Exclusive light particle measurements for the system ^{19}F+^{12}C at 96 MeV

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Decay sequence of the hot ^{31}P nucleus has been investigated through exclusive light charged particle measurements using the reaction ^{19}F(96 MeV)+^{12}C. Information on the sequential decay chain has been extracted through comparison of the experimental data with the predictions of the statistical model. It is observed from the present analysis that exclusive light charged particle data may be used as a powerful tool to probe the decay sequence of hot light compound systems.

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In recent years, the evaporation of light charged particles has been proved to be a powerful tool to probe deeply into the statistical properties of hot rotating nuclei (see, for example, [1–15] and references therein). The relevant information is usually extracted through comparative analysis of the experimental data in the framework of statistical model. So far as the earlier measurements are concerned, most of them were inclusive in nature. However, in some cases, light charged particles have been measured in coincidence with all evaporation residues (ER) together. These measurements led to a good understanding of the gross statistical properties and deformation aspects of the compound nuclei. Very recently, there have been a few attempts [6–8,13–15] to measure light charged particles in coincidence with individual evaporation residues to probe the finer details of the reaction meachanism. Such studies may enable one to explore the evaporation decay cascade of the compound nucleus. Moreover, the contributions from other nonevaporative (i.e., fissionlike, preequilibrium) decay channels may also be estimated from such measurement. Here, we report an exclusive measurement of light charged particles emitted in coincidence with individual evaporation residues of hot ^{31}P nucleus produced in the ^{19}F(96 MeV)+^{12}C reaction and show that such exclusive data may provide important clues to reveal the intricacies of the decay cascade.

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 125-μg/cm^2 self-supporting ^{12}C target. The beam current was typically 20–80 nA. The light charged particle energy spectra were measured at various laboratory angles in coincidence with the evaporation residues. The evaporation residues formed in the reaction have been detected at the laboratory angle $\theta_{lab}=15°$ by a gas ΔE and silicon E (thickness $\sim$300 μm) telescope. The gas ΔE detector used in the experiment was an axial ionization chamber of continuous flow type [16]. P10 gas (90% Ar +10% CH_4) was used at 80$\pm$1 torr. A thin polypropylene foil of thickness 1.5 μm was used as the window of the gas section. The solid angle subtended by the detector was 1.3 msr. The light charged particles have been detected in three solid state telescopes. The telescopes were of two elements consisting of 100-μm, 45-μm, 40-μm ΔE Si(SB) and 5-mm, 5-mm, 2-mm Si(Li) E detectors, respectively. Typical solid angles were 1.5 msr, same for all the three telescopes. Analog signals from the detectors were processed using the standard electronics and the data were collected on event-by-event basis using an on-line CAMAC based multiparameter data acquisition system. The gas telescope was calibrated using the elastically scattered F ions from C and Bi targets. The light charged particle telescopes were calibrated with ^{228}Th α source. Absolute energy calibrations were done using standard kinematics and considering energy loss calculations.

Inclusive energy distributions of the fragments Mg, Na, and Ne at the laboratory angle of 15° are displayed in Fig. 1. The predictions of the statistical model calculations using the code LILITA [17] (the solid histograms) are found to be in good agreement with the experimental data (filled circles). The centroids of the distributions also lie close to the energies corresponding to the fragment velocity $v_{cn}\cos\theta_{lab}$, where v_{cn} is the compound nucleus velocity and θ_{lab} is the laboratory angle of the fragment detector. The inclusive distributions indicate that Mg, Na, and Ne are dominantly evaporation residues.

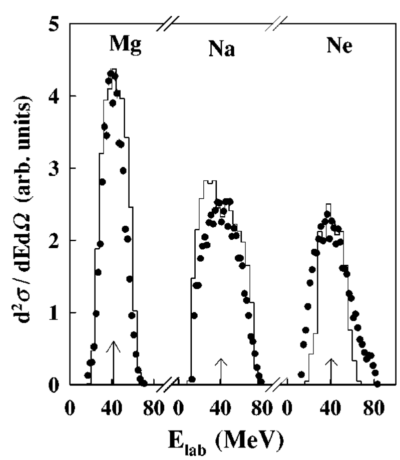

FIG. 1. Inclusive (filled circles) energy spectra for Mg, Na, and Ne at $\theta_{lab}=15°$. The solid histograms are the statistical model predictions (using code LILITA) and the solid arrows indicate the energy corresponding to $v_{cn}\cos(\theta_{lab})$.

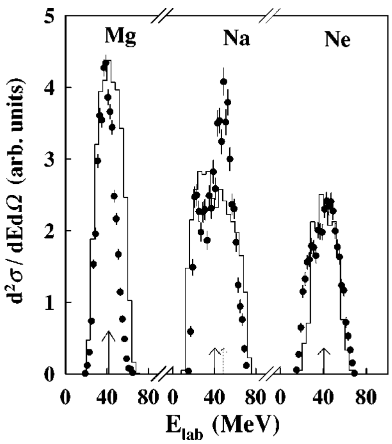

FIG. 2. Exclusive (filled circles) energy spectra for Mg, Na, and Ne at $\theta_{lab}=15°$. The solid histograms are the statistical model predictions (using code LILITA) and the solid and dashed arrows indicate the energy corresponding to $v_{cn}\cos(\theta_{lab})$ and the expected fission fragment kinetic energies.

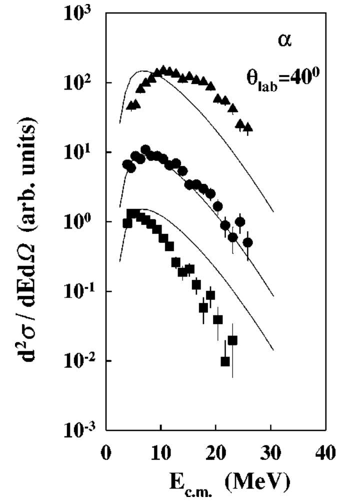

FIG. 3. Energy distributions of α particles measured in coincidence with Mg (filled triangles), Na (filled circles), and Ne (filled squares) at $\theta_{lab}=40°$. Solid lines are the predictions of code CASCADE for the summed evaporation spectra in ^{19}F(96 MeV) $+^{12}$C reaction.

Exclusive energy distributions of the fragments Mg, Na, and Ne, measured in coincidence with the light charged particles, are displayed in Fig. 2. The exclusive energy distributions of Mg and Ne are seen to follow the statistical model predictions (solid histograms), implying that the light charged particles measured in coincidence with Mg and Ne are emitted through fusion-evaporation channel, in the successive decay of ^{31}P compound nucleus. The solid arrows show the energies corresponding to the fragment velocity $v_{cn}\cos\theta_{lab}$. However, in case of Na, two peaks are seen in the energy distribution. Apart from the evaporation residue peak (at lower energy; solid arrow in the figure), the peak at higher energy may originate from some binary fragmentation channel. In the present case, the energy of the second peak is found to match with the respective fragment energy in the binary channel $^{31}P\rightarrow^{23}Na+^{8}Be$, as calculated from Viola systematics (the dashed arrow) [18]. Such particle unstable (^{8}Be) binary decay channel was also conjectured from inclusive measurements of the residue velocity distributions at very forward angles [19]. The unstable fragment ^{8}Be decays into two α particles, and contributes to the α-emission spectra. The presence of such binary channels in light particle emission spectra has been reported in the literature [6].

Some interesting features have been observed in the shape of the α-particle spectra (Fig. 3) obtained in coincidence with different evaporation residues. Filled triangles, circles, and squares correspond to the α-particle spectra measured in coincidence with Mg, Na, and Ne residues, respectively. The solid lines represent the theoretical predictions of CASCADE [20] for the summed evaporation spectra of α particles. A deformed configuration of the compound nucleus, represented by an optimum value of the radius parameter (r_0 $\sim$1.56 fm) [1,12], was used in the present calculation. It has been shown earlier that, statistical model predictions using the above configuration were quite successful in explaining the α-particle spectra measured in coincidence with all evaporation residues for the same reaction under consideration [12]. However, the same prescription fails to explain the observed α-particle spectra in coincidence with individual evaporation residues as evident from Fig. 3. It is indicative of the fact that the α particles follow some specific decay path to populate a particular evaporation residue and the path is different as one goes from one residue to another. Thus, the study of light particle spectra in coincidence with individual residues is likely to reveal some interesting details of the compound nuclear decay sequence.

In order to understand the shapes of the exclusive α-particle spectra observed in coincidence with the residue Mg, we have calculated the α-particle evaporation spectra from each possible stage of the decay cascade to populate Mg. The possible parent nuclei that may emit α particles to populate Mg are ^{31}P, ^{30}P, ^{30}Si, and ^{29}Si. The measured

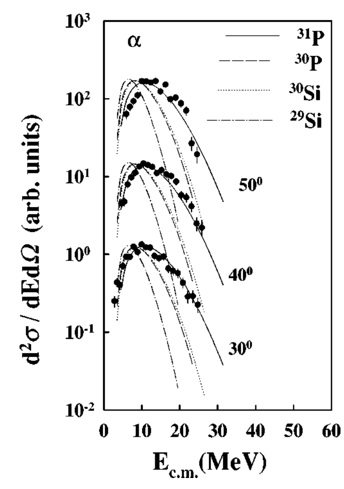

FIG. 4. Energy distributions of α particles measured in coincidence with Mg at different laboratory angles. Different curves are the statistical model predictions using code CASCADE for the emission of α particles from different nuclei in the decay chain (see text).

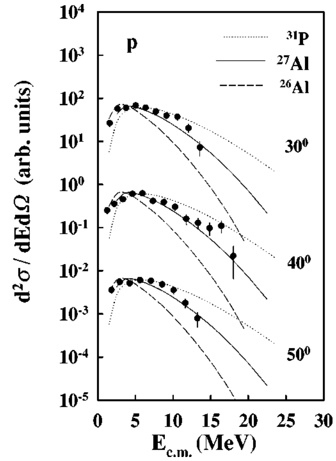

FIG. 5. Same as Fig. 4 for protons.

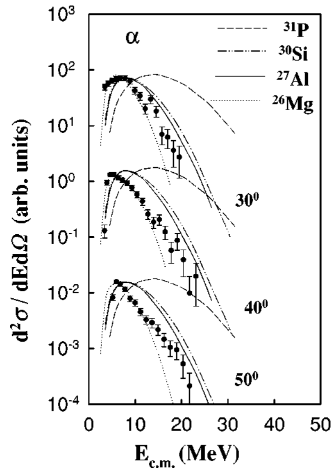

FIG. 7. Same as Fig. 4 for α-particles in coincidence with Ne.

α-particle spectra (filled circles) in coincidence with Mg for different laboratory angles have been displayed in Fig. 4 along with the respective theoretical predictions. The solid, dashed, dotted, and dash-dotted lines correspond to the theoretical α-particle spectra obtained from the CASCADE calculations for the decay of ^{31}P, ^{30}P, ^{30}Si, and ^{29}Si nuclei, respectively. From the figure, it is observed that the shapes of the experimental spectra are in fair agreement with the spectra obtained for the first chance emission from ^{31}P nucleus. It indicates that α particles detected in coincidence with Mg are dominantly from the first stage decay of ^{31}P nucleus.

This is further supported by the proton spectra measured in coincidence with Mg as shown in Fig. 5. The possible parent nuclei that may emit protons (either preceeded or followed by one α-emission) to populate Mg are ^{31}P, ^{27}Al, and ^{26}Al. The experimental proton spectra (filled circles) along with the CASCADE predictions for proton emission from ^{31}P (dotted lines), ^{27}Al (solid lines), and ^{26}Al (short dashed lines) are displayed in Fig. 5. It is seen from the figure that the shapes of the experimental proton energy distributions match well with those of theoretical predictions for the case of proton emission from ^{27}Al. Hence, from the analyses of exclusive proton and α-particle spectra measured in coincidence with Mg, it may be inferred that Mg may have been populated in the decay of ^{31}P nucleus predominantly through a first stage α emission from ^{31}P, followed by one proton emission.

It has been observed earlier [21] that the emission of light charged particles with $Z=1$ (i.e., proton, deuteron, and triton) in coincidence with Na is very much inhibited, which may indicate that Na is populated predominantly through the sequential α decay of the compound nucleus. Figure 6 shows the α-particle energy spectra at various laboratory angles in coincidence with Na. The solid and dashed lines correspond to the CASCADE predictions for the α-particle emissions from ^{31}P and ^{27}Al, respectively. It is apparent from the shapes of the spectra that there may be contributions from both the stages of the decay.

It is observed from Fig. 3 that the α-particle spectra in coincidence with Ne are much squeezed in energy, indicating that these α particles may be emitted from a relatively colder nuclei. Figure 7 shows α-particle spectra (filled circles) observed at different laboratory angles in coincidence with Ne. In the figure, the short dashed, dash-dot-dashed, solid and dotted lines correspond to respective CASCADE calculations for the emission of α particles from ^{31}P, ^{30}Si, ^{27}Al, and

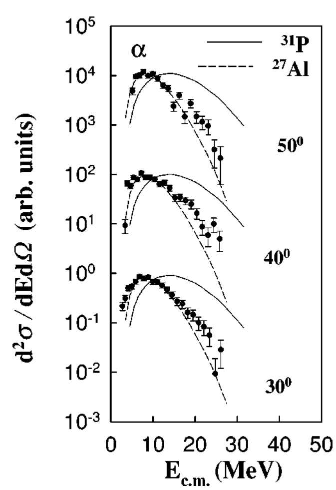

FIG. 6. Same as Fig. 4 for α particles in coincidence with Na.

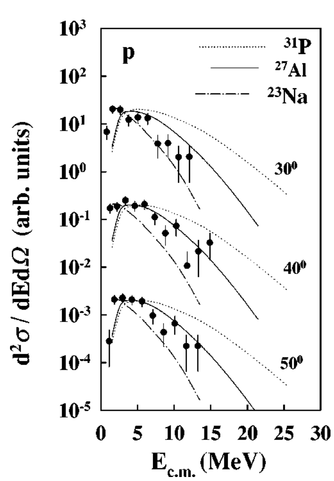

FIG. 8. Same as Fig. 4 for protons in coincidence with Ne.

^{26}Mg nuclei, respectively. The slopes of the lower energy side of the α-particle spectra are found to be in fair agreement with the respective theoretical predictions assuming the emission from ^{26}Mg nucleus. In addition, there is a high energy tail in the observed spectra, which may be due to a combination of contributions from other stages of decay as well. This is further elucidated by the proton spectra observed in coincidence with Ne as displayed in Fig. 8. The dotted, solid, and dash-dot-dashed lines in Fig. 8 correspond to the predictions of CASCADE calculations from ^{31}P, ^{27}Al, and ^{23}Na nuclei, respectively. From the figure it is apparent that the proton spectra may correspond to the emissions from both ^{27}Al and ^{23}Na nuclei. Thus, combining the anlyses of the proton and α-particle spectra, it is possible to conjecture the decay path, at least partially, in this case that may be as follows; from ^{27}Al, it may either emit a proton to reach ^{26}Mg, which then decays by α emission to populate Ne. Alternatively, it may emit an α particle to reach ^{23}Na, which thereby emits a proton to populate Ne. From Figs. 7 and 8, it is apparent that the former sequence is more dominant. However, in this case the picture is not complete, as from the above figures it is not quite clear how the system evolved from ^{31}P to ^{27}Al. More detailed experiments (e.g., ER-particle-particle coincidence measurements) may throw more light on the complete decay sequence.

To conclude, some interesting features in the shapes of the exclusive light charged particle spectra have been observed in the decay of ^{31}P nucleus, which may be correlated in a qualitative manner with the decay chain of hot ^{31}P. It may be inferred from the α-particle and proton spectra observed in coincidence with Mg that the decay sequence in this case is predominantly through a first chance α emission followed by a proton emission. Similarly, in case of Na, where proton emission is very much inhibited, it may be inferred that Na has been populated preferentially by sequential emission of two α particles from ^{31}P nucleus. For the Ne residue, the corresponding α-particle spectra may have contributions from different stages of the decay. Disentanglement of the exact decay sequence is more complicated in this case. More elaborate and exhaustive experiments are required to explore the decay chain completely.

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