{1}H + (A-Z)\,{}^{1}_{0}n \leftrightarrow {}^{A}_{Z}X$ is characterized by K_c (Equilibrium Constant)

Methodology of the analysis is simple:

$$K_c(A,Z) = \frac{\rho(A,Z)}{\rho_p^Z \rho_n^{(A-Z)}}$$

- **The data is sorted according to different thermodynamical conditions (expanding systems cooling over time)**
- **We extract the particle production rates**
- **Within the statistical equilibrium framework:**
  - **Temperature from Yields (2H 4He)/(3H 3He)**
  - **Proton fraction from Yields (3H/3He)**
  - **Volume from Yields of cluster and proton thus density (Bayesian analysis with an effective Binding energy shift)**

This allows all the useful information to be deduced



References: Bougault et al. Physical Review C97 (2018) 024612, Bougault et al. Journal of Physics G 47 (2020) 025103, H. Pais et al. Physical Review Letters 125 (2020) 012701, H. Pais et al. Journal of Physics G 47 (2020) 105204

INDRA versus Model RMF:

(Xe+Sn 32 A MeV / GANIL)

Final result for identified clusters

^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{6}He

In-medium effects from DATA/MODEL comparison
➔ Mass Shift information for studied clusters

Relativistic Mean-Field with clusters

H. Pais et al. PRC97, 045805 (2018) – H. Pais et al. PRC99, 055806 (2019)

mesons: mediation of nuclear force

$$\mathcal{L} = \sum_{i=p,n} \mathcal{L}_i + \mathcal{L}_e + \mathcal{L}_\sigma + \mathcal{L}_\omega + \mathcal{L}_\rho + \mathcal{L}_{\omega\rho}$$

nucleons, electrons, mesons, non-linear mixing coupling

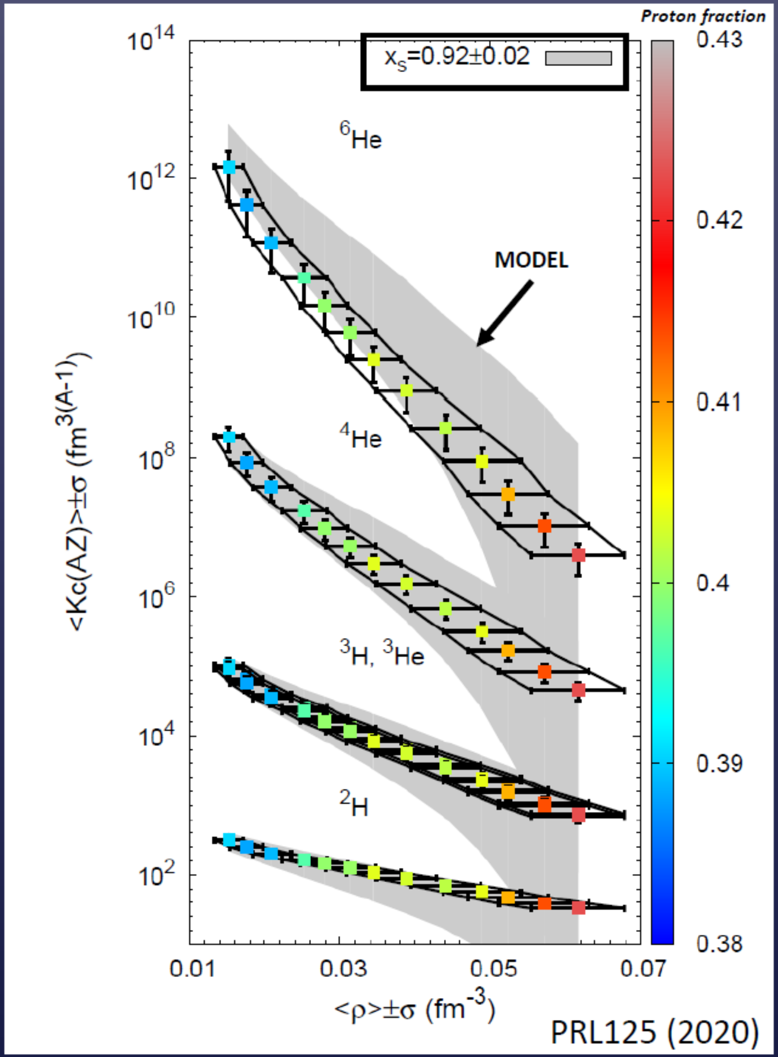
RMF approach: clusters as new degrees of freedom, with effective mass dependent on density.

In the medium, clusters are coupled to the effective mesons, leading to a binding energy shift

The scalar cluster-meson coupling is modified

$$g_{sj} = x_s A_j g_s$$

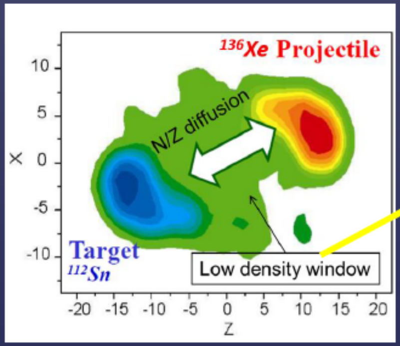
x_s changes the effective mass of nucleons bound in cluster “j”



X_s<1 means evidence of in-medium effects

INDRA experiment: limitations

(Xe+Sn 32 A MeV / GANIL)



STUDY of a Gas
composed of light clusters
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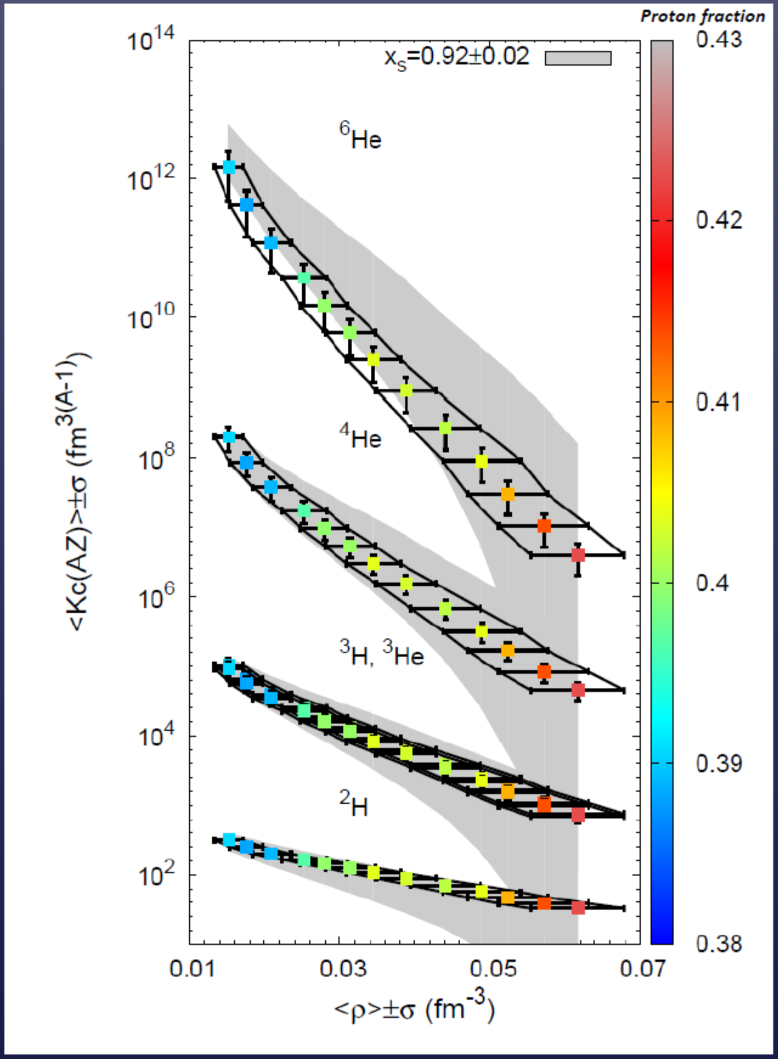
$^{136,124}Xe+^{124,112}Sn$ 32 A MeV



Disadvantages:

- INDRA identifies (A,Z) only light clusters
- The ½ rapidity gas of particles does not contain many elements heavier than helium

^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{6}He

Need of new measurements:

^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{6}He, ... ^{12}C

INFORMATION ON MASS SHIFT FOR HEAVIER CLUSTERS

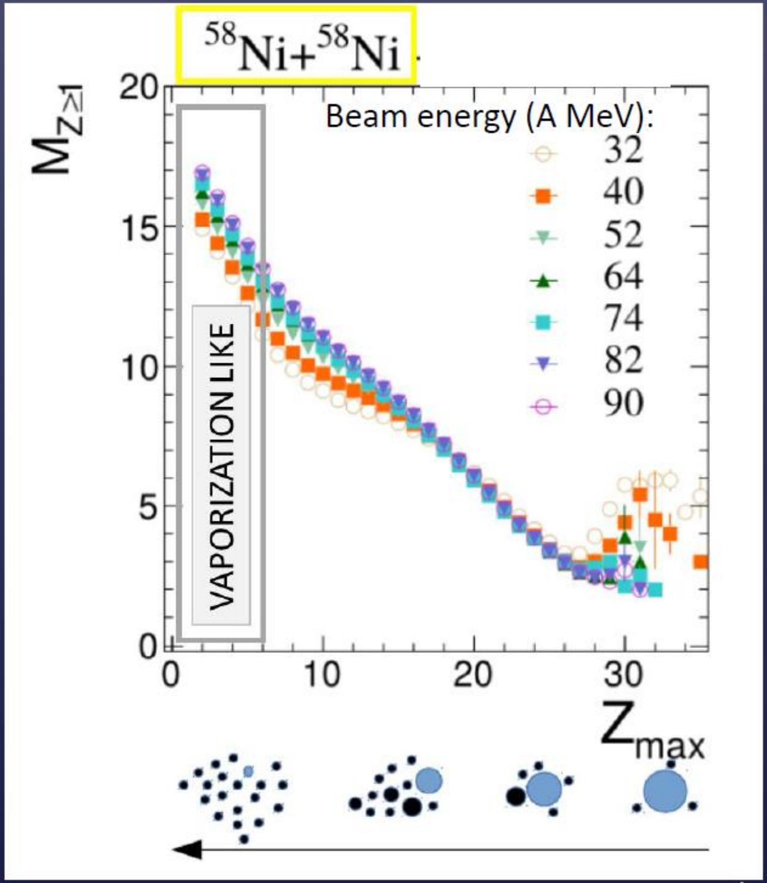
- **Because the mass shift is expected to disappear for very heavy clusters.**
- **Answer to the following question for a large range of masses: where are the Mott points (density, temperature) at which a cluster binding energy vanishes?**

NEW DATA: Projectile vaporization-like events (low density)

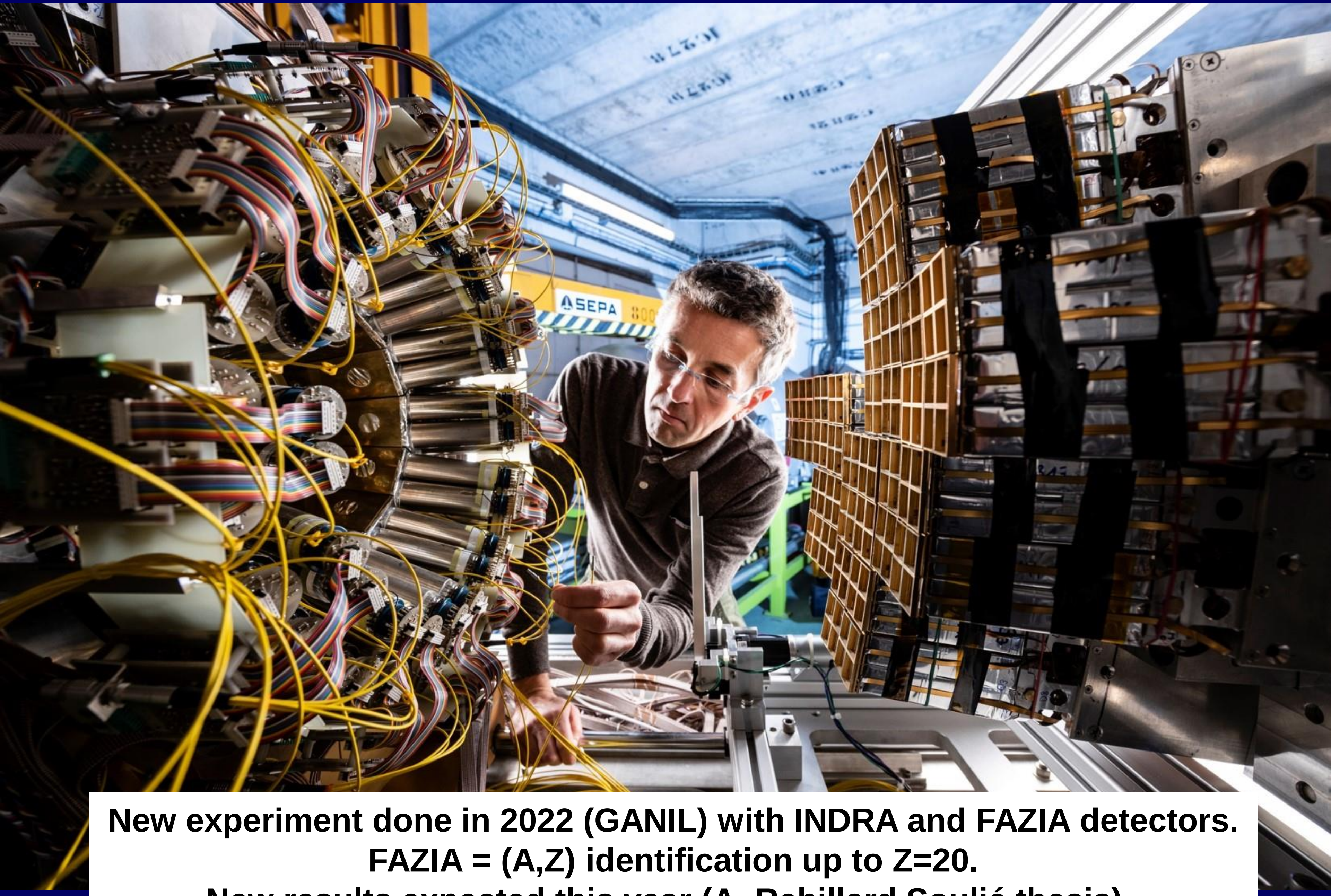
This type of events has been registered with INDRA in the past. But INDRA (A,Z) identification is limited and total number of events is too low to perform such analysis.

NEW EXPERIMENT PERFORMED AT GANIL in 2022:

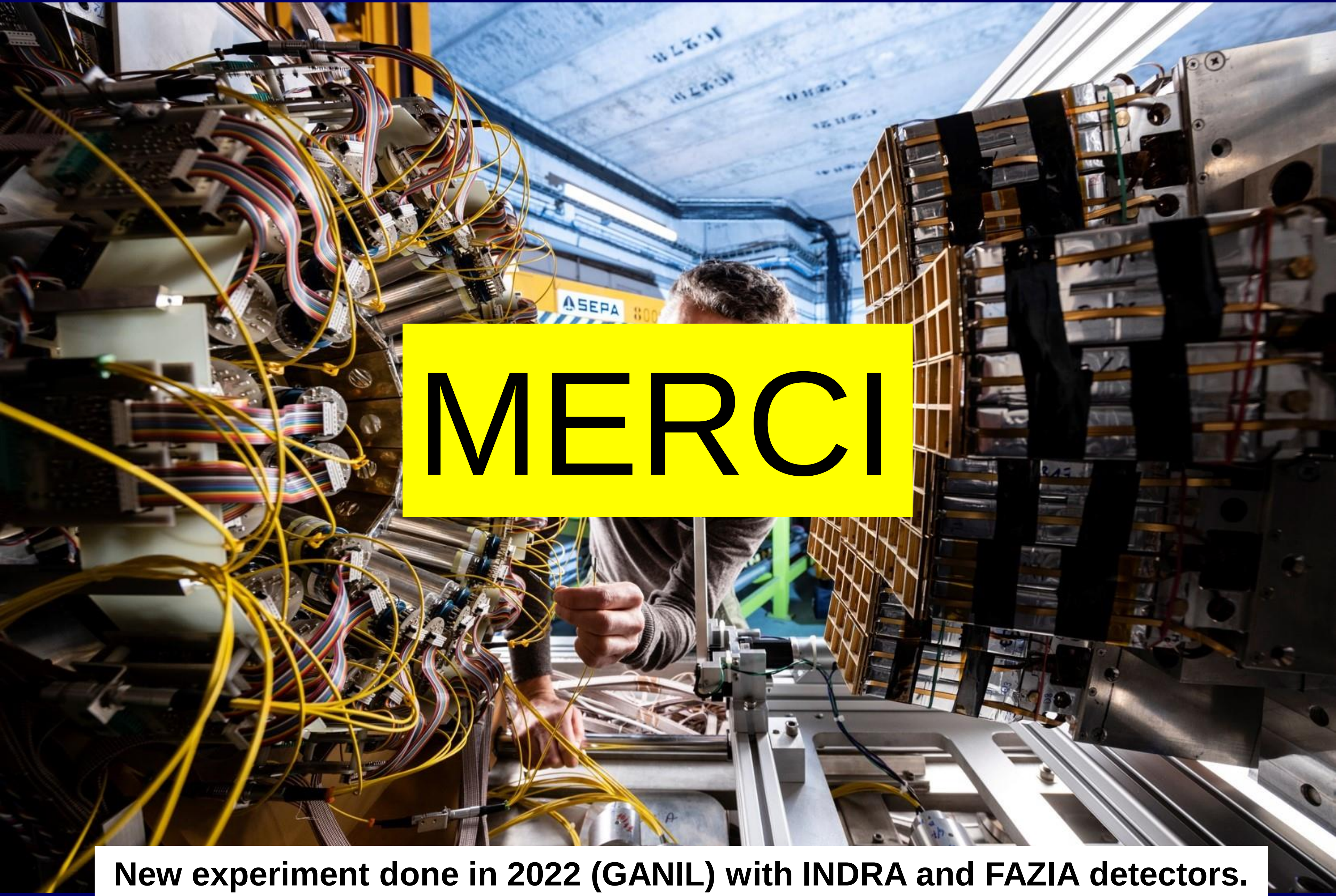
BEAM	TARGET	BTU
74 A MeV ^{58}Ni	^{58}Ni	30 BTU
74 A MeV ^{36}Ar	^{58}Ni	10 BTU



E. Bonnet Subatech (INDRA)



New experiment done in 2022 (GANIL) with INDRA and FAZIA detectors.
FAZIA = (A,Z) identification up to Z=20.
New results expected this year (A. Rebillard Soulié thesis).



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New experiment done in 2022 (GANIL) with INDRA and FAZIA detectors.
New results expected this year.

Statistical/equilibrium framework

S. Das Gupta and A.Z. Mekjian Phys. Rep. 72 (1981) 131
S. Albergo et al. Nuovo Cimento 89 (1985) 1

For each Vsurf bin (i.e. time)

1- Temperature: from Yields (^2H ^4He)/(^3H ^3He)

$$T = \frac{B(4,2)+B(2,1)-B(3,2)-B(3,1)}{\ln(\sqrt{9/8}(1.59\ R_{v_{surf}}))} MeV \text{ with } R_{v_{surf}} = \frac{M(2,1)M(4,2)}{M(3,1)M(3,2)}$$

B(A,Z)=Binding energy cluster $^A_Z X$

2- Neutrons: from Yields (^3H/^3He)

$$(N/Z)_{free} = \frac{M(3,1)}{M(3,2)}\ e^{((B(3,2)-B(3,1))/T)}$$

3- Momentum space density Power law:

$$\frac{d^3M(A,Z)}{d^3p_A} = R_{np}^N \frac{(2s+1)\ e^{B(A,Z)/T}}{2^A} \left(\frac{h^3}{V_0}\right)^{A-1} \left(\frac{d^3M(1,1)}{d^3p}\right)^A$$

Cluster momentum spectrum versus (proton momentum spectrum)^A
(neutron spect. = proton spect., Coulomb correction)

Relativistic Mean-Field with clusters

Helena Pais (CFisUC, University of Coimbra, visitor LPC), F. Gulminelli (LPC-Caen),
C. Providência (Univ. Coimbra), G. Roepke (Univ. Rostock).

mesons: mediation of nuclear force

$$\mathcal{L} = \sum_{i=p,n} \mathcal{L}_i + \mathcal{L}_e + \mathcal{L}_\sigma + \mathcal{L}_\omega + \mathcal{L}_\rho + \mathcal{L}_{\omega\rho}$$

nucleons ($\mathcal{L}_i$), electrons ($\mathcal{L}_e$), mesons ($\mathcal{L}_\sigma$, $\mathcal{L}_\omega$, $\mathcal{L}_\rho$), non-linear mixing coupling ($\mathcal{L}_{\omega\rho}$)

RMF approach: clusters as new degrees of freedom, with effective mass dependent on density.

- In-medium effects: clusters interact with medium via the meson couplings, or effective mass shifts, or both

the scalar cluster-meson coupling

$$g_{sj} = x_{sj} A_j g_s$$

Change the cluster effective mass
(model parameter)

Broadly speaking:
Free nucleons & nucleons within nuclei: same mean-field (Xs=1)
Free nucleons & nucleons within nuclei: different mean-field (Xs<1)

H. Pais et al. PRC97, 045805 (2018) – H. Pais et al. PRC99, 055806 (2019)

NEED of new measurements

^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{6}He, …. ^{12}C

Open question from previous measurements

- **We can observe a slight mass effect which does not seem fully accounted by the present calculation.**
  - **overestimation of the heaviest species (6He)**
  - **underestimation of the lightest cluster (2H)**

- **This might suggest that the hypothesis of the model, namely the fact that the coupling to the meson fields scales linearly with the number of nucleons bound in each cluster, could be not fully correct, and a more ab-initio treatment would be in order.**

This is a fundamental theoretical point.

The scalar cluster-meson coupling

$$g_{sj} = x_s A_j g_s$$

A_j = Number of nucleons bound in cluster « j »