Hindrance factors in the double fine structure of ^{252}Cf

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Introduction

Cold fission is a special case of fission in which major part of the fission energy (Q) is appeared as Kinetic Energy (K.E) of fragments and the remaining as intrinsic excitation and deformation energies of fragments. In cold binary fission process, the two primary fragments at scission are formed with excitation energies below the neutron binding energy (less than 8 MeV) and with high kinetic energies approximately equal to the Q value [1]. The fine structure in emission processes is sensitive tools to probe the nuclear structure details. The study of the double fine structure can bring very important information on the collective and single-particle aspects of nuclei [2] and can open up new insights into cold fragmentation phenomena. Using the triple-gamma coincidence technique the double fine structure in the neutron-less fission of ^{252}Cf has been detected experimentally for the splitting ^{104}Mo-^{148}Ba, ^{106}Mo-^{146}Ba, ^{108}Mo-^{144}Ba and ^{104}Zr-^{148}Ce in the transitions leading to the final fragments which are similar to the well-known fine structure revealed in the alpha decays and in heavier cluster decays of odd-mass nuclei [2].

Theory

In the present work we are interested to characterize the double fine structure in the cold fission of ^{252}Cf by computing Hindrance Factor (H.F) by using proximity potential. Different approaches were used in the literature to find out these quantities. Our approach is analogous to that developed for alpha decay of even-even nuclei. Hindrance Factors are model dependent. It measures the attenuation of the decay probabilities and for the transitions that are not favored have large hindrance factors. A study of the H.F will be helpful in establishing the deformation of the ground state and the excited states of the fragments if the deformation of the decaying nucleus is known or vice versa [3]. In microscopic theory H.F are expressed in terms of ratio of formation amplitudes in the nuclear states which is evaluated starting from the single-particle degrees of freedom of the neutrons and protons. In the present case H.F is computed as the ratio between the pre-formation probabilities of two nuclear states. i.e. ratio of pre-formation of the ground state with the excited state as done for alpha decays [4]. For the computation of pre-formation probability different methods such as microscopic, empirical etc. were used in the literatures. Here we use a simple method proposed by Poenaru et al. [5]. Within fission model the authors interpreted pre-formation probability as the penetrability of the pre-scission part of the barrier and is a measure of the overlapping region of the potential barrier. We have calculated this quantity by the estimating the contribution of the overlap region (internal part of the barrier) which is represented by a simple power law between the contact configuration and configuration of the parent nucleus [6]. The potential for the overlapping region is given by

$$V = a\left(L - L_0\right)^n \quad (1)$$

Where L refers to the overall length of the configuration of the fissioning system, L_0 is the diameter of the parent nuclei and

$$a = \frac{V_c}{\left(L_c - L_0\right)^n} \quad (2)$$

in which L_c is the sum of fragment diameters at contact and

$$n = \frac{V_c^{'}\left(L_c - L_0\right)}{V_c} \quad (3)$$

V_c is the Coulomb potential at touching configuration. The pre-scission region penetrability or pre-formation probability is given by

$$P_0 = \exp\left(-K_{ov}\right) \quad (4)$$

$$K_{ov} = \frac{2}{\hbar}\int_{\varepsilon_i}^{\varepsilon_t}\sqrt{2B(z)E(z)}\,dz \quad (5)$$

The symbols ε_i and ε_f are the inner and outer turning points of the potential barrier defined by $V(\varepsilon_i) = V(\varepsilon_f) = Q$ and ε_t is the turning point corresponding to the touching configuration. The interaction potential contains the Coulomb part and nuclear part and is given as

$$V = \frac{Z_1 Z_2 e^2}{r} + V_N(z), \text{ for } z > 0 \quad (6)$$

Here Z_1 and Z_2 are the atomic numbers of the daughter and emitted cluster, 'z' is the distance between the near surfaces of the fragments, 'r' is the distance between fragment centers, V_N is the proximity potential of Blocki et al. [7, 8] which has the advantage that it is free from adjustable parameters. The proximity potential V_N proposed by Blocki et al., is given by the expression

$$V_N = \frac{4\pi\gamma b C_1 C_2 \phi(\varepsilon)}{C_1 + C_2} \quad (7)$$

with nuclear surface tension coefficient given by

$$\gamma = 1.2496\,[1 - 2.3\,(N - Z)^2 / A^2]\ \text{MeV/fm}^2 \quad (8)$$

Here N, Z and A refer to neutron, proton and mass numbers respectively of the parent nuclei.

$\phi(\varepsilon)$ is the universal proximity potential given as

$$\phi(\varepsilon) = -4.41\, e^{\frac{-\varepsilon}{0.7176}} \text{ for } \varepsilon \geq 1.9475 \quad , \quad (9)$$

$$\phi(\varepsilon) = -1.7817 + 0.927\varepsilon - 0.1696\varepsilon^2 - 0.05148\varepsilon^3 \text{ for } 0 \leq \varepsilon \leq 1.9475. \quad (10)$$

Here $\varepsilon = \frac{z}{b}$, z being the tip distance and b the width of the diffuseness of the nuclear surface.

Results and discussion

Hindrance factor has been computed using the above formalism for the splitting of ^{252}Cf in to ^{146}Ba and ^{106}Mo. It is found that Hindrance factor increases with excitation energy. They are found to be in the order 1, 1.5, 3.0, 7.8, 16.7 for ^{146}Ba and for the ^{104}Mo in the order 1, 1.4, 3.0, 9.0, 38, in both cases the other fragment is in the ground state. If we take the convention that HF > 5 are hindered, this result suggest that the transition to I = 6^+, 8^+ states are highly hindered and is more in ^{106}Mo compared to ^{146}Ba. The microscopic calculation based quasi particle random phase approximation (QRPA) predicts that the H F pattern for ^{146}Ba is according to the pattern low, medium, high which shows the efficacy of the phenomenological potential of Blocki et al. [7, 8]. It is to be noted that in the case of cluster decay of odd A nuclei the H.F pattern is reversed. In the case of ^{14}C radioactivity from ^{223}Ra nuclei the HF pattern are observed in the order 600, 3 and 3 which is same order that observed for alpha decays from odd A, reflection asymmetric deformed nuclei [8] which implies that transition towards the excited state is stronger than that to the ground state. These differences in the pattern of H.F are due to the uncoupled nucleon in the parent and daughter nuclei. In the case of odd A nuclei if the uncoupled nucleon is left in the same state in both the parent and heavy fragment, the transition is favored. Otherwise the difference in structure leads to a large hindrance. These results show that fine structure is linked to odd-even effect in the fragment yields.

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