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^{12}C induced transfer reactions on ^{56}Fe

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Abstract. Transfer reactions ^{56}Fe(^{12}C, xN) have been investigated. Angular distributions of particles following elastic scattering, one neutron and one proton transfer reaction channels leading to low lying states in respective residual nuclei have been measured. These are analysed using the coupled reaction channel (CRC) formalism. Starting with a double folded real potential, the elastic scattering angular distribution is calculated using the computer code FRESCO. Inclusion of couplings to first excited states in both the target and the projectile already tends to describe the experimental elastic scattering distribution. Additional coupling of one neutron transfer reaction to first five excited states in ^{55}Fe and one proton transfer reaction to first three low lying states in ^{57}Co improves fit to the elastic scattering angular distribution. Further refinement in fit is brought about by addition of a weak imaginary potential to the complex potential calculated by FRESCO to simulate the absorption effects due to those channels whose coupling is not included explicitly. Such a potential describes the experimental angular distributions for elastic, one neutron and one proton transfer channels correctly in shape and magnitude without any arbitrary normalisation.

Keywords. Nuclear reactions ^{56}Fe(^{12}C, ^{12}C), (^{12}C, ^{11}B), (^{12}C, ^{13}C); $E = 60$ MeV; measured angular distributions; coupled reaction channel formalism; heavy ion reaction mechanism.

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1. Introduction

Multi nucleon transfer between heavy ions represents an important reaction mechanism to understand correlation among nucleons. Unambiguous data on multi nucleon transfer reactions is not easily available. A good charge, mass and Q-value resolution and at the same time a high detection efficiency is a difficult task to achieve experimentally. As the number of nucleons transferred increases, the mechanism of transfer becomes more complicated because of the many paths the reaction can follow. An unanswered question thus far is the definition of the relevant degrees of freedom one has to include in models to have an adequate description of the reaction mechanism. In particular, one would like to know the relative weight of single nucleon transfer mode compared to the more complicated processes involving transfer of pairs or even cluster of nucleons. It is generally believed that single nucleon transfer reactions are well described in the DWBA framework [1]. The validity of such a description assumes:

1. The transfer of nucleon takes place directly from the initial to the final states – other particles are not disturbed from their original state.
2. The wave functions for the relative motion between partners in the reaction are assumed to be correctly described by the optical potential.
3. The reaction is assumed to be sufficiently weak so that it can be treated in the first order.

A number of studies involving inelastic scattering [2] of various projectiles (from electrons to heavy ions) from ^{12}C nuclei tend to support the conclusion that the ground state of ^{12}C is based on an intrinsic state having a strong oblate deformation $\beta_2 = -0.6$. Therefore, while describing the transfer reactions induced by ^{12}C projectiles, it is appropriate to ask to what extent a state can be described as a linear combination of nucleon(s) coupled to an undisturbed core and nucleon(s) coupled to collective excitations. The method for coupling all possible indirect channels in the heavy ion induced multi-nucleon transfer reactions is described in the coupled reaction channel (CRC) approach [3]. In the present communication, we report data on one proton stripping and one neutron pickup reactions on the system $^{12}\mathrm{C} + {}^{56}\mathrm{Fe}$. The data for two-proton and three nucleon transfer have already been reported in our earlier study [4]. The data are consistently analysed in the CRC approach by including additional pathways for the intermediate states involving excitation of the 0.836 MeV (2^+) state in $^{56}\mathrm{Fe}^+$ and 4.43 MeV (2^+) state in ^{12}C in addition to a number of low lying excited states in ^{57}Co and ^{55}Fe nuclei.

2. Experimental details

The experiments reported here, namely, ^{56}Fe(^{12}C, ^{13}C)^{55}Fe and ^{56}Fe(^{12}C, ^{11}B)^{57}Co at incident carbon ion energies of 60 MeV have been investigated using the carbon ions from the 14UD Pelletron accelerator at Mumbai, India. The target, $^{\mathrm{nat}}$Fe (^{56}Fe abundance $\approx 91.72\%$) is a self supporting foil of thickness ≈ 275 μg/cm^2 as determined by thickness gauge monitor. The reaction products are detected and identified with three counter telescopes each consisting of a 30 μm thick silicon surface barrier ΔE detector placed in front of a 300 μm E-detector. Two dimensional spectra of ΔE vs $(E + \Delta E)$ have been obtained in the angular range $11^\circ < \theta_{\mathrm{lab}} < 35^\circ$. The details can be found in ref. [4].

3. Results

Energy spectra corresponding to various reaction channels are obtained by putting an appropriate banana gate in the two dimensional spectra of ΔE vs $(E + \Delta E)$ and projecting onto the total energy axis. An energy resolution of 500 keV is obtained for the elastic group. Absolute differential cross sections have been measured for all the channels reported in the present study.

3.1 *The reaction* ^{56}Fe (^{12}C, ^{11}B) ^{57}Co

The energy spectrum of ^{11}B obtained in the (^{12}C, ^{11}B) reaction at $\Theta_{\mathrm{lab}} = 19^\circ$ is shown in figure 1a. The transition to the ground state $(7/2)^-$ in ^{57}Co is identified. The first

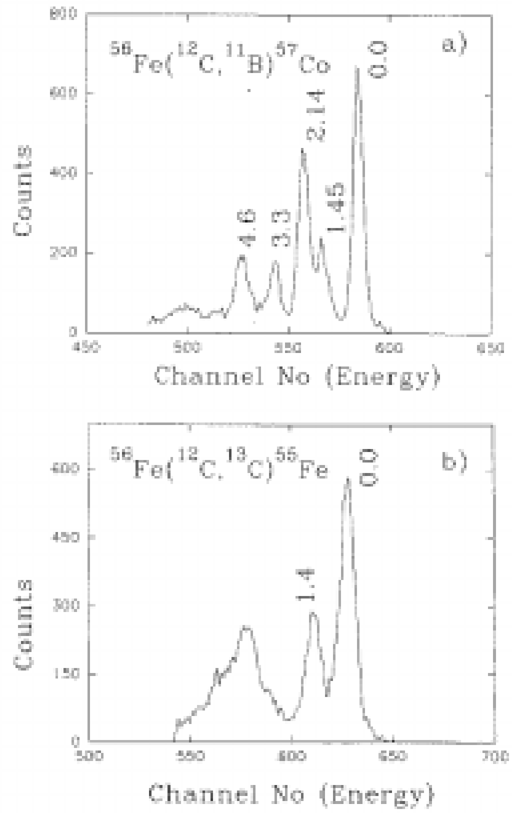

Figure 1. Energy spectrum of **(a)** ^{11}B in ^{56}Fe(^{12}C, ^{11}B) and **(b)** ^{13}C in ^{56}Fe(^{12}C, ^{13}C) reaction at E(^{12}C) = 60 MeV and $\Theta_{\rm lab} = 19°$.

excited state $(9/2)^-$ at Ex = 1.22 MeV is not populated in the present study. It is also not observed in (^{3}He, d) reaction [5] and is attributed to the possible origin of this state as due to a $1f7/2$ proton hole coupled to first 2^+ vibrational state in ^{58}Ni. The next peak at 1.4 MeV excitation energy will have contributions from the $(3/2)^-$ state at Ex = 1.37 MeV and the $(1/2)^-$ state at Ex =1.5 MeV. The origin of the peak at 2.14 MeV excitation energy is identified with the excitation of the 2.135 MeV $(5/2)^-$ state in ^{57}Co. The ground state transition $(7/2)^-$ due to the reaction ^{54}Fe(^{12}C, ^{11}B)^{55}Co is kinematically expected to occur at an excitation energy of 962 keV above the ground state transition of ^{57}Co. Assuming a similar cross-section, an abundance of 6% in the target would imply a peak count of around 40 and is difficult to decipher from the spectrum.

The measured angular distribution for the transition to the ground state is shown in figure 2a. The angular distribution for the 1.4 MeV is shown in figure 2b. As noted earlier, the present study cannot resolve levels at 1.379 MeV $(3/2)^-$ and 1.507 MeV $(1/2)^-$. Three more group of states at excitation energies 2.14, 3.2 and 4.7 MeV are clearly seen at all the angles measured. With the energy resolution achieved in the present investigation, it is

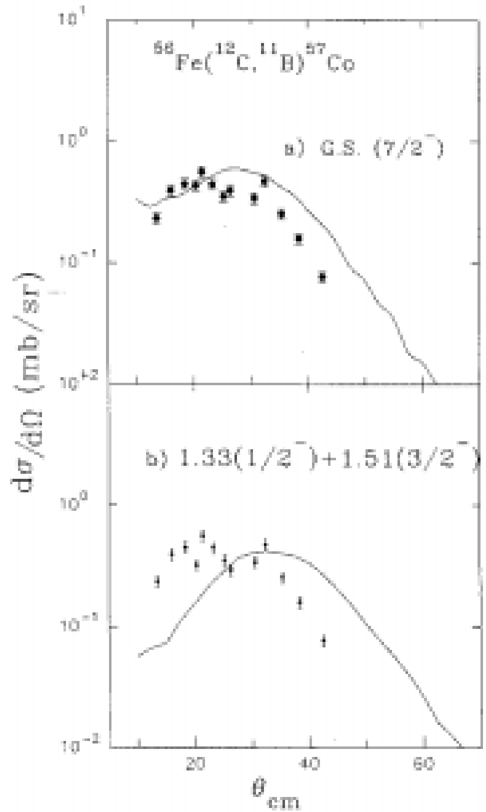

Figure 2. Angular distribution of ^{11}B in transition to **(a)** the ground state and **(b)** the 1.45 MeV group. The solid lines are CRC calculations.

hard to assign individual levels at this excitation energy. Therefore, even though angular distributions could be extracted, no attempt has been made to analyse them further and are not included.

3.2 *The reaction* $^{56}Fe(^{12}C, ^{13}C)\,^{55}Fe$

An energy spectrum of ^{13}C obtained in the one neutron pick up reaction ^{56}Fe(^{12}C,^{13}C)^{55}Fe is shown in figure 1b. Two groups of states can be identified. The ground state group, as identified by the kinematics, consists of the ground state transition (3/2)$^-$ of ^{55}Fe and the first excited state (1/2)$^-$ at 411 keV which could not be resolved within the experimental energy resolution. The next strong peak at Ex = 1.4 MeV could include the contribution from the states at 0.93 MeV (5/2)$^-$, 1.32 MeV (7/2)$^-$ and 1.41 MeV (7/2)$^-$ in ^{55}Fe. The ground state transition (7/2)$^-$ due to the reaction ^{54}Fe(^{12}C, ^{13}C)^{53}Fe is kinematically expected to occur at an excitation energy of 2.1 MeV above the ground state transition of ^{55}Fe. Assuming a similar cross-section, an abundance of 6% in the target would

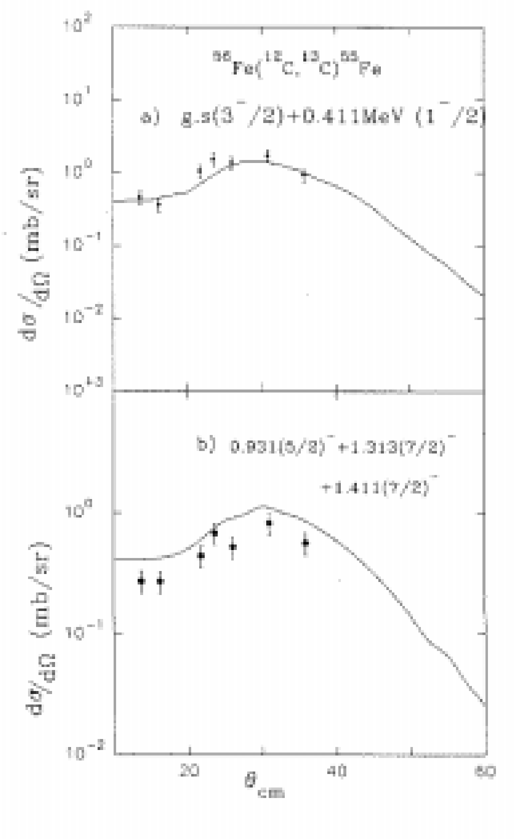

Figure 3. Angular distribution of ^{13}C in transition to **(a)** the unresolved ground state and 0.411 MeV state and **(b)** the 1.4 MeV group. The solid lines are the resulting CRC fits.

imply a peak count of 40 and is difficult to decipher from the spectrum. Moreover, this is beyond the region of interest under discussion. Angular distributions (figure 3a, b) for these two group of states have been extracted for further analysis.

4. Coupled reaction channel analysis

The angular distributions of particles detected in the following reactions are considered for analysis in the CRC approach:

1. the elastic scattering ^{56}Fe(^{12}C, ^{12}C),
2. one proton stripping reaction ^{56}Fe(^{12}C, ^{11}B) ^{57}Co,
3. one neutron pick up reaction ^{56}Fe(^{12}C, ^{13}C)^{55}Fe – all measured simultaneously.

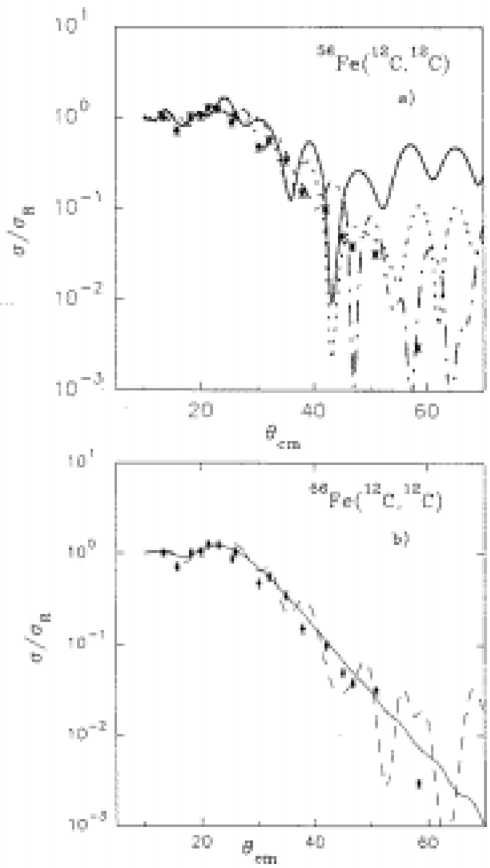

Figure 4. The ratio of measured elastic scattering differential cross section to Rutherford cross section for ^{12}C $-$ ^{56}Fe at 60 MeV are plotted as a function of $\theta_{\rm cm}$. These are fitted in **(a)** with FRESCO calculations with double folded real potential and $W = 0$ for the elastic channel (solid line) with no coupling. Dotted and dash-dot curves represent the calculations with coupling of 2^+ inelastic state in ^{12}C and ^{56}Fe respectively. The elastic scattering calculations with full coupling (see text for details) and $W = 0$ is shown by dashed curve in **(b)**. The solid line fit in (b) represents the same calculations in which a weak imaginary potential with parameters $W = -15$ MeV, $r_0 = 1.191$ fm and $a_0 = 0.69$ fm is added to account for the absorption due to channels which are not explicitly included in the calculations.

Coupled channel calculation have been performed with the help of CRC code FRESCO [6]. In a coupled channel calculation, the starting point is the calculation of elastic scattering angular distribution employing a ‘bare potential’. A double folded real potential was obtained using the code DFPOT [7] with charge densities taken from the atomic and nuclear data tables [8]. The following form was used for the M3Y effective interaction (in MeV):

$$V_{00}(r) = 7999 \exp(-4r)/4r - 2134 \exp(-2.5r)/2.5r - 262\Delta(r). \qquad (1)$$

Imaginary potential depth was set to zero; the elastic scattering angular distribution obtained with such a potential is shown by solid line in figure 4a. Coupling of the 2^+ (0.836 MeV) state in ^{56}Fe and 2^+ (4.43 MeV) state in ^{12}C results in fits to elastic scattering angular distribution as shown in figure 4a by dashed and dotted curves respectively. The effects of coupling of one proton transfer to ground state, 1.32 and 1.51 MeV states in ^{57}Co and one neutron transfer to ground state, 0.411, 0.9, 1.3 and 1.5 MeV states of ^{55}Fe in addition to the inelastic couplings mentioned above were investigated. The effects are shown in figure 4b by dotted line. The resulting description is already close to the experimental distribution.

Till now no external imaginary potential is put by hand. In order to simulate the effects of all the other channels which are not explicitly included, a Woods–Saxon volume form of imaginary potential with a depth parameter $W = -15$ MeV; radius parameter $r_0(w) = 1.191$ fm and diffuseness parameter $a_0(w) = 0.69$ fm was introduced. The resulting fit describes the elastic angular distribution well as shown by solid line in figure 4b. Coupled channel calculations for the neutron pick up channel leading to ground state group transition in ^{55}Fe reproduce the experimental data (figure 3a) in shape and magnitude without any arbitrary normalization. The data includes excitation of two states namely ground state $(3/2)^-$ and 0.411 MeV $(1/2)^-$ which can not be resolved within the presently obtained resolution. The FRESCO calculations shown in figure 3a represent the cross section obtained by incoherent addition of the contributions from these two individual states. The spectroscopic strength are taken from (p, d) studies [9]. The fits shown in figure 3a are the results of calculation with $W = 15$ MeV. A parametric variation of W was carried out to investigate the effect on differential cross section. While the elastic angular distribution fit did not significantly change, the magnitude of the reaction cross section reduced by a factor 10 when the value of W was changed from 5 to 15 MeV.

Similarly, the calculated result for Ex = 1.4 MeV group (figure 3b) is the incoherent addition of individual contributions from the three states at 0.93 MeV (5/2), 1.32 MeV $(7/2)^-$ and 1.41 MeV $(7/2)^-$ with the relative strength that are taken from ref. [10]. The shape and magnitude of the measured angular distribution in both the cases are well reproduced by the FRESCO calculations.

The angular distributions of outgoing ^{11}B in transition to the ground state and first excited states in residual nucleus ^{57}Co have been shown in figure 2. The CRC calculations with $W = -15$ MeV reproduce the data well in magnitude. No attempt has been made to fit the shape. No normalization constants (so called unhappiness factors in standard DWBA finite range calculations) are needed.

5. Conclusions

The present experiment indicates that meaningful analysis of the data requires performing finite range coupled channel calculations. This, as we have seen, obviates the necessity for introducing any arbitrary normalization constant. The results have also shown that it is necessary to include both the target and the projectile excitations in addition to transfer channels. In particular, the 4.43 MeV(2^+) state in ^{12}C must be accounted for in view of the oblate nature of ^{12}C with a large deformation.

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