

Three nucleon interaction in heavy ion collisions at intermediate energies

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High energy proton emission were studied experimentally by Germain et al. in $^{36}\text{Ar}+^{181}\text{Ta}$ at 94A [1] MeV and by Coniglione *et al.* in $^{36}\text{Ar}+^{51}\text{V}$ at 44A MeV [2]. In their experiments proton energy often exceeds 3-4 times the incident energy per nucleon. In our recent study [3], we demonstrated that a careful treatment of the Fermi motion in a transport model, especially for the high momentum distribution of the Fermi motion in hot nuclear matter, is crucial for the production of high energy protons. In the present work, theoretical studies are performed, based on an antisymmetrized molecular dynamics (AMD) [4]. In the extended AMD [5,6], the Fermi motion is taken into account as a quantum fluctuation, a quantum branching of the wave packets called a diffusion process in the nucleon propagation in a mean field. In our work in Ref. [3], we also take into account the quantum fluctuation in each collision process and the modified code is called AMD-FM. These treatments are quite different from that in most other transport models, in which the Fermi motion is added to nucleons only once in the initial nuclei, whereas in AMD-FM, a new Fermi motion is assigned as a momentum fluctuation in the diffusion process and each collision process, thus many times throughout the calculation. The AMD-FM significantly improves the reproduction of the high energy protons in above available experimental data. We extend this study to include a 3N collision term at higher incident energies in this study.

The importance of the 3N collision term at intermediate heavy ion collisions was first pointed out by Mrowczyński [7]. Bonasera et al. studied it in detail and put it into a transport model formalism [8–10]. The 3N collision term was applied in the experimental data, using a perturbed calculation based on a BNV transport model in Ref.[1]. A 3N collision term is incorporated into AMD-FM following the description in Ref. [10]. We will refer this version of AMD as AMD-FM(3N). The 3N interaction is simply calculated by a succession of three binary collisions where one couple of nucleons interacts twice when three nucleons are in the collision distance each other. In each collision, the same treatment as in Ref. [3] is made for each nucleon momentum to take into account the Fermi motion and avoid double counting with the diffusion process. The effect is called "Fermi boost".

The AMD-FM(3N) is applied for the $^{40}\text{Ar}+^{51}\text{V}$ reactions at 100, 200, 300 and 400A MeV, to overview the 3N collision effect on the high energy proton emission. The calculated results (histograms) are compared AMD-FM (circles) in Fig. 1. At 100A MeV on the left, the energy spectra are very similar at different angles between two calculations, but the yields of AMD-FM(3N) are slightly larger, by a factor of 2 at most. When the incident energy increases to 200A MeV, the shape of the energy spectra show a distinct difference, that is, the energy slope of AMD-FM(3N) show much harder slopes than those of AMD-FM. Similar differences are also observed at higher incident energies. One should note that the slope of the spectra barely depend on the impact parameter range, because they originate essentially from the 2N or 3N collisions. One can also see broader peaks at the lower proton energy in the forward spectra for the AMD-FM(3N) simulations. This can be explained as follows: At the low energy side, the spectra of AMD-FM show a semi-Gaussian distribution. The contribution from the 3N collisions also becomes a Gaussian distribution, because of the Fermi boost for the third nucleon, and thus they are overlaid on top

of each other, which causes a broadening of the distribution. In the high energy side, on the other hand, the spectra of AMD-FM show an exponential fall off and the 3N contribution becomes visible only in the higher energy side.

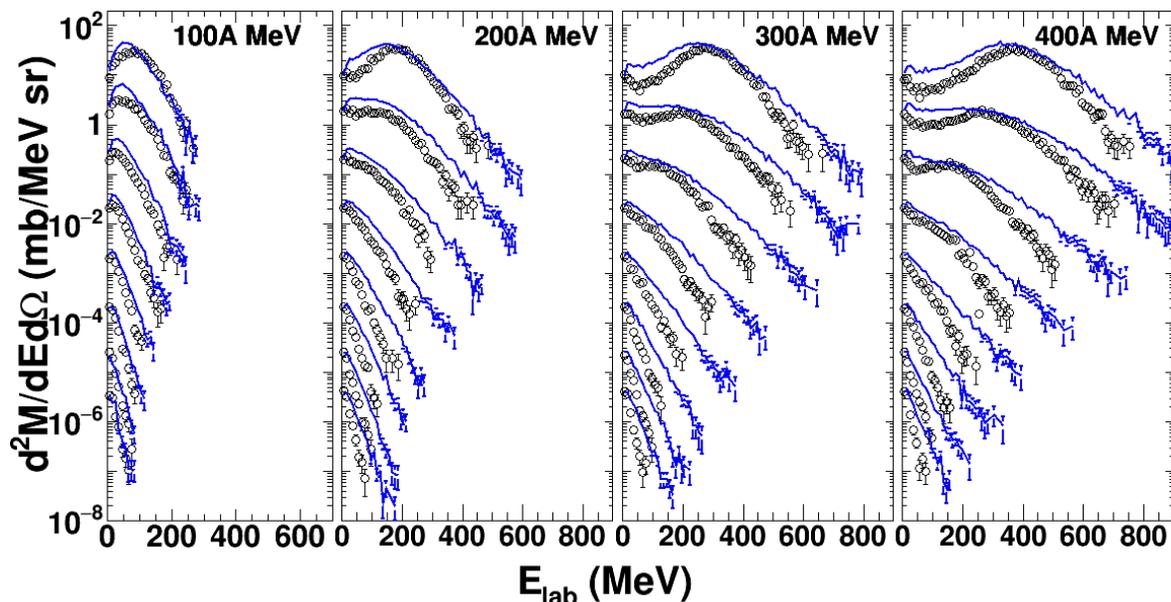


FIG. 1. Simulated results of proton energy distributions for $^{40}\text{Ar} + ^{51}\text{V}$ at different incident energies. Histograms represent the results of AMD-FM(3N) and circles are from AMDFM. The spectra in each column are plotted every 20° from $\theta = 10^\circ$ ($\times 1$) at the top to $\theta = 170^\circ$ ($\times 10^6$) at the bottom.

In the insert in Fig. 2, the number of collisions is plotted as a function of reaction time for attempted collisions and Pauli-allowed collisions at 100A MeV in (a) and 300A MeV in (b). At both energies, the maximum number of collisions per time occurs at the time of overlap between the projectile and target. Around this time period, the shape of the collision distributions are very similar between attempted and Pauli-allowed collisions. When the peaks are fit by a Gaussian distribution, the width for the 3N collisions is less than half of that of the 2N collisions, indicating that the 3N collisions are more localized in time, at the time of the maximum density. This is what is expected from Eq. (1). This width difference in the numbers between the 2N and 3N collisions indicates how quickly the overlap region expands in time.

In Fig. 2 a summary of the number of collisions is plotted as a function of the incident energy. The number of collisions is calculated around the peak, using a Gaussian fit as shown in the insert. Collisions at later stages are not included. The number of the 2N collisions decreases rapidly as the incident energy increases from 44A to 100A MeV, whereas the number of the 3N attempted collisions increases rapidly in this energy range. The number of the Pauli-allowed 3N collisions below 60A MeV is small and increases very slowly. At 100A MeV, about 50% of the attempted 2N collisions are blocked by the Pauli exclusion principle. The blocking is more significant for the 3N collisions, where nearly 90% of the collisions are blocked. At 300A MeV, about 40% of the 2N collisions are Pauli-blocked, whereas for

the 3N collisions about 75% are blocked. These numbers of blocking indicate that, even above 100A MeV, a careful treatment of the Pauli blocking is still very important, especially for the 3N collisions.

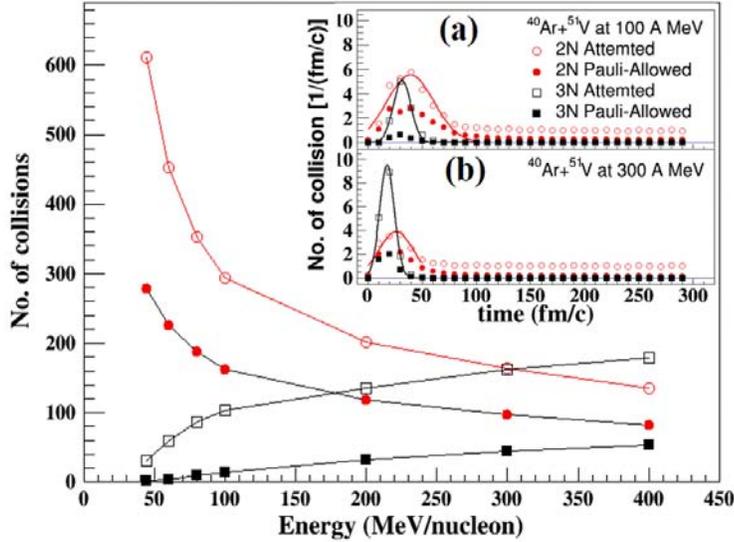


FIG. 2. Summed number of 2 body (circles) and 3 body (squares) collisions are plotted as a function of incident energy. Lines are guides of eyes. Insert: Number of 2N and 3N collisions are plotted as a function of reaction time. (a) $^{40}\text{Ar}+^{51}\text{V}$ at 100A MeV. The density in the overlap region becomes maximum at $t = 30\text{fm}/c$ at this energy. (b) $^{40}\text{Ar}+^{51}\text{V}$ at 300A MeV. The density becomes maximum at $t = 20\text{fm}/c$ at this energy. The sigma of the Gaussians are 21.7 (15.9) for 2N and 8.0 (6.8) for 3N attempted collisions at 100A (300A) MeV, respectively.

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