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DETECTION OF TERNARY AND QUATERNARY FISSION FRAGMENTS FROM ^{252}Cf WITH A POSITION-SENSITIVE $\Delta E{-}E$ TELESCOPE BASED ON SILICON DETECTORS

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The silicon-based pixel detector Timepix is a multi-parameter detector which gives simultaneously information about position, energy and arrival time of a particle hitting the detector. Applying the $\Delta E{-}E$ method with these detectors makes it possible to determine types of detected particles, separating them by charge. Using a thin silicon detector with thickness of 12 μm combined with a Timepix (300 μm), a $\Delta E{-}E$ telescope has been constructed. The telescope provides information about position, energy, time and type of registered particles. The emission probabilities and the energy distributions of ternary particles (He, Li, Be) from ^{252}Cf spontaneous fission source were determined using this telescope. Besides the ternary particles, a few events were collected, which were attributed to the "pseudo" quaternary fission.

Кремниевый пиксельный детектор Timepix — многопараметрический детектор, который дает одновременно информацию о координате, энергии и времени взаимодействия регистрируемых частиц с детектором. Применение таких детекторов в составе телескопа $\Delta E{-}E$ позволяет идентифицировать частицы по заряду. Телескоп $\Delta E{-}E$ был построен с использованием тонкого кремниевого детектора толщиной 12 мкм в комбинации с детектором Timepix (300 мкм). Телескоп выдает информацию о пространственном положении, энергии, времени и типе регистрируемых частиц. Выходы и энергетические распределения частиц He, Li и Be из тройного спонтанного деления ^{252}Cf были определены с помощью этого телескопа. Кроме тройных частиц зарегистрировано несколько событий, которые были интерпретированы как события из псевдочетверного деления.

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INTRODUCTION

Normally, fission is a binary process, in which the fissioning nucleus splits into two fission fragments. This is the case in general for both spontaneous and induced nuclear fission. Sometimes, however, instead of the standard "binary fission" a higher-multiplicity process with three or more charged particles emitted in the outgoing channels is observed. The accompanying particles are lighter compared to the main binary fragments. Therefore, they are called light charged particles (LCP). In ternary fission process, mostly H and He isotopes are emitted, although particles up to mass 36 have been observed [1–3]. The ternary fission process for different nuclei has already been extensively investigated with various detectors and methods. About 87% of ternary fission events are the ternary ^{4}He particles with mean energy around 16 MeV. These are often called Long-Range Alpha (LRA) particles [4, 5]. Due to the strong focusing effect of the Coulomb field, the particles are mainly emitted at about 83° to the fission axis [5]. The rare ternary fission process is of particular interest not only for the understanding of the fission process itself, but also as a source of various neutron-rich light nuclei [6, 7]. An even rarer particle-accompanied fission mode, with probabilities in the range of 10^{-7} to 10^{-6}, is quaternary fission (QF), where a pair of LCPs is simultaneously emitted in one fission event [8]. QF mode can originate either from the break-up of unstable species among the LCPs, e.g., ^{7}Li*, ^{8}Be, ^{9}Be* ("pseudo" quaternary fission), or from the independent emission of two LCPs ("true" quaternary fission) [8, 9]. QF mode has not been purely studied because of its exceedingly low yield.

1. A $\Delta E{-}E$ TELESCOPE

The measuring system is composed of two $\Delta E{-}E$ telescopes. Each of them consists of a thin silicon detector and a Timepix [11] semiconductor pixel detector. The thin detector is used for ΔE and the Timepix detector for E measurements. Each ΔE detector has an area of 10×10 mm and a thickness of 12 μm with non-uniformity of 8%. The thickness and active area of the Timepix detector is 300 μm and 14×14 mm, respectively. A simplified electronics scheme of the set-up is presented in Fig. 1. All signals from the ΔE detector are first pre-amplified. Signals from a charge-sensitive preamplifier are split in two channels. One signal is fed to a spectroscopic amplifier for energy measurements. The second signal is sent to a fast-timing filter amplifier with leading-edge discriminator used for triggering the Timepix detector (E). A 250 MHz DT5720 CAEN digitizer is used for pulse-height spectrum measurements for the ΔE detector [10]. Each telescope was placed at a distance of 8 mm from the source. A 31-μm-thick Al foil was placed in front of the detectors for stopping the background alpha particles from natural radioactivity of ^{252}Cf (6.2 MeV) in the experiment. The Timepix detector is equipped with integrated per-pixel signal electronics. Each pixel is equipped with a counter operating in one of the three modes: Medipix mode (the counter counts incoming particles), Timepix mode (the counter works as a timer and measures time of interaction of the particle) and time-over-threshold (TOT) mode. In the last mode of operation, the Timepix pixels operated analogously to a Wilkinson type ADC, allowing direct energy measurement in each pixel. From its TOT mode of operation, the Timepix device can count the amount of charge being deposited by a particle in a given pixel element. Timepix

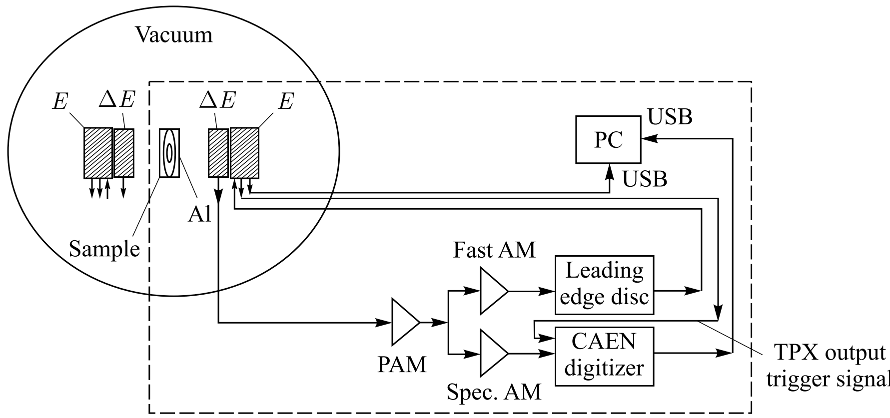

Fig. 1. Schematic layout of the telescope configuration. Each side of the set-up has a thin ΔE detector (12 μm silicon) and the pixel detector Timepix as E detector (300 μm silicon)

consists of a matrix of 256×256 square pixels (total 65536 pixels) with pitch of 55 μm [11]. The total energy of the particle is measured by summing over all pixels in the cluster of activated pixels. In the case of heavy charged particles the measured charge distributions can be fitted to a Gaussian shape, permitting the determination of the point of interaction of the particle in the device with sub-pixel precision. The spatial resolution can be achieved down to few μm [12]. The Timepix detector is powered and controlled by the integrated readout interface FITPix [13] which plugs directly to any PC via USB port. The interface and the detector can be controlled via Pixelman software [14].

2. MEASUREMENT

For the measurements we used a thin (both sides) spontaneous fission source of ^{252}Cf with activity of about 100 Bq mounted on a 60 μg/cm^2 foil backing of Al_2O_3 and coated with a thin layer of gold (of less than 10 mg/cm^2). The source thickness is assumed to be uniform to within 20%. The source was round with outer diameter 18 mm and inner diameter 2.1 mm. The experiment was carried out in vacuum (< 0.4 mbar) with two telescopes oppositely placed at 8 mm from the source. The count rate for ternary fission was 0.3/min on each telescope.

3. TERNARY FISSION

A $\Delta E{-}E$ spectrum of LCPs measured with the telescopes is shown in Fig. 2. The ternary particles from ^{3}H to Be were discriminated as shown in Fig. 2. Because of the high energy threshold in the ΔE detector, isotopes lighter than ^{3}H are not well resolved in Fig. 2. Due to the 31-μm Al foil and 12-μm ΔE detector, the lowest energy (threshold) of α particles which can reach the E detector was about 7.5 MeV. Energy spectra were plotted for identified ternary particles using graphical cut-off method. For comparison of our results with the other/previous works, the energy spectra from different experiments are normalized on the yields of our data.

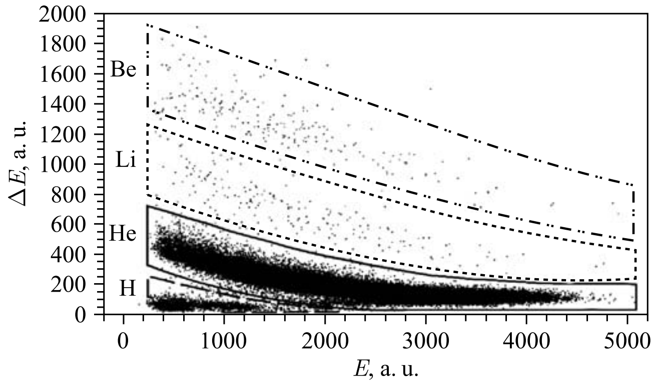

Fig. 2. $\Delta E - E$ patterns from ternary LCPs in ^{252}Cf. The contour lines define the identification windows used for the analysis. A 31-μm-thick Al foil was used for protecting the telescopes from being hit by fission fragments and the 6.2-MeV background alpha particles

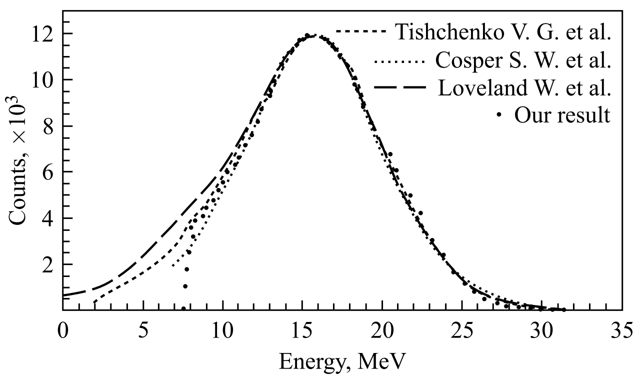

Fig. 3. Energy distribution for the ternary α particles emitted in ^{252}Cf (SF) including comparison with results obtained by V. G. Tishchenko et al. [4], S. W. Cosper [15] and W. Loveland [16]

The comparison of energy spectra is shown in Fig. 3. As shown in Fig. 3, in the high energy region (> 10 MeV) all spectra coincide quite well. The LCP energy spectra obtained with the telescope in the ternary fission modes with He, Li and Be emission are displayed in Fig. 4. All spectra were corrected for energy loss in the absorber foil and the ΔE detector. For the heavier LCP species the accessible range of LCP energy was more seriously limited by the cutoff. This further imposed a strong distortion on the energy spectrum. Heavier LCP particles deposit only part of their energy in the telescopes and were thus registered at higher energies. Li and Be LCPs emitted in ^{252}Cf ternary fission with kinetic energy over 16.5 and 25.5 MeV, respectively, were identified and their relative yields and energy distribution parameters were estimated. A Gaussian fit to the ternary α data points above 12.5 MeV were performed to determine the average energy and sigma, as well as extrapolated counting rates. The results obtained for the various ternary particles are listed in the table. The estimated yields are in agreement with the experimental data from [5].

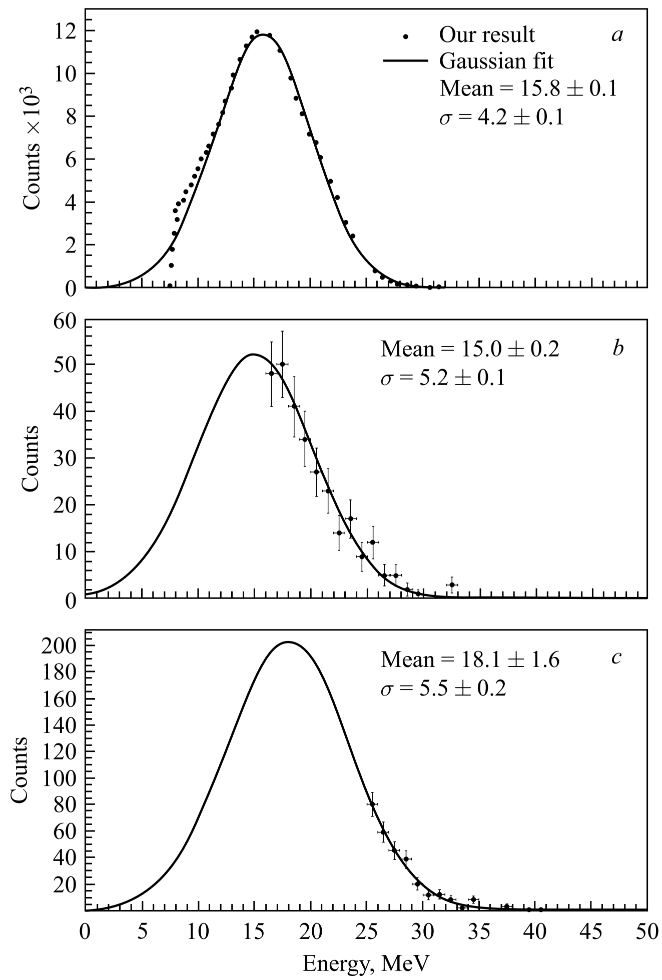

Fig. 4. Energy distribution for the ternary particles He (*a*), Li (*b*) and Be (*c*) emitted in ^{252}Cf (SF), measured with the Al shielding foil. Correction was done for losses on the Al foil and ΔE detector

Relative emission probabilities of the various ternary particles and the energy distribution for the spontaneous fission of ^{252}Cf

Ternary particles	Events	Threshold energy, MeV	Energy, MeV	Sigma, MeV	Yield per $10^4\alpha$
He	10^5	7.5	15.8 (0.1)	4.2 (0.1)	10^4
Li	210	16.5	15.3 (0.6)	5.2 (0.4)	51 (11)
Be	214	25.5	18.1 (1.6)	5.5 (0.2)	224 (22)

4. QUATERNARY FISSION

QF particles were also analyzed using the same spontaneous ^{252}Cf fission double-sided thin source. A total of 63 (α, α) and 9 (α, t) coincidences were registered. Due to low activity and the protecting Al foil, random coincidences were negligibly rare. The detector geometry chosen permitted us to cover an angular range between 3–83° and 100–1803° for the mutual opening angles θ between two measured LCPs. The simulated geometry distribution for our detector system is shown in Fig. 5. As seen from Fig. 5, the most probable mutual angle was around 35 and 145°. Corrections from a Monte Carlo calculation were applied for the probability of double hits in the geometry of the telescope systems. Due to limited geometry, the experimental angular distribution had to be divided by the simulated geometry for obtaining the correct angle distribution. Uncorrected angular distributions measured for (α, α) and (α, t) coincidences are displayed in Fig. 6, *a*. Corrected angular distributions measured for (α, α) and (α, t) coincidences are shown in Fig. 6, *b*. The presented data on angular distributions are in close agreement with the early work of P. Jesinger et al. and Kataria et al. [9, 15]. Since the ΔE detector was a thin single pad detector, it could not give information about position and angular distribution. Therefore, the double α hits in a telescope should add up as an admixture to the pattern between α and Li LCPs. In the evaluation an attempt was,

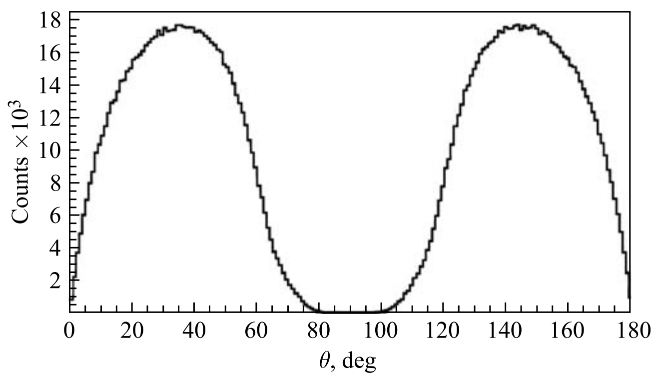

Fig. 5. Simulated geometry distribution for the detector system

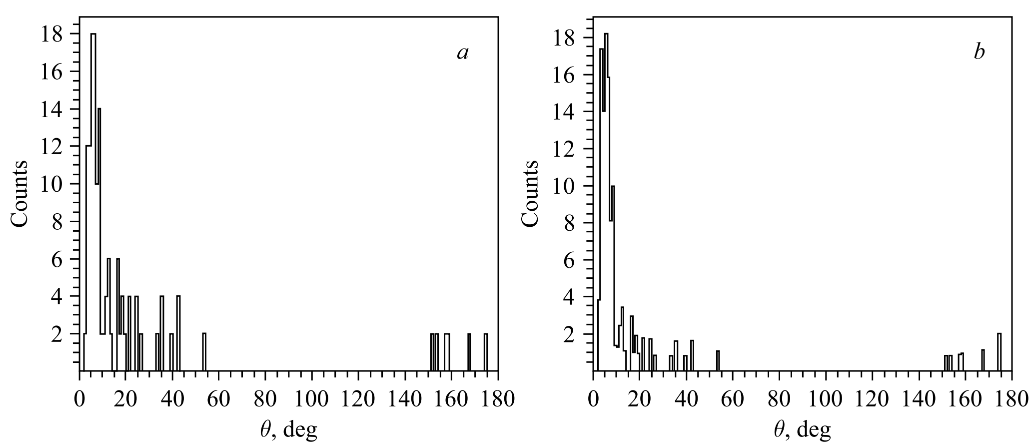

Fig. 6. Distribution of opening angles between two LCPs from quaternary fission of ^{252}Cf. *a*) Uncorrected; *b*) corrected both coincidences. θ denotes angles between the centers of two signal clusters registering two LCPs

hence, made to disentangle these double α events from the $\Delta E{-}E$ scatter plot. Thanks to the per pixel sensitivity of Timepix, we could identify (α, α) and (α, t) pairs by analyzing the signal cluster size and registered energy. A 3D spectrum for (α, α) and (α, t) pairs is shown in Fig. 7. As shown in the figure, the cluster sizes and energies for (α, α) pairs are about equal, but for (α, t) pairs they differ by about 2 times. The distribution of relative angles between the two α particles for ^{252}Cf is shown in Fig. 6. As seen from Fig. 6, at smaller mutual angles there was a clear enhancement in the probability of emission of two α particles which indicated the presence of a second component of QF. The pronounced correlation in angle was traced to the decay of ^{8}Be, which is unstable even in its ground state. An enhancement in the coincidence rate at smaller angles θ was observed in Fig. 6 also for (α, t) pairs. The (α, α) coincidences were disentangled with opening angles $\theta \leqslant 8^\circ$. The events were not analyzed for the case of $\theta > 60^\circ$ due to very low statistics. In the decay of ^{8}Be from the ground state, the comparatively long half-life ($T_{1/2} = 0.07$ fs) together with the low Q-value of the reaction ($Q = 0.092$ MeV) led to an angular correlation between the

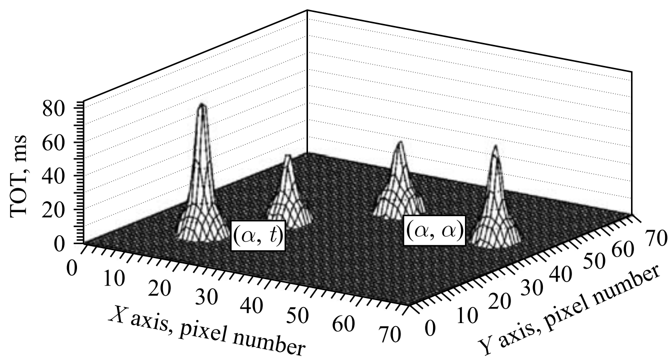

Fig. 7. The 3D spectrum for (α, α) and (α, t) pairs. The cluster sizes and energies for (α, α) pairs are about equal, but for (α, t) pairs they differ about 2 times from each other

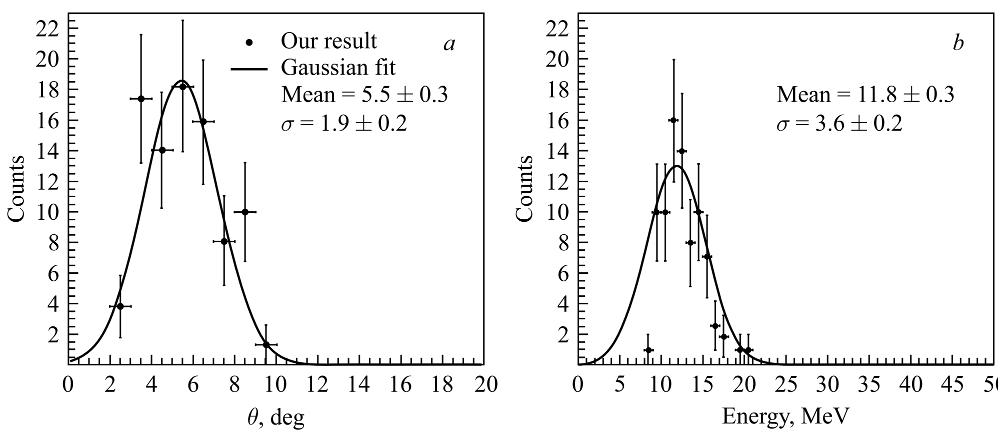

Fig. 8. Distribution of opening angles between two LCPs and energy spectrum for ^{8}Be ground state from quaternary fission of ^{252}Cf. *a*) Angle between (α, α); *b*) (α, α) energy spectrum. The (α, α) coincidences were taken for which the angle was less than 11°

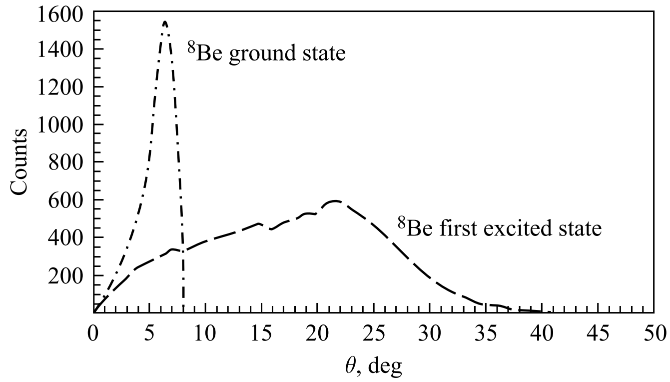

Fig. 9. Angular distribution from trajectory calculation

two α's. Calculations simulating the kinematics of the decay yielded a maximum opening angle $\theta_{\max}$ of 8°, at the average kinetic energy of ^{8}Be. The smallest angle for detection of α pair in the telescopes was $\theta = 3°$ depending on the particle energy. The decay from excited states of ^{8}Be could also contribute to the observed enhancement at angles $\theta \leqslant 60°$ as shown in Fig. 6. The resulting angle and energy spectra for ^{8}Be ground state are plotted in Fig. 8, *a* and *b*, respectively. Both spectra were fitted by Gaussian functions (solid curves). As seen in the figure, α particles from (α, α) coincidences in QF had lower energies than those from ternary decays. The kinetic energy of (α, α) coincidences was corrected for energy losses in the absorbers in front of the telescopes and in the ΔE detectors. The angular distribution from the trajectory calculation is shown in Fig. 9 for ^{8}Be ground and excited states. As shown in the figure, there is good agreement of the experimental data. The fractional yields for ^{8}Be (g.s.) and the excited states of ^{8}Be were estimated with systematic errors of 20%. The yield for the ground state (α, α), when calculated per 10^4 alphas, was 3.4 ± 0.7.

5. SUMMARY AND CONCLUSIONS

Ternary particles from ^{252}Cf spontaneous fission source were studied in the experiment. Results obtained are in good agreement with previous and other works. Despite low statistics, "pseudo" quaternary fission was studied too. The angle between (α, α) pairs from both ^{8}Be ground state was measured. The per pixel sensitivity of Timepix allowed measuring angles over 3°. The angle, yields and energy of $(\alpha,\ \alpha)$ pairs from ^{8}Be (ground state) were 5.6°, 3.4 events per 10^4 alphas and 11.8 MeV, respectively. These results are corroborated by calculations. In addition, ternary particles allowed us to test the response of Timepix detector to different particle species. Compared with other authors' results, the response of Timepix detector to He, Be and Li particles is the same.

Long-term measurements are planned for studies of quaternary fission using a higher activity spontaneous fission source of ^{252}Cf. Use of different thickness of the ΔE detector will serve to enhance the identification capability of the assembled telescopes and study another quaternary fission pairs ($\alpha{-}t$, $\alpha{-}p$, etc.). The set-up will be used to study rare fission mode processes with spontaneous and neutron-induced fission reactions.

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