Study of rare modes of "Collinear Cluster Tri-Partition" of ^{252}Cf(sf)

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Abstract. In our previous experiments we have observed multiple manifestation of a new ternary decay of low excited nuclei called “Collinear Cluster Tri-partition” (CCT). A special mode of this new type of ternary decay was observed based on the double magic ^{132}Sn cluster. A pre-scission configuration which brings a question whether the observed double magic ^{132}Sn can be replaced by double magic ^{208}Pb is being studied. A specially designed experimental setup has been put in place to give better statistics and more precise time-of-flight measurements. An improved calibration procedure is presented.

1. Introduction

In our previous experiments [1-4] we identified multiple manifestations of a new ternary decay of low excited nuclei called "Collinear Cluster Tri-partition" (CCT) due to the features of the process observed. The unusual decay channel was revealed both in the framework of "missing mass" method, meaning that only two decay partners were detected, the other one was missing [1,2]. The third partner is determined by subtracting the sum of the observed two masses from the total mass of ^{252}Cf. In this way all three decay partners are accounted for [3,4]. Recently a specific CCT mode was observed based on the double magic ^{132}Sn cluster. The mass-mass distribution of the events selected by velocities and energies is shown in figure 1.

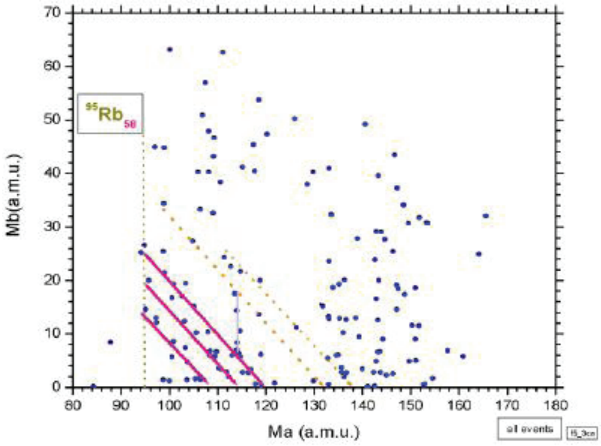

Figure 1. Mass-mass distribution of fragments selected by velocities and energies

The tilted red lines in the figure correspond to the missing magic clusters of ^{132}Sn and ^{144}Ba. This missing cluster can be clearly seen in the mass spectrum in figure 2 which is the projection along these lines.

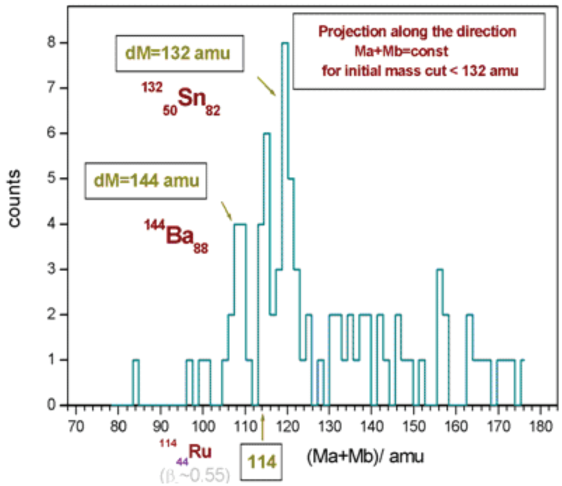

Figure 2. Mass spectrum for the structures marked by red lines in figure 1.

Pre-scission configuration which presumably gives rise to the mode under discussion is shown in figure 3. As we can see from the figure, the Sn cluster can "move" as a whole along the cylinder-like configuration that consists of residual nucleons. Two light fragments accompanying this cluster marked by M1 and M2 were actually detected in previous experiments. The value of M2 lies between 0 amu and the difference between the initial mass of ^{252}Cf and the detected fragments. M1 cannot assume any value less than 95amu (deformed magic ^{95}Rb) due to the fact that experimentally the Sn cluster is always observed and the detected mass of the third fragment suggest that the lowest value of M1 should be 95amu.

2. Motivation

The main aim of our study is to investigate the pre-scission configuration which is almost collinear. The question that arises is whether ^{132}Sn can be replaced by double magic ^{208}Pb in this mode. Theoretical indications of such a mode were obtained in [5] and are illustrated in figure 4 which shows the potential energy of the fissioning nucleus of ^{252}Cf corresponding to the bottoms of the potential valleys as a function of parameter Q proportional to the quadrupole moment of the system.

The panels depict the shapes of the fissioning system at the points marked by arrows. Both in valley of mass-asymmetrical shapes (4) and mass-symmetrical shapes (5) the system consist of pairs of magic clusters (Sn/Ni, Sn/Ge and so on) and nucleons left over forming a "neck" between the clusters [6]. Valley 1 in figure 4 is due to the preformation of double magic ^{208}Pb. Evolution of the nuclear shape in this mode is presented above the figure.

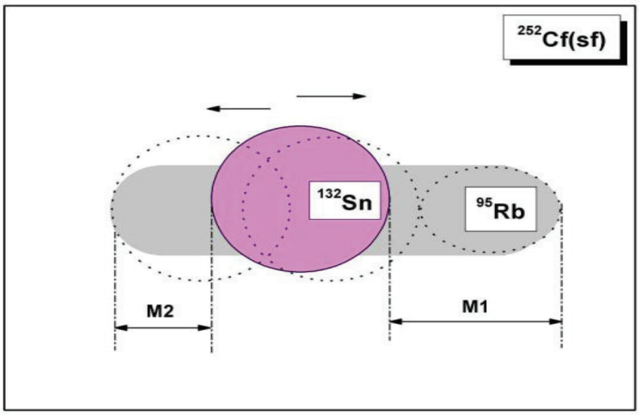

Figure 3. Schematic pre-scission configuration of the CCT mode based on the double magic ^{132}Sn cluster.

Coming back to the question whether ^{132}Sn can be replaced by double magic ^{208}Pb, if so, this will lead to a new type of lead radioactivity. Searching for such a mode is one of the goals of our forthcoming experiment, which will require better statistics and more precise time-of-flight measurements.

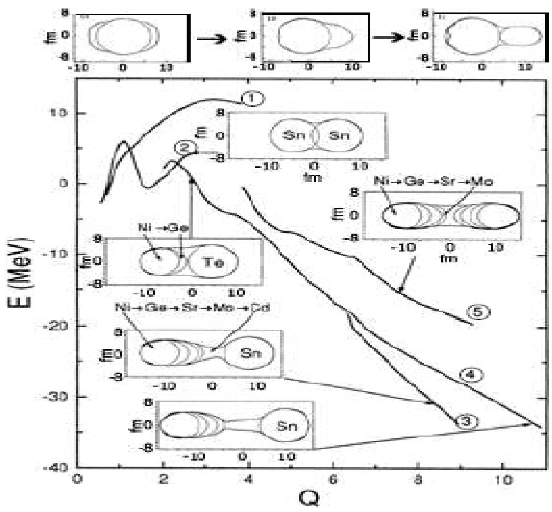

Figure 4. The bottoms of the fission valleys as a function of parameter Q (proportional to the quadruple moment) for ^{252}Cf nucleus.

3. Experimental problems

As we can see in figure 1 the masses of fragments defining the modes under investigation differ radically that is, one is very light while the second one is very heavy. Therefore we have a problem involving the method of measuring the correct energy and time-of-flight of heavy ions in the wide range of energies and masses using PIN diodes as "stop" detectors (as it is a case from our previous experiments).

The problem we have is due to the negative influence of the known "plasma delay" in registering time-of-flight of fission fragments and the "pulse-height defect" (PHD) in registering energy of fission fragments using semiconductor detectors. In order to exclude the influence of "plasma delay" for timing of the fragments, three micro-channel plate (MCP) timing detectors shown in figure 5 will be used. The first MCP will be used to deliver a start signal and the other two MCPs will be used for stop signal in both arms. This setup will enable us to measure the influence of plasma delay by analyzing the difference between the time signal from MCP detectors and PIN diodes.

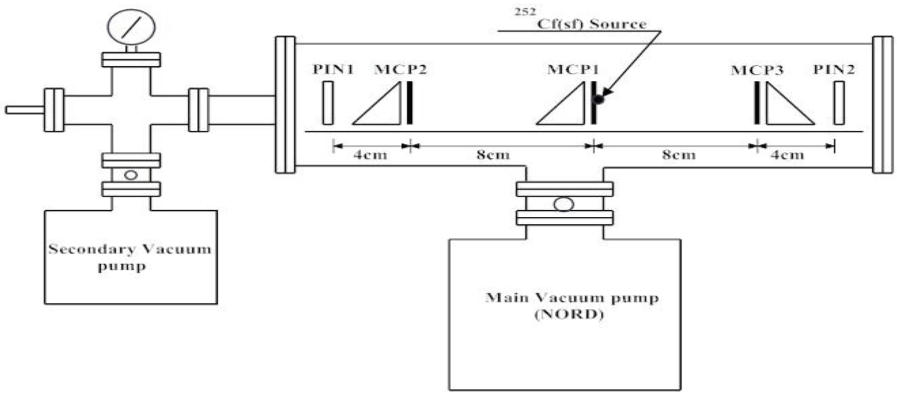

Figure 5. Schematic view of our setup.

4. Calibration and reconstruction of FF masses

The calibration process comprises of a selection of raw data and performs a direct transformation of energy in channels to energy in Mega-electron Volts. This first step of processing is referred to as "a first approximation" because in this approach the PHD is only approximated roughly. In the second step we perform a so called "true calibration" where we take the PHD into account and reconstruct the masses of the fission fragments.

4.1. "The First Approximation" in the FF mass reconstruction

In "first approximation" the energy in channels *E[ch]* is converted to the energy in MeV, *E[MeV]* according to the following equation:

$$E_i[\mathrm{MeV}] = C \cdot \exp\left(-\frac{E_i[\mathrm{ch}]}{D}\right) + E_0 \tag{1}$$

The values of *C, D,* and E_0 are determined by using the known positions for the energy peak of light and heavy fragment and the natural alpha peak from ^{252}Cf with Eα = 6.118MeV. The subscript *i* in equation (1) shows that each event is processed individually. The time in channels *T[ch]* is converted according to the following equation to the time in nanoseconds *T[ns]*:

$$T_i[\mathrm{ns}] = A \cdot T_i[ch] + B \tag{2}$$

The values of *A* and *B* are determined by using the known velocities $V_{L,H}^{ref}$ of light and heavy fragment from literature and the flight path of fission fragments. Once the values of *A* and *B* are obtained we apply equation (2) to our raw data to calculate time in nanoseconds and we use the time to calculate the velocity in centimeters per nanoseconds as follows:

$$V_i[cm/ns] = \frac{L_{TOF}}{T_i[ns]} \tag{3}$$

Equation (1) and (3) allows us to calculate the mass of the FF as follows:

$$M_i[amu] = \frac{1.9297 E_i[MeV]}{\left(V_i[cm/ns]\right)^2} \tag{4}$$

4.2. True calibration and reconstruction of the FF masses

The true calibration and reconstruction of FF masses is quiet a complicated task due to the influence of pulse-height defect (PHD). The channel number of energy in which we register the fission fragment depends on the energy of the fission fragment as well as on the PHD. But on the other hand, the PHD depends on the mass and the kinetic energy of the registered fragment. To combine together the calculation of true energy and reconstruction of fission fragments masses we use a specially designed procedure presented in [6].

The energy E in MeV, of the registered fission fragment is defined as the sum of the detected energy E_{det} and the pulse-height defect denoted by $R(M,E)$:

$$E = E_{\det} + R(M, E) \tag{5}$$

Where the detected energy of fission fragments is given by:

$$E_{\det}[\mathrm{MeV}] = E[\mathrm{ch}] \cdot E_{gr} + E_0 \tag{6}$$

Where E_{gr} and E_0 are calibration parameters calculated experimentally by using a high precision pulse generator and the natural alphas from ^{252}Cf source. The expression for the pulse-height defect in equation (5) was proposed by *Mulgin* and his colleagues [7] as given by the following empirical expression:

$$R(M, E) = \frac{\lambda \cdot \mathrm{E}}{1 + \varphi \cdot \dfrac{E}{M^2}} + \alpha \cdot ME + \beta \cdot E \tag{7}$$

Where $\{\lambda, \varphi, \alpha, \beta\}$ are parameters for the true calibration. In addition we know that:

$$E = \frac{M \cdot V^2}{1.9297} \tag{8}$$

Where E is the energy of the FF in *MeV*, M is the mass of the FF in *amu* and V is the velocity of the FF in *cm/ns*. The velocity for this purpose is calculated using the parameters obtained from time calibration. From the above equations, (5, 6, 7 and 8) we can calculate the mass of the fission fragment provided the parameters $\{\lambda, \varphi, \alpha, \beta\}$ are known. It is worth noting that the numerical values for the parameters $\{\lambda, \varphi, \alpha, \beta\}$ proposed in [7] make it impossible to reconstruct the mass M_{TE} for the FF. In order to find the correct values of the parameters $\{\lambda, \varphi, \alpha, \beta\}$ a special iterative procedure has been designed. This procedure consists of obtaining a solution of the following equation analytically:

$$G(\{\lambda, \varphi, \alpha, \beta\}, M) = 0 \tag{9}$$

Where G depends on the parameters $\{\lambda, \varphi, \alpha, \beta\}$ and the mass. To obtain the solution of equation (9) above, we combine equation (5), (7), and (8) as follows:

$$\frac{MV^2}{k} = E_{\det} + \frac{\lambda \cdot \frac{MV^2}{k}}{1 + \varphi \cdot \frac{V^2}{Mk}} + \alpha \cdot \frac{M^2V^2}{k} + \beta \cdot \frac{MV^2}{k} \quad (10)$$

Where $k = 1.9297$ and we obtain the following third order equation:

$$M^3 + aM^2 + bM + c = 0 \quad (11)$$

Where

$$a = \frac{\varphi V^2}{k} + \frac{\beta + \lambda - 1}{\alpha}, b = \frac{kE_{\det}}{\alpha V^2} + \frac{\varphi V^2}{\alpha k}(\beta - 1), c = \frac{\varphi E_{\det}}{\alpha}$$

Using the above procedure we process each event individually based on the current values of $\{\lambda, \varphi, \alpha, \beta\}$ and select the mass of the fission fragment from the calculated values in equation (11). The mass is selected from the condition $M_{TE} \in [1\ \text{amu}, 252\ \text{amu}]$. After processing an amount of data a mass spectrum is obtained.

The procedure uses the MINUIT package to minimize the following criterion function by changing the parameters $\{\lambda, \varphi, \alpha, \beta\}$:

$$F = [(< ML_T > - < ML >)^2 + (< MH_T > - < MH >)^2] + \mu \sum_{M_{TE}} \frac{(Y(M_{TE}) - Y_T(M_{TE}))^2}{Y(M_{TE})} \quad (12)$$

Where μ is a free parameter that is chosen by the user and it is used as an input parameter to the MUNUIT minimization procedure. This parameter plays a role of specific relative weight of the second term in the criterion function F. The values $< ML >$ and $< MH >$ are average masses of light and heavy fragments calculated from the experimental mass spectrum $Y(M_{TE})$. In the above equation the known values from literature are denote by "T".

5. Conclusion

In our previous experiments the “first approximation” approach presented above was used for the purpose of energy calibration and reconstruction of fission fragment masses. The “true calibration” is the improved version for the calculation of the fragment mass, and will be used for the calibration and reconstruction of the fission fragment masses in our current experiment. It is worth noting that the code for calibration is based on the iterative procedure using the MINUIT package to minimize equation (12).

References

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