Study of isospin transport in ^{40,48}Ca+^{40,48}Ca reactions at 35 MeV/nuc

Quentin Fable*
INDRA-FAZIA collaboration

L2IT, UMR 5033 CNRS-UT3, Toulouse
*quentin.fable@l2it.in2p3.fr

Nuclear equation of state and asymmetry energy

Equation of state :

- The nuclear equation of state (NEoS) describes the behaviour of the energy of a nuclear system under the variation of temperature, density and neutron-to-proton (isospin) asymmetry.
- The NEoS plays a key role in modeling :
  - Nuclear systems (and reaction mechanisms) probed in laboratory experiments ;
  - Core-collapse supernovae and mergers of compact binary stars [1] .

Asymmetry energy :

- The energy is usually described as the sum of a symmetric ε_0 and asymmetric ε_{asym} components :

$$\varepsilon(\rho,\delta) = \varepsilon_0(\rho,\delta=0) + \varepsilon_{asym}(\rho)\cdot\delta^2 + \mathcal{O}\left\{\delta^4\right\} \qquad \delta = (N-Z)/A \qquad (1)$$

- ε_{asym} describes the energetic cost of converting symmetric matter into pure neutron matter.
  → largely unknown when we move away from T=0 and $\rho=\rho_0$

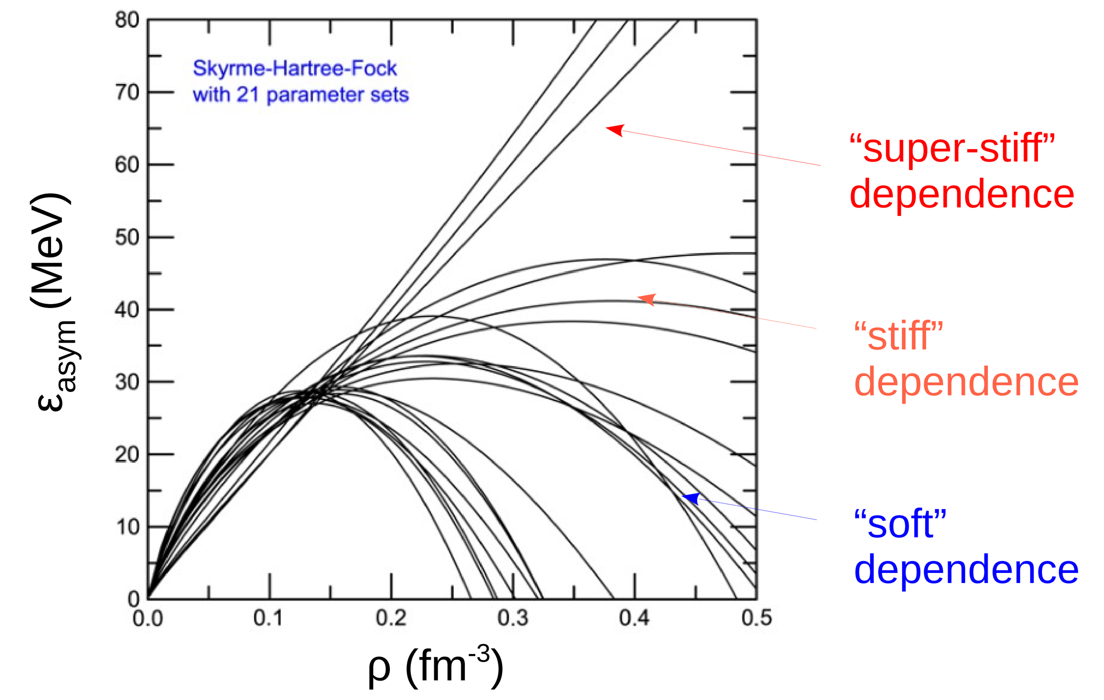


Fig.1 : Various predictions of the density dependence of the asymmetry energy (Skyrme-Hartree-Fock approach) [2].

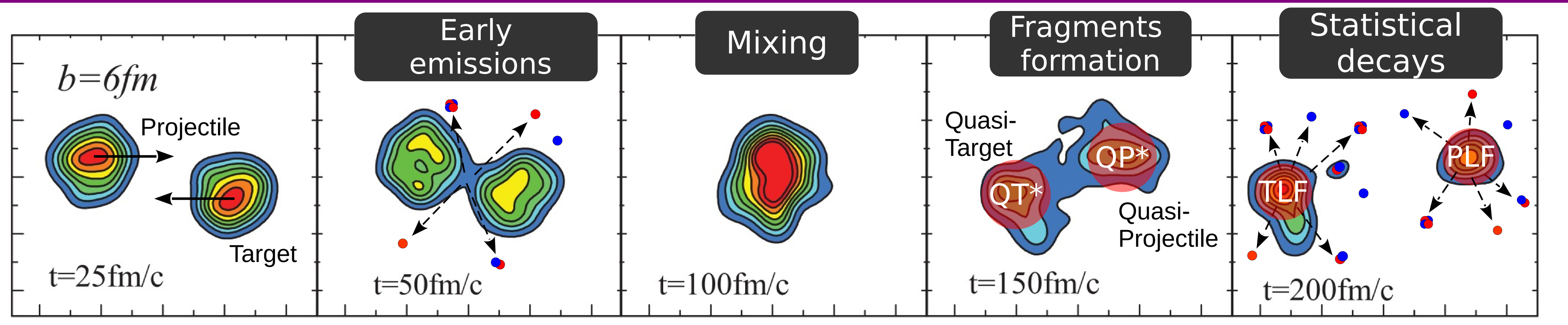


Fig.2 : Illustration of Heavy Ion Collisions at intermediate energies from ImQMD transport model [3].

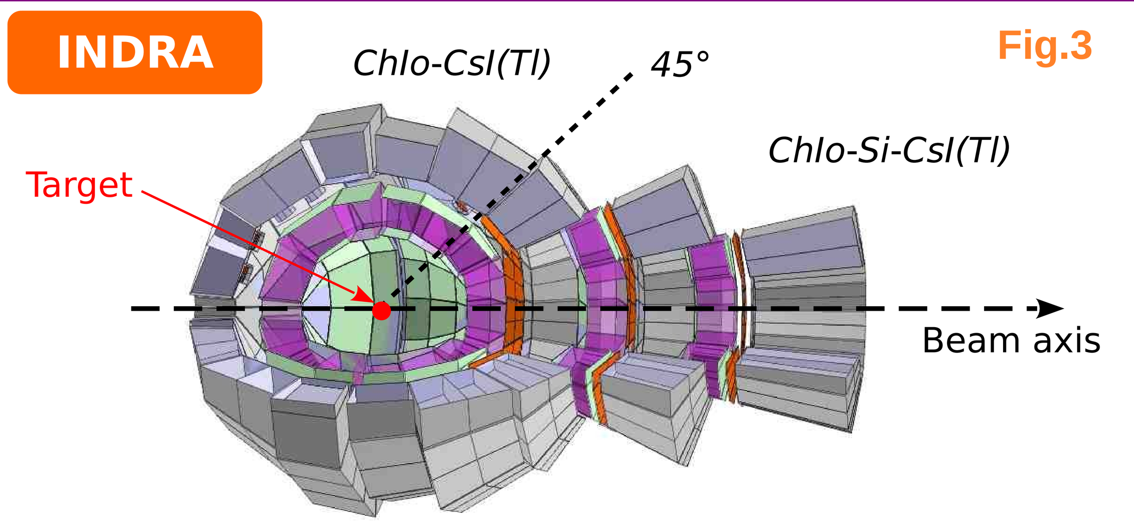
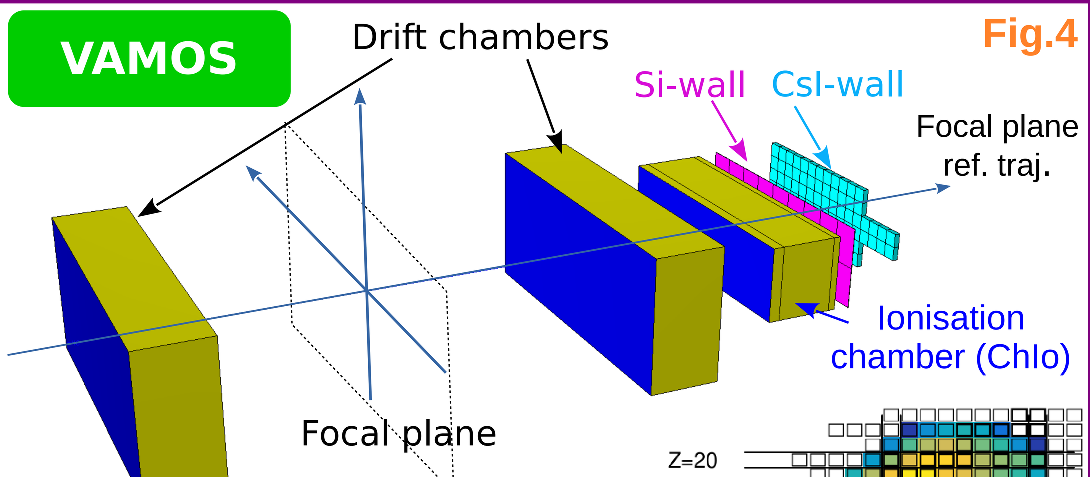


Fig.3

- 14 rings centered around beam axis (~300 identification modules)
- Identification :
  → (Z,A) for Light Charge Particles (Z≤2)
  → Z up to Z~25
- $\Theta_{LAB} \approx$ 7°- 176°
- Event characterization (*impact param, E*, T,...*)



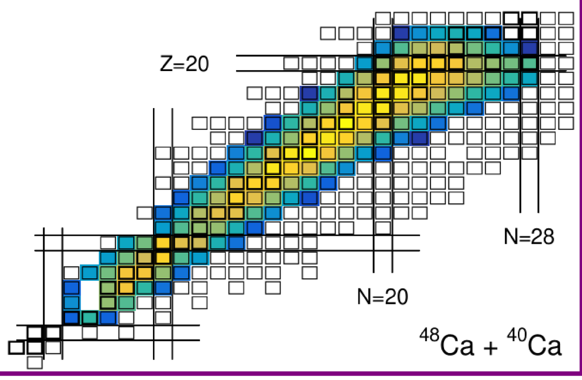


Fig.4

- $\theta_{LAB} \approx$ 2.5°-6.5°
  $\varphi_{LAB} \approx$ 220°-320°
- 12 Bρ settings :
  → $B\rho_0 \approx$ 0.661-2.220 T.m
- PLF identification

Heavy ion collisions

Heavy-ion collisions (HIC)

- Submit nuclei to various ρ, P and T under laboratory-controlled conditions ;
- Unique way to form exotic nuclei with a large neutron to proton asymmetry and high excitation energies.

Peripheral and semi-peripheral collisions

- Intermediate energies (15 < E_{beam} < 100 MeV/nuc) ;
- Described as two-step process (Fig.2) :
  → Primary excited fragments formed with properties similar to the projectile and the target (Quasi-Projectile/Target, QP/QT) ;
  → Decay by evaporation of Light-Charged Particles (LCP), leading to Projectile/Target-Like Fragment (PLF/TLF) residues.
- Experimentally : only the secondary fragments are detected.

Experimental details - INDRA-VAMOS coupling [4]

- ^{48,40}Ca+^{48,40}Ca at 35 MeV/A ;
- VAMOS high acceptance spectrometer (trigger, Fig.4) :
  → PLF identification (Z_V, A_V) ;
- INDRA ~4π detector :
  → coincident LCP identification (Fig.3) ;
- Neutrons are not detected ;
- Peripheral/semi-peripheral collisions
- Near-saturation density domain is expected.

Isospin transport phenomena

Isospin migration

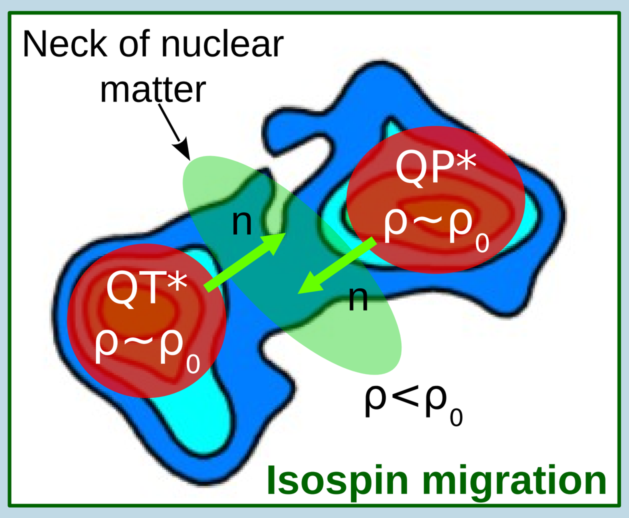
- Local density gradient of nuclear matter leads to the migration of neutron to low-density region ($\rho<\rho_0$)
- Related to the slope of the asymmetry energy : $\dfrac{\partial\varepsilon_{asym}}{\partial\rho}$

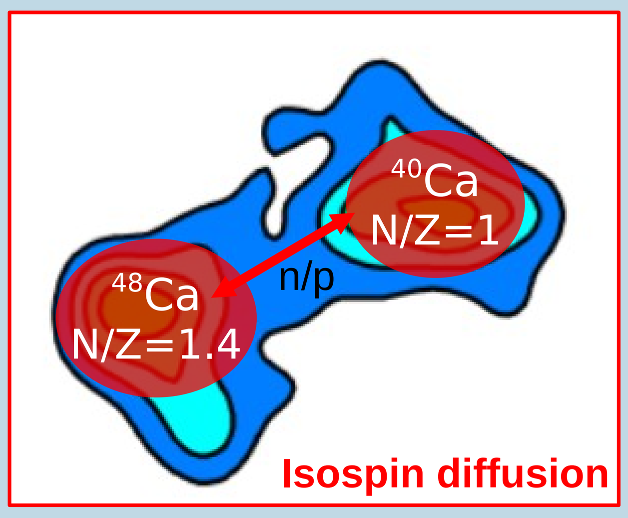
Isospin diffusion

- Minimisation of N/Z concentration gradient of nuclear matter leads to neutron and proton currents between the projectile and the target ;
- Related to the value of ε_{asym}

Isospin transport

- Isospin transport is the competition between isospin **migration** and isospin **diffusion** [5] ;
- This transport phenomena is directly related to $\varepsilon_{asym}(\rho)$;
- It depends on the time interaction between projectile and target :
  → Impact parameter (initial distance between projectile and target) ;
  → Beam energy.
- Its study requires :
  → High isotopic resolution ;
  → Special attention to statistical decays ;
  → Evaluation of the interaction time and dissipation of the collision.





Isospin transport ratio

Isospin equilibration is studied with the isospin transport ratio of an isospin-sensitive observable "x"

$$R_x = \frac{2x^M - x^{NR} - x^{ND}}{x^{NR} - x^{ND}} \quad (2) \qquad ; x = \delta$$

M : asymmetric system – ^{40}Ca+^{48}Ca and ^{48}Ca+^{40}Ca
NR : neutron-rich system – ^{48}Ca+^{48}Ca
ND : neutron-deficient system – ^{40}Ca+^{40}Ca

Centrality estimation

Collision centrality is estimated from the transverse energy of light charged particles detected in INDRA (~90% efficiency)

$$E_{t12} = \sum_{i:Z_i\leq 2} E_i \sin^2\theta_i \qquad (3)$$

To avoid system-dependence, it is more convenient to sample the events with the experimental centrality defined as :

$$c_{E_{t12}} \equiv \int_{E_{t12}}^{+\infty} P(\tilde{E}_{t12})\,\mathrm{d}\tilde{E}_{t12} \qquad (4)$$

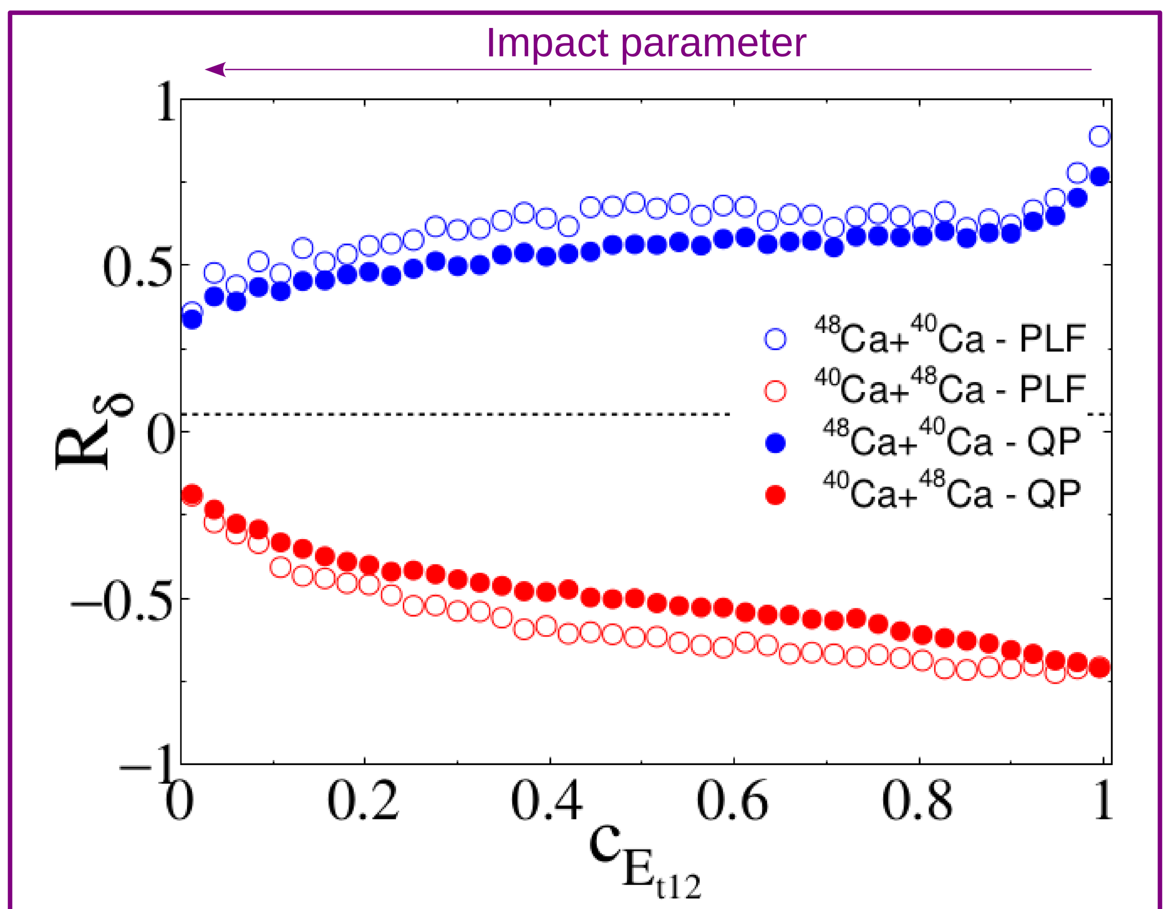


Fig.2 : Experimental isospin transport ratio as a function of experimental centralitycentrality for the PLF detected in VAMOS and the reconstructed Quasi-Projectile [6].

Results and outlooks

The **isospin equilibration** taking place in peripheral HIC at intermediate energies was investigated by means of the **isospin transport ratio** [6].

- The N/Z asymmetry of the PLF detected in VAMOS is used as an isospin-sensitive observable ;
- The transverse energy was exploited for experimental centrality sorting ;
- A reconstruction of the Quasi-Projectile was also attempted, based on the relative velocities between the reaction products detected in INDRA and the PLF [4].

A gradual decrease of the ratio is observed with decreasing charge, from **0.75** for the most peripheral collisions (c_{Et12}~1) towards **0.25** for the most dissipated (c_{Et12}~0) .

These findings demonstrates :

- A clear experimental evolution towards isospin equilibration, while a full N/Z equilibration is not reached ;
- An effect of the statistical decay on the ratio as a smoother evolution is observed for the QP (full circles) compared to the PLF (open circles).

The presented results show the potential of the INDRA-VAMOS coupling to provide further constraints on the asymmetry energy term in the NEoS.

Comparisons with various dynamical models (QMD-like and BUU-like), based on Bayesian analysis, are undergoing.

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[2] L.W. Chen, C.M. Ko, B.A. Li, Phys. Rev. Lett. 94, 032701 (2005)
[3] Y. Zhang et al., Phys. Rev. C 85, 024602 (2012)
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