Production mechanism of high energy protons at intermediate heavy ion collisions

R. Wada, X. Liu, W. Lin, and M. Huang

In experiments, high energy proton emission has been observed at intermediate heavy ion reactions. The energy of the ejected protons often exceeds more than 4 times of the incident beam energy per nucleon. Coniglione *et al.* reported the energetic proton emissions in ^{40}Ar + ^{51}V at 44 MeV/nucleon using the MEDEA detector array and compared the energy spectra to those of BNV calculations [1]. In their BNV, Fermi distribution with a sharp cut off is incorporated as the Fermi motion of the nucleons, neglecting the stability of the initial nuclei, and suggested that the Fermi motion is a possible origin for the observed high energy protons. Germain et al. reported high energy proton emissions in ^{36}Ar + ^{181}Ta collisions at 94 MeV/nucleon [2]. In the analysis, a BNV code is used to calculate the density of nucleons during the time evolution and collisions are made in a perturbed way, using the calculated nucleon density. Since they cannot reproduce the high energy proton spectra by the two collision process alone, they added a three body collision process in their calculation and concluded that the three-body collision term takes a significant role to reproduce the observed high energy proton spectra.

We report here the results of AMD simulations in which the Fermi motion is taken into account explicitly in the nucleon-nucleon collision process in addition to the fluctuation in the dynamical time evolution of the wave packets through a diffusion process which has been built in in the ordinal AMD. The modified code is called AMD-FM. In AMD, each nucleon is expressed by Gaussian distributions in coordinate and momentum space. The wave packets propagate in a given mean field by solving classically the Vlasov equation using the centroid of the Gaussian wave packet. The width of the Gaussian distribution is partially taken into account in the quantum branching, called a diffusion process. In addition to that, in AMD-FM, the momentum fluctuation is added as a Fermi boost in the collision process. When two nucleons are at the collision distance Sqrt(σ_{NN})/π, a momentum fluctuation along the Gaussian distribution is added for each nucleon as

$$\boldsymbol{P}_i = \boldsymbol{P}_i^0 + \Delta\boldsymbol{P}_i' \quad (i = 1, 2)$$

where

$$\Delta\boldsymbol{P}_i' = \sqrt{\left(\frac{|\Delta\boldsymbol{P}_i|^2}{2M_0} - T_0\right) 2M_0} \frac{\Delta\boldsymbol{P}_i}{|\Delta\boldsymbol{P}_i|}$$
$$\Delta P_{i\tau} = \hbar\sqrt{\nu}(rho/\rho_0)_i^{1/3} G(1)$$

here P_i^0 is the centroid of the Gaussian distribution, and G(1) is a random number generated along the Gaussian distribution, with Σ = 1. T_0 ~ 10 MeV being the expectation value of the average energy of the Gaussian distribution and subtracted to avoid the double counting between the diffusion process and collision process.

First, we compare the experimental results of ^{40}Ar+^{51}V at 44 A MeV with those of the ordinal AMD and CoMD calculations. The results are shown in Fig.1. In CoMD, a process is added to QMD to prevent the violation of the Pauli principle in the wave packet propagation in time in a stochastic manner.

Different from AMD, in CoMD the Fermi motion is explicitly taken into the initial ground state nuclei. When the initial nuclei are prepared, the momentum is assigned to each nucleon under a local Fermi Gas assumption with a sharp cut off momentum. In order to get the enough stability during calculations with a proper binding energy of these nuclei, the nuclei are further cooled by a friction method. Therefore the momentum distribution becomes much smaller values in the initial nuclei. In AMD, the centroid of the wave packet of the Gaussian distribution in the initial nuclei is set to nearly zero. This means that the initial nuclei are "frozen" and makes the initial nuclei stable in time. One should note that, in the results of AMD, the calculated spectra have slightly harder slopes than those of CoMD, even though the initial nuclei are ”frozen” in the AMD calculation. This enhancement is caused from the diffusion process discussed earlier.

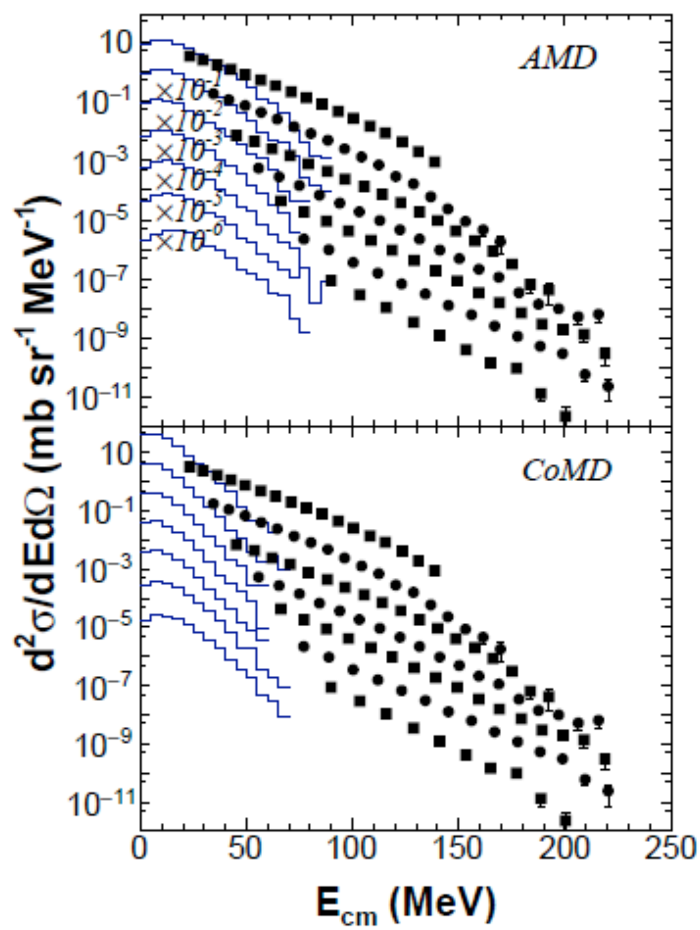

FIG. 1. The Center of Mass frame proton energy spectra of AMD (Top), CoMD (Bottom) in an absolute scale are compared with the experimentally observed inclusive data for 40Ar + 51V at 44 MeV/nucleon at θ = 72◦, 90◦, 104◦,116◦, 128◦, 142◦ and 160◦ from top to bottom. The experimental data are taken from Ref. [1].

Fig. 2 shows the comparisons between the experimental proton energy spectra and those of AMD-FM with b = 0−5fm in (a) and b = 0−9fm in (b) in an absolute scale. The experimental data are inclusive. A few hundred thousand events have been generated for AMD-FM calculation. No afterburner is used for this comparison. The results for b = 0 − 5fm can reproduce the experimental data pretty well. If we take the impact parameter range of b = 0 − 9fm, the calculated cross sections become about twice larger at four forward angles.

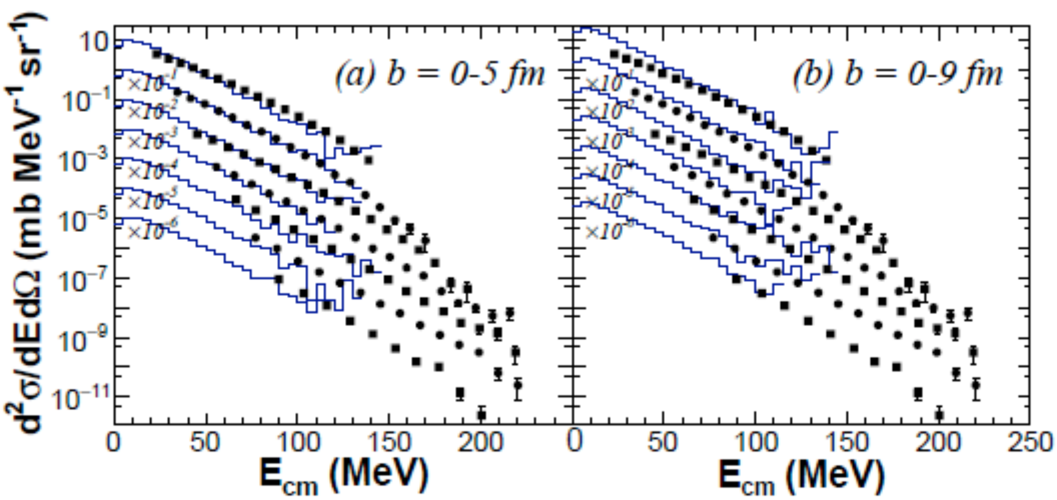

FIG. 2. Proton energy spectra of the AMD-FM calculation for b = 0 - 5fm (a) and b = 0   9fm (b) are compared in an absolute scale with the experimentally observed inclusive data of ^{40}Ar + ^{51}V at 44 MeV/nucleon. See also the figure caption of Fig.1.

This comparison confirms that, at 44 MeV/nucleon, the high energy protons are solely generated by the Fermi boost, which is characterized by the Gaussian distribution with sigma ~80 MeV/c.

It is interesting to extend the comparisons at higher incident energies. The high energy protons are generated at an early stage of the collisions where the nuclear density is high. If the three body collisions contribute, the contribution comes more significant at higher incident energy, because the three body collisions occur in proportion to the third power of the nuclear density whereas the two body collisions to the second power. In order to test the validity of AMD-FM at higher incident energies, the experimental data of ^{36}Ar + ^{181}Ta at 94 MeV/nucleon by Germain et al. [2] are used. The experimental data are inclusive, and therefore the impact parameter range of b = 0 − 9fm is used for the AMD-FM calculation. The calculated proton energy spectra with AMD-FM at 75° (red histogram) and 105° (green histogram) are plotted in Fig. 3 in the laboratory reference frame together with those of the experiment (full symbols) in an absolute scale. Though the statistic is still not enough for detailed comparisons, one can see that the slopes of the experimental energy spectra are well reproduced by AMD-FM for both of angles as well as the amplitudes. This comparison indicates that the high energy protons observed at 94 MeV/nucleon originates essentially from the co-play of the Fermi boost in the diffusion and collision processes. However, from this analysis, we cannot exclude the necessity of the three body collision term, but the contribution is small even if it contributes some.

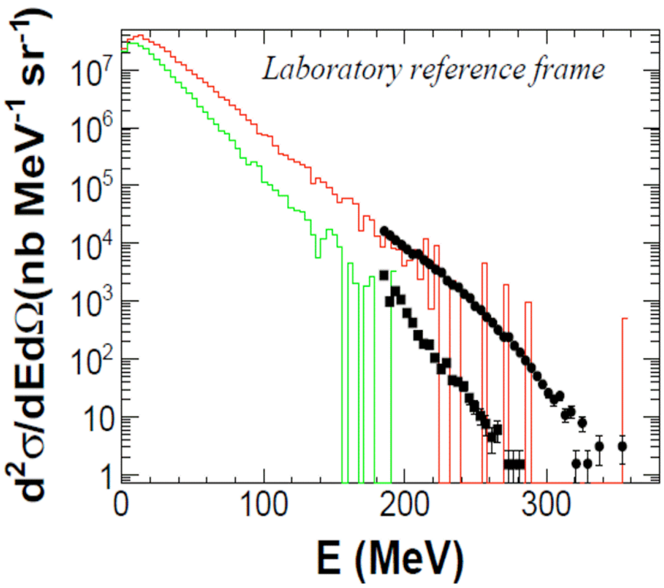

FIG. 3. Proton energy spectra of the AMD-FM calculation for b ≤ 9fm (histograms) are compared in an absolute scale with the experimentally observed inclusive data of ^{36}Ar + Ta at 94 MeV/nucleon (dots) at 75° and 105° in the laboratory frame.

[1] R. Coniglione *et al.*, Phys. Lett. B **471**, 339 (2000).
[2] M. Germain *et al.*, Nucl. Phys. **A620**, 81 (1997).