Projectile structure effects in multi-nucleon and cluster transfers in $^{16,18}$O+$^{164}$Dy, $^{208}$Pb reactions

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Abstract: The yield of projectile like fragments (PLFs) has been measured in the reactions of $^{16,18}$O with $^{164}$Dy and $^{208}$Pb targets at energies above the Coulomb barrier. The experimental data are analyzed to ascertain the role of projectile structure on the multi-nucleon and cluster correlations in transfer reactions. The variation of transfer probability with the number of nucleons transferred from the projectile to the target nucleus at the grazing angle has been investigated for both the systems. In the case of $^{18}$O induced reactions the cross sections of the two neutron (2n) stripping as well as the 2n-correlated cluster transfer are strongly enhanced as compared to the $^{16}$O induced reactions. These results have been discussed on the basis of the possible influence of the valence di-neutrons in the $^{18}$O nucleus on multi-particle transfer reactions.

1. Introduction

Study of multi-nucleon transfer reactions got renewed interest due to the availability of the radioactive ion beams. Multi-nucleon transfer in heavy ion induced reactions provides information on the role of particle-particle correlations and possible formation of cluster states in nuclei. In the transfer reactions between two complex nuclei, there are possibilities of various reaction paths such as sequential transfer, cluster transfer and/or multi-nucleon exchange processes. The complex dependence of transfer probability on the projectile structure and ground-state Q-values of the reactions in multi-nucleon and cluster transfer reactions have been studied earlier [1–4]. The role of nuclear structure governing the reaction mechanism in heavy ion induced transfer and fusion reactions has been vigorously pursued. It is established that the cross section of the transfer channels decreases with the increase in the number of transferred nucleons, while the overall trend is independent of beam energy [5].

Corradi et al. [6] have measured the angular and Q-value distributions for a large variety of charge and mass partitions populated in the $^{40}$Ca+$^{124}$Sn reaction using a time-of-flight magnetic spectrometer. The experimental data on the cross sections and energy distributions are compared with the results of theoretical calculations based on the independent single-neutron transfer process. The two nucleon transfer reactions provide useful information on the pairing correlations in nuclei [7,8]. The pairing correlation effects in the multi-nucleon transfer processes have been investigated in the $^{62}$Ni + $^{208}$Pb system at energies near the Coulomb barrier [9]. In case of $^4$He induced reactions, the observed enhancement in the 2n-transfer cross section has been explained by treating the $^4$He nucleus as a $^4$He core and two valence neutrons as a ‘‘di-neutron’’ configuration outside the core [10–12]. The importance of the di-neutron configuration in the projectile nucleus for the fusion reactions has been studied earlier [13–15]. In a previous work, we have reported the evidence of di-neutron configuration in $^{16}$O projectile in the case of $^{16}$O+$^{144}$Yb reaction [16]. It has been observed that the presence of two valence neutrons in the $^{18}$O nucleus outside the $^{16}$O core strongly influence the multi-nucleon transfer process. The multi-nucleon transfer process for various target-projectile systems can provide crucial information on the nuclear structure effects in understanding the reaction mechanism. In the present work, we have studied the influence of pair correlations on the di-neutron configuration of $^{18}$O and the
role of target deformation on multi-nucleon transfer probabilities in $^{16}$O induced reactions with spherical ($^{208}$Pb) and deformed ($^{164}$Dy) targets.

2. Experimental details and data analysis
The experiment is performed at 14 UD BARC-TIFR Pelletron accelerator facility at Mumbai, India. Beams of $^{16}$O and $^{18}$O respectively bombarded the self-supporting target of $^{164}$Dy (1.2 mg/cm$^2$) at energies of 96 and 90 MeV. For $^{208}$Pb (1.0 mg/cm$^2$) target the experiment is performed at 96 MeV with both $^{16}$O and $^{18}$O projectiles. The reaction products are identified using three silicon $\Delta E$(25µm)-$E$(1mm) telescopes, mounted inside the general purpose scattering chamber. The angular distribution measurements are carried out in the angular range of 30$^\circ$ to 120$^\circ$. A collimator of 5.0 mm diameter is placed in front of each of the three silicon detector telescopes. Another silicon detector of 300 micron thickness is placed at a distance of 42 cm from the target at an angle of 20$^\circ$ with respect to beam direction to measure Rutherford scattering events. This detector with a collimator of 1.0 mm is for absolute normalization of the yields at various angles. The data at overlapping angles are taken for normalization of the solid angles for the silicon detector telescopes. The amplifier gains are adjusted such that the data from Z=2 to 8 could be recorded in a $\Delta E$-$E_{\text{res}}$ two-dimensional matrix for off-line analysis.

![Graph](image)

**Figure 1.** The $\Delta E$ versus $E_{\text{res}}$ correlation plot for $^{16}$O+$^{164}$Dy reaction at $\theta_{\text{lab}}$=70$^\circ$.

Fig.1 shows the $\Delta E$ versus $E_{\text{res}}$ correlation plot of PLFs at $\theta_{\text{lab}}$=70$^\circ$ in $^{16}$O+$^{164}$Dy reaction for 96 MeV bombarding energy. A reasonably good isotopic separation is observed for the PLFs as shown in Fig.1. In the present work the target-projectile systems are highly asymmetric and the excitation energy is carried predominantly by the heavier nucleus. Thus, the evaporation of particles from the PLFs is minimal before its detection. The measured yield of the PLFs, therefore, represents the primary yield of the reactions. The particle identification (PI) of the different isotopes is carried out using the following algorithm [5]:

$$PI = [(E+\Delta E)^b - E^b] = KM^{(b-1)/2}$$
where, K and b are constants. It is observed that best isotope separation for all the elements is achieved with values of b from 1.65 to 1.75. The particle identification spectrum is shown in Fig.2 in $^{16}$O+$^{164}$Dy reaction for 96 MeV at $\theta_{lab}$=70$^o$.

![Figure 2](image.png)

**Figure 2.** The particle identification (PI) spectrum for $^{16}$O+$^{164}$Dy reaction at 96 MeV.

The mass calibration has been checked from the elastically scattered particles in $^{16}$O and $^{18}$O induced reactions. A mass resolution, $\sigma(M)$ of 0.5 amu is achieved. The isotopic yields of different transfer products has been obtained from the Gaussian de-convolution of the mass distribution of different elements as shown in Fig.3 for $^{16,18}$O+$^{164}$Dy reactions. For both $^{164}$Dy and $^{208}$Pb targets, the dominant transfer channels are due to charge transfer, $\Delta Z =1$ and 2. The corresponding yields of nitrogen and carbon isotopes are significantly larger in comparison to other channels.

![Figure 3](image.png)

**Figure 3.** The PI spectrum for $^{16,18}$O+$^{164}$Dy reactions at energy, $E_{lab}$=96 MeV, showing isotopes of carbon, nitrogen and oxygen. Solid lines show the Gaussian fittings to the yield of various isotopes.
3. Results and discussions

The angular distributions of PLFs are shown in Fig.4. In general, the angular distributions are bell-shaped and the grazing angle corresponding to the maximum yield shifts towards the forward angle with the increase of the beam energy. From Fig. 4, it is observed that the grazing angle for $^{16}$O+$^{164}$Dy system is around 50° at 96 MeV and it is 65° at 90 MeV. The grazing angle is around 75° for $^{16}$O+$^{208}$Pb system at 96 MeV.

![Figure 4](image)

Figure 4. The differential cross-section of the dominant PLF channels in $^{16}$O+$^{164}$Dy, $^{208}$Pb reactions. Solid and dashed lines are smooth fits to the experimental data.

In order to obtain the quantitative information on the transfer mechanism, the transfer probabilities ($P_u$) have been calculated at the grazing angles. The value of $P_u$ is calculated by using the expression:

$$P_u = \frac{(d\sigma/d\Omega)_u}{(d\sigma/d\Omega)_R}$$

where, $(d\sigma/d\Omega)_u$ and $(d\sigma/d\Omega)_R$ are the transfer and the Rutherford elastic scattering cross sections respectively. In Fig.5 (a) and 5(b), the transfer probabilities as a function of number of transferred nucleons ($\Delta N$) at the grazing angle have been shown for $^{16}$O+$^{164}$Dy, $^{208}$Pb systems at 96 MeV. The experimental results for these inclusive transfer data suggest a dominance of a sequential mechanism in the transfer process. For both $^{16}$O+$^{164}$Dy, $^{208}$Pb systems, the yield of $^{15}$N channel corresponding to 1p transfer is significantly larger than the other nitrogen isotopes. In the case of $^{16}$O+$^{208}$Pb system, the yield of $^{14}$C (2p transfer) is significantly large in comparison to the other carbon isotopes, whereas, for $^{18}$O+$^{164}$Dy system the yield of $^{12}$C channel (2p2n or $\alpha$ transfer) is the dominant channel among all the isotopes of carbon. It is observed that in general, the transfer probabilities decrease exponentially with increasing $\Delta N$ for both the systems. However, for the case of $^{12}$C, corresponding to $\Delta N = 4$, there is strong enhancement in $P_u$ value. The enhancement in the transfer probability for $\Delta N = 4$, can be due to admixture of sequential multi-nucleon transfer as well as due to the direct $\alpha$ cluster transfer from the projectile to the target nucleus. This feature is more prominent in the case of $^{16}$O+$^{164}$Dy system in comparison to $^{16}$O+$^{208}$Pb system, which may be due to the large deformation of $^{164}$Dy nucleus in comparison to $^{208}$Pb nucleus.

The transfer probabilities as a function of number of transferred nucleons ($\Delta N$) at the grazing angles in $^{18}$O+$^{164}$Dy, $^{208}$Pb reactions are shown in Fig. 5(c) and 5(d). In comparison to $^{16}$O induced reactions, strong deviations are seen from the smooth behavior in the region $\Delta N = 2$ to 6 nucleon transfer channels in case of $^{18}$O induced reactions. However for both the targets, it is evident that the yield of 2n transfer ($^{16}$O channel) is significantly large in comparison the 1p+1n transfer ($^{15}$N) channel. Similar enhancement in the yield of 2n+1p ($^{13}$N channel) is observed as compared to $^{17}$N channel which corresponds to 1n transfer. Similarly for (2n+2p) transfer channel ($^{14}$C), there is a strong
enhancement and this is expected from a sequential as well as correlated $\alpha$-cluster transfer contribution of four nucleons from projectile to the target nucleus. The enhancement of 2n and 2n-correlated transfers in the reactions of $^{18}$O with $^{164}$Dy and $^{208}$Pb targets can be interpreted by considering $^{18}$O as $^{16}$O core with two valence neutrons outside the core in a “di-neutron” configuration. It seems that the 2n-correlated transfer in $^{18}$O and $^4$He induced transfer reactions are similar, even though the two neutron separation energy ($S_{2n}$) for $^4$He is 0.97 MeV, where as, it is 12.19 MeV in case of $^{18}$O. These results need further investigation to understand the transfer reaction mechanism.

![Figure 5](image)

**Figure 5.** Transfer probabilities, $P_T$ as a function of $\Delta N$ for $^{16}$O, $^{18}$O+$^{164}$Dy, $^{208}$Pb reactions at 96 MeV.

4. Summary and Conclusions

In summary, the role of the projectile structure in multi-nucleon transfer reactions has been investigated in the present work. It is found that the structure of the projectile nucleus has strong influence on the transfer of multi-nucleons and/or clusters from the projectile to the target nucleus. It is observed that the pairing correlations as di-neutron configuration in the heavy ion induced transfer reactions are important. A comparative study of the various multi-nucleon transfer probabilities show that in $^{18}$O + $^{164}$Dy, $^{208}$Pb reactions, the two neutron stripping and two neutron correlated cluster transfer are strongly enhanced as compared to the $^{16}$O induced reactions. This implies that the two valence neutrons in the $^{18}$O nucleus outside the $^{16}$O core exhibit the features of a loosely bound “di-neutron” configuration. Such configuration could in turn be also responsible for large enhancements in the 2n-correlated transfers in the $^{18}$O induced reactions, which may have important implications on the study of nuclear reactions with neutron-rich radioactive ion beams.

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