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Statistical model calculations for evaporation residue and fission cross-sections in ^{210}Po compound nucleus

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Abstract. Statistical model calculations for evaporation residue and fission cross-sections are performed for ^{210}Po nucleus populated by ^{18}O + ^{192}Os system in the excitation energy range of 52.43 - 83.51 MeV. Experimental fusion cross-sections are fitted using CCFULL code. Evaporation residue and fission cross-sections are then fitted using Bohr-Wheeler formalism including shell effects in level density and fission barrier by using scaling factor (K_f) in the range of 1.0 to 0.75. The results of the calculations are in good agreement with the experimental data.

1 Introduction

Heavy ion induced fusion-fission reactions are important to study the dynamics and decay of hot nuclear matter. These reactions are sensitive to entrance channel mass asymmetry between the target and projectile, the spin and deformation of the target, the mass of the projectile and the bombarding energy with respect to fusion barriers and coupling of various degrees of freedom [1, 2]. At low energies, compound nucleus decays predominantly by emission of particles and fission. Experimental observations clearly show that fusion cross-section is significantly reduced in medium mass region even for very asymmetric systems due to onset of non-compound nuclear processes like quasi fission [3]. Evaporation residues are signature of compound nucleus formation and useful probe to study the statistical as well as dynamical aspects of fusion-fission reactions. For gaining a better insight into heavy ion reactions, a detailed study of the decay products of the compound nucleus, such as evaporation residues and compound nucleus fission fragments is necessary. In this regard, evaporation residue and fission cross-section measurements are useful probes to understand the fusion-fission dynamics.

Sagaidak *et al.* [4], have found that LDM fission barrier has to be reduced in order to fit the evaporation residue and fission excitation functions leading to Polonium compound nuclei in the framework of the standard statistical model. With same motivation, statistical model calculations for evaporation residue and fission cross-sections have been performed for ^{210}Po populated by ^{18}O +^{192}Os system in the excitation energy range 52.43 - 83.51 MeV. The experimental data for evaporation residue and fission cross-sections have been extracted from [2]. Coupled channels calculations (CCFULL) reproduce the experimental fusion cross-sections satisfactorily [5]. Then, in order to fit the experimental data for evaporation residue and fission cross-sections, final theoretical calculations were performed using Bohr-Wheeler formalism including shell-corrections in the level density and fission barrier. Different scaling factors (K_f) for the finite-range liquid drop model fission barrier in the range 1.0 to 0.75 are used to fit the experimental data.

2 Statistical model analysis

In the framework of statistical model, emission of neutrons, protons, alpha particles and giant dipole resonance (GDR) gamma rays are considered along with fission as the possible decay channels of a compound nucleus [6]. Statistical model calculations for evaporation residue and fission cross-sections have been performed assuming that the system forms a fully equilibrated compound nucleus after capture of projectile and contribution from non-compound nuclear processes such as quasi fission and fast-fission are negligible. The Bohr-Wheeler fission width used in the present calculations is given by [7]:

$$\Gamma_{BW} = \frac{1}{2\pi\rho(E^*)} \int_0^{E^*-V_B} d\epsilon \rho^*(E^* - V_B - \epsilon) \qquad (1)$$

Here, V_B is the fission barrier and the nuclear potential is obtained from the finite range liquid drop model (FRLDM). The level density parameter used in the present work is taken from the work of Ignatyuk *et al.* [8], which takes into account the nuclear shell structure at low excitation energies and goes over to its asymptotic form at high excitation energies as given below:

$$a(E^*) = a(1 + \frac{f(E^*)}{E^*}\delta M) \qquad (2)$$

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where,

$$f(E^*) = 1 - \exp^{\frac{-E^*}{E_D}} \quad (3)$$

Here, a is the asymptotic level density parameter and E_D determines the rate at which the shell effects disappear at high excitation energy and δM is the shell correction in the LDM masses, i.e.

$$\delta M = M_{experimental} - M_{LDM} \quad (4)$$

A value of 18.5 MeV was used for E_D, which was obtained from an analysis of s-wave neutron resonances [9]. The shell-corrected temperature-dependent fission barrier is given by:

$$V_B(T) = K_f V_{LDM} - \delta M \exp^{\frac{-E^*}{E_D}} \quad (5)$$

where K_f is the scaling factor [4], V_{LDM} is the fission barrier from the finite-range rotating LDM potential and E^* is the compound nucleus excitation energy. In our analysis, evaporation residue and fission cross-sections are fitted with the adjustment of scaling factor K_f in the fission barrier. In this work, shell correction is applied only to the ground state mass, and it is assumed that the shell correction at the saddle deformation can be neglected [10-12]. The above assumption of neglecting the shell correction at the saddle deformation follows from the work of Myers and Swiatecki [10]. A particular decay channel is selected by performing Monte-Carlo sampling between all the particles and gamma emission widths. Spin distribution of the fused system is obtained by fitting the experimental fusion cross-section using a suitable model. So, to reproduce the experimental fusion cross-section coupled channels calculations have been performed using CCFULL [5].

2.1 CCFULL

Fusion reactions at energies near and below the Coulomb barrier are strongly influenced by couplings of the relative motion of the colliding nuclei to several nuclear intrinsic motions. The program CCFULL solves the coupled-channels equations to compute the fusion cross-sections and mean angular momenta of compound nucleus, taking into account the couplings to all orders. It works on the ingoing-wave boundary condition inside the Coulomb barrier to account for fusion, along with the isocentrifugal approximation, which works well for heavy ions. The nuclear potential in the entrance channel is defined by parameters V_0, r_0 and a_0; where V_0 is the depth parameter of the Woods-Saxon potential, r_0 is the radius parameter, and a_0 is the surface diffuseness parameter.

3 Results and discussions

Spin distribution of the compound nucleus is an important ingredient of statistical model and this can be obtained either from Frobrich systematics or by fitting the experimental fusion cross-section with some appropriate model. In this work, spin distribution of the fused system has been generated using CCFULL code. Depending upon the value of E(4^+) / E (2^+), nuclei can be classified as vibrator or rotor. If this ratio is 3.3, the nucleus is treated as rotor and as vibrator if this value is 2. In case of ^{18}O +^{192}Os system, the projectile ^{18}O is treated as a vibrator and target ^{192}Os is treated as a rotor. The deformation parameters along with the value of E(4^+) / E (2^+) are given in the Table 1.

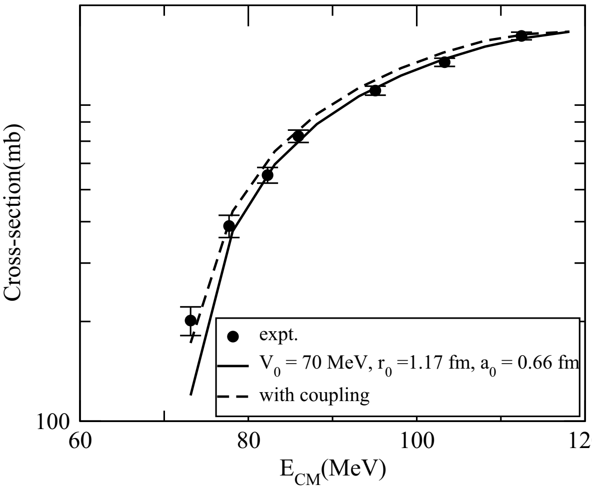

Figure 1. Experimental capture cross-section (full dots) for ^{18}O + ^{192}Os as a function of E_{CM} (center of mass energy). Dashed line shows coupling and solid line shows no coupling.

Table 1. Values of β_2, β_4 and E(4^+) / E (2^+)

Nucleus	β_2	β_4	E(4^+) / E (2^+)
^{18}O	0.355	-	1.8
^{192}Os	0.167	-0.081	2.82

The potential parameters used in the present coupled channels calculations were chosen by fitting the experimental capture cross-section and is shown in Figure 1. The fitted values V_0, r_0 and a_0 are given in Table 2. Here, V_0 is the depth parameter of the Woods-Saxon potential, r_0 is the radius parameter, and a_0 is the surface diffuseness parameter.

Table 2. Fitting parameters from CCFULL code

Nucleus	V_0	r_0	a_0
^{210}Po	70 MeV	1.17 fm	0.66 fm

From Figure 1, it is clear that the energy points above the Coulomb barrier are reproduced without including the coupling effects whereas energy points well below the Coulomb barrier are reproduced taking into consideration the coupling effects. This is because coupling among the intrinsic degrees become more dominant at energies near and close to the Coulomb barrier.

After fitting, CCFULL gives the spin distribution (for capture cross-sections) which is then used as the spin distribution of compound nucleus for statistical model code to fit the experimental evaporation residue and fission cross-sections. In order to fit the experimental data for evapo-

Table 3. Evaporation residue and fission cross-sections (in mb) calculated using statistical model for ^{18}O + ^{192}Os as a function of E_{Lab}(MeV). σ_{ER} and $\sigma_{fission}$ are the evaporation residue and fission cross-sections, calculated using Bohr-Wheeler fission width, respectively.

	$K_f = 1.0$		$K_f = 0.95$		$K_f = 0.90$		$K_f = 0.80$		$K_f = 0.75$	
E_{Lab}(MeV)	σ_{ER}	$\sigma_{fission}$	σ_{ER}	$\sigma_{fission}$	σ_{ER}	$\sigma_{fission}$	σ_{ER}	$\sigma_{fission}$	σ_{ER}	$\sigma_{fission}$
80	220.2	1.4	219.5	2.1	218.5	3.1	215.0	6.6	212.2	9.3
85	404.4	5.8	401.4	8.8	398.7	11.5	388.8	21.4	381.3	28.9
90	550.5	18.0	545.5	23.1	539.5	29.0	518.5	50.1	501.1	67.4
94	686.6	39.9	676.0	50.5	660.2	66.4	624.0	102.6	543.6	132.9
104	799.6	194.9	767.3	227.3	734.8	259.8	635.1	359.4	578.6	415.9
114	729.9	502.4	690.2	542.1	644.9	587.4	535.6	696.8	474.8	757.5
123	606.4	833.3	560.2	879.5	523.2	916.5	419.1	1020.6	364.4	1075.3

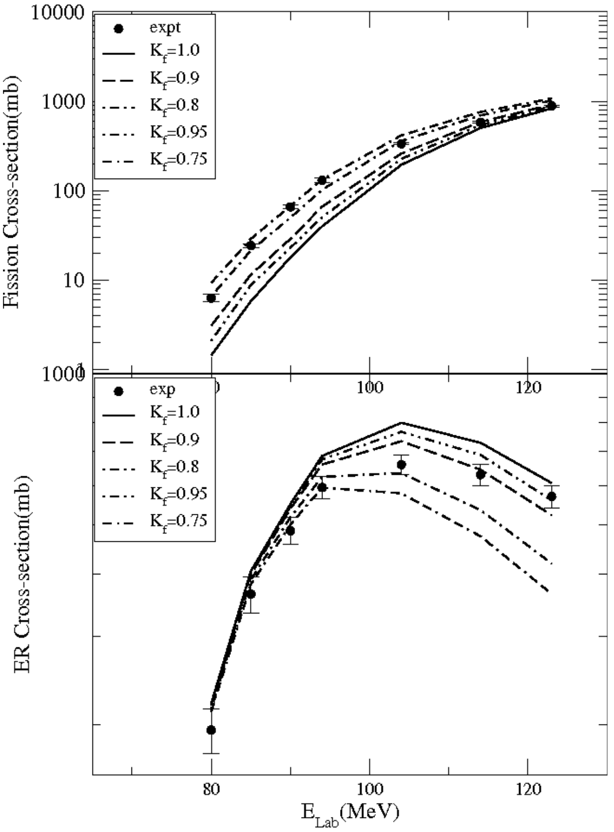

Figure 2. Solid circles are the experimental data and different lines are the theoretical calculations for different scaling factor, K_f (as given inside the diagram): (a) For Fission cross-section (b) For Evaporation residue cross-section.

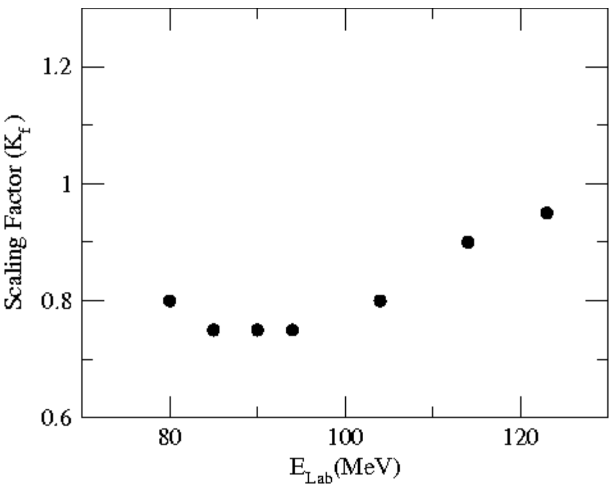

Figure 3. Variation of scaling factor (K_f) with E_{Lab}(MeV)

ration residue and fission cross-sections, final theoretical calculations were performed using Bohr-Wheeler formalism including shell-correction in the level density and fission barrier. For reproducing the data, different scaling factors (K_f) in the range 1.0 to 0.75 have been used. The evaporation residue and fission cross-sections calculated using statistical model and Bohr-Wheeler formalism are enumerated in Table 3. The fitted fission and evaporation residue cross-sections are shown in Figure 2.

From Figure 2, it becomes clear that the scaling factor has to be reduced from $K_f = 1.0$ to 0.75 to describe the excitation function in the whole range of compound nucleus excitation energy. As the scaling factor is directly related to fission barrier, decreasing the scaling factor implies a reduced fission barrier. It was observed that the statistical model results using Bohr-Wheeler approach overpredict the evaporation residue cross-sections, especially at high excitation energies and, underpredict the fission cross-sections throughout the entire energy range under study. Also, at lower energies, fission cross-section is a very small fraction of total fusion cross-section. Hence, to fit the evaporation residue cross-section in the desired range, we have to increase the fission cross-section and this is done by reducing the fission barrier. In other words we can say that for reducing the fission barrier we have to reduce the scaling factor (K_f) to fit the evaporation residue and fission cross-section data. For the present system we have found that the scaling factor increases with increase in the lab energy as shown in Figure 3.

This may be due to quasi fission events which are important for asymmetric systems in recent studies. It was believed that quasi fission becomes dominant only when the charge product $Z_P Z_T > 1600$. In an experiment, quasi fission events are detected as fission events and since quasi fission does not go through compound nucleus formation, there will be a reduction in evaporation residue cross-section. Hence, does not reflect the true fission barrier and is certainly not due to any shell effects in fission barrier. Such strong reduction of fission barrier in statistical model calculations, however, points to quasi fission in the system.

4 Conclusion

Present study indicates the need to reduce the FRLDM fission barrier in order to fit the experimental evaporation residue and fission cross-sections. More systematic data are required in order to understand the reason for lowering of the fission barrier. Such experiments are planned to be carried out at IUAC, New Delhi in the near future.

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