Interpretation of Fission-Fragment Angular Distributions in Heavy-Ion Fusion Reactions

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(Received 7 June 1984)

Fission-fragment angular distributions in a number of heavy-ion–induced fusion reactions are explained on the basis that for composite systems with fission barrier heights comparable to their intrinsic temperatures, a fraction of the fission events take place before the fused system equilibrates fully in the K degree of freedom. A value of about 8×10^{-21} s is deduced for the characteristic time for K equilibration.

PACS numbers: 25.70.Jj, 25.85.Ge

In a number of recent measurements of the fragment angular distributions in heavy-ion–induced fusion-fission reactions,[1–7] the data are not consistent with the predictions of the conventional theory[8,9] of fragment angular distributions in fission following compound-nucleus formation. Theoretical approaches different from the conventional theory have been proposed[10,11] to account for the discrepancy but no single quantitative theory exists at present to explain all the measured distributions. In this work, we present a model based on the suggestion that in heavy-ion–induced fusion reactions the observed fission events consist of an admixture of events of two types: (i) compound-nucleus fission (CNF), and (ii) non-compound-nucleus fission (NCNF) of a composite system which has equilibrated in all degrees of freedom except the K degree of freedom, where K is the projection of the angular momentum on the nuclear symmetry axis. Reaction mechanisms such as fast fission,[12] taking place for the case of composite systems with zero fission barriers, and quasifission,[13] taking place for composite systems with fission-barrier shapes more compact than the entrance-channel contact configuration, are cases of type (ii). Another class of NCNF events which has not been considered before includes those occurring in a time comparable to the characteristic relaxation time in the K degree of freedom when the fission-barrier heights become comparable to the temperature of the composite system.

For the CNF events we use the conventional theory[8,9] with a small modification[14] to include also the dependence of transition-state shape on the quantum number K. For calculating the deformation and rotational energies, we have used the shape parametrization of Brack *et al.*[15] and the liquid-drop-model parameters of Pauli and Ledergerber[16] which were arrived at by them to reproduce the systematics of the liquid-drop-model fission-barrier heights for actinide nuclei. A value of the radius parameter $r_0 = 1.22$ fm was used to calculate the moments of inertia. For calculating the temperature, a value of the level density parameter $a = A/7$ was used. The use of another reasonable set of these parameters will result in only slightly different angular distributions (5%–10% change in anisotropy values) for this component. We have also made the reasonable assumption that all CNF events correspond to first-chance fission.

There exists at present no theoretical formulation for calculating fragment angular distributions for type-(ii) events. However, in some recent experiments[3] involving very high spin and large values of Z^2/A of the composite system where the compound-nucleus formation probability is very small, highly anisotropic angular distributions have been measured. Since these are characteristic of a rather narrow distribution of K states around $K=0$, Lesko *et al.*[3] have suggested that a memory of the entrance-channel reaction plane with $K=0$ is retained in these reactions leading to a highly anisotropic $1/\sin(\theta)$ type of angular distribution. We suggest here that one should also include the possibility of a spread in the K distribution of this component due to such processes as nucleon exchange between the target and the projectile in the entrance channel and the finite time for fission even in the absence of a fission barrier. Let σ_θ be the angular variance representing misalignment of the symmetry axis of the fused composite system with respect to the $K=0$ plane. The corresponding variance σ_κ of the K distribution for NCNF events is then given by $\sigma_\kappa^2 = I^2\sigma_\theta^2$.

Figure 1 shows the measured angular distributions[1,2] for the systems $^{19}F + {}^{208}Pb$, $^{24}Mg + {}^{208}Pb$, $^{28}Si + {}^{208}Pb$, and $^{32}S + {}^{208}Pb$ at three bombarding energies. The corresponding limiting angular-momentum values, I_{cr}, for fusion as deduced from measured fission cross sections and the rotating-liquid-drop-model[17] limit for vanishing fission barrier, I_F^{RLDM}, are also shown in the figure. The dashed curves in Fig. 1 shown for the cases of lowest bombarding energies represent the calculated angular distributions on the assumption that all the fission events are of type (i). The effect of the modification introduced in Ref. 14 to the standard theory[8,9] can be seen in the figure by comparison of the dashed curve with the dotted curve, shown for the case of $^{32}S + {}^{208}Pb$. If the NCNF events originated only from the fast fission process, one would have expected that, for all the cases of bombarding energies where $I_{cr} < I_F^{RLDM}$, the measured angular distributions

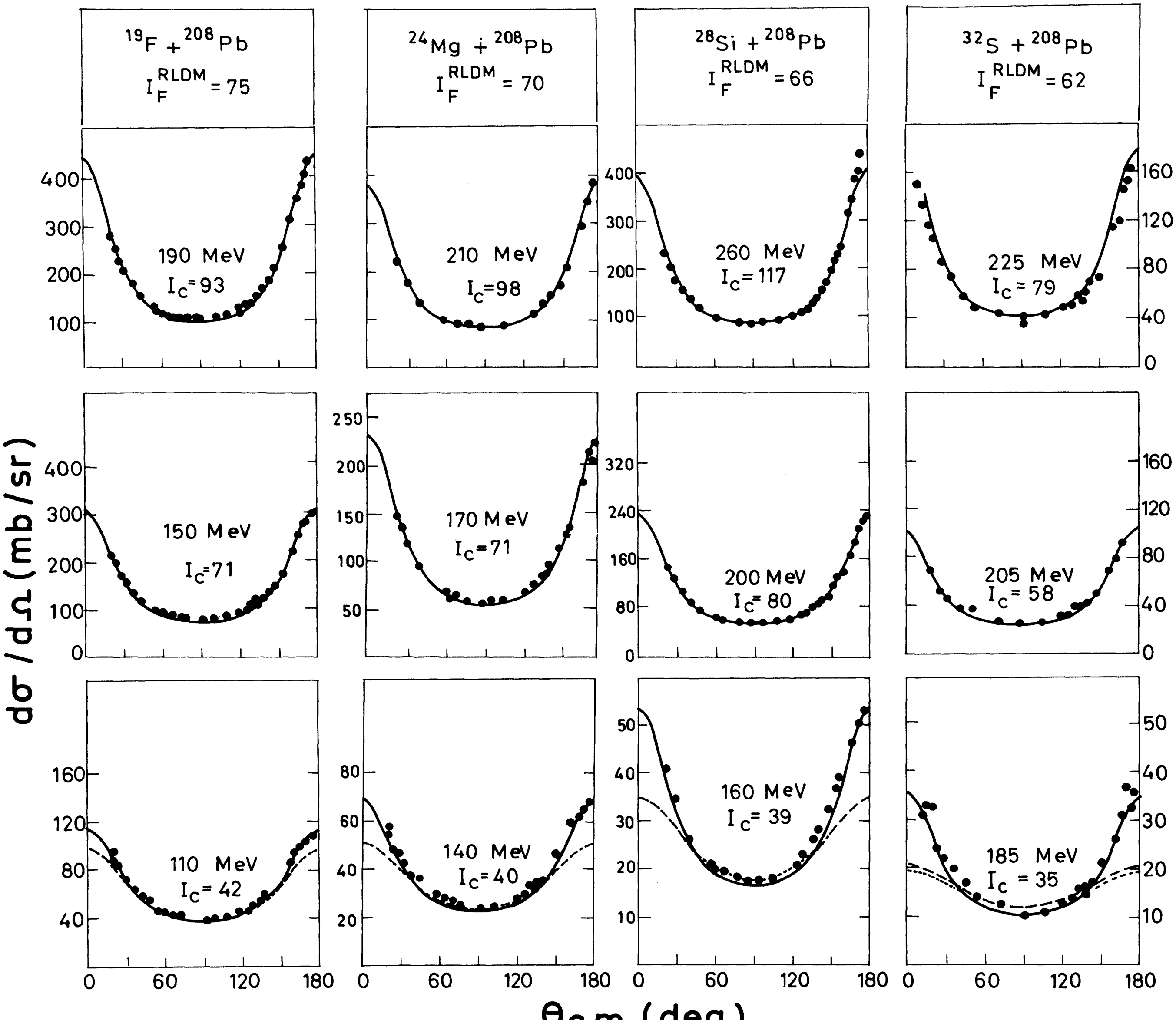

FIG. 1. Experimental (Refs. 1 and 2) and calculated fission-fragment angular distributions. The continuous curves are the results of the present calculations. The dashed lines are the calculated distributions for type-(i) events with the modification of Ref. 14. For the case of $^{32}S + ^{208}Pb$ (185 MeV) the calculation without the above modification is also shown as the dotted line for comparison.

should be in agreement with the above predictions for type-(i) events. However, even for the cases of lowest bombarding energies where $I_{cr} < I_F^{RLDM}$, a systematic deviation of the statistical-theory prediction from the experimental results is seen in Fig. 1. While this deviation is quite small for composite systems with small values of Z^2/A, it increases with increasing Z^2/A of the fissioning system. Since this discrepancy points to the presence of NCNF events, attempts[1] have been made to ascribe these deviations to the presence of quasifission events. This, however, needed a modification of the constants of the extra-push model for quasifission.[13] We propose here that the above discrepancy arises from the presence of fission events occurring on a time scale comparable to the characteristic relaxation time in the K degree of freedom when the fission-barrier height of the composite system becomes comparable to its temperature.

Let us consider a fused composite system with an angular momentum I less than I_F^{RLDM} and a temperature T. This system is initially formed predominantly in a $K=0$ configuration with a small width in the K distribution. Let $B_F(I,K)$ be the height of the barrier preventing this system from a fast binary split (fast fission). Left to itself, the system will then relax in the shape and orientation degrees of freedom to form a fully equilibrated compound nucleus. However, if the fission time is comparable to the characteristic time τ for K relaxation, the composite system has a finite probability of undergoing fission in a time shorter than the K equilibration time and the fragment angular distribution of such events will carry the memory of the entrance-channel K distribution. For a given $B_F(I,K)$, one can calculate the fission probability per unit time from the Bohr-Wheeler theory[18] and therefore the probability P_{NCNF} of fission in a time less than τ.

Figure 2 shows a plot of the probabilities P_{NCNF} vs the barrier height $B_F(I,K)/T$ for different values of the K equilibration time τ. The vertical bars represent the range of P_{NCNF} values for the temperature range $1.0 < T < 2.0$ MeV for the same B_F/T value. In principle, the evolution of the K distribution is continuous and the effective K distributions for fission events taking place at different times are different. However, for the sake of simplicity we assume that only those composite systems that survive fission for a time longer than τ will result in the formation and subsequent fission of a fully equilibrated compound nucleus while all fission events taking place in a time less than τ carry a memory of the entrance-channel K distribution. We have fitted the experimental data on the fragment angular distributions shown in Fig. 1 in terms of the model described above. It was found that all the data shown in the figure can be fitted with a single set of parameters corresponding to $\tau = 8\times10^{-21}$ s and $\sigma_\theta^2 = 0.06$. The calculated angular distributions are shown in Fig. 1 as solid lines. The dashed line in Fig. 2 corresponds to a simplified expression for P_{NCNF} vs B_F/T given by

$$P_{\mathrm{NCNF}}(I) = \exp[-0.5 B_F(I,K=0)/T], \qquad (1)$$

which is also found to fit the data.

The differential cross sections for fission following compound-nucleus formation versus l as deduced from the present analysis are shown in Fig. 3 as dashed lines, along with the total differential fusion cross sections given by the solid lines, for the two typical cases of $^{19}\mathrm{F}+{}^{208}\mathrm{Pb}$ and $^{32}\mathrm{S}+{}^{208}\mathrm{Pb}$. While on the basis of the usual assumption of an l window for fast fission, compound-nucleus formation is expected for all partial waves with $l < I_F^{\mathrm{RLDM}}$, the present analysis demonstrates that true compound-nucleus formation is considerably reduced over a significant range of l values even below I_F^{RLDM}.

In conclusion, we have shown that the apparently anomalous angular distributions observed in a number of heavy-ion–induced fusion-fission reactions can be explained on the basis that, for the composite systems with fission-barrier heights comparable to their temperatures, the fission width becomes sufficiently large that a fraction of the fission events take place during

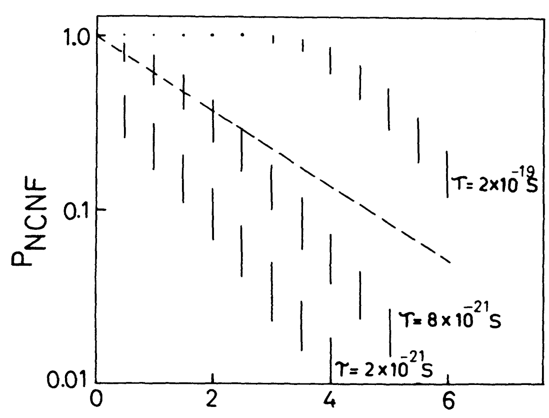

FIG. 2. Plots of P_{NCNF} vs B_F/T for different τ values. The dashed line is based on Eq (1).

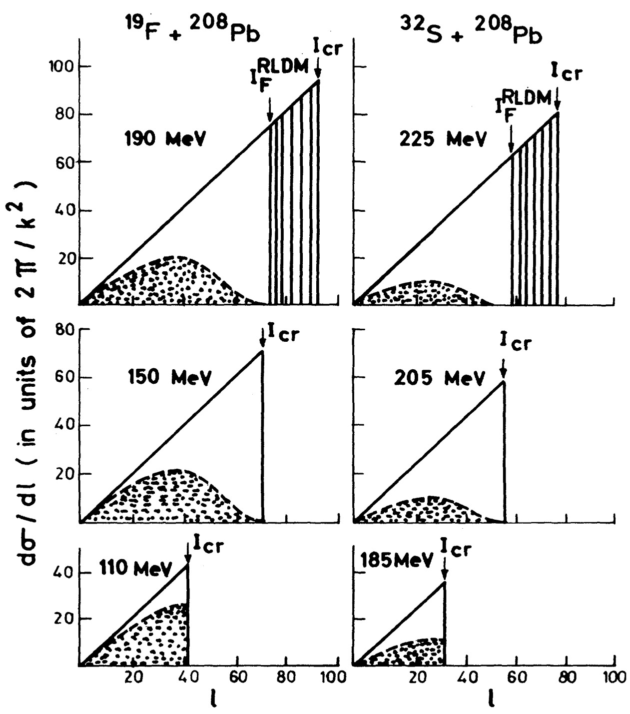

FIG. 3. $d\sigma/dl$ vs l (in units of $2\pi/k^2$; k is the entrance-channel momentum). The shaded area represents the CNF events as deduced from the present analysis. The vertical lines define the angular-momentum window for fast fission, $I_F^{\mathrm{RLDM}} < l < I_{\mathrm{cr}}$.

the time the system is equilibrating in the K degree of freedom. The measured angular distributions are found to be consistent with a value of about 8×10^{-21} s for the characteristic time for K equilibration.

We are grateful to Dr. R. Ramanna for many useful discussions on this work. We also gratefully acknowledge very useful discussions with Professor J. M. Alexander and Dr. M. Prakash from the State University of New York, Stony Brook.

[1]B. B. Back *et al.*, Phys. Rev. Lett. **50**, 818 (1983).
[2]M. B. Tsang *et al.*, Phys. Lett. **129B**, 18 (1983).
[3]K. T. Lesko *et al.*, Phys. Rev. C **27**, 2999 (1983).
[4]B. B. Back *et al.*, Phys. Rev. Lett. **46**, 1068 (1981).
[5]H. Rossner *et al.*, Phys. Rev. C **27**, 2666 (1983).
[6]M. B. Tsang *et al.*, Phys. Rev. C **28**, 747 (1983).
[7]A. Gavron *et al.*, Phys. Rev. Lett. **52**, 589 (1984).
[8]A. Bohr, in *Proceedings of the United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955* (United Nations, New York, 1956), Vol. 2, p. 131.
[9]I. Halpern and V. M. Strutinski, in *Proceedings of the United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958* (United Nations, New York, 1958), Vol. 15, p. 408.
[10]P. D. Bond, Phys. Rev. Lett. **52**, 414 (1984).
[11]H. Rossner *et al.*, Phys. Rev. Lett. **53**, 38 (1984).
[12]C. Gregoire, C. Ngo, and V. Remaud, Phys. Lett. **99B**, 17 (1981).
[13]W. J. Swiatecki, Phys. Scr. **24**, 113 (1981).
[14]M. Prakash *et al.*, Phys. Rev. Lett. **52**, 990 (1984).
[15]M. Brack *et al.*, Rev. Mod. Phys. **44**, 320 (1972).
[16]H. C. Pauli and T. Ledergerber, Nucl. Phys. **A175**, 545 (1971).
[17]S. Cohen, F. Plasil, and W. J. Swiatecki, Ann. Phys. (N.Y.) **82**, 557 (1974).
[18]N. Bohr and J. A. Wheeler, Phys. Rev. **56**, 426 (1939).