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Experimental Investigations of Nuclear Reactions

Experiment Aimed at the Study of ^{252}Cf Binary and Ternary Fission*

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Abstract—A new experiment devoted to the fission of ^{252}Cf is described. It continued a series of our experiments based on correlation measurements of γ rays emitted by fission fragment pairs. The measurements of γ–γ and γ–γ–γ coincidences were done at Gammasphere with closed ^{252}Cf sources. The open source was used for the first time in the last experiment. Fission fragment detectors were arranged in the center hole of Gammasphere. Correlations between fission fragment masses, total kinetic energy, and γ rays were observed. The first, preliminary results of data analysis are discussed.

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1. INTRODUCTION

Investigation of ^{252}Cf spontaneous fission using the correlation measurements of prompt γ rays emitted by fission fragments has taken place during the last 12 years [1–5]. It has been shown that the given method allows one to obtain the yields of fission fragment pairs and the distributions of neutron multiplicity for different charge splits of ^{252}Cf [1, 3]. The excitation energy distributions of the fission fragments have been extracted from our data [2, 3]. The ternary fission of ^{252}Cf has been studied by using γ–γ coincidences only [4] and, in addition, recording the light charged particles (LCPs) emitted in ternary fission [5]. In the present case, we measured the energies of the two complementary fission fragments emitted in coincidence with γ rays.

2. EXPERIMENT

The experiment was carried out at Argonne National Laboratory by using Gammasphere, six LCP detectors, and two fission fragment detectors. Gammasphere was set to record γ rays with energy less than ~5.4 MeV. The γ-ray detection efficiency varied from a maximum value of ~17 to ~4.6% at the γ-ray energy about 3368 keV. The arrangement of the LCP and fission fragment detectors is shown schematically in Fig. 1.

Detector arrangement (D denotes distance to source)

Parameter	DSS	ΔE	E
Strips	32	–	–
Area [mm^2]	60×60	10×10	20×20
Thickness [μm]	400	9.5–10	300
D [mm]	80	19	33

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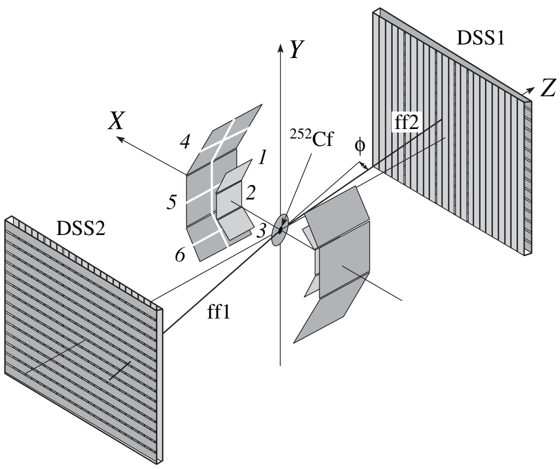

Fig. 1. Schematic diagram showing the detector array. The source of ^{252}Cf is in the center of the detector array. Fission fragments ff1 and ff2 hit the detectors DSS1 and DSS2. Telescopes installed along X axis detect ternary-fission light charged particles.

A source of ^{252}Cf giving $\sim 4 \times 10^6$ spontaneous fissions per second was installed in the center of a reaction chamber, which was placed in a hollow sphere inside Gammasphere. The source was prepared from a ^{252}Cf specimen that was deposited in a 5-mm spot on a 2-μm titanium foil. Six similar ΔE–E telescopes were used to measure the LCPs emitted in ternary fission. Two double-side strip (DSS) detectors were used for measuring kinetic energy and flight directions of the fission fragments. The arrangement details and sizes of the detectors are summarized in the table.

3. ANALYSIS AND PRELIMINARY RESULTS

Events of binary fission were analyzed at first. Strips in detectors were numbered in such a manner that any pair of strips from DSS detectors A and B, having identical numbers, were located symmetrically in relation to the source. As a result, one could expect that the fragments emitted in a binary-fission event fire strips with the identical numbers, predominantly. Taking into consideration the multiple scattering of fission fragments in the titanium foil, a relatively wide distribution was obtained for the fired strips in the second, complementary, detector relative to a single fired strip in the first detector. The obtained experimental distribution is shown in Fig. 2. Approximately 98% of all events correspond to ± 5 strips fired along $(X_A - X_B)$ directions.

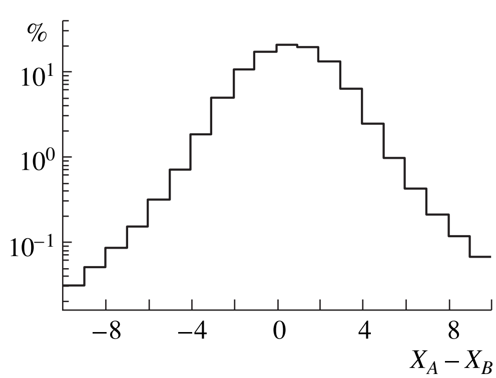

Fig. 2. Distribution of events vs. the difference between strip number of DSS1 and DSS2 detectors for the pairs of complementary fission fragments.

Energy calibration was made in accordance with the well-known method described in [6, 7]. A general form for the energy calibration of the solid state detector for the fission fragment may be written in the following form:

$$E = (a + a')x + b + b'M, \quad (1)$$

where a, a', b, and b' are constants for the particular detector; E and M are the kinetic energy and mass of heavy fragment; and x is a pulse height. Usually, one can calculate parameters a, a', b, and b' using only positions of two peaks P_L and P_H corresponding to the light and heavy fission fragments in the pulse-height spectrum measured for the ^{252}Cf spontaneous fission and four constants a_0, a_0', b_0, and b_0' presented in [6]:

$$a = a_0/(P_L - P_H), \quad a' = a_0'/(P_L - P_H), \quad (2)$$
$$b = b_0 - a_0 P_L, \quad b' = b_0' - a_0' P_L.$$

Constants a_0, a_0', b_0, and b_0' allow one to take account of the ionization defect in silicon and are

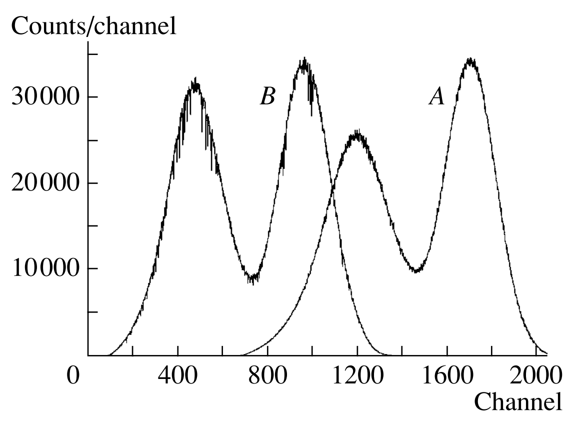

Fig. 3. Simulated pulse-height spectra of the fission fragments. A is the original mass, energy, and neutron evaporation distributions for the ^{252}Cf spontaneous fission; B is the spectrum simulated for the same sampling of fission fragments taking into account the energy loss in the 2-μm titanium Ti foil and 1.5-μm "dead" layers in Si detectors.

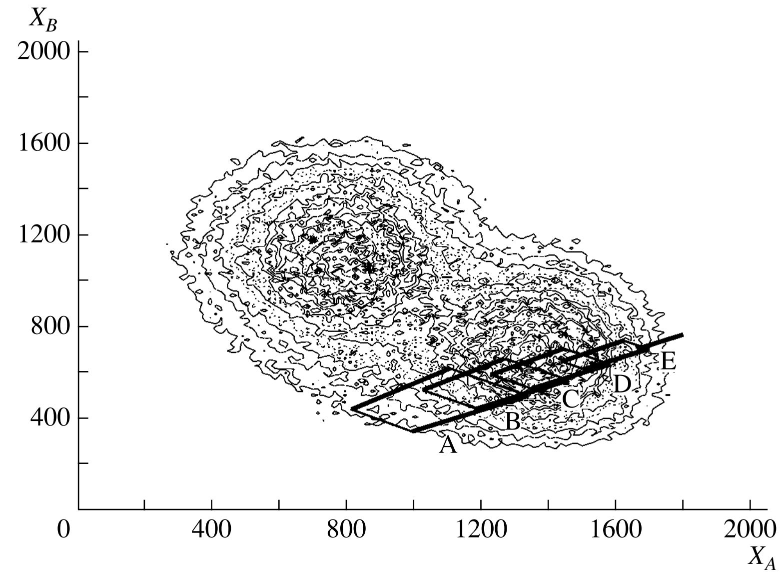

Fig. 4. Two-dimensional pulse-height spectrum X_A vs. X_B and calculated loci for the fission fragment pairs: A is for pair ^{106}Mo–^{138}Ba, B is for pair ^{106}Mo–^{140}Ba, C is for pair ^{106}Mo–^{142}Ba, D is for pair ^{106}Mo–^{144}Ba, and E is for pair ^{106}Mo–^{146}Ba.

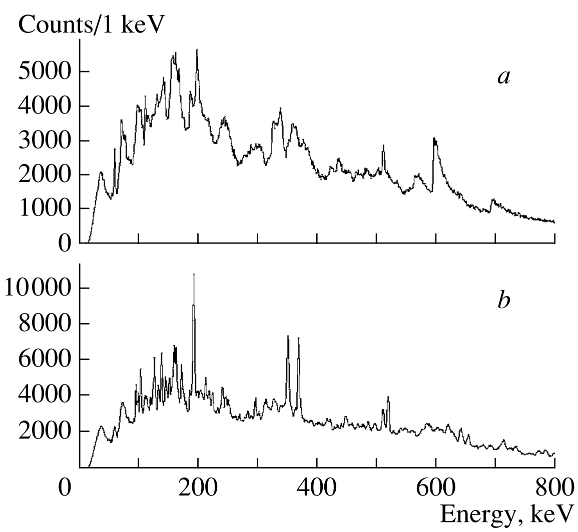

Fig. 5. Gamma spectra of ^{104}Mo fission fragments emitted in the ^{104}Mo–^{146}Ba pairs are shown (a) without and (b) with Doppler correction. Gates were opened at the 181-keV γ line of ^{146}Ba.

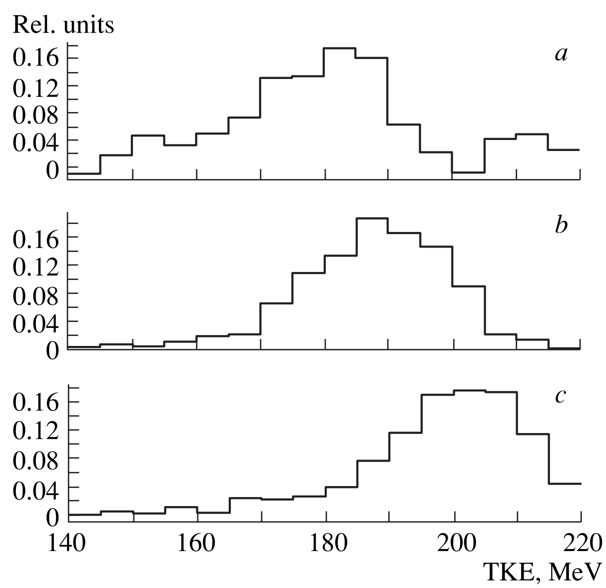

Fig. 6. Yields of fission fragment pairs are shown as function of TKE: (a) for ^{106}Mo–^{140}Ba, (b) for ^{106}Mo–^{142}Ba, and (c) for ^{106}Mo–^{146}Ba.

universal for many types of silicon detectors. Taking into consideration the energy loss of fission fragments occurring in our experiment, we rewrote Eqs. (1) and (2) in the following manner:

$$a_{0n}a_0' = a_{0n}'a_0, \tag{3}$$
$$a_{0n}[(b_{0n}' - b_0')\Delta P - a_{0n}'P_L]$$
$$= a_{0n}'[(b_{0n} - b_0)\Delta P - a_{0n}P_L],$$
$$E_L\Delta P = (a_{0n} + a_{0n}'m_L)P_L + (b_{0n} - a_{0n}P_L)$$
$$+ (b_{0n}'\Delta P - a_{0n}'P_L)m_L,$$
$$E_H\Delta P = (a_{0n} + a_{0n}'m_H)P_H + (b_{0n} - a_{0n}P_H)$$
$$+ (b_{0n}'\Delta P - a_{0n}'P_H)m_H,$$

where a_0, a_0', b_0, and b_0' are the original coefficients from [6]; a_{0n}, a_{0n}', b_{0n}, and b_{0n}' are the new coefficients calculated for our case; E_L, E_H, m_L, and m_H are fragment energies and masses associated with the two peaks in the experimental pulse-height spectrum; and ΔP and P_L are, respectively, the distance between the two peaks and the peak position of the light fission fragments. It was shown that the solution to system (1) relative to a_{0n}, a'_{0n}, b_{0n}, and b'_{0n} does not depend on ΔP and P_L and can be written in the following form:

$$a_{0n} = P_A + P_{AL}E_L + P_{AH}E_H, \tag{4}$$
$$a'_{0n} = P'_A + P'_{AL}E_L + P'_{AH}E_H,$$
$$b_{0n} = P_B + P_{AL}E_L, \quad b'_{0n} = P'_B + P'_{AL}E_L,$$

where coefficients P_A, P'_A, P_B, P'_B, P_{AL}, P_{AH}, P'_{AL}, and P'_{AH} depend on a_0, a'_0, b_0, b'_0, m_L, and m_H only. To estimate the values of E_L, E_H, m_L, and m_H, we simulated the pulse-height spectra for the original mass–energy distribution of fission fragments for the spontaneous fission of ^{252}Cf and for the same fragments going through the 2-μm titanium foil and the 1.5-μm "dead" layers which were present in our DSS detectors Fig. 3.

The positions of the two peaks in curve B presented in Fig. 3 agree well with the detector response to the light and heavy fragments corresponding to the two peaks in curve A and having kinetic energies reduced to take into account the calculated energy losses in the titanium foil and in the "dead" layer of the DSS detector. This observation allows us to estimate the energy calibration parameters using these values in Eqs. (2).

Having energy calibration of our DSS detectors, we could calculate the loci corresponding to different fission fragment pairs in the two dimensional plot X_A vs. X_B. One example of such calculations is shown in Fig. 4 for the following five fission fragment pairs ^{106}Mo with ^{138}Ba, ^{140}Ba, ^{142}Ba, ^{144}Ba, and ^{146}Ba. Of course, different fragment pairs could not be separated totally using only the data coming from the DSS detectors. But the contributions of other fission fragment pairs are reduced in the γ–γ coincidence matrices created for the selected pair.

Two variants of implementing Doppler correction were used for creating the γ–γ coincidence matrices. When only γ transitions in the heavy or light fragment were of interest, the Doppler correction was made with the assumption that all detected γ rays came either from the light or from the heavy fragment. Being interested in the γ–γ events associated with the complementary fragments, we made the Doppler correction two times for each γ ray. As a result, the number of γ rays was doubled. At first, one-half of the total number of γ rays was corrected assuming that they were emitted by the light fragment, whereas the other half was corrected assuming that these γ rays were emitted by the heavy fragment. Only coincidences between the γ rays of these two groups were placed in the γ–γ energy matrix in such a way that the corrected energy values of γ rays from the two groups were placed on the two different axes of the matrix. The result of this procedure is demonstrated in Fig. 5. The two γ-ray spectra shown in Fig. 5 correspond to the ^{104}Mo–^{146}Ba fission fragment pair. These spectra were created using the same gate $2^+ \to 0^+$ ^{146}Ba on the γ–γ coincidence matrices built without (Fig. 5*a*) and with (Fig. 5*b*) Doppler correction. One can see clear peaks of the γ transitions of ^{104}Mo in spectrum (Fig. 5*b*), which are smeared in spectrum (Fig. 5*a*).

In Fig. 6, the loci of the different fission fragment pairs are confined in TKE between the reaction Q value, on one hand, and the $Q - \Delta E$ value on the other hand. Here, ΔE is a sum of the kinetic energies of neutrons evaporated from the fission fragment and the rest excitation energies of these fission fragments. If one divides one locus into small TKE bins, the dependence of fission fragment yield on TKE will emerge. The preliminary results of this approach are demonstrated in Fig. 6 for the fission fragment pairs ^{106}Mo–^{140}Ba, ^{106}Mo–^{142}Ba, and ^{106}Mo–^{146}Ba. We note that such distributions were obtained for the first time in a nuclear fission study.

REFERENCES

1. G. M. Ter-Akopian et al., Phys. Rev. Lett. **73**, 1477 (1994).
2. G. M. Ter-Akopian et al., Phys. Rev. Lett. **77**, 32 (1996).
3. G. M. Ter-Akopian et al., Phys. Rev. C **55**, 1146 (1997).
4. A. V. Ramayya et al., Phys. Rev. Lett. **81**, 947 (1998).
5. A. V. Daniel et al., Phys. Rev. C **69**, 041305(R) (2004).
6. H. W. Schmitt et al., Phys. Rev. **137**, B837 (1965).
7. H. W. Schmitt et al., Phys. Rev. **141**, 1146 (1966).