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Enhanced Fission Probability of Even-Z Fragments in the Decay of Hot and Rotating ^{210}Rn* Compound System

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ABSTRACT

Mass and charge distribution of the cross-section for the fission fragments obtained in the decay of hot and rotating compound system formed in the reaction ^{48}Ca + ^{162}Dy → ^{210}Rn* at an incident energy 139.6 MeV has been calculated using the dynamical cluster-decay model. Isotopic composition for each element belonging to the symmetric mass region has been obtained. The shell closure at N=50 for light and at Z=50 for heavy mass binary fragments gives a deep minima in the fragmentation potential at touching configuration and governs the fission partition of the compound system. The fission fragments of the symmetric mass region have their dominating presence along with strong odd-even staggering i.e., even-Z fission fragments are more probable than the odd ones, similar to the observed trends of the yield.

1. Introduction

It is well known that the most probable outcomes of the low-energy heavy-ion reactions with massive nuclei are quasi-fission and fusion-fission. Both these processes inhibit the formation of a compound nucleus and their knowledge is important for the selection of a suitable path for the synthesis of heavy or superheavy nuclei. The outcome of a low energy heavy-ion reaction not only depends on the properties of the incoming channel like incident energy, angular momentum, mass asymmetry, isospin asymmetry, shell structure, etc. but also depends on the shell closures of the outgoing fragments. Depending on the properties of the incoming channel, the colliding nuclei may result in an equilibrated compound nucleus or the splitting of the compound system before attaining the state of equilibrium. The fission of a compound system from an equilibrated state is known as fusion-fission and before attaining the state of equilibrium is quasi-fission. Based on the mass asymmetry or mass of the fission fragments, the fission has been categorised as: symmetric (A/2 ± 20) and asymmetric fission. A symmetric or asymmetric fission process governed by the shell closures is known as quasi-fission. For example, asymmetric quasi-fission is caused by the shell closures at Z=28, 82 and N=50, 126 while the symmetric quasi-fission is due to the shell closures at Z=50 and N=82 [1]. The fission fragments of the symmetric mass region are populated through both the equilibrated (compound) and non-equilibrated (non-compound nucleus) processes, but a clear-cut distinction between these processes is still missing. Now, the mass distribution of the cross-section plays a vital role to understand the origin of the outgoing channels. So, addition knowledge of fusion-fission and quasi-fission dynamics is a step forward in the search of optimal condition(s) to synthesize heavy superheavy elements etc. Nuclear charge distribution is a quantity accessible to experiments like the mass distribution and odd-even effects in the charge distribution of the fission fragments has been measured by [2, 3] in inverse kinematics, but not for ^{210}Rn*. So, a qualitative analysis of both mass and charge distribution of the cross-section of the fission fragments of a hot and rotating compound system formed in ^{48}Ca + ^{162}Dy → ^{210}Rn* reaction at 139.6 MeV has been done using the dynamical cluster-decay

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model. The choice of the reaction is due to the fact that the product of Z_1Z_2 (=1320) of the incoming channel is less than the value (1600 predicted by dynamical models) beyond which the presence of the quasi-fission process starts [4] and the compound nucleus formed is near the shell closures at Z=82 and N=126. In our model, fragment production is a two-step process: first a fragment is formed inside the compound nucleus and then it penetrates through the interaction barrier. In other words, fragment production is a dynamical mass motion of the preformed fragments through the interaction barrier. The number of partial waves considered in the calculation of the cross-section is equal to $\ell_{DCM}^{B_{f=0}}$, obtained as per the recent work of one of us DSV [5]. It is found that the fission of the compound system is governed by the shell closure at N=50 for the light and at Z=50 for the heavy mass fragments and a good number of the fission fragments of the symmetric mass region have the cross-section close to the most probable channel. Odd-even staggering is found in the charge distribution. In the following sections, we have discussed the methodology used, calculations and results and the conclusion of the study.

2. Methodology

Dynamical cluster-decay model [6,7] define the decay/fission cross-section of a hot and rotating compound system in terms of partial waves as

$$\sigma = \frac{\pi}{k^2}\sum_{\ell=0}^{\ell_{DCM}^{B_{f=0}}}(2\ell+1)P_0P;\ \text{ where } k=\sqrt{\frac{2\mu E_{cm}}{\hbar^2}}$$

Here, the penetrability P refers to R-motion, and P_0, the preformation probability, refers to mass motion in mass asymmetry coordinate $\eta = (A_1 - A_2)/(A_1 + A_2)$. The reduced mass is $\mu = (1/4)mA(1-\eta^2)$, expressed in terms of nucleon mass m, mass asymmetry η and the mass of the compound system A ($=A_1 + A_2$). The fragment production is considered as the dynamical collective mass motion of the preformed fragments through the interaction barrier. The fragment preformation probability $P_0(A_i) = |\psi(\eta(A_i))|^2\sqrt{B_{\eta\eta}}\left(\frac{2}{A}\right)$ is obtained from the solution of the stationary Schrödinger equation

$$\left[\frac{1}{2}\frac{-\hbar^2}{\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta}\frac{1}{\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta}+V(\eta)\right]\psi(\eta)=E_\eta^\nu\psi^\nu(\eta)$$

in η-coordinate for the fragmentation potential V(R, η, T) given as

$$V(R,\eta,T)=\sum_{i=1}^{2}[V_{LDM}(A_i,Z_i,T)+\delta U_i(T)]+V_P(T)+V_C(T)$$
$$+V_l(T)$$

at a fixed R ($=R_a = R_1+R_2$). The term $\beta_{\eta\eta}$ representing the smooth hydrodynamical masses [9] and the eigen solution of the Schrödinger equation in which temperature dependence is included through Boltzmann-like function as

$$|\psi(\eta(A_i))|^2=\sum_{\nu=0}^{\infty}|\psi^\nu(\eta(A_i))|^2\exp(-E_\eta{}^\nu/T)$$

where ν = 0, 1, 2, 3.., referring to ground state (ν = 0) and excited states (ν = 1, 2, 3...) solutions, i =1 and 2 refers to the heavy and light binary fragment, respectively. The term V_{LDM} is liquid drop energy [10] with its bulk and asymmetry constants adjusted by [11] and references therein, δU is the shell correction [12], V_P is the nuclear proximity potential [13], V_C (T) = $e^2Z_1Z_2/R(T)$ is the Coulomb potential and the centrifugal potentials is $V_\ell = \hbar^2\ell(\ell+1)/2I$, where $I=\mu R_a^2+\frac{2}{5}A_1mR_1{}^2+\frac{2}{5}A_2mR_2{}^2$ is the moment of inertia in the complete sticking limit. The penetrability P is obtained by using WKB integral, given as

$$P=\exp\left[\frac{-2}{\hbar}\int_{R_a}^{R_b}\left\{2\mu\left[V(R)-Q_{eff}\right]\right\}^{1/2}dR\right]$$

where R_a and R_b are first and second turning points of the penetration path. The temperature and angular momentum-dependent scattering potential $V(R, T) = V_P(R, T) + V_C(R, T) + V_\ell(R, T)$.
The second turning point R_b satisfy the condition $V(R_a, \ell) = V(R_b, \ell) = Q_{eff}(T, \ell)$ = TKE(T) i.e., the potential the first turning point ($V(R_a)$) acts as an effective Q-value for the decay of hot compound nucleus, at temperature T, into two fragments at T = 0. The temperature-dependent nuclear radii [10], given as (i =1, 2).

$$R_i(T) = (1.28A_i^{1/3}-0.76+0.8A_i^{-1/3})(1+0.0007\,T^2)$$

The energy transfer of kinetic energy of incident channel (E_{cm}) to the total excitation or total kinetic energy, TXE or TKE of the outgoing channel follows the relation $E_{CN}^* = E_{cm} + Q_{in} = |Q_{out}(T)| + TKE(T) + TXE(T)$, where $Q_{out}(T)$ = B(T) – $B_1(T)$ – $B_2(T)$ is the temperature-dependent Q-value of the outgoing channel and B's are the respective binding energies. The relationship between E_{CN}^* and T (in MeV) is $E_{CN}^* = (A/9)T^2 - T$, where A is the mass of the compound nucleus.

3. Calculations and Results

Fig. 1 shows the mass distribution of the cross-section of the fission fragments in the decay of the hot and rotating compound system formed in the reaction ^{48}Ca + ^{162}Dy at an incident energy of 139.6 MeV by considering the binary fragments in touching configuration. The most probable fission channel is ^{86}Kr+^{124}Sn, where the respective binary fragment has shell closure at N and Z=50. Other light mass binary fragment ^{85}Br has shell closures at N=50 and the heavy mass fragments $^{122\text{-}123}$Sn at Z=50. The most probable channel lies in the symmetric mass region (A/2 ± 20), governed by the shell closures at N and Z=50 with a transfer of 16 protons and 22 neutrons from the target to the projectile. Such is a huge transfer of 38 nucleons and the probability of the most probable channel being close to the other fission channels of the symmetric mass region indicates that the reaction must have proceeded through the compound nucleus reaction mechanism, with a small contribution of the quasi-fission due to the shell closures at N and Z=50 (qualitative report only). It may be noted that the cross-section for the evaporation and intermediate-mass fragment production is of the order of 10^{-4} mb, which is very small as compared to the cross-section of the fission fragments of the symmetric mass region.

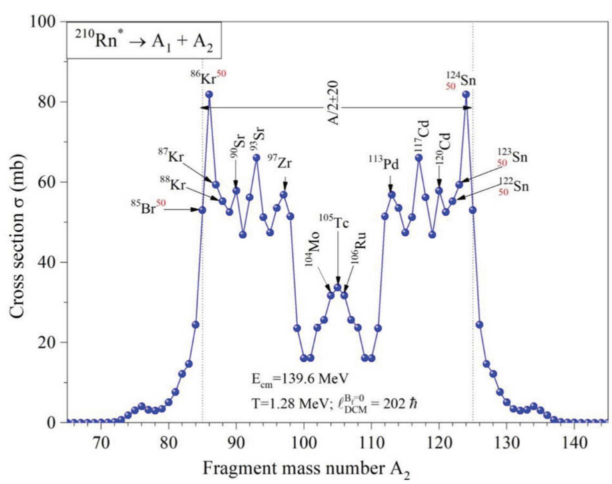

Figure 1: Mass distribution of the cross-section of the fission fragments in the decay of the compound system ^{210}Rn* formed in the reaction ^{48}Ca + ^{162}Dy at an incident energy of 139.6 MeV.

Fig. 2 is the same as Fig.1, but for the charge distribution of the cross-section of the fission fragments. A strong odd-even staggering in the charge distribution of the cross-section of the fission fragments of the symmetric mass region has been seen i.e., there is a preferential production of fragments with an even value of atomic number. Similar trends have been seen in measured charge distribution of the yield for isotopes of the Th, U and Pu [3]. The most probable channel in terms of charge asymmetry belonging to the symmetric mass region is due to the isotopes of Sr + Cd. The isotopic composition for each charge number of the symmetric mass region is shown in the figure. It is clear from the labelling of Fig. 2 that the number of isotopes contributing to the most probable fission channel is highest (five) followed by the number of isotopes contributing to the fission fragments of even atomic number (three) and no isotopic composition for the fission fragments of odd atomic number, except for Z_2=41 (and it complementary fragment of atomic number 45), where there is the contribution of three isotopes. The probability of the symmetric split i.e., the fission to ^{105}Tc + ^{105}Tc is least probable in the symmetric mass region.

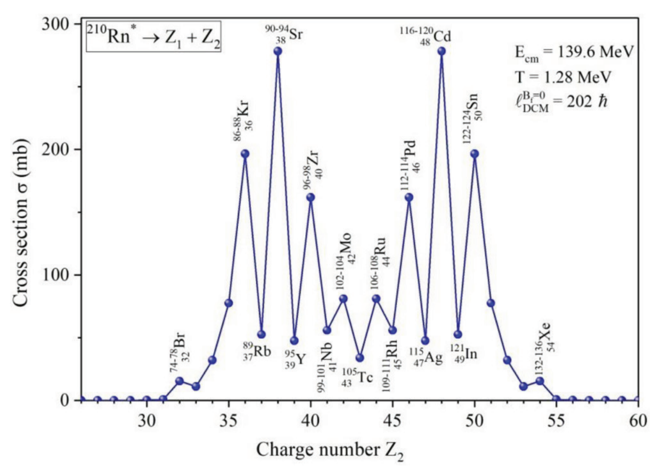

Figure 2: Same as Fig. 1, but for the charge distribution of the fission fragments.

Conclusions

Mass distribution of the fission fragments shows that the most probable fission channel is governed by the relatively deep energy minima which arises due to the shell closures at N = 50 for light and Z = 50 for heavy mass fragments. A Large mass transfer from target to the projectile for the most probable channel and its cross-section close to a good number of symmetric fission channels indicate that the major contribution to the fission channels is due to the compound nucleus process. The charge distribution indicates the presence of odd-even staggering for the fission channels of the symmetric mass region i.e., enhanced fission probability for even-Z fragments. Number of isotopes for even atomic numbers is higher than for odd one.

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