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Evaporation residue cross section for the synthesis of superheavy element Fl in the reactions ^{242,244}Pu+^{48}Ca

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Abstract: *Systematic calculations of the production cross section for the synthesis of superheavy elements ^{290,292}Fl using the reactions ^{48}Ca+^{242}Pu and ^{48}Ca+^{244}Pu are performed. We have studied the interaction barriers for these reactions against the distance between the centers of the projectile and target by taking Coulomb and proximity potential as the scattering potential. The fusion probability and survival probability of excited compound nucleus are calculated. At energies near and above the Coulomb barrier, capture, fusion and evaporation residue cross sections have been evaluated. The maximum value of 3n channel evaporation residue cross section for ^{48}Ca+^{242}Pu, ^{48}Ca+^{244}Pu reactions are 4.349 pb and 5.746 pb respectively. The highest yields for the 4n channel for these reactions are 4.006 pb and 9.079 pb respectively. Our calculated results are in good agreement with experimental data.*

Keywords: *Superheavy elements, Cross section, Coulomb and proximity potential, Evaporation residue*.

I. Introduction

Studies on the synthesis of superheavy elements (SHEs) have been a great interest in the area of both experimental and theoretical nuclear physics [1-2]. Elements heavier than uranium are not usually found in nature but they can be produced forcefully using nuclear fusion reactions. Two mechanisms, namely hot and cold fusion reactions are employed for the production of SHEs. In hot fusion reactions, ^{48}Ca is mainly used as projectile and actinide as targets. In cold fusion reactions Pb or Bi is used as target nucleus. Theoretical studies predict the existence of "island of stability" located within a sea of radioisotopes in the region of SHEs.

The studies predicts Z=114, 116, 120,126 and N=126, 184 as magic numbers for proton and neutron respectively [4-6].

Elements up to Z=118 have been synthesized in the laboratory [3] and an attempts to produce Z=120 is done [2, 4] and is still going on. Recently IUPAP/ IUPAC announced the names of element 113,115,117 and 118 as nihonium, moscovium, tennessine and oganesson respectively and updated the periodic table. Usually the measured cross section for the production of SHE is in order of pico barn and hence it is very sensitive to the projectile-target pair used, center of mass energy, probability of CN formation, and survival probability.

In the present work, we have calculated the excitation functions for the reactions ^{48}Ca+^{242}Pu and ^{48}Ca+^{244}Pu leading to the compound nuclei (CN) ^{290}Fl and ^{292}Fl respectively. Experimental studies using these reactions are already been performed at different laboratories [7-12]. For the reaction ^{242}Pu+^{48}Ca at the energy E*=40.2 MeV, the maximum value of evaporation residue (ER) cross sections measured by Oganessian et al., are $\sigma_{3n} = 3.6^{+3.4}_{-1.7}$ pb and $\sigma_{4n} = 4.5^{+3.6}_{-1.9}$ pb [7-8]. Stavsetra et al., measured the cross section of $1.4^{+3.2}_{-1.2}$ pb for the same reaction (3n-4n) leading to the CN ^{290}Fl [9]. This value is later revised to $3.1^{+4.9}_{-2.6}$ pb [10]. In 2010, Ellison et al, measured the cross section $0.6^{+0.9}_{-0.5}$ pb for the ^{242}Pu+^{48}Ca reaction for 5n channel. For the reaction ^{244}Pu+^{48}Ca leading to ^{292}Fl, the maximum cross section measured by Oganessian et al., [8, 11] is $\sigma_{3n} = 1.7^{+2.5}_{-1.1}$ pb and $\sigma_{4n} = 5.3^{+3.6}_{-2.1}$ pb. Isotopes of element Fl were produced by Gates et al., [12] in irradiation of ^{244}Pu targets with ^{48}Ca beams at excitation energies around 37.5-41.7 MeV.

In the present work, we have used the Coulomb and proximity potential as the interaction barrier for calculating the Coulomb barrier. The excitation functions are systematically calculated by considering the probability of CN formation and survival probability. The details of the scattering potential and the methodologies used in the estimation of the cross sections are described in Sec.2. In Sec.3, results and discussion are given, and the entire work is summarized in Sec.4.

II. Theory

2.1 The Potential

The interaction barrier for the two colliding nuclei is given as:

$$V = \frac{Z_1 Z_2 e^2}{r} + V_P(z) + \frac{\hbar^2 \ell(\ell+1)}{2\mu r^2}, \tag{1}$$

where Z_1 and Z_2 are the atomic numbers of projectile and target, r is the distance between the centers of the projectile and target, z is the distance between the near surfaces of the projectile and target, ℓ is the angular momentum, and μ is the reduced mass.

The term $V_P(z)$ is the proximity potential [13] given as:

$$V_P(z) = 4\pi\gamma b \frac{C_1 C_2}{C_1 + C_2} \phi(\frac{z}{b}) \tag{2}$$

with the nuclear surface tension coefficient:

$$\gamma = 0.9517[1 - 1.7826(N-Z)^2 / A^2] \tag{3}$$

ϕ, the universal proximity potential is given as:

$$\phi(\xi) = -4.41\exp(-\xi/0.7176), \quad \text{for } \xi \geq 1.9475 \tag{4}$$

$$\phi(\xi) = -1.7817 + 0.9270\xi + 0.01696\xi^2 - 0.05148\xi^3, \text{ for } 0 \leq \xi \leq 1.9475 \tag{5}$$

$$\phi(\xi) = -1.7817 + 0.9270\xi + 0.0143\xi^2 - 0.09\xi^3, \text{ for } \xi \leq 0 \tag{6}$$

with $\xi = z/b$, where the width (diffuseness) of nuclear surface $b \approx 1$ fm and C_i is the Susmann Central radii.

For R_i, we use the semi empirical formula in terms of mass number A_i as:

$$R_i = 1.28A_i^{1/3} - 0.76 + 0.8A_i^{-1/3}$$

2.2 Cross Section

2.2.1 Capture Cross section

The capture cross section at a given center-of-mass energy E can be written as the sum of the cross section for each partial wave ℓ:

$$\sigma_{capture} = \frac{\pi}{k^2}\sum_{\ell=0}^{\infty}(2\ell+1)T(E,\ell) \cdot \tag{7}$$

Wong [14] approximated the various barriers for different partial waves by inverted harmonic oscillator potentials of height E_ℓ and frequency ω_ℓ and arrived at the total cross section for the fusion of two nuclei. For energy E, the probability for the absorption of ℓ^{th} partial wave given by Hill-Wheeler formula [15] is:

$$T(E,\ell) = \{1 + \exp[2\pi(E_\ell - E)/\hbar\omega_\ell]\}^{-1} \tag{8}$$

Using some parameterizations in the region $\ell = 0$ and replacing the sum in Eq. (8) by an integral, Wong gave the total/capture cross section as:

$$\sigma_{capture} = \frac{R_0^2 \hbar\omega_0}{2E} \ln\left\{1 + \exp\left[\frac{2\pi(E - E_0)}{\hbar\omega_0}\right]\right\}, \tag{9}$$

where R_0 is the barrier radius and E_0 is the barrier height, $\hbar\omega_0$ is the curvature of the inverted parabola for $\ell = 0$.

2.2.2 Fusion cross section

The fusion cross section is expressed as

$$\sigma_{fusion} = \frac{\pi}{k^2}\sum_{\ell=0}^{\infty}(2\ell+1)T(E,\ell)P_{CN}(E,\ell), \tag{10}$$

where P_{CN} is the probability of compound nucleus formation which is described in next section.

2.2.2.1 Probability of compound nucleus formation, P_{CN}

Ambruster [16] has suggested:

$$P_{CN} = 0.5\exp(-c(x_{eff} - x_{thr})). \tag{11}$$

We used the energy dependent expression for fusion probability to calculate P_{CN} and it is given by:

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$$P_{CN}(E,\ell)=\frac{\exp\{-c(x_{eff}-x_{thr})\}}{1+\exp\left\{\frac{E_B^*-E^*}{\Delta}\right\}} \qquad (12)$$

where E^* is the excitation energy of the compound nucleus is, E_B^* denotes the excitation energy of the CN when the center-of-mass beam energy is equal to the Coulomb and proximity barrier, Δ is an adjustable parameter ($\Delta=4MeV$) and x_{eff} is the effective fissility defined as:

$$x_{eff}=\left[\frac{(Z^2/A)}{(Z^2/A)_{crit}}\right]\left(1-\alpha+\alpha f(k)\right) \qquad (13)$$

with $(Z^2/A)_{crit}$, $f(k)$ and k is given by:

$$(Z^2/A)_{crit}=50.883\left[1-1.7286\left(\frac{(N-Z)}{A}\right)^2\right] \qquad (14)$$

$$f(k)=\frac{4}{K^2+K+\frac{1}{k}+\frac{1}{k^2}} \qquad (15)$$

$$k=(A_1/A_2)^{1/3} \qquad (16)$$

where Z, N and A represent the atomic number, neutron number and mass number respectively. A_1 and A_2 are mass number of projectile and target respectively. x_{thr}, c are adjustable parameters and α =1/3. The best fit to the cold fusion reaction, the values of c and x_{eff} are 136.5 and 0.79 respectively. For hot fusion reaction, the best fit for x_{eff} $\leq$ 0.8 is c =104 and x_{thr} =0.69; while x_{eff} $\geq$ 0.8, the values are c = 82 and x_{thr} = 0.69. These constants are suggested by Loveland [17]. This form of energy dependence of fusion probability is similar to the one proposed by Zargrebeav [18].

2.2.3. Evaporation residue cross section

The cross section of SHE production in a heavy ion fusion reaction with subsequent emission of *x* neutrons is the product of capture cross section $\sigma_{capture}$, the fusion probability P_{CN} and survival probability W_{sur}.

$$\sigma_{ER}^{xn}=\frac{\pi}{k^2}\sum_{\ell=0}^{\infty}(2\ell+1)T(E,\ell)P_{CN}(E,\ell)W_{sur}^{xn}(E^*,\ell), \qquad (17)$$

W_{sur} is the probability for the compound nucleus to decay to the ground state of the final residual nucleus via evaporation of light particles and gamma ray for avoiding fission process and is described in next section.

2.2.3.1 Survival probability

The survival probability under the evaporation of *x* neutrons is

$$W_{sur}=P_{xn}(E_{CN}^*)\prod_{i=1}^{i_{max}=x}\left(\frac{\Gamma_n}{\Gamma_n+\Gamma_f}\right)_{i,E^*} \qquad (18)$$

where the index 'i' is equal to the number of emitted neutrons, P_{xn} is the probability of emitting exactly *xn* neutrons [19], E^* is the excitation energy of the compound nucleus, Γ_n and Γ_f represent the decay width of neutron evaporation and fission respectively. To calculate Γ_n/Γ_f, Vandenbosch and Huizenga [20] have suggested a classical formalism:

$$\frac{\Gamma_n}{\Gamma_f}=\frac{4A^{2/3}a_f(E^*-B_n)}{K_0a_n[2a_f^{1/2}(E^*-B_f)^{1/2}-1]}\exp[2a_n^{1/2}(E^*-B_n)^{1/2}-2a_f^{1/2}(E^*-B_f)^{1/2}], \qquad (19)$$

where A is the mass number of the nucleus considered, E* is the excitation energy, B_n neutron separation energy. The constant K_0 is taken as 10MeV. $a_n=A/10$ and $a_f=1.1a_n$, are the level density parameters of the daughter nucleus and the fissioning nucleus at the ground state and saddle configurations respectively. B_f is the fission barrier and this height is a decisive quantity in the competition between processes of neutron evaporation and fission.

III. Results and discussion

We have studied the interaction barriers (scattering potential energy curve) for the fusion of the projectile ^{48}Ca on ^{242,224}Pu target against the distance between the centers of the colliding nuclei and the corresponding barrier height V_B, the barrier radius R_B are noted. The scattering potential energy curves for these

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reactions are shown in Fig. 1. The barrier height for the reactions ^{242}Pu+^{48}Ca, ^{244}Pu+^{48}Ca are 200.683 MeV and 200.3 MeV respectively and the corresponding barrier positions are 12.64 fm and 12.67 fm respectively. The probabilities of CN formation for these reactions are calculated using equation (15) and are shown in Fig.2. It is found that P_{CN} is larger for the more asymmetric combination ^{48}Ca+^{244}Pu leading to the compound nucleus ^{292}Fl.

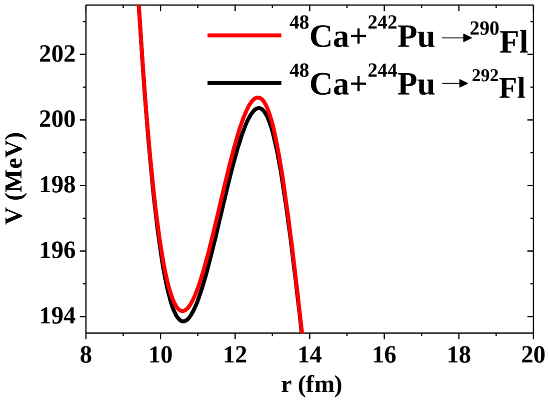

Fig. 1: Scattering potential for the reactions ^{48}Ca+^{242}Pu and ^{48}Ca+^{244}Pu.

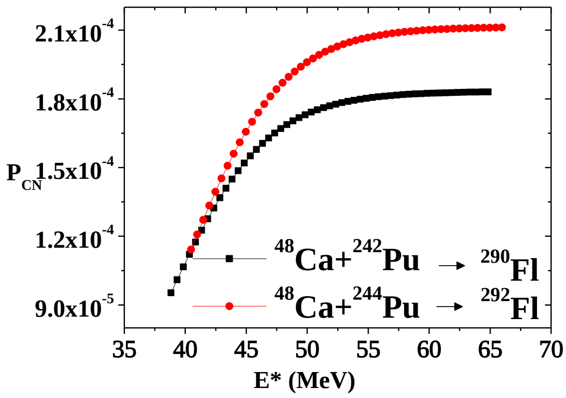

Fig. 2: The plot of P_{CN} vs E* in MeV for the reactions ^{48}Ca+^{242}Pu and ^{48}Ca+^{244}Pu.

We have evaluated the capture cross sections as a function of excitation energy (excitation function) for the ^{48}Ca+^{242,244}Pu reactions using the Wong formula. The fusion cross sections of these two reactions are also calculated. The corresponding excitation functions for the two reactions are shown in Fig. 3 and 4. In Fig. 3 and 4, the black line represents the capture cross section and red line represents the fusion cross section.

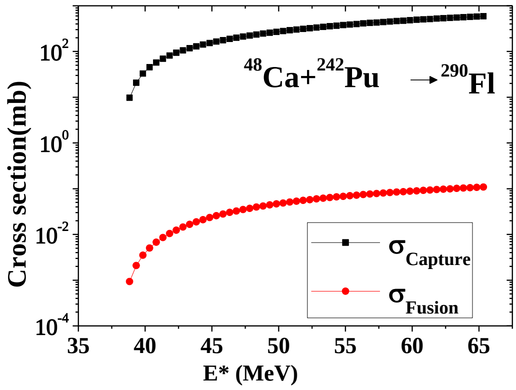

Fig. 3: Calculated capture and fusion cross section for ^{48}Ca+^{242}Pu.

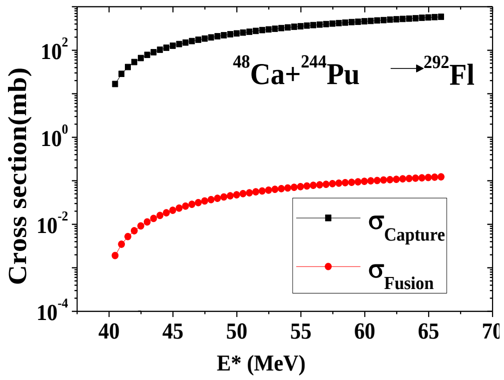

Fig. 4: Calculated capture and fusion cross section for ^{48}Ca+^{244}Pu.

We have estimated the survival probability of excited CN and then ER cross sections for the fusion of ^{48}Ca+^{242,244}Pu is calculated. The calculated ER cross sections in 3n, 4n and 5n evaporation channels are presented in Figs. 5 and 6. The maximum value of ER cross section for 3n, 4n, and 5n channel for the fusion reaction ^{48}Ca+^{242}Pu leading to CN ^{290}Fl are 4.349, 4.006, 0.140 pb respectively. For the reaction ^{48}Ca+^{244}Pu leading to CN ^{292}Fl, the ER cross section for 3n, 4n, 5n channel are 5.746, 9.079, 1.004 pb respectively. Our calculated values are in good agreement with experimental data [7-12]. The calculated ER cross section for the more asymmetric combination ^{48}Ca+^{244}Pu is found to be higher than less asymmetric combination ^{48}Ca+^{242}Pu.

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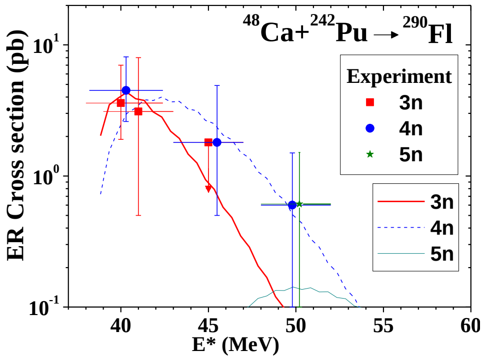

Fig. 5: Calculated ER excitation function for $^{48}Ca+^{242}Pu$. Experimental values are taken taken from the Refs. [7-10]

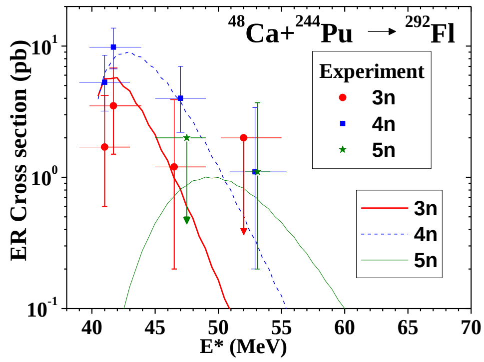

Fig.6: Calculated ER excitation functions for $^{48}Ca+^{244}Pu$. Experimental values are from the Refs.[11,12].

IV. Conclusion

In summary we have calculated the fusion excitation functions for the fusion of $^{48}Ca+^{242}Pu$, $^{48}Ca+^{244}Pu$ leading to the CN, ^{290}Fl and ^{292}Fl respectively. We have evaluated the ER cross sections in the 3n, 4n, 5n evaporation channel for these fusion reactions and the values are in good agreement with experimental data. Our result shows that the $^{48}Ca+^{244}Pu$ give maximum probability for the synthesis of superheavy element Fl.

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