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A study of stopping power in nuclear reactions at intermediate energies

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For INDRA Collaboration

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Motivations

Study of transport phenomena in nuclear reactions

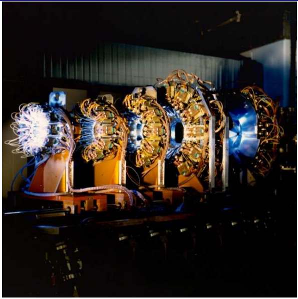
- link with the viscosity (macroscopic degrees of freedom) at low energy ($E < E_f$)
- link with the in-medium nucleon-nucleon cross-section (microscopic dof) at high energy ($E > E_f$)

Be of interest to describe

- the process of supernova collapse and formation of a neutron star[1]
- the various mechanisms in nuclear reactions: fusion, deep-inelastic, incomplete fusion [2]

1: J.M. Lattimer and M. Prakash : Astrophys. J **550**, 426 (2001).
2: E. Suraud, D. Durand and B. Tamain *Nuclear Dynamics in the Nucleonic Regime*

INDRA dataset



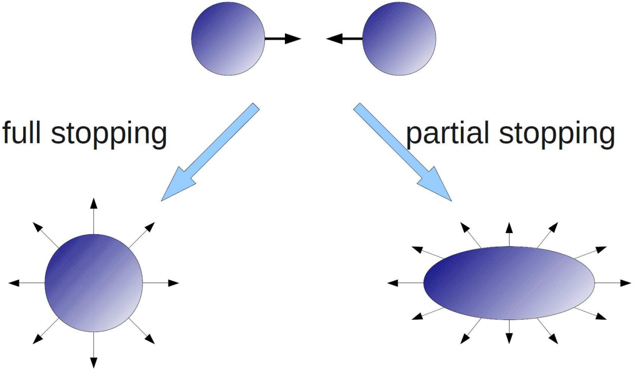
Symmetric collisions

- Incident energy between 12 and 100 MeV/A
- Total size between A=80 and A=400

Isospin pairs at 32 and 45 MeV/A

- $^{124}Xe + ^{112}Sn \quad \Rightarrow \quad N/Z = 1.27$ ○ → ○ *PP*
- $^{124}Xe + ^{124}Sn \quad \Rightarrow \quad N/Z = 1.38$ ○ → ○ *PN*
- $^{136}Xe + ^{112}Sn \quad \Rightarrow \quad N/Z = 1.38$ ○ → ○ *NP*
- $^{136}Xe + ^{124}Sn \quad \Rightarrow \quad N/Z = 1.50$ ○ → ○ *NN*
- *N/Z variation around 15-20%*

Stopping power measurement



- memory of entrance channel is lost
- no preferential axis

- memory of the entrance channel is partially conserved
- preferential direction along the beam axis

Method

$$E_{iso} = \frac{1}{2}\frac{\sum E_{\perp}}{\sum E_{\parallel}}$$

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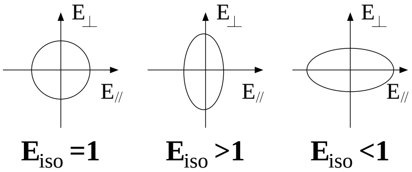

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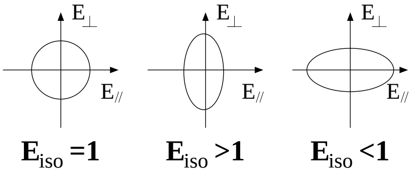
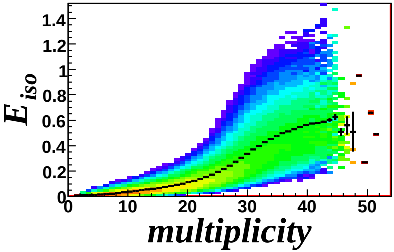


^{129}Xe+^{nat}Sn @ 50 MeV/A



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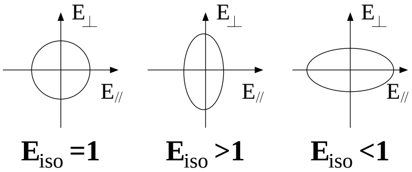

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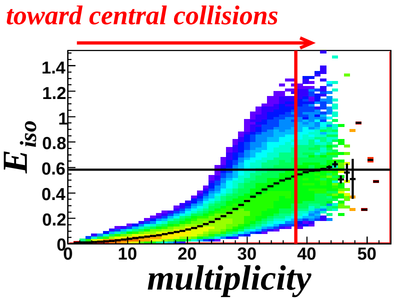

$\Rightarrow$ cross section $\approx 50mb$ $(0.1b_{max})$

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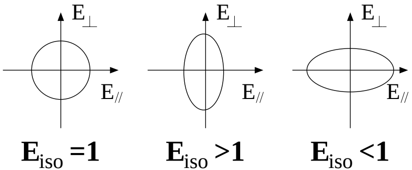

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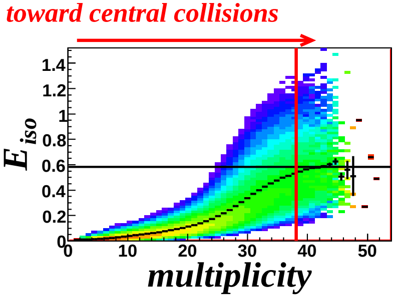

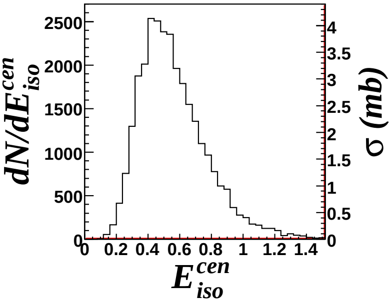

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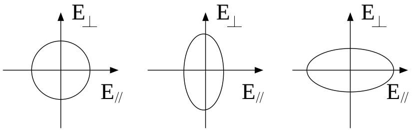


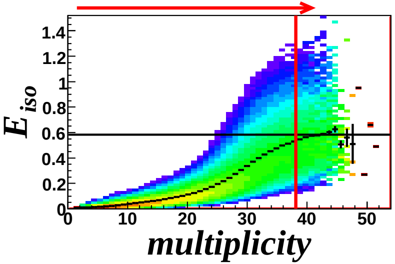
$E_{iso}=1$ $E_{iso}>1$ $E_{iso}<1$

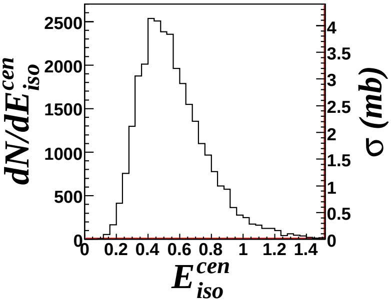
^{129}Xe+^{nat}Sn @ 50 MeV/A

no full stopping

$E_{iso}^{cen} < 1$

toward central collisions





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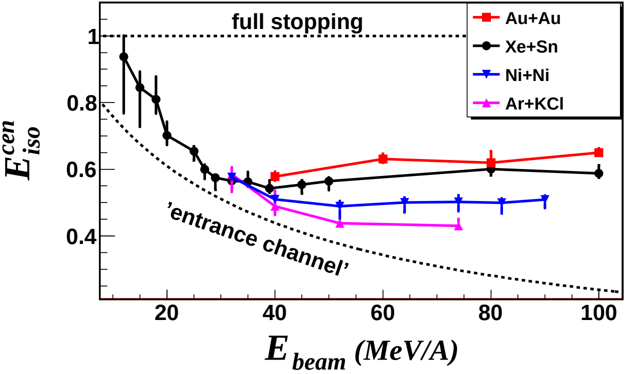
Systematics



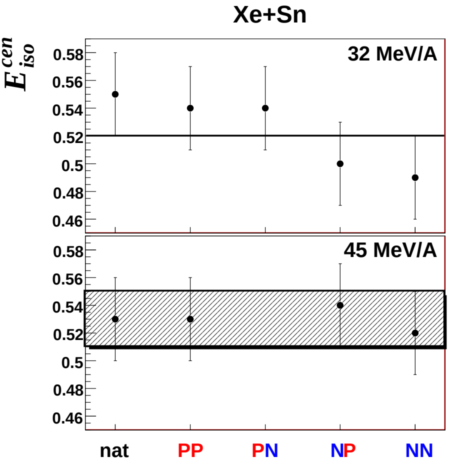
- minimum at $E = E_f$
- saturation above E_f, and hierarchy with the mass of the system: the higher A_{tot}, the higher E_{iso} is
- transition from one-body to two-body dissipation

G. Lehaut, *et al.*, PRL **104**, 232701 (2010)

Isospin effect

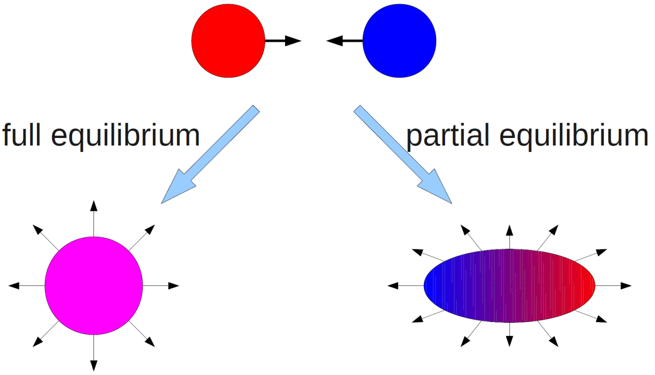
- $^{129}Xe + ^{119}Sn \quad \Rightarrow$ nat
- $^{124}Xe + ^{112}Sn \quad \Rightarrow PP$
- $^{124}Xe + ^{124}Sn \quad \Rightarrow PN$
- $^{136}Xe + ^{112}Sn \quad \Rightarrow NP$
- $^{136}Xe + ^{124}Sn \quad \Rightarrow NN$

- Error bars are here systematics



- small effect of the isospin content at E around E_f (extension to higher and lower E are in the perspectives)

Isospin equilibration



- memory of entrance channel is lost
- same isospin everywhere

- memory of the entrance channel is partially conserved
- dependence of the isospin along the beam axis

Isospin diffusion

Imbalance ratio

$$\tilde{R}_{p/t} = \frac{2R_{p/t} - R_{p/t}^{NN} - R_{p/t}^{PP}}{R_{p/t}^{NN} - R_{p/t}^{PP}}$$

where $R_{p/t}$ is the normalized yield of different particles in isospin here

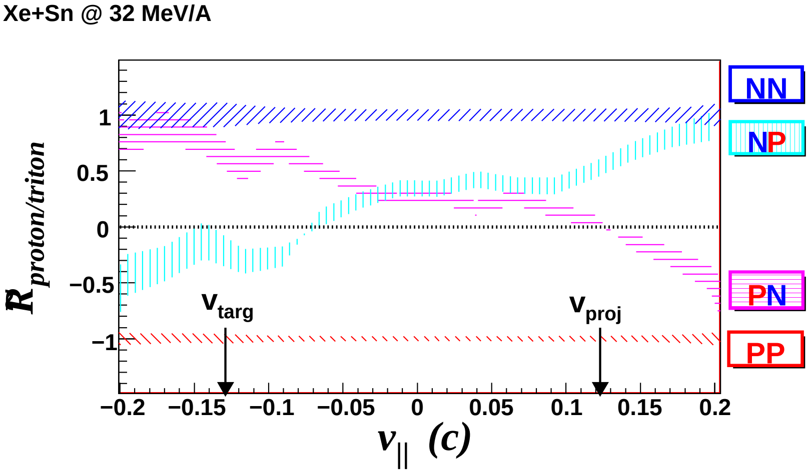
proton over triton.

$$\tilde{R}_{proton/triton} = \begin{cases} +1 & if \quad R_{p/t} = R_{p/t}^{NN} \\ -1 & if \quad R_{p/t} = R_{p/t}^{PP} \end{cases}$$

F. Rami, PRL **84**, 1120 (2000)

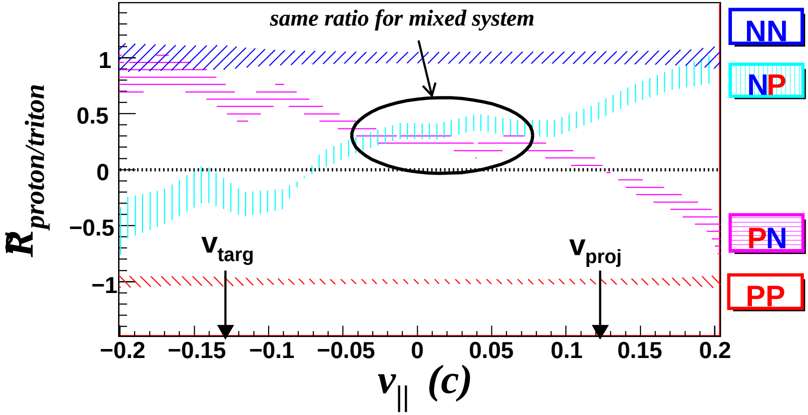
V. Baran, PRC **72**, 064620 (2005)

Proton triton ratio along the beam axis (in central collisions)



Proton triton ratio along the beam axis (in central collisions)

Xe+Sn @ 32 MeV/A



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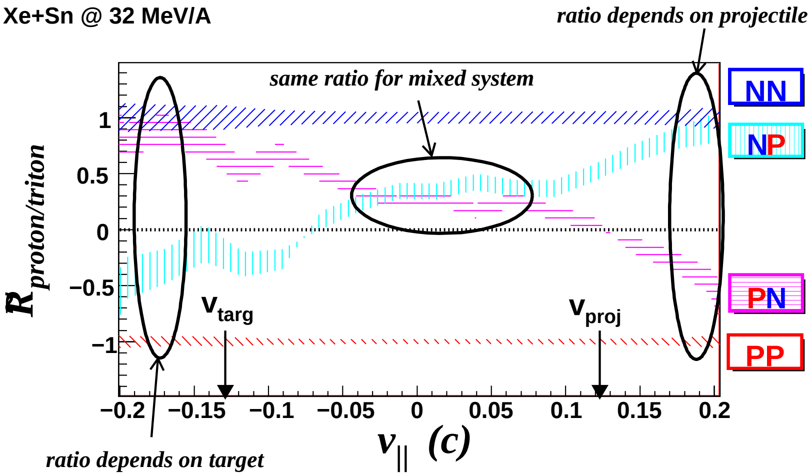
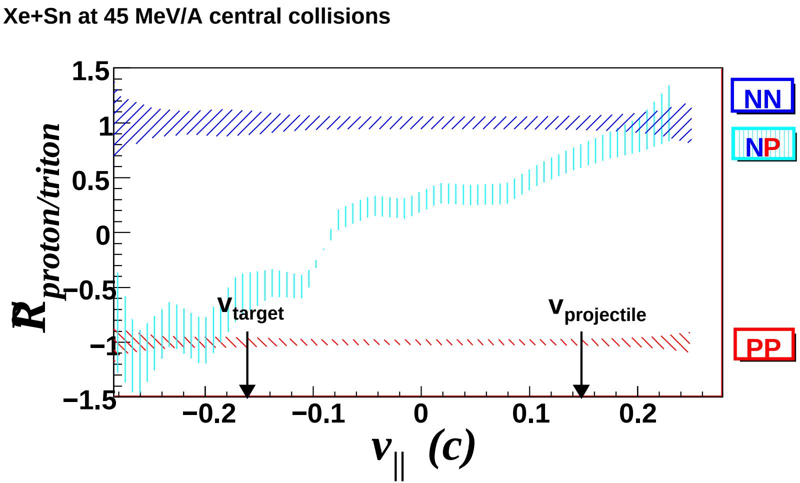


- Imbalance ratios shows nuclear transparency at 32A MeV for central collisions

Proton triton ratio along the beam axis (in central collisions)



- Imbalance ratios shows nuclear transparency at 45A MeV for central collisions

Comparison with a microscopic model: ELIE

Entrance channel

- geometry + nn collision: mean free path λ
- conservation laws are taken into account : $\vec{p}$, E, Z, N
- maximal internal temperature T=5.5 MeV for primary fragments ($A > 6$)
- discrete excited levels are considered up to A=10, above Fermi gas level density is assumed
- N/Z memory of the entrance channel : no isospin relaxation
- nucleons momentum distributions are 2 Fermi spheres at T=0 : sudden approximation (valid at $E > E_f$)

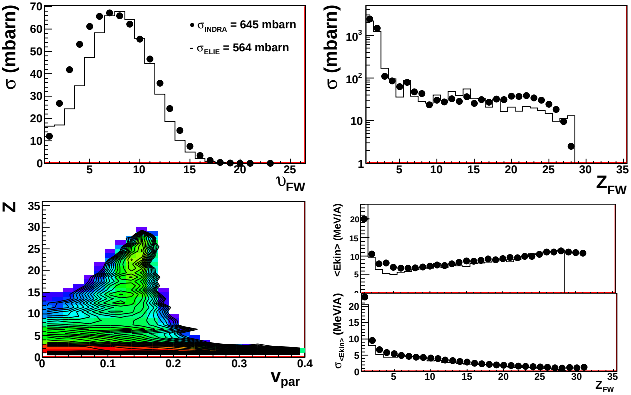
Exit channel

The partition $\{Z_i, A_i, \vec{r_i}, \vec{p_i}\}$ is propagated in space-time and in-flight statistical secondary decays are considered : SIMON code

D. Durand, in preparation

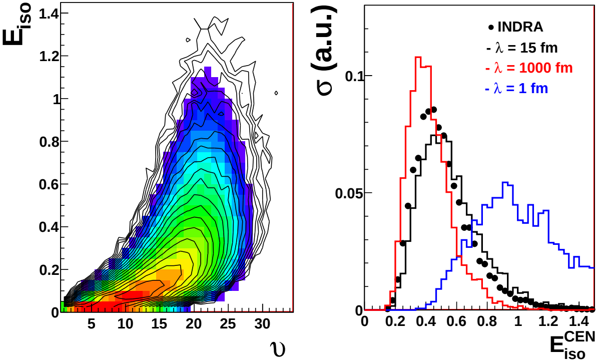
Comparison on some basic observables : $Ni + Ni@52A.MeV$

INDRA : selection $Z_{tot}^{FW} \in [0.8; 1.2]$ ELIE filtered : selection $Z_{tot}^{FW} \in [0.8; 1.2]$



- An excellent agreement between ELIE and the INDRA data is found

Comparison on stopping: $Ni + Ni@52A.MeV$, central collisions $\nu > 26$



- sensitivity to λ is found for E_{iso}^{cen}, especially for $\lambda < (R_{proj} + R_{targ})$
- data is closer to $\lambda = 15$ fm ($> R_{proj} + R_{targ}$), suggesting no complete thermalization since the number of collisions per participant is less than 1.

Summary and Perspectives

Summary

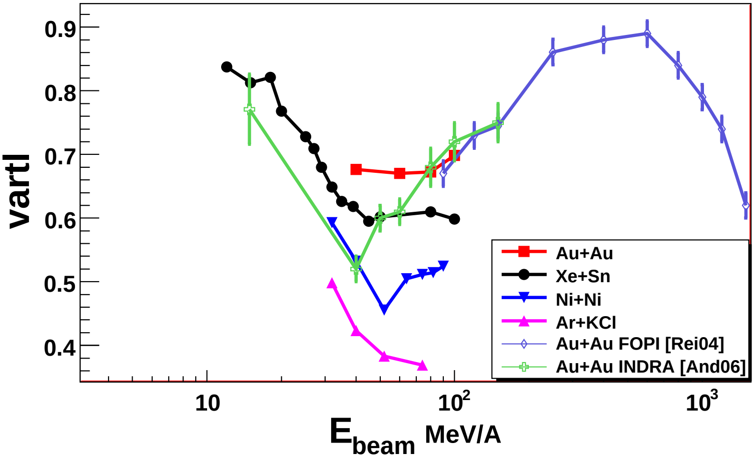
- Stopping power is minimum around the Fermi energy (30-40 MeV/A)
- The isospin of the entrance channel has no effect on the stopping around $E = E_f$. Is it still true for $E < E_f$ and $E >> E_f$?
- The study of imbalance ratios shows nuclear transparency at 32 and 45A MeV for central collisions

Perspectives

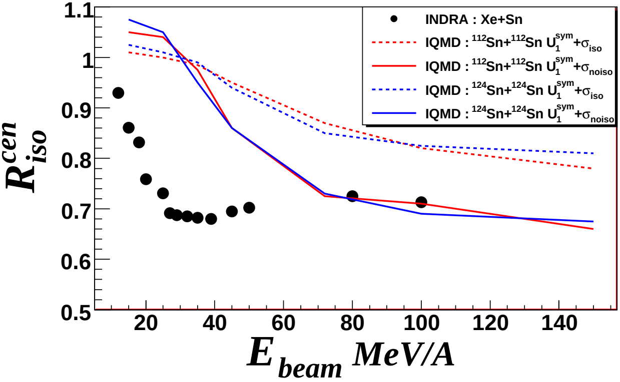
- Systematic comparison with microscopic models (ELIE, HIPSE, QMD) , . . .
- Study the asymmetric collisions: $^{181}Ta +^{64,68} Zn@19, 32, 39A.MeV$ $\Rightarrow$ INDRA experiment planned at GANIL in 2011.

Comparison with FOPI

$$vartl = \frac{var(y_\perp)}{var(y_\parallel)}$$



Comparison IQMD[1]



[1] J.-Y. Liu, *et al.*, PRL **86** 975 (2001)

Imbalance ratio $^3He/t$