Transport properties of nuclear matter in the Fermi energy domain

Olivier LOPEZ

LPC Caen, France
(INDRA Collaboration)
Content

➢ Study of the **stopping reached in central collisions** for HIC between 15A and 100A MeV

➢ Analysis of **exclusive data** recorded with **INDRA 4π array**:
  Large scale analysis: 42 symmetric systems from 72 to 476 uma

➢ **Energy** and **mass dependence** for stopping

➢ Determination of **in-medium properties** of nucleons in nuclear matter: $\lambda_{nn}$ and $\sigma_{nn}$
Motivations

➢ Aspects connected to the transport properties in the nuclear medium: energy dissipation and isospin diffusion

➢ Transport properties are mandatory for:

- the description of **supernova collapse** and formation of **neutron stars**

- the determination of the **nuclear EOS** via the underlying properties of the **nuclear interaction**

- **microscopic descriptions** as one of the fundamental ingredient for the dissipative features: **EOS** and **collision term**
Theoretical background

➢ Mean-Field effects: **1-body dissipation** and **viscosity/friction**
   Collective properties: **nuclear** degrees of freedom (Mean-Field)

➢ **NN** collisions: **2-body dissipation** and \( \lambda_{NN}, \sigma_{NN} \)
   Individual properties: **nucleonic** degrees of freedom (collisions)

➢ **Crossover** in incident energy should be observed where
   MF weakens and **NN** collisions become more and more likely

➢ **In-medium effects** for **NN** collisions:
   - Renormalization of \( \sigma_{NN} \) as compared to vacuum: **quenching factor**
   - Due to **Pauli blocking** (2-body) but also to **higher-order correlations** (density effects via many-body correlations).
Theoretical background

- **Mean-Field effects**: 1-body dissipation and viscosity/friction
  Collective properties: **nuclear** degrees of freedom (Mean-Field)

- **NN collisions**: 2-body dissipation and $\lambda_{NN}, \sigma_{NN}$
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- **Crossover** in incident energy should be observed where
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**Mean free path is (quite) constrained both theoretically and experimentally above** $E_{inc}/A>100$ MeV: $\lambda_{NN} = 4-5$ fm but not below...

Experimental background

Overview of **degree of stopping** between 10A MeV and 2000A MeV

- **FOPI data** for Au+Au between 90A and 1930A MeV: **saturation** for the maximal stopping around 200A-400A MeV

- **INDRA data** for Ar+KCl/Ni+Ni/Xe+Sn/Au+Au between 15A and 100A MeV: **minimum** around $E_{\text{inc}} = 35A$ MeV, **transition** from 1b to 2b dissipation

**Goal of the present study**:

- Extend the former analysis for the full set of INDRA data for symmetric systems: Ta+Au, Gd+U, U+U
- Relate the stopping properties to $NN$ collisions: in-medium $\lambda_{NN}$ and $\sigma_{NN}$ at high incident energy, i.e. above the transition energy
Event selection

- Study the **isotropy ratio** for complete (forward) events:

\[ R_E = \frac{\sum_{i}^{N} E_i^\perp}{2\sum_{i}^{N} E_i^\parallel} \]

- Use of the total charged particle multiplicity \( M_{ch} \) (scalar quantity)

- Select events by \( M_{ch} \) such as \( <R_E> \) is maximal in \( <R_E> \otimes M_{ch} \)

- Cross sections around 50-150 mb: \( b=0-2 \text{ fm} \)...
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- Cross sections around 50-150 mb : \( b=0-2 \text{ fm} \)...

**We want here to insure a minimum bias measurement for \( R_E \) concerning the selected events \( (b<2 \text{ fm}) \)
Event selection

- Xe+Sn 15A MeV
- Xe+Sn 25A MeV
- Xe+Sn 39A MeV
- Xe+Sn 65A MeV

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Event selection

Saturation for $<R_E>$
From previous studies...

\[ R_E = \frac{\sum_i^N E_i^\perp}{2\sum_i^N E_i^\parallel} \]

- Minimum of stopping around 35A MeV
- Mass hierarchy at high energy: attributed to NN (elastic) collisions

Here \( R_E \) is calculated with all charged products...
Stopping in central HIC

42 (quasi)-symmetric systems,
Only protons for $<R_E>$...

Nuclear Stopping

$$R_E(\alpha) = \frac{1}{1 + 5(\alpha P_{rel}/P_{Fermi})^2}$$

Adiabatic
Full stopping

Sudden approx.
Full transparency
Why using only protons? (1)

From IQMD calculations: $R_E (R_p)$ is strongly influenced by the clusterization.


See also:
Why using only protons? (2)

- Velocity plots for protons are significantly different from $\alpha$ or composite particles/IMFs

- Mid-rapidity and transverse velocity components are dominant: preequilibrium effects

- Contribution from secondary decay are rather small:
  
  $\sim 20\%$ for Xe+Sn at $50A$ MeV

Stopping ratio

Distance to non-relaxed Fermi spheres

\[ s = \frac{R_E^p - R_E(\alpha = 1)}{R_E(\alpha = 1) - R_E(\alpha = 0)} \]

 INDRA data for High \( M_{\text{LCP}} \) gate, \( Z=1 \) (total)
- Gd/U+U, \( A_{\text{tot}}=404-476 \)
- Ta/Au+Au, \( A_{\text{tot}}=378-394 \)
- Xe+Sn, \( A_{\text{tot}}=248 \)
- Ni+Ni, \( A_{\text{tot}}=116 \)
- Ar+Ni, \( A_{\text{tot}}=94 \)
- Ar+KCl, \( A_{\text{tot}}=72 \)

O. Lopez, EPJ web of conferences, INPC'13

\[ \text{Stopping ratio and NN collisions?} \]
Phase space: 2 Fermi spheres + $NN$ collisions

% of $NN$ collisions: random choice of nucleons in the 2 Fermi spheres

Elastic $NN$ collision (semi-classical): rotation in $p$-space

Pauli exclusion principle (fermions): some rotations are forbidden

Isotropy ratio $R_E$ and stopping ratio $S$ are computed for all collisions (accepted or not)

\[
R_E = \frac{\sum_i^N E_i^\perp}{2\sum_i^N E_i^{\parallel}}
\]

\[
s = \frac{R_E^\alpha - R_E(\alpha = 1)}{R_E(\alpha = 1) - R_E(\alpha = 0)}
\]
Stopping ratio and $NN$ collisions

- 100,000 collisions are produced

- The number of accepted collisions is modulated from 0 (none) to 100 % (all accepted)

- $C$ is the ratio between attempted and accepted (realized) collisions
Stopping ratio and $NN$ collisions

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- $C$ is the ratio between attempted and accepted (realized) collisions

From MC simulation, we get:

$$C = S^\beta$$

$$\beta(E_{\text{rel}}) = 1.42 - 0.0063E_{\text{rel}}$$
Mass scaling and Characteristic Length

Mass scaling: \( \frac{C}{A^\gamma} \)  

Characteristic length: \( L \propto A^{1/3} \)

\( \gamma = 0.250 \)

\( \gamma = 0.333 \)

\( \gamma = 0.667 \)

\( \gamma = 1.000 \)
Nucleon Mean Free Path

Assuming: \( C = L/\lambda_{NN} \)

\[ \lambda_{NN} = 4-5 \text{ fm} \]

Renberg et al., Nucl. Phys. A 183 (1972)
Nucleon Mean Free Path

Assuming: \( C = \frac{L}{\lambda_{NN}} \)

\( \lambda_{NN} > R \) : complete stopping and thermalization are not achieved...
See also J. Su and F.S. Zhang, Phys. Rev. C 87, 017602 (2013), AMD
But...
Contradictory findings with SMF by M. Colonna and E. Bonnet, PRC (2014)

\( \lambda_{NN} = 4-5 \) fm

Rios and Soma, PRL 108, 012501 (2012)
Renberg et al., Nucl. Phys. A 183 (1972)

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$\sigma_{NN} \approx 1/\rho \lambda_{NN}$, taking $\rho = 1.2 \rho_0$ for central (overlapping) collisions
In-medium effects: Pauli correction

Pauli Correction Factor \( P = \frac{\sigma_{\text{in-medium}}}{\sigma_{\text{free}}} \)

Many prescriptions:
- Chen et al., nucl-th 1304.6096v1 (2013)
- Su and Zhang, PRC 87, 017602 (2013)

K. Kikuchi and M. Kawai, North Holland (1968)

\[ z = \frac{E_{\text{rem}}}{(E_{\text{rem}} + E_{\text{inc}})} \]

- \( 1 - \frac{7}{5}z \) for \( z < 0.5 \)
- \( 1 - \frac{7}{5}z + \frac{2}{5}z(2 - \frac{1}{2})^{0.2} \) for \( z > 0.5 \)
In-medium effects: PB correction

'Free' NN cross section (Pauli-corrected), \( \sigma_{NN} = \frac{1}{(\lambda_{NN} \rho_0 \cdot P(E_{inc}))} \) with \( \rho = 1.5 \rho_0 \)

![Graph showing the cross section as a function of incident energy for different reactions, with data points and fitted curves.](image-url)
In-medium effects: quenching factor

In-medium reduction factor for $p/p_0=1.2$

- Coupland et al., PRC 84, 054603 (2011)
- Ropke et al., PRC 57, 806 (1998)
- Xiangzhou et al., PRC 58, 572 (1998)
- Klakow et al., PRC 48 (1993)
- Li and Machleidt, PRC 48 (1993)

**MF regime**

\[ F = \sigma_{\text{NN}}^{\text{in-medium}} / \sigma_{\text{NN}}^{\text{free}} \]

\[ \sigma_{\text{NN}} = 8.5/\rho^{2/3} \]

**Danielewicz (phenom.):**

\[ F = \sigma_0 \tanh(\sigma_{\text{free}}^{\text{free}} / \sigma_0), \text{ with } \sigma_0 = 8.5/\rho^{2/3} \]

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Conclusions

➢ **Mass scaling** is observed for $R_E$ : size of the system => characteristic length $L$

➢ **Mean Free Path** in nuclear matter, decrease by a factor of 2 between

40A and 100A MeV :

\[ \lambda_{NN} = 11 - 5 \text{ fm} \]

Complete stopping and thermalization are not achieved in this energy range for the selected central events... *tbc*

➢ Study of *in-medium effects* :
  • Pauli effect is effective but …
  • Density effects (**many-body correlations**) are also important and **cannot be neglected** in the Fermi energy range : *reduction x2-5*
  • Best description from **Danielewicz (Coupland) et al.**

➢ Perspectives :
  ▪ **Low incident energy** domain (<30A MeV) : **MF effects** to be evaluated properly
  ▪ RIB : **isospin dependence** of the in-medium quantities and **isovector** properties of **NN interaction**
Event selection...

What can we learn from HIPSE?
HIPSE Xe+Sn 32A MeV

Isotropy Ratio $R_E$

Total

Complete events (60%)

Flow+complete selection

$M_{ch}$ +complete

HIPSE $b=0.12$fm +INDRA filter
- $M_{tot}>3$
- $Z_{tot}>0.600000$ (30.1%)
- $Z_{tot}>0.600000 + \theta_{flow}>60$ deg. (5.6%)
- $Z_{tot}>0.600000 + M_{tot}>22$ (4.0%)
HIPSE Xe+Sn 32A MeV, \( R_E \otimes b \)

- \( M_{ch} \) does not bias \( R_E \)

- HIPSE \( b=0-12 \text{fm} \) +INDRA filter
  - Comp. \( \otimes M_{tot}>22 \) : 4.0%
  - Comp. \( \otimes \theta_{\text{flow}}>60 \text{ deg.} \) : 5.6%

Legend:
- \( \triangle \) Flow
- \( \square \) \( M_{ch} \)
- \( \bullet \) \( b \)