Search for entrance channel effects in heavy ion induced fusion reactions via neutron evaporation

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Neutrons from the fusion reactions $^{16}O+^{64}Zn$ at 91 MeV and $^{32}S+^{48}Ti$ at 120 and 125 MeV have been observed in two series of complementary experiments using the time of flight technique. The energies are selected so that both the systems lead to the compound nucleus $^{80}Sr^*$ with the same value of the angular momentum and the excitation energy. The spectra from the asymmetric reaction $^{16}O+^{64}Zn$ are found to be consistent with the predictions of the statistical model calculations using rotating liquid drop model values of the moment of inertia and the transmission coefficients for the spherical nuclei in the inverse absorption channel. However, the experimental spectra in the case of the symmetric reaction $^{32}S+^{48}Ti$ show deviations at higher as well as lower energies from the normal statistical model calculations. This indicates the effect of the entrance channel on the dynamics of the neutron evaporation of the compound system. The effective level density parameter a is found to be smaller, indicating the evaporation at a higher temperature, for the same compound nucleus formed in the case of the symmetric system as compared to the asymmetric system.

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I. INTRODUCTION

An important facet of the heavy-ion physics is the dynamics of the ion-ion collisions. However, it is not yet clear how the collision properties and the nuclear aspects govern the division of the total reaction cross section into the particle cross sections for the complete fusion, incomplete fusion, fast fission, deep-inelastic, and quasielastic reactions. To solve this problem it is important first to understand the dynamics of the complete fusion at low incident energies without the complications introduced by the presence of other strongly competing reaction channels. Heavy ion induced fusion reactions are capable of producing compound nuclei with high angular momentum, high excitation energy, and large deformation. High excitation energy implies that the nucleus deexcites by emitting several particles and γ rays, so that the decay pattern involves a number of different paths [1–17]. 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 neutron emission remains essential for evaluating the validity of the statistical model and the choice of the parameters within it. The emission of neutrons in the heavy ion fusion reactions has been used to understand the behavior of the hot rotating nuclei in several investigations [16–22]. 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 composite nuclei at moderate energies and angular momenta, such as those produced with the light ion projectiles, the experimental evaporation spectra are well explained in terms of the standard statistical model employing optical model transmission coefficients [23,24]. However, over the past decade, there have been several claims of serious discrepencies between the standard statistical model predictions and the experimental neutron evaporation from the heavy ion reactions, where the higher excitation energies and the angular momenta are involved [17–22]. In such cases measured neutrons have been characterized as having more average energies than predicted. In such cases the statistical model has done a good job of predicting neutron spectra when reasonable choices are made for the level densities and the yrast line [18,19,22]. Recently, the level density has been calculated with shell model single particle levels [25]. For the high excitation energy region, the result shows drastic deviation from the level density obtained by the parameterization at low excitation energies based on the Fermi gas model. The calculated spin dependence of the level density seems to require an excitation energy dependence of the spin cutoff parameter when the conventional level density parametrization is applied to fit them. Thus, it is highly desirable to systematically obtain the level density information for the high excitation energy and the high spin region. The present method is very useful for such a purpose, since neutrons are free from the Coulomb barrier and the whole spectrum (including the low energy neutrons) directly reflects the level densities of the sequentially decaying nuclei. Here we have reported the neutron energy spectra for the compound nucleus $^{80}Sr^*$, populated through the asymmetric ($^{16}O+^{64}Zn$) and the symmetric system ($^{32}S+^{48}Ti$), to study the effect of the entrance channel on the evaporation of the neutrons. Statistical model calculations with different level densities have been done in order to understand the possible entrance channel effects in the formation and the decay of the compound nucleus through neutron channel.

II. EXPERIMENT

The experiment was performed with the ^{16}O pulsed beam of 91 MeV on 1 mg/cm^2 thick ^{64}Zn target and the ^{32}S pulsed beam of 120 and 125 MeV on 1 mg/cm^2 thick ^{48}Ti target from 15UD pelletron accelerator at NSC, New Delhi, India. All the beam energies mentioned are the mid target energies and both the targets were enriched to 99.93%. The experiment was done using the 1.5 m diameter stainless steel general purpose scattering chamber. The chamber ports are replaced with thin stainless steel flanges (thickness 2–3 mm) to make it 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 buildup on the target during the experiment. The energy dispersive x-ray analysis of the target samples after the experiment shows that the C and O impurities were insignificant. The target ladder was insulated from the scattering chamber so as to measure the beam current and the total charge falling on the target. Neutron time of flight was measured using the standard technique of a time-of-flight setup. Two neutron detectors were used in the present experiment having liquid scintillator cells of BC501 of 12.5 cm diameter and thicknesses of 5 and 12.5 cm placed at angles of 30° and 60°, respectively, with respect to the beam direction at a distance of about 1 m from the target. These scintillators were backed by the RCA 8575 photomultiplier tubes with the lucite light guides. Pulses from the neutron detectors were discriminated for the n and γ using a pulse shape discriminator. Time of flight of the neutrons was measured with the start-stop-type time to amplitude convertors (TAC). A pulse from the neutron detector after the constant fraction discriminatior starts the TAC while the stop pulse to the TAC is provided by the beam pulse. The pulse shape discriminator eliminates most of the γ ray pulses. A small part of the γ rays were allowed so as to get a prompt peak with the beam pulse in the time spectrum. This allowed us to calibrate the time spectrum and to measure the overall resolution of the setup. Energy threshold of the neutrons was selected using the standard γ ray sources. In the present case the neutron threshold was fixed at 0.5 MeV in both the detectors. The time-of-flight spectra thus obtained were converted into the laboratory neutron energy spectra. The neutron detection efficiency code MODEFF [26], which depends on the neutron energy, scintillator geometry, and the neutron threshold, was utilized for calculating the neutron detector efficiency.

III. ANALYSIS

A. Statistical model calculations

The statistical model computer code CASCADE [27] 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. The fusion cross section is calculated with the following equation [27–29]:

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

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 [30] 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 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 the optical model parameters [31] for the inverse fusion reactions. In heavy ion 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 l and for both the parties 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 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

$$\mathcal{J}_{\mathcal{O}} = \tfrac{2}{5} \mathrm{MR}^2 \quad \text{and } \mathrm{R} = \mathrm{r}_0 \mathrm{A}^{1/3}, \tag{5}$$

where 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 the excitation energies, it must be emphasized that the 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 [32] 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 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 thus directly effect 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 the low-spin systems [33,34]. 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 calcula-

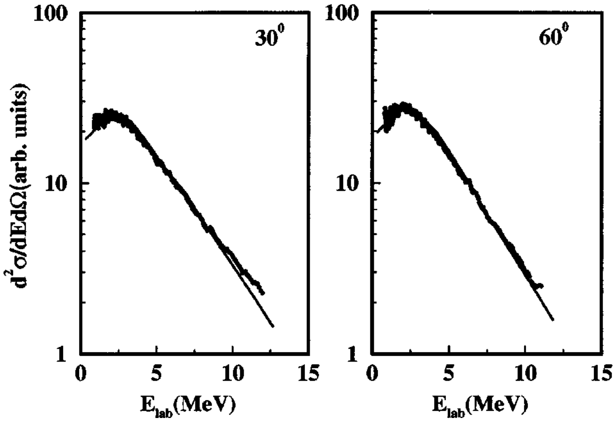

FIG. 1. Comparison of the experimental neutron spectra (circles) with statistical model (solid line) using $r_0=1.25$ and $a=A/8$ for the asymmetric reaction $^{16}O+^{64}Zn$ with $l_{max}=41\hbar$ and $E^*=72$ MeV at $E_{lab}=91$ MeV. The theoretical center-of-mass spectra are converted into laboratory frame incorporating Gallielian invariance and the finite time response due to the detector length.

tions for the heavy ion induced reactions. However, very little is known experimentally about the spin dependence of the level densities for the large spins and high excitation energies.

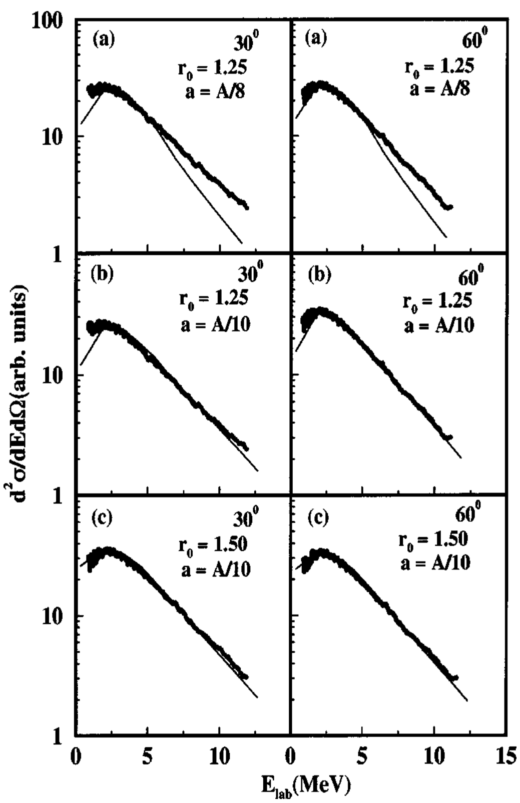

FIG. 2. Comparison of the experimental neutron spectra (circles) with statistical model (solid line) for the symmetric reaction $^{32}S+^{48}Ti$ with $l_{max}=41\hbar$ and $E^*=68$ Mev and $E_{lab}=120$ MeV (a) for $a=A/8$ and $r_0=1.25$, (b) for $a=A/10$ and $r_0=1.25$, (c) for $a=A/10$ and $r_0=1.5$.

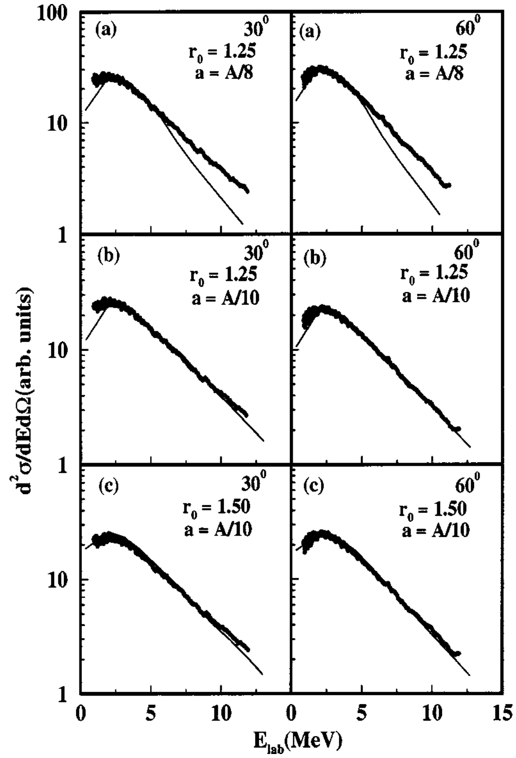

FIG. 3. Comparison of the experimental neutron spectra (circles) with statistical model (solid line) for the symmetric reaction $^{32}S+^{48}Ti$ with $l_{max}=43\hbar$ and $E^*=72$ MeV at $E_{lab}=125$ MeV. (a) for $a=A/8$ and $r_0=1.25$, (b) for $a=A/10$ and $r_0=1.25$, (c) for $a=A/10$ and $r_0=1.5$.

IV. RESULTS AND DISCUSSION

The experimental results for the energy spectra of neutrons in the laboratory frame, emitted in the fusion reactions $^{16}O+^{64}Zn$ at 91 MeV and $^{32}S+^{48}Ti$ at 120 and 125 MeV, are presented in Figs. 1–3, respectively, and discussed in terms of the statistical model CASCADE calculations. The center-of-mass spectra obtained from the CASCADE calculations are converted into the laboratory frame for comparison using the normal kinematical relations and the Gallielian invariance. This transformation also takes care of the finite time spread (≈ 5 ns) due to the detector length which is about 10% of the total flight time of the neutrons. The calculated spectra are folded with the corresponding energy resolution. As shown in Fig. 1, the neutron spectra of the composite system $^{80}Sr^*$, formed through the asymmetric reaction $^{16}O+^{64}Zn$ at maximum angular momentum $41\hbar$ and excitation energy of 72 MeV, are in good agreement with the statistical model calculations using the rotating liquid drop model values of moment of inertia and the optical model transmission coefficients for the respective inverse absorption channels. In contrast, the neutron emission with respect to the statistical model predictions in the case of the symmetric system $^{32}S+^{48}Ti$ at different angles cannot be explained for the same angular momentum ($41\hbar$) as shown in Fig. 2(a) and for the same excitation energy (72 MeV) as shown in Fig. 3(a). In the symmetric system, lower as well as the higher energy part of the neutron spectra are not in agreement with the statistical model calculations. The slope of the high energy part of the neutron spectra is very sensitive to a, while the lower energy part of the neutron spectra is mainly determined by r_0, which enters into the Cascade calculations in two ways: first as an optical model parameter in the calculation of transmission coefficient and second as a shape parameter in the calculation of the moment of inertia [Eq. (5)]. It has been noticed that the change of r_0 does not affect the transmission coefficients in the case of neutrons very much, but it affects the lower energy spectra due to the change of moment of inertia and the level densities. In order to verify quantitatively the experimental trends, the statistical model calculation was performed in which the level density parameter was changed to $a = A/10\ \text{MeV}^{-1}$, effectively raising the theoretical emission temperature. Results of these calculations are shown in Figs. 2(b) and 3(b), which provide a much better description of the data. The value of the level density parameter $a = A/10\ \text{MeV}^{-1}$ reproduces the data at higher energy side but does not reproduce the lower energy part as shown in Figs. 2(b) and 3(b). Changing the value of r_0 and keeping the value of $a = A/10\ \text{MeV}^{-1}$, the lower energy as well as the higher energy part of the spectra agree well with the experimental spectra as shown in Figs. 2(c) and 3(c). In particular, the critical level density parameter in CASCADE is assumed to be given as $a = A/8\ \text{MeV}^{-1}$, while the value of the effective radius parameter is assumed to be given by $r_0 = 1.25$. According to Kasagi and co-workers [18,22], a larger r_0 serves to increase the level density and thus enhancing the phase space in the sequentially decaying nuclei, and thereby it increases the lower energy neutron yield, while the higher energy part of the neutron spectrum is explained due to the higher temperature of the composite system than expected from the systematics.

V. SUMMARY

The present data indicate the effect of the entrance channel on the neutron evaporation from the compound system. The nucleus $^{80}\text{Sr}^*$ is formed in the heavy ion fusion reactions by $^{16}\text{O} + ^{64}\text{Zn}$ (asymmetric system) and $^{32}\text{S} + ^{48}\text{Ti}$ (symmetric system), with the same value of the angular momentum and the excitation energy. A rich set of the experimental data is collected by measuring the neutron spectra in two series of experiments. Energy spectra of the asymmetric system $^{16}\text{O} + ^{64}\text{Zn}$ are well described at different angles by the statistical model predictions. However, in the case of the symmetric system $^{32}\text{S} + ^{48}\text{Ti}$, a scaling according to $a = A/10\ \text{MeV}^{-1}$ for the higher energy part and $r_0 = 1.5$ is required to explain the lower energy part of the neutron spectrum obtained from the compound nucleus $^{80}\text{Sr}^*$. The lower value of the level density parameter a indicates the evaporation of the neutrons due to the temperature of the composite system being higher than expected from the systematics, and the larger value of the r_0 serves to increase the density of the states in the sequentially decaying nuclei, thus affecting the neutron yield at low energies.

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