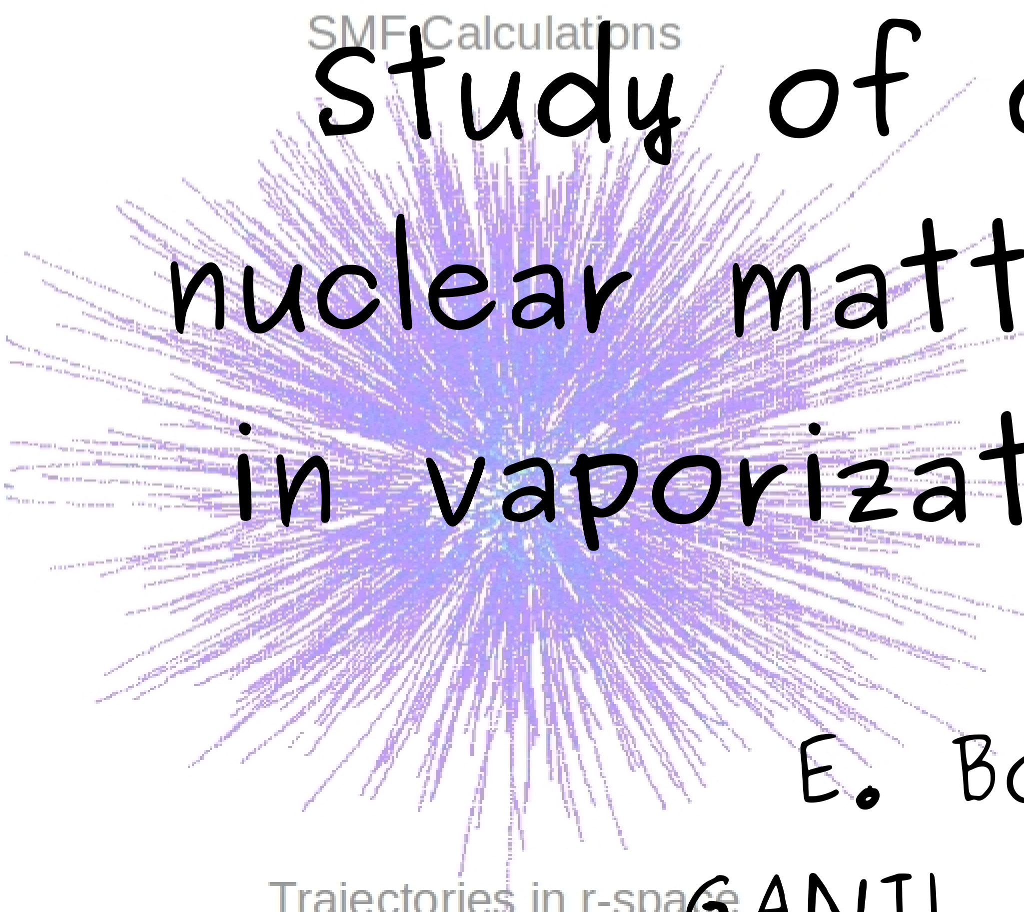
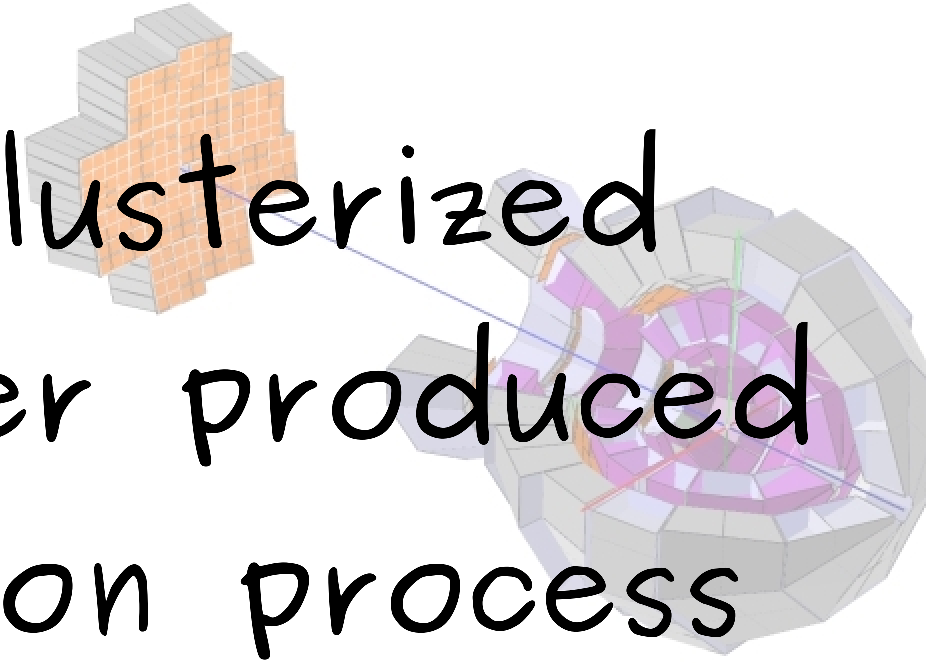
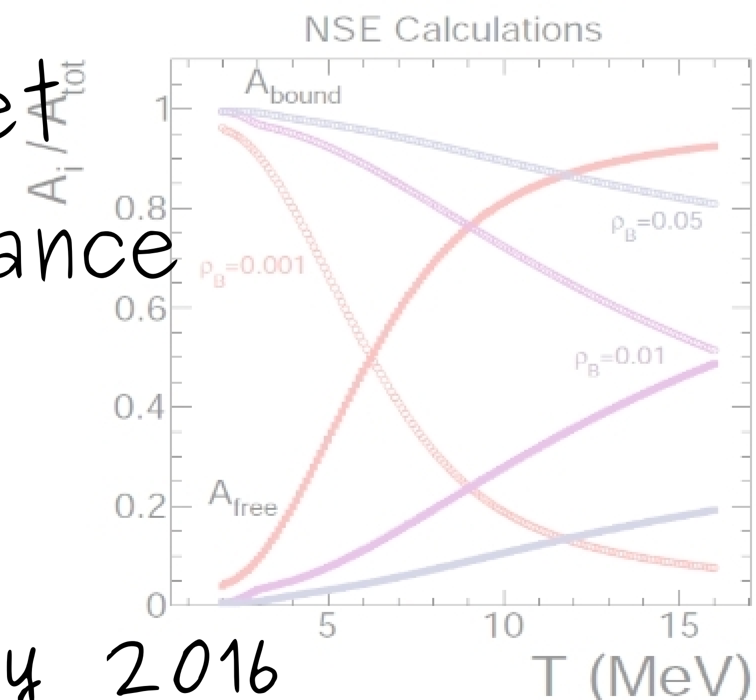
Study of clustered nuclear matter produced in vaporization process





E. Bonnet
GANIL, France



FUSTIPEN May 2016

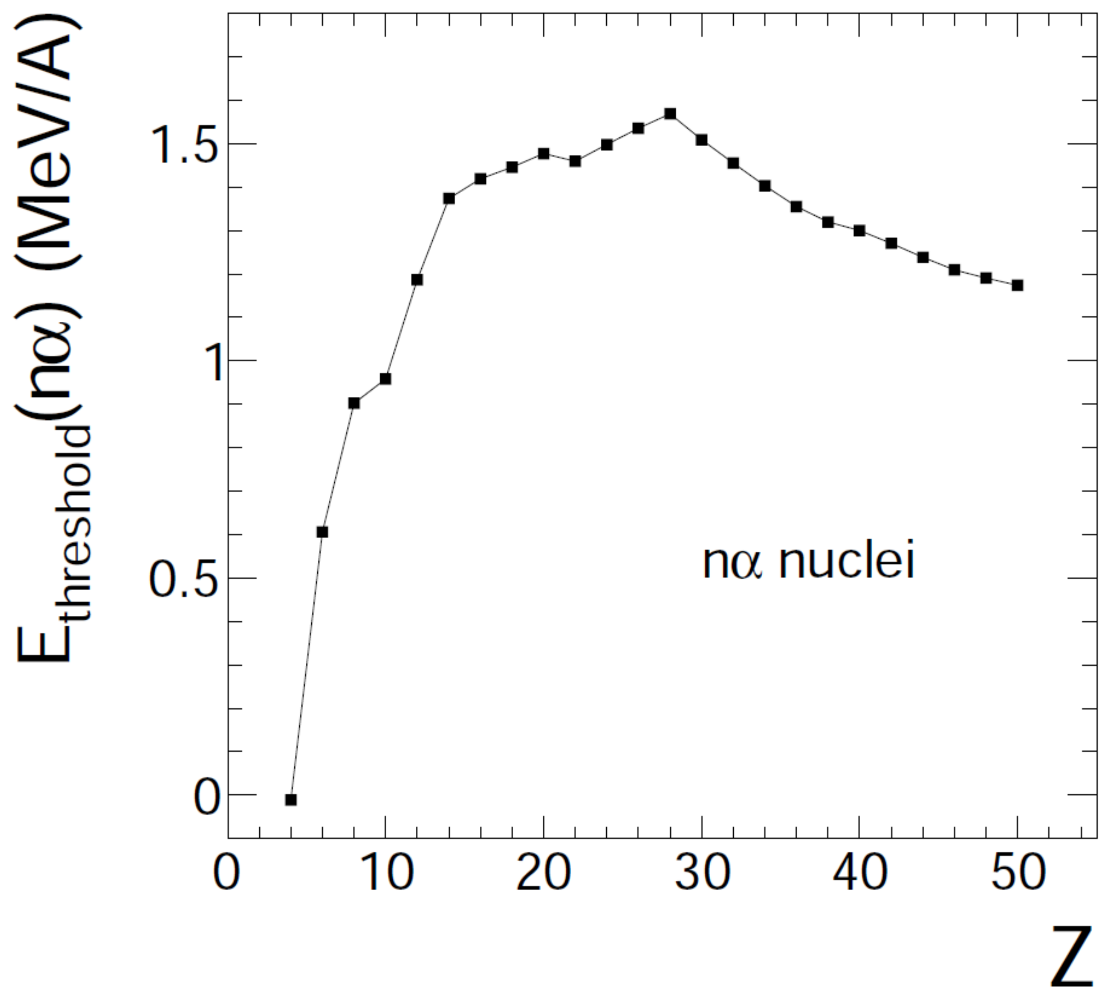
Outline

- Introduction
  - General features of HIC in Fermi energy domain
  - Multifragmentation to vaporization in exp. data
  - Motivations for updated analysis
- INDRA data 58Ni+58Ni@90MeV/A
  - Vaporization observed in :
    - Central reactions
    - Selected Peripheral reactions
  - Data described as a Perfect classical gaz of clusters & nucleons
- Comparison with NSE model (F. Gulminelli, Ad. Raduta)

Vaporization : mixing of clusters surrounded by free nucleons

$$E_{threshold} = n \times \delta_{alpha} - \delta(Z, 2 \times Z)$$

Complete break-up of nuclei into n alpha is allowed at low excitation energy : 1 MeV/A



General context

- 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), ECT*14 Workshop)
- Data in the subsaturation ($\rho < \rho_0$) densities region and finite temperature (T<30 MeV) are needed to constrain new developments and approaches in these topics :
  - "In-medium" nuclear data shift
  - Non homogeneous matter, Gas-Clusters interaction, Surface effects …
  - Isovector part of the energy functional (symmetry energy)

General context

- 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

Rise-and-Fall : from multifragmentation to vaporization

C.A. Ogilvie et al,
Phys. Rev. Lett. 62, 1724 (1991)

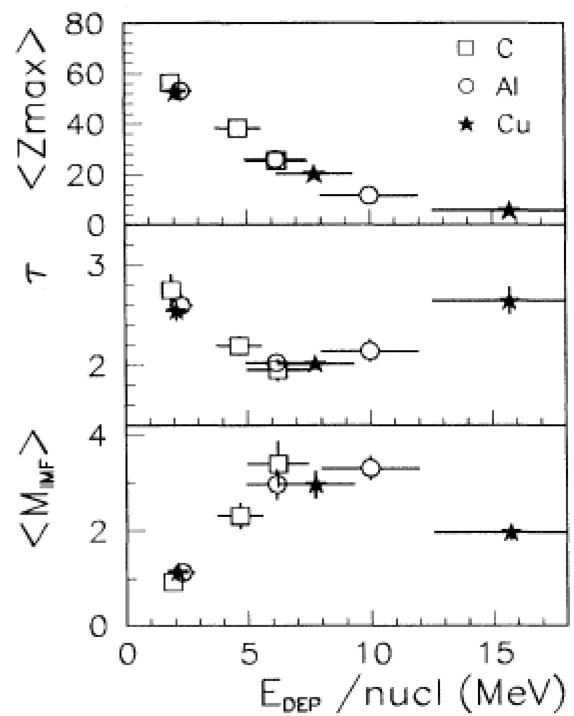


FIG. 3. The average maximum charge in each event, the fitted τ parameter from the charge distribution, and the mean IMF multiplicity plotted vs the calculated deposited energy per nucleon. The squares, circles, and stars represent collisions on the C, Al, and Cu targets, respectively. Each point within a target group corresponds to peripheral, mid-central, and central collisions with the deposited energy increasing with centrality.

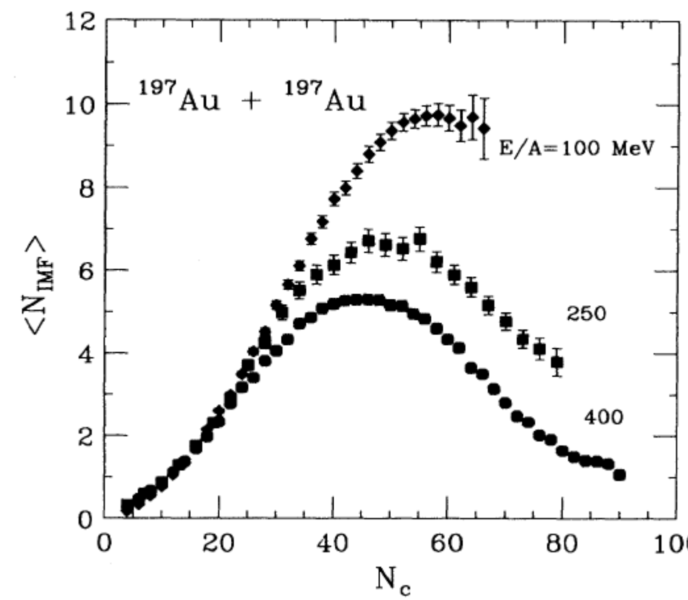


FIG. 1. Correlation between $\langle N_{IMF} \rangle$, the mean fragment multiplicity, and N_C, the multiplicity of charged particles detected in the Miniball/Miniwall. These are the measured quantities and are not corrected for the energy and angle dependent detection efficiency of the experimental apparatus.

B. Tsang et al,
Phys. Rev. Lett. 71, 1502 (1993)

Vaporization in HIC : Gas phase of the phase transition in nuclear matter

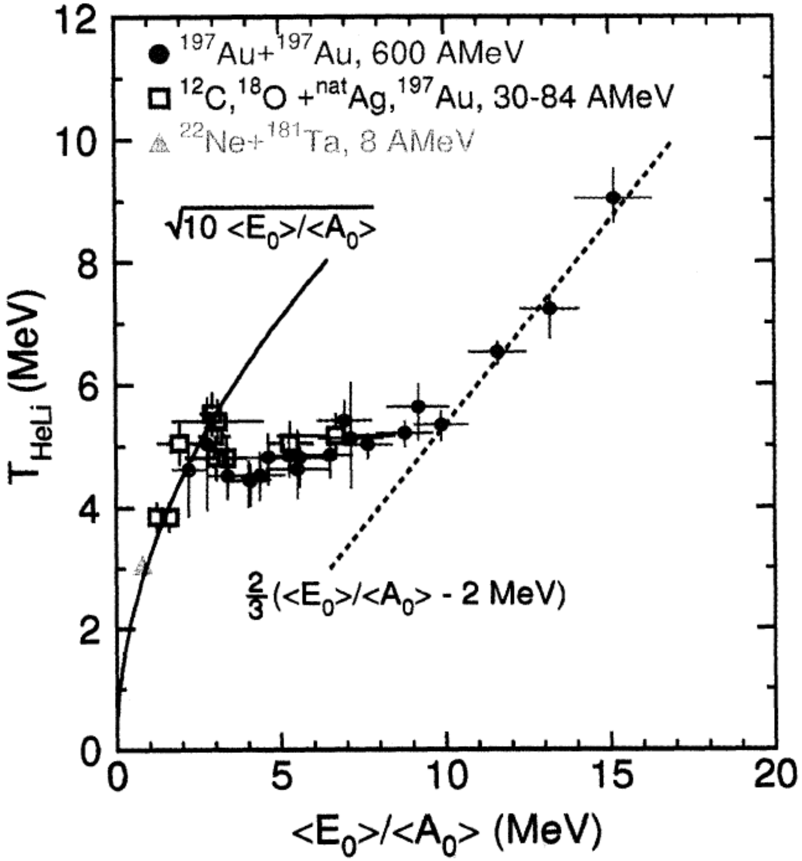


FIG. 2. Caloric curve of nuclei determined by the dependence of the isotope temperature T_{HeLi} on the excitation energy per nucleon. The lines are explained in the text.

J. Pochodzalla et al,
Phys. Rev. Lett. 75, 1040 (1995)

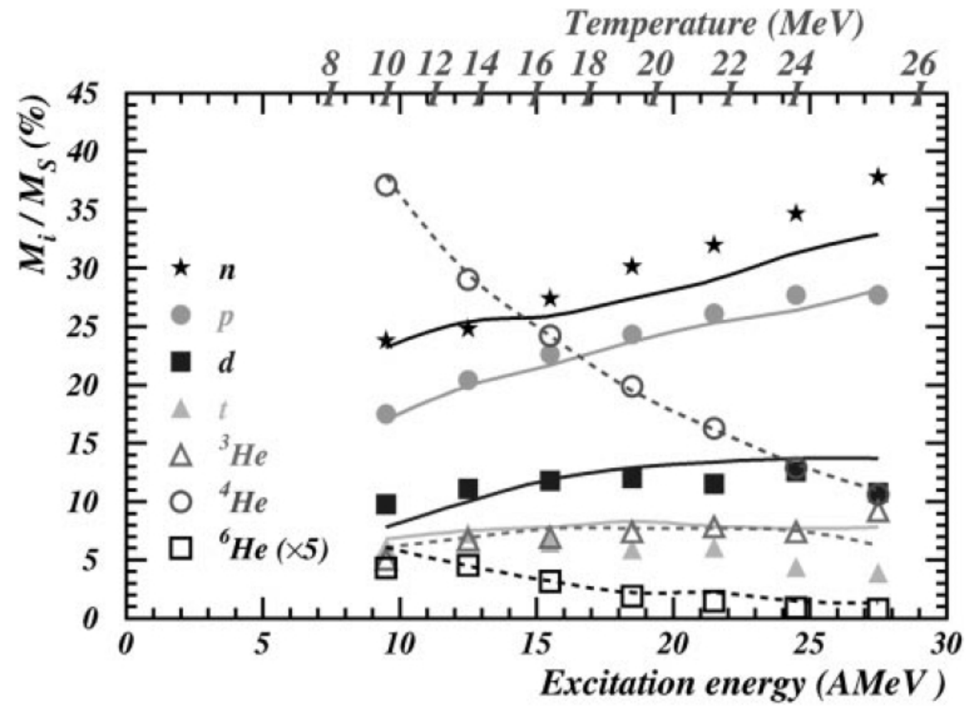


Fig. 3. Composition of the QP as a function of its excitation energy. Symbols are for data while the lines (dashed for He isotopes) are the results of the model. The temperature values used in the model are also given (see text)

B. Borderie et al,
Eur. Phys. J. A 6, 197{202 (1999)

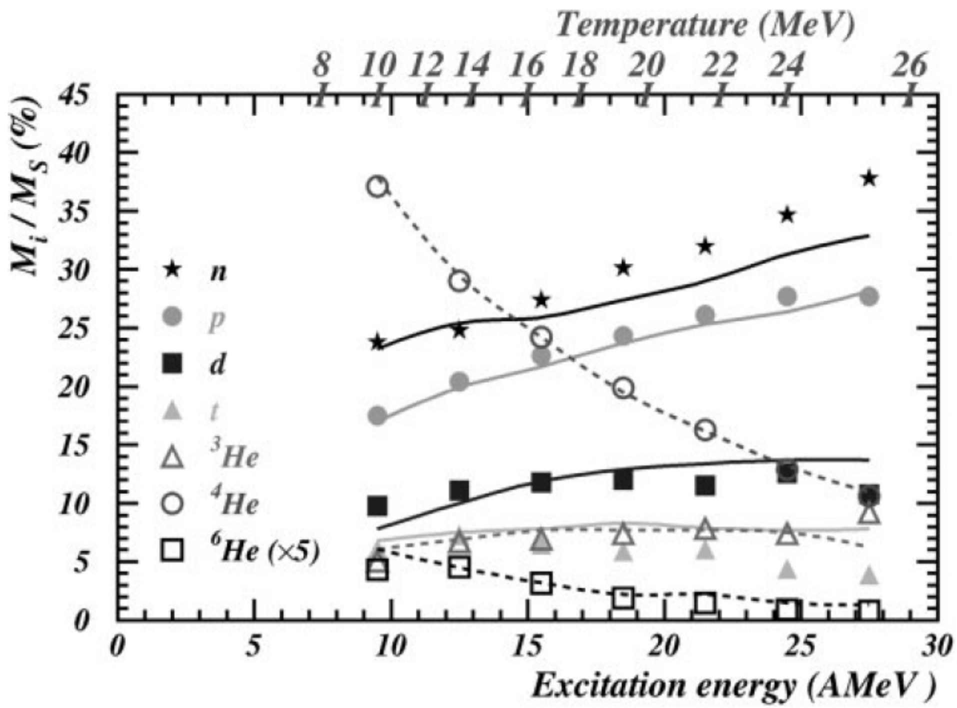
Results on Fragment production in HIC collisions for astrophysical inputs

- HIC and core-collapse supernova
  - SN community : simulations show that nuclear matter has conditions in temperature and density similar to those obtained in HIC.
  - HIC community : use to study experimental fragment production and explain it with different theoretical approaches (statistical/dynamical, spinodal/aggregation etc …)
  - How to make the bridge and make reliable results from HIC for astrophysical applications ?

Results on Fragment production in HIC collisions for astrophysical inputs

- Vaporization events in HIC
  - Fast and Explosive process leading to gas of free nucleons and clusters (low density and high temperature)
  - Composition of the gas (free nucleons + clusters) and kinetic energy
  - Mass dependence of the process
  - Influence of N/Z content to be closer to SN condition

Why vaporization ?



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B. Borderie et al,

Eur. Phys. J. A 6, 197{202 (1999)

"Easy" way to have full isotopically resolved events

Precedent study show that clusters Yields, 1st and 2nd moments are coherent with the predictions of a model describing the properties of a quantum weakly-interacting gas of nuclear species in thermal And chemical equilibrium

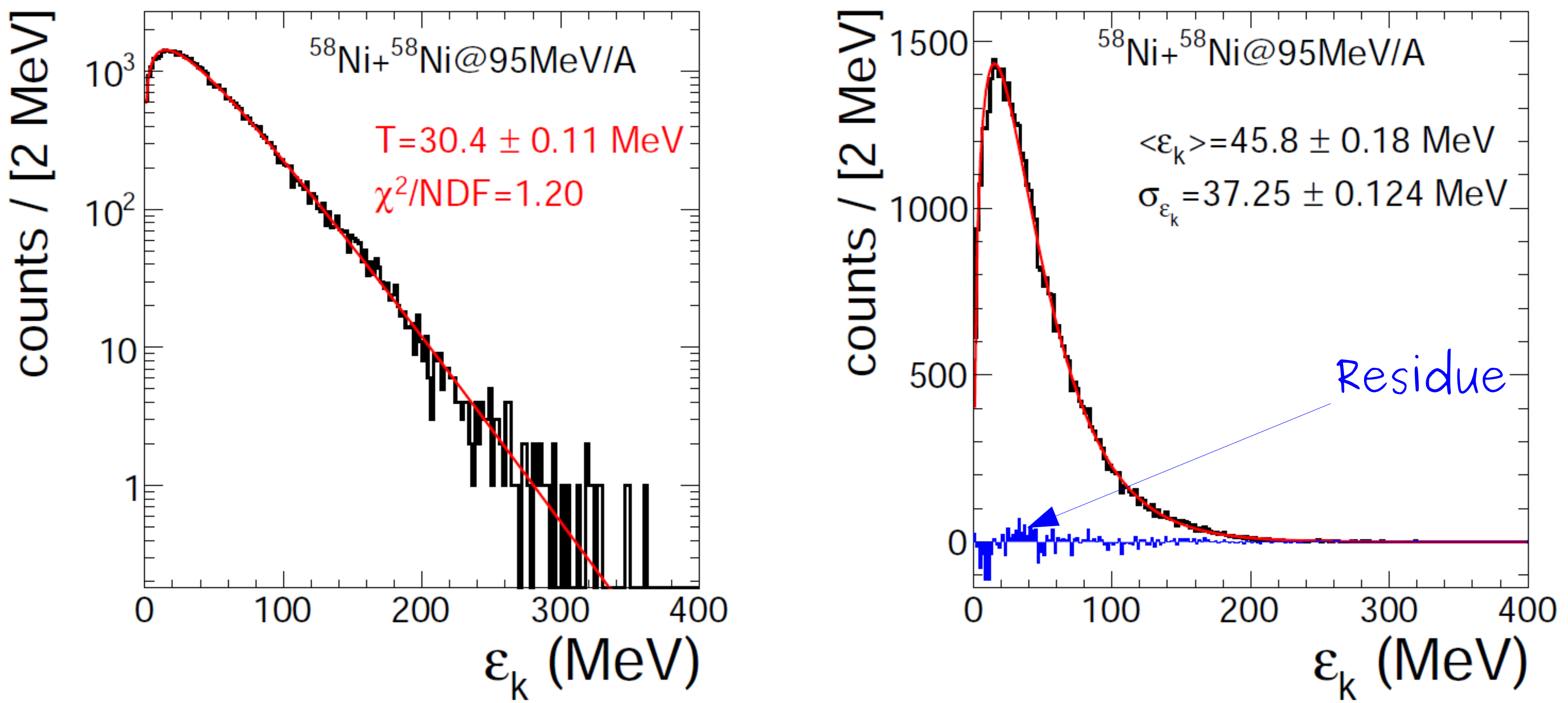
Density is fixed at rho0/3

Vaporization events produce in the reaction 58Ni+58Ni@90 MeV/A

- We look at full event (no dynamical selection)
- We have to be sure that only small pieces have been produced
  - kept well detected events :
    - Zmissing <= 2 compare to Zsystem=56
- To have sufficient statistics, events with Zmax<=6 are kept
- Work in the theoretical centre-of-mass of the reaction

Kinetic energy spectra compatible with perfect gas

Maxwell Boltzmann distribution : $P(\epsilon_k) = a_0\sqrt{\epsilon_k}e^{-\frac{\epsilon_k}{T}}$



Expected Canonical ensemble values : 1.5

$$\left(\frac{<\epsilon_k>}{\sigma_{\epsilon_k}}\right)^2 = 1.52 \quad \text{and} \quad \frac{<\epsilon_k>}{T} = 1.51$$

Excitation energy (E*)

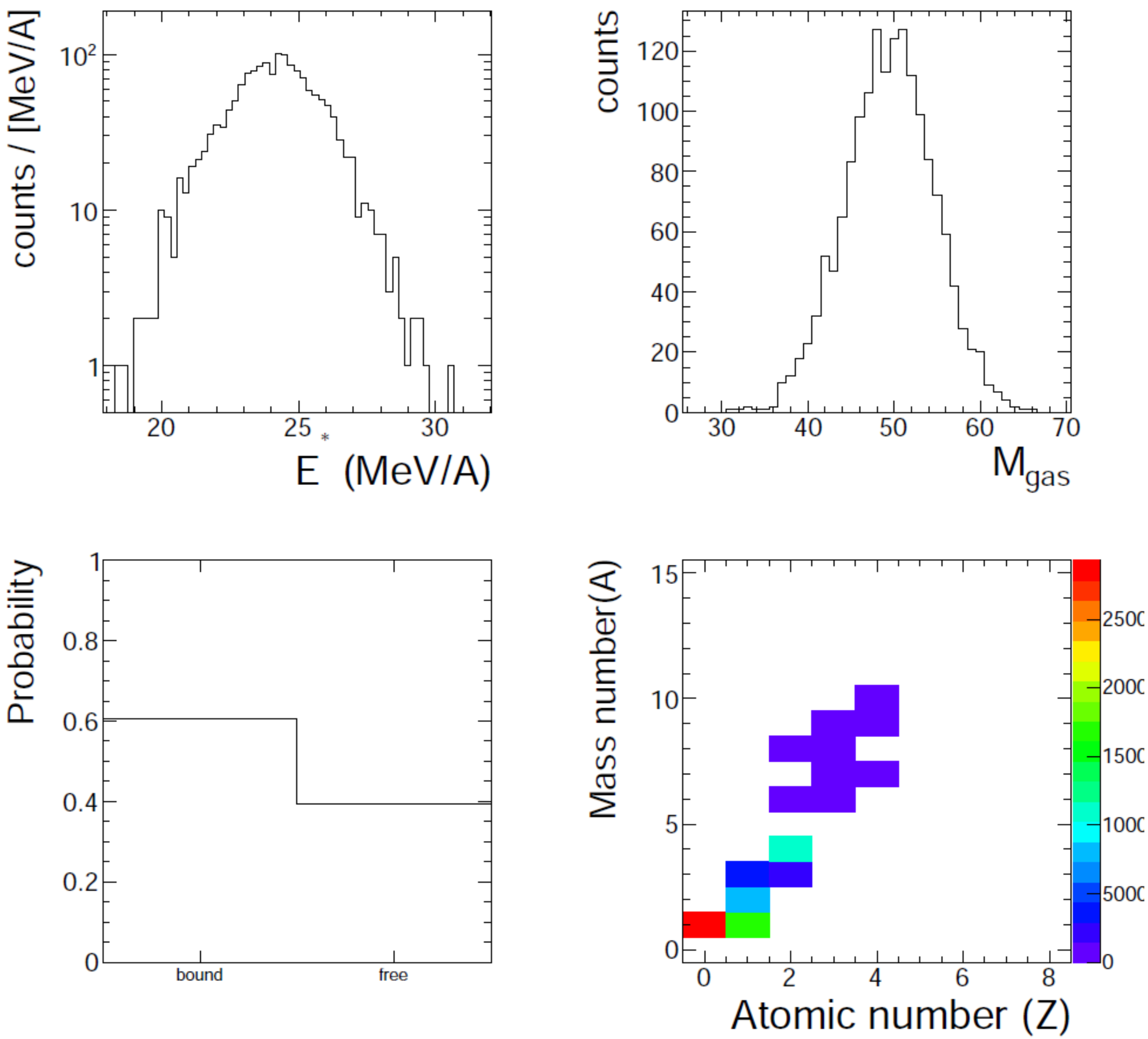
- Obtained from calorimetry procedure = Energy balance : $E* = \sum(\epsilon_k^{(i)} + \delta^{(i)}) - \delta_{ini}$
  - For undetected neutrons
    - Kinetic energy from temperature :

$$E_k^{(neutrons)} = M^{(neutrons)} \times \frac{3}{2}T$$

    - Multiplicity from N/Z conservation :

$$M^{(neutrons)} = \left(\frac{A}{Z}\right)_{syst} \times Z_{tot} - A_{tot}$$

Properties of the gas



<E*>=24 MeV/A

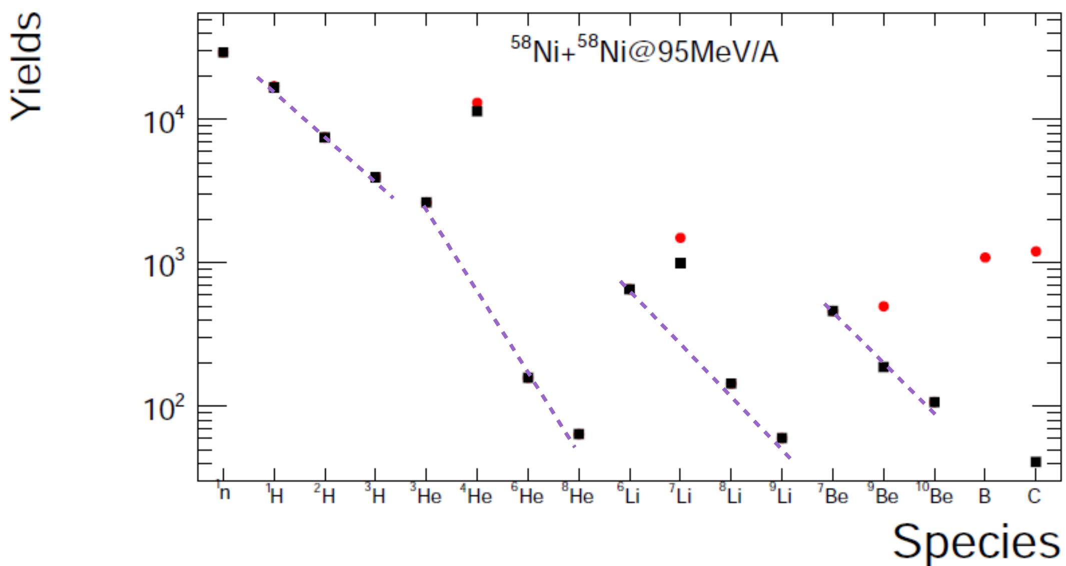
<Mgas>=50

Nucleons sharing

Free=0.40

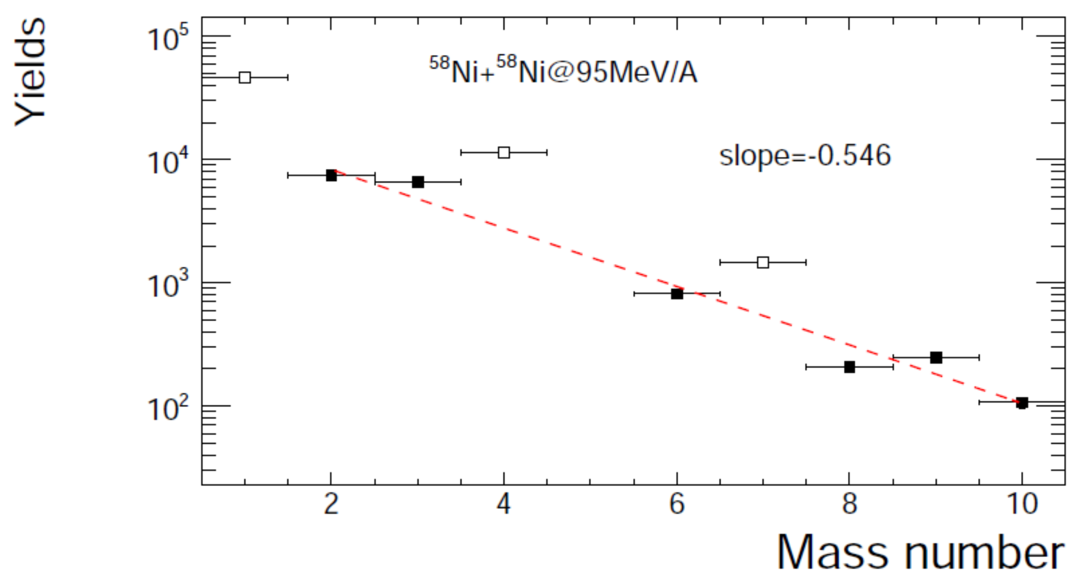
Bound=0.60

Cluster Yields



Follow exponential law
as expected in
grand canonical approach

$$Y(A) \propto e^{\frac{1}{T}(\mu A + \mu_3 (N-Z))}$$



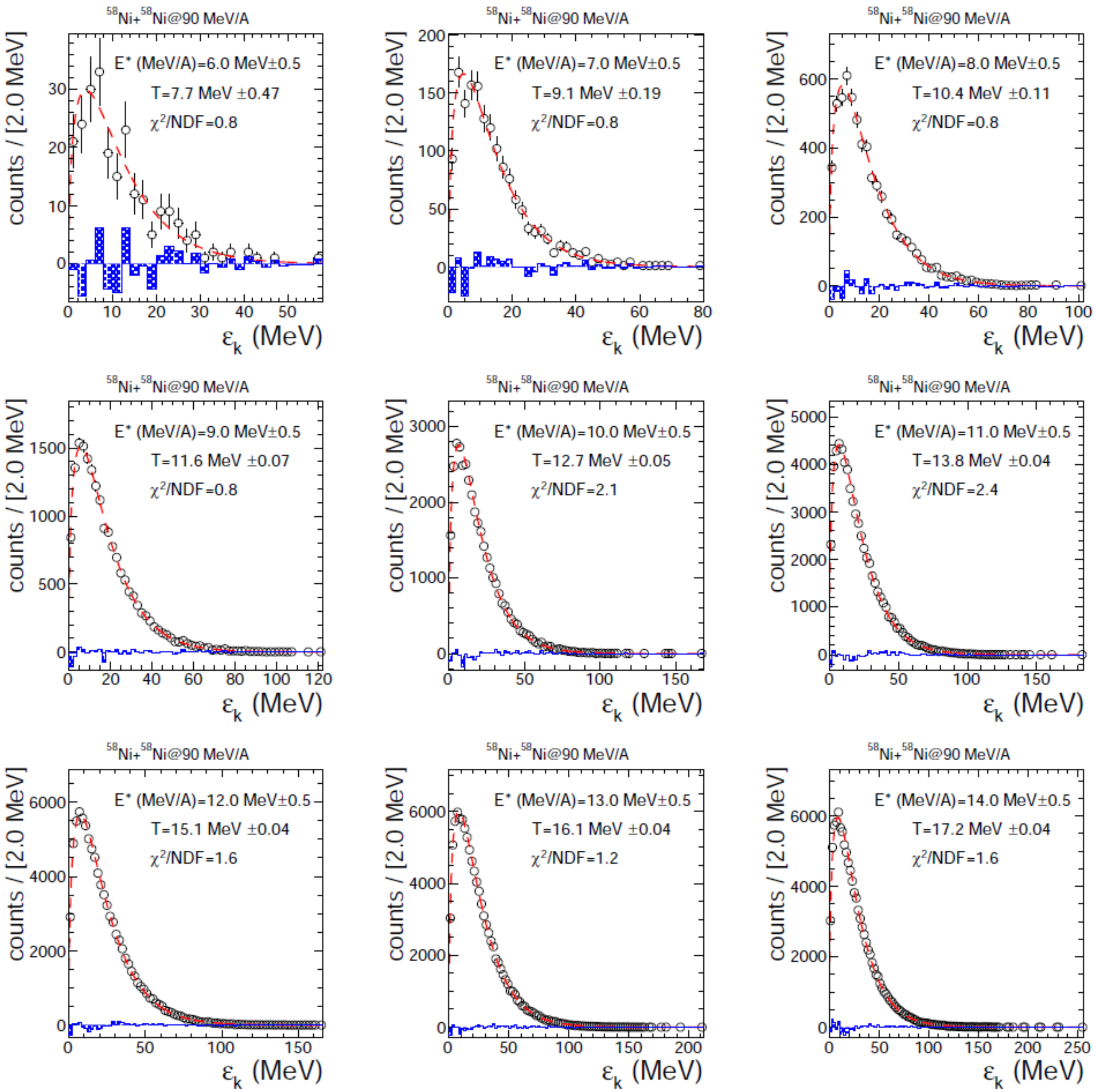
Vaporization is observed in $^{58}Ni+^{58}Ni$@90 MeV/A reaction

- Well characterized as nuclear perfect gas made of free nucleons + clusters
- Temperature is extracted
- Yields of clusters respect to their mass are coherent with grand canonical prescription

Vaporization in binary collisions

- In the same reaction $^{58}Ni+^{58}Ni$@90MeV/A
  - Focus on the FW part of each event and take as reference the projectile
  - Reconstruction of the centre-of-mass of the projectile-like
  - Zmissing <= 3 compare to Zprojectile=28 (10%)
  - events with Zmax<=4 are kept
  - Need to sort events according to the dissipation :
    - Same calorimetry as before (perfect gas)

Evolution of kinetic energy spectra for different excitation energies (E*)



Temperature is extracted from fit procedure with Maxwell–Boltzmann distribution

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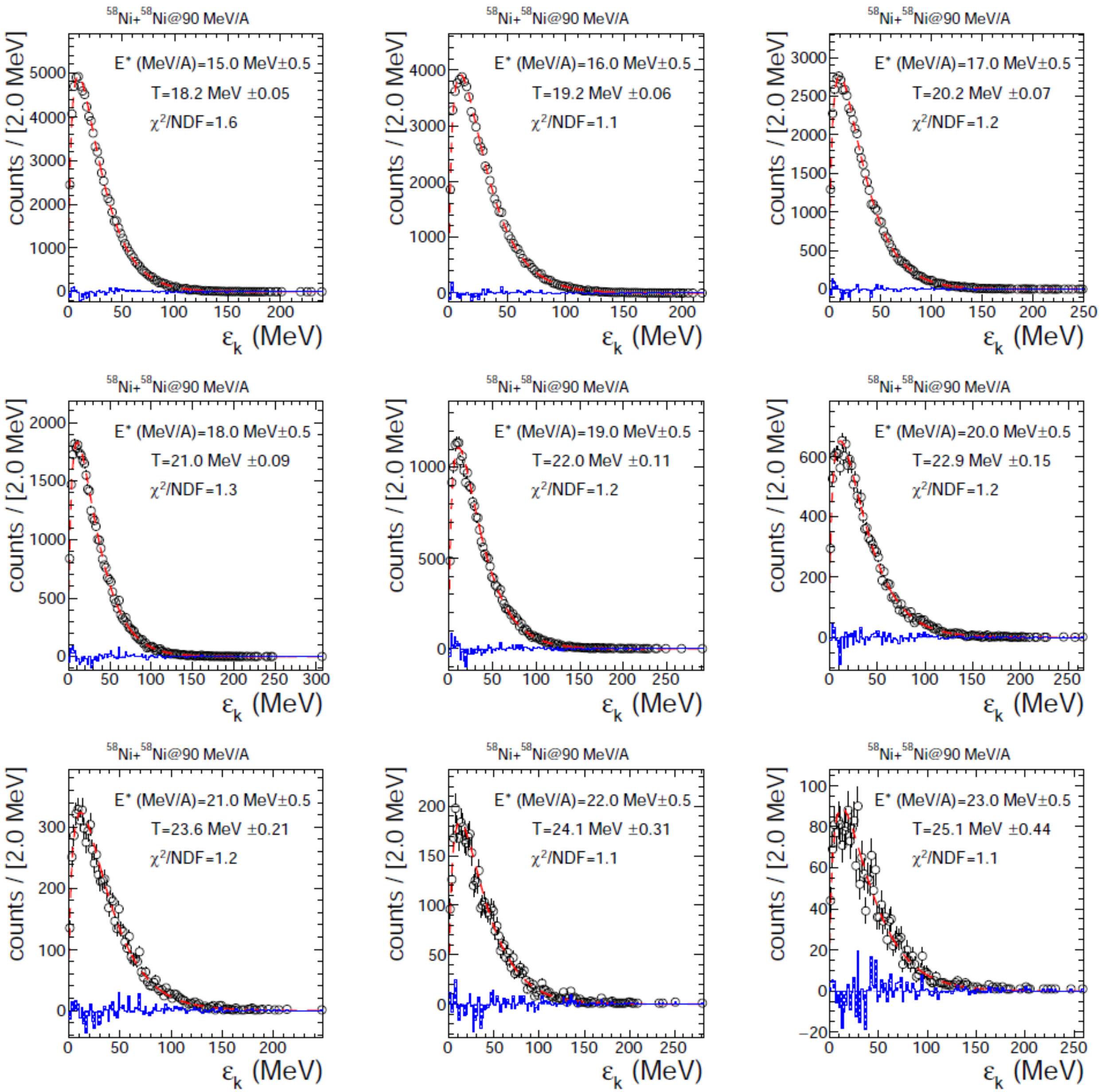
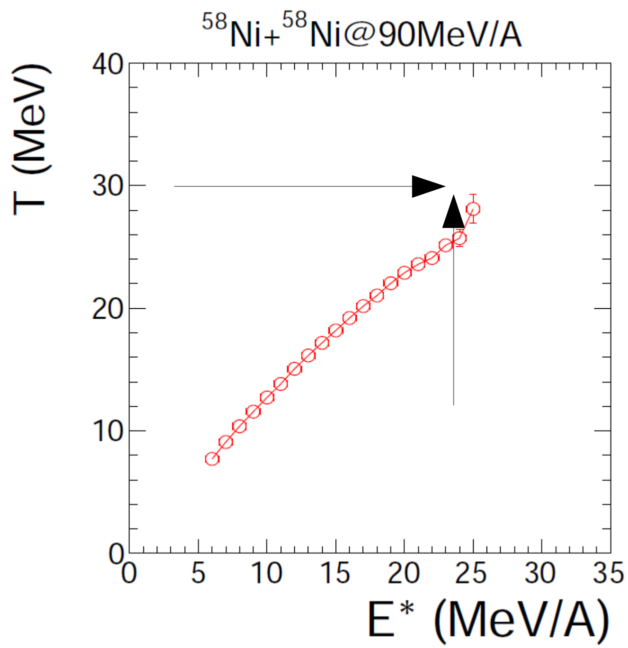
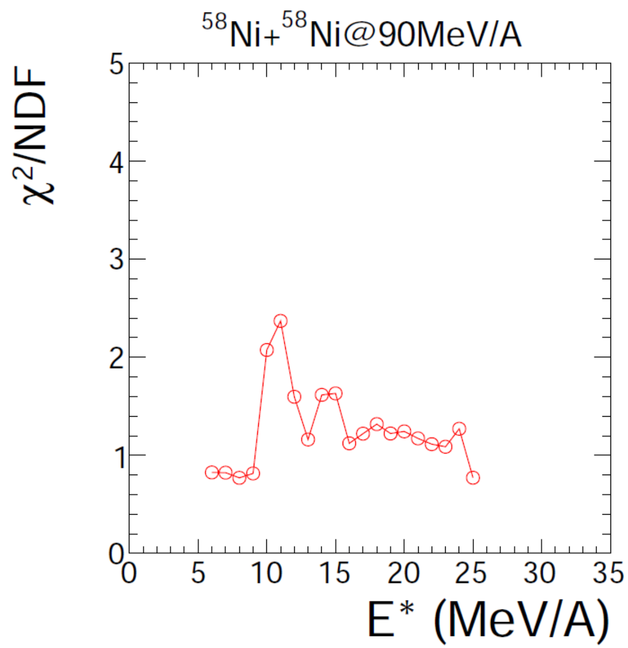


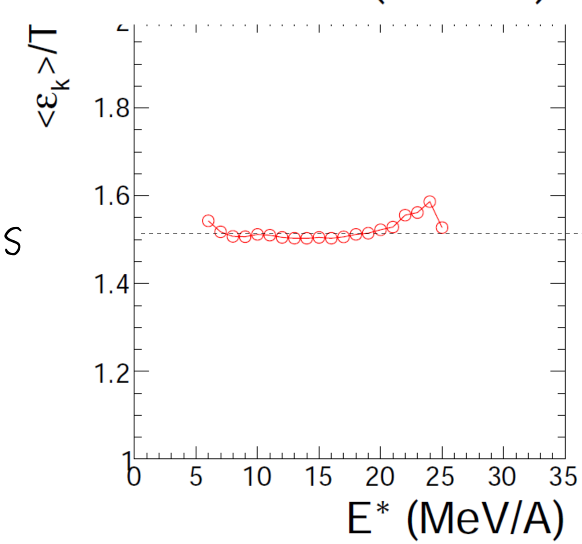
Temperature is extracted from fit procedure with Maxwell–Boltzmann distribution

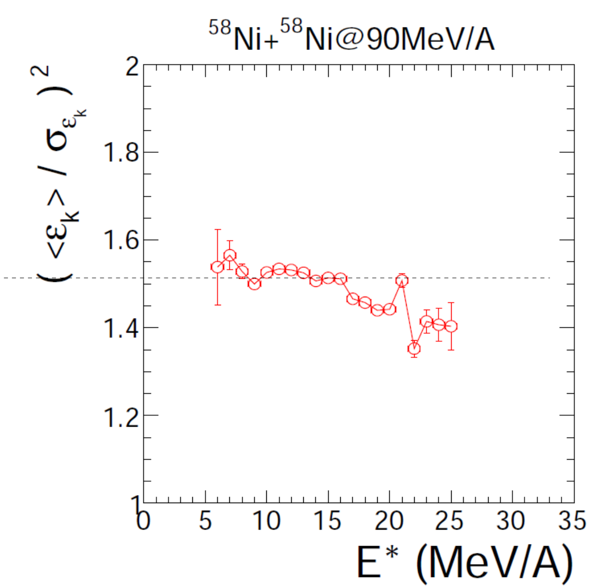
Very good reproduction on a 20 MeV/A range



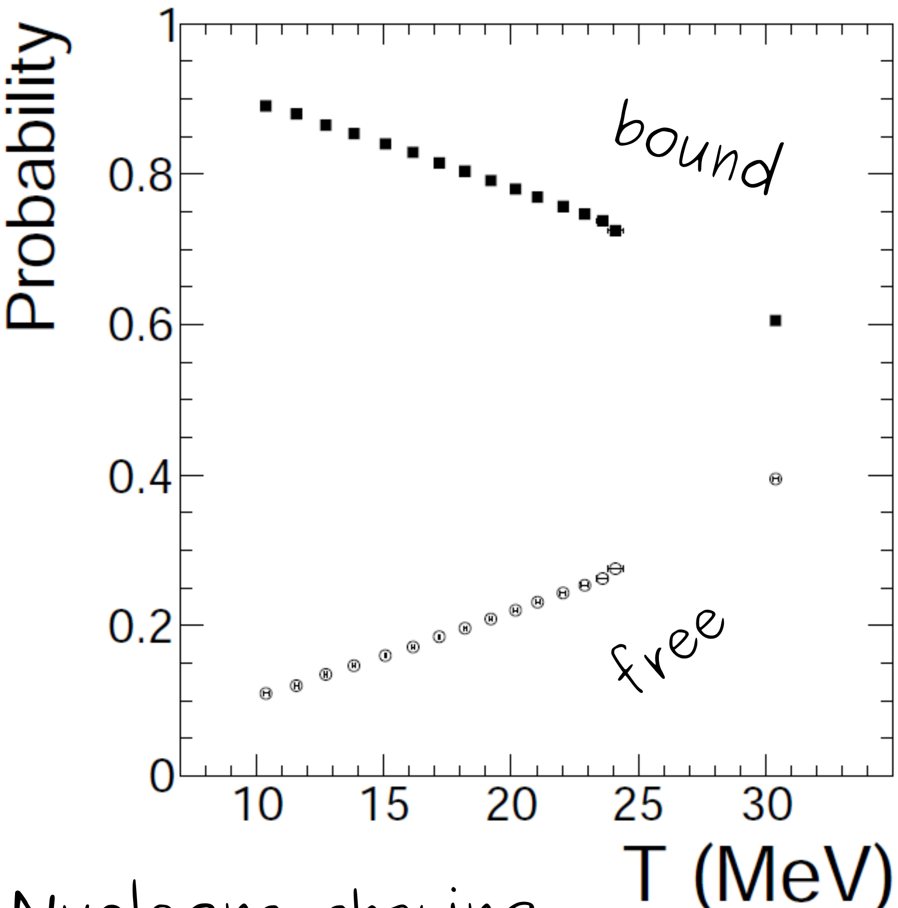


Canonical values



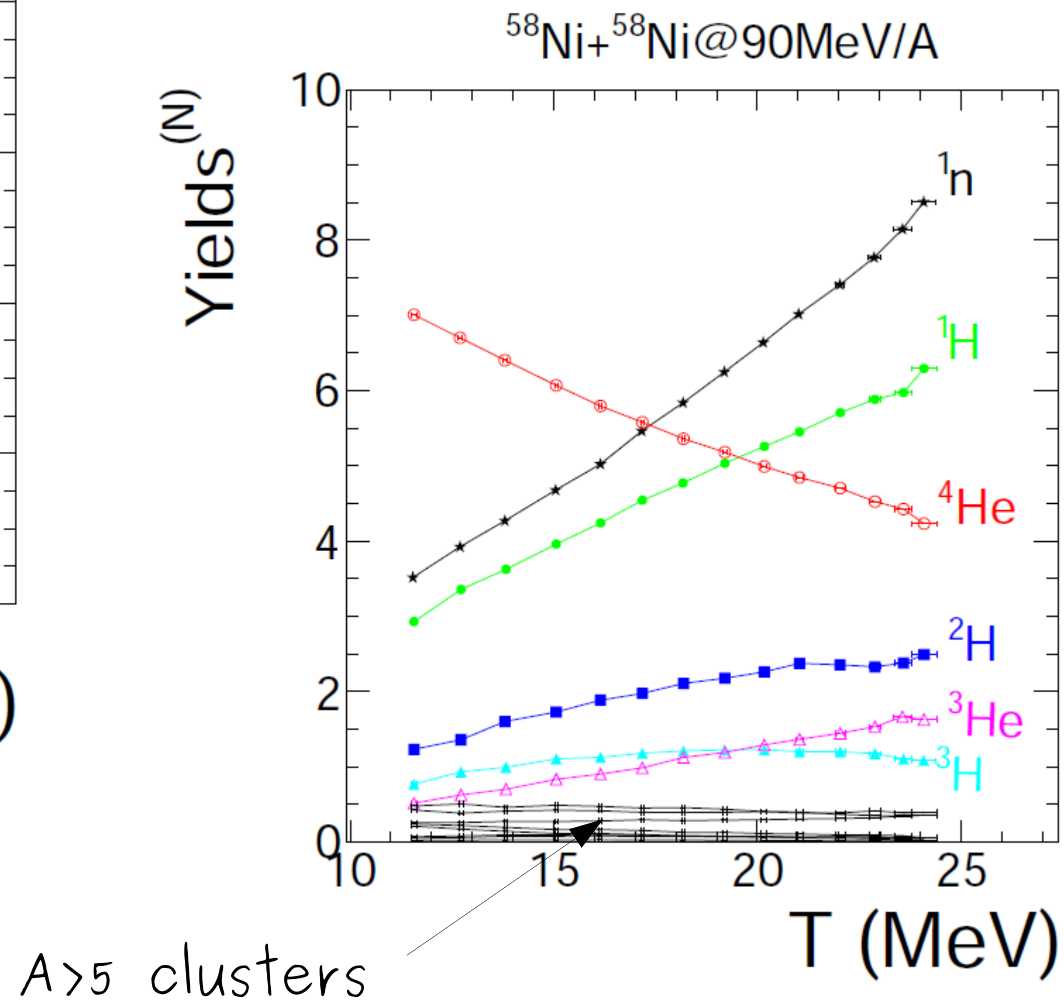


Next step : extract density from yields

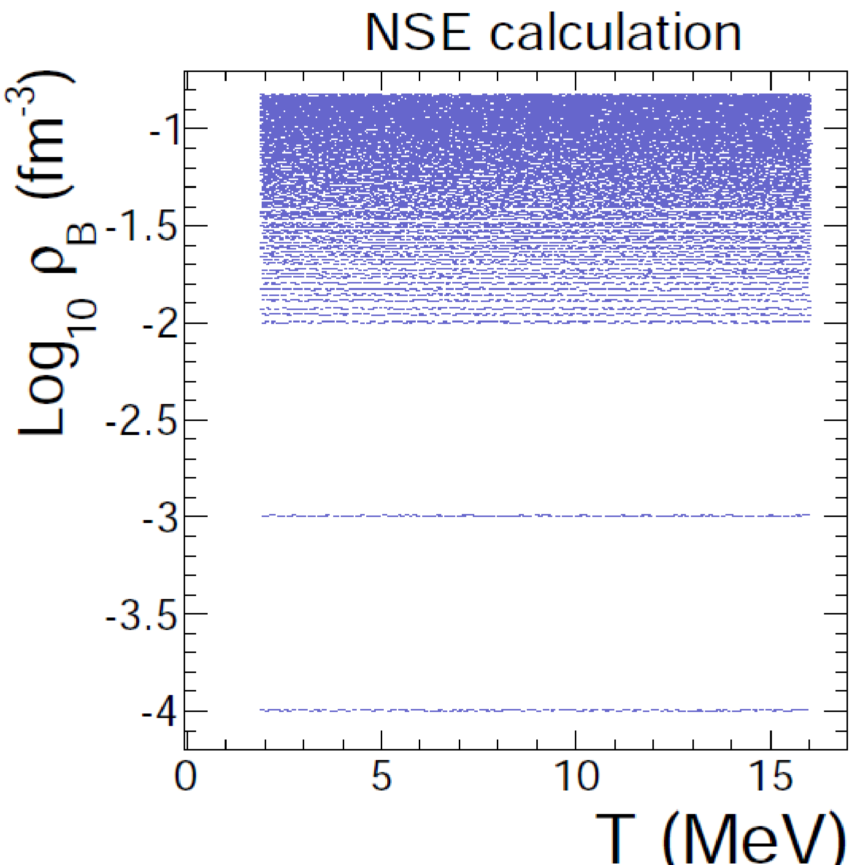


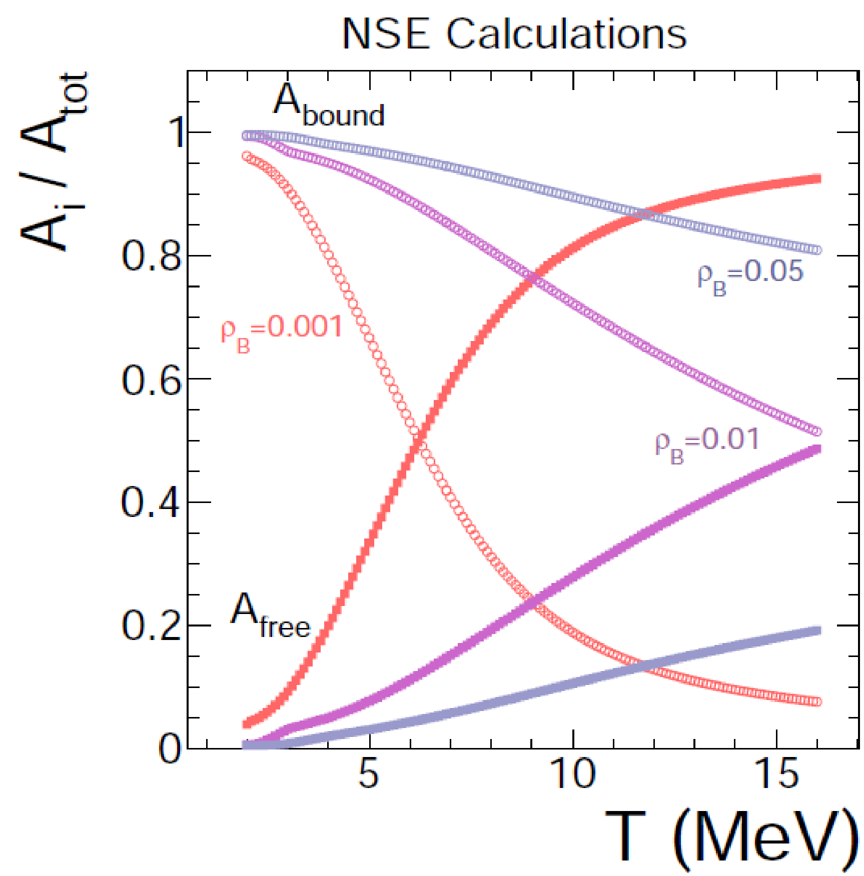
Nucleons sharing

Normalized yields



And start comparison with NSE model developed by F. Gulminelli and A. Raduta

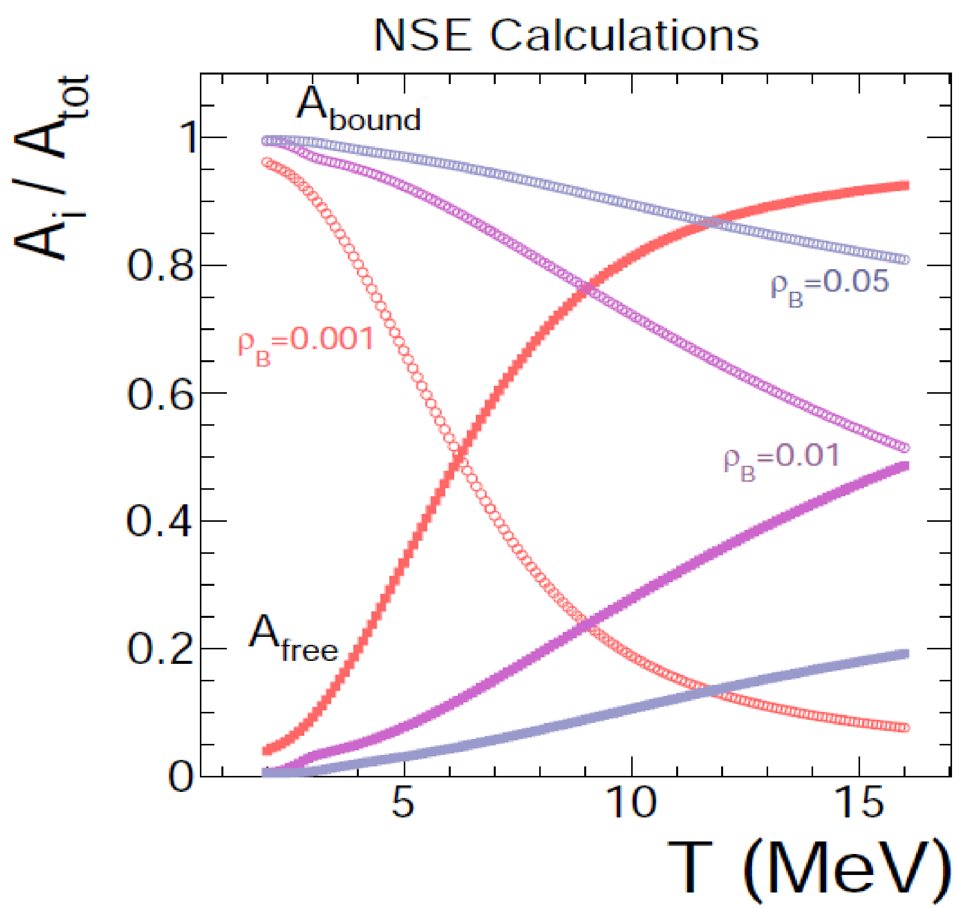


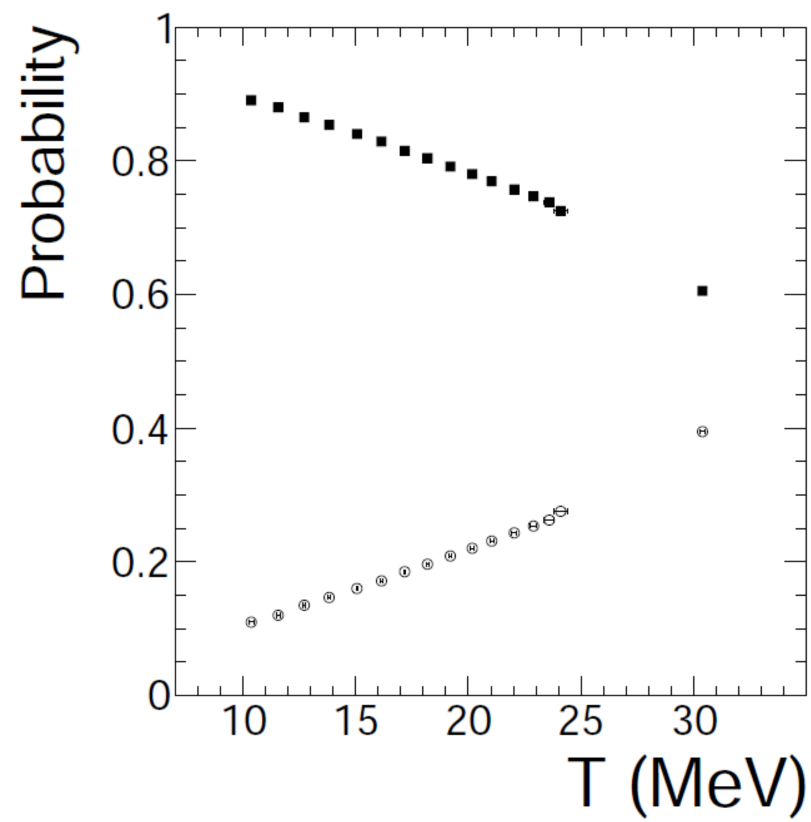


Sample temperature and density values

Evolution of nucleon repartition Between gas and bound clusters

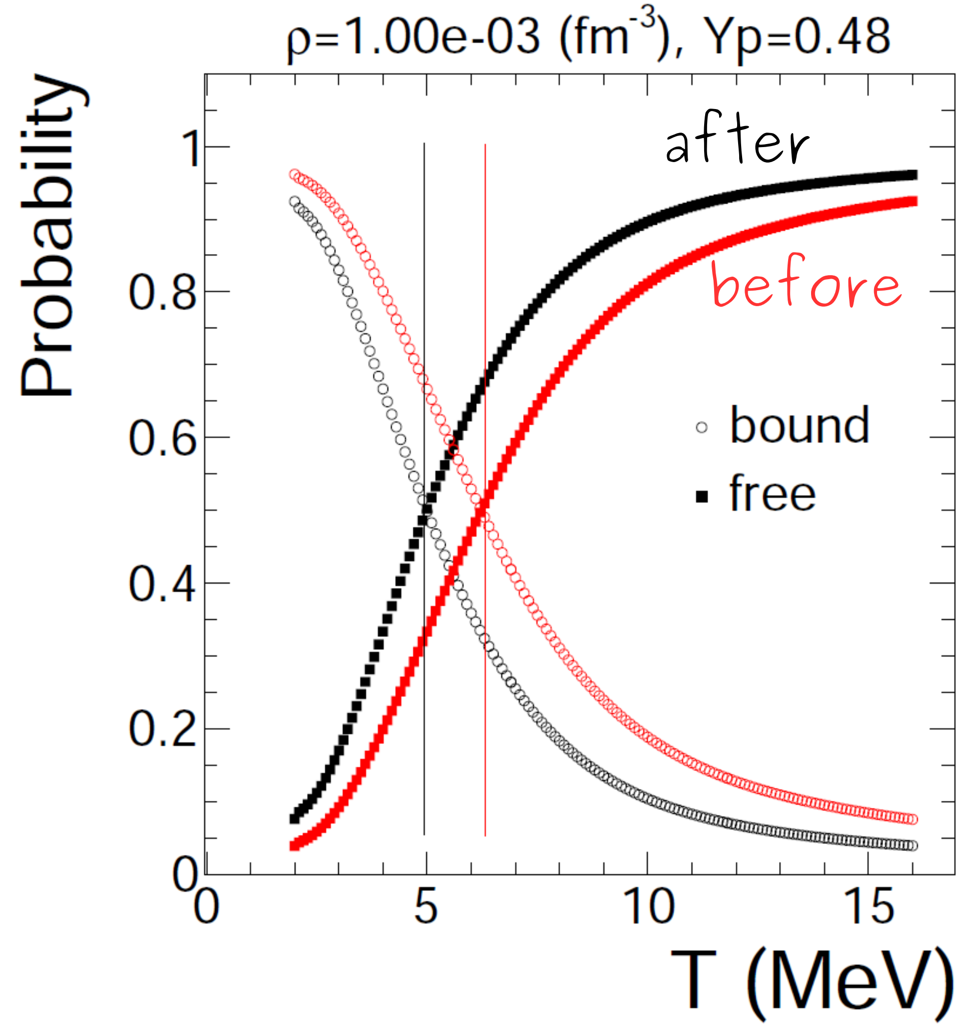
Comparison based on cluster yields and free nucleons multiplicity



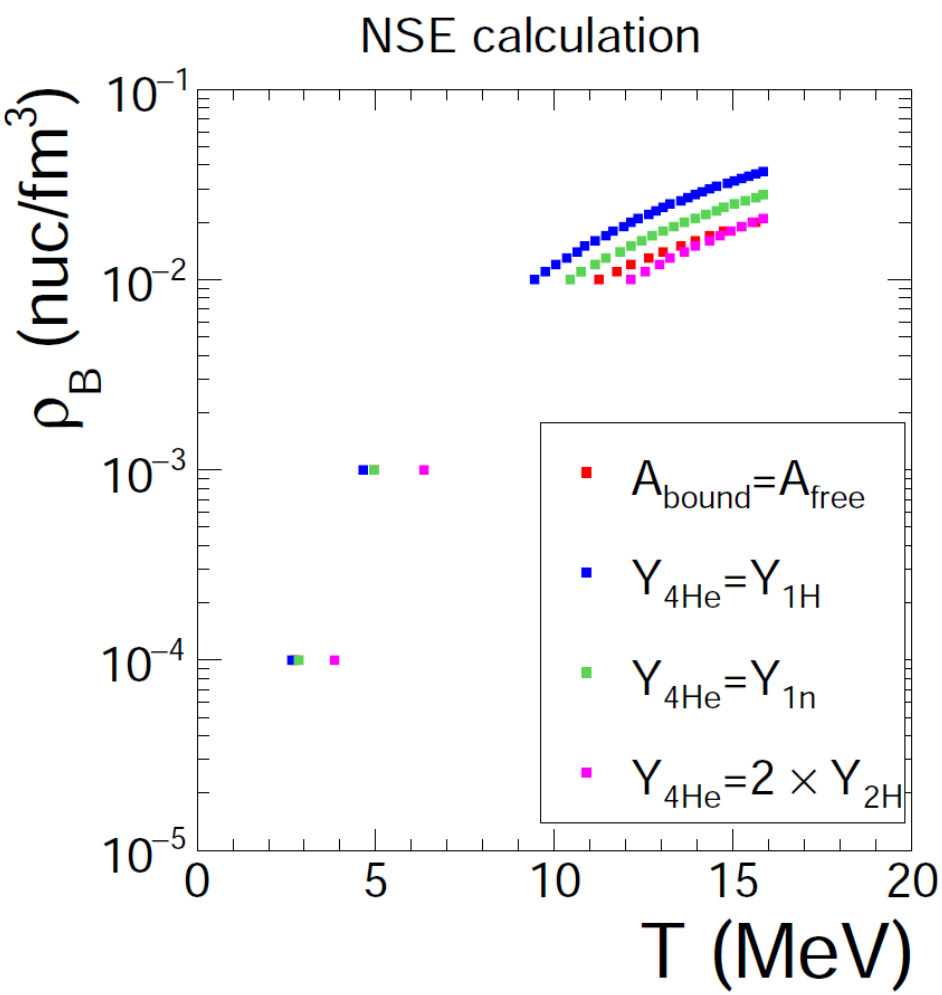


Comparison with NSE calculation :
Effects of de-excitation

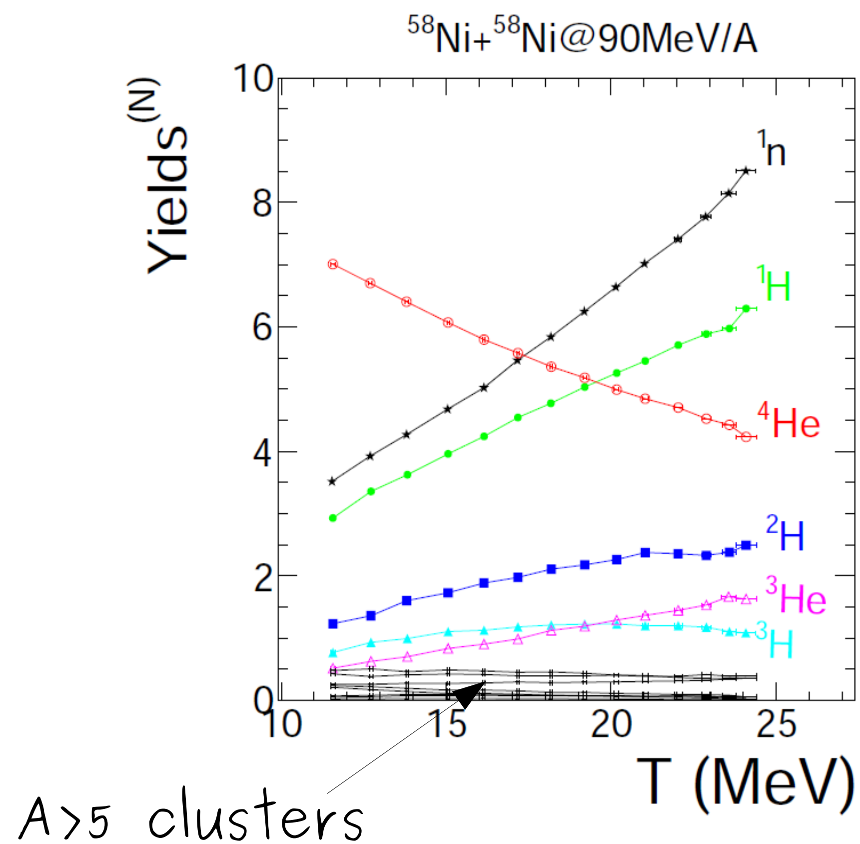
Delta T around 1 MeV



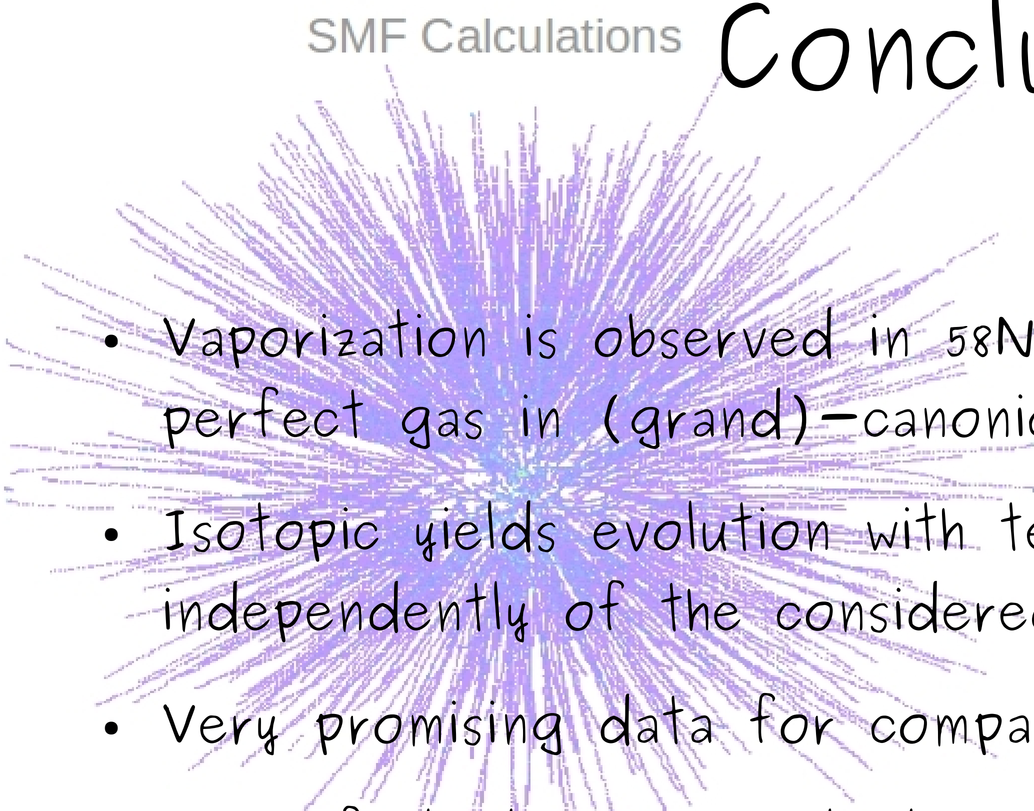
Yields comparison will define T-rho region where calculations fit the data

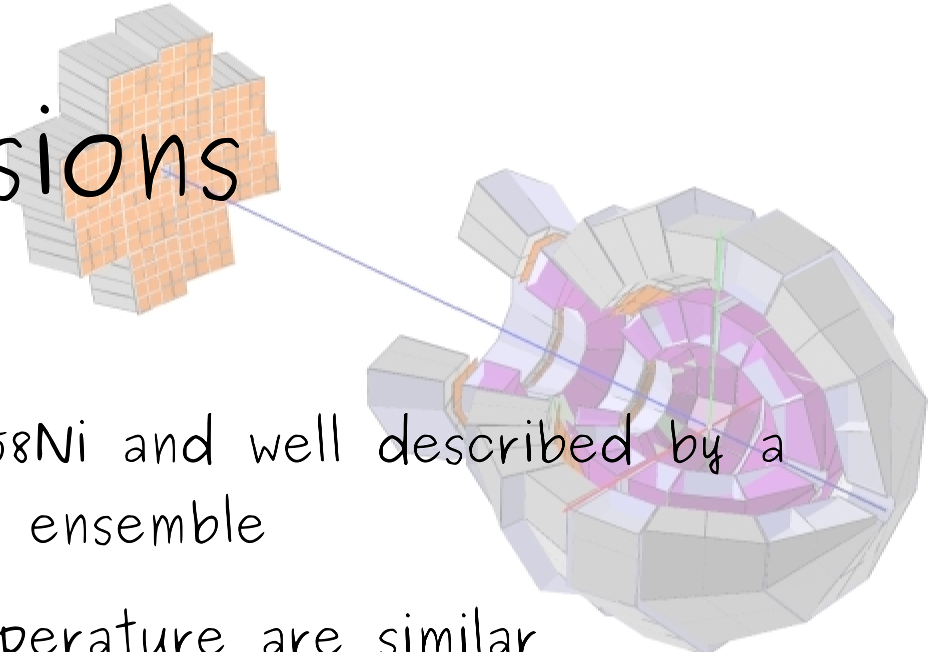


Normalized yields

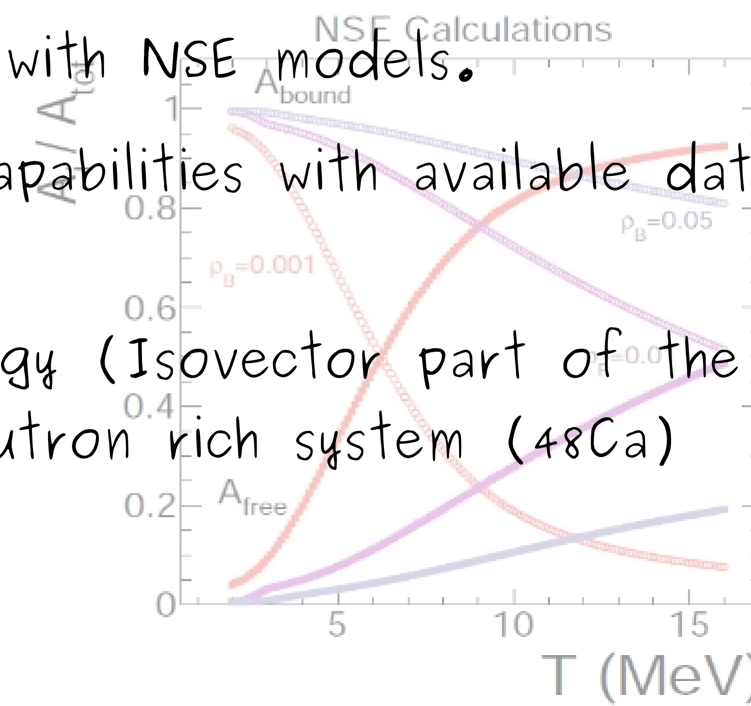


Conclusions



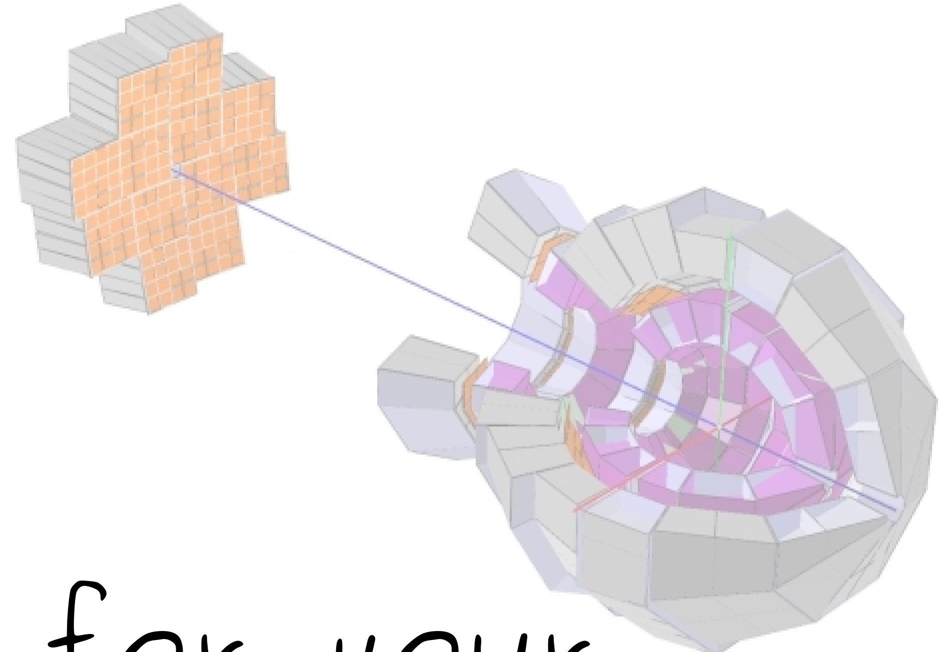


- Vaporization is observed in $^{58}Ni+^{58}Ni$ and well described by a perfect gas in (grand)-canonical ensemble
- Isotopic yields evolution with temperature are similar independently of the considered sizes (from A=40 to 100)
- Very promising data for comparison with NSE models.
  - In first step check, test model capabilities with available data for N/Z~1
  - Then constrain the symmetry energy (Isovector part of the energy functional) using more neutron rich system (^{48}Ca)



SMF Calculations

Trajectories in r-space



Thank you for your attention

NSE Calculations