

Statistical model calculations for evaporation residue and fission cross-section for $^{48}\text{Ti} + ^{122}\text{Sn}$ system

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Abstract. Statistical model calculations are performed for $^{48}\text{Ti} + ^{122}\text{Sn}$ system to reproduce the experimentally available evaporation residue (ER) and fission cross-section data using the spin distribution obtained from the CCFULL code after fitting the experimental fusion cross-section at every energy point. For this, the fission barrier (B_f) is scaled by a scaling factor (K_f) in the statistical model code input which varies in the range of 0.5 to 1.0.

1 Introduction

Heavy ion induced reactions are very important to synthesize heavier elements [1]. The synthesization occurs due to complete fusion of two massive nuclei and it is a very complex process. When a projectile comes in contact with a target nucleus then along with evaporation residue (ER) formation, other processes like fission, quasi-fission (QF) [2] and fast-fission etc. can take place, which hinder the formation of heavy residues. All these processes take away the flux associated with formation of ERs. There are other factors like shell effect, deformation and entrance channel etc., which also influence the formation of heavy residues. Due to the presence of these factors, it has observed that the fusion barrier gets modified. Schematically, fusion enhancement [3] and fusion hindrance phenomena both are present in the energy range around the Coulomb barrier for heavy systems. In order to understand the fusion-fission dynamics [4], a detailed study of the decay products is very important, which can be probed through the ER and fission cross-section measurements.

To understand the behaviour of heavy projectile induced reactions on fusion-fission dynamics, we have planned to study ^{48}Ti induced reactions. We are also interested to investigate the effect of deformation, shell and entrance channel, etc., in heavy mass target. Our aim was to choose the system for which experimental data on ER and fission cross-section is already available. In the present work, we have chosen a $^{48}\text{Ti} + ^{122}\text{Sn}$ system for theoretical calculations because experimental data on an ER cross-section [5] and fission cross-section [6] are available. Theoretical calculations performed using statistical model code [7]. Details of the statistical model code and the calculations are given in section 2 and the results are given in section 3.

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2 Theoretical calculations

2.1 Statistical model of CN decay

Statistical concepts and models are very useful to extract information of nuclear processes. Statistical model of the compound nucleus (CN) decay is based on the assumption that the whole nuclear flux leads to the CN formation, i.e. complete fusion between target and projectile after capture while the possibility of non-compound events are neglected. The CN formed in fusion-fission reaction decays via two major channels: ER and fission. It deals with various decay modes like the evaporation of light charged particles (proton, α -particle), neutron along with γ -ray emission and fission. The emission of a particle says ν (neutron, proton or α -particle) is governed by partial decay width Γ_ν , which is defined by $\Gamma_\nu = \hbar/\tau_\nu$, where τ_ν is the corresponding decay time. The particle and γ partial decay widths are obtained from the standard Weisskopf formula [8].

The competition between neutron width (Γ_n) and fission width (Γ_f) is the main determining factor for deciding the fate of the CN. At lower l values Γ_f is much less than the Γ_n but with the increase in l values these widths become comparable and at much higher l values Γ_f becomes larger than Γ_n . These widths depend upon the temperature, spin and the mass number of the CN and hence evaluated after each particle or γ -ray emission during evolution of the CN.

2.2 Coupled channel calculations

The analysis of experimentally obtained fusion cross-section is performed using the coupled channel (CC) code CCFULL [9], which takes into account nonlinear coupling of all orders. It makes use of the ingoing wave boundary conditions that are imposed at the minimum of the

pocket of the entrance potential along with no-coriolis approximation, which suits to describe the fusion of heavy systems at sub-barrier energies. Considerable progress has achieved in understanding enhancement of the fusion cross-section by including various degrees of freedom such as deformation, nucleon transfer and nonlinear coupling. These effects reveal an interesting interplay between the dynamics of the reaction and the structure of the participant nuclei.

One of the important input of the statistical model code is the spin distribution of the fused system, which can be obtained by fitting the experimental fusion cross-section by using a suitable model. The projectile ^{48}Ti has a permanent quadrupole deformation. The coupling of the first 2^+ states of the projectile ($E_{ex} = 0.983$, $\beta_2 = 0.27$) and the target ($E_{ex} = 1.140$ MeV, $\beta_2 = 0.103$) are considered as vibrational excitations. The low-lying octupole vibration of the target ($E_{ex} = 2.49$ MeV, $\beta_3 = 0.12$) is also included in the CC calculations. In addition to it, the effect of one nucleon transfer channel is also considered. One neutron pickup to the ground state is chosen as the most favorable one based on Q value ($Q_{TRANS} = 0.67$ MeV) for single nucleon transfer. In these calculations the default single nucleon transfer form factor (FTR) of value 0.2 is used. In the input file, potential adjustable parameters have adjusted to reproduce the experimental fusion cross-section. The values obtained were $V_0 = 130$ MeV, $R_0 = 1.16$ fm and $A_0 = 0.61$ fm, where V_0 is the depth parameter of the Woods-Saxon potential, R_0 is the radius parameter r_0 , and A_0 is the surface diffuseness parameter a .

After using all the above parameters in the CCFULL input, we performed the CC calculations with and without coupling. The fitted experimental fusion cross-section for $^{48}\text{Ti} + ^{122}\text{Sn}$ system is shown in Figure 1. The quality of fit

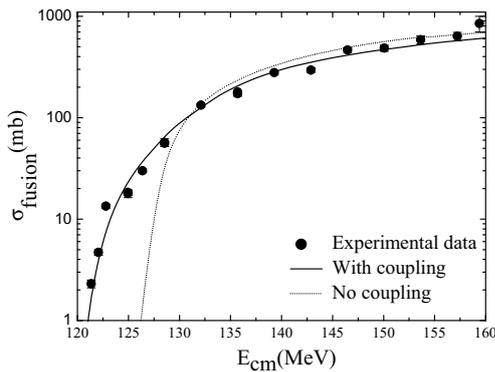


Figure 1. Fusion cross-section versus center of mass energy (E_{cm}) for $^{48}\text{Ti} + ^{122}\text{Sn}$ system. Full dots for the experimental fusion cross-section, solid line for the theoretical calculation with coupling and dashed line corresponds to theoretical calculation without coupling.

in the present CC calculation is similar to the one obtained in [5] from the code CCDEF [10]. We have performed the CC calculation at each energy point and fitted the fusion cross-section by adjusting the potential adjustable param-

eters. The CN spin distribution obtained from CCFULL code at each energy point is subsequently used as an input in the statistical model code.

2.3 Statistical model calculations

The final theoretical calculations are performed using Bohr-Wheeler (BW) formalism [11] including shell-correction in the level density. The BW fission width (Γ_{BW}) is obtained as a phase space integral over all the available states at the saddle point [12], is given by

$$\Gamma_{BW} = \frac{1}{2\pi\rho_g(E_i)} \int_0^{E_i - B_f} \rho_s(E_i - B_f - \varepsilon) d\varepsilon \quad (1)$$

where ρ_g and ρ_s are the level densities at the ground state and at the saddle point respectively. E_i is the initial excitation energy of the CN and B_f is the fission barrier, which is obtained from the finite-range liquid drop model (FRLDM) [13].

Now, we have introduced a scaling factor (K_f) for the FRLDM barrier and treated it as an adjustable parameter to fit the experimental ER and fission cross-section [14, 15]. The K_f is varies between 0.5 to 1.0 as shown in Figure 2 and we have adjusted K_f value to reproduce the experi-

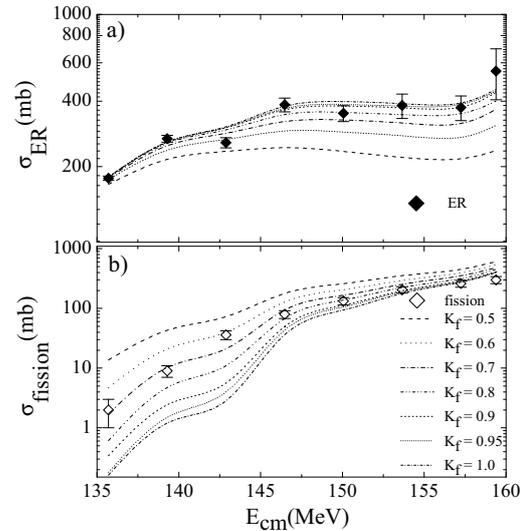


Figure 2. a) Experimental ER cross-section (filled diamond) versus center of mass energy (E_{cm}) along with theoretical results by using statistical model calculation for different values of K_f , and b) Experimental fission cross-section (open diamond) versus center of mass energy (E_{cm}) along with theoretical results by using statistical model calculation for different values of K_f .

mental cross-section at every energy point. The best-fit value of K_f is found to be 0.8 as shown in Figure 3. We found an energy dependence of K_f as we fitted the individual data point and the best-fitted K_f value 0.8 lies between the dispersion of K_f (0.6-1.0) values.

It is to be noted that in another recent calculation by Sagaidak *et al.* [16], best-fit value of K_f is reported to

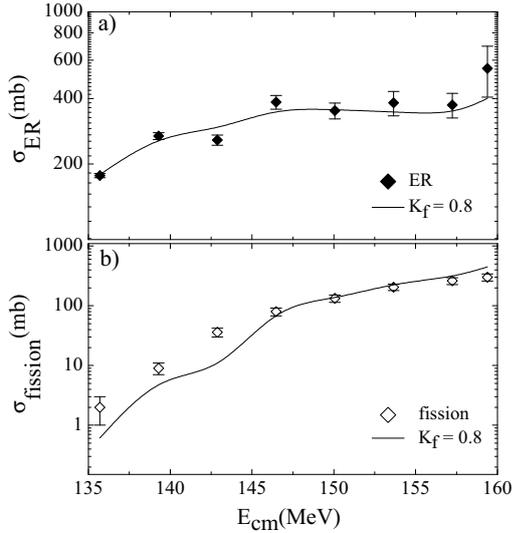


Figure 3. a) ER cross-section and b) fission cross-section versus center of mass energy (E_{cm}). Diamonds (filled and open) for experimental data and the solid line is for the best-fitted $K_f = 0.8$ using the statistical model calculation including shell-correction in the level density.

be 0.8 at higher excitation energies. Our results show a better fit at $K_f = 0.8$ for lower excitation energies. The difference is possibly due to the choice of different input parameters in the calculations. They have used a shell-corrected fission barrier while we have used FRLDM barrier which is lower. Consequently, our ER cross-sections are smaller than that found in [16], which means a higher value of best-fit K_f in our case. Further, we included the shell-correction in level density parameter which was taken from the work of Ignatyuk *et al.* [17]. The effect of including shell-correction in level density parameter is to reduce the ER cross-section. A better description of the energy dependence of K_f can be obtained when shell effects are included in both the fission barrier and the level density parameter. We plan to do such studies in our future works.

3 Result and discussion

From the Figure 4 it is found that, for ER and fission cross-sections at lower energies, K_f varies in the range of 0.5-0.8 but at higher energies, K_f varies in the range of 0.9-1.0. The lower values of K_f at lower energies may indicate quasi-fission (QF), which reduces the fusion cross-section. There is deviation of K_f from the general trend (for both ER and fission) at two energy points (142.88 MeV and 150.06 MeV), which essentially reflects a higher ER cross-section and lower experimental fission cross-section at those particular energy points. This deviation from the general trend is not understood at present. Hence, more measurements are necessary to understand the ER and the fission competition for ^{48}Ti -like induced reactions in this mass region. Such measurements are also

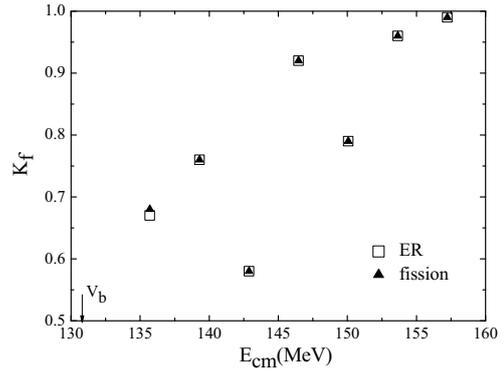


Figure 4. Best-fitted K_f value versus center of mass energy (E_{cm}) for $^{48}\text{Ti} + ^{122}\text{Sn}$ system using statistical model calculations.

necessary to disentangle QF versus shell effect. Using the HYRA [18] spectrometer, we plan to do such experiments on ER and fission cross-section measurements for $^{48}\text{Ti} + ^{150}, ^{142}\text{Nd}, ^{144}\text{Sm}$ systems.

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