Role of quantum phase transition in spontaneous fission

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I. INTRODUCTION

Generally, the observed fission fragment (FF) mass distribution has been obtained either by measuring energy or by using the γ-γ coincidence spectroscopy. The former measurement highlights the dominance of magic and/or semi-magic nuclei in their mass split [1], whereas the mass distribution spectrum resulted from the later technique confirms the dominance of the FFs with incompletely filled shells rather than the closed-shell nuclei [2].

The purpose of this presentation is two fold. First one is to develop the systematics of quantum phase/shape transition (QPT) (which is deeply rooted to single particle levels) that will help us in selecting most appropriate decay channels of the low-energy fissioning system (particularly the spontaneous fission). Secondly, this study is expected to resolve the apparent anomalies between the results obtained by using two different experimental techniques, namely, the time of flight technique (which ensures the dominance of magic and/or semi-magic nuclei in their mass split) and the γ-γ coincidence technique (in which the FFs with incompletely filled shells dominate over those of closed shell configurations).

II. SYSTEMATIC STUDY OF QPT IN SPONTANEOUS FISSION

Atomic nuclei exhibit phase/shape transitions as a function of their constituent protons and neutrons. QPTs in nuclei develop due to rapid changes in the equilibrium deformations of their ground states and are generally induced by the variation of a non-thermal control parameter (i.e., the number of nucleons) due to the competition of phases with different shapes. Such changes in the ground state shape parameters influence the evolution of various nuclear properties, and, in order to characterize this type of QPT, it is important to identify observables that can play the role of order parameters. A simple, empirical signature of QPT was introduced by the ratio of the energy of the first excited 4^+ level to the energy of the first excited 2^+ state [3, 4]. This ratio provides an effective order parameter which is not only easy to measure, but also distinguishes between first and second order phase transitions and takes on an extremum value at specific Z and/or N choices.

Firstly, we use the experimental fission data to pinpoint the signatures of QPT in spontaneous fission. Ter-Akopian and collaborators [5] have done a pioneering work on the quantitative determination of mass distribution yields of correlated Ba-Mo FF pairs corresponding to 0 to 10 neutron emission channels in spontaneous decay of ^{252}Cf. Since the observed mass distributions of Ba (Z=56) and Mo (Z=42) FF pairs involve 0 to 10 neutron evaporation channels, therefore, the analysis of these decay channels will answer many questions. The experimental data of Ter-Akopian and collaborators [5] for the isotopic mass distributions of Ba corresponding to each Mo-isotope are shown in Figs.1. In order to introduce a physical quantity similar to the ratio "$R_{\frac{4}{2}}$" for a fissioning system, we proceed as follows.

Since the single particle states of lighter and heavier FFs are non-degenerate [6], therefore, the rotational spectra of correlated FF pair based on their respective Fermi levels are also non-degenerate and the rotational energy spacing between lighter and heavier FFs follows a regular systematic trends by varying the isotopic structure of one of its partner. For a particular correlated pair of FF, a small difference of only few nucleons with an isotopic increase in one of the FF partners is sufficient to change the shell structure and pairing correlation of a resulting fissioning state and causes an abrupt deviation in the rotational energy spacing from its regular behavior. The irregularities from systematic trends are responsible for quantum phase/shape transitions. On the basis of this conclusion, we have introduced the concept of QPT which in turn is related to the ratio of relative excitation energies of I^{Π}=4^+ to I^{Π}=2^+ states between heavier and lighter FFs, to fix the decay modes of spontaneous fission and is defined as

$$\delta R = \frac{(E_{4_1^+})_H - (E_{4_1^+})_L}{(E_{2_1^+})_H - (E_{2_1^+})_L}. \qquad (1)$$

Here, the experimental excitation energies of the I^{Π}=2^+ ($E_{2_1^+}$) and I^{Π}=4^+ ($E_{4_1^+}$) levels in heavier and lighter even-even FFs are taken from ref. [7]. A systematic variation of this ratio is solely determined by the relative inertia tensors between the heavier and lighter FFs. One can say that an effective inertia tensor of a fissioning system determines the systematic variations in δR. A small difference of only few nucleons with an isotopic increase in one of the fission partners causes an abrupt change in that inertia tensor; and hence a deviation in the energy spacing occurs from its regular behavior. An extremum value of this ratio decides the most probable decay.

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We have considered the decay of ^{252}Cf into two FFs along with the emission of q neutrons, i.e.,

$$^{252}Cf \rightarrow F_1(Z_1 = 42, N_1) + F_2(Z_2 = 56, N_2) + q_0^1n, \quad (2)$$

with $N_1 + N_2 + q$=154. The neutron evaporation channels are varied between $0 \leq q \leq 10$. We have made the possible correlated pairs of FFs with masses lying within 138≤ A_H ≤148 and 102≤ A_L ≤108 limits by conserving the baryon numbers and their calculated ratios are shown in Fig.2. Each extremum (i.e., minimum or maximum) value of δR, corresponding to even-even $^{102-108}Mo$ isotopes, represents the decay channel with finite probability and all these channels are listed in the plots shown in Fig.2. If the 0-neutron emission channel in each one of these plots is ignored, the next extremum value of δR represent the channels corresponding to 2 and 4 neutron emission and are in reasonably in agreement with the observed ones as shown in Fig.1.

Thus, we have introduced a simple, empirical observable, $\delta R = \frac{\left(E_{4_1^+}\right)_H - \left(E_{4_1^+}\right)_L}{\left(E_{2_1^+}\right)_H - \left(E_{2_1^+}\right)_L}$ of the energies of the 2^+ and 4^+ states which can serve as an order parameter identifying phase transitional behavior. It is shown for the first time that the QPT plays a very vital role in fixing the decay channels of spontaneous fission.

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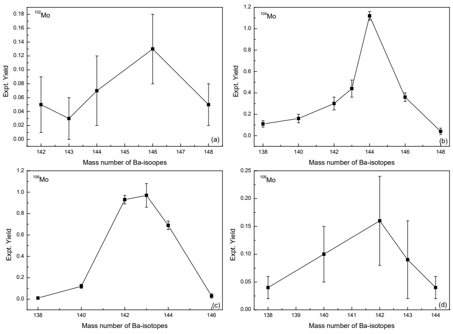

FIG. 1: Expt. data

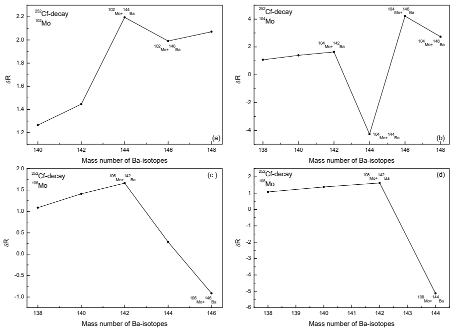

FIG. 2: Theo. plots