migration and **diffusion** in *isospin-sensitive experiments* at *FRIB* : *from transport theory to measurable observables*

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• *isospin drifts* : not so elusive after all, we can revisit them with isospin-sensible detection

• tool : *BLOB11 + mesoscopic tracking*
→ we expect a new understanding of the process

Scenario : currents of neutrons and protons

- isospin-asymmetric systems ($\eta = \frac{\rho_n - \rho_p}{\rho} \neq 0$) involve different *chemical potentials*

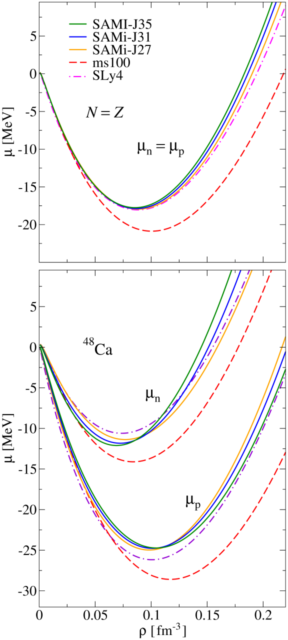
$\mu_n = \frac{\partial(\rho e)}{\partial \rho_n} \quad \neq \quad \mu_p = \frac{\partial(\rho e)}{\partial \rho_p}$

- corresponding *currents* $\vec{J}_{n,p} = -\nabla \mu_{n,p}$ arise

$\Rightarrow$ neutrons and protons streaming out of phase

- *isovector currents* $\vec{J}_a = \vec{J}_n - \vec{J}_p$ exhibit ρ dependence of the *Symmetry energy S* and $\frac{\partial S}{\partial \rho}$ and momentum dependence of n,p potentials

$\rightarrow$ a suitable probe : HIC at Fermi energy



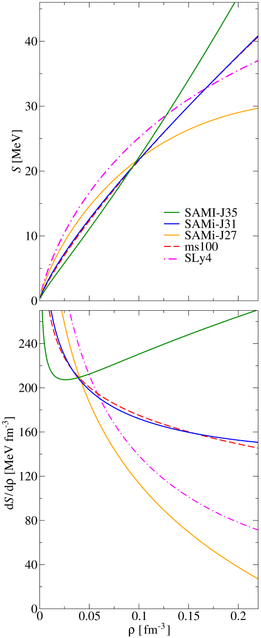
Transport coefficients and symmetry energy

Each current combines diffusion and migration, driven by asymmetry gradients $\nabla\mu$ and density gradients $\nabla\rho$, and the associated *drift coefficients* $D_{\eta,n}$, $D_{\eta,p}$, $D_{\rho,n}$, $D_{\rho,p}$, so that

$$\begin{aligned}\vec{J}_n &= -D_{\eta,n}\nabla\eta + D_{\rho,n}\nabla\rho \\ \vec{J}_p &= -D_{\eta,p}\nabla\eta + D_{\rho,p}\nabla\rho\end{aligned}$$

The *asymmetry current* $\boldsymbol{j}_a = \boldsymbol{j}_n - \boldsymbol{j}_p$ can be expressed in terms of *asymmetry drift coefficients* $D_{\eta,a}$, $D_{\rho,a}$, which are proportional to the symmetry energy and its density derivative,

$$\begin{aligned}\vec{J}_n - \vec{J}_p &= -D_{\eta,a}\nabla\eta + D_{\rho,a}\nabla\rho \\ &= -4\kappa S(\rho)\nabla\eta + \frac{\partial S(\rho)}{\partial\rho}\eta\nabla\rho\end{aligned}$$

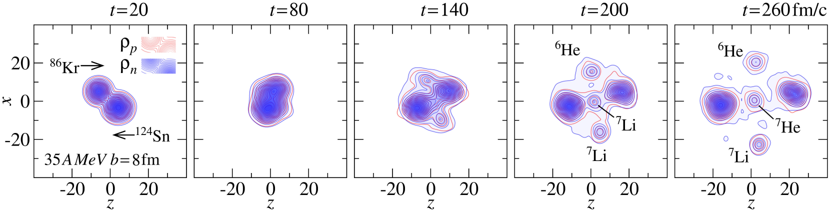


Fermi regime

Owing to the dissipative nature of HIC at Fermi energy :

- All parts af the system interact for a long time span

$\Rightarrow$ *mesoscopic signatures* (connecting transport quantities to thermodynamics and EOS) get entangled, overlap, interfere



- *Modelling this regime :*

combining collective motion and beyond-mean-field dissipation

- *Analysing this regime (from the model, not from calculated data) :*

partial derivatives under some thermodynamical conditions

$\rightarrow$ finest possible mean-field to avoid coarse graining, and issues related to spacial/momentum kernels.

BLOB11

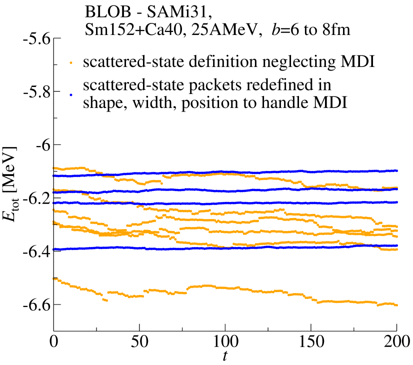
BLOB 11 involves a number of improvements :

• improved initialisation protocol, based on a more strict survey of occupancies → better description of excitation energies in peripheral collisions.

• introduction of relativistic kinematics (but not covariant) → extension to intermediate energies

• Full treatment of the momentum dependence in the mean field and in the final states of scattered

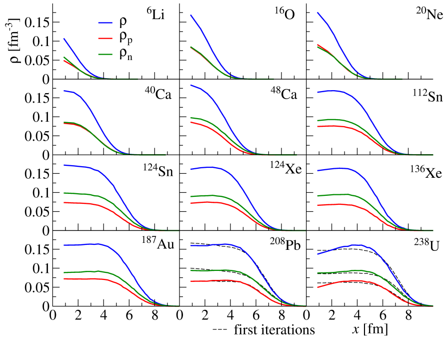
energy conservation when handling several n-n collisions :

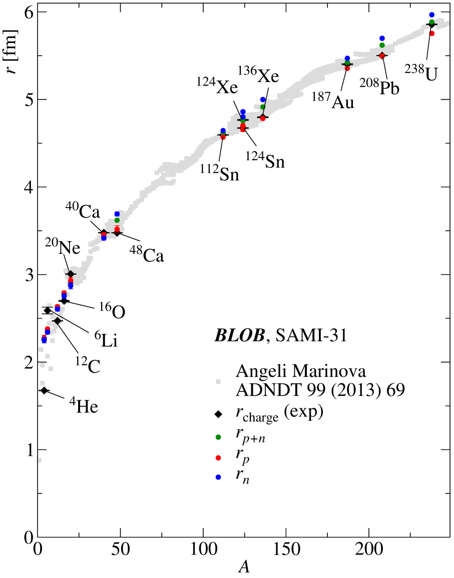


Application : BLOB11 + SAMi-J31

We select *SAMi-J31* : accurate isospin properties in structure, collective motion in nuclei, NM

[Roca-Maza Coló Sagawa PRC86 2012, [Roca-Maza PRC87 2013, Zheng PRC94 2016, Zheng PLB769 2017, Zheng PRC98 2018, Burrello PRC99 2019, Shvedov PRC111 2025]

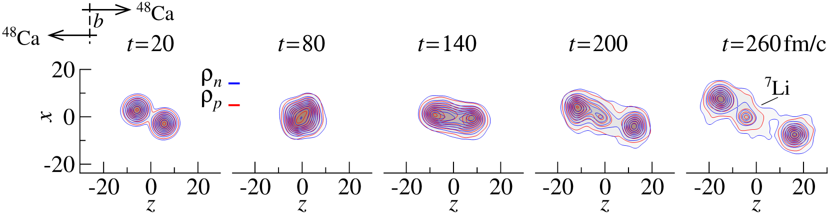




Application to Ca+Ca (because data exist)

Application to Ca+Ca at 35 *A* MeV, already studied experimentally by INDRA/FAZIA at Ganil
[Fable PRC106 2022, PRC107 2022]

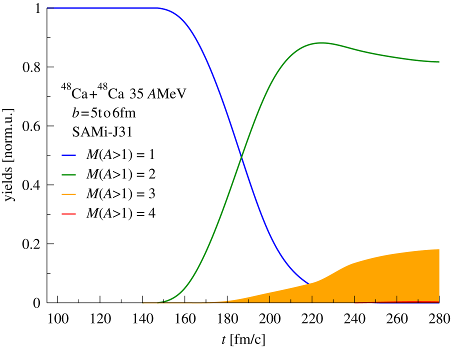
- well suited to study isospin effects
- positioned at the threshold for the neck mechanism

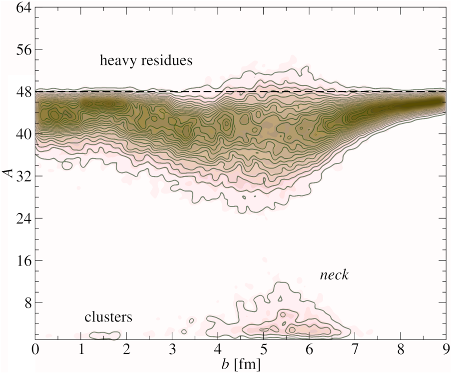


⇒ [CASE STUDY 1] the neck emerges from the low-density phase all of a sudden, it does not detach from QP ot QT !
→ different behaviour than in models with off-shell ternary collision treatment.

Survey of global (isoscalar) observables

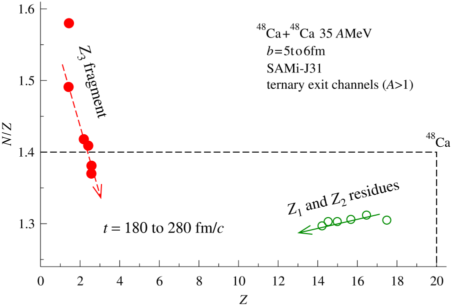
$^{48}Ca+^{48}Ca$ *35AMeV* : survey of global isoscalar observables : multiplicity, neck production

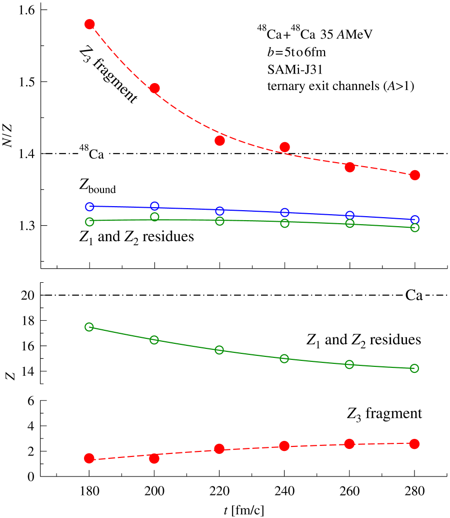




Global observables tracking isospin dynamics

Selection of ternary events with Z_3 at midrapidity :





→ this analysis requires time information and microscopic selection, it is not directly accessible.

→ Can we find a better observable ?

Isospin demon : migration everywhere

Build variance-like observables, experimentally accessible :

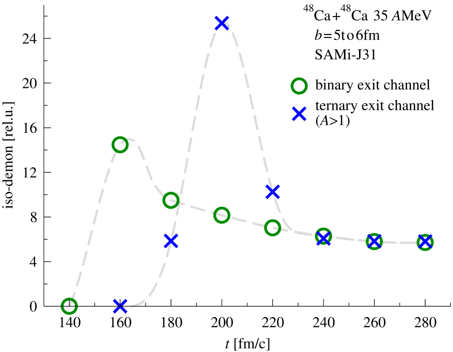
- *binary exit channel :*

isospin demon =
$$\frac{\left\langle \left(\frac{N_1}{Z_1} - \frac{N_2}{Z_2} \right)^2_{\mathrm{event}_i} \right\rangle}{\left\langle \left[\left(\frac{\sum N}{\sum Z} \right)_{\mathrm{event}_i} - \left(\frac{\sum N}{\sum Z} \right)_{\mathrm{event}_j} \right]^2 \right\rangle}$$

- *ternary with Z_3 at midrapidity :*

isospin demon =
$$\frac{\left\langle \left(\frac{N_1}{Z_1} - \frac{N_2+N_3}{Z_2+Z_3} \right)^2_{\mathrm{event}_i} \right\rangle}{\left\langle \left[\left(\frac{\sum N}{\sum Z} \right)_{\mathrm{event}_i} - \left(\frac{\sum N}{\sum Z} \right)_{\mathrm{event}_j} \right]^2 \right\rangle}$$

Both binary and ternary events tend to identical isospin variance, larger than uncorrelated combinations :



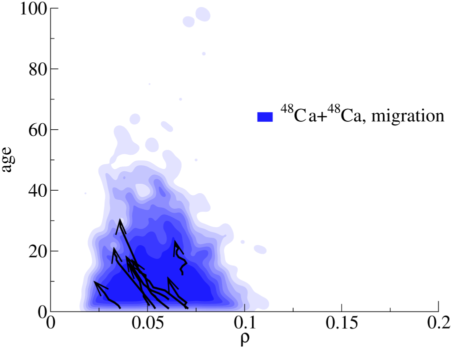
⇒ [CASE STUDY 2] migration also in binary events !

Mesoscopic analysis of ripples

Here we access the phenomenology of isospin migration (density-driven isovector transport) and diffusion (asymmetry-driven transport).
Migration is driven by the isovector chemical potential embedded in an isoscalar density environment.

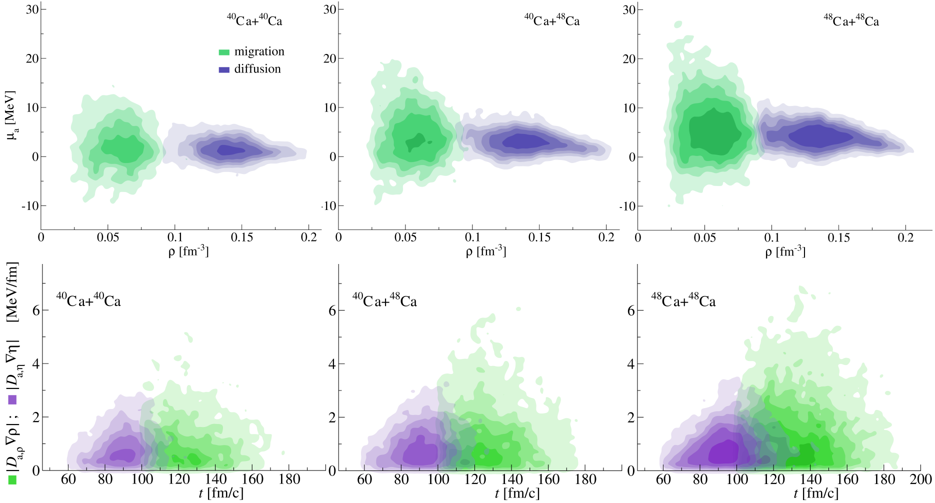
Migration : compressibility-like response of isoscalar channel
→ it seems to occur in a very short time spot

Diffusion : sensitivity of isovector potential to composition
→ it precedes migration



[CASE STUDY 3] Migration runs faster than we expected

Mesoscopic analysis of ripples



[CASE STUDY 4] Migration is preceded by diffusion. Both are determined by local perturbation so that they may occur also in symmetric systems

Conclusions

• migration in identical neutron rich colliding nuclei at different energies from 25 to 45 AMeV. Different sizes. Larger system and isospin symmetric systems could be interesting as well.

• isotopic identification + correlation (high resolution crucial also for selections)

• observables related to variances (isospin demon) even if binary exit channels $\rightarrow$ still to check : robustness against secondary-decay.

[CASE STUDY 1] the neck emerges from the low-density phase all of a sudden, it does not detach from QP ot QT!
[CASE STUDY 2] migration also in binary events!
[CASE STUDY 3] Migration runs faster than we expected
[CASE STUDY 4] Migration is preceded by diffusion. Both are determined by local perturbation so that they may occur also in symmetric