COLLINEARITY LIMIT FOR THE MOVEMENT OF COMPLEMENTARY FRAGMENTS FROM THE SPONTANEOUS FISSION OF ^{252}Cf NUCLEI DETERMINED BY IMPLEMENTATION OF THE (2*E*, 2*V*)-MEASUREMENT METHOD

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1. Introduction

The $(2E, 2V)$-measurement method was used for the study of mechanisms of nuclear disintegrations induced by relativistic projectiles. The account of this study is published in this issue [1]. The special attention was paid to collinear disintegrations induced in heavy and medium-heavy nuclei. The $(2E, 2V)$-measurement method was realized at the proton beam of the PNPI synchrocyclotron in the form of an angle-velocity-energy correlation spectrometer (SAVEC) described in Ref. [1]. The time and energy calibrations of the SAVEC were performed with the use of a weightless source of ^{252}Cf. At the same time it was supposed that because of the two-body kinematics of the spontaneous decay of ^{252}Cf-nuclei complementary fission fragments should move on the straight line with the folding angle between the two fragments equal to 180°. Any deviation from 180° would have physical reasons. Our experimental practice showed that there is a necessity to check this assumption. Since two distinct experiments were carried out with fission fragments of the same ^{252}Cf-source one can compare collinearity for two different experimental conditions.

2. Different variants of mosaic constructions

Two massive complementary fission fragments were detected by the SAVEC which comprises a vacuum chamber with two time-of-flight tubes. In the end of each tube at the distance L a mosaic of N semiconductor silicon surface-barrier detectors (SSBSD) was located. Two mosaics of SSBSD in combination with the independent start signal device (SSD) made it possible to measure kinetic energies E_i and times of flight T_i for both (i = 1, 2) complementary fragments. So each of the registered events may be characterized by the collection of six measured parameters ($A_1, E_1, T_1; A_2, E_2, T_2$) related to the two detected fragments. Ordinal numbers of SSBSD in mosaics were denoted by A_1 and A_2. When the kinetic energy E_i and time of flight T_i for each of the two complementary fragments are measured simultaneously, one can determine, unlike in $(2E)$- or in $(2V)$-measurement methods, fragment's absolute masses $M_i \sim E_i \cdot T_i^2$ and momenta $P_i \sim E_i \cdot T_i$. They may be used for the elimination of the distorted experimental events [1].

We want to describe two variants of the SAVEC construction which were implemented in experiments with fission fragments from the ^{252}Cf-source. They differ from each other by L = 1060 mm, N = 33 and L = 688 mm, N = 8. Both mosaic variants are shown in Figs. 1, 2. The first variant was used in experiments in which the maximum area of detecting elements was required. In this case among $33 \times 33 = 1089$ address combinations there were large variations for the folding angles between the two complementary fission fragments. For the second variant of the SAVEC construction, among $8 \times 8 = 64$ address combinations there were only 6 variations for the folding angles. This circumstance made angular measurements more effective. The binary code for the enumeration of detectors prevented the implementation of the variant with $9 \times 9 = 81$ address combinations which is shown in Fig. 3. For this case 6 variations for the folding angle detection are preserved. Figure 4 also shows a possible mosaic variant with $7 \times 7 = 49$ address combinations which have only 4 variations for the folding angle detection. Tables 1 and 2 contain all the information concerning values of difference $180 - \langle\theta\rangle$ in degrees for the $9 \times 9 = 81$ and $7 \times 7 = 49$ address combinations. In both cases $\langle\theta\rangle$ is an average folding angle for a certain address combination.

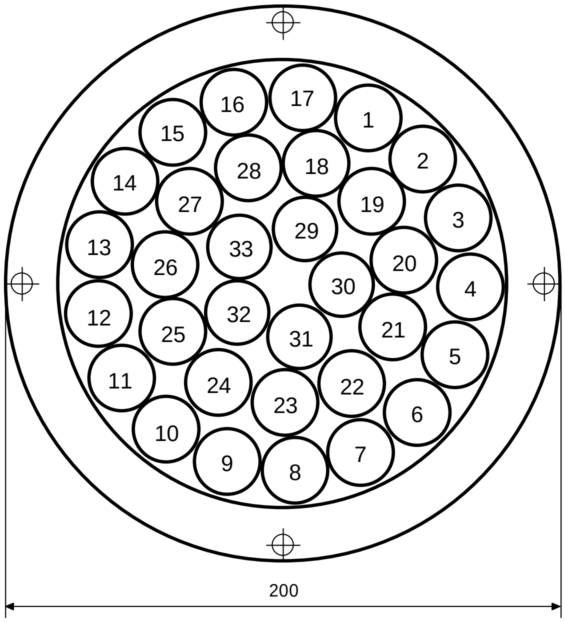

Fig. 1. Mosaic of the SAVEC construction with N = 33, L = 1060 mm

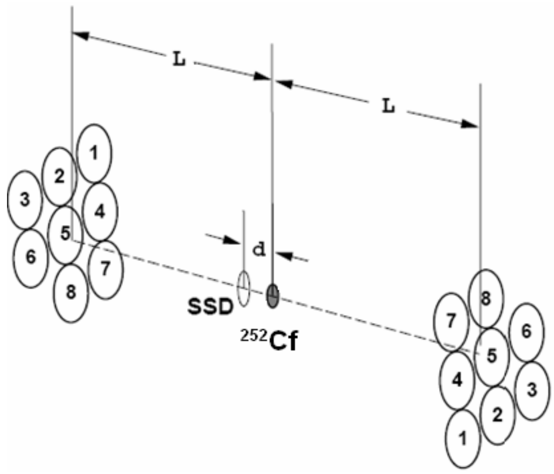

Fig. 2. Two mosaics of the SAVEC construction with N = 8, L = 688 mm. The distance between the ^{252}Cf-source and the start- signal device (SSD) d = 37 mm

Comparing mosaic constructions shown in Figs 2-4 one can conclude that they are almost equally effective for measurements of angular distributions. The chosen construction in Fig. 2 is nothing else but a truncated variant of N = 9 shown in Fig. 3.

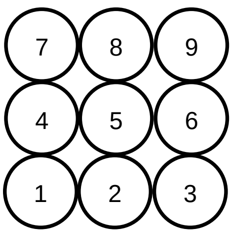

Fig. 3. Mosaic construction variant with N = 9

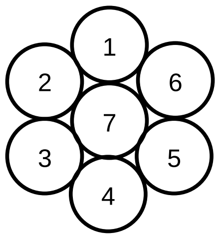

Fig. 4. Mosaic construction variant with N = 7

Table 1

	1	2	3	4	5	6	7	8	9
1	0	2.5	5.0	2.5	3.53	5.62	5.0	5.62	7.07
2	2.5	0	2.5	3.53	2.5	3.53	5.62	5.0	5.62
3	5.0	2.5	0	5.62	3.53	2.5	7.07	5.62	5.0
4	2.5	3.53	5.62	0	2.5	5.0	2.5	3.53	5.62
5	3.53	2.5	3.53	2.5	0	2.5	3.53	2.5	3.53
6	5.62	3.53	2.5	5.0	2.5	0	5.62	3.53	2.5
7	5.0	5.62	7.07	2.5	3.53	5.62	0	2.5	5.0
8	5.62	5.0	5.62	3.53	2.5	3.53	2.5	0	2.5
9	7.07	5.62	5.0	5.62	3.53	2.5	5.0	2.5	0

Table 2

	1	2	3	4	5	6	7
1	0	2.5	4.5	5.0	4.5	2.5	2.5
2	2.5	0	2.5	4.5	5.0	4.5	2.5
3	4.5	2.5	0	2.5	4.5	5.0	2.5
4	5.0	4.5	2.5	0	2.5	4.5	2.5
5	4.5	5.0	4.5	2.5	0	2.5	2.5
6	2.5	4.5	5.0	4.5	2.5	0	2.5
7	2.5	2.5	2.5	2.5	2.5	2.5	0

3. Experimental results

In the case of the SAVEC performance with L = 1060 mm, N = 33 and 33 × 33 = 1089 address combinations there were no detailed analysis on the angular distribution of the complementary fission fragments of ^{252}Cf nuclei. Since it was obtained at the level of 1.5% statistical accuracy, the value of the standard deviation of the total angular distribution from the collinearity σ_θ = 21 mrad. Advantages of the (2E, 2V)-measurement method were not utilized in this case for the further analysis. They were used in the second variant of the SAVEC performance with L = 688 mm, N = 8 and 8 × 8 = 64 address combinations. Owing to (2E, 2V)-measurement method it was possible to obtain a bi-dimensional plot (P_1, P_2) for complementary fragments of spontaneous fission of ^{252}Cf nuclei. The plot shown in Fig. 5 contains all the events in which at least one of the momenta P_1 or P_2 was smaller than 4000 MeV/c, as well as a small part of the total statistics where both P_1 and P_2 were greater than 4000 MeV/c.

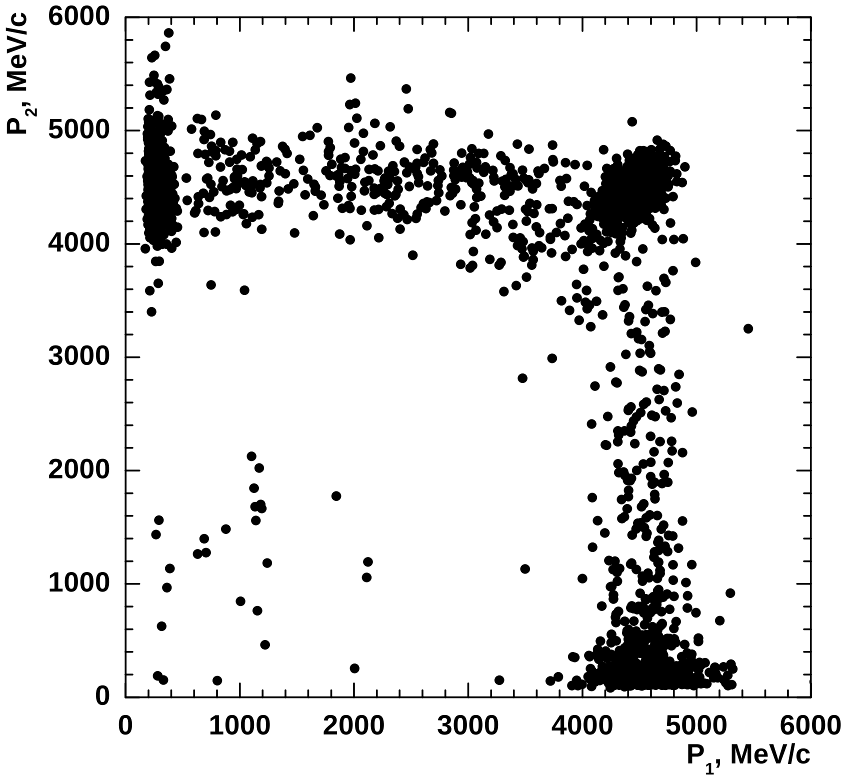

Fig. 5. Bi-dimensional plot P_2 versus P_1 for experimental events in which at least one of the momenta P_1 and P_2 is smaller than 4000 MeV/c as well as a small part (~0.5%) of the total statistics is used

Symmetric distribution of the events in Fig. 5 with respect to the diagonal $P_1 = P_2$ testifies the identity of both arms of the SAVEC. Events in which at least one of the momentum P_1 or P_2 was smaller than 4000 MeV/c comprised 1.3% of the total statistics. The events with clearly unbalanced momenta look like an evidence for the third body influence upon the two-body kinematics of the separating fragments. They can be considered as distorted events with respect to the normal fission events. One more advantage of the (2E, 2V)-technique compared with other experimental methods is an opportunity to measure a missing mass

$$\Delta M = M_0 - (M_1 + M_2), \tag{1}$$

where M_0 is the mass of the target nucleus and $M_{1,2}$ are the masses of the detected fragments. Using the information measured by the SAVEC one can determine the masses M_1 and M_2 for each distorted event. It turned out that one of the masses M_1 or M_2 was normal, *i.e.* belonged to the light or heavy group of the fragments, the other one being much smaller, imitating a large missing mass. The normal mass had the normal fragment momentum (*i. e.* it was larger than 4000 MeV/c), the smaller mass having much smaller momentum (less than 4000 MeV/c). The detailed analysis showed that among the distorted events, composed 0.4% of the total statistics, only 0.12% belonged to the fragments of the light mass group and 0.28% to the heavy mass group. This observation testifies that a considerable part of the distorted events represents the Rutherford scattering. Since in the calibration experiment with the ^{252}Cf-source the amplitude thresholds were very low, it was rather difficult to separate the effect of the Rutherford scattering from random coincidences for small momenta in both arms of the SAVEC. In Ref. [2] the presence – among the detected fragments – of the masses in the range from 55 to 65 u, characteristic for the natural mixture of nickel isotopes, was demonstrated. The distorted events differ from normal ones also by address combinations (A_1, A_2) of the detectors hit by fragments. The number of non-collinear fragments is much larger for distorted events [3]. Thus the calibration experiment with registration of fragments of the spontaneous fission of ^{252}Cf nuclei by (*2E*, *2V*)-technique showed how to reject the distorted events. Figore 5 helps to eliminate all the distorted events. For this purpose elimination thresholds for P_1 > 4000 MeV/c and P_2> 4000 MeV/c were chosen. The corresponding bi-dimensional plot (P_1, P_2) is shown in Fig. 6. The angular distribution for experimental events from Fig. 6 is demonstrated in Fig. 7.

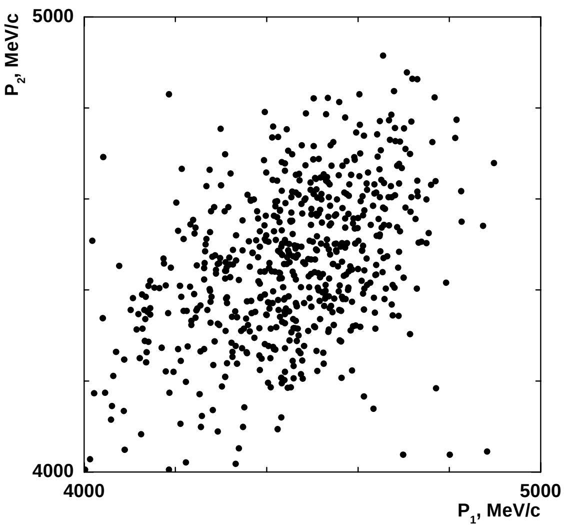

Fig. 6. Bi-dimensional plot (P_1, P_2) for events with momentum ranges 4000–5000 MeV/c

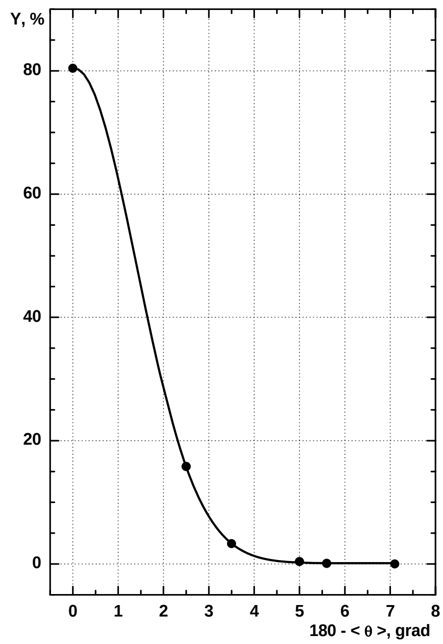

Fig. 7. Folding angle distribution for experimental events shown in Fig. 6

At the level of 4% statistical accuracy the spectrum shown in Fig. 7 satisfies to the standard deviation of the total angular distribution σ_θ = 19.2 mrad. Later on two attempts were undertaken. At first the momentum thresholds for P_1 and P_2 were decreased to 3800 MeV/c and after that they were increased to 4200 MeV/c. In both cases values of the standard deviation for these angular distributions became larger than 19.2 mrad. Thus the value of σ_θ = 19.2 mrad can be considered as a minimal possible standard deviation for angular distribution of complementary fragments from the ^{252}Cf-source measured with the help of the (*2E, 2V*)-measurement method.

Returning to the experimental practice at the proton beam of the PNPI synchrocyclotron we can justify the division of experimental nuclear disintegration events in two groups according to the collinearity. The first group of events denoted by stars belongs to the folding angle interval of (180°–177.5°), the second group with events denoted by points belongs to the interval of (176.5°–172.9°). Fig. 8 shows two momentum distributions one of which is nothing else as a repetition of Fig. 6 for complementary fission fragments from the ^{252}Cf-source. The second distribution refers to the complementary fragments from disintegrations induced in tungsten nuclei by 1 GeV protons.

Experimental events for tungsten disintegrations were taken from Fig. 3 of Ref. [1]. All experimental events were denoted by stars and points in accordance with the value of the folding angle between complementary fragments.

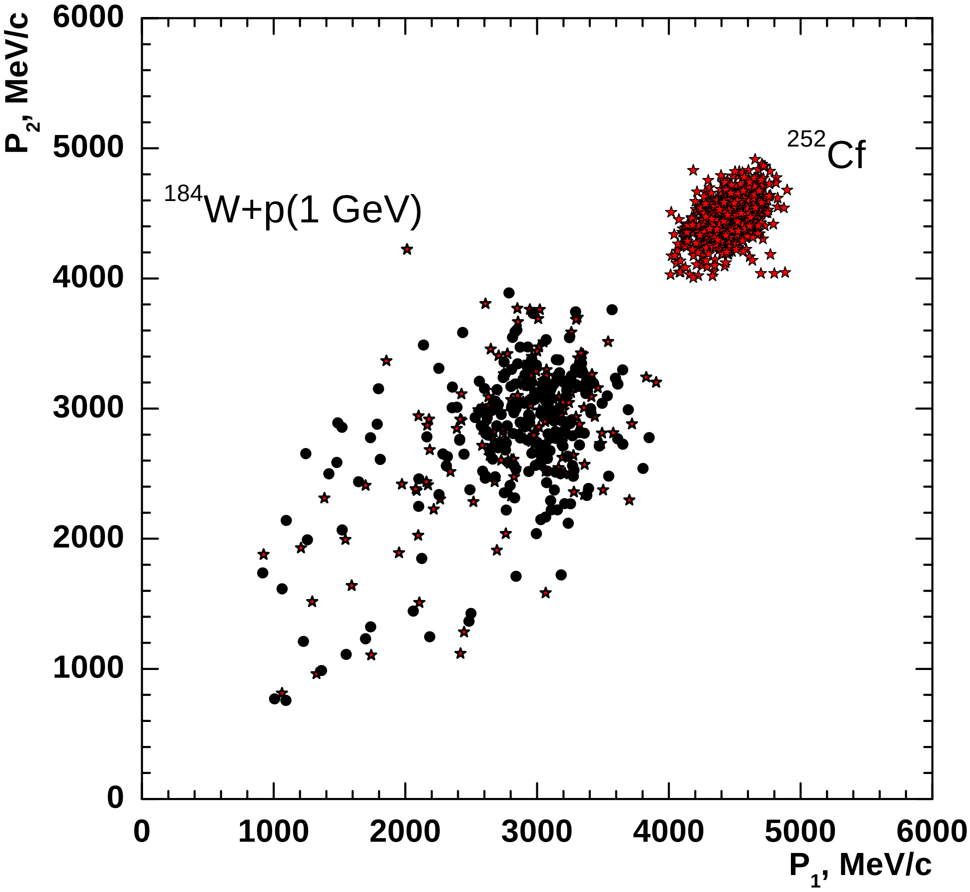

Fig. 8. Correlated momentum distributions (P_1, P_2) for complementary fragments from disintegrations induced in tungsten nuclei by 1 GeV protons and from the ^{252}Cf-source taken from Fig. 6. Stars and points are explained in the text

4. Conclusion

The value of σ_θ = 19.2 mrad was obtained with detectors having angular acceptance $\delta\theta$ = 43.6 mrad. It means that there is a possibility to get a better value for the measured standard deviation if one chooses detectors with a smaller angular acceptance. This limiting standard deviation can be evaluated according to the formula

$$\sigma_\theta^{\lim} = \left[(\sigma_\theta)^2 - \frac{(\delta\theta)^2}{12} \right]^{1/2} . \qquad (2)$$

Thus the final possible limiting standard deviation may be as low as $\sigma_\theta^{\lim}$ = 14.5 mrad.

References

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2. A.V .Kravtsov and G.E. Solyakin, Phys. Rev. C **60**, 017601 (1999).
3. A.V. Kravtsov and G.E. Solyakin, in *Proceedings of the 1st International Workshop on Physics of Isomers* (St.-Petersburg, 18 – 21 June 2000), Sarov, VNIIFF, 2001. p. 74.