Study of angular momentum variation due to entrance channel effect in heavy ion fusion reactions

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Abstract. A systematic investigation of the properties of hot nuclei may be studied by detecting the evaporated particles. These emissions reflect the behavior of the nucleus at various stages of the deexcitation cascade. 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. 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. Some papers have claimed that experimental evaporation spectra from heavy-ion fusion reactions at higher excitation energies and angular momenta are no longer consistent with the predictions of the standard statistical model.

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 \(^{76}_Kr^*\) at the excitation energy of 75 MeV. Neutron energy spectra of the asymmetric system \((^{12}_C+^{64}_Zn)\) at different angles are well described by the 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 the change in the value of \(a = A/10\) MeV\(^{-1}\). The delayed evolution of the compound system in 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 the neutron emission at higher temperature, while the protons and alpha particles are evaporated after neutron emission when the system is sufficiently cooled down and the higher \(Q\) values do not contribute in the formation of the compound nucleus for the symmetric entrance channel in case of charged particle emission.

1. Introduction

Heavy-ion induced fusion reactions are capable of producing compound nuclei with high angular momentum, high excitation energy and large deformations. High excitation energy implies that the nucleus de-excites by emitting several particles and \(\gamma\)-rays so that the decay pattern involves a number of different paths. While the statistical model has been used for many decades to analyze a variety of observables related to the compound nucleus decay, the successful description of the particle emission remains essential for evaluating the validity of the model and the choice of the parameters within it. The emission of the light particles in heavy ion fusion reactions has been used very frequently to understand the behavior of the
hot rotating nuclei in several investigations. Detailed experimental data and different model calculations allow us to probe whether the foundation of the statistical model holds for the compound nuclei populated in these reactions. In the case of the compound nuclei at moderate energies and angular momenta, such as those produced with light ion projectiles, the experimental charged particle spectra are well explained in terms of the statistical models employing the optical model transmission coefficients. However, in the case of heavy ion induced fusion reactions, there have been several claims of serious discrepancies between the predictions of the standard statistical model and the measured light charged particle energy spectra [1-9]. Measured light charged particle spectra have been characterized as having lower energy than predicted. 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 higher excitation energy and the angular momentum [2-7]. 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 [10-14].

Assuming that the statistical nature of the compound nucleus decay is experimentally ascertained, some open questions are still related to the description of the average shapes of the highly excited, rapidly rotating nuclei and their influences on the basic nuclear properties like level densities, yrast line position and emission barrier heights [15-16]. Several papers have been devoted to these topics and the field is not yet free from controversies. 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 [17-18] that experimental neutron evaporation spectra from heavy-ion fusion reactions at higher excitation energies and angular momenta are no longer consistent with the predictions of the standard statistical model. Specially, it has been observed that in such cases measured neutrons have been characterized as having higher average energies than predicted [17-18]. This is interpreted as neutron emission from the temperature-equilibrated intermediate di-nuclear complex during the time of its evolution towards compound nucleus formation. In order to confirm these observations, we have studied two systems, a mass-symmetric channel $^{31}$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 as well charged particle 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 entrance channel the experimental neutron spectra is harder than the statistical model calculations, indicating the entrance channel effects in the neutron evaporation spectra, while the charged particle spectra shows opposite kind of trends w.r.t the statistical model calculations.

2. Experiment
The data were obtained using 15 UD Pelletron at Inter University Accelerator Centre (IUAC), 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. In the other experiment $^{31}$P beam at 120 MeV on $^{45}$Sc target was used so that the compound nucleus ($^{76}$Kr*) is formed to match the excitation energy of 75 MeV of the asymmetric system. All the beam energies mentioned are the mid target energies. The self-supporting isotopically enriched (99.93%) targets of 1mg/cm$^2$ thickness were used in both cases. The experiment was done using the 1.5m
diameter stainless steel general purpose scattering chamber (GPSC) available at IUAC. 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 n-\gamma pulse-shape discrimination was employed to reduce the g 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 \gamma-ray peak with the neutron spectrum allowed us to calibrate the \gamma-ray spectrum and the overall time resolution of <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 [19]. A neutron energy threshold of 0.5 MeV was selected for all the detectors using standard \gamma-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 \mu m–5 mm) detector telescopes.

3. Analysis

(a) Statistical model calculations:: The statistical computer code CASCADE [20] 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 maximum value of the angular momentum \( l_{\text{max}} \) is calculated by the Bass model [21] 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 affect 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 [22] 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 de-excitation cascade.

The dependence of the level density on deformation caused by the periodic changes in the shell structure is well known for low-spin systems [23-24]. 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.

(b) Dynamical trajectory model calculations (HICOL):: T In the model developed by Feldmeier [25], various aspects of the 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 the classical trajectories and the upper limit is to ensure that the mean field approximation is valid. The macroscopic properties of a
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 [26], 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 consists 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, the neck coordinate, and the asymmetry coordinate.

The potential is obtained as a double volume integral of a Yukawa plus exponential folding function and 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 the particle exchange model. One-body dissipation is assumed to be predominant as it has been found to be more relevant for these types of reactions [27]. 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 the various composite systems formed in nucleus-nucleus collisions in a wide range of impact parameters.

4. Results and Discussion

The neutron spectra of the composite system $^{76}$Kr* formed through the asymmetric reaction ($^{12}\text{C}+^{64}\text{Zn}$) at a maximum angular momentum of 41 ħ and excitation energy of 75 MeV are shown in Fig. 1(a) for angles at 30°, 60°, 90°, and 120° with respect to the beam direction. The angles (≥30°) are selected so that the contribution, if any, from inelastic, transfer, deep inelastic, and pre-equilibrium processes are negligible as these are focused in the forward direction [9]. 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.

**FIG. 1.** Comparison of the experimental neutron spectra (dots) with the statistical model (solid line) (a) using $r_0=1.25$ and $a=\Lambda/8$ for the asymmetric reaction $^{12}\text{C}+^{64}\text{Zn}$ with $\ell_{\text{max}}=41$ ħ and $E^*=75$ MeV at $E_{\text{lab}}=85$ MeV (b) $r_0=1.25$ and $a=\Lambda/8$ for the symmetric reaction $^{31}\text{P}+^{45}\text{Sc}$ with $\ell_{\text{max}}=43$ ħ and $E^*=75$ MeV at $E_{\text{lab}}=120$ MeV.
The neutron emission for the comparatively mass-symmetric \( ^{31}\text{P} + ^{45}\text{Sc} \) system at different angles for the same excitation energy (75 MeV) is shown in Fig. 1(b). As is clear from the figure 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 \( a \).

\[ \text{FIG. 2. (a) Comparison of the experimental neutron spectra (dots) with the statistical model (solid line), using } r_0=1.25 \text{ and } a=A/10 \text{ for the symmetric } ^{31}\text{P} + ^{45}\text{Sc} \text{ with } \ell_{\text{max}}=43\hbar \text{ and } E^*=75\text{MeV at } E_{\text{lab}}=120 \text{ MeV. (b) Comparison of the experimental neutron spectra for the symmetric reaction } ^{31}\text{P} + ^{45}\text{Sc} \text{ (triangle) and for the asymmetric system } ^{12}\text{C} + ^{64}\text{Zn} \text{ (dots), in the center-of-mass system.} \]

In order to verify quantitatively the experimental trends, the statistical model calculation was performed by changing the value of the level density parameter \( a=A/10 \text{ MeV}^{-1} \). Results of these calculations are shown in Fig. 2(a) for the symmetric \( ^{31}\text{P} + ^{45}\text{Sc} \) reaction at 120 MeV. 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 \( a=A/10 \text{ MeV}^{-1} \) manifests an effective higher nuclear temperature \( T=\langle(E/a) \rangle \) 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 \( ^{28}\text{Si} + ^{118}\text{Sn} \) and \( ^{28}\text{Si} + ^{124}\text{Sn} \) has also been reported by Wile \textit{et al.} [15]. We have also compared the experimental neutron spectra for the two entrance channels in the center-of-mass system in Fig.2(b) in order to avoid any kinematic bias. The spectrum for the symmetric system was found to be harder than the asymmetric system.

In order to understand the behavior of nuclear reaction dynamics more clearly, 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 Figs. 3(a) and 3(b) for
asymmetric and symmetric systems.

![Fig. 3](image)

**FIG. 3.** Comparison of the experimental alpha and proton spectra with the statistical model (solid line) using the transmission coefficients for the spherical nuclei and the RLDM moment of inertia for the (a) asymmetric reaction $^{12}$C+$^{64}$Zn with $\ell_{\max} = 41\hbar$ and $E^*=75$ MeV at $E_{\text{lab}}=85$ MeV and (b) symmetric reaction $^{31}$P+$^{45}$Sc with $\ell_{\max} = 43\hbar$ and $=75$ MeV at $E_{\text{lab}}=120$ MeV.

In the case of the charged particles we find that the experimental data is very consistent with statistical model calculations for asymmetric system ($^{12}$C+$^{64}$Zn), while the high energy part of evaporation spectra found to be softer as compared to the theoretical spectra in case of symmetric system ($^{31}$P+$^{45}$Sc). This is contrary to the neutron spectra, which are found to be harder as compared to the statistical model calculation.

In order to explain the difference in behavior of the proton and alpha spectra from the symmetric system, we carried out dynamical model calculations using the HICOL code. The excitation energies as well as the elongations of the fusing nuclei are plotted as a function of time in Figs. 4 and 5, respectively.

![Fig. 4](image)

**FIG. 4.** Calculated evolution of the excitation energy ($E^*$) of the colliding nuclei as a function of time for the reactions (a) $^{12}$C+$^{64}$Zn at 85 Mev and (b) $^{31}$P+$^{45}$Sc at 120 MeV.

![Fig. 5](image)

**FIG. 5.** Calculated evolution of the separation(s) of the colliding nuclei as a function of time for the reactions (a) $^{12}$C+$^{64}$Zn at 85 Mev and (b) $^{31}$P+$^{45}$Sc at 120 MeV.

One finds that the higher $\ell$ values fuse slowly and are saturated at lower excitation energies. In the case of the asymmetric system, the $\ell_{\max}$ contribution to the fusion process is equal to 41 h, the same as suggested by the Bass model [21], but in the case of the symmetric system the maximum value of angular momentum which fuses is 30 h as opposed to 43 h obtained from the Bass model. The time evolution of the two reactions for an angular
momentum of 30 ћ is shown in Fig. 6. One finds that the symmetric system \(^{31}\text{P} + ^{45}\text{Sc}\) evolves more slowly compared to the asymmetric \(^{12}\text{C} + ^{64}\text{Zn}\) system and the formation time of the asymmetric system is significantly smaller than the decay time while the formation time in the case of the symmetric system is closer to the decay time as shown in Table I.

| S. No. | System | \(E_{\text{Lab}}\) (MeV) | \(\ell_{\text{max}}\) \(\text{Bass Model}\) | Excitation Energy (MeV) | Formation Time \((10^{-22}\text{ s})\) | Decay Time \((10^{-22}\text{ s})\) | HICOL predicted \(\ell_{\text{max}}\) |
|--------|--------|----------------|----------------|----------------|----------------|----------------|----------------|
| 1. | \(^{12}\text{C} + ^{64}\text{Zn} \rightarrow ^{76}\text{Kr}\) * | 85 | 41h | 75 | 29 | 37 | 41h |
| 2. | \(^{31}\text{P} + ^{45}\text{Sc} \rightarrow ^{76}\text{Kr}\) * | 120 | 43h | 75 | 37 | 40 | 30h |

**TABLE I.** Comparison of the various parameters used for the two systems.

The statistical model calculations with the HICOL predicted value of \(\ell = 30\) ћ for the symmetric system is compared with experimental alpha and proton spectra in Fig. 7. The excellent agreement with theory suggests that the deviation from the statistical model results from dynamical effects arising from the mass symmetry of the entrance channel during the formation of the compound nucleus.

**FIG. 6.** Dynamical model time evolution of the reactions (a) \(^{12}\text{C} + ^{64}\text{Zn}\) and (b) \(^{31}\text{P} + ^{45}\text{Sc}\).

**FIG. 7.** Comparison of experimental spectra with the statistical model for the reaction \(^{31}\text{P} + ^{45}\text{Sc}\) using the HICOL predicted \(\ell_{\text{max}}\) = 30 ћ (a) \(\alpha\)-spectra (b) Same for proton spectra.
5. 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. 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$^{-1}$. However the charged particle spectra for the symmetric system is not consistent with the statistical model calculation by using the angular momentum obtained by Bass model and the experimental charged particle data for symmetric system is very consistent with statistical model, when the HICOL predicted angular momentum value is used.

But again if the HICOL predicted angular momentum is used for symmetric system particle spectra (charged particle and neutrons), the neutron spectra becomes more harder comparative to statistical model calculation. So to get more clear information about the variation of angular momentum, we need to do more experiments for determination of the value of fused angular momentum in both type of systems i.e. symmetric as well as asymmetric system.

More likely the delayed evolution of the compound system in the case of the symmetric system may lead to the formation of a temperature-equilibrated system, 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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