# STUDY OF RARE MODES OF "COLLINEAR CLUSTER TRI-PARTITION" OF $^{252}$Cf (SF)

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## INTRODUCTION

In our experiments devoted to the study of a new ternary decay of low excited heavy nuclei called "collinear cluster tri-partition" (CCT) [1–3], a specific CCT mode was observed based on the double magic $^{132}$Sn cluster. Mass-mass distribution for the events selected by velocities and energies is shown in fig. 1. Tilted red lines correspond to missing magic clusters of $^{132}$Sn and $^{144}$Ba. They are vividly seen as well in the mass spectrum (fig. 2) which is the projection along these lines.

Pre-scission configuration which presumably gives rise to the mode under discussion is shown in fig. 3. Sn cluster can "move" as a whole along the cylinder like configuration which consists of residual nucleons. Two light fragments marked by symbols M1 and M2 were actually detected in previous experiment. The mass M2 changes in the range {0÷(252–132–95)} amu while M1 cannot be less 95 amu (deformed magic $^{95}$Rb nucleus).

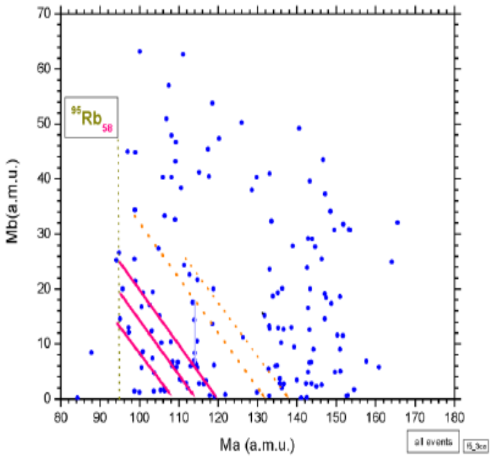


**FIGURE 1.** Mass-mass distribution of fragments selected by velocities and energies.

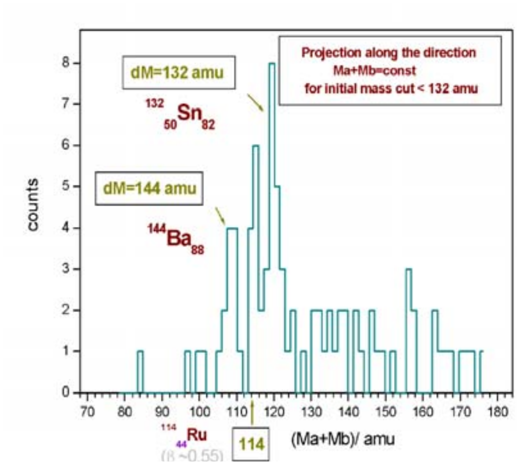


**FIGURE 2.** Mass spectrum for the structures marked by red in fig. 1. Missing magic clusters of $^{132}$Sn and $^{144}$Ba are vividly seen.

## MOTIVATION

The question arises whether $^{132}$Sn can be changed by also double magic $^{208}$Pb? Theoretical indication on such mode was obtained in [4] (fig. 4). It would be a new type of lead radioactivity. Searching for such mode is one of the goals of our forthcoming experiment.

We need as well better statistics to be collected and more precise measurement of time-of-flights for studying of the CCT modes observed earlier.

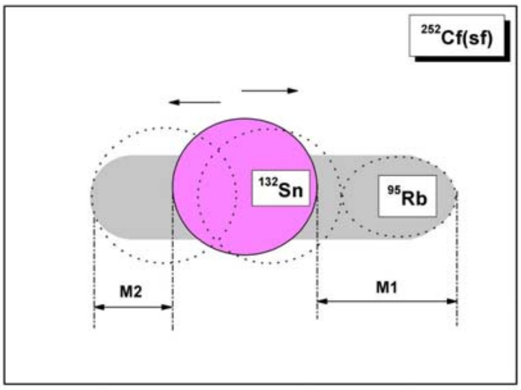


**FIGURE 3.** Schematic pre-scission configuration of the CCT mode based on the double magic $^{132}$Sn cluster.

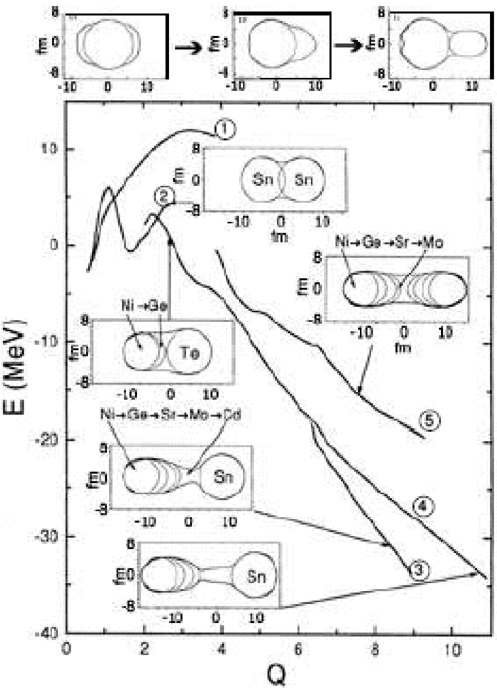


**FIGURE 4.** The bottoms of the fission valleys as a function of parameter Q (proportional to the quadruple moment) for $^{252}$Cf nucleus. The panels depict the shapes of the fissioning system at the points marked by arrows. Valley 1 in the figure is due to preformation of double magic $^{208}$Pb. Evolution of the nuclear shape in this mode is presented above the figure.

## EXPERIMENTAL PROBLEMS

As can be referred from fig. 1 the masses of fragments defining the modes under investigation differ radically, namely one of them 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. In order to exclude negative influence of the known “plasma delay” effect for timing of the fragments, three micro-channel based timing detectors will be used (fig. 5).

Also well known “pulse height defect” in silicon semiconductor detectors will be taken into account using special procedure worked out by us earlier [5]. In our previous experiments first approximation approach was used for this purpose (fig. 6).

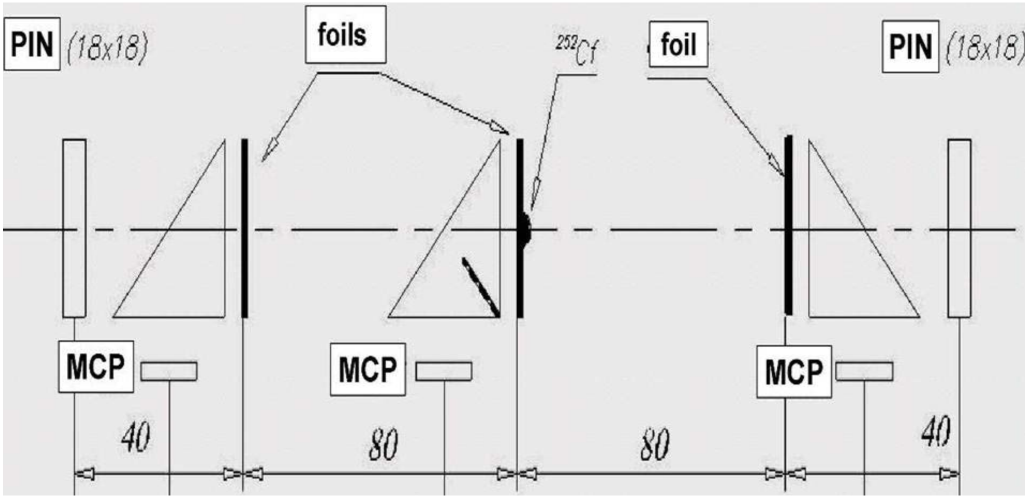


**FIGURE 5.** Schematical view of the setup to be used.

The "first approximation" is based on the simple transformation of energy and time in channels to MeV and nanoseconds (ns), respectively. Using these values we calculate the mass of the heavy and light fission fragment in atomic mass units (amu). This "first approximation" approach neglects the energy lost in the entrance window of the "start" detector and the source backing, while the PHD is estimated rather roughly. We also neglect the so called "plasma delay" in the time signal.

The "first approximation" comprises of reading the raw data and performs the necessary transformations into the required units. The energy in channels E [ch] is converted according to the following equation to the energy in MeV, E [MeV]:

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

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 = 6.118 MeV. The subscript *i* in equation (1–2) 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. The experimental expected time-of-flight in nanoseconds of the light and heavy fragment is calculated as follows:

$$T_{L,H} = \frac{L_{TOF}}{V_{L,H}^{\ ref}}, \tag{3}$$

where $L_{TOF}$ is the flight path of fission fragments. Knowing the values of $T_{L,H}$ from equation (3) we calculate the value of *A* as follows:

$$A = \frac{T_H[ns] - T_L[ns]}{T_H[ch] - T_L[ch]} \tag{4}$$

Therefore the value of *B* is calculated as follows:

$$B_{H,L} = T_{H,L}[ns] - A \cdot T_{H,L}[ch] \tag{5}$$

In principle the value of $B$ obtained from the heavy fragment and the value of $B$ obtained from the light fragment has a significantly small difference from each other, so the average between the two values is used and is given by the following:

$$B = \frac{B_H + B_L}{2} \tag{6}$$

Once we have obtained the values of $A$ and $B$ we apply equation (2) to our raw data to calculate the time in nanoseconds. We then use the time from equation (2) to calculate the velocity in centimeters per nanoseconds as follows:

$$V_i[cm/ns] = \frac{L_{TOF}}{T_i[ns]} \tag{7}$$

Equation (1) and (7) allows us to calculate the mass as follows:

$$M_i[amu] = \frac{1.9297 E_i[MeV]}{\left(V_i[cm/ns]\right)^2} \tag{8}$$

After processing an amount of data, a mass spectrum is obtained. The process of the “First Approximation” approach is illustrated in fig. 6.

The improved version of code for calculating of fragment mass is presented in fig. 7. The true energy calibration and reconstruction of FF masses is quiet a complicated task do 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 [7–8].

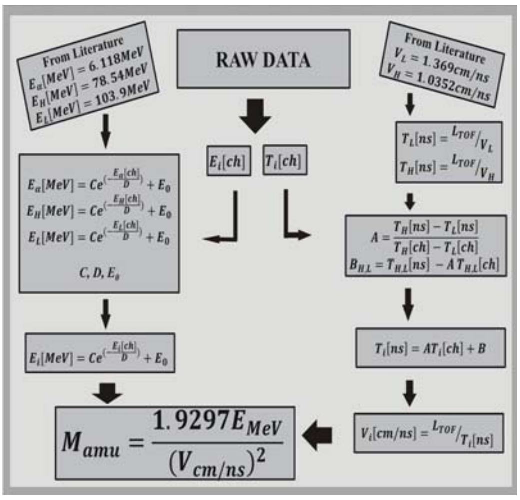


**FIGURE 6.** “First approximation” approach for calculation of fragment mass.

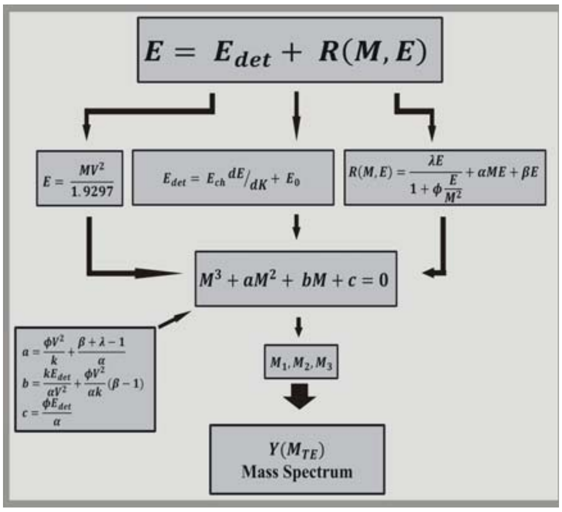


**FIGURE 7.** Processing of velocity- energy data for calculation of fragment mass. Code is based on parameterization [6] of pulse height defect in PIN diodes.

The main idea of the procedure is to calculate the FF mass spectrum $Y_{ex}(M_{TE})$ depending on current values of parameters and compare this spectrum with a known one from the literature [9]. This procedure is applied to every single detector. 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):

$$E = E_{\det} + R(M, E), \tag{9}$$

where the detected energy of fission fragments is given by:

$$E_{\det}[\text{MeV}] = E[\text{ch}] \cdot dE/dk + E_0, \tag{10}$$

where dE/dk and $E_0$ are calibration parameters. These parameters are calculated experimentally by using a high precision pulse generator (in our case we use ORTEC 448 Research Calibrator) and the natural alphas from $^{252}$Cf source. The expression for the pulse-height defect in equation (9) was proposed by Mulgin and his colleagues [6] as the following empirical expression:

$$R(M, E) = \frac{\lambda \cdot \mathrm{E}}{1 + \phi \cdot \frac{E}{M^2}} + \alpha \cdot ME + \beta \cdot E, \tag{11}$$

where {λ, ϕ, α, β} are parameters for the true calibration. In addition we know that:

$$E = \frac{M \cdot V^2}{1.9297}, \tag{12}$$

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, we can calculate the mass of the fission fragment provided the parameters {λ, ϕ, α, β} are known. It is worth noting that the numerical values for the parameters {λ, ϕ, α, β} proposed in [6] make it impossible to reconstruct the mass $M_{TE}$ for the FF.

In order to find the correct values of the parameters {λ, ϕ, α, β} a special iteration procedure has been designed. This procedure consists in obtaining the solution of the following equation analytically:

$$G(\{\lambda, \phi, \alpha, \beta\}, M) = 0 \tag{13}$$

To obtain the solution of equation (13) above, we combine equation (9), (11), and (12) as follows:

$$\frac{MV^2}{k} = E_{\det} + \frac{\lambda \cdot \frac{MV^2}{k}}{1 + \phi \cdot \frac{V^2}{Mk}} + \alpha \cdot \frac{M^2V^2}{k} + \beta \cdot \frac{MV^2}{k}, \tag{14}$$

where k = 1.9297. The above equation can be written as follows:

$$M^3 + aM^2 + bM + c = 0, \tag{15}$$

where

$$\begin{aligned} a &= \frac{\phi V^2}{k} + \frac{\beta + \lambda - 1}{\alpha} \\ b &= \frac{kE_{\det}}{\alpha V^2} + \frac{\phi V^2}{\alpha k}(\beta - 1) \\ c &= \frac{\phi E_{\det}}{\alpha} \end{aligned} \tag{16}$$

As we can see equation (15) is a third order equation, which means its solution consists of three roots. To select the roots that must be used from the three possible roots, we must take note of the fact that the mass cannot be negative, so any root that is negative we neglect it. We also neglect the complex roots. In case of three real roots which are greater than zero, we compare them with the value of the mass obtained from “first approximation”, i.e. we take the root that is closest to the value of the mass obtained from first approximation. A special program for this purpose was designed using FOTRAN-99 codes.

Using the above procedure we process each event individually based on the current values of $\{\lambda, \phi, \alpha, \beta\}$ and calculate the mass of the fission fragment. The mass is calculated under the condition that $M_{TE} \in$ [1 amu, 252 amu]. After processing an amount of data a mass spectrum is obtained.

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

$$\begin{aligned} F = [&\left(<ML_T> - <ML>\right)^2 \\ &+\left(<MH_T> - <MH>\right)^2] \\ &+\mu \sum_{M_{TE}} \frac{\left(Y\left(M_{TE}\right) - Y_T\left(M_{TE}\right)\right)^2}{Y\left(M_{TE}\right)} \end{aligned} \tag{17}$$

where $\mu$ 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”. It is worth noting that the first square bracket term in equation (17) is sensitive to the difference between the centers of the mass peaks for the fission fragments while the second term is responsible for the agreement in shapes between the experimental mass spectrum $Y(M_{TE})$ and the mass spectrum from literature $Y_T(M_{TE})$.

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