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Evidence of massive cluster transfers in $^{19}F+^{232}Th$ reaction at near barrier energies

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Yields and angular distributions of the transfer reaction products have been measured in the $^{19}F+^{232}Th$ reaction at bombarding energies near the Coulomb barrier. The transfer probabilities were calculated (P_{tr}) from the measured differential cross sections at the grazing angle, for the most dominant channels for given (ΔN) transfers. The values of P_{tr} show, in general, an exponential dependence on the ground state Q value (Q_0) of the reaction and the large cross sections observed for 1α and 2α transfer channels are largely accounted by the Q-value variations. However, the transfer channels of $\Delta N=5$, 9, and 12 leading to ^{14}C, ^{10}Be, and ^{7}Li products, respectively, show strong enhancements in the transfer probabilities. The large cross sections in these channels may imply simultaneous correlated transfers of (αp), $(\alpha p,\alpha)$, and (3α) clusters from the ^{19}F projectile to the target.

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In the reactions between two complex nuclei, simultaneous transfer of several nucleons commonly known as cluster or multinucleon transfer often occurs with a probability comparable to that of one nucleon transfer. Study of multinucleon transfer process is important from the point of understanding the role of particle correlations and possible formation of cluster states in nuclei. In heavy ion induced transfer reactions, a number of mechanisms of different complexity, viz., sequential transfer, cluster transfer, and multistep nucleon exchange, etc., can contribute to a given transition and the possibility of different reaction paths increases with the number of transferred nucleons. There have been a number of studies carried out in the past on the transfer reactions with a view to obtain information on the mechanism of the transfer process, which in many cases appears to be dominated by direct transfer of a correlated nucleon group [1–6]. In spite of considerable progress, the complex problem of multinucleon transfer has not yet been adequately solved and therefore, much of the nuclear structure information extracted so far from the data is still of a qualitative nature. A large amount of work has been reported on four-nucleon or α-particle transfer in order to establish the mechanism of the transfer process and to test relevant nuclear structure models involving α clustering in nuclei. The ($^{16}O,^{12}C$) reaction has been studied extensively on target nuclei upto $A=90$ and on targets in the $2s1d$ shell [7–13]. Study of ($^{16}O,^{8}Be$) and ($^{12}C,^{8}Be$) reactions are difficult because of technical problems of detecting the ^{8}Be nucleus [13–15]. Studies of transfer reactions on heavy targets show that sequential nucleon and α-cluster transfer are the dominant process in explaining the yields of various transfer products [3,4].

So far there have been no reported measurements of cluster transfers in ^{19}F induced reactions. In the present work we have studied the multinucleon and cluster transfer reactions in the $^{19}F+^{232}Th$ reaction. In such highly asymmetric systems the excitation energy is carried predominantly by the heavier nucleus and evaporation from the projectile-like particle (PLP) is minimal before its detection. The measured yield of the PLP's, therefore, represents the primary yield of the reactions.

The experiment was performed using the ^{19}F beam from the Bhabha Atomic Research Centre-Tata Institute of Fundamental Research 14UD Pelletron accelerator at Bombay. A self-supporting ^{232}Th target of 1.8 mg/cm^2 thickness was used for the experiment. The measurements were carried out at beam energies of 113.6, 106.5, 98.4, 95.2, and 92 MeV after the energy loss in the target foil. The projectile-like particles were measured in the angular range 40° to 150° by using two telescopes, each consisting of ΔE (17 μ) and E (500 μ) surface barrier detectors. The mass and charge identification of the different isotopes was carried out following the algorithm $[(E+\Delta E)^b-E^b]=KM^{(1-b)}Z^2$, where K and b are constants. It was observed that the best isotope separation for all elements is achieved with a value of $b=1.65$. The mass calibration was checked by measuring the elastically scattered ^{19}F and ^{16}O particles in both the telescopes in a separate experiment. A mass resolution $\sigma(M)$ of about 0.5 a.m.u. was achieved for all masses. The isotopic yields of different transfer products were obtained by Gaussian deconvolution of the mass distribution of different elements. The fluorine isotopes could not be separated because of the high counts of the elastic particles and hence the yield of $1n$ transfer channel has not been reported.

Figure 1 shows the angular distributions of different transfer products for the $^{19}F+^{232}Th$ reaction, measured at 113.6 MeV and 106.5 MeV. The distributions are in general bell shaped and gradually become broader with increasing nucleon transfer, suggesting an increase in the mean interaction time as the nucleon transfer increases. The oxygen, nitrogen, and carbon ejectiles are the most abundant transfer products produced in the reaction accounting for about 95% of the total transfer cross section at all bombarding energies. It was seen that as the beam energy is decreased, the peak of the angular distributions of various transfer products shifts toward larger angles and at near and below barrier energies, the distributions are backward peaked.

Detail isotopic yield measurements were carried out with the telescopes placed around the peak of the angular distri-

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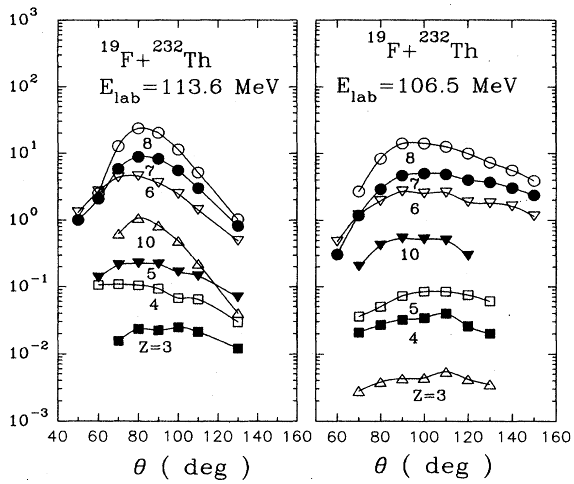

FIG. 1. Angular distribution of transfer reaction products at 113.6 MeV and 106.5 MeV in ^{19}F+^{232}Th reaction.

TABLE I. Transfer probability of various channels for different beam energies.

Transfer channel	Transfer probability (P_{tr}) 113.6 (MeV)	106.5 (MeV)	98.5 (MeV)	95.3 (MeV)	92.0 (MeV)
^{18}O	5.20e-2	6.69e-2	6.65e-2	6.76e-2	4.30e-2
^{17}O	2.20e-2	2.09e-2	2.00e-2	1.69e-2	1.08e-2
^{16}N	7.60e-3	8.89e-3	6.70e-3	5.63e-3	2.05e-3
^{15}N	1.93e-2	2.24e-2	1.70e-2	1.69e-2	8.21e-3
^{14}C	1.05e-2	1.33e-2	1.21e-2	1.10e-2	3.89e-3
^{13}C	2.10e-3	1.66e-3	1.16e-3	9.39e-4	6.86e-4
^{12}B	1.70e-4	1.58e-4	6.65e-5	2.8e-5	
^{11}B	4.91e-4	3.57e-4	1.70e-4	8.16e-5	
^{10}Be	2.4e-4	1.63e-4	6.13e-5	3.57e-5	
^{9}Be	6.05e-5	3.51e-5	1.85e-5	1.03e-5	
^{8}Li	1.81e-5	6.50e-6			
^{7}Li	5.03e-5	1.52e-5			

bution at all bombarding energies. For a given number of transferred nucleons (ΔN), many different isotopes contribute to the transfer channels. We consider here only the most abundant channel for a given ΔN. Figure 2 shows the cross section of the different transfer products as a function of number of transferred nucleons (ΔN). It is observed that, in general, the cross section decreases as the number of transferred nucleons increases. The yield of ^{18}O channel, corresponding to $\Delta N=1$, is maximum at all energies indicating that the last unpaired proton is easily stripped off from the projectile nucleus. It is also seen from the figure that there are strong enhancements in the cross section in the regions of $\Delta N=4$, 8, and 12 corresponding to 1α, 2α, and 3α transfers, respectively. This feature is observed to be common for all beam energies ranging from 92.0 MeV to 113.6 MeV.

In order to derive more quantitative information on the transfer mechanism, the cross-section data were transformed to transfer probability by using the the semiclassical formalism [16]. In this formalism for a given transfer, the probability is calculated using the expression

$$P_{tr}=\frac{(d\sigma/d\Omega)_{tr}}{(d\sigma/d\Omega)_{Ruth}} \quad (1)$$

where $(d\sigma/d\Omega)_{tr}$ and $(d\sigma/d\Omega)_{Ruth}$ are the transfer and Rutherford elastic cross sections, respectively. The values of P_{tr} calculated for different transfer channels are given in Table I and are also plotted in Fig 3 as a function of bombarding energy for different ΔN. The error in the P_{tr} values vary 5% to 10% depending on the cross section of the individual channels. It is observed that for small ΔN, the transfer probability does not significantly depend on beam energy except at below barrier energy, where it shows a drop. However for ΔN more than 5, the P_{tr} value decreases continuously with decrease of beam energy. This result may be understood in the following way. For large nucleon transfers,

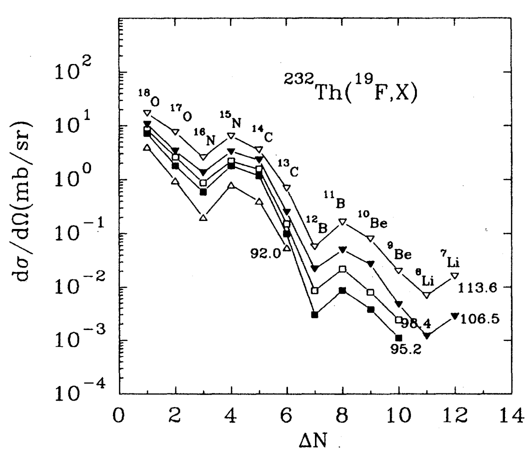

FIG. 2. Differential cross section of various transfer channels as a function of the number of transferred nucleons (ΔN) at the grazing angle for different bombarding energies.

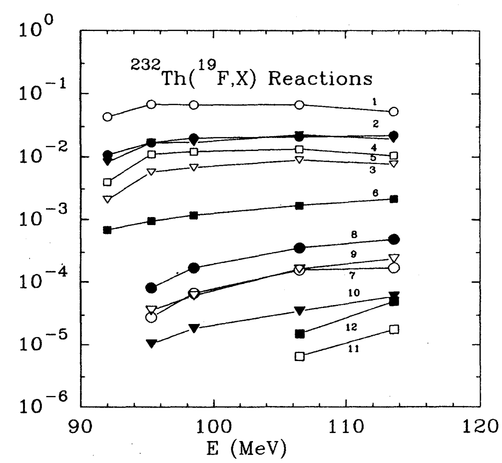

FIG. 3. Transfer probability (P_{tr}) as a function of beam energy for different ΔN (number of transferred nucleons).

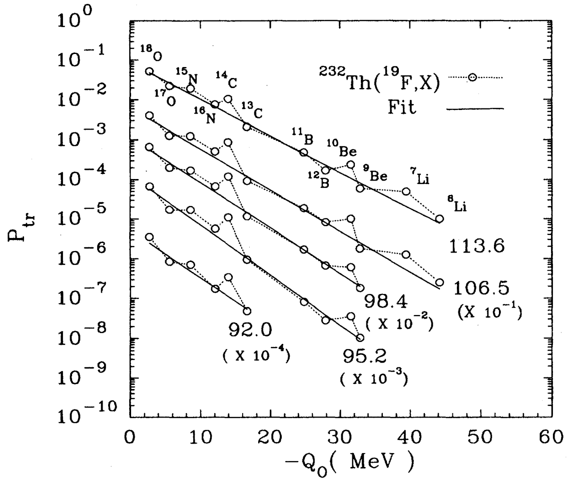

FIG. 4. Variation of transfer probability on the ground state Q value $(-Q_0)$. The solid lines are the exponential fit to the data.

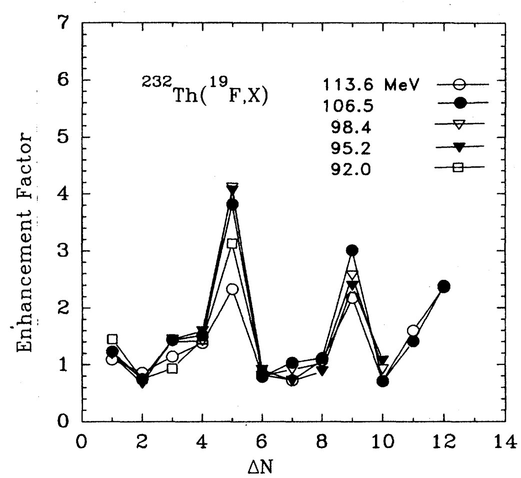

FIG. 5. Enhancement factor as a function of number of nucleons transferred in ^{19}F+^{232}Th reaction at various bombarding energies.

the projectile and target are required to have a large nuclear overlap, and with decreasing beam energy, the probability of large nuclear overlaps decreases. One may also try to understand the P_{tr} values of the multinucleon transfer channels, by calculating the probabilities for sequential transfer of nucleons and clusters. The large cross section observed for the ^{15}N channel implies large α-cluster transfer probabilities from the projectile to target in this reaction. Assuming the transfer probabilities for proton and α-cluster transfers (as given in the table), the probability for sequential transfer of an alpha particle and a proton from the projectile to the target nucleus works out to be about $\approx 10^{-3}$, which is an order of magnitude smaller than the transfer probability derived for the ^{14}C channel corresponding to $\Delta N=5$ (αp) transfer. The large enhancement observed in P_{tr} for ^{14}C channel, therefore implies correlated transfer (αp cluster) of a proton and α particle from the projectile to the target nucleus. The enhancement in the cross section for ^{11}B and ^{10}Be channels can, in turn be explained in terms of sequential transfers of two α clusters and $(\alpha p, \alpha)$ clusters, respectively. The yield of ^{7}Li channel (^{12}C transfer) is however, seen to be again very much enhanced in comparison to sequential transfer of 3α clusters.

Since the transfer probability, P_{tr} is known to depend strongly on the ground state Q value (Q_0) of the reaction we have tried to systematize the observed P_{tr} values with respect to the Q value of the reaction. Figure 4 shows the variation of P_{tr} with Q_0 for all the beam energies. It is seen that, P_{tr} has much smoother dependence on the Q value and the enhancement in cross section seen in Fig. 3 for 1α and 2α transfer channels can be largely accounted by the Q value variations. The large cross section in these channels is mainly because of the Q value favoring in these reactions. The P_{tr} data were fitted with a smooth exponential function $P_{tr}=Ke^{-Q_0/T}$ as shown by the solid lines in Fig. 4. The slope of the exponential is seen to vary from 4.675 to 3.645 MeV, as one goes from the highest to the lowest bombarding energy of the experiment. Pagano *et al.* [17], in their earlier work on ^{16}O+^{238}U reaction, have tried to explain the transfer cross sections in terms of the separation energy $(Q_{g.s.o.})$ of the transfer product from the projectile nucleus, and obtained the value of slope parameter $T=8.2$ MeV interpreting it as mean nucleon binding energy in the nuclear matter. In the present work, however, we do not find smooth dependence of the reaction cross section on separation energy.

It is seen from Fig. 4 that although, in general, the transfer probability decreases exponentially with increasing Q value, there are still some enhancements seen for $\Delta N=5$, 9, and 12. This fact is brought out more clearly in Fig. 5, where an enhancement factor, defined as

$$\text{enhancement factor}=\frac{P_{tr}}{[Ke^{-Q_0/T}]_{\text{fit}}} \qquad (2)$$

is plotted as a function of the number of transferred nucleons. It is observed that the enhancement is present at all the bombarding energies for multinucleon transfer channels corresponding to $\Delta N=5$, 9, and 12. The strong enhancements for the above massive cluster transfer channels may be ascribed to the structure of the ^{19}F projectile, where an odd unpaired proton exists and also there is large α clustering probability in the nucleus.

In summary, we have measured the cross sections of different transfer channels in the ^{19}F+^{232}Th reaction at various bombarding energies around the Coulomb barrier. Large yields are observed for multinucleon transfer channels at all energies. The transfer probabilities derived from the cross-section data show, in general, a smooth dependence on the ground state Q value of the reaction channel. However, there are strong enhancements seen in $\Delta N=5$, 9, and 12 channels, corresponding to (αp), $(\alpha p,\alpha)$, and (3α) transfers, which point out to the possibility of correlated cluster and nucleon transfers from the projectile to the target nucleus in this system.

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