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Reaction mechanisms in the ^{6}Li+ ^{52}Cr system

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Abstract. Reactions induced by the weakly bound ^{6}Li projectile interacting with the intermediate mass target ^{52}Cr are investigated. The choice of this particular reaction in our study is because it is proposed as a surrogate reaction [^{6}Li(^{52}Cr, d)^{56}Fe*] for the measurement of ^{55}Fe(n,p) reaction cross-section, which has been found to be very important in fusion reactor studies. All the conditions which have to be satisfied for using the surrogate method have been checked. The energy of ^{6}Li beam is selected in a way so as to get equivalent neutron energy in the region of 9-14 MeV, which is of primary interest in fusion reactor application. In the present work, statistical model calculations PACE (Projection-Angular-Momentum-Coupled-Evaporation), ALICE and Continuum-Discretized–Coupled-Channel (CDCC: FRESCO) have been used to provide information for the ^{6}Li + ^{52}Cr system and the respective contributions of different reaction mechanisms. The present theoretical work is an important step in the direction towards studying the cross-section of the ^{55}Fe(n, p)^{55}Mn reaction by surrogate method.

1 Introduction

Studies of interactions of weakly bound nuclei with intermediate mass targets are of immense importance in different applications like nuclear astrophysics, production of medical radio-isotopes and fusion reactor applications. In the present study the interaction of ^{6}Li with ^{52}Cr is done mainly for fusion reactor applications.

There are many long-lived radio-nuclides which are produced in the fusion reactor environment like ^{53}Mn ($t_{½}$ = 3.74×10^{6} years), ^{55}Fe ($t_{½}$ = 2.73 years), ^{59}Ni ($t_{½}$ = 7.6×10^{4} years) [1]. These isotopes are quite important in the fusion reactor but non availability of the neutron induced cross-sections introduces major uncertainities in the design of its components. The measurement of neutron induced cross-sections of these nuclides is extremely difficult as they do not exist in nature. But they are produced in large amounts inside the fusion reactor during operation and have a very long life time. There is a large probability that neutrons will react with these long-lived nuclides. Hence, neutron induced cross-sections on these produced radio-nuclides are required in the neutron energy range 9-14 MeV [2]. Surrogate method, which is an indirect way of determining cross-sections for nuclear reactions that proceed through a compound nucleus, is a promising method for the measurement of neutron induced cross-sections of such nuclides [3]. This method has an advantage that the target material required for the experiment is stable and the compound nucleus is formed via the interaction of light charged particles (p, d, t,α,^{3}He, ^{6}Li etc.) with the target nuclei.

This particular study is performed keeping in mind that the proposed ${}^{6}_{3}Li + {}^{52}_{24}Cr \rightarrow d + ({}^{55}_{26}Fe)*$ reaction as a surrogate of the $n + {}^{55}_{26}Fe \rightarrow ({}^{55}_{26}Fe)* \rightarrow p + {}^{55}_{25}Mn$. ^{55}Fe ($t_{1/2}$ = 2.73 years) is one of the radio-nuclides which is produced in large quantities inside the fusion reactor via the ${}^{56}_{26}Fe(n,2n){}^{55}_{26}Fe$, ${}^{58}_{28}Ni(n,\alpha){}^{55}_{26}Fe$ [4]. Neutron induced cross-sections for long-lived activation products produced in fusion reactor are a very important concern since they could pose a serious radiation damage & radioactive waste disposal problem. Reactor system studies show that after the shutdown of a fusion reactor, the inventory of radionuclides could be more than 10^{9}Ci [5]. Therefore, neutron induced cross-section of radionuclides or unstable targets are needed for estimation of inventory of residual radioactivity in the material after shutdown of the reactor. These cross-sections are also very important for reactor system studies, for fusion experiment diagnostics and as fluence monitors for radiation damage experiments. In such an estimate, cross section data for unstable or radionuclei are also required to be included in nuclear data libraries. Surrogate method has been used

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earlier for (n,f), (n,γ) reactions, mainly for actinides of interest for nuclear fission. Here, our attempt is to initiate the measurement of (n,p) (n,α) reaction cross-section for the radioactive nuclides of interest in fusion. Such studies would be the first of their kind on fusion materials.

The paper is organized as follows: Section2 examines if the reaction ^{52}Cr(^{6}Li,d)^{56}Fe* satisfies all the conditions for being a surrogate reaction of the desired reaction ^{55}Fe(n,p). Section 3 contains the theoretical study of ^{6}Li+ ^{52}Cr system with statistical model calculations of ALICE/PACE [6] and CDCC [7]. Finally, the conclusions are summarised in Section 4.

2 $^{52}_{24}Cr(^{6}_{3}Li,d)^{56}_{26}Fe*$ as a surrogate reaction for $^{55}_{26}Fe(n,p)$

In order to develop a framework for planning and interpreting surrogate experiments, the following questions need to be addressed:
1. The J^{π} Population mismatch 2.Identification of the final reaction product and its excitation energy. 3. The role of pre-equilibrium reactions. 4. The role of projectile break-up.

Detailed theoretical studies on the first three of the above conditions have been performed [8-10]. Here the main emphasis is on the study of 'role of projectile break-up' i.e. if a stripping reaction such as (d, p) (^{3}He, d), (^{6}Li,d) (in the present study) is to be used in the surrogate experiment, projectile break-up in the Coulomb-plus-nuclear field of the target nucleus must be take into account. The Coulomb barrier is ~ 12 MeV for the ^{6}Li + ^{52}Cr reaction. The energy of the lithium beam ranges from 22-33 MeV. The equivalent neutron energy corresponding to 33MeV lithium-6 is 14.09 MeV.

3 Theoretical model calculations

As a light weakly bound stable nucleus ^{6}Li shows low nucleon separation energies (for ^{6}Li: Q= - 1.47 MeV for the α + d break up), therefore it is a good candidate for important break up (BU) cross-sections. This possibility affects the dynamics of fusion reaction (^{6}Li + ^{52}Cr) due to the fact that a part of the incoming flux may be lost from the entrance channel before over coming the fusion barrier and, moreover one of the fragments removed from the projectile may fuse leading to an important InCompleteFusion (ICF) or Transfer Reaction (TR) contribution. ICF is a two step process i.e. after the break up of the projectile one of the fragments, with approximately projectile velocity, interacts with the target leading to a compound system formation. On the other hand, TR would be a one-step process in which there is a transfer of fragment from the projectile to unbound states of the target followed by particle evaporation [11]. The final residual nucleus is same in both cases. When ^{6}Li interacts with ^{52}Cr all the following possible reactions can take place :

$$^{6}_{3}Li + ^{52}_{24}Cr \rightarrow ^{6}_{3}Li* + ^{52}_{24}Cr \rightarrow \alpha + d + ^{52}_{24}Cr \quad \text{(BU)} \qquad (1)$$

$$^{6}_{3}Li + ^{52}_{24}Cr \rightarrow \alpha + (^{54}_{25}Mn)* \rightarrow subsequent\ decay \quad \text{(d-ICF or d-TR)} \quad (2)$$

$$^{6}_{3}Li + ^{52}_{24}Cr \rightarrow d + (^{56}_{26}Fe)* \rightarrow subsequent\ decay \quad (\alpha\text{-ICF or }\alpha\text{-TR}) \qquad (3)$$

$$^{6}_{3}Li + ^{52}_{24}Cr \rightarrow ^{5}_{3}Li + (^{53}_{24}Cr) \rightarrow subsequent\ decay \quad \text{(Single n stripping from}^{6}\text{Li)} \quad (4)$$

$$^{6}_{3}Li + ^{52}_{24}Cr \rightarrow ^{5}_{2}He + ^{53}_{25}Mn* \rightarrow subsequent\ decay \quad \text{(Single p stripping from}^{6}\text{Li)} \quad (5)$$

$$^{6}_{3}\text{Li} + ^{52}_{24}\text{Cr} \rightarrow ^{58}_{27}\text{Co}* \rightarrow \text{subsequent decay} \quad \text{(CF)} \quad (6)$$

Reaction Q values for the (1) – (5) are -1.473, 11.8, 6.139, 22.75, 21.26 MeV respectively. Process (1) is identified as a breakup of ^{6}Li, which could be either direct or resonant (sequential). In the case there is no further capture of the BU products by the target, it will be called non-capture breakup (NCBU). Process (2) is identified as either ICF of d + ^{52}Cr (d-ICF) after BU or a direct one step d transfer (d-TR), both with subsequent decay of the excited ^{54}Mn*. Here the α is left as a "spectator". In the same way, process (3) can be identified as either ICF of α + ^{52}Cr (α-ICF) after BU or a direct one step α - transfer (α-TR), both with subsequent decay of the excited ^{56}Fe*. In this case the d is left as a "spectator". Processes (4) and (5) represent single neutron and single proton stripping from the ^{6}Li projectile, respectively with subsequent decay of the unstable ^{5}Li and ^{5}He leaves as an α particle plus a neutron or proton. Process (6) is simply identified as a complete fusion (CF).

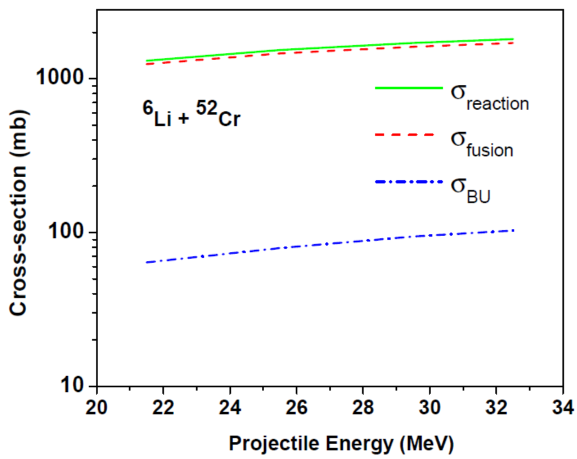

Figure 1. CDCC calculations for ^{6}Li+^{52}Cr

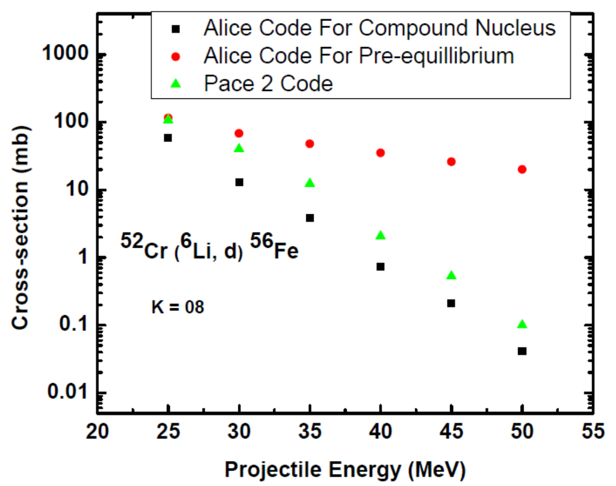

Figure 2. PACE & ALICE calculations for $^{6}Li(^{52}Cr,d)^{56}Fe^{*}$

Figure1 shows the total reaction cross-section, which is the sum of absorption and break-up cross-sections. The solid line , short dash and dash-dot lines represent the total reaction cross-section, absorption and break up cross-sections respectively using CDCC calculations in FRESCO code. The absorption cross-section is the sum of complete fusion (CF), Incomplete Fusion (ICF) and Transfer Reaction (TR) as shown in Equation (7). The complete fusion contribution (The process of the de-excitation of the excited compound nuclei) has been calculated using PACE & ALICE for $^{6}Li(^{52}Cr,d)^{56}Fe^{*}$ as shown in Figure 2. PACE code uses the Monte Carlo simulation procedure to determine the decay sequence of an excited compound nucleus using the Hauser Feshbach Formalism [12].Equation (8) shows the sum of all outgoing deuteron possibilities.

$$\sigma_{reaction} = \sigma_{abs} + \sigma_{BU}$$

$$= (\sigma_{CF} + \sigma_{ICF} + \sigma_{TR}) + \sigma_{BU} \qquad (7)$$

$$\sigma_{d} = \sigma_{\alpha-ICF} + \sigma_{\alpha-TR} + \sigma_{NCBU} + \sigma_{d-CF} \qquad (8)$$

Equation (9) shows the formation of the same compound nucleus (^{56} Fe) * with absolute surrogate method via $^{6}Li(^{52}Cr, d)^{56}Fe^{*}$. In the experiment it is planned to measure the deuteron in single and proton (which comes after the decay of $^{56}Fe^{*}$) and deuteron in coincidence. The decay probability of the excited (^{56}Fe)* is given in equations (10) & (11).

$$\left.\begin{array}{l} {}^{55}_{26}Fe + {}^{1}_{0}n \rightarrow ({}^{56}_{26}Fe)^{*} \\ {}^{52}_{24}Cr + {}^{6}_{3}Li \rightarrow d + ({}^{56}_{26}Fe)^{*} \end{array}\right\} \rightarrow {}^{55}_{25}Mn + {}^{1}_{1}H \qquad (9)$$

$$P^{CN}_{surro\ decay}\ (E_{ex}) = \frac{N^{coin}_{eje-decay}}{N_{single}}\ (E_{ex}) \qquad (10)$$

$$P^{56Fe}_{surro\ decay}\ (E_{ex}) = \frac{N^{coin}_{d-p}}{N_{d}}\ (E_{ex}) \qquad (11)$$

4 Conclusions

In this work we have presented fusion results for the intermediate mass target $^{6}Li+^{52}Cr$ reaction involving the interaction of weakly bound ^{6}Li. A statistical model analysis, CDCC calculations were used as tools to provide information on the competing process. On the basis of the present study an experiment has been proposed at the BARC-TIFR Pelletron facility in Mumbai (India) to measure the cross-section of the $^{55}Fe(n,p)^{55}Mn$ reaction with surrogate reaction $^{6}Li(^{52}Cr,d)^{56}Fe$. It is strongly recommended that the nuclear model calculation is carried out with reliable parameter sets to get a further understanding of the cross-sections and energy spectra of outgoing particles of the proposed surrogate reaction $^{52}Cr(^{6}Li,d)^{56}Fe^{*}$.
The self-supporting target of natural Cr and enriched $^{52,53}Cr$ are being prepared using various sputtering techniques, evaporation techniques and electroplating, as normal rolling does not work due to its brittle nature. For 1-3 micron Cr target deposition, we are using sub micron grade polished NaCl crystal as substrate.

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