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Realistic estimates for promptly emitted particles

S. Bhattacharya and K. Krishan
Variable Energy Cyclotron Centre, Calcutta 700064, India

S. K. Samaddar
Saha Institute of Nuclear Physics, Calcutta 700009, India

J. N. De*
Variable Energy Cyclotron Centre, Calcutta 700064, India
and Grand Accélérateur National d'Ions Lourds, 14021 Caen Cedex, France
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Spectra of emitted nucleons in nuclear collisions are calculated at different angles in the model of promptly emitted particles and are compared with experimental data in the energy range of 10–25 MeV/nucleon. Inclusion of two-body collisions, dynamically evolving nucleon momentum distributions, barrier penetration, and driving force for nucleon transfer gives a very good fit of the theoretical calculations with the experimental results.

Several models have been employed by various authors to explain preequilibrium emission of particles in heavy ion collisions around and below the Fermi energy domain. The simple moving source model[1] is quite successful in explaining several characteristics of the emission spectra, but there is little physical understanding of the free parameters employed in this phenomenological model characterizing the emitting sources. The exciton model[2] or the Harp-Miller-Berne model modified by Blann[3] are also successful in explaining the energy spectra; here two free parameters, namely, the initial exciton number and the transition rate scaling factor are used to fit the experimental data. However, the apparent anomaly[4] of the variation of exciton number with bombarding energy is not understood.

Several attempts have been made to estimate the preequilibrium nucleon emission using the parameter-free model of "Fermi jets"[5] or promptly emitted particles[6–8] (PEP). It is assumed in this model that the coupling of the nuclear relative velocity and the intrinsic velocity of a nucleon may give a transferred nucleon in the recipient nucleus enough boost in energy so that it may be emitted in the continuum in a very early stage of the collision. But this model has not been put to rigorous experimental test by including the influence of two-body collisions, the dynamically changing momentum distribution due to deposition of energy in the colliding partners, the influence of the driving force on the nucleon transfer probability, and the effect of penetration through the barrier, including the Coulomb barrier for protons. In the present paper we have included all the above mentioned effects and have confronted our calculated results with the exclusive experimental spectra in the energy range of 10–25 MeV/nucleon.

The most difficult task is to incorporate correctly the dynamical evolution of the momentum distribution of the colliding ions. The nonequilibrium flow of energy and momentum between the interacting nuclei changes their momentum distributions from those of their respective ground states and a satisfactory treatment of this problem may be obtained from microscopic time-dependent Hartree-Fock (TDHF) calculations with two-body collisions[9] or semiquantal Vlasov-Uhlenbeck[10] (VUU) calculations. These calculations are, however, very time consuming. In our present paper, we have simplified this problem by assuming the momentum distributions to be diffuse Fermi distributions, where the "temperature parameter" T is obtained from the relation

$$T_{A,B}=(10E^*_{A,B}/M_{A,B})^{1/2} . \quad (1)$$

Here the subscripts A and B refer to the two reacting nuclei, M is their dynamical mass number, and E^* the instantaneous excitation energy of the respective systems. Recent experimental data[11] and supportive theoretical calculations[12] show nonequilibrium division of energy in asymmetric nuclear collisions. The consequent different momentum distributions in asymmetric partners are suggested through Eq. (1) and taken care of in the present paper. We have followed our previous work[12,13] for calculating the time-dependent exchange flux in the dynamical trajectory. Each nucleon transfer generates a hole excitation in the donor nucleus and a particle excitation in the recipient nucleus. This transferred nucleon, if of sufficient energy, may suffer a refraction at the recipient surface (because of orbital angular momentum conservation in a central field which we assume) and be emitted in the continuum as a PEP, or it may be absorbed in the recipient nucleus. The excitation energy E^* in a nucleus is the sum of nucleon-exchange generated hole and particle excitation energies in the nucleus except for the collective rotational energy (the particle excitation energy associated with an emitted PEP is not counted). The time-dependent barrier is approximated by a static local-time inverted parabola and then the transmission probability is calculated from the Hill-Wheeler formula. The driving force is obtained from the shell-corrected liquid-drop mass formula.

The transferred nucleons travelling through the recipient nucleus may suffer two-body collisions and the collision probability is simulated through the mean free path λ. The flux of promptly emitted particles is therefore attenuated by the factor $e^{-d/\lambda}$ where d is the path length of the nucleon traversed in the recipient nucleus. The particles thus emitted without suffering any collision would be called one-body PEP's. The mean free path is calculated from the nucleon-nucleus optical potential and is given by

$$\lambda = \hbar v / 2W , \qquad (2)$$

where W is the energy dependent absorptive part of the optical potential taken as

$$W = 3.0 + 0.07\varepsilon_{\infty} . \qquad (3)$$

In Eqs. (2) and (3), v refers to the velocity of the nucleon in the recipient nucleus, and ε_{∞} refers to the asymptotic energy of the emitted PEP.

The nucleon removed from the transferred flux due to two-body collision with another in-medium nucleon may not be absorbed in the recipient. The angular distribution of the colliding nucleons is assumed to be isotropic in the two-nucleon center-of-mass system, within the phase space allowed by the Pauli principle. Both or one of these scattered nucleons, if of sufficient energy, may be emitted in the continuum (with attenuated flux, as in the case of one-body PEP's) and these nucleons would be called two-body PEP's.[6] The emission of PEP's from further collisions of the scattered nucleons may not be of sufficient importance in the energy range we consider.

In the present paper we have studied the reactions induced by ^{20}Ne at 220, 292, and 402 MeV bombarding energies[14] and ^{12}C at 300 MeV (Ref. 4) incident on ^{165}Ho. In Fig. 1 the calculated neutron double differential multiplicities are plotted as a function of emitted energy at several laboratory angles for the reaction Ne + Ho at 402 MeV along with the experimental data. Since the contribution due to evaporation is not included, our calculated results should be compared with the experimental data for the relatively higher energy part of the spectra. The emitted neutrons were measured only for fusion events corresponding to maximum angular momentum of $60\hbar$ and hence the calculation is confined to these incident angular momenta. The dashed lines correspond to calculations at zero temperature, and the solid lines represent calculated results obtained by using "finite temperature" momentum distribution. It is seen that the high energy tails of the energy spectra are significantly enhanced with

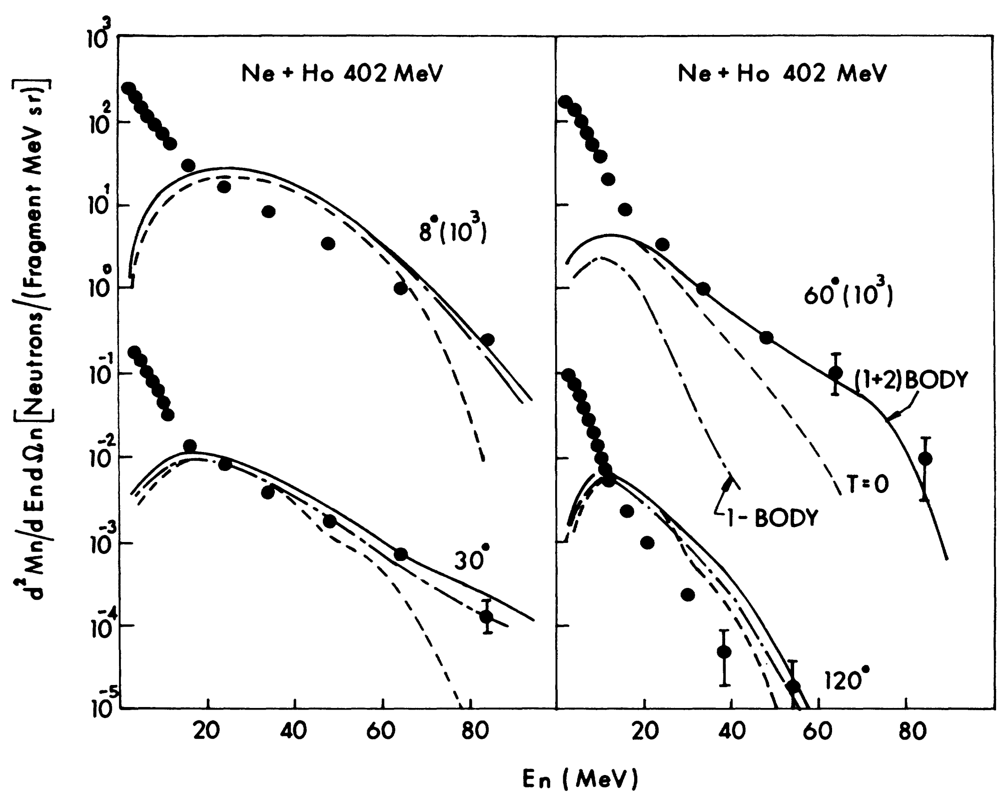

FIG. 1. Double differential neutron PEP multiplicities for the reaction ^{20}Ne + ^{165}Ho at 402 MeV bombarding energy at different laboratory angles. The solid and the dash-dotted lines refer to the calculated results for (one plus two)-body and one-body PEP's at finite temperature, and the dashed lines represent (one plus two)-body results at zero temperature. The experimental points are denoted by the solid circles.

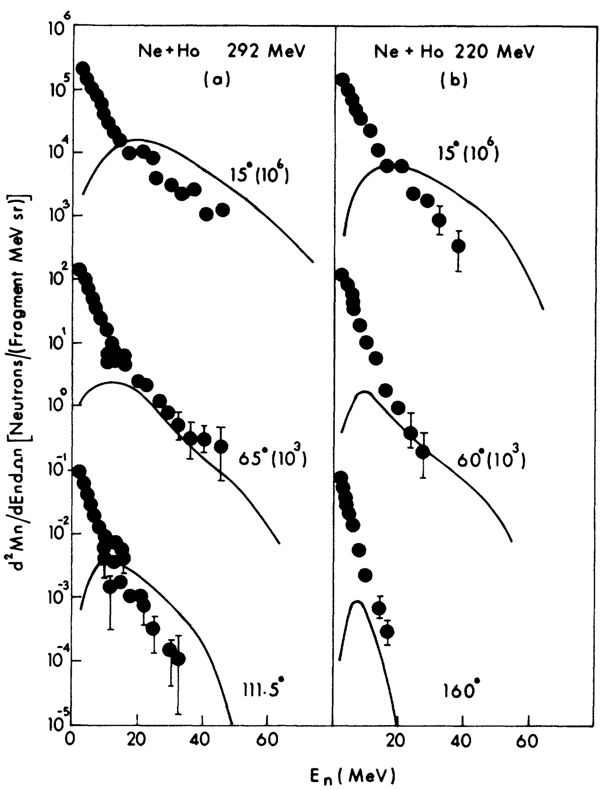

FIG. 2. The same as in Fig. 1 at (a) 292 MeV and (b) 220 MeV bombarding energies for (one plus two)-body PEP's at finite temperature.

the inclusion of diffuse momentum distribution. The dash-dotted lines represent results for one-body PEP at finite temperature. We note that the contribution of the two-body PEP's is very significant at 60° and it has been found that the two-body PEP is primarily confined to within a small cone around 60°. In Figs. 2(a) and 2(b), the neutron double differential multiplicities for the reactions Ne + Ho at 292 and 220 MeV are displayed. The same quantities are plotted for the reaction C + Ho at 300 MeV in Fig. 3. The importance of the diffuse momentum distributions and two-body PEP's for these reactions (not shown in the figures) is the same here as in the case of the Ne induced reaction at 402 MeV. The effect of the driving force on the PEP emission has been found to be not very significant for all the reactions mentioned above.

In Fig. 4 the effective "temperature" extracted from the calculated inclusive energy distribution of neutron PEP's is plotted as a function of bombarding energy per nucleon above the Coulomb barrier along with those obtained from the experimental data for the above mentioned reactions. The calculated apparent "temperatures" are seen to agree very well with the experimental values.

The total PEP multiplicity (neutron plus proton) as a function of per particle incident energy above the Coulomb barrier is displayed in Fig. 5(a) for the asymmetric system $^{20}Ne+^{165}Ho$ and for the symmetric system $^{90}Zr+^{90}Zr$ having almost the same number of nucleons. In Fig. 5(b) the ratio of two-body to one-body PEP's as a

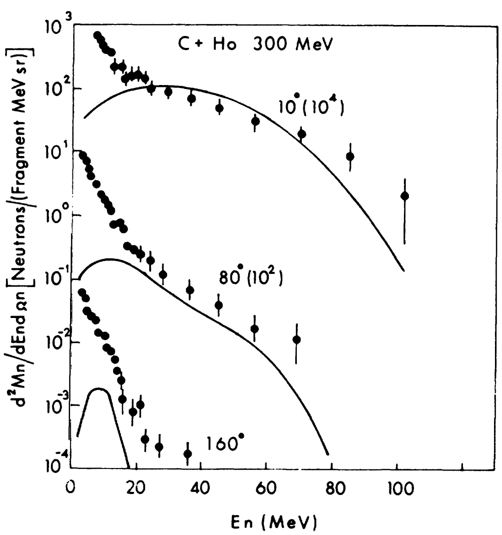

FIG. 3. The same as in Fig. 1 for the reaction $^{12}C+^{165}Ho$ at 300 MeV.

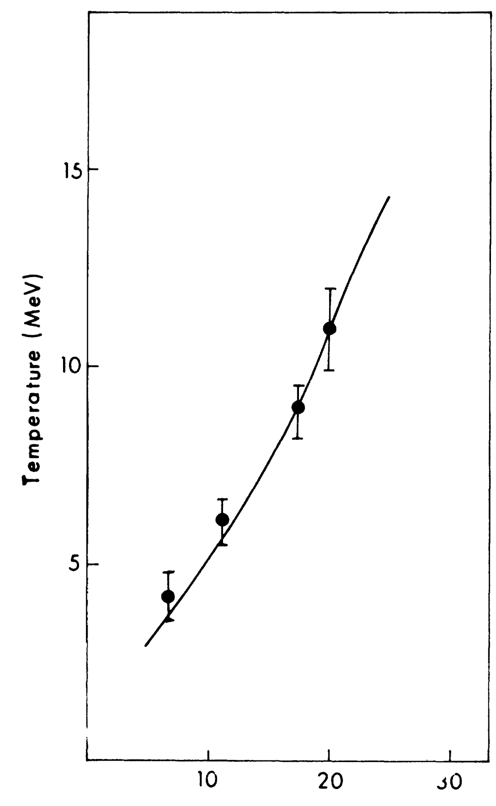

FIG. 4. The effective temperature from neutron inclusive energy spectra as a function of per particle incident energy above the Coulomb barrier. The solid line refers to the calculated result for the system Ne + Ho, and the experimental points (Ref. 4) are for the systems Ne + Ho at 220, 292, and 402 MeV and C + Ho at 300 MeV.

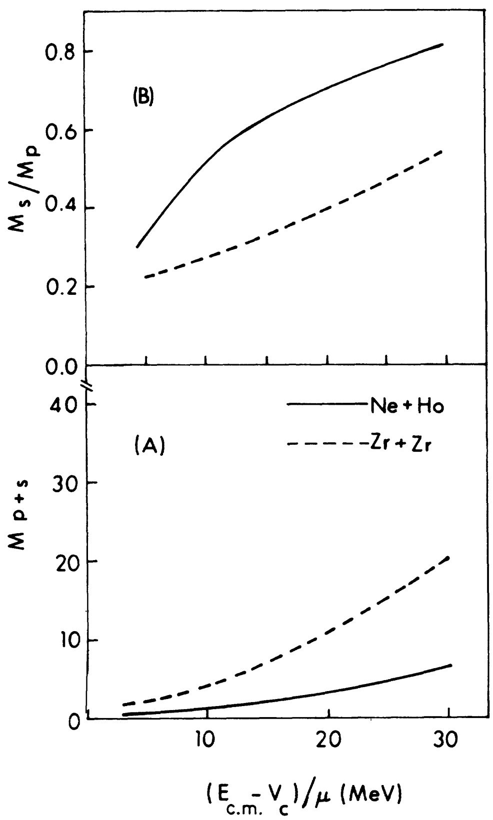

FIG. 5. (A) The total PEP multiplicity (neutron plus proton) as a function of per particle energy for the systems $^{20}Ne+^{165}Ho$ and $^{90}Zr+^{90}Zr$. (B) Ratio of two-body (M_s) to one-body (M_p) PEP multiplicities for the same systems.

function of incident energy is shown for the same systems. We note that this ratio increases quite rapidly as a function of energy. We further note that whereas the PEP multiplicity (one-body plus two-body) is considerably larger for the symmetric system as compared to the asymmetric one, the secondary to primary ratio is larger for the asymmetric system. We found that this is a consequence of different effective absorptions in these systems.

The overall good fit of the theoretical and experimental results for the systems studied here shows that the coupling of the nucleon's intrinsic velocity with the nuclear relative velocity plays a dominant role in the preequilibrium emission of nucleons in nuclear collisions. It is seen that the effect of two-body collisions becomes increasingly important with higher energies, particularly at sidewards angles. Moreover, the dynamical changes in momentum distributions in individual colliding nuclei (which we simulate through a temperature distribution) are extremely significant for a proper explanation of the energy distributions at different angles. For reaction C + Ho at 25 MeV/nucleon, the calculated energy distribution at very backward angle (160°) underestimates the experimental data very much; this departure from the general trend at an energy around the Fermi domain at backward angles may possibly be a reflection of a coexisting reaction mechanism like the formation of a hot spot.[15] The use of straight line trajectories for the prompt particles may be thought of as a limitation (use of wave packets[16] for nucleons are known to diffuse the angular spectra) in this calculation, but for the energetic particles we consider, this limitation may not be very serious and therefore judging from the good fit we obtained with the experimental data, the PEP mechanism based on mean field dynamics with the inclusion of two-body collisions may be considered as a viable mechanism for the explanation of high energy particle spectra in heavy ion collisions.

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*Permanent address: Variable Energy Cyclotron Centre, Calcutta 700064, India.

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