Excited nuclear matter at Fermi energies: From transport properties to the equation of state

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Excited nuclear matter at Fermi energies: From transport properties to the equation of state

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Abstract

Properties of excited nuclear matter are one of the main subject of investigation in Nuclear Physics. Indeed, the response of nuclear matter under extreme conditions encountered in heavy-ion induced reactions (large compression, thermal and collective excitations, isopin diffusion) around the Fermi energy is strongly needed when studying the nuclear equation of state and the underlying in-medium properties concerning the nuclear interaction. In this contribution, we will present some experimental results concerning the transport properties of nuclear matter, focusing specifically on the determination of in-medium quantities such as mean free pathes and nucleon-nucleon cross sections around the Fermi energy. We will see that, in this specific energy range, energy and isospin dissipations exhibit very peculiar features, such as the crossover between 1-body to 2-body dissipation regimes corresponding to the transition between the nuclear response from Mean-Field to the nucleonic response through the appearance of nucleon-nucleon collisions.

1 Introduction

The study of transport phenomena are of primary importance for understanding the fundamental properties of nuclear matter [1]. They are critical in the description of the supernova collapse and the formation of a neutron star [2], hence they could provide important insights for the determination of the nuclear equation of state. Transport properties are also one of the basic ingredients for microscopic models [3, 4]. In this study, we are looking at the global energy dissipation achieved in heavy-ion induced reactions in the Fermi energy domain. We are using the large experimental dataset available in this energy range for symmetric systems recorded with the 4π array *INDRA* [5]. We are specifically looking at central collisions, *i.e.* collisions corresponding to the maximal overlap and thus leading to the maximal dissipation. Doing so, we will extract information concerning the stopping encountered in such collisions and relate it to the nucleon mean free path and cross section in the nuclear medium.

2 Stopping for central collisions

In this work, we are studying *INDRA* data coming from central collisions, selected through the total multiplicity of charged particle as proposed in [6]. The data span a large body of symmetric systems, with total mass between 70 and 500 mass units, and incident energies covering the full range of the Fermi domain $E_{inc}/A = 10 - 100\ MeV$. To evaluate the degree of stopping achieved in central collisions, we are using the energy isotropy ratio R_E as defined in [6]. This ratio is taking positive values, with 1 for an isotropic emission. We only consider $Z = 1$ particles (p, d, t) in this study since we are mainly interested in the properties for nucleon-nucleon collisions. We find here higher R_E values than those of [6]. Indeed, the isotropy ratio in [6] was computed by using all charged products, including fragments. It has be shown in [7] that clusterization effects on nucleon phase space lower the isotropy ratio, mainly below $100A\ MeV$. We display in Fig. 1 the mean isotropy ratio $< R_E >$ calculated for central collisions as a function of incident energy. It is worthwhile to note that in case of asymmetric systems, the incident energy should be conveniently replaced by the total available cm energy.

The different curves on Fig. 1 correspond to several analytical calculations associated to the entrance channel; we consider here 2 Fermi spheres separated by the relative momentum $(1-\alpha)p_{rel}$ corresponding to the relative energy of the entrance channel. α is a free parameter which represents the level of dissipation observed in the collision; $\alpha = 1$ (red curve) means full dissipation while $\alpha = 0$ (thick black curve) corresponds to the *sudden* approximation without any dissipation. The displayed error bars correspond

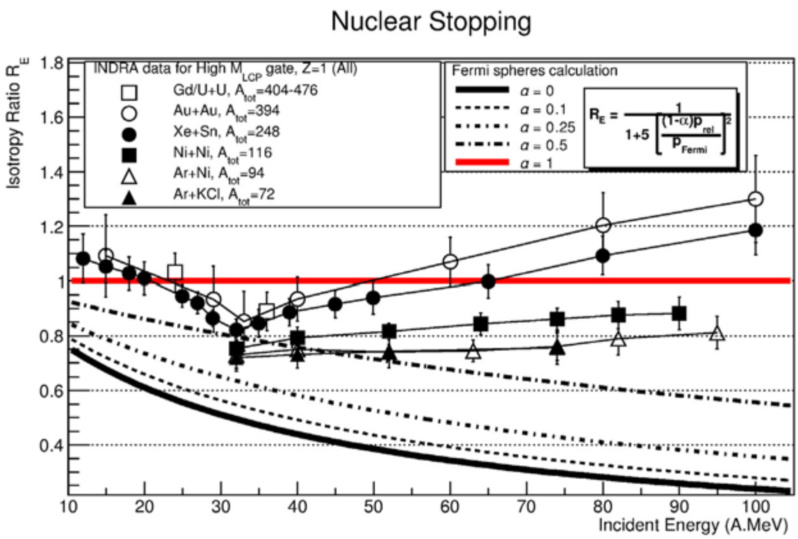

Figure 1: Mean Isotropy ratio $< R_E >$ as a function of incident energy for central collisions in symmetric systems recorded with *INDRA* (symbols). The error bars correspond to statistical + systematic errors.

to statistical supplemented by an estimation of systematic errors coming from the determination of the mean value [6]. We observe that the closest distance to the *no-dissipation* scenario ($\alpha = 0$) corresponds to an incident energy slightly below the Fermi energy, around $30A\ MeV$. Above the Fermi energy, in the nucleonic regime, we can observe a nice mass hierarchy concerning the stopping: the heavier the system, the larger the stopping is. This is fully consistent with a *Glauber* picture where the degree of stopping is closely related to the number of participants. To get further on this point, we have performed Monte Carlo simulations of 2 Fermi spheres, taking into account nucleon-nucleon collisions through the definition of the nucleon mean free path in the nuclear medium λ_{NN}. A simple relationship between the degree of stopping and the nucleon mean free path can then be obtained [8].

3 Nucleon mean free path in nuclear medium

By applying this to the experimental data, we obtain the results displayed by Fig. 2. We note that all curves exhibit the same behaviour whatever is the total mass. We observe a maximum at incident energy corresponding to minimal stopping at $E_{inc} \approx 30A\ MeV$ as can be expected from Fig. 1. The non-physical decrease at low incident energy (below $30A\ MeV$) can be attributed to the Mean-Field dissipation which is well active in this energy domain, and consequently affects the entrance channel values; in this domain, we should adjust the α parameter to better describe the energy dissipation in the entrance channel. In the limited scope of the present study, we are mainly interested on the nucleonic regime, *i.e.* incident energy larger than the Fermi energy. Focusing on this incident energy domain, we observe a decrease from $\lambda_{NN} \approx 10\ fm$ to $\lambda_{NN} = 5\ fm$ at $E_{inc}/A \approx 100\ MeV$. It is worthwhile to mention that the value at high incident energy is in agreement with recent microscopic *Dirac-Brueckner-Hartree-Fock* calculations using realistic interactions [9] and hence gives credit to our rather crude determination of the mean free path.

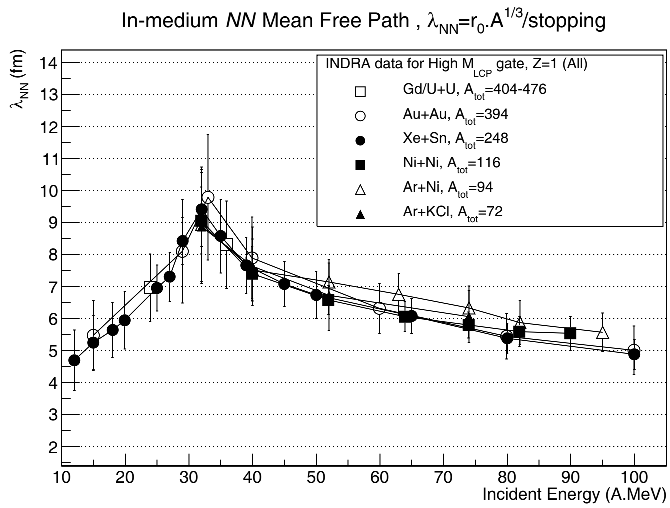

Figure 2: Nucleon mean free path $< \lambda_{NN} >$ as a function of incident energy extracted from experimental data. The errors bars correspond to the statistical+systematic errors.

4 In-medium effects for nucleon-nucleon cross section

From the mean free path, we can estimate the nucleon-nucleon cross section by taking the well-known formula: $\sigma_{NN} = 1/(\rho\lambda_{NN})$ where ρ is the nuclear density which varies linearly from $\rho = \rho_0$ at $E_{inc}/A = 30\ MeV$ to $\rho = 1.5\rho_0$

at $E_{inc}/A = 100\ MeV$ in order to take into account compression effects [1]. To get the *real* nucleon-nucleon cross section, we have then to correct from the *Pauli* blocking as a trivial (but essential) 2-body effect in the medium. To do so, we use the prescription of ref. [10]. More sophisticated approaches concerning the *Pauli* blocking estimation can be found in the litterature [11] but should not change significantly the results. Then, we compute the quenching factor $F = \sigma_{NN}^{in-medium}/\sigma_{NN}^{free}$ by taking the energy-dependent free nucleon-nucleon cross sections σ_{NN}^{free} available in the litterature [12].

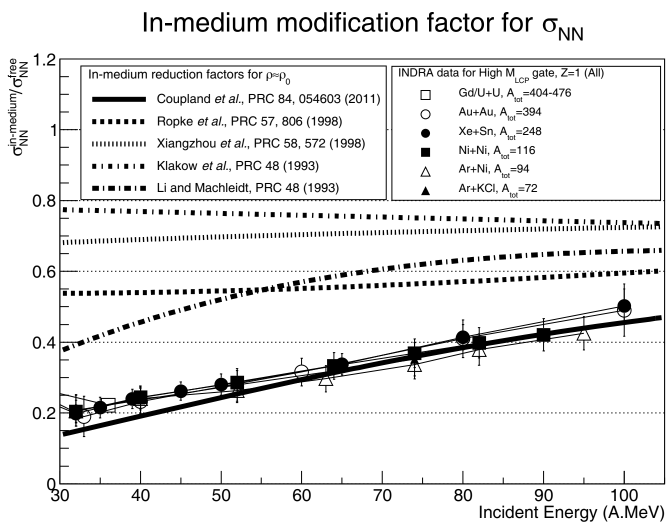

Figure 3: Mean in-medium quenching factor $< F >= \sigma_{NN}^{in-medium}/\sigma_{NN}^{free}$ as a function of incident energy for experimental data (symbols) and various theoretical prescriptions (curves). The errors bars for data correspond to the statistical+systematic errors.

The results for the quenching factor F are displayed on Fig. 3 for the incident energy range above $E_{inc}/A = 30\ MeV$. The 'experimental' values (symbols) are compared to standard theoretical prescriptions derived from various works and currently used in microscopic transport models [13–17]. We have taken the same linear density dependence as mentioned before to account for compressional effects. We can see that the medium effects, out-of-*Pauli* blocking, suppress strongly nucleon-nucleon collisions at low energy with $F \approx 15\%$. We obtain values close to $F = 50\%$ at the highest incident energy, here at $100A\ MeV$. It is interesting to note that all parametrizations and the data seem to converge toward a common value around $60 - 70\%$, indicating that in-medium effects should be quite correctly taken into account above $100A\ MeV$ incident energy. For the low energy domain ($30A - 100A\ MeV$), the parametrizations give quite different results. The best prescription is the one of ref. [17]. It is worthwhile to mention that this parametrization is rather strongly density-dependent and produces large reduction factors compared to other prescriptions [17].

5 Conclusions

In this study, we have studied the degree of stopping connected to the energy dissipation in heavy-ion reactions. We have found a minimal stopping around $E_{inc} = 30A\ MeV$ connected to the crossover between 1-Body to 2-Body dissipation regime. For the latter, we have estimated the nucleon mean free path in the nuclear medium from the degree of stopping achieved in central collisions. The mean free path decreases from $\lambda_{NN} \approx 10\ fm$ at $E_{inc}/A = 30\ MeV$ to $\lambda_{NN} = 5\ fm$ at $E_{inc}/A = 100\ MeV$. These values are in agreement with recent theoretical findings using microscopic approaches. The large value relative to the nuclear size ($\lambda_{NN} > R$) around the Fermi energy suggests that *full thermalization* is not achieved in such central collisions [6]. In-medium effects, namely *Pauli* blocking and *high-order correlations*, have also been evaluated and are found to be large in the Fermi energy range; it is clear that this energy/density dependence of the nucleon-nucleon cross section has to be properly taken into account in any microscopic transport model used in the Fermi energy range. The best agreement for the in-medium factor F is the one proposed in [17], based on simple geometrical arguments. More detailed analyses of experimental data and comparisons with transport models on stopping properties are indeed welcome to confirm these results. As a perpective, the advent of new radioactive beam facilities will indeed provide the opportunity to investigate the isovector properties of the nucleon-nucleon interaction by scanning the isospin degree of freedom concerning mean free pathes and cross-sections.

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