Dissipative collisions in $^{16}\text{O} + ^{27}\text{Al}$ at $E_{\text{lab}}=116$ MeV

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Abstract

The inclusive energy distributions of fragments ($3 \leq Z \leq 7$) emitted in the reaction $^{16}\text{O} + ^{27}\text{Al}$ at $E_{\text{lab}}=116$ MeV have been measured in the angular range $\theta_{\text{lab}}=15^\circ - 115^\circ$. A non-linear optimisation procedure using multiple Gaussian distribution functions has been proposed to extract the fusion-fission and deep inelastic components of the fragment emission from the experimental data. The angular distributions of the fragments, thus obtained, from the deep inelastic component are found to fall off faster than those from the fusion-fission component, indicating shorter life times of the emitting di-nuclear systems. The life times of the intermediate di-nuclear configurations have been estimated using a diffractive Regge-pole model. The life times thus extracted ($\sim 1 - 5 \times 10^{-22}$ Sec.) are found to decrease with the increase in the fragment charge. Optimum Q-values are also found to increase with increasing charge transfer i.e. with the decrease in fragment charge.

25.70 Jj, 24.60 Dr, 25.70 Gh

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The phenomenon of fragment emission in light heavy-ion collision at energies $\leq 10$ MeV/u has evolved a lot of interest in recent years ([1] and references therein). The origin of these fragments extends from quasi-elastic (QE)/projectile-breakup [2,3], deep inelastic (DI) transfer and orbiting [4–10], to fusion-fission (FF) [1,10–15] processes and in some cases the structure of the nuclei has been found to play an important role. The distinction between different reaction mechanisms, in general, and the DI and FF processes, in particular, is very difficult for light system ($A_{cn} \leq 40$) [1,10] as in these cases there is strong overlap in the elemental distributions of the fragment emitted in the two processes. The DI components are characterised by large energy damping and the fully damped yields, in general, correspond to FF components. The energy damping observed in DI processes is due to the manifestation of nuclear viscosity. Thus, by a systematic study of DI fragments it is possible to extract information on the nuclear viscosity parameters which are important for understanding nuclear fission dynamics. This is usually accomplished by studying the systematics of optimum Q values vs. mass transfer and angle of rotation of the dinuclear complex. Thus, it is very much essential to decipher the data to extract the contribution of each component (e.g. DI, FF) present in the fragment emission spectra, in order to understand the underlying reaction dynamics.

Several studies made earlier for $^{16}$O + $^{27}$Al system at incident energies in the range of $\sim 60 – 100$ MeV have indicated that fragments emitted in the reaction are mainly originating from cluster transfer [16], projectile sequential breakup [3] and multi-nucleon transfer [7–9] processes. The role of direct two-body and three-body projectile breakup in fragment emission from $^{16}$O + $^{27}$Al reaction in the energy range of $\sim 70 – 125$ MeV have also been investigated recently [3]. However, none of the earlier workers did attempt to estimate the contribution of fusion-fission as a competing process for fragment emission in $^{16}$O + $^{27}$Al reaction. It is well established, both theoretically [10,17] and experimentally (e.g. [1]), that for systems lying below the Businaro-Gallone point, asymmetric fission of the compound nucleus (CN) contributes significantly in the fragment emission scenario. In the present work we have studied the fragment emission spectra from the reaction $^{16}$O + $^{27}$Al at $E_{lab} = 116$ MeV and report here, for the first time, a simple prescription to extract the FF and the DI components of the fragments yield following the decay of light composite systems ($A_{cn} \leq 43$).

The experiment was performed using 116 MeV $^{16}$O$^{5+}$ ion beam from the Variable Energy Cyclotron at Kolkata, which was recently upgraded with electron cyclotron resonance (ECR) heavy ion source. The target used was 420 $\mu$g/cm$^2$ self-supporting $^{27}$Al. The fragments were detected using three solid state(Si(SB)) telescopes ($\sim 12\mu m$ $\Delta$E, $300\mu m$ $E$) mounted in one arm of the 91.5 cm scattering chamber. Typical solid angle subtended by each detector was $\sim 0.3$ msr. A monitor detector ($\sim 300\mu$ Si(SB)) was placed in the other arm of the scattering chamber for normalisation purpose. The telescopes were calibrated using elastically scattered $^{16}$O ion from Au target and $\alpha$-particle from (Th-\(\alpha\)) source. Typical energy resolution obtained for the elastic $^{16}$O peak was $\sim 375$ keV.

Inclusive energy distributions for various fragments ($3 \leq Z \leq 7$) were measured in the angular range 15$^\circ$–115$^\circ$. The energy spectra of the emitted fragments ($3 \leq Z \leq 7$) have been shown in fig. 1 for $\theta_{lab} = 20^\circ$. The systematic errors in the data, arising from the uncertainties in the measurements of solid angle, target thickness and the calibration of current digitizer have been estimated to be $\approx 10\%$.

It is evident from Fig. 1 that the shapes of the energy spectra of heavier fragments (viz.
C, N) are quite different from those of the lighter fragments viz, Li and Be. It is mainly due to variation of relative contributions of DI and FF processes for different fragments. We adopt the following prescription for the estimation of FF, DI components present in the spectra. The energy spectra of different fragments at each angle have been fitted with two Gaussian functions in the following way. In the first step, the FF contributions have been obtained by fitting the energy distributions with a Gaussian having centroid at the energies obtained from Viola systematics \[18,19\] of total kinetic energies(TKE) of mass-symmetric fission fragments duly corrected for asymmetric factor \[20\]. The width of the Gaussian was obtained by fitting the lower energy tail of the spectra, assuming it to be originating from purely FF process. The FF component of the energy spectrum thus obtained is then substracted from the full energy spectrum. In the next step, the DI component is obtained by fitting the substracted energy spectra with a second Gaussian. The above procedure is illustrated in Fig. 1 for the fragments ranging from Li to N at 20°. The dotted line in Fig. 1 shows the contribution of FF component and the dashed dotted line shows the contribution of DI component. The solid line shows the sum total contribution of both FF and DI components. In each spectrum the arrow at lower energy corresponds to the centroid of the Gaussian for the FF component obtained from Viola systematics and the arrow at higher energy corresponds to the centroid of the Gaussian for the DI component.

The FF and the DI components of the fragment angular distributions have been obtained by integrating the respective energy distributions obtained in the manner discussed above. The centre of mass (c.m.) angular distributions of FF components of the fragments (3≤Z≤6) have been displayed as a function of c.m. angle \(\theta_{c.m.}\) in Fig. 3 (left). The transformation from the laboratory system to the c.m. system has been done with the assumption of a two body kinematics averaged over the whole range of c.m. angles. The solid lines correspond to 1/sin\(\theta_{c.m.}\) function. It is clear that the FF angular distributions for different fragments follow the 1/sin\(\theta_{c.m.}\) type of dependence, which is characteristic of the decay of a fully equilibrated system (fusion-fission of compound nucleus and/or orbiting dinuclear system). Total elemental yield of FF component of the fragment emission cross-sections has been compared with the theoretical estimates of the same obtained from the Extended Hauser-Feshbach Method (EHFM) \[12,20\]. The EHFM calculations have been performed by using a critical angular momentum value of \(l_{crit} = 34\hbar\) and a neck parameter consistent with the systematics given in ref. \[20\]. The calculated fragment emission cross-sections are shown in Fig. 3(a) as solid histogram and compared with the experimental estimates of the same (filled circles). It is seen from the figure that the theoretical predictions are in fair agreement with the experimental results. Therefore, it may be inferred that the extraction of the FF component of the fragment spectra following the prescription described above, (using the Gaussian with centroid given by the Viola systematics) is quite successful.

The c.m. angular distributions of DI components of the fragments (3≤Z≤6) have been displayed as a function of c.m. angle \(\theta_{c.m.}\) in Fig. 3 (right). A rapid fall of the angular distribution than predicted by 1/sin\(\theta_{c.m.}\) distribution indicates a shorter life time of the composite system. Such lifetimes are incompatible with the formation of an equilibrated compound nucleus, but may still reflect significant energy damping within a deep-inelastic mechanism. From the measured forward peaked angular distribution it is possible to estimate the life time of the intermediate di-nuclear complex using a diffractive Regge-pole model \[8,20\]. The angular distributions are fitted with the following expression...
\[ \frac{d\sigma}{d\Omega} = \left( C / \sin \theta_{\text{c.m.}} \right) (e^{-\theta_{\text{c.m.}}/\omega t}) \]  

and the fit to the DI component of the spectra is shown in Fig. 2(right). This expression describes the decay of a di-nucleus rotating with angular velocity \( \omega = \hbar l / \mu R^2 \) where \( \mu \) represents the reduced mass of the system, \( l \) its angular momentum (which should fall somewhere between grazing \( l_g \) and critical \( l_{cr} \) angular momentum), \( R \) represents the distance between the two centres of the di-nucleus and \( t \) is the time interval during which the two nuclei remain in a solid contact in the form of the rotating di-nucleus. Small values of the ‘life angle’ \( \alpha (= \omega t) \) lead to forward peaked angular distributions, associated with fast processes, whereas large values of \( \alpha \), associated with longer times as compared to the di-nucleus rotation period \( t(=2\pi/\omega) \), are consequently associated with long lived configurations and lead to more isotropic angular distributions. In the limiting case of very long-lived configurations, the distributions approach a \( \sigma/\Omega \propto 1 / \sin \theta_{\text{c.m.}} \) dependence. The time scales thus obtained are given in Table I for different fragment charge \( Z \). As found in a previous study by Mikumo et. al. \[8\] for the same reaction at 88 MeV, the time scales decrease as the fragment charges increase. This is expected because the heavier fragments (nearer to the projectile) require less number of nucleon transfer and therefore less time; on the other hand the emission of lighter fragments requires exchange of more number of nucleons and therefore longer times. Our quantitative analysis is consistent with a recent qualitative study of formation time in light heavy ion reactions \[21\].

In Fig. 4, the optimum Q values \(<Q>\) generated for FF and DI components of different fragments have been plotted as a function of fragment charge \( Z \) for a typical angle \( \theta_{\text{lab}}=20^\circ \). From the figure, it is observed that \(<Q>\) for FF fragments is more negative than for DI components and does not show much variation. This is due to the fact that for FF process, energy relaxation is complete and the system is fully equilibrated. The small variation in \(<Q>\) is due to the variation of mass asymmetry of the fragments. In case of DI component, the large variation in \(<Q>\) values is due to the different extent of energy damping corresponding to variation in the degree of mass transfer. Similar results have been observed at lower incident energies for the same reaction \[4,16,8,9\]. However, the \(<Q>\) for each fragment is much higher than those observed earlier \[8,9\] at lower projectile energies. Such energy dependence of \(<Q>\) may be due to long life time of the di-nuclear system.

The total fusion-fission (\( \sigma_{\text{FF}} \)) and the total deep-inelastic (\( \sigma_{\text{DI}} \)) cross-sections for different fragments have been obtained by integrating the energy distribution of fusion-fission component and DI component, respectively (as discussed earlier) over the corresponding energies and over the measured angles. The cross-section thus obtained for different fragments have been displayed in fig 3a and 3b respectively, as a function of fragments \( Z \). Total uncertainties in the estimation of \( \sigma_{\text{FF}} \) due to experimental threshold and the limited angular range of the data have been shown by the error - bars in Fig. 3. It has been found that a large fraction of C and N cross section is due to DI mechanism.

In conclusion we have measured the inclusive double differential cross-sections for fragments emitted in the reactions \(^{16}\text{O} + ^{27}\text{Al} \) at \( E_{\text{lab}} = 116 \text{ MeV} \). Total emission cross-sections for various fragments have been deduced from the double differential cross-section data. The shapes of the energy spectra of lighter fragments e.g. Li and Be, are quite different from those of the heavier fragments. This may be due to additional contributions of QE and DI components in the spectra of heavier fragments. It is observed that the angular
distribution of the FF component for different fragments follow the $1/\sin \theta_{c.m.}$ type of dependence, which is characteristic of the fission like (fusion-fission and/or orbiting) decay of an equilibrated compound nucleus. Moreover, the predicted fragment emission cross-sections using the Extended Hauser-Feshbach Method agree quite well with those coming from the FF component. However, the c.m. angular distributions of DI components do not follow $1/\sin \theta_{c.m.}$ type of dependence. The angular distributions of the DI components have been fitted using the function $(C/\sin \theta_{c.m.})(e^{-\theta_{c.m.}/\omega t})$ and the time scale for the emission of different fragments have been estimated. The emission time is found to decrease as the fragment charge increases which is expected to be true intuitively. The total fusion-fission ($\sigma_{FF}$) and deep-inelastic ($\sigma_{DI}$) cross-sections for different fragments have been obtained by integrating the energy distribution of fusion-fission component and DI component (as discussed in the text) over the corresponding energies and over the measured angles. Although a large fraction of C and N cross section is due to DI mechanism, the FF process is found to be rather competitive in the $^{16}$O + $^{27}$Al reaction, in agreement with the previous studies of the neighbouring $^{16}$O + $^{28}$Si system [10].

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FIG. 1. Energy spectra of different fragments obtained at 20° for the $^{16}\text{O}+^{27}\text{Al}$ reaction (solid lines). Dotted and dash-dot lines are the Gaussian fit to FF and DI components, respectively. Left and right arrows correspond to the centroids of FF and DI components, respectively.

FIG. 2. Centre of mass angular distributions of different fragments FF component (left) and DI component (right).
FIG. 3. Fusion- Fission Fragment emission cross-sections. Filled circles and solid lines correspond to the experimental and calculated results (EHFM), respectively.

FIG. 4. $<Q>$ value for FF and DI components of different fragments.
## TABLES

**TABLE I.** Life times of the dinuclear systems for different emitted fragments.

| Fragment | Li       | Be | B   | C  | N  |
|----------|----------|----|-----|----|----|
| Time     | (10^{-22} sec) | 4.7 | 3.5 | 1.9 | 1.1 | 0.8 |
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