Anomalous behavior of the level density parameter in neutron and charged particle evaporation

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The compound nucleus ^{76}Kr* was populated at the excitation energy of 75 MeV and angular momentum of $39\hbar$ in fusion reactions with two complementary, mass-symmetric (^{31}P+^{45}Sc) and mass-asymmetric (^{12}C+^{64}Zn) entrance channels. The neutron evaporation spectra were measured and compared with the predictions of statistical model calculations using the transmission coefficients for the spherical nuclei in the inverse absorption channel, the rotating liquid drop model moment of inertia, and the normal systematic value of $A/8$ for the level density parameter a. The results for the mass-asymmetric reaction are found to be consistent with the predictions of the statistical model calculations. However, for the mass-symmetric reaction (^{31}P+^{45}Sc), the experimental spectra are found to be harder than the theoretical neutron spectra and the statistical model calculations require a lower value of $A/10$ for the parameter a to reproduce the shape of the experimental spectra, indicating the neutron to be evaporated at higher temperature for the same excitation energy and angular momentum in symmetric system. According to the dynamical model, the formation time (37×10^{-22} sec) of the compound nucleus for the symmetric ^{31}P+^{45}Sc system is significantly higher than that (29×10^{-22} sec) for the asymmetric ^{12}C+^{64}Zn system. This may probably lead to the formation of a temperature-equilibrated dinuclear complex that may be responsible for neutron emission at higher temperature in the case of the symmetric system.

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I. INTRODUCTION

A systematic investigation of the properties of hot nuclei may be studied by detecting the evaporated particles [1–13]. These emisssions reflect the behavior of the nucleus at various stages of the deexcitation cascade. The statistical model has often been used to describe the decay of a highly excited nucleus. When the nucleus is formed by the collision of a heavy nucleus with a light particle, the statistical model has done a good job of predicting the distribution of evaporated particles when reasonable choices were made for the level densities and yrast lines [14–22]. Comparison to more specific measurements could, of course, provide a more severe test of the model and enable one to identify the deviations from the statistical model as the signature of other effects not included in the model. The decay of the compound nucleus at a moderate excitation energy and high spin has received a renewed interest in recent years due to advent of heavy-ion accelerators [23–25]. New detailed experimental data and sophisticated model calculation allow us to probe whether the foundations of the statistical model hold for the compound nuclei (CN) populated in the heavy-ion reactions. Assuming that the statistical nature of the compound nucleus decay is experimentally ascertained, questions are still related to the description of the average shapes of highly excited, rapidly rotating nuclei and their influences on the basic parameters of the calculation—e.g., moment of inertia, deformation and level densities, etc. Recently several papers have been devoted to these topics and the field is not yet free from controversies on the degree of deformation induced by nuclear rotation. The study of the neutron emission is advantageous because of the absence of Coulomb effects which complicate the interpretation of the charged-particle spectra in terms of a uniform nuclear temperature. Recently some papers have claimed [18,19,22] that experimental neutron evaporation spectra from heavy-ion fusion reactions at higher excitation enrgies and angular momenta are no longer consistent with the predictions of the standard statistical model. Specifically, it has been observed that in such cases measured neutrons have been characterized as having higher average energies than predicted [18,26]. This is interpreted as neutron emission from the temperature-equilibrated intermediate dinuclear complex during the time of its evolution towards compound nucleus formation [26]. In order to confirm this prediction we have employed two systems, a mass-symmetric (^{31}P+^{45}Sc) and a mass-asymmetric channel (^{12}C+^{64}Zn), leading to the same compound nucleus ^{76}Kr*. We compared the neutron evaporation spectra with the statistical model calculations and observed that for the asymmetric entrance channel there is no deviation from the statistical model calculations. However, for the symmetric entrace channel the experimental neutron spectra is harder than the statistical model calculations, indicating the entrance channel effects in the neutron evaporation spectra.

II. EXPERIMENT

The data were obtained using 15 UD Pelletron at Nuclear Science Centre (NSC), New Delhi, India. The ^{12}C pulsed beam of 85 MeV on a ^{64}Zn target was used to form the compound nucleus ^{76}Kr* with excitation energy of 75 MeV and angular momentum of $39\hbar$. In the other experiment ^{31}P beams of energies at 112 and 120 MeV on ^{45}Sc targets were used so that in one case with 120 MeV beam energy the compound nucleus (^{76}Kr*) is formed to match the excitation

energy of 75 MeV and in the other case with 112 MeV beam energy it matches the angular momentum of $39\hbar$ of the asymmetric system. All the beam energies mentioned are the midtarget energies. The self-supporting isotopically enriched (99.93%) targets of 1 mg/cm^2 thickness were used in both cases. The experiment was done using the 1.5-m-diam stainless steel general purpose scattering chamber (GPSC) available at NSC. The chamber ports were replaced with thin stainless steel flanges (thickness 2–3 mm) to make them suitable for neutron spectroscopy work. The scattering chamber was operated under a high vacuum of 10^{-7} Torr to avoid oxygen, carbon, or any other impurity built up on the target during the experiment. This was confirmed by the energy-dispersive x-ray analysis (EDXA) done on the targets after the experiment. The beam was dumped in a Faraday cup 3 m down the stream from the target which was heavily shielded with paraffin and lead bricks in order to reduce the background of neutrons produced by the beam dump. Neutron detectors having liquid scintillator cells of BC501 of 12.5 cm diameter and thicknesses of 12.5 cm were used at an angle of 30°, 60°, 90°, and 120°, respectively, with respect to the beam direction and were placed at a distance of 1 m apart from the target. The γ-n pulse-shape discrimination was employed to reduce the γ background. The neutron energy was determined by the time-of-flight technique. The pulse from the neutron detectors was used as the start while the stop pulse to the time-to-analog converter (TAC) was provided by the pulsed beam. The γ-ray peak with the neutron spectrum allowed us to calibrate the time spectrum and the overall time resolution of $\approx$1 ns. The time-of-flight spectra thus obtained were converted into neutron energy and the intensity was normalized using the neutron detection efficiency code MODEFF [27]. A neutron energy threshold of 0.5 MeV was selected for all the detectors using standard γ-ray sources with proper electron to neutron energy conversion. We have also measured the charged-particle spectra during this experiment using $\Delta E-E$ (40 μm–5 mm) detector telescopes, to see wheather charged particles behave in a similar manner or otherwise.

III. ANALYSIS

Statistical model calculations. The statistical computer code CASCADE [28] was used to perform theoretical calculations, which assumes the reaction to occur in two steps: first the formation of a compound nucleus and second the statistical decay of the equilibrated system. The fusion cross section is calculated with the following equation [28–30]:

$$\sigma_l = \pi\lambda^2 \sum_{l=0}^{l_{max}} (2l+1) T_l, \tag{1}$$

where T_l is taken to be

$$T_l = \left[1 + \exp\frac{(l - l_{max})}{d}\right]^{-1}. \tag{2}$$

The maximum value of the angular momentum l_{max} is calculated by the Bass model [31] and the diffuseness (d) is assumed to be $2\hbar$.

There are two aspects of the physical processes which govern the flow of an evaporation cascade: the spin-dependent level density defining the available phase space and the transmission coefficients that control the access to this phase space. The transmission coefficients mainly effect the lower-energy part of the particle spectrum. In the standard application of CASCADE, the transmission coefficients are derived for neutrons using optical model parameters [32] for the inverse fusion reactions. In heavy-ion fusion reactions at high excitation and in particular the levels with high angular momentum have a meaningful influence on the deexcitation cascade. The level density formula for a given angular momentum l and for both parities π can be written as

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

where a is the level density parameter, t is the thermodynamic temperature, Δ is the pairing correction, and E_I is the rotational energy. The rotational energy in terms of the rigid-body moment of inertia $\mathcal{J}_\mathcal{O}$ is given by

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

where $\mathcal{J}_\mathcal{O}$ is taken to be

$$\mathcal{J}_\mathcal{O} = \frac{2}{5} MR^2, \quad R = r_0 A^{1/3}, \tag{5}$$

and δ_1 and δ_2 are the input parameters providing a range of choices for the spin dependence of the level density. However, in the application of the above formula to nuclei of high spins and 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 [33] 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 a rear-

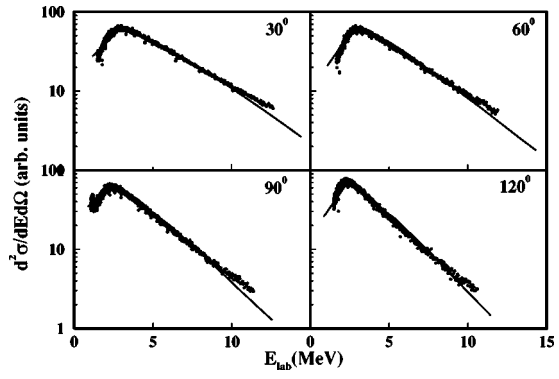

FIG. 1. Comparison of the experimental neutron spectra (dots) with the statistical model (solid line) using r_0=1.25 and a=A/8 for the asymmetric reaction ^{12}C+^{64}Zn with l_{max}=39$\hbar$ and E^* =75 MeV at E_{lab}=85 MeV.

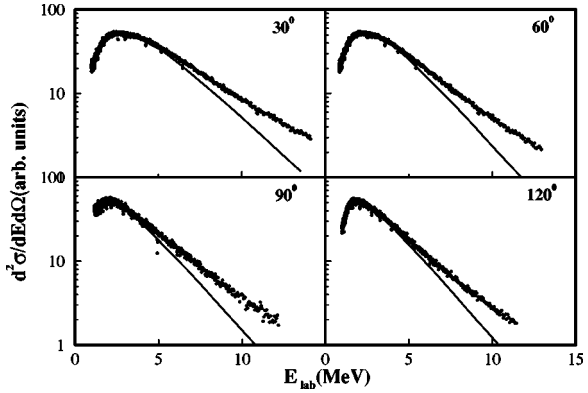

FIG. 2. Comparison of the experimental neutron spectra (dots) with the statistical model (solid line) using $a=A/8$ and $r_0=1.25$ for the symmetric reaction $^{31}P+^{45}Sc$ with $l_{max}=39\hbar$ and $E^*=70$ MeV at $E_{lab}=112$ MeV.

rangement of the single-particle levels near the Fermi energy that is associated with the spin-dependent nuclear deformation and thus directly affects the level densities due to the change of nuclear structure. 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 low-spin systems [34,35]. 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 statistical model calculations for the heavy-ion- induced reactions. However, very little is known experimentally about the spin dependence of level densities for the large spins and high excitation energies.

IV. RESULTS AND DISCUSSION

The neutron spectra of the composite system $^{76}Kr^*$ formed through the asymmetric reaction ($^{12}C+^{64}Zn$) at a maximum angular momentum of $39\hbar$ and excitation energy of 75 MeV are shown in Fig. 1 for angles at 30°, 60°, 90°, and 120° with respect to the beam direction. The angles ($\theta \geqslant 30°$) are selected so that the contribution, if any, from inelastic, transfer, deep inelastic, and preequilibrium processes are negligible as these are focused in the forward direction [24]. The neutron spectra are in good agreement with the statistical model calculations using the normal-level density parameter $a=A/8$ MeV^{-1}, the rotating liquid drop model moment of inertia, and the optical model transmission coefficients for the respective inverse absorption channels. The neutron emission for the comparatively mass-symmetric ($^{31}P+^{45}Sc$) system at different angles for the same angular momentum ($39\hbar$) and for the same excitation energy (75 MeV) are shown in Figs. 2 and 3 respectively. As is clear from the figures these spectra are not in agreement with the statistical model predictions using normal parameters as used for the asymmetric system. It is also clear that the high-energy part of the neutron spectra in the case of a symmetric system are harder than the statistical model predictions, indicating neutron evaporation at a higher temperature. The slope of the high-energy part of the neutron spectra is very sensitive to the level density **(**$\rho \approx \exp[2(aE)^{1/2}]$**)** and thus on the level density parameter a. In order to verify quantita-

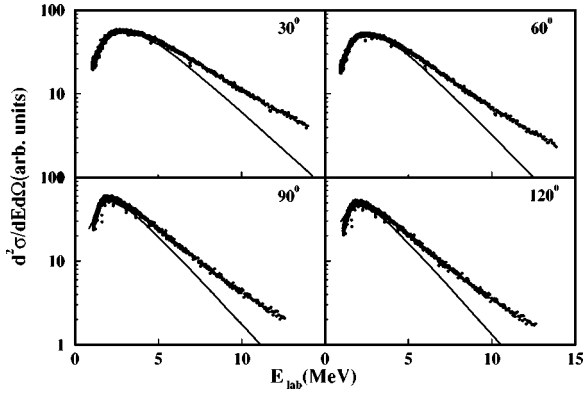

FIG. 3. Comparison of the experimental neutron spectra (dots) with the statistical model (solid line) using $a=A/8$ and $r_0=1.25$ for the symmetric reaction $^{31}P+^{45}Sc$ with $l_{max}=43\hbar$ and $E^*=75$ MeV at $E_{lab}=120$ MeV.

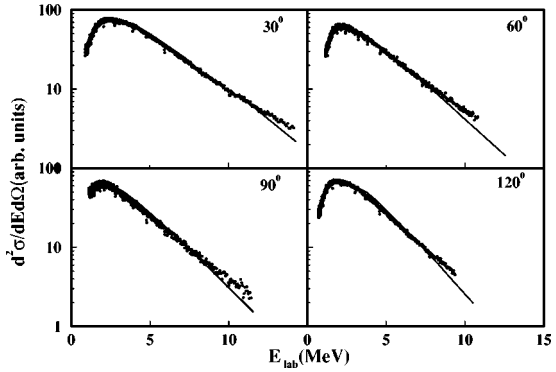

FIG. 4. Comparison of the experimental neutron spectra (dots) with the statistical model (solid line) using $a=A/10$ and $r_0=1.25$ for the symmetric reaction $^{31}P+^{45}Sc$ with $l_{max}=39\hbar$ and $E^*=70$ MeV at $E_{lab}=112$ MeV.

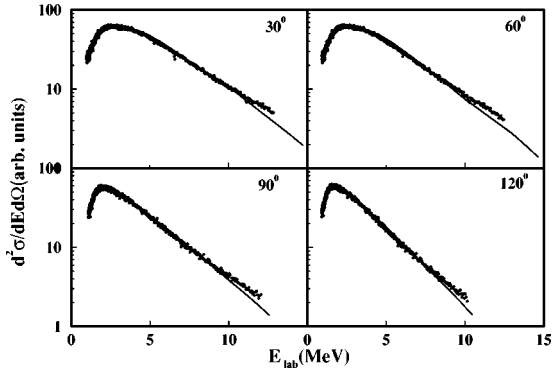

FIG. 5. Comparison of the experimental neutron spectra (dots) with the statistical model (solid line) using $a=A/10$ and $r_0=1.25$ for the symmetric reaction $^{31}P+^{45}Sc$ with $l_{max}=43\hbar$ and $E^*=75$ MeV at $E_{lab}=120$ Mev.

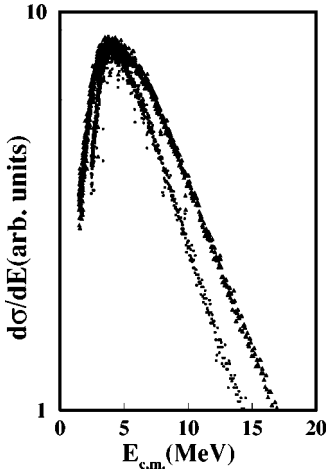

FIG. 6. Comparison of the experimental neutron spectra for the symmetric reaction $^{31}P+^{45}Sc$ (triangle) and for the asymmetric system $^{12}C+^{64}Zn$ (dots), in the center-of-mass system.

tively the experimental trends, the statistical model calculation was performed by changing the value of the level density parameter $a=A/10$ MeV^{-1}. Results of these calculations are shown in Figs. 4 and 5 for the symmetric $^{31}P+^{45}Sc$ reaction at 112 MeV and 120 MeV, respectively. This provides a reasonable description of the data and reproduces the shape of the spectra very well. The lower value of the level density parameter ($a=A/10$ MeV^{-1}) manifests an effective higher nuclear temperature [$T=\sqrt{(E/a)}$] for the neutron evaporation in the case of the mass-symmetric system. This change of level density parameter a in the case of neutron evaporation from $^{28}Si+^{118}Sn$ and $^{28}Si+^{124}Sn$ has also been reported by Wile *et al.* [22]. We have also compared the experimental neutron spectra for the two entrance channels in the center--of-mass system in Fig. 6 in order to avoid any kinematic bias. The spectrum for the symmetric system was found to be harder than the asymmetric system. The experimental spectra for the symmetric system in the center of mass has been

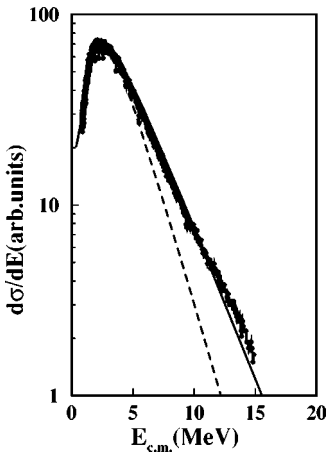

FIG. 7. Comparison of the experimental neutron spectra in the center-of-mass system (circles) with statistical model using $a=A/8$ and $r_0=1.25$ (dashed line) and using $a=A/10$ and $r_0=1.25$ (solid line) for the symmetric reaction $^{31}P+^{45}Sc$ with $l_{max}=43\hbar$ and $E^*=75$ MeV at $E_{lab}=120$ MeV.

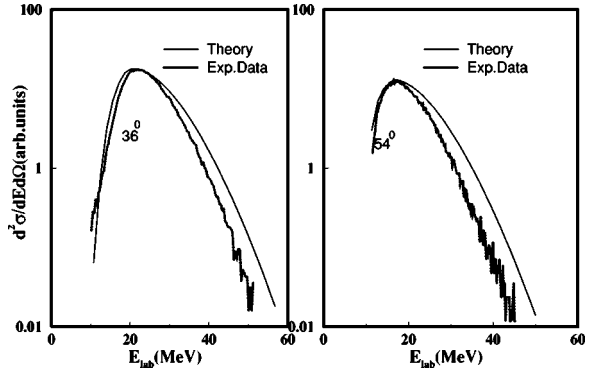

FIG. 8. Comparison of the experimental alpha spectra (dots) with the statistical model (solid line) using the transmission coefficients for the spherical nuclei and the RLDM moment of inertia for the symmetric reaction $^{31}P+^{45}Sc$ with $l_{max}=43\hbar$ and $E^*=75$ MeV at $E_{lab}=120$ MeV.

compared with theory in Fig. 7 and found that $a=A/10$ gives a better agreement, as has been observed in laboratory spectra.

In order to understand the behavior of the level density parameter a, we have also compared the experimental charged-particle spectra with statistical model calculations using the normal-level density parameter $a=A/8$ for alpha and protons in Fig. 8 and 9, respectively. In the case of the charged particles we find the high-energy part of evaporation spectra to be softer as compared to the theoretical spectra. This is contrary to the neutron spectra, which are found to be harder as compared to the experimental spectra. According to the dynamical model calculation, the formation time (37×10^{-22} sec) of the compound nucleus for the symmetric $^{31}P+^{45}Sc$ system is significantly higher than that of (29×10^{-22} sec) for the asymmetric $^{12}C+^{64}Zn$ system. This may lead to the formation of an intermediate temperature-equilibrated dinuclear complex which may be responsible for neutron emission at higher temperature in the case of the symmetric system, while the charged particles are emitted when the system is completely relaxed.

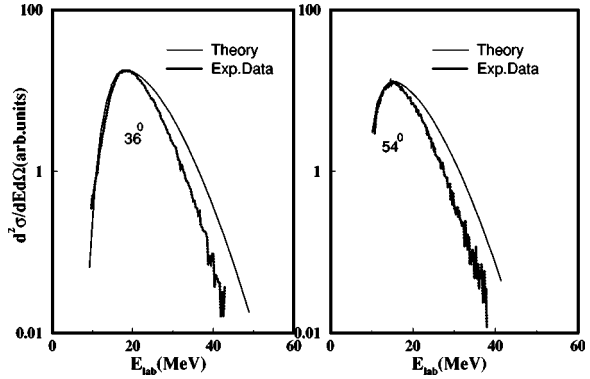

FIG. 9. Comparison of the experimental proton spectra (dots) with the statistical model (solid line) using the transmission coefficients for the spherical nuclei and the RLDM moment of inertia for the symmetric reaction $^{31}P+^{45}Sc$ with $l_{max}=43\hbar$ and $E^*=75$ MeV at $E_{lab}=120$ MeV.

V. SUMMARY

The compound nucleus ^{76}Kr* is formed in heavy-ion fusion reactions by an asymmetric entrance channel ^{12}C $+^{64}$Zn and the symmetric entrance channel ^{31}P$+^{45}$Sc at the excitation energy of 75 MeV and angular momentum of 39$\hbar$. Neutron energy spectra of the asymmetric system (^{12}C $+^{64}$Zn) at different angles are well described by statistical model predictions using the normal value of the level density parameter $a=A/8$ MeV^{-1}. However, in the case of the symmetric system (^{31}P$+^{45}$Sc), the statistical model interpretation of the data requires a change in the value of $a=A/10$ MeV^{-1}. The delayed evolution of the compound system in the case of the symmetric ^{31}P$+^{45}$Sc system may lead to the formation of a temperature-equilibrated dinuclear complex which may be responsible for neutron emission at higher temperature, while the protons and alpha particles are evaporated after neutron emission when the system is sufficiently cooled down. However, this needs to be explored further with other systems.

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