Isospin effects on the nuclear equation of state at low densities

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• Nuclear equation of state
• Isospin transport
• Experimental results: isospin diffusion and migration
• Comparison to models
• Conclusion
Nuclear equation of state

\[ \varepsilon(\rho, \delta) = \varepsilon(\rho, \delta = 0) + \varepsilon_{\text{sym}}(\rho) \cdot \delta^2 + \ldots \]

\[ \delta = (\rho_n - \rho_p) / \rho \]

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

parametrization

- The asymmetric term \( \varepsilon_{\text{sym}} \) 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
isospin transport

- 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
- observables Drift and diffusion
Isospin drift and diffusion

♦ diffusion; exchange between PLF and TLF proceeds towards a direction that tends to equilibrate N/Z.

♦ depend on the interaction time
  - Long == equilibration
  - Short == partial transparency

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

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

\[
\propto E_{\text{sym}}
\]

\[
\delta = \frac{N - Z}{N + Z}
\]
Experiments

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

♦ VAMOS high acceptance spectrometer, angle 2-7°
  ➢ charge and masse identification (more than 10 isotopes / Z
♦ INDRA $4\pi$ detector, 7-176°
  ➢ Z identification for Z>4
  ➢ Z and A identification for Z<5
Experimental results:

VAMOS

INDRA
Experimental results: isospin diffusion

Different evolution depending on the N/Z of the system

- Projectile: available number of neutron in entrance channel
- Target: isospin diffusion

$V_Z^{PLF}$ reflect collision dissipation

- Initial N/Z not reached
  - Statistical decay

Behavior of N/Z of the fragment in VAMOS

- $^{48}\text{Ca} + ^{48}\text{Ca} \rightarrow N/Z=1.4$
- $^{48}\text{Ca} + ^{40}\text{Ca}
  \rightarrow N/Z=1$
- $^{40}\text{Ca} + ^{48}\text{Ca}
  \rightarrow N/Z=1.2$
Comparison to models: isospin diffusion data

\[ \langle N/Z \rangle_{PLF} \]

- **Data**
  - \( {^{40}\text{Ca} + ^{40}\text{Ca}} \)
  - \( {^{40}\text{Ca} + ^{48}\text{Ca}} \)
  - \( {^{48}\text{Ca} + ^{40}\text{Ca}} \)
  - \( {^{48}\text{Ca} + ^{48}\text{Ca}} \)

- **AMD-soft**

\[ V_Z^{PLF} \text{ (cm/ns)} \]
systems having $^{40}$Ca as projectile

- ELIE and AMD are similar
- Overestimate n-enrichment of fragments

systems having $^{48}$Ca as projectile

- AMD-soft reproduce the data
- High sensitivity to the EOS for the less dissipative collisions ($V_{z}^{PLF} \neq V_{proj}$)
- Isospin diffusion reproduced by AMD
Experimental results: isospin migration

Isotopic ratios

♦ For a given bin of $V_{Z}^{PLF}$ detected in VAMOS

\[
\frac{<N>}{<Z>}_{CP} = \frac{\sum_{Nevt's} Z N_{v}}{\sum_{Nevt's} Z_{v}}
\]

\[
v = 2,3H, 3,4,6He, 6,7,8,9Li, 7,9,10Be
\]
Experimental results: isospin migration

Isotopic ratios

♦ Hierarchy of the isotopic ratios within the n-enrichment of projectile and then the target

♦ Symmetric systems:
  - n-enrichment of mid-rapidity
  - Direct experimental measurement
  - Isospin migration
Comparison to models: isospin migration

- The $(N/Z)_{CP}$ of light charged particles emitted at mid-rapidity are not reproduced by AMD. Moreover, the n-enrichment of neck is not observed in AMD.
Imbalance ratio

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

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

$R(X_{A+A}) = R(X_{A+B}) = 1$  projectile

$R(X_{B+B}) = R(X_{B+A}) = -1$  target

$R(X_{A+B}) = R(X_{B+A}) = 0$  comple mixing, equilibration

$X = \text{sensitive to the symmetry energy}$

$X = \langle N/Z \rangle$ of fragments detected in VAMOS
Imbalance ratio

♦ preliminary analysis
♦ interesting observable less sensitive to:
  - secondary decay
  - experimental efficiencies
♦ It can be compared to different transport models
Imbalance ratio

- farther analysis as a function of the fragment velocity detected in VAMOS are foreseen
- important evolution of N/Z are expected with the velocity, ($V_{PLF}$ vs $V_{neck}$)
- Imbalance ratio is easier to be compared to different classes of transport models
conclusion

♦ observation of isospin diffusion in PLF by direct measure of the PLF residue with VAMOS no reconstruction with hypothesis

♦ Imbalance ratios calculated for N/Z of PLF
  ➢ further analysis as a function of the fragment velocity detected in VAMOS are foreseen

♦ observation of isospin migration (thanks to INDRA) in coincidence with VAMOS

♦ 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.