Role of Two-Body Collisions in Limiting Momentum Transfer and Energy Deposition in Nucleus-Nucleus Collisions

S. Bhattacharya, J. N. De, and K. Krishan
Variable Energy Cyclotron Centre, 1/AF, Bidhan Nagar, Calcutta-700064, India

S. K. Samaddar
Saha Institute of Nuclear Physics, 92, Acharya Prafulla Chandra Roy Road, Calcutta-700009, India

(Received 14 June 1988)

The observed saturations of temperature and of linear momentum transfer per incident nucleon in intermediate-energy nuclear reactions are studied in the model of promptly emitted particles. We demonstrate that only with the inclusion of two-body collisions is very good agreement with experimental data obtained.

PACS numbers: 25.70.Jj

Extensive experimental studies have recently been made to understand the phenomena of incomplete linear momentum transfer in fusionlike nucleus-nucleus reactions.[1-3] A number of models[4-9] have been used with varying degrees of success to explain the basic features of the data like (a) approximate universality of the scaling of fractional momentum transfer with heavy-ion projectile mass[10,11] and (b) apparent saturation of that momentum transfer in the range of 170–220 MeV/c per incident nucleon.[1,12,13] A recent measurement of nuclear "temperature" in 60-MeV/A Ar+Au reactions[14] has also indicated that there may be some kind of dynamical limitation to the excitation-energy storage and vis-à-vis temperature in the residual system. A schematic model prediction[2] for the linear momentum transfer and detailed Landau-Vlasov calculations for the excitation-energy storage in the nucleus[15] both point to the fact that the origin of the saturation, either in linear momentum transfer per incident nucleon (P_T/A) or in nuclear temperature (T), may lie in the partial breakdown of mean-field effects and gradual dominance of two-body collisions, which is supported by a number of experimental observations[1] where fusion cross sections are found to decrease with an increase in bombarding energy.

To have a simple but transparent understanding of the importance of two-body collisions in intermediate-energy fusionlike reactions, we have undertaken a detailed dynamical calculation of the linear momentum transfer and excitation-energy deposition in nuclei using a realistic model of promptly emitted particles (PEP's)[16,17] where the effect of two-body collisions has been explicitly taken into account. The effects of dynamically changing momentum distributions due to energy deposition are also taken care of by simulation of excitation effects through temperature.[17] This model has been quite successful in explaining the angular distributions of emitted nucleons in heavy-ion reactions[17] as well as the dependence of velocities of fused residues on entrance-channel mass asymmetry.[18] A similar piece of work done by Randrup and Vandenbosch[19] also highlights the success of the model.

The basic formulation of the PEP model has been described elsewhere[16,17] and will be mentioned here in brief. When two nuclei come closer than some critical distance, a window is formed between them through which nucleons are exchanged from one nucleus to another. Part of the transferred nucleon flux may be completely absorbed in the recipient due to collisions, the rest (the attenuation is given by $e^{-d/\lambda}$, d being the path length in the recipient and λ being the energy-dependent mean free path calculated as in Ref. 16) may be emitted in the continuum provided the energy is sufficient to overcome the nuclear barrier. These emitted nucleons that have suffered no collisions along their path are called one-body PEP's. The particle absorption may, however, be reduced, because after the first collision suffered by the transferred nucleon both the collision partners or one of them may be emitted in the continuum subject to further attenuation (taken as e^{-d_i/λ_i}, $i=1,2$) and the energy restrictions just mentioned. These emitted particles are termed two-body PEP's. With an increase in bombarding energy, further reduction of particle absorption as a result of emission from sequential multiple collisions is possible, but in the energy range we consider (up to ~60 MeV/A) it may not be important and has been neglected here. A competition between one-body and (one + two)-body nucleon emissions may ultimately lead to saturation in temperature. We make some further observations. Since momentum transfer originates from absorption, in the (one +two)-body PEP picture, momentum transfer is expected to be comparatively less because of reduced absorption. On the other hand, the two-body PEP's are emitted preferentially around 60°–70° to the beam direction[17] and therefore carry less amount of forward momentum per particle than that of one-body PEP's which are emitted mostly in forward directions. These opposing effects coupled with the gradual dominance of two-body PEP's over one-body PEP's with increasing bombarding energy may lead to the saturation of linear momentum transferred per incident nucleon. Both of these intuitive predictions have been found to be justified in the calculation reported here. The dynamical calculations have been done as in Ref. 20 with nucleon exchanges simulated through a Monte Carlo technique and two-body collisions incorporated as in Ref. 17.

We have chosen three systems for our study, namely ^{20}Ne+^{56}Fe, ^{30}S+^{90}Zr, and ^{14}N+^{40}Ca for both normal and inverse kinematical reactions. The calculations are done only for those dynamical trajectories which lead to incomplete fusion. For energies $\gtrsim 20$ MeV/A, this corresponds to central and near central conditions (maximum impact parameter $b_{\max} \sim 3.0$ fm) for the systems considered. The results reported here have been found to be not very sensitive to these impact parameters. Therefore, in the following we present results for a representative impact parameter $b = 0.25$ fm. The fractional linear momentum transfer ρ ($=P_T/P_i$, P_i and P_T being the incident momentum and momentum transferred, respectively) is plotted in Fig. 1 as a function of $(E_{\text{lab}}/A)^{1/2}$ for finite-temperature one-body and (one+two)-body calculations. The values of ρ obtained from zero-temperature (one+two)-body calculations are also displayed. For normal kinematical reactions (lower part of Fig. 1), it is found that ρ obtained from one-body calculations saturates to a limiting value of ~ 0.8 with an increase in energy. This is quite inadequate to reproduce the trend of the experimental data as indicated by the Viola system. However, with the inclusion of two-body collisions, the theoretical values are found to be in very good agreement with the Viola systematics. Even the results obtained from the zero-temperature calculation agree fairly well with the phenomenological systematics. The results obtained for the inverse kinematical reactions (shown in the upper half of Fig. 1) also show a similar trend as obtained for the normal systems but for the fact that they are not in agreement with the Viola systematics. Similar results have been obtained in calculations reported in Ref. 6. This is indicative of the fact that the Viola systematics does not hold well for all types of target-projectile combinations and a more general systematics is needed to explain the whole range of data.

The effect of two-body collisions on linear-momentum transfer is displayed in more detail in Fig. 2, where the linear momentum transferred per incident nucleon has been plotted as a function of E_{lab}/A. It is clear from Fig. 2 that the calculations in the one-body picture do not lead to any saturation in P_T/A. However, when the two-body collision is switched on, P_T/A is found to satu-

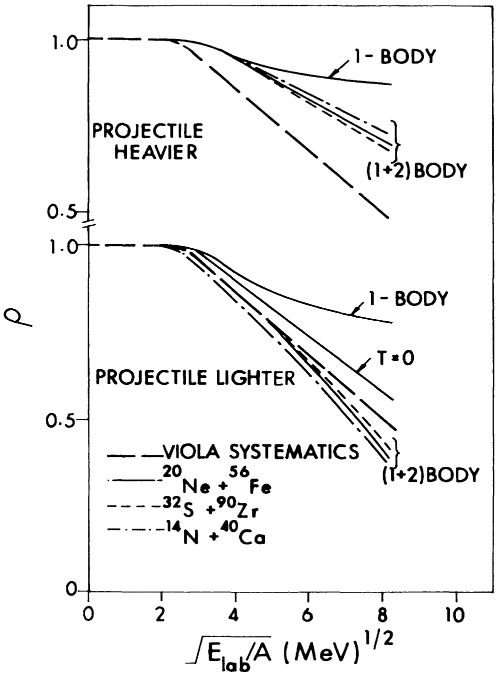

FIG. 1. Fractional linear momentum transfer ρ as a function of $(E_{\text{lab}}/A)^{1/2}$ for the systems ^{14}N+^{40}Ca, ^{20}Ne+^{56}Fe, and ^{32}S+^{90}Zr for both normal (lower half) and inverse kinematical reactions (upper half). 1-BODY corresponds to a one-body calculation at finite temperature; $T=0$ and (1+2)BODY correspond to zero-temperature and finite-temperature calculations, respectively, where possible particle emission due to two-body collisions has explicitly been taken into account.

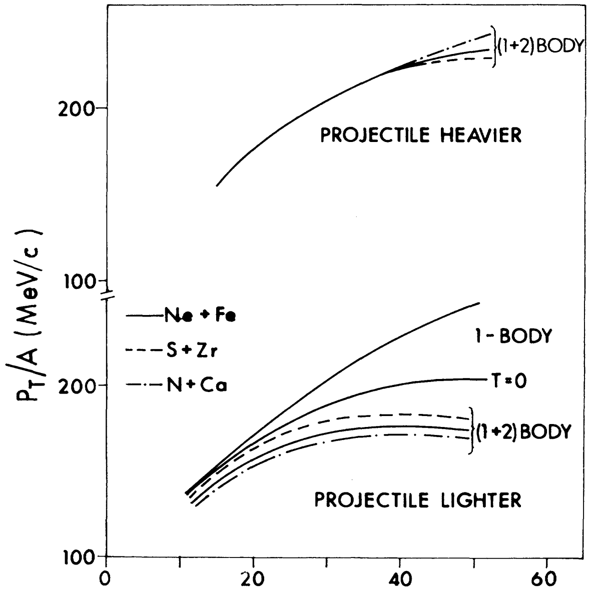

FIG. 2. Linear momentum transferred per incident nucleon (P_T/A) as a function of incident energy per nucleon (E_{lab}/A) for the systems ^{14}N+^{40}Ca, ^{20}Ne+^{56}Fe, and ^{32}S+^{90}Zr for both normal (lower half) and inverse kinematical reactions (upper half). The notations 1-BODY, $T=0$, and (1+2)-BODY are explained in Fig. 1.

rate at ~180 MeV/c (~220 MeV/c for the inverse kinematical systems). A zero-temperature calculation also shows similar saturation in P_T/A at a somewhat higher value of ~200 MeV/c, which can be easily understood from the fact that PEP emission and momentum carried by them are more at finite temperatures; this lowers the value of P_T/A. These limiting values of P_T/A are in very good agreement with the experimental data.[12,13] Saturation in P_T/A is found to occur at around 30-40 MeV/A incident energy. It is interesting to note that the incomplete-fusion (ICF) cross sections, as measured experimentally,[1] decrease sharply in this energy range. The sharp fall in ICF cross sections reflects the weakening of the mean-field effects in the sense that a large number of nucleons can now no longer be trapped in the one-body potential.[1] This is in accordance with our calculations which clearly demonstrate that the gradual dominance of two-body collisions ultimately results in saturation in P_T/A.

The crucial role played by two-body collisions in explaining the nonequilibrium phenomena in intermediate-energy nucleus-nucleus collisions is further demonstrated in Fig. 3. Here we have plotted the temperature (T) of the fused residue as a function of incident energy per nucleon. The temperature is defined by the relation $E^* = aT^2$, where $a = A_{\text{res}}/10$, E^* and A_{res} being the total excitation energy dumped in the residual system of mass number A_{res}. A simple empirical relationship[1] predicts that even if there is saturation in P_T/A, the energy deposited in the residual system continues to increase with energy, so that the excited residual system may ultimately reach its stability limit. Recent experimental results[14] of 60-MeV/A Ar on Au indicate that the measured temperature (~4-5 MeV) is quite low compared to various theoretical predictions. The insensitivity of the measured temperature with charged-particle multiplicity observed in coincidence[14] is indicative of the fact that there may exist some dynamical limitation to the energy storage in the system in the form of cooling through particle emission or collective excitation models. This particular aspect of dynamical limitation to energy deposition through nonequilibrium particle emission can be inferred from Fig. 3. We find here that consideration of only one-body effects does not lead to any saturation in temperature. However, with the inclusion of two-body collisions, temperature is found to saturate, its limiting value being ~6 MeV, which varies slightly from system to system. This is quite consistent with the results obtained from experiments.[14] Incidentally, we may note that the saturation in nuclear temperature also occurs at around 30-40 MeV/A bombarding energy. The decisive role played by two-body collisions in the saturation phenomena is thus evident. In Fig. 4, we explicitly show a typical impact-parameter dependence of the temperature of the residue for the studied systems at $E/A = 30$ and 40 MeV. We find that in the narrow range of impact parameters leading to fusion, the temperature is almost independent of impact parameter.

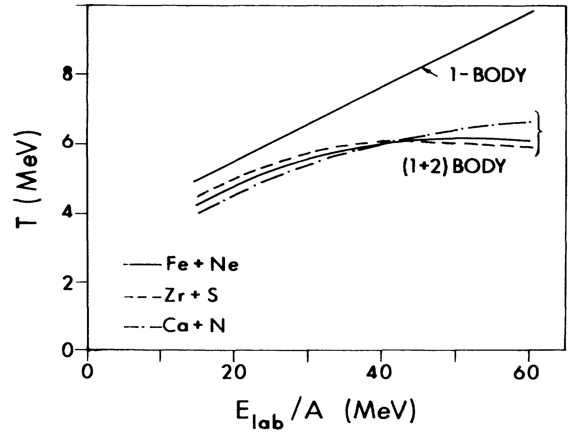

FIG. 3. Temperature (T) as a function of incident energy per nucleon (E_{lab}/A).

In passing, we note that the violent collisions discussed here may lead to density fluctuations in the system which may alter the mean free path and thus influence our results. It has, however, been observed that at the particle energies concerned (the transferred particles have on the average ~40-50-MeV energy above the Fermi surface in the recipient system), the mean free path is nearly independent of temperature and of density[21] if the density is not too far from equilibrium (this is possibly the case[22] in the early emission stage which is of importance in the present context). We therefore do not expect our observations to be influenced much because of the density fluctuations. We further note that the energy left in the composite system after prompt emission (in our calculation, this occurs in the very early stage of the collision, in a time ~40 fm/c after contact) or part of it may possibly allow development of a compression mode in the system. From Landau-Vlasov calculations, as suggested in Ref. 14, at $E/A = 60$ MeV, the compression mode devel-

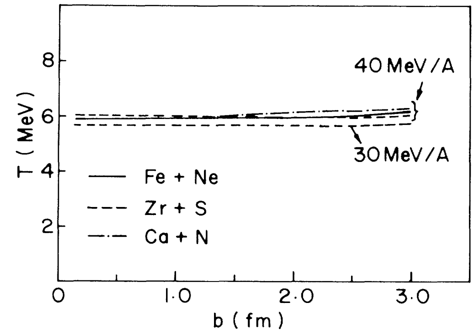

FIG. 4. The impact-parameter dependence of temperature shown at $E_{\text{lab}}/A = 40$ MeV. At 30 MeV, we display results for only one system; the others show the same behavior.

ops after ~60 fm/c. During decompression, if the system enters the spinodal region, it would develop instability towards disintegration and rupture into several fragments. For the systems considered here the excitation energy per particle is, however, too low ($E^*/A = T^2/10 \sim 3.6$ MeV) for such a scenario to occur (for compression, the onset of fragmentation is found to be at ~6.5 MeV/nucleon in the Landau-Vlasov calculation[23]). Rather the energy involved in the collective compression mode is later damped to incoherent thermal energy with subsequent thermal emission. Since we are interested in the deposition energy that later equilibrates, the dynamical development after nonequilibrated energy release through prompt particle emission may possibly not alter our findings regarding the limiting temperature.

To summarize, we have done a detailed dynamical calculation for the incomplete transfer of linear momentum and energy in the model of promptly emitted particles. The effects of two-body collisions have been explicitly taken into account in the calculation. We find that the two-body collision plays an extremely important role in quantitatively explaining the incomplete momentum transfer data over a wide range of energy. In the (one + two)-body PEP picture, because of less effective absorption compared to the one-body PEP picture, the momentum transfer is less. The observed saturations of temperature and of linear momentum transferred per incident nucleon follow naturally from the inclusion of two-body collisions in our calculations and their very good agreement with the experimental data firmly establishes the importance of two-body collisions in intermediate-energy nuclear reactions.

---

[1] S. Leray, in *Proceedings of the International Conference on Heavy Ion Collision in the Fermi Energy Domain, Caen, France, 12–16 May 1986* [J. Phys. Paris, Colloq. **47**, Suppl. 8, C4-275 (1986)].

[2] J. B. Natowitz *et al.*, Z. Phys. A **325**, 467 (1986).

[3] T. Batsch *et al.*, Phys. Lett. B **189**, 287 (1987).

[4] G. S. F. Stefans *et al.*, Phys. Lett. **161B**, 60 (1985).

[5] C. Ngo and S. Leray, Z. Phys. A **322**, 419 (1985).

[6] S. Leray *et al.*, Z. Phys. A **320**, 383 (1985).

[7] M. Blann, Phys. Rev. C **31**, 1285 (1985).

[8] D. J. Fields *et al.*, Phys. Rev. C **30**, 1912 (1984).

[9] C. Gregoire and F. Scheuter, Phys. Lett. **146B**, 21 (1984).

[10] V. E. Viola *et al.*, Phys. Rev. C **26**, 178 (1982).

[11] G. LaRana *et al.*, Nucl. Phys. **A407**, 233 (1983).

[12] J. Galin *et al.*, Phys. Rev. Lett. **48**, 1787 (1982).

[13] M. B. Tsang *et al.*, Phys. Lett. **134B**, 169 (1984).

[14] F. Saint-Laurent *et al.*, Phys. Lett. B **202**, 190 (1988).

[15] C. Gregoire *et al.*, Nucl. Phys. **A465**, 317 (1987).

[16] J. P. Bondorf *et al.*, Nucl. Phys. **A333**, 285 (1980).

[17] S. Bhattacharya *et al.*, Phys. Rev. C **37**, 2916 (1988).

[18] K. Krishan *et al.*, Phys. Lett. B **211**, 269 (1988).

[19] J. Randrup and R. Vandenbosch, Nucl. Phys. **A474**, 219 (1987).

[20] S. K. Samaddar, J. N. De, and K. Krishan, Phys. Rev. C **31**, 1053 (1985).

[21] A. Lejeune *et al.*, Nucl. Phys. **A453**, 189 (1986).

[22] C. Gregoire *et al.*, Nucl. Phys. **A465**, 317 (1987).

[23] L. Vinet *et al.*, Nucl. Phys. **A468**, 321 (1987).