Investigation of the EOS at low densities.

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( GANIL)

- Nuclear equation of state
- Density dependence of $E_{\text{sym}}(\rho)$
  - Isospin diffusion and migration
  - Width of isotopic distribution of fragments
- Presentation of GANIL
- Conclusion
Nuclear equation of state

\[ \epsilon(\rho, \delta) = \epsilon(\rho, \delta = 0) + \epsilon_{\text{sym}}(\rho) \cdot \delta^2 + \ldots \]
\[ \delta = (\rho_n - \rho_p) / \rho \]

parametrization

\[ \epsilon_{\text{sym}}(\rho) = \frac{C_{\text{kin}}}{2} \left( \frac{\rho}{\rho_0} \right)^{2/3} + \frac{C_{\text{pot}}}{2} \left( \frac{\rho}{\rho_0} \right)^\gamma \]

- The asymmetric term \( \epsilon_{\text{sym}} \) is unknown for \( \rho \neq \rho_0 \)
- Relevant to describe:
  - structure of exotic nuclei and the neutron skin
  - GDR, pygmy dipole
  - Dynamics of heavy-ion collisions
- Relevant to the properties of astrophysical phenomena
  - mechanism of supernova explosion
  - cooling and composition of neutron star

[2] M. Colonna et al., EPJA50:30
Tools to probe the EOS

- HIC at intermediate energies with asymmetric nuclei provide a unique opportunity:
  - production of exotic nuclei with a wide isospin range
  - exploration of nuclear matter under extreme conditions of $\rho$, $P$, $T$ and $J$
  - offer a unique terrestrial tool to produce nuclear matter in a large range of densities
  - explore the density dependence of the symmetry energy
  - At intermediate energies only low densities are explored

- However, HIC is a complicated process (dynamics, transport, evaporation...)

- Observables $\text{Esym}(\rho)$:
  - Drift and diffusion
  - Width of isotopic distribution of fragments (HIC)
Isospin Transport

\[ j_n - j_p = \left( D_n^\rho - D_p^\rho \right) \nabla \rho - \left( D_n^\delta - D_p^\delta \right) \nabla \delta \]

\[ \propto \frac{\partial E_{\text{sym}}}{\partial \rho} \quad \propto E_{\text{sym}} \]

- the difference of the neutron and proton current between the 2 colliding nuclei
- density gradient: referred as drift or migration of the isospin
- isospin gradient: diffusion
- drift and diffusion depend on the interaction time and the two gradients:
  - Long == equilibration
  - Short == partial transparency
Experiments to probe $E_{\text{sym}}(\rho)$

- $^{40}\text{Ca}+^{40}\text{Ca}$  \( N/Z = 1 \)  @ $E/A=35$ MeV
- $^{40}\text{Ca}+^{48}\text{Ca}$  \( N/Z=1.2 \)  diffusion
- $^{48}\text{Ca}+^{40}\text{Ca}$  \( N/Z=1.2 \)  diffusion
- $^{48}\text{Ca}+^{48}\text{Ca}$  \( N/Z=1.4 \)

- **VAMOS high acceptance spectrometer, angle 2-7°**
  - charge and mass identification (more than 10 isotopes / Z)
  - 12 Brho sets measurements in order to cover the whole velocity range of fragments
  - special attention to the normalization between Brho based in Zgoubi package.
  - many thanks to Q. Fable and P. St-Onge, did a lot effort to perform this normalization.

- **INDRA $4\pi$ detector, 7-176°**
  - Z identification for $Z>4$
  - Z and A identification for $Z<5$
Overview of the experiments

detection  Dipole  Q2  Q1  INDRA

beam
Chart of Nuclides identified in VAMOS

Identification in charge and mass for a wide range of isotopes for Z=5-22
Proton drip line is populated
The fragments measured for the 48Ca projectile are more n-rich than those for the 40Ca projectile for all Z’s. Small effect of the target is observed (open symbols).
Average neutron excess vs $Z_{\text{vamos}}$

- EAL defined as the line in N. Chart towards which an ER of excited source moves as it cools.
- For $Z = 20$
  - For $^{48}\text{Ca}$ projectile we observe $<N>-Z = 3.5$;
  - For $^{40}\text{Ca}$ projectile we observe $<N>-Z = -2$
- In both cases we reach the EAL
- This is the first direct measurement of the EAL.

Average neutron excess vs $Z_{vamos}$

- reaching the EAL is the interplay between isospin diffusion and secondary decay
- How to disentangle the two contributions?
- Using observables involving ratio of n-rich / n-poor systems, (isoscaling, imbalance ratio) to minimize the effect of secondary decay.
- reconstruction of primary quantities
Imbalance ratio applied to the neutron excess

For a given neutron rich nuclei A and neutron poor B, A+A, B+B, A+B reactions

\[ R_i(X) = \frac{2(X - (X_{A+A} + X_{B+B})/2)}{X_{A+A} - X_{B+B}}. \]

x sensitive to isospin = \( <N-Z>/A \)

R = 0, equilibration, diffusion
R = +/- 1, no equilibration, no diffusion

- complete equilibration is not reached
- differences between primary and secondary are observed
comparison to AMD (transport model)

- AMD (antisymmerized molecular dynamics) : reproduction of data
- hard to distinguish between the two interactions.
- Comparison to the primary quantities might help to distinguish between the two interactions: Work in progress...
Isospin migration

INDRA

$\frac{N_{n}/Z_{n}}{N_{T}/Z_{T}}$, $\rho_{p} = \rho_{0}$,

mid-rapidity

$67^\circ < \theta_{\text{CM}} < 90^\circ$

Forward angle

$7^\circ < \theta_{\text{CM}} < 30^\circ$

$^{40}\text{Ca}+^{40}\text{Ca}$

$^{40}\text{Ca}+^{48}\text{Ca}$

$^{48}\text{Ca}+^{40}\text{Ca}$

$^{48}\text{Ca}+^{48}\text{Ca}$

$\left(\frac{N}{Z}\right)_{CP}$

$V_{Z}^{PLF} (\text{cm/ns})$
Isospin migration comparison to AMD

♦ AMD : not enough statistic to show differences of the \((N/Z)_{CP}\) of LCP emitted at mid-rapidity and at projectile zone.
$E_{\text{sym}}(\rho)$ from the width of isotopic distribution of fragments
Reconstruction of the primary $Z_{pr}$ and $A_{pr}$ distributions

Why?
The observable (width) can be distorted by the secondary decay of the primary isotopic distribution, affect the extracted $E_{sym}$

$$Z_{pr} = Z_{PLF} + \sum_{i=1}^{M_{LCP}} z_i$$

$$A_{prwon}(Z_{pr}) = A_{PLF}(Z_{pr}) + \sum_{i=1}^{M_{LCP}} a_i$$
comparison of the primary isotopic distribution $\sigma(A_{pr})$ to transport calculations AMD
symmetry energy from the width of the primary isotopic distributions

\[ -\ln Y(N, Z) = \xi(Z)N + \eta(Z) + \zeta(Z) \frac{(N - Z)^2}{N + Z} \]

Statistical treatment

\[ \xi(Z) \propto \frac{1}{\sigma} \propto C_{sym}(Z) / T \]
How to get rid of the temperature?
- ratio of AMD-Soft/Exp(E_{sym})
- ratio of AMD-Soft/Stiff (density)
determination of density, $C_{\text{sym}}$ and Temperature

$\rho/\rho_0 = 0.78 \pm 0.03$,

$C_{\text{sym}} = 24$ MeV;

$T = 3.4.8$ MeV

Lin et al., PhysRevC.89.021601_2014
Liu et al., PhysRevC.90.014605_2014
Short presentation of GANIL
Overview of GANIL

Cyclotrons / SPIRAL1

- RIB produced by fragmentation (LISE, T > 10 µs)
- RIB with SPIRAL1 (ISOL, T>10ms): accelerated with CIME up to 20 MeV/u
Overview of GANIL

- **LINAC driver**: high intense beams
  - 33 MeV proton and 40 MeV deuteron (5 mA)
  - 14.5 MeV/u heavy-ion (1 mA)
- **NFS** beams of neutron (a few MeV to 40 MeV)
- **S3** super separator spectrometer (fusion ev. reactions, spectroscopy for SHE, N=Z)
- **DESIR**: study of exotic ions at low E, from S3 / SP1
- Production of fission fragments induced by n + U reactions (stand by)
Highlights from GANIL

• Start of the commissioning of SPIRAL2 – LINAC after getting the full authorization from the safety authority.

• New beams from the SPIRAL1 upgrade

• Experimental campaigns with AGATA coupled to NEDA DIAMANT and to MUGAST+VAMOS

• New detectors: NEDA, ACTAR TPC, FAZIA, MUGAST
conclusion

♦ observation of isospin diffusion in PLF by direct measure of the PLF residue with VAMOS
♦ Imbalance ratios indicate no complete equilibration for secondary and primary fragments.
♦ observation of isospin migration in coincidence with PLF size
♦ AMD reproduces the data for the PLF but no sensitivity to EOS soft and stiff interactions, work in progress
♦ consistent way to deduce density, symmetry energy and temperature from the width of the primary isotopic distributions
♦ We have a set of data that for the first time measure different isospin sensitive observables in the same reaction.
♦ The set of data is open to comparison to all transport models engaged to link data to the symmetry energy.
♦ Q. Fable et al, PRC+PRL in preparation
Constraining the density dependence of the symmetry energy

In progress...

courtesy of A. Le Févre
isospin migration: case of t/3He yield ratio

- Y(t)/Y(3He) at mid-rapidity increases with n-rich system
- no way to reproduce it with the AMD calculation
- improvement of the code is in progress, introduction of correlation to reproduce the clusters
- Is it migration/drift of neutron matter to the low density region at mid rapidity?
accessing the symmetry energy from the isotopic distribution

AMD simulations: $^{48}\text{Ca}+^{48}\text{Ca}$ and $^{40}\text{Ca}+^{40}\text{Ca}$, E/A=35 MeV and $b > 6$ fm

Primary fragment distributions


$$-\ln Y(N,Z) = \xi(Z)N + \eta(Z) + \xi(Z) \frac{(N-Z)^2}{N+Z}$$

Statistical treatment

$$\xi(Z) \propto \frac{1}{\sigma} \propto C_{\text{sym}}(Z)/T$$
Application to the reconstructed of the primary charge: study of the odd-even staggering effect on the charge distribution as a function of the isospin
Overview of the experiment

- $Z_{vamos} - \Sigma Z_{indra}$: good detection of QP products
- $Z_{vamos} - E_{TRANS}$: degree of dissipation or impact parameter estimate.
- $Z_{vamos} - V_z$: high cx at $V_z$ close to $V_{proj}$ and high charge, originate from QP: PLF
Excitation energy? How to deduce the evaporated neutrons?

- from t/3He?
- conservation of the N/Z?
- directly from the N/Z of the mean primary isotopic distribution predicted by AMD.
- Apr – nev distribution is shifted by the neutron number.
- the width of the isotopic distribution is then not modified.