Evaporation of alpha particles from $^{31}$P nucleus

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The energy spectra of $\alpha$-particles have been measured in coincidence with the evaporation residues for the decay of the compound nucleus $^{31}$P, produced in the reaction $^{19}$F (96 MeV) + $^{12}$C. The data have been compared with the predictions of the statistical model code CASCADE. It has been observed that significant deformation effect in the compound nucleus need to be considered in order to explain the shape of the evaporated $\alpha$-particle energy spectra.

One of the main motivations of the low energy heavy ion reactions studies has been to extract informations on the statistical properties of the hot, rotating nuclei. The informations on the main ingredients of the statistical description, i.e., the nuclear level densities and the barrier transmission probabilities, are usually obtained from the study of the evaporated light particle spectra. The validity of the statistical model depends crucially on the successful description of the light particle emission data and the model, so far, has been overwhelmingly successful in explaining a wide variety of nuclear reaction data in low energy regime. In this perspective, recent studies on the evaporated $\alpha$-particle energy spectra has evoked a lot of interest (see, for example, ref. [1] and references therein). It has been observed that the standard statistical model calculations failed to predict the shape of the evaporated $\alpha$-particle energy spectra satisfactorily. A large number of experiments have been performed to study this anomaly over a wide range of compound nuclear masses $A_{CN}$ in the range of $\sim$60–170 and in all cases it has been found that the average energies of the measured $\alpha$-particle energy spectra are much lower than the corresponding theoretical predictions. Several attempts have been made in the past few years to explain this anomaly. Some of the authors [2,3] argued that the discrepancy was due to the lowering of the emission barriers of the hot nuclei as compared to the fusion barriers for the corresponding relatively ‘cold’ inverse absorption channels as a result of the excitation energy and angular momentum dependent deformation of the emitting system in the former. On the other hand, there is another group of authors who claim that the anomaly may be well explained by incorporating spin dependent level density in the standard statistical model prescription and emission barriers need not be changed [4,5]. Moreover, it has also been observed that the magnitude of the discrepancy has some entrance channel dependence [6], the discrepancy being more for the more symmetric entrance channels. This is indicative of the fact that the magnitude of the phenomena may also be linked with the entrance channel dynamics of the system. Intuitively, the shape of the $\alpha$-particle spectra would be affected by the deformation of the equilibrating system if it remains deformed over a time scale comparable to the mean life time of $\alpha$ emission. For heavier nuclei ($A_{CN} > 60$), the theoretical calculations of shape equilibration time, using the code HICOL [7] show that these time scales are comparable to mean $\alpha$ life times for moderate excitations. Interestingly, for lighter systems too, the trend of the predictions are similar. This prompted us to explore the scenario in the lower mass composite system ($A \leq 60$), as there is practically no data available in this region, to the best of our knowledge.

The system chosen for the present studies is $^{31}$P, produced in the reaction $^{19}$F (96 MeV) + $^{12}$C. The $\alpha$-particle energy spectra at various laboratory angles, were measured in coincidence with the evaporation residues. The experiment was performed at the Bhabha Atomic Research Centre - Tata Institute of Fundamental Research 14 UD pelletron accelerator laboratory, Mumbai, with 96 MeV $^{19}$F beam on 100$\mu$gm/cm$^2$ self-supporting $^{12}$C target. Two gas telescopes, each consisting of a gas $\Delta$E and 500$\mu$m Si surface barrier (SB) detectors were kept at 20$^\circ$ and 30$^\circ$. The gas detectors were of axial configuration, continuous flow type and the gas (P10 : 90% Ar, 10% CH$_4$) pressure was maintained at 80±1 torr. The $\alpha$-particles have been detected in coincidence with the evaporation residues in three solid state telescopes in an angular range of 20$^\circ$–60$^\circ$. Among these three, two telescopes were of two elements each consisting of 45$\mu$m $\Delta$E Si(SB) and 2 mm Si(Li) detectors. The third one was of three elements consisting of 30$\mu$m, 46$\mu$m Si(SB) and 2 mm Si(Li) detectors. Gas telescopes were calibrated using the elastically scattered F ions from C and Bi targets. The light particle telescopes were calibrated with recoil protons produced in the reaction of 96 MeV Flourine on 3.5$\mu$m mylar target and with the radioactive $^{228}$Th $\alpha$-source. Absolute energy calibrations were done using standard kinematics and considering energy loss calculations.

The centre of mass angular distribution of the exclusive $\alpha$-particles have been displayed as a function of the centre of mass emission angles in Fig. 1. It is observed from the figure that the values of $d\sigma/d\theta$ is constant over the range
of the observed centre of mass emission angles. This implies that the \( \frac{d\sigma}{d\Omega} \sim 1/\sin \theta_{\text{c.m.}} \), which is characteristics of the emission from a thermally equilibrated compound nucleus. The average velocities of the exclusive \( \alpha \)-particles have been plotted in Fig. 3 as a function of the velocities parallel \((v_{||})\) and perpendicular \((v_{\perp})\) to the beam direction. It is observed that the average velocities fall on a circle around the compound nucleus velocity \((v_{0n})\) which implies that the average velocities (as well as the average kinetic energies) of the \( \alpha \)-particles are independent of the centre of mass emission angles. It is a further indication of the fact that the energy relaxation is complete and \( \alpha \)-particles are emitted from a fully equilibrated source moving with the velocity \( v_{0n} \).

The exclusive c.m. energy spectra of \( \alpha \)-particle for three representative angles have been compared with the theoretical predictions of the same using the code CASCADE [8], and the results are displayed in Fig. 3. For the present calculation, the critical angular momentum for fusion, \( l_{cr} \), was taken to be \( 21h \), obtained from the compilation of fusion cross section data [7]. The solid curves are the results of CASCADE calculations with the default parameters of the code. It is clear from the figure that the theoretical predictions using the default values of the parameters differ significantly from the experimental data on both lower and higher energy sides of the spectra. It is also clear that the experimental values of the mean \( \alpha \)-particle energies are somewhat lower than those predicted from the theory. It implies that some of the input parameters of the code need to be modified to explain the data properly.

The change in the emission barriers and vis-a-vis the transmission probabilities affects the lower energy part of the calculated evaporation spectra. On the other hand the high energy side of the spectra depends crucially on the available phase space obtained from the energy level densities. In hot rotating nuclei formed in heavy ion reactions, the energy level density at higher angular momentum is spin dependent. The level density, \( \rho(E, I) \), for a given angular momentum \( I \) and excitation energy \( E \) is given by [8],

\[
\rho(E, I) = \frac{(2I + 1)/12}{\sqrt{\hbar}} \frac{2\sqrt{2J_{\text{eff}}}^{3/2}}{(E - \Delta - T - E_I)^{3/2}} \exp[2(a(E - \Delta - T - E_I))]^{1/2}
\]

where \( a \) is the level density parameter, which is taken to be \( A/8 \) for the present calculation, \( T \) is the thermodynamic temperature, \( \Delta \) is the pairing correction, and \( E_I \) is the rotational energy which can be written in terms of the effective moment of inertia \( J_{\text{eff}} \) as

\[
E_I = \frac{\hbar^2}{2J_{\text{eff}}} (I + 1),
\]

where

\[
J_{\text{eff}} = J_0 \times (1 + \delta_1 I^2 + \delta_2 I^4),
\]

and the rigid body moment of inertia, \( J_0 \), is given by,

\[
J_0 = \frac{2}{5} A^{5/3} r_0^2.
\]

Here, \( A \) is the mass number and \( r_0 \) is the radius parameter. Non zero values of the parameters \( \delta_1, \delta_2 \) introduce spin dependence in the effective moment of inertia resulting in spin dependent level densities in Eq. 3.

An increase in the radius parameter \( r_0 \) results in an increase the available phase space, due to an increase in the effective moment of inertia. Simultaneously, the transmission probability also increases as the emission barrier decreases due to the increase of \( r_0 \). Therefore, with the variation of a single input parameter, \( r_0 \), in the code CASCADE, it is possible to modify the low energy as well as the high energy part of the calculated spectra. So, in the present calculation, we varied the parameter \( r_0 \) only, and kept the spin dependent parameters \( \delta_1, \delta_2 \) in Eqn. 2 equal to zero, to reproduce the experimental spectra. The dashed curves in Fig. 3 are the predicted energy spectra using the code CASCADE with the value of \( r_0 = 1.56 \) fm. It is clear from Fig. 3 that the calculated spectra agree quite well with the exclusive experimental spectra both in the low energy as well in the high energy regions. The large value of the parameter \( r_0 \) (as compared to its default value of 1.29 fm) indicates that the nucleus is deformed in the exit channel. The increase in the radius parameter \( r_0 \) is \( \sim 20\% \) which also agrees well with the other observations available in the literature [11]. Interestingly, similar deformation effects have been observed in our earlier studies on intermediate mass fragment (IMF) emission from the same \( ^{31}\text{P} \) nucleus [10].

In summary, we have measured \( \alpha \)-particle energy spectra in coincidence with the evaporation residues. The \( \alpha \)-particles are emitted from an equilibrated compound nucleus as evidenced from the angular distributions and the velocity diagrams. The measured energy spectra are underpredicted by the statistical model calculations with spherical compound nuclear configuration. However, a satisfactory description of the measured energy spectra has been achieved by invoking a deformed configuration of the compound nucleus through the modification of the radius parameter \( r_0 \). Thus, it may be concluded that the evaporation spectra of \( \alpha \)-particles from light compound nuclear systems, such as \( ^{31}\text{P} \), can be satisfactorily reproduced by introducing only an effective deformation in the exit channel through the modification of the radius parameter. Further experiments may be needed to confirm this finding in other light nuclear systems in the range \( A \leq 60 \).
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FIG. 1. Centre-of-mass angular distribution, $d\sigma/d\theta$. The dashed line correspond to fissionlike angular distribution ($d\sigma/d\Omega \sim 1/\sin\theta_{\text{c.m.}}$) fits to the data.

FIG. 2. Average velocities of the $\alpha$-particles as a function of velocities parallel ($v_\parallel$) and perpendicular ($v_\perp$) to the beam direction. The arrow indicates the velocity of the compound nucleus.

FIG. 3. Exclusive (filled circles) $\alpha$-particle energy spectra in centre-of-mass frame measured at different laboratory angles. Curves are the prediction of CASCADE calculations with the default (solid curves) and the modified (dashed curves) values of the radius parameter, $r_0$ (see text).