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Measurement of multinucleon transfer cross-sections in ^{58}Ni,^{56}Fe(^{12}C, x); x: ^{13,11}C, ^{11,10}B, ^{10,9,7}Be, ^{8}Be$_{g.s.}$ and ^{7,6}Li at $E(^{12}\mathrm{C}) = 60$ MeV

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Abstract. Cross-sections for one- and multinucleon transfer reactions, namely, ^{58}Ni(^{12}C, ^{13}C), ^{58}Ni(^{12}C, ^{11}C), ^{58}Ni(^{12}C, ^{11}B), ^{58}Ni(^{12}C, ^{10}B), ^{58}Ni(^{12}C, ^{10}Be), ^{58}Ni(^{12}C, ^{9}Be), ^{58}Ni(^{12}C, ^{8}Be$_{g.s.}$), ^{58}Ni(^{12}C, ^{7}Be), ^{58}Ni(^{12}C, ^{7}Li) and ^{58}Ni(^{12}C, ^{6}Li) have been measured at an incident energy of 60 MeV. The reaction cross-section for the corresponding transfer channels in the system ^{12}C+^{56}Fe have also been measured under the same kinematical conditions. Angular distribution of the elastic scattering cross-section is measured at 60 MeV. The measured elastic scattering angular distributions for these two systems have been analysed using the optical model search code SFRESCO and the potential parameters are extracted. The multinucleon transfer data are analysed to obtain cross-section dependence on the number of nucleons transferred and on the ground state Q-values. The transfer probabilities for multinucleon stripping are extracted. A detailed comparison in the multiparticle stripping and elastic scattering cross-sections between these two systems are made to understand the mechanism of multinucleon transfer and possible role of two extra protons in ^{58}Ni target nucleus as compared to the ^{56}Fe core.

Keywords. Nuclear reactions ^{58}Ni(^{12}C, x), ^{56}Fe(^{12}C, x), x =^{13}C, ^{11}C, ^{11}B, ^{10}B, ^{10}Be, ^{9}Be, ^{8}Be$_{g.s.}$, ^{7}Be, ^{7}Li, ^{6}Li; $E = 60$ MeV; measured reaction cross-section; elastic scattering angular distribution; deduced transfer probabilities and enhancement factors.

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1. Introduction

In heavy-ion-induced multinucleon transfer reactions, a number of mechanisms having different complexities, e.g., cluster transfer, sequential transfer etc., can contribute to a given transfer reaction. Measurement of such multinucleon transfer cross-sections may provide insight into the underlying peripheral reaction processes. In spite of considerable progress, the reaction mechanism of multinucleon transfer and its effect on other channels are not so well understood. The cross-section for multinucleon transfer around and above the Coulomb barrier is found to be enhanced in many cases in comparison to what is expected for successive non-correlated transfer of nucleons. In a semiclassical description, the cross-section for the transfer of N nucleons can be written as [1,2] $(\mathrm{d}\sigma/\mathrm{d}\Omega)_{\mathrm{tr}} = P_N \times (\mathrm{d}\sigma/\mathrm{d}\Omega)_{\mathrm{el}}$, where $(\mathrm{d}\sigma/\mathrm{d}\Omega)_{\mathrm{tr}}$ and $(\mathrm{d}\sigma/\mathrm{d}\Omega)_{\mathrm{el}}$ are the transfer and elastic scattering cross-sections, respectively. The probability of N nucleon transfer, P_N, would be equal to $P_N = (P_1)^N$ inclination for uncorrelated transfer. Deviation from this value would be a simple measure of clustering/correlation amongst nucleons.

With a motivation to understand the reaction mechanism aspects, we have made a systematic study of multinucleon transfer in different projectile–target combinations [3–8]. In one of our previous work [8] on the multinucleon transfer reactions in ^{90}Zr(^{18}O, x) and ^{90}Zr(^{16}O, x), the role of two extra valence neutrons in the projectile ^{18}O compared to the ^{16}O core was investigated. The present communication reports our recent measurement on multinucleon transfer reactions in the $^{12}\mathrm{C}+{}^{58}\mathrm{Ni}$ and $^{12}\mathrm{C}+{}^{56}\mathrm{Fe}$ systems at an incident ^{12}C energy of 60 MeV under the same kinematical conditions. In these two systems, the projectile (^{12}C) is the same, but the target nucleus ^{58}Ni has two additional protons compared to ^{56}Fe. Both ^{56}Fe and ^{58}Ni nuclei are close to the doubly closed shell ($Z = 28$, $N = 28$) with ^{58}Ni being the proton shell closed nucleus. A detailed comparison between these two systems in the elastic and multinucleon transfer channels would indicate the possible effect of two extra protons in the target.

2. Experimental procedure

The measurements were carried out at the Inter University Accelerator Centre, New Delhi. The ^{12}C beams of 60 and 45 MeV energy were used and the targets were self-supporting and isotopically-enriched ^{58}Ni ($\sim$99%) and ^{56}Fe ($>$99%) of 495 and 170 μg/cm^2 thickness, respectively. Projectile-like fragments (PLF) were detected using silicon surface barrier detector telescopes in $\Delta E - E$ configuration ($\Delta E = 30$ μm and $E = 300$ μm) mounted on two movable arms inside a 1.5 m diameter general purpose scattering chamber. A clear charge and mass separation has been achieved for the light ejectiles corresponding to the transfer of several nucleons (figures 1 and 2). Using $\Delta E - E$ particle separation technique, it was possible to obtain not only charge but also mass separation, thus allowing one to carry out a detailed study of multinucleon transfer reactions in these two systems.

The four-nucleon transfer reaction (^{12}C, ^{8}Be) is not studied well because of the complexity involved in the detection of the unstable ^{8}Be nucleus. The ^{8}Be nucleus in its ground state is unstable with respect to the breakup into two α-particles with a breakup Q-value of +92 keV. The cross-section for this α transfer reaction is expected to be large due to Q-value effect (less negative Q-value as compared to other transfer channels (see table 1)). ^{8}Be(g.s.) has a short lifetime ($\approx 10^{-16}$ s) due to which it breaks up before leaving the target nucleus. Therefore, it must be detected indirectly by means of a coincidence measurement of the two α-particles. The lifetime is sufficiently long for ^{8}Be nucleus to

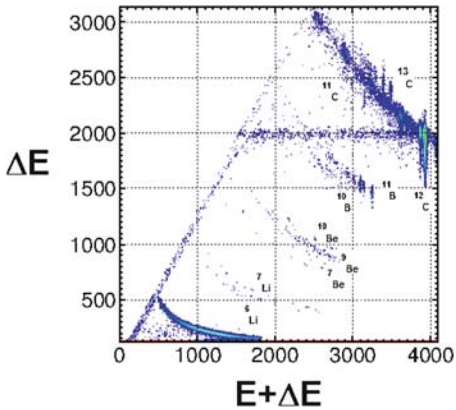

Figure 1. Mass spectrum (ΔE vs. $E + \Delta E$) in ^{56}Fe(^{12}C, x) at $E_{\rm inc} = 60$ MeV and $\theta_{\rm lab} = 30°$.

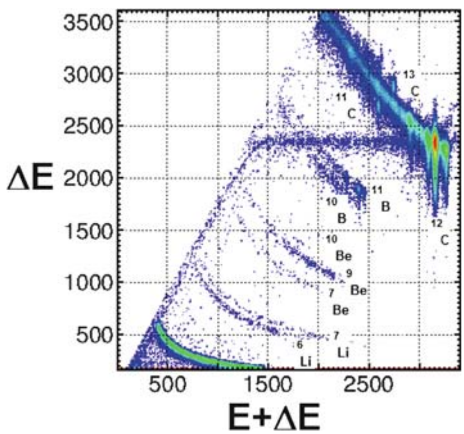

Figure 2. Same as figure 1 but for the reaction ^{58}Ni(^{12}C, x).

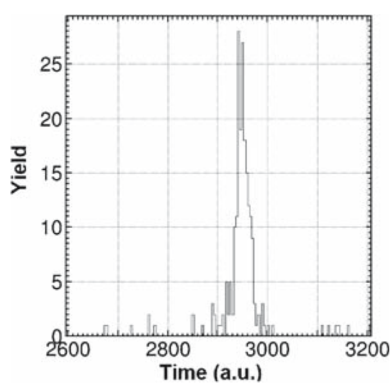

Figure 3. Timing spectrum (TAC output) from a typical α–α coincidence measurement in ^{58}Ni(^{12}C, ^{8}Be) with ^{8}Be decaying into ^{8}Be$\rightarrow$ $\alpha\alpha$ measured for an incident E(^{12}C) energy of 60 MeV.

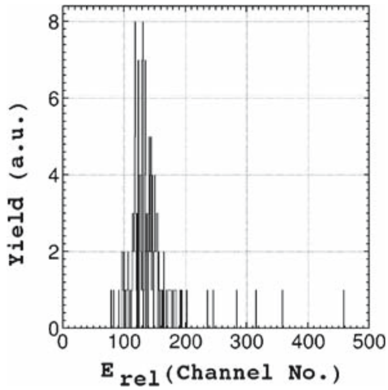

Figure 4. Spectrum of the relative energy between two αs from ^{8}Be decay $^8\mathrm{Be} \rightarrow \alpha\alpha$. The peak corresponds to the detection of two α-particles coming from the decay of ^{8}Be in ground state as detailed in the text.

Table 1. The differential cross-section measured for various reaction channels in ^{12}C + ^{58}Ni and ^{12}C + ^{56}Fe studied at the same incident energy of 60 MeV. The differential cross-sections listed are for the excitation energy integrated data. The reaction Q values (Q_0) listed in the table are ground-state Q values. For the (^{12}C,^{8}Be) reaction, the ^{8}Be angle is 33°. The entry in the last column is for cross-section for ^{58}Ni(^{12}C, ^{8}Be) at $E(^{12}\mathrm{C}) = 45$ MeV and $\theta_{\mathrm{lab}}(^8\mathrm{Be}) = 41°$.

Reaction	Q_0 (MeV)	$d\sigma/d\Omega$ (mb/sr) @30°	$d\sigma/d\Omega$ (mb/sr) @36°	$d\sigma/d\Omega$ (mb/sr)
^{58}Ni(^{12}C,^{13}C)	−7.27	1.57 ± 0.062	0.92 ± 0.027	
^{58}Ni(^{12}C,^{11}C)	−9.72	1.65 ± 0.063	0.92 ± 0.027	
^{58}Ni(^{12}C,^{11}B)	−12.54	1.00 ± 0.028	0.77 ± 0.024	
^{58}Ni(^{12}C,^{10}B)	−13.34	0.45 ± 0.019	0.22 ± 0.013	
^{58}Ni(^{12}C,^{10}Be)	−18.66	0.02 ± 0.003	0.007 ± 0.002	
^{58}Ni(^{12}C,^{9}Be)	−15.23	0.24 ± 0.014	0.18 ± 0.012	
^{58}Ni(^{12}C,^{8}Be$_{\mathrm{g.s.}}$)	−4.0	29.87 ± 2.3	–	
^{58}Ni(^{12}C,^{7}Be)	−13.78	0.08 ± 0.008	0.07 ± 0.007	
^{58}Ni(^{12}C,^{7}Li)	−18.6	0.10 ± 0.009	0.10 ± 0.009	
^{58}Ni(^{12}C,^{6}Li)	−15.48	0.22 ± 0.013	0.13 ± 0.010	
^{56}Fe(^{12}C,^{13}C)	−6.25	1.55 ± 0.073	0.58 ± 0.037	
^{56}Fe(^{12}C,^{11}C)	−11.08	0.44 ± 0.039	0.18 ± 0.021	
^{56}Fe(^{12}C,^{11}B)	−9.93	1.16 ± 0.063	0.47 ± 0.034	
^{56}Fe(^{12}C,^{10}B)	−12.81	0.39 ± 0.037	0.07 ± 0.013	
^{56}Fe(^{12}C,^{10}Be)	−12.99	0.052 ± 0.013	0.04 ± 0.010	
^{56}Fe(^{12}C,^{9}Be)	−10.80	0.25 ± 0.030	0.15 ± 0.019	
^{56}Fe(^{12}C,^{8}Be$_{\mathrm{g.s.}}$)	−1.08	11.47 ± 2.96	–	5.8±1.55[a]
^{56}Fe(^{12}C,^{7}Be)	−12.15	0.03 ± 0.010	0.015 ± 0.006	
^{56}Fe(^{12}C,^{7}Li)	−13.53	0.05 ± 0.013	0.05 ± 0.011	
^{56}Fe(^{12}C,^{6}Li)	−11.91	0.07 ± 0.015	0.05 ± 0.011	

[a] For ^{58}Ni(^{12}C, ^{8}Be) at 45 MeV.

be treated as a stable particle in participation in nuclear reactions, thus the two-body kinematics can be applied for the reaction (^{12}C, ^{8}Be) and the outgoing ^{8}Be(g.s.) will have a unique kinetic energy at a given laboratory angle. To measure the cross-section for the four-nucleon transfer reaction, (^{12}C, ^{8}Be), a coincidence set-up was used to detect two αs coming from the ^{8}Be$\rightarrow \alpha\alpha$ decay. Two $\Delta E - E$ detector telescopes were used and the α–α opening angle was kept at $\sim 6°$. A fast coincidence was employed and the typical α–α time coincidence spectrum (TAC output) is shown in figure 3.

From the measured kinetic energy of two αs and relative angle between them, the relative energy spectrum ($E_{\rm rel}$) between two αs was calculated, as detailed in [9]. The relative energy $E_{\rm rel}$ is given by $E_{\rm rel} = 1/2(E_1 + E_2 - 2\sqrt{E_1 E_2}\cos\Theta_{12})$, where E_1, E_2 are the kinetic energies of two αs and Θ_{12} is the relative angle between them. A sharp peak shown in figure 4 in the relative energy spectrum was identified as the signature of ^{8}Be$_{\rm g.s.}$. A cut was then applied around this peak-like structure to select events corresponding to the reaction (^{12}C, ^{8}Be$_{\rm g.s.}$). It is to be mentioned that the contribution from ^{8}Be decay at higher excited states is not expected to contribute significantly in the present coincidence measurement because the α-particles are emitted in a cone with much larger angle. The efficiency of the ^{8}Be detection was calculated by following the prescription given [10]. An approximate expression was used as the detectors were small and a uniform distribution of events over the breakup cone was assumed.

The Q-integrated cross-sections for various reaction channels for both the ^{12}C+^{58}Ni and ^{12}C + ^{56}Fe systems are listed in table 1 along with the Q-values. The errors given in the table are the statistical errors.

3. Results and discussion

The measured elastic scattering angular distribution of the system ^{12}C + ^{58}Ni is plotted in figure 5. The data have been compared with the system ^{12}C + ^{56}Fe and the possible influence of two extra protons in ^{58}Ni nucleus has been investigated. The optical model (OM) search code SFRESCO [11] was used for the analysis and the potential parameters

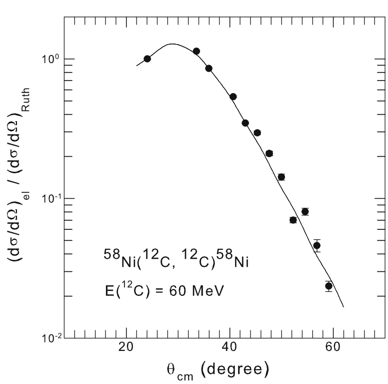

Figure 5. Elastic scattering angular distribution for the ^{12}C + ^{58}Ni system at E(^{12}C) = 60 MeV. The OM fit to the measured data is also shown by the solid line. The error bars are within the data symbol.

were extracted from a fit to the measured data. A volume Woods–Saxon form for the real and imaginary potentials was used. The OM potential parameters for the $^{12}C + ^{56}Fe$ system at 60 MeV were derived in one of our earlier studies [6]. These parameters, listed in the column 2 of table 2, were used as the initial parameters for the analysis of $^{12}C + ^{58}Ni$ data at 60 MeV. A search was made on the potential parameters and the resulting parameters for which a best fit was obtained are shown in table 2. It has been observed that a decrease in the potential parameters (r_0 by 12, a_0 by 1.4, r_i by 4.6 and a_i by 20%) was needed to achieve the best fit to the data. In this study about 30% reduction in the cumulative reaction cross-section in going from $^{12}C + ^{56}Fe$ to $^{12}C + ^{58}Ni$ is observed. The variation in the potential parameters, especially 20% change in a_i and 12% change in r_0 is significant.

The Q-value systematics of transfer cross-section has been studied for both the systems. From earlier studies [4,8,12–20], it is known that the differential cross-section for isotope production of each charge decreases exponentially with increasing negativity of the ground-state Q-value (Q_0) ($\mathrm{d}\sigma/\mathrm{d}\Omega \sim \mathrm{e}^{Q_0/T}$) and this is understood in the context of a partially statistical equilibrium of a dinuclear system with an effective temperature T. Similar exponential dependence can also be explained in the framework of direct reaction mechanism where slope parameter T is related to the mean energy loss per transferred nucleon and the probability for single nucleon transfer [17]. The measured cross-sections for the production of C, B, Be and Li isotopes in $^{56}Fe(^{12}C, x)$ are plotted in figure 6a, while that for the $^{12}C + ^{58}Ni$ system are shown in figure 7a. In general, the yields of different isotopes for a given element decrease with Q_0 becoming more negative. However, no unique set of lines (with the same slope) can be defined to explain the data in both these systems. As was observed in our earlier studies [8] and also in [15,16], the pairing energy corrections (the so called 'non-pairing' corrections) play significant roles in the Q-value systematics. The pairing energy corrections have been applied to the present data and the cross-sections are re-plotted in figure 6b (for $^{12}C + ^{56}Fe$) and in figure 7b (for $^{12}C + ^{56}Fe$) as a function of the modified Q-value. Though some changes are observed, the pairing energy corrections have no dramatic effect on the present data. It is necessary to mention that the effects of pairing correction are significant in reactions with oxygen on zirconium

Table 2. OM potential parameters extracted using the search code SFRESCO. The cumulative reaction cross-sections are also listed. The data in column 2 are taken from [6].

Potential parameter	$^{12}C + ^{56}Fe$ @60 MeV	$^{12}C + ^{58}Ni$ @60 MeV
V_0 (MeV)	48.0	48.0
r_0 (fm)	1.191	1.04
a_0 (fm)	0.643	0.63
W (MeV)	12.0	12.0
r_i (fm)	1.191	1.14
a_i (fm)	0.634	0.50
$\sigma_{\mathrm{reaction}}$ (mb)	1537	1047

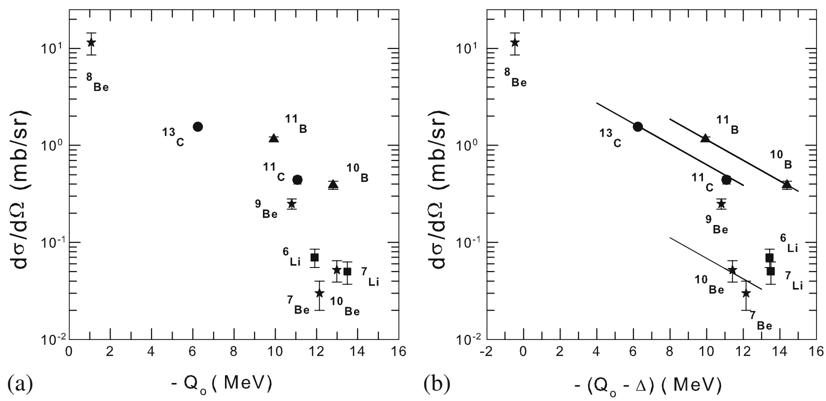

Figure 6. (**a**) Reaction cross-section vs. Q values for ^{56}Fe(^{12}C, x) at $E(^{12}\mathrm{C}) = 60$ MeV and $\theta_{\mathrm{lab}} = 30°$. For ^{8}Be, the angle was $\theta_{\mathrm{lab}} = 33°$. (**b**) The pairing energy corrections (Δ) have been applied.

[8,15]. The straight lines in figures 6b and 7b are the predictions from the Q-value systematics. The lines have same slope corresponding to an effective temperature of 4.1 MeV which is somewhat higher than the values obtained from other reactions [15,16]. For the elements $Z = 5$ (boron) and 6 (carbon) in the reaction ^{56}Fe(^{12}C, x) and $Z = 5$ in the case of ^{58}Ni target, the isotope production cross-section follows the Q-value systematics. In the case of beryllium ($Z = 4$), it is very clear from these figures that the isotope production cross-section for ^{8}Be and ^{9}Be are relatively enhanced in both the $^{12}\mathrm{C} + {}^{56}\mathrm{Fe}$ and $^{12}\mathrm{C} + {}^{58}\mathrm{Ni}$ systems.

In figures 8 and 9, we have plotted the multinucleon transfer cross-sections as a function of the number of nucleons transferred (ΔN). In general, the cross-section decreases with the increase in the number of transferred nucleons. For the $^{12}\mathrm{C} + {}^{58}\mathrm{Ni}$ system, in the beryllium isotope production it has been seen that the cross-section for ^{9}Be and ^{8}Be production, corresponding to three- and four-nucleon stripping, respectively, is more than

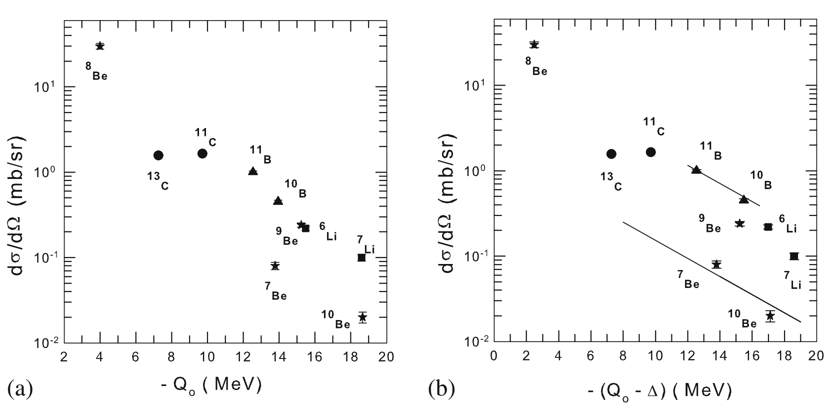

Figure 7. Same as figure 6 but for the reaction ^{58}Ni(^{12}C, x). In (**a**) the dependence on the ground state Q-value is shown while in (**b**) the pairing energy corrections (Δ) are included.

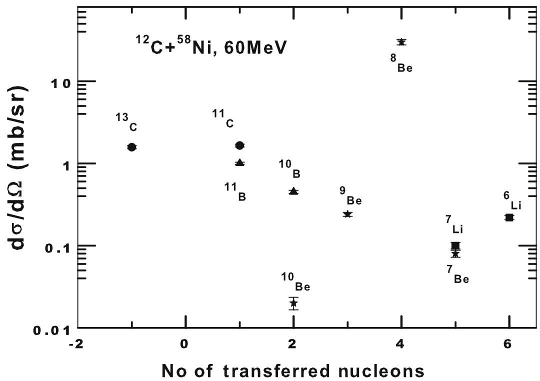

Figure 8. Reaction cross-section vs. number of particles transferred for ^{58}Ni(^{12}C, x) measured at an incident ^{12}C energy of 60 MeV and $\theta_{\rm lab} = 30°$. For ^{8}Be, the angle $\theta_{\rm lab} = 33°$.

^{10}Be production (two-nucleon stripping). Cross-section for (^{12}C, ^{9}Be) is higher by an order of magnitude than the cross-section for (^{12}C, ^{10}Be) and the four-nucleon transfer channel (^{12}C, ^{8}Be) is enhanced by three orders of magnitude compared to the corresponding two-nucleon transfer (^{12}C, ^{10}Be) (table 1). This clearly indicates the cluster transfer of nucleons, ^{3}He($2p1n$) in the (^{12}C, ^{9}Be) reaction and $\alpha(2p2n)$ for the (^{12}C, ^{8}Be) reaction. This is also evident from our analysis in terms of the Q-value systematics (figures 6 and 7). For heavy-ion transfer reactions, the general characteristics of the yields of isotope production for a given element is understood in terms of the Q-value systematics. However, the clustering phenomena in nuclei are equally important and depending on the projectile–target combination the reaction cross-section in the respective channels may be enhanced due to the clustering effect. A good history of the cluster structure in nuclei can be found in [21]. In our earlier study [3] of reactions with ^{12}C + ^{88}Sr evidence of ^{3}He cluster transfer is observed. In the present case, when the measured isotope

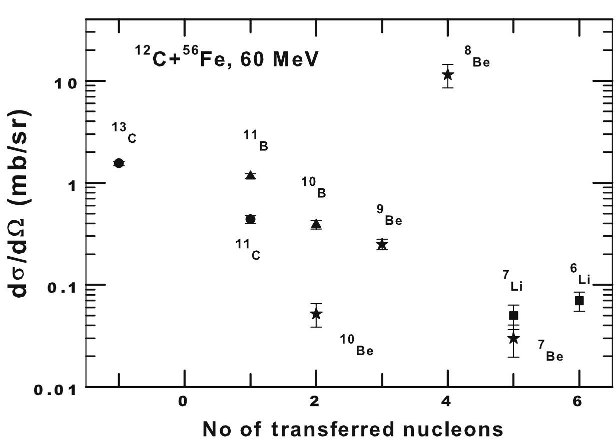

Figure 9. Same as figure 8 but for the reaction ^{56}Fe(^{12}C, x).

production yields for the beryllium isotopes are compared with the predictions from the Q-value systematics (after incorporating the pairing energy correction), cross-section for the reactions (^{12}C, ^{8}Be) and (^{12}C, ^{9}Be) are clearly enhanced relatively. Even the five-nucleon stripping reaction (^{12}C, ^{7}Be) is observed to have significantly higher cross-section than the two-nucleon stripping reaction, suggesting the possible mechanism of (αn) transfer. Interestingly, the cross-section for the other five-nucleon transfer reaction (^{12}C, ^{7}Li) is similar to the cross-section for the (^{12}C, ^{7}Be) reaction. In this case αp stripping from the projectile could be a dominant transfer mechanism for this. The observed cross-section for the six-nucleon transfer channel (^{12}C, ^{6}Li) is even higher than the five-nucleon transfer reaction (^{12}C, ^{7}Li). The above observations are also valid for the ^{12}C + ^{56}Fe system as shown in figure 9. It is to be mentioned that for $\Delta Z = 2$ transfer, when beryllium isotope production cross-section in these two systems are compared, the two-proton stripping reaction on ^{56}Fe target (^{56}Fe(^{12}C, ^{10}Be)^{58}Ni) is observed to be relatively enhanced. This two-nucleon transfer reaction populates the proton shell closed ($Z = 28$) nucleus ^{58}Ni and the observed increased cross-section in this reaction could be associated with the effect of shell closure. The detailed transfer probability calculations have been followed for further understanding of the data.

Apart from the cluster transfer, sequential transfer of uncorrelated nucleons can also contribute to a given transfer reaction and depending on the nature of the transition, the multistep sequential transfer in some cases can be compared to the one-step direct transfer. The experimentally measured transfer probabilities for multinucleon transfer when compared with the corresponding probabilities for multistep sequential transfer of

Table 3. Deduced transfer probabilities, P_N and enhancement over the uncorrelated transfer of N nucleons, EF$_1$. EF$_2$ is defined as the enhancement over the two-step sequential transfer of α and a neutron/proton/deuteron as detailed in the text. The quantities labelled as ^{56}Fe correspond to data for the target ^{56}Fe and those labelled as ^{58}Ni correspond to data for the target ^{58}Ni.

Reaction	Charge transfer (ΔZ)	Process	$P_N^{56\mathrm{Fe}}$ (%)	$P_N^{58\mathrm{Ni}}$ (%)	$\mathrm{EF}_1^{56\mathrm{Fe}}$	$\mathrm{EF}_2^{56\mathrm{Fe}}$	$\mathrm{EF}_1^{58\mathrm{Ni}}$	$\mathrm{EF}_2^{58\mathrm{Ni}}$
(^{12}C,^{13}C)	0	$+1n$	0.50	0.106	1		1	
(^{12}C,^{11}C)		$-1n$	0.14	0.111	1		1	
(^{12}C,^{11}B)	1	$-1p$	0.38	0.072	1		1	
(^{12}C,^{10}B)		$-1p-1n$	0.128	0.032	240		~ 400	
(^{12}C,^{10}Be)	2	$-2p$	0.017	0.001	12		~ 20	
(^{12}C,^{9}Be)		$-2p-1n$	0.083	0.017				
(^{12}C,^{8}Be)		$-2p-2n$	3.65	2.13				
(^{12}C,^{7}Be)		$-2p-3n$	0.01	0.006	$\sim 10^9$	$\sim 2^{\mathrm{a}}$	$\sim 10^{11}$	$\sim 2.5^{\mathrm{a}}$
(^{12}C,^{7}Li)	3	$-3p-2n$	0.017	0.007	$\sim 10^9$	$\sim 1^{\mathrm{b}}$	$\sim 10^{11}$	$\sim 4.7^{\mathrm{b}}$
(^{12}C,^{6}Li)		$-3p-3n$	0.022	0.016	$\sim 10^{12}$	$\sim 5^{\mathrm{c}}$	$\sim 10^{14}$	$\sim 20^{\mathrm{c}}$

[a] $\mathrm{EF} = P_N/P_\alpha P_{-1n}$.
[b] $\mathrm{EF} = P_N/P_\alpha P_{-1p}$.
[c] $\mathrm{EF} = P_N/P_\alpha P_{-(1n1p)}$.

uncorrelated nucleons, measured simultaneously, may indicate the importance of direct cluster transfer of nucleons. From the present data, transfer probabilities P_N, as defined earlier, are extracted from the measured one- to six-nucleons transfer cross-sections and elastic scattering cross-section, both measured simultaneously. The deduced probabilities are shown in table 3 for both the $^{12}C + ^{56}Fe$ and $^{12}C + ^{58}Ni$ systems. P_N stands for the measured probability of N nucleons (involving z number of protons and n number of neutrons) transferred. In the absence of any correlation, the probability of sequential transfer of N nucleons would be $P_N \approx (P_1)^N$ [2,3]. Comparison of P_N with $(P_1)^N$ defines an enhancement factor $\mathrm{EF} = P_N/(P_1)^N$ and therefore may be indicative of the importance of the interaction responsible for direct/cluster transfer of correlated particles. The deduced enhancement factors are given in table 3. The factor EF_1 is the enhancement over the uncorrelated transfer of N nucleons. As the N nucleons transferred corresponds to a transfer of z protons and n neutrons, to calculate the factor $(P_1)^N$, the corresponding proton and neutron stripping probabilities were taken. Thus, $(P_1)^N$ was calculated as $(P_1)^N = (P_{-1p})^z \times (P_{-1n})^n$. For the four-nucleon ($2p2n$) transfer reaction (^{12}C, ^{8}Be), the large experimental values are clear indications of the α-cluster transfer in both the systems. For the five-nucleon transfer reaction (^{12}C, ^{7}Be), as the probability for α stripping reaction is observed to be the largest, the measured probability has also been compared with the probability of a two-step process involving transfer of an α and a neutron and an enhancement factor EF_2 is defined as $\mathrm{EF}_2 = P_N/(P_\alpha P_{-1n})$. Similarly, for the other five-nucleon stripping reaction (^{12}C, ^{7}Li), the ratio $\mathrm{EF}_2 = P_N/(P_\alpha P_{-1p})$ gives a comparison with the probability of a two-step process involving an α and a proton transfer. In the case of (^{12}C, ^{6}Li) reaction, the measured probability has been compared with the probability of a two-step process involving transfer of α and (np) ($\mathrm{EF}_2 = P_N/(P_\alpha P_{-(1n1p)})$). As can be seen from table 3, columns 7 and 9, the present data for the five-nucleon transfer reactions show a strong evidence of the dominance of a two-step process involving α and a nucleon transfer. The transfer probabilities are plotted in figure 10. As can be seen for the $\Delta Z = 2$ transfer, the two-proton stripping cross-section leading to the proton shell closed nucleus ^{58}Ni is relatively enhanced in $^{12}C + ^{56}Fe$.

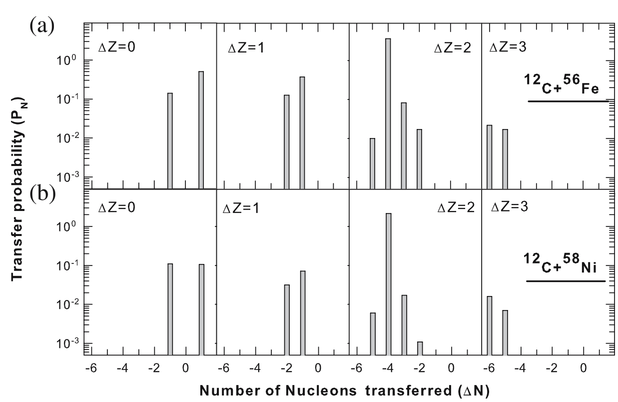

Figure 10. Transfer probabilities (P_N) deduced from the measured data plotted as a function of the number of nucleons transferred: (**a**) is for the ^{56}Fe(^{12}C, x) reaction and (**b**) is for the $^{12}C + ^{58}Ni$ reaction.

4. Conclusions

The cross-section of one- and multinucleon transfer reactions in (^{12}C, x); $x = {}^{13,11}$C, ^{11,10}B ^{10,9,8,7}Be and ^{7,6}Li, have been measured on two target nuclei ^{56}Fe and ^{58}Ni at the same incident energy of 60 MeV. Transfer of up to 6 nucleons has been observed with significant cross-section. A clear charge and isotope separation for light ejectiles from lithium to carbon has been achieved using surface barrier detectors in a $\Delta E - E$ configuration. The measured elastic scattering angular distributions was analysed using the optical model programme SFRESCO and the potential parameters derived from this analysis were compared. Some of the potential parameters were observed to change significantly in going from ^{12}C + ^{56}Fe to ^{12}C + ^{58}Ni system. The data, when plotted as a function of ground-state Q-value for different isotopes, the general trend of reduction of cross-section with increasing negative Q-value was understood in terms of the Q-value systematics. The pairing energy correction to the data was observed to be less significant in the present systems. Cross-section dependence on the number of nucleons transferred was studied and transfer probability for the multinucleon stripping reactions was extracted and compared with the probability of uncorrelated multistep transfer of nucleons. The data are suggestive of transfer of α and ^{3}He cluster in the four-nucleon ($2p2n$) and three-nucleon ($2p1n$) stripping reactions, respectively. For the (^{12}C, ^{7}Be) and (^{12}C, ^{7}Li) reactions, the observed enhancement seems to suggest the dominance of a two-step transfer process of an α and a nucleon.

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