# $\alpha$-particle emission as a probe of dynamical deformations

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We have measured $\alpha$-particle spectra at different laboratory angles from the fusion reaction $^{28}Si+^{51}V$ at 140 MeV. These spectra deviate at higher energies from the statistical model calculations using rotating liquid drop model values of the moment of inertia. In order to explain the experimental spectra, changes were required in the moments of inertia corresponding to deformation, which suggests dynamical effects on the deexcitation process for charged-particle emission. The comparison of decay times with formation times implies that light charged particles are preferentially emitted prior to the full relaxation of the compound nucleus. Statistical models and dynamical calculations have been employed in an attempt to interpret the experimental data. The results were compared with the $^{28}Si+^{27}Al$ system studied earlier in order to understand the symmetric and asymmetric entrance channel effects in the formation of the compound system. [S0556-2813(98)02203-1]

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## INTRODUCTION

Heavy-ion reactions are routinely used to produce composite nuclei with large angular momentum and excitation energies. Over the past few years, there has been a strong interest directed towards inferring the statistical properties of these hot, rapidly rotating nuclei. Statistical-model reaction simulations are used in conjunction with experimental data in order to infer these properties. High excitation energy implies that the nucleus deexcites by emitting several particles and $\gamma$ rays so that the decay pattern involves a number of different paths. High spins are expected to favor the emission of complex clusters which are more effective than nucleons in removing the angular momentum. While the statistical model has been used for many decades to analyze a variety of observables related to compound nucleus decay [1], the successful description of light-particle emission remains essential for evaluating the validity of the model and the choice of parameters within it. Studies of evaporated particle energy spectra yield direct information about the main statistical model ingredients, the nuclear level densities, and barrier penetration probabilities. Determination of these properties has applications to current research into fusion and fission dynamics which often depends on the statistical model in some form for comparison to data.

Over the past decade, there have been several claims of serious discrepancies between standard statistical model predictions and measured light charged particle energy spectra [2–13]. Measured light charged particles have been characterized as having lower average energies than predicted. Several papers reported that these nuclei are subjected to lower emission barriers as compared to inverse absorption channels due to large deformations at the higher excitation energy and the angular momentum [2–10]. Some other authors claim that these spectra may be well explained in terms of a statistical model incorporating only a spin-dependent level density and without lowering the emission barriers [10–13]. Possible deficiencies of an ''average'' one step [6,7] or two step decay [12] approximation employed in some statistical model codes were pointed out, as well as the need for proper treatment of level density for expected rotating liquid drop model (RLDM) deformations [5,8,13,14].

Furthermore, the assumption of a very short formation time in 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. Recent dynamical descriptions of heavy-ion collisions do not support this assumption in many cases [15,16]. In symmetric entrance channels and for collisions where center-of-mass energy is well above the Coulomb barrier, formation time can be even larger than decay time of the resulting composite system. In such cases a realistic approach will be to couple the dynamical evolution of the intrinsic excitation of the composite system to a time-dependent statistical model calculation. Such calculations have been reported where the dynamical part is calculated using a realistic macroscopic description of the nucleus-nucleus collision based on the concept of one body dissipation [17–19]. However, in these calculations the structure or shape of the forming compound nucleus at each time stage in terms of its level density, and transmission coefficients for particle emissions have not been considered adequately. This can result in a major discrepancy in prediction for all particle channels, if the formation time is comparable to or longer than the decay time of the eventually formed compound nucleus. Recently some authors have suggested the possibility of the dynamical effects on the deexcitation process [20,21].

A simplistic attempt to describe the collision has been based on a schematic picture of the collision process in terms of the topology of the entrance channel potential. If the resultant force is attractive, the collision will lead to fusion. Calculations become elaborate if the dynamics of the process is considered explicitly along the whole reaction path,

 

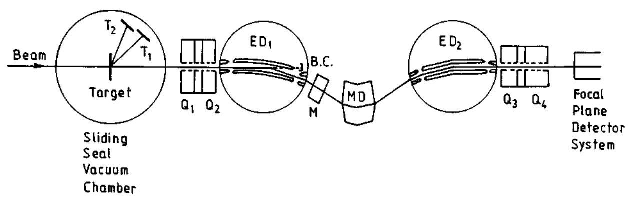


FIG. 1. The schematic layout of the scattering chamber and HIRA. B.C. is the beam catcher; $Q_1$, $Q_2$, $Q_3$, $Q_4$, the quadrupoles; ED1, ED2, the electric dipoles; M the multipole; MD the magnetic dipole, and $T_1$, $T_2$ are the two telescopes.

through the multidimensional space of relevant collective degrees of freedom of the nuclear system by incorporating dissipation [22]. A more correct approach will be to divide the total decay time in two parts (i) decay during the formation of the equilibrated system, and (ii) decay of the equilibrated compound nucleus. However, results from this approach also become qualitative as noted by Thoennessen *et al.* [19], since the statistical model is being applied to the nonequilibrated system also.

In the present work, we have measured the $\alpha$-particle energy spectra in coincidence with evaporation residues for the $^{79}$Rb* compound system, produced in the heavy-ion fusion reaction with great experimental care. Statistical model and dynamical calculations have been used in an attempt to interpret the experimental data.

## EXPERIMENT

The experiment was performed with the 15UD Pelletron at NSC, New Delhi, India. The 140 MeV $^{28}$Si beam was used to bombard a 1000 $\mu$g/cm$^2$ spectroscopically pure $^{51}$V foil as target. The experiment was done using the heavy ion reaction analyzer (HIRA) (recoil mass separator). The evaporation residues were separated from the beam and were detected by the focal plane detector at different angles of HIRA to take into account the recoil due to the $\alpha$-particle emission. Figure 1 shows the experimental setup. High quality particle spectra were obtained at different laboratory angles using $\Delta E - E(40\ \mu\text{m} - 5\ \text{mm})$ detector telescopes ($T_1$ and $T_2$) 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 oxygen and carbon built-up on the target. Light charged particle spectra were taken in coincidence with the evaporation residues in order to discriminate the particle evaporation from various mechanisms viz. evaporation from projectilelike nuclei. The compound nucleus $^{79}$Rb* was formed at an excitation energy of 85 MeV with $l_{\max}=56\hbar$.

## ANALYSIS

*Statistical model calculations.* The statistical computer code CASCADE [23] was used to perform the 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 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, $\Delta$ is the pairing correction, and $E_I$ is the rotational energy. The rotational energy in terms of rigid body moment of inertia $J_0$ is given by

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

where $\delta_1$ and $\delta_2$ are the input parameters providing a range of choices for the spin dependence of the level density.

Figure 2 compares the experimental data with the cumulative $\alpha$ and proton spectra from cascade calculations using rotating liquid drop model moment of inertia and the optical model transmission coefficients for the respective inverse absorption channels. The experimental data is presented for singles as well as in coincidence with the residues. The coincidence measurements are done by rotating the HIRA setup from 0° to 15° to account for the recoil of the residual nucleus. The coincidence data at different angles of HIRA is then normalized by the total charge on the target and then integrated. It can be seen that the experimental spectra differ from the theoretical calculations. In order to fit these spectra, we introduced a spin-dependent level density with $E_I$ values generated with increased values of $\delta_1$ and $\delta_2$ and without changing the optical model transmission coefficients. The spin dependence of the level density, effected by the variation of $E_I$ produces a noticeable change in the slope of high-energy tail of the spectrum. However, the peak position and the lower-energy part of the spectrum remains unchanged. Increasing the values of $\delta_1$ and $\delta_2$ parameters and thus reducing the value of $E_I$, enhances the available phase space for low $l$-wave emission of neutrons and protons from high spin compound nuclear states relative to the higher $l$-wave emission of $\alpha$ particles from these states. As a result the more strongly competing neutron and proton emission suppresses the early emission of $\alpha$ particles from high spin states. The suppression of first chance $\alpha$-particle emission leads to the softening of the high-energy part of the $\alpha$ spectrum. However, the lower-energy part of the spectrum remains uneffected due to this change of level density.

The present results were compared with $^{28}$Si+$^{27}$Al system studied by us earlier [10]. It is found that the experimental spectra in the present case of $^{28}$Si+$^{51}$V system may be explained by the statistical model calculations taking into account much less deformation of the compound nucleus as compared to the $^{28}$Si+$^{27}$Al system, though the average angular momentum of $\approx 40\hbar$ in the $^{28}$Si+$^{51}$V asymmetric system is higher as compared to $\approx 30\hbar$ in $^{28}$Si+$^{27}$Al symmetric system. To understand the above behavior, we did dynamical

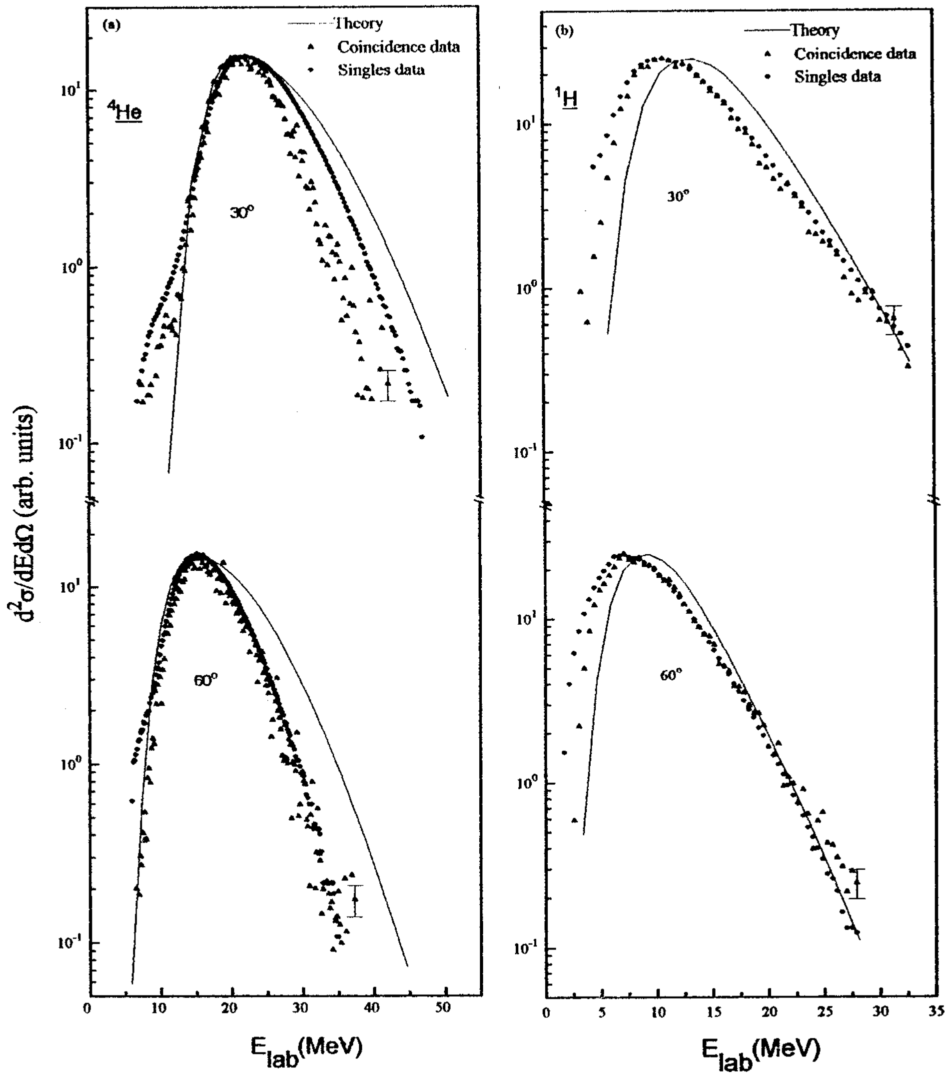


FIG. 2. Comparison of the experimental spectra (triangles for coincidence with ER and circles for singles) with the statistical model (solid line) using transmission coefficients for the spherical nuclei and the RLDM moment of inertia with $l_{max}=56\hbar$ for the reaction $^{28}Si+^{51}V$. (a) $\alpha$ spectra at angles 30° and 60°. (b) Same for the proton spectra.

analysis in order to verify the symmetric and asymmetric entrance channel effects on the formation of the compound nucleus.

*Dynamical trajectory model calculations.* In the model developed by Feldmeier [24], various aspects of dissipative heavy-ion collisions are brought out for the 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 collective degrees of freedom is treated in a microscopic picture of particle exchange [25], 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 ($\sigma$), and the asymmetry coordinate ($\Delta$), defined as

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

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

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

where $V_0$ is the total volume of the system and is independent of the $s$, $\sigma$, and $\Delta$. $R_1$ 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

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

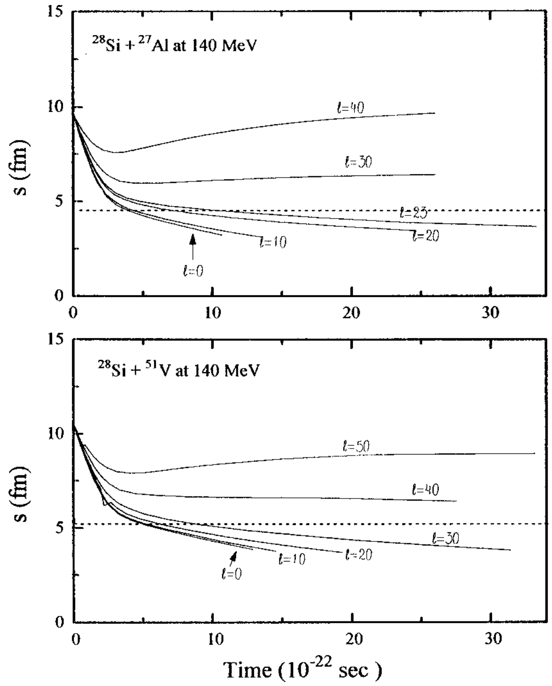


FIG. 3. Calculated evolution of the separation ($s$) of the colliding nuclei as a function of time for the reactions $^{28}Si+^{27}Al$ and $^{28}Si+^{51}V$ at 140 MeV. The dashed line corresponds to the radius $R=R_0A^{1/3}$ for the compound nuclei $^{55}Co$ and $^{79}Rb$ for the two systems (see text).

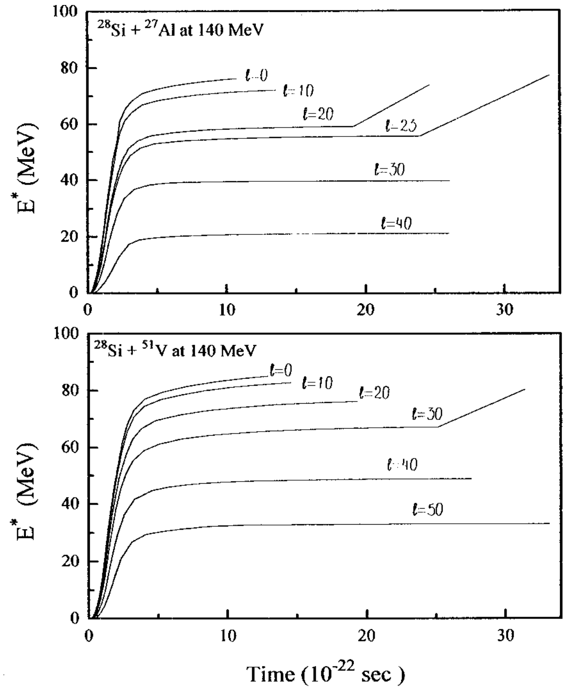


FIG. 4. Calculated evolution of the excitation energy of the colliding nuclei ($E^*$) as a function of time for the reactions $^{28}Si+^{27}Al$ and $^{28}Si+^{51}V$ at 140 MeV.

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

where $T$ is the collective kinetic energy, $M$ is the mass tensor, $V$ is the conservative potential, and $X(t)$ is the fluctuating force due to 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 a strong dissipative force $X(t)$, which is related to the friction and the diffusion terms obtained from particle exchange model [25]. One-body dissipation is assumed to be predominant as it has been found to be more relevant for these types of reactions [26]. This model gives a realistic macroscopic description of the nucleus-nucleus collision, based on the concept of one-body dissipation. It does not contain free parameters 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 HICOL calculations are given in Figs. 3 and 4. In Fig. 3, the elongation of the fusing nuclei is plotted as a function of time. The calculations were done for various $l$ values for the whole range of $l$ values and these values are given in the plot. It can be observed that for high $l$ values, trajectories do not lead to a spherical compound nucleus but remained elongated for long times and it is a general feature of both the systems studied. The dashed lines in the figure show the radii ($R=R_0A^{1/3}$) of the compound nuclei $^{79}Rb(^{28}Si+^{51}V)$ and $^{55}Co(^{28}Si+^{27}Al)$. This line indicates that the $l$ values with separation greater than this value do not lead to the fusion. The thermal excitation energy as a function of time is plotted in Fig. 4. It can be seen that the excitation energy available for particle emission achieves its final value roughly in $5\times10^{-22}$ sec 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 the particle emission decreases as the angular momentum increases.

Decay times were estimated using the computer code PACE2 [27]. 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 decay times for $^{28}Si+^{51}V$ and $^{28}Si+^{27}Al$ systems are $3.1\times10^{-21}$ sec and $1.78\times10^{-21}$ sec, respectively. The average formation times for $^{28}Si+^{51}V$ and $^{28}Si+^{27}Al$ systems are $2.5\times10^{-21}$ sec and $2.09\times10^{-21}$ sec, respectively. The formation times for both the systems are comparable to the decay times, therefore the influence on particle decay during the formation process of the compound nucleus will be significant in both the cases. The $\alpha$ particles emitted due to the fragments in the precompound process are focused in the forward direction and hence, the spectra for $\theta>30°$ will be mainly dominated by the statistical decay of the compound equilibrated system. As is evident from Fig. 2, at 30° the singles and the coincidence spectra do not coincide with each other. However, at 60° they completely overlap, indicating that there is no contribution from the fragmentlike or precompound emission.

The semiclassical code HICOL does not predict fusion to

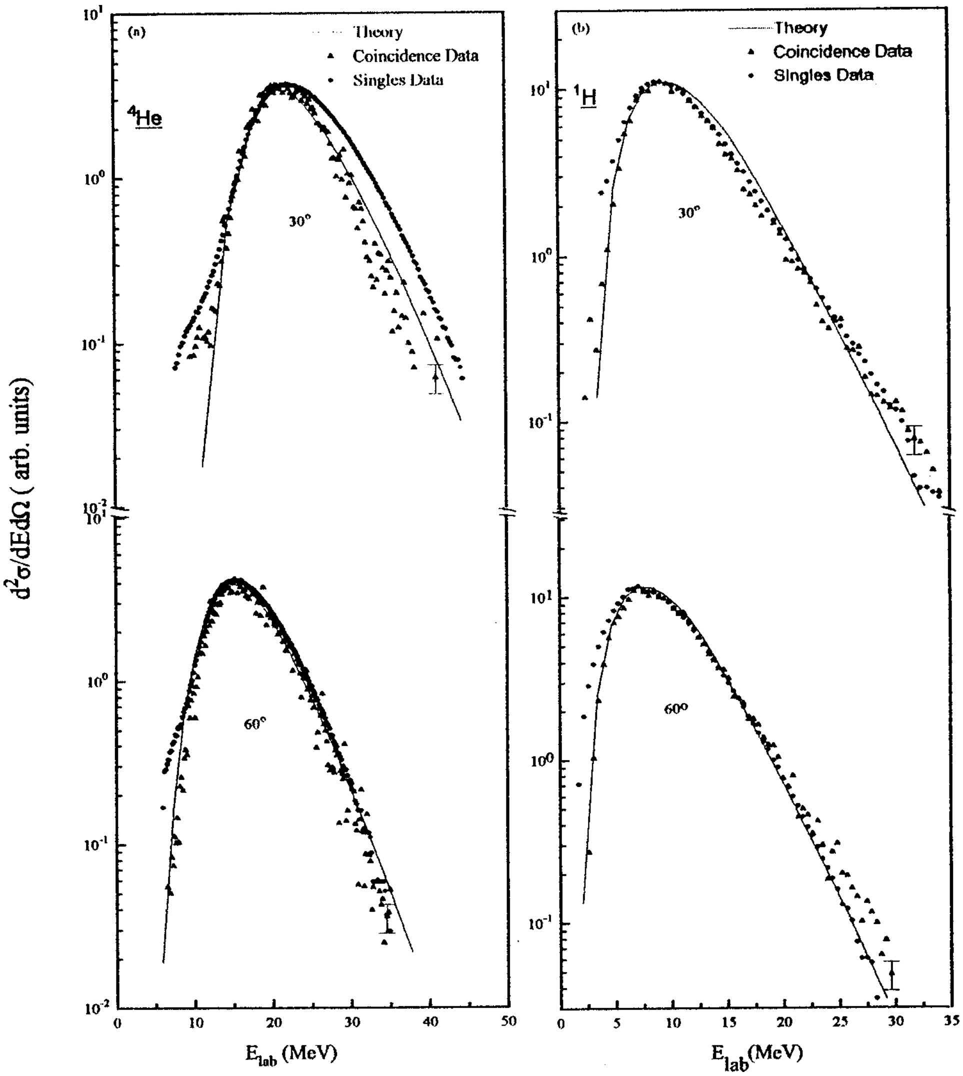


FIG. 5. Comparison of the experimental spectra (triangles for coincidence with ER and circles for singles) with the statistical model (solid line) using the transmission coefficients for the spherical nuclei and the RLDM moment of inertia with $l_{max}=30\hbar$ as predicted by the dynamical model (HICOL) for the reaction $^{28}Si+^{51}V$. (a) $\alpha$ spectra at angles 30° and 60°. (b) Same for the proton spectra.

occur for $^{28}Si+^{51}V$ system for angular momentum larger than $30\hbar$, instead the system remains in a rotating configuration for long times. In this case the maximum value of angular momentum for which the system fuses is $30\hbar$. In the case of $^{28}Si+^{27}Al$ system the maximum value of angular momentum for which the code HICOL predicts the fusion to occur is $23\hbar$. Taking these values of $l_{max}$, we did the statistical model calculations for both the systems. Figure 5 shows the experimental data for the $\alpha$ particles and the protons compared with the theoretical predictions for the $^{28}Si+^{51}V$ system with $l_{max}=30\hbar$ and the RLDM moment of inertia. It is evident from the figure that the statistical model predictions are in agreement with the experimental data with the HICOL predicted $l$ values without taking into account the deformation of the compound nucleus. It is remarkable to note that the theoretical calculations agree well for both the $\alpha$'s and the protons. Figure 6(a) shows the experimental data for the $\alpha$ particles compared with the theoretical predictions for the $^{28}Si+^{27}Al$ system with $l_{max}=23\hbar$ and RLDM moment of inertia. It can be seen that the high-energy part of the $\alpha$ spectrum can be well fitted but the lower-energy part of the spectrum remains unexplained by taking the low $l$ values in this case. The lower-energy part of the spectrum is therefore fitted by changing the effective radius of the compound nucleus. This change is about 20% larger than the half density radius of the Woods-Sexon potential assumed in the calculation of the transmission coefficients for the inverse absorption channel. With the changed transmission coefficients and using the same value of $l_{max}$, i.e., $l_{max}=23\hbar$, the $\alpha$ spectra are obtained as shown in Fig. 6(b) which are in agreement with the experimental data. However, the observed proton spectra in Fig. 7(a) for the symmetric system $^{28}Si+^{27}Al$ have such low energies that it deviates at the lower as well as the higher-energy part of the spectrum with the statistical model calculations using the RLDM moment of inertia and $l_{max}=23\hbar$ as predicted by the dynamical model (HICOL). The change of the radius parameter by 20% in Fig. 7(b), as was done in the case of $\alpha$-spectrum, also fall short of representing the experimental data. It indicates that a reasonable nuclear deformation may not account for the measured very low pro-

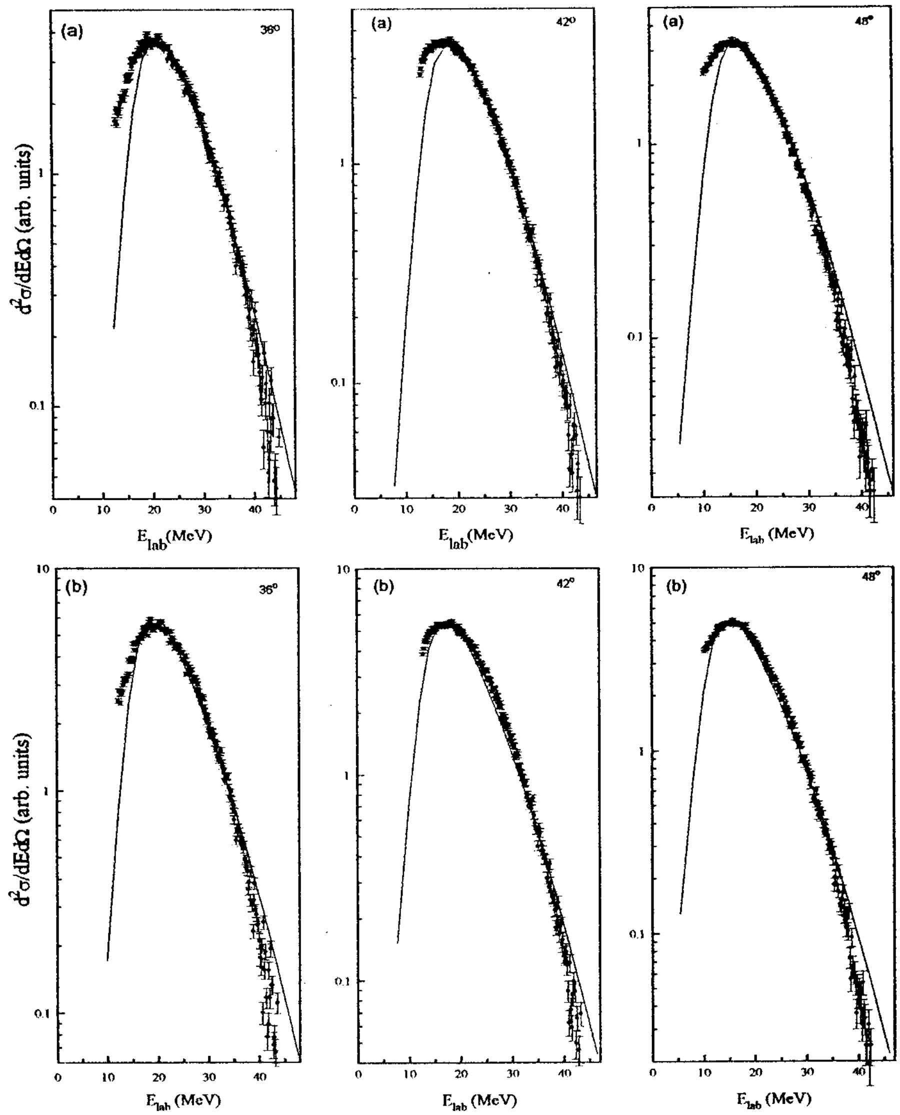


FIG. 6. (a) Comparison of the experimental $\alpha$ spectra (circles) at different angles with the statistical model (solid line) using the transmission coefficients for the spherical nuclei and the RLDM moment of inertia with $l_{max}=23\hbar$ as predicted by the dynamical model (HICOL) for the reaction $^{28}Si+^{27}Al$. (b) Same with the transmission coefficient changed for deformed nuclei having the average radius increased by 20%.

ton energies as reported by Parker *et al.* [9]. It seems that in the symmetric systems the collisions in the early stages of the nuclear reaction excite particularly those nucleons which are near to the surface of the nucleus. In the outer fringes of the reacting system, the emission barriers would be lower than in the central region resulting in the unexpectedly low average particle energies for the protons.

## SUMMARY

We have measured the evaporation residue-gated $\alpha$ spectra from the $^{79}Rb^*$ composite nuclei. The measured spectra are softer than those predicted by standard statistical model calculations. A satisfactory description of data can be obtained by varying the level density parameters and invoking the deformation in the transmission coefficient calculations considering that most $\alpha$ emission comes from the tips of the nucleus. However, when considering the symmetric $^{28}Si+^{27}Al$ and the asymmetric $^{28}Si+^{51}V$ system, it was noted that the deformation in the former system having a lower average angular momentum of $30\hbar$ was larger than the latter system having a greater average angular momentum of $40\hbar$ which indicates that the deformation of the compound system depends not only on its angular momentum but also on the entrance channel. The dynamical effects prior to the formation of the compound system, therefore, seem to 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 $l$ values for fusion in both cases and were found to be responsible for the higher-energy part of the $\alpha$ spectrum of the two systems. The deformation of the system plays a role in describing the lower-energy part of the $\alpha$ spectrum and was found to be present in $^{28}Si+^{27}Al$ system. However, the observed proton spectra for this symmetric system have such low energies that it is impossible to fit the statistical model calculations

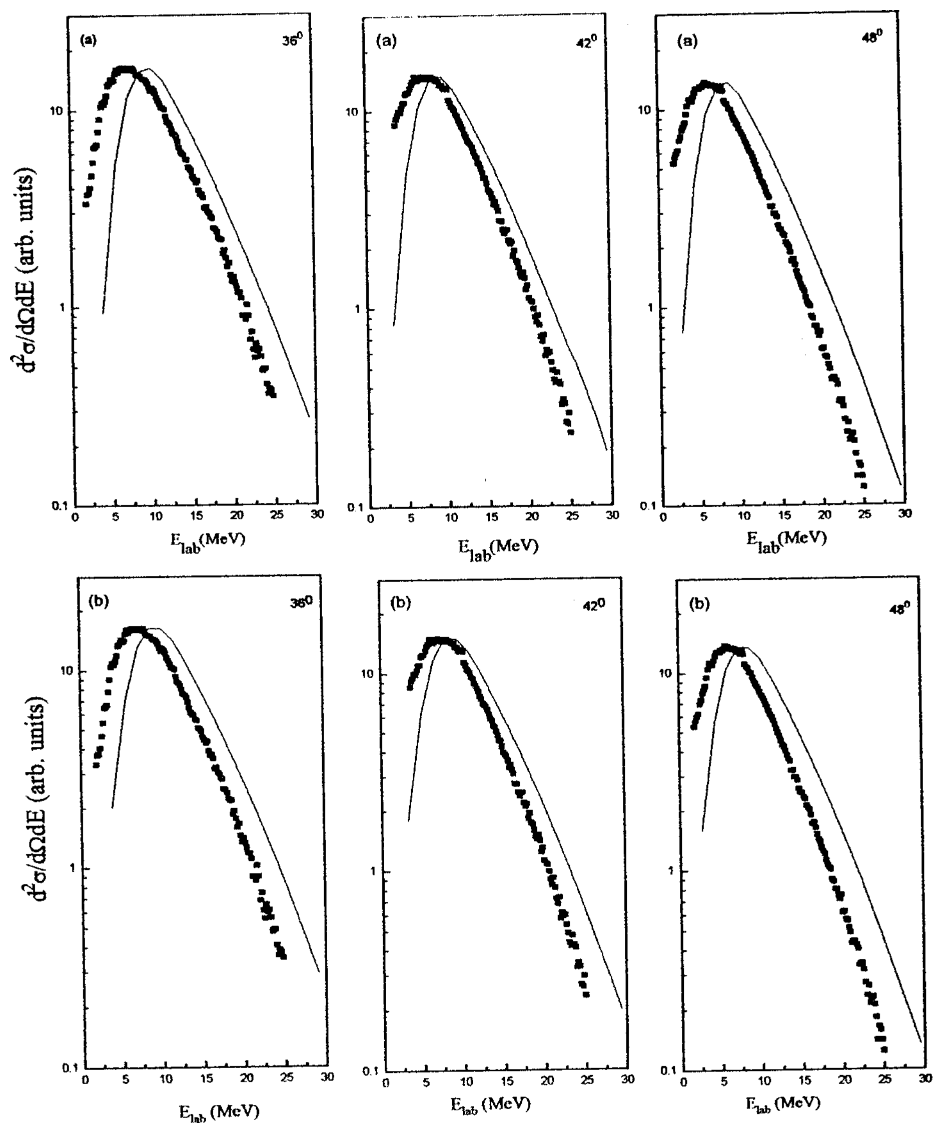


FIG. 7. Comparison of the experimental proton spectra (circles) with the statistical model using the transmission coefficients for the spherical nuclei and RLDM moment of inertia, with $l_{max}=23\hbar$ as predicted by the dynamical model (HICOL) for the reaction $^{28}Si+^{27}Al$. (b) Same with the changed transmission coefficients for the deformed nuclei with the average radius increased by 20%.

with RLDM moment of inertia and HICOL predicted $l$ values with a reasonable deformation. This indicates that in the symmetric systems probably the collisions in the early stages of the equilibration, predominantly excite the nucleons near the surface of the nucleus resulting in the unexpectedly low emission barrier and thus the low average particle energies. The present study gives a new insight regarding the role of the dynamics of the nuclear reaction in the evaporation of $\alpha$ particles from hot nuclei.

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