Dynamical effects in the decay of a compound nucleus

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We have measured the α-particle spectra at different laboratory angles from the fusion reaction $^{16}O+^{54}Fe$ at 110 MeV. The results are compared with the $^{28}Si+^{27}Al$ symmetric system. In the case of the asymmetric $^{16}O+^{54}Fe$ system α spectra are consistent with the predictions of the statistical model calculations but in the case of the symmetric $^{28}Si+^{27}Al$ system, experimental spectra deviate at higher as well as at lower energies from the statistical model calculations. The results are also compared with a less asymmetric $^{28}Si+^{51}V$ system. There is a systematic change in the formation time of the compound nucleus as we move from the asymmetric to the symmetric systems. The dynamical trajectory model calculations have been done to understand the possible entrance channel effects on the formation and the decay of the compound nucleus.

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INTRODUCTION

Over the past few years, there has been a strong interest directed towards inferring the statistical properties of the hot rapidly rotating nuclei. Evaporative light charged particles from the compound nucleus have proved to be a powerful probe for the properties of the emitting nuclei such as the temperature, the effective emission barriers, and the spins [1–19]. In the case of the composite nuclei at moderate energies and angular momenta, such as those produced with light-ion projectiles, the evaporation spectra are well explained in terms of the standard statistical model employing the optical model transmission coefficients [2–6]. However, over the past decade, there have been several claims of serious discrepancies between the standard statistical model predictions and the experimental light charged-particle evaporation from heavy-ion fusion reactions [7–19]. Several papers reported that these nuclei are subjected to the lower emission barriers as compared to the inverse absorption channels due to the large deformations at these higher excitation energy and angular momentum [7–15]. Some other authors claim that these spectra may be well explained in terms of the statistical model incorporating only a spin dependent level density and without lowering the emission barriers [15–19]. Possible deficiencies of an ''average'' one step [11,12] or two step decay [17] approximation employed in some statistical model codes were pointed out, as well as the need for a proper treatment of the level density for the expected deformations at higher angular momentum [10,13,18,20].

It has been known for a long time that dissipation influences the formation and decay of the compound nucleus in the heavy-ion reactions. One example of the process in which the dissipation plays a role is the mass transfer in the deep-inelastic collisions; a second example is the hindrance of fusion in certain very symmetric reactions first explained within the framework of the dissipative dynamical model by Swiatecki and co-workers [21]. The hindrance of fusion due to the energy dissipation into internal degrees of freedom leads to a long compound nucleus formation times which might be comparable to the decay times and thus might have an important influence on the subsequent decay of the compound nucleus. The assumption of a very short formation time in the statistical model is one extreme of the general evolution process which in fact is a continuous relaxation process, leading to the composite system from the entrance channel to the equilibrated configuration. Recently some authors have suggested the possibility of the dynamical effects on the deexcitation process [22–28].

In the present work, we have reported the α-particle energy spectra for the $^{70}Se^*$ compound system, produced in the heavy ion fusion reaction of $^{16}O+^{54}Fe$ asymmetric system. The results are compared with the $^{28}Si+^{27}Al$ symmetric system and an intermediate less symmetric $^{28}Si+^{51}V$ system. Statistical model and the dynamical trajectory model calculations have been done in order to understand the possible entrance channel effects in the formation and the decay of the compound nucleus.

EXPERIMENT

The experiment was performed with the 15UD Pelletron at Nuclear Science Centre, New Delhi, India, using the 1.5 m diameter stainless steel scattering chamber. This chamber is specifically designed for the charged particle spectroscopy. A 1-mg/cm^2-thick spectroscopically pure ^{54}Fe foil was used as the target and was located at the center of the scattering chamber. The target was bombarded with 110 MeV ^{16}O projectile beam. The α particles were detected with $\Delta E-E$ (40 μm$-$5 mm) detector telescopes. High quality light charged particle spectra were obtained at different laboratory angles with proper precautions regarding the energy calibration and a very good vacuum of roughly 10^{-7} Torr in the scattering chamber so as to avoid the oxygen and the carbon buildup on the target. The telescopes were calibrated with the 5.486 MeV α particles from ^{241}Am source as well as from the hydrogen recoil peak in proton spectra. The compound nucleus $^{70}Se^*$ was formed at an excitation energy of $\approx$85 MeV with $l_{max}=48\hbar$. The angles ($\theta \geqslant 30°$) were selected so that the contribution of the α particles from preequilibrium, inelastic, or breakup processes which are focused in the forward direction is negligible.

ANALYSIS

Statistical model calculations

The statistical computer code CASCADE [29] was used to perform theoretical calculations, which assumes the reaction to occur in two steps. First the formation of the compound nucleus and second the statistical decay of the equilibrated system. There are two aspects of the physics which govern the flow of an evaporation cascade: the spin dependent level density defining the available phase space and the transmission coefficients that control access to this space. The change in each of these quantities is associated with deformation or shape of the nucleus. The transmission coefficients mainly effect the lower energy part of the particle spectrum. In heavy ion induced fusion reactions, high excitation and in particular the levels at high angular momentum have an essential influence on the deexcitation cascade. The level density formula, for a given angular momentum I and both parities $\pm\pi$, can be written as

$$\rho(E,I)=\frac{2I+1}{12}a^{1/2}\left(\frac{\hbar^2}{2J}\right)^{3/2}\frac{1}{(E-\Delta-t-E_I)^2}\times\exp\{2[a(E-\Delta-t-E_I)]^{1/2}\},$$

where a is the level density parameter, t is the thermodynamic temperature, and Δ is the pairing correction. This level density formula is based on the approximation of a Fermi gas with equidistant single-particle levels and a constant level density parameter ($a=A/8$ MeV^{-1}). While such a simple nuclear model clearly has insufficiencies, it is assumed that it can be used to approximate the realistic level density at the total excitation energy E and the spin I by evaluating the model level density at an energy reduced by a pairing correction Δ and a spin-dependent parameter E_I. In the calculation, the quantity E_I is parametrized as

$$E_I=\frac{\hbar^2}{2J}I(I+1)=\frac{\hbar^2}{2J_0}\frac{I(I+1)}{(1+\delta_1 I^2+\delta_2 I^4)}$$

in terms of the rigid-body moment of inertia J_0. The quantities δ_1 and δ_2 are the adjustable input parameters providing a range of choices for the spin dependence of the moment of inertia J and the level density.

However, in the application of the above formula to nuclei of high spins and the excitation energies, it must be emphasized that E_I is not necessarily the yrast energy. In particular, this quantity should be equated neither to the yrast energy of a rigid body with a spin-independent moment of inertia as employed by Lang [30] nor to the yrast energy (collective rotational plus deformation energy) of a rigid body with a spin dependent moment of inertia. In general, the quantity E_I has a much more complex interpretation. This is due, in part, to the rearrangement of the single-particle levels near the Fermi energy that is associated with the spin dependent nuclear deformation, and the direct effect of this nuclear structure change on the level density. In the formulation of $\rho(E,I)$ any dependence of the level-density parameter a on the spin or deformation is incorporated into E_I.

The dependence of the level density on deformation caused by the periodic changes in the shell structure is well known for the low-spin systems [31,32]. In the high-energy limit, the shell effect on the level density can be described in terms of a constant correction to the intrinsic excitation energy at which this density is to be derived using the Fermi gas formula. The dependence of the level density on the excitation energy and the spin is a crucial quantity in the statistical model calculations for heavy-ion induced reactions. However, very little is known experimentally about the spin dependence for the large spins and high excitation energies. Therefore, to achieve the best fit to the experimental data, it appears justifiable to select to some extent a spin dependence of the level density, e.g., by adjusting the parameters δ_1 and δ_2 in equation for E_I. In the standard application of CASCADE, the transmission coefficients are derived for neutrons [33], protons [34], and α particles [35] using optical model parameters for the inverse fusion reactions.

Figure 1 compares the cumulative α-particle spectra from cascade calculations using the rotating liquid drop model (RLDM) moment of inertia and the normal optical model transmission coefficients with the experimental data for ^{16}O $+^{54}$Fe system leading to ^{70}Se* at an excitation energy of $\approx$85 MeV and $l_{\rm av}\approx 34\hbar$. It can be seen that the experimental spectra can be well explained by the statistical model calculations using the RLDM moment of inertia corresponding to $\delta_1=2.45\times10^{-5}$ and $\delta_2=3.01\times10^{-8}$ [36] and the normal transmission coefficients. The present results for the ^{16}O $+^{54}$Fe asymmetric system were compared with the ^{28}Si $+^{27}$Al symmetric system, studied by us earlier [15]. In the case of symmetric ^{28}Si$+^{27}$Al system, the compound nucleus ^{55}Co* was formed at an excitation energy of 84 MeV with $l_{\rm max}\approx 42\hbar$. In order to explain the experimental spectra in this case, the changes were required in the moment of inertia and the emission barriers corresponding to a large nuclear deformation.

The present result were also compared with the ^{28}Si $+^{51}$V a less asymmetric system studied by us earlier [19] where the compound nucleus ^{79}Rb* was formed at the same excitation energy of 85 MeV with $l_{\rm av}\approx 42\hbar$. Light charged particle spectra were taken in coincidence with the evaporation residues (ER's) in order to discriminate the particle evaporation from various mechanisms viz. evaporation from projectile or targetlike nuclei or breakup reaction, etc. The experimental spectra could not be explained by the RLDM values of moment of inertia. It is found that though the average angular momentum of $\approx 42\hbar$ in the case of ^{28}Si $+^{51}$V system is higher as compared to $\approx 34\hbar$ in the case of ^{16}O$+^{54}$Fe system, yet the α spectra are softer indicating that the former system being less asymmetric allows higher l values to decay before the system is relaxed. In the case of ^{28}Si$+^{27}$Al system it is found that the experimental α spectra is much softer than the predicted spectra by the statistical model. This may lead to the conclusion that the α-particle spectra are effected by the dynamics of the entrance channel. In order to verify the symmetric and asymmetric entrance

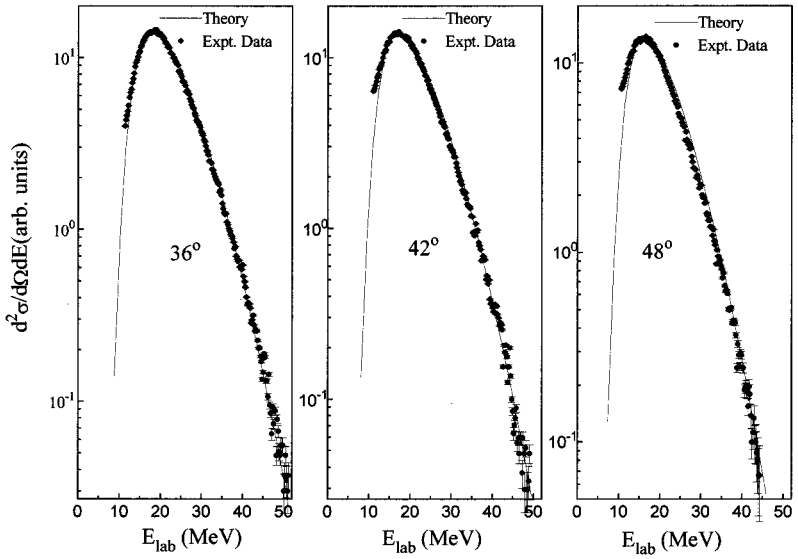

FIG. 1. Comparison of the experimental α spectra (circles) at different angles with the statistical model (solid line) using transmission coefficients for the spherical nuclei and the RLDM moment of inertia with $l_{max}=48\hbar$ for the reaction $^{16}O+^{54}Fe$ at 110 MeV.

channel effects on the formation and subsequent decay of the compound nucleus, we did dynamical trajectory model calculations.

Dynamical trajectory model calculations

In the model developed by Feldmeier [37], various aspects of the dissipative heavy-ion collision are brought out for center of mass energies ranging from the Coulomb barrier up to several MeV per nucleon above the barrier. The lower limit is for treating classical trajectories and the upper limit to ensure that the mean field assumption is valid. The macroscopic properties of large scale nuclear motion are obtained, where the coupling between the intrinsic and the collective degrees of freedom is treated in a microscopic picture of particle exchange [38], which provide the friction and the diffusion tensor. The dynamical evolution of the two colliding nuclei is described by a sequence of shapes which basically consist of two spheres connected by a conical neck. Throughout the collision the volume of the shape is conserved so that the uniform mass and charge densities remain the same. The macroscopic shapes of the nuclear system are represented by axially symmetric configurations with sharp surfaces. These shapes are uniquely determined by three macroscopic degrees of freedom: the distance between the nuclei s (elongation), the neck-coordinate (σ), and the asymmetry coordinate (Δ), defined as

$$s = \text{distance between two spheres},$$

$$\sigma = \frac{V_0-(4\pi/3)R_1^3-(4\pi/3)R_2^3}{V_0} = \frac{\text{neck volume}}{\text{total volume}},$$

$$\Delta = \frac{R_1-R_2}{R_1+R_2} = \text{asymmetry},$$

where V_0 is the total volume of the system and is independent of the s, σ, and Δ. R_1 and R_2 are the radii of the two interacting nuclei. In addition there are three rotational degrees of freedom for the intrinsic and relative rotation of the dinuclear complex. Denoting the six macroscopic coordinates and their momenta by $[q(t),p(t)]$, the Langevin dynamical equations of motion can be written as

$$d\mathbf{p}/dt = -dT/dq - dV/dq + X(t),$$

$$d\mathbf{q}/dt = M^{-1}p,$$

where T is the collective kinetic energy and M is the mass tensor, V is the conservative potential, and $X(t)$ is the fluctuating force due to the coupling of the collective degrees of freedom to the intrinsic degrees of freedom. The mass tensor is calculated from the profile function by assuming incompressible and irrotational flow of mass during the shape evolution in the collision. The potential energy V is calculated by associating with each shape the nuclear and Coulomb energies; the nuclear potential is obtained as a double volume integral of a Yukawa plus exponential folding function, the Coulomb potential is calculated assuming a uniform charge distribution with a sharp surface. The motion of the system is governed by strong dissipative force $X(t)$, which is related to the friction and the diffusion terms obtained from particle exchange model [38]. One-body dissipation is assumed to be predominant as it has been found to be more relevant for these type of reactions [39]. This model gives a realistic macroscopic description of the nucleus-nucleus collision, based on the concept of one-body dissipation. It does not contain any free parameter and consistently describes the dynamical evolution of various composite systems formed in nucleus-nucleus collisions in a wide range of impact parameters.

The results of the HICOL calculations are given in Figs. 2 and 3. In Fig. 2, the elongation of the fusing nuclei is plotted as a function of time. The calculations were done for the whole range of l values as given in the plot. Since the compound nucleus is formed for the trajectories which are caught behind the barrier, it is imperative that for the higher l values trajectories do not lead to an equilibrated compound nucleus

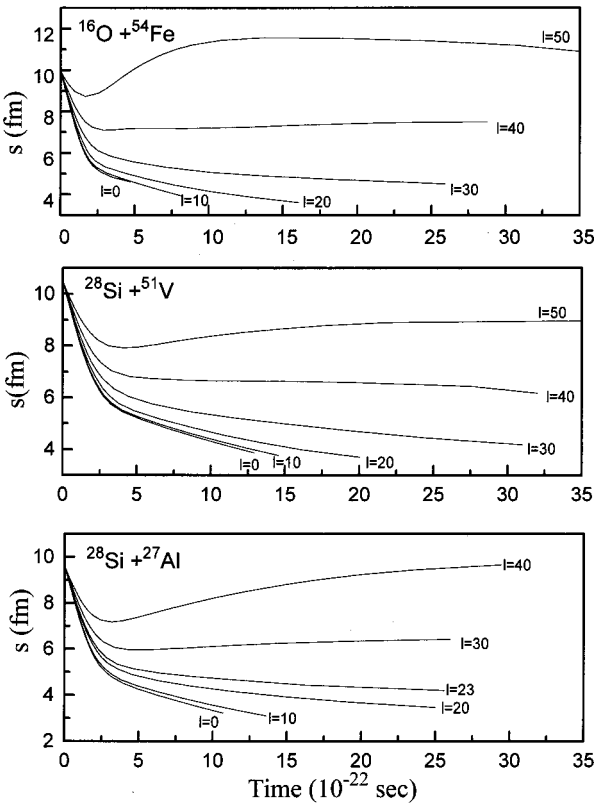

FIG. 2. Calculated evolution of the separation (s) of the colliding nuclei as a function of time for the reactions ^{16}O+^{54}Fe at 110 MeV, ^{28}Si+^{51}V at 140 MeV, and ^{28}Si+^{27}Al at 140 MeV.

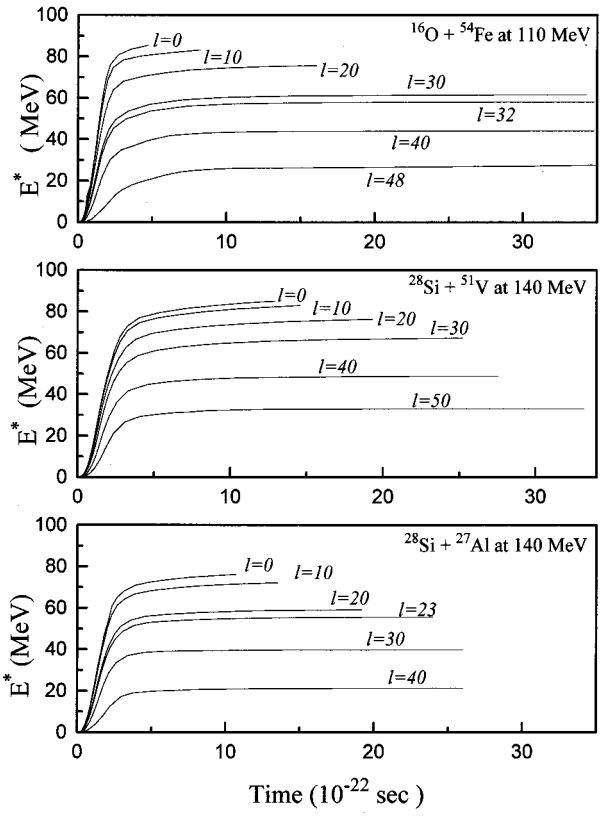

FIG. 3. Calculated evolution of the excitation energy of the colliding nuclei (E^*) as a function of time for the reactions ^{16}O +^{54}Fe at 110 MeV, ^{28}Si+^{51}V at 140 MeV, and ^{28}Si+^{27}Al at 140 MeV.

due to the lowering of the barriers. The thermal excitation energy as a function of time is plotted in Fig. 3. It can be seen that the excitation energy available for particle emission achieves its final value roughly in 5×10^{-22} s after the zero time. Zero time is defined as the time when the participating nuclei begin to feel the nuclear force and deviate from the earlier Coulomb trajectories. Furthermore, the excitation energy available for particle emission decreases as the angular momentum increases.

In the dynamical model calculations the shapes for which the neck area between the two nuclei is small compared to surface area are called dinuclear shapes. Mononuclear shapes do not have a neck and are more or less convex objects. The wall friction and window friction are the two main sources of the dissipation of the total energy. The window disappears in mononuclear shapes so dissipation is only due to wall friction and system reaches in the equilibrium state. The time taken in this process to reach the full shape equilibrium is the formation time. Decay times were estimated using the computer code PACE2 [40]. These times were compared with the formation times of the compound nuclei in order to see whether evaporation is significant during the formation process. The average formation times and average decay times for all the systems studied are given in Table I. It can be seen that the formation time for ^{16}O+^{54}Fe system is much less than the formation time for the ^{28}Si+^{51}V and ^{28}Si+^{27}Al systems. This is in accordance with the fact that the symmetric systems evolve more slowly as compared to the asymmetric systems. As is evident from Fig. 4 where the time evolution of all the reactions for an angular momentum of $20\hbar$ is plotted, the symmetric system ^{28}Si+^{27}Al evolve more slowly as compared to the less symmetric ^{28}Si+^{51}V and asymmetric ^{16}O+^{54}Fe systems. This indicates that there is a gradual increase in the formation time of the compound nucleus as one goes from the asymmetric to the symmetric systems in the entrance channel.

In the case of ^{16}O+^{54}Fe system the formation time is found to be much less than the decay time. Therefore, in this case one does not expect much evaporation during the formation process and therefore the evaporation is mostly governed by the statistical model without any modifications. The α particles emitted from the composite system before relax-

TABLE I. Comparison of formation times with decay times.

S. No.	System studied	Average formation time (s)	Average decay time (s)
1	^{16}O+^{54}Fe at 110 MeV	15.7×10^{-22}	26.3×10^{-22}
2	^{28}Si+^{51}V at 140 MeV	20.0×10^{-22}	31.0×10^{-22}
3	^{28}Si+^{27}Al at 140 MeV	25.0×10^{-22}	17.8×10^{-22}

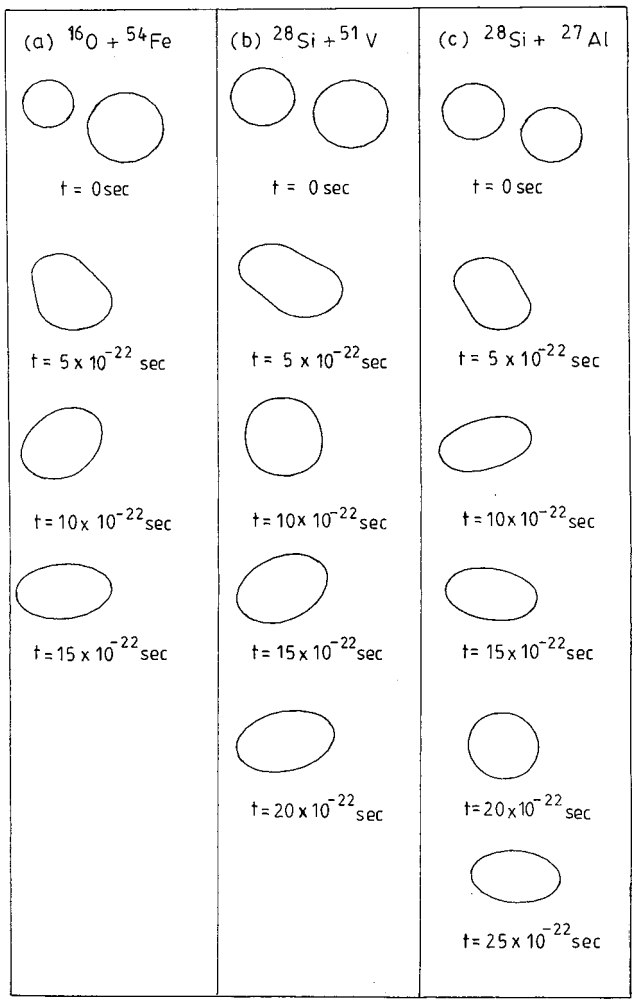

FIG. 4. Time evolution for an angular momentum of $20\hbar$ for the reactions (a) $^{16}O+^{54}Fe$ at 110 MeV, (b) $^{28}Si+^{51}V$ at 140 MeV, and (c) $^{28}Si+^{27}Al$ at 140 MeV.

ation are focused in the forward direction and hence, does not contribute significantly to the spectra for $\theta > 30°$. This is evident from the coincidence spectra with the evaporation residue in case of $^{28}Si+^{51}V$ system shown in Fig. 5. The singles and the coincidence spectra slightly deviate from each other at 30°, while at 60° they completely overlap indicating that the contribution from the breakup, fragmentlike, or precompound emission for the angles $\geqslant 30°$ is insignificant.

The semiclassical code HICOL does not predict the fusion to occur for $^{28}Si+^{27}Al$ system [19] for angular momentum larger than $23\hbar$, instead the system remains in a rotating configuration for long times. Figure 6 shows the experimental data compared with the theoretical predictions for $^{28}Si+^{27}Al$ system with the HICOL predicted $l_{max}=23\hbar$. It is evident that the statistical model predictions are in good agreement with the experimental data with the HICOL predicted l values. A similar effect was also noticed in the $^{28}Si+^{51}V$, a less asymmetric system [19]. However, in the case of $^{16}O+^{54}Fe$ asymmetric system most of the l values undergo fusion, the α-particle spectra are therefore well explained by

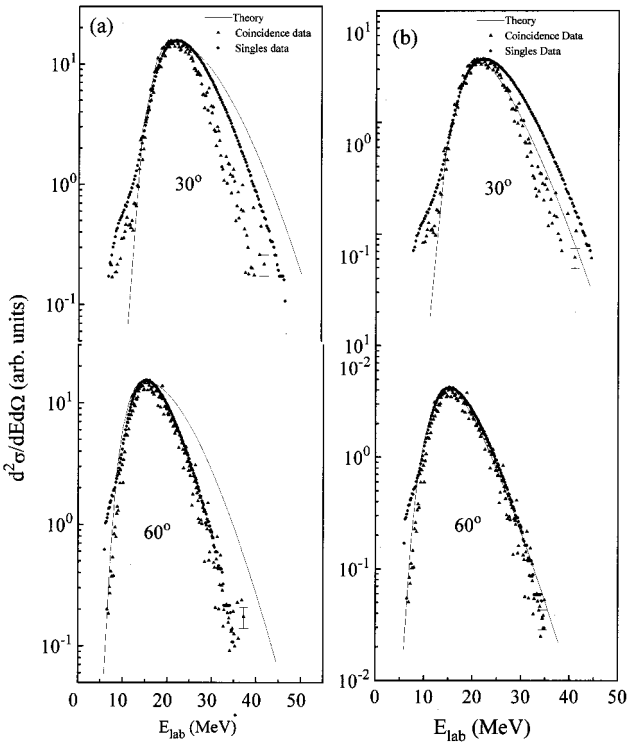

FIG. 5. Comparison of the experimental α spectra (triangles for coincidence with ER and circles for singles) at different angles with statistical model (solid line) using normal transmission coefficients for the inverse fusion reactions and the RLDM values of the moment of inertia for the reaction $^{28}Si+^{51}V$. (a) With $l_{max}=56\hbar$. (b) Same with $l_{max}=30\hbar$.

the standard statistical model calculations. Further in the statistical model calculations, the assumption for the formation times to be much smaller than the decay times is true only for the asymmetric systems. However, in the case of the symmetric systems this assumption is no longer true and the experimental spectra are explained only by using HICOL predicted l values since higher l values do not lead to the com-

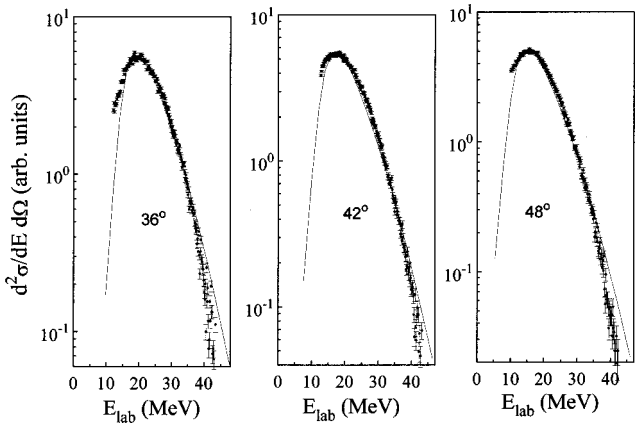

FIG. 6. Comparison of the experimental α spectra for the reaction $^{28}Si+^{27}Al$ at different angles with the statistical model (solid line) with $l_{max}=23\hbar$ as predicted by the dynamical model (HICOL) calculations.

pound nucleus formation. The above results clearly indicate the role played by the entrance channel dynamics in the formation and the decay of the compound nucleus.

SUMMARY

We have measured the evaporated α-particle energy spectra from the ^{70}Se* (^{16}O+^{54}Fe) composite nucleus at 85 MeV excitation energy. The measured spectra are consistent with the prediction of the standard statistical model calculations using RLDM values of moment of inertia and the optical model transmission coefficients for the respective inverse absorption channels. The results are compared with the symmetric ^{28}Si+^{27}Al and ^{28}Si+^{51}V systems studied earlier where the dynamical effects prior to the formation of the compound system play an important role in deciding the final l values and the excitation energy of the compound nucleus. Dynamical trajectory model (HICOL) calculations predicted lower formation times for asymmetric ^{16}O+^{54}Fe system than the symmetric ^{28}Si+^{51}Al system. Therefore, the spectra in the case of ^{16}O+^{54}Fe system are well explained by the standard statistical model calculations using RLDM moment of inertia and optical model transmission coefficients. While in the case of symmetric systems, the experimental spectra are explained only by using HICOL predicted l values since higher l values do not lead to the compound nucleus formation. As the symmetry of the system increases the formation times becomes more and more comparable to the decay times of the resulting compound nucleus and can even be greater than the decay times. Therefore, the statistical model which assumes the formation times to be much smaller than the decay times, seems to overpredict the evaporation spectra for the symmetric systems using the RLDM values of moment of inertia and the normal optical model transmission coefficients. The present study gives new insight regarding the role of the dynamics of the nuclear reaction in the evaporation of the α particles from the hot rotating nuclei formed in the heavy-ion collisions.

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