MONTE-CARLO CALCULATIONS OF OPENING ANGLES BETWEEN TWO LIGHT PARTICLES IN “PSEUDO”-QUATERNARY FISSION

S.A. Telezhnikov[a], **G.S. Ahmadov**[a,b,c], **Yu.N. Kopatch**[a], **F.I. Ahmadov**[b,c], **A.A. Garibov**[b,c], **C. Granja**[d], **S. Pospisil**[d]

[a] *Frank Laboratory of Neutron Physics, JINR, 141980 Dubna, Moscow reg, Russia*
[b] *Institute of Radiation Problems-ANAS, AZ1143, Baku, Azerbaijan*
[c] *National Nuclear Research Centre of Ministry of Communications and High Technologies, AZ1143, Baku, Azerbaijan*
[d] *Institute of Experimental and Applied Physics, Czech Technical University, 128 00 Prague 2, Czech Republic*

Abstract: In studying of fission with multiple outgoing charged particles many experiments were devoted to the analysis of ternary and quaternary fission. Some time ago two ΔE-E telescopes from thin silicon detectors with thickness of 12 μm combined with two Timepix detectors (300 μm) were used for such a measurement. The emission probabilities and the energy distributions of ternary particles (He, Li, Be) from ^{252}Cf spontaneous fission source were determined using these telescopes. Besides the ternary particles, a few events were collected, which were attributed to the “pseudo”-quaternary fission. Such events appear when light unstable particles brake up into two charged particles during their flight from fission nucleus to a detector. Angle between these two particles depends on the velocity of the unstable particle and on the internal energy of its decay. The analysis of this angle can help to distinguish between different modes of this process. Calculation of this angle is a simple dynamic task but for comparison of the results of calculations with experimental data energy distribution of flying particles and random angle of particles after the breakup with the direction of fly must be considered. For the unstable ^{8}Be three modes of decay can be analyzed: decay of ^{8}Be into two α-particles when ^{8}Be is in the ground state and when it is in the first and the second excitation levels. ^{7}Li in the ground state is stable but if it is in the second excited state or higher it splits on α and ^{3}H nucleus. By analyzing opening angles between these two particles these modes can be separated. In this work Monte-Carlo calculations of opening angles for several modes were performed in which an experimental distribution of energies of unstable particles and random angle of decay were taken into account.

1. Introduction

In studying of fission with multiple charged outgoing particles many experiments were devoted to analyzing of ternary and quaternary fission. Some times ago two ΔE-E telescopes have been constructed by us. Each telescope consists from a thin silicon detector with thickness of 12 μm combined with a Timepix. The hybrid pixel device Timepix [1] consists of a semiconductor detector chip from Si with thicknesses 300 μm and is a position sensitive detector with matrix 256 x 256 square pixels with pitch of 55 μm. This device can register different types of particles which give charge in volume of a detector and matrix of pixels can give position, track or area of registered event. In one mode of operation Timepix gives charge of registered particle and therefore energy of particle can be obtained.

The emission probabilities and the energy distributions of ternary particles (He, Li, Be) from ^{252}Cf spontaneous fission source were determined using these telescopes. Besides the ternary particles, a few events were collected, which were attributed to the “pseudo”-

quaternary fission. Such events appear when light unstable particles break up on two charged particles during fly from fission nucleus to a detector. Angle between these two particles depends on energy of unstable particle and internal energy of decay and in analyzing of this angle different modes of this process can be distinguish. Now mode of the process is determined by internal energy of unstable particle. For unstable ^{8}Be three modes of decay can be analyzed: decay of ^{8}Be to two α-particles when ^{8}Be is on the ground state and when it is on the first and the second exiting levels. ^{7}Li in the ground state is stable but if it is on the second exited state or upper it splits on α and ^{3}H nucleus. In analyzing of opening angle between two particles these modes can be separated.

For comparison of experimental opening angle with theoretical one some calculations must be provided. Calculation of this angle is a simple dynamic task but for comparison of results of calculations with experimental data energy distribution of flying particles and random angle of particles after the breakup with the direction of fly must be considered. In this work Monte-Carlo calculations of opening angles for different modes were performed in which an experimental distribution of energies of unstable particles and random angle of particles after decay were taken into account.

2. Physical picture of the process

Normally, fission is a binary process, in which the fissioning nucleus splits into two fission fragments in both spontaneous and induced nuclear fissions. Sometimes, however, instead of the standard binary fission a higher-multiplicity process with three or more charged particles in the outgoing channel is observed, but with the accompanying particles being very light compared to the fission fragments. Therefore, they are called light charge particles (LCP). Among them process with three outgoing particles is the most probable. In this so-called ternary fission process, mostly H and He isotopes are emitted, although particles up to mass 36 have been observed [2, 3]. In about 87% of ternary fission events are the ternary ^{4}He particles and being fairly energetic (16 MeV), 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 under about 83^0 to the fission axis [5]. 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 [6]. QF mode can originate either from a decay of unstable species among the LCPs, e.g. ^{7}Li*, ^{8}Be, ^{8}Be* ("pseudo"-quaternary fission), or from the independent emission of two LCPs (true quaternary fission) [6, 7].

"Pseudo"-quaternary fission is a process in which flying unstable particle splits when flies from fission nucleus to a detector. For isolated unstable particle only two energies determine dynamics of process - energy of fly and energy of decay. It is a simple dynamic process. As energy of decay is constant for each mode of decay two variables determine opening angle between two particles after decay – energy of fly and angle of resulting particles to the direction of fly. As acceleration of the third particle in ternary fission is not instant some time must pass before this particle will have full energy of fly. If this time is comparable with $T_{1/2}$ of decaying particle decay can happen when flying particle does not have full energy and therefore opening angle between two resulting particles will be not the same as after full acceleration of unstable particle. In view of this two different scenarios can be proposed:

1. Unstable particle splits when it have full energy after full acceleration.

2. Unstable particle splits before it has full energy.

The second scenario is more complicated for analyzing because of random time of break up in relation to acceleration of particle.

In this work only the first scenario is analyzed.

For next analysis in this work 6 modes of decay were chosen – 3 modes of dissociation of ^{8}Be and 3 modes of dissociation of ^{7}Li. For ^{8}Be they are: decay of nucleus on the ground state, decay of nucleus on the first exited level (3030 keV) and decay of nucleus on the second exited level (11350 keV). For ^{7}Li modes are dissociations of nuclei which are on 3 exited levels (4630, 6680 and 7459.5 keV) because the ground state is stable and for dissociation of the first exited level Q of reaction is negative.

For comparing of time of acceleration and time of dissociation of nuclei the next very rough estimations were used.

1. Acceleration must be ended at the distance smaller than radius of atom Cf which was taken as 295×10^{-12} m.

2. Energies of accelerating particles from 5 to 35 MeV are considered.

3. Distance which unstable particle can fly at time $T_{1/2}$ is calculated and this distance is compared with radius of atom and radius of nucleus Cf which was taken as 7.8×10^{-15} m.

Some information about 6 modes of dissociation of unstable ^{8}Be and ^{7}Li* are shown in Tab.1. B_α is the energy of separation of α-particle which is negative for ^{7}Li. $l_{1/2}$ is a distance which particle with energy 20 MeV flies at time $T_{1/2}$. Value N_R in the sixth column of the table is number of radiuses of nucleus Cf in $l_{1/2}$.

Table 1. Information about 6 modes of dissociation of ^{8}Be and ^{7}Li (see text)

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Nucleus and B_α (keV)	Level (keV)	Q (keV)	$T_{1/2}$ (s)	$l_{1/2}$ (m)	N_R
^{8}Be 91.84	0	92	8.2×10^{-17}	1.8×10^{-9}	230000
	3030	3122	3.0×10^{-22}	6.6×10^{-15}	0.8
	11350	11442	1.3×10^{-22}	2.9×10^{-15}	0.4
^{7}Li -2467.62	4630	2162	4.9×10^{-21}	1.1×10^{-13}	15
	6680	4212	5.2×10^{-22}	1.2×10^{-14}	1.6
	7460	4992	5.1×10^{-21}	1.2×10^{-13}	15

It can be seen from Tab.1 that the most $T_{1/2}$ is for the first mode of Be^8. Value $l_{1/2}$ is more then radius of Cf atom. It means that dissociation of this mode is after full acceleration of unstable nucleus. Values $l_{1/2}$ of the first and the third modes of Li^7 are more then 10 radiuses of Cf nucleus. It also means that dissociation of these modes are after the full acceleration. Dissociation of other three modes can be before the full acceleration of unstable nucleus. But it can be noted that the third particle in ternary fission obtains the greatest impulse at the moment of separation because of the greatest electric field.

3. Theory

As was said above calculation of decay of flying particle is a simple dynamic task. Vector diagram of impulses of decay of unstable flying particle is shown in Fig.1. In this

Fig. $\mathbf{p}_1$ and $\mathbf{p}_2$ are impulses of two particles flying with the same velocity before decay. Vectors $\mathbf{p}_0$ and $\mathbf{-p}_0$ are impulses of two particles after dissociation in their own system. Vectors $\mathbf{p}_x$ and $\mathbf{p}_y$ are impulses of two particles after dissociation in laboratory system. Angle α is angle between path of the first particle after dissociation and path of decaying particle before dissociation. Angles β and γ are angles of resulting particles to path of decaying particle before dissociation. Opening angle which must be calculated is obtained by summing of β and γ angles.

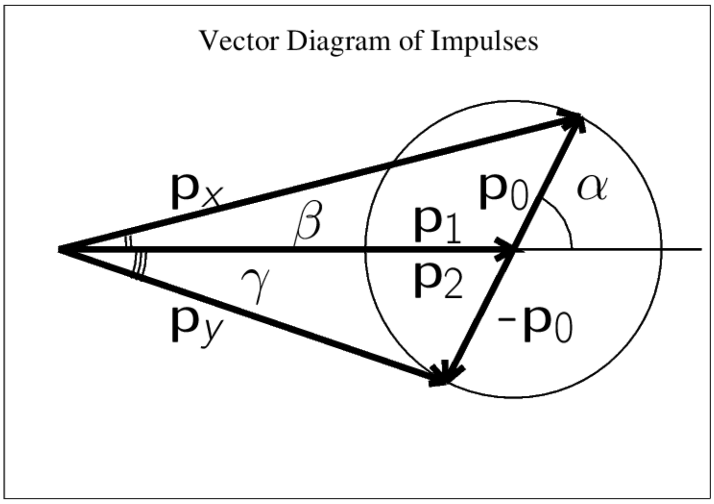

Fig.1. Vector diagram of impulses of decay of flying unstable particle.

For each energy of unstable particle there are four constants and one variable in this task. Two constants m_1 and m_2 are masses of two particles after dissociation and mass of unstable particle is $M = m_1 + m_2$. Other two constants are E and Q. E is energy of unstable particle, Q is energy of dissociation. $E = E_1 + E_2$, where E_1 and E_2 are energies of the first and the second particles before decay. Variable in this task is angle α. As result E_x, E_y, angles β and γ must be obtained. Here E_x and E_y are energies of the first and the second particles after dissociation.

From conservation of impulses and energy one can write the next expressions:

$$\mathbf{p}_x = \mathbf{p}_1 + \mathbf{p}_0$$
$$\mathbf{p}_y = \mathbf{p}_2 - \mathbf{p}_0$$
$$E_x + E_y = E + Q$$

One can write some relationships:

$$p_0^2 = 2Qm_1m_2/M, \qquad p_1^2 = 2Em_1^2/M, \qquad p_2^2 = 2Em_2^2/M.$$

As results the next expressions can be obtained:

$$p_x^2 = 2m_1(Em_1 + Qm_2 + A\cos\alpha)/M$$
$$p_y^2 = 2m_2(Em_2 + Qm_1 - A\cos\alpha)/M$$
$$\cos\beta = (p_1 + p_0\cos\alpha)/p_x$$
$$\cos\gamma = (p_2 - p_0\cos\alpha)/p_y$$
$$E_x = (Em_1 + Qm_2 + A\cos\alpha)/M$$
$$E_y = (Em_2 + Qm_1 - A\cos\alpha)/M$$

Here $A = 2\sqrt{EQm_1m_2}$.

4. Monte-Carlo calculations

To compare experimental data with theory one must to consider real energy distribution of unstable particles and angle distributions of resulting particles. Distribution of each resulting particle in internal coordinate system has spherical symmetry.

First of all parameters of energy distributions of unstable particles must be chosen for calculations. Some information about energy distribution was obtained in our experiment with two telescopes. As ^{8}Be and ^{7}Li can not be detected one can use parameters of energy distributions for other isotopes of these nuclei. Parameters of energy distribution of Be isotopes were obtained in our experiment. This result is shown in Fig.2. Low energy part of distribution was cut off by Al foil and ΔE detector.

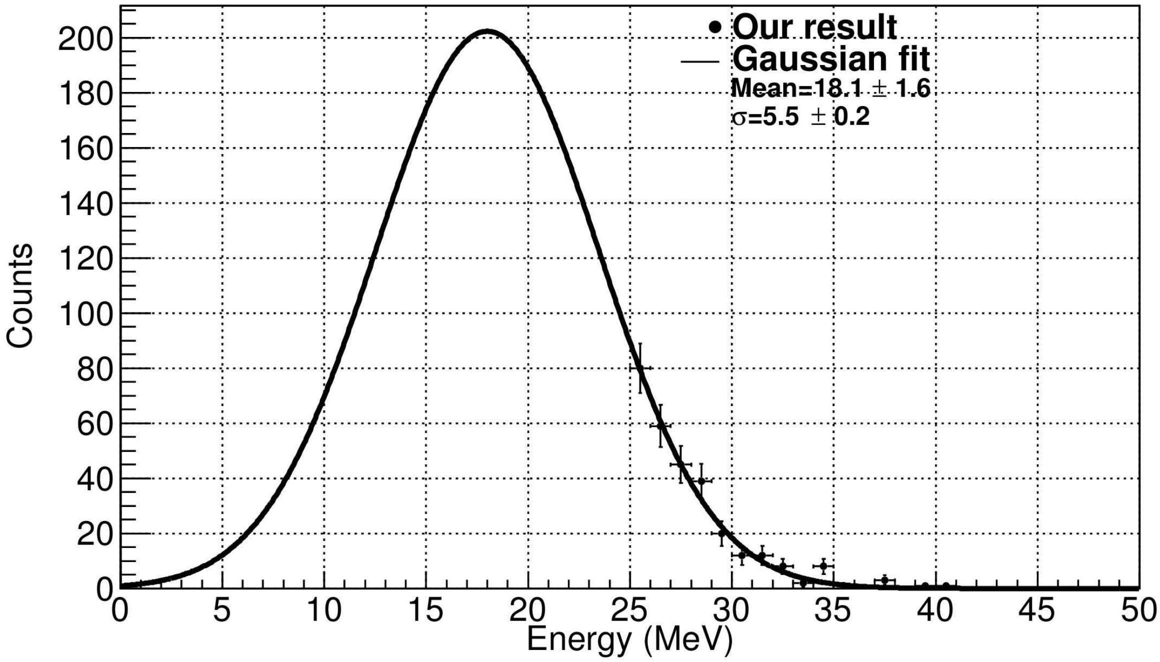

Fig.2. Energy distribution of Be isotopes as the third particles in ternary fission of ^{252}Cf spontaneous fission obtained in our experiment.

Parameters of energy distributions of Be isotopes were obtained in [8]. Results for three isotopes are the next: for ^{9}Be E=19.0 MeV and FWHM=15.0, for ^{11}Be E=19.3 MeV and FWHM=15.9 MeV, for ^{12}Be E=20.4 and FWHM=16.1. Here E is mean energy. These results were obtained in about the same energy region as our results. Parameters of energy distributions of Be isotopes were obtained in more wide energy range in [9]. Part of Fig.12 from this work is shown in Fig.3.

Our result for Li isotopes is E=15 MeV and FWHM=13 MeV. Result from [9] is E=20 MeV and FWHM=6.6 MeV. If FWHM is more distribution of open angles will be wider. One of the aims of this work is to obtain boundaries for extracting events of each mode. Use more wide region must give more reliable result.

In our calculations for ^{8}Be and ^{7}Li next parameters of energy distributions of unstable particles were used: E=20 MeV, FWHM=15 MeV.

Monte-Carlo calculations of open angles for 6 modes which were shown in Tab.1 were performed by us. In all calculations generation of energy distributions with these parameters was made. An example of Monte-Carlo energy distribution is shown in Fig.4.

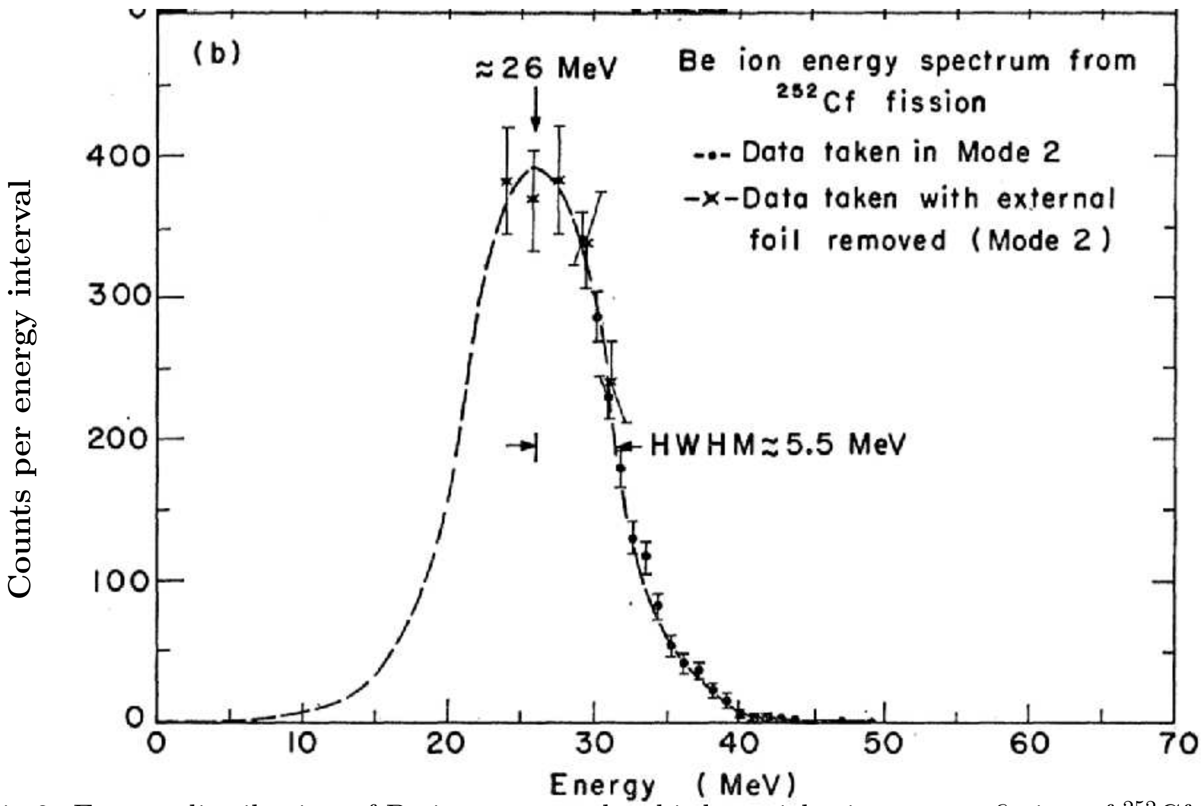

Fig.3. Energy distribution of Be isotopes as the third particles in ternary fission of ^{252}Cf spontaneous fission. This picture is part of Fig.12 from [9].

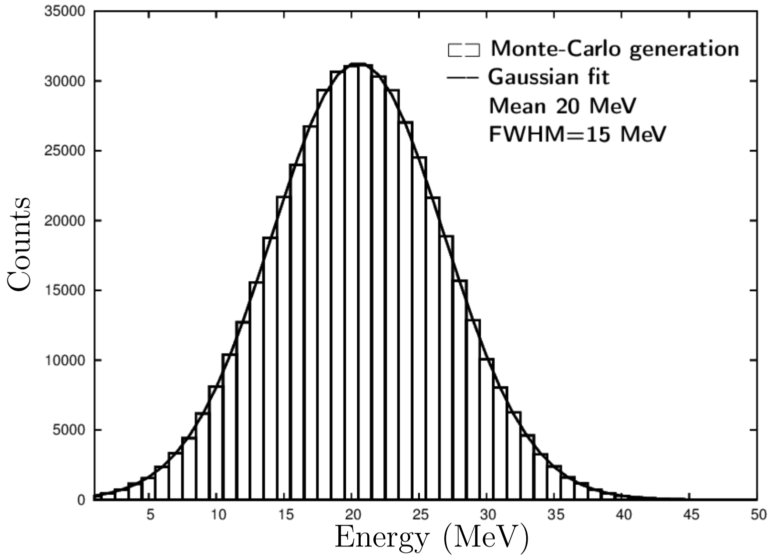

Fig.4. Energy distribution of unstable particles obtained in Monte-Carlo generation in one of calculated modes.

As was said above for calculation of open angles one must use two Monte-Carlo generators: the first for energy distributions of unstable particles and the second for generation of an angle between path of unstable particle and one resulting particle (angle α in Fig.1). This angle in internal coordinate system of two resulting particles has spherical symmetrical behavior. For checking of this generator the next procedure was used. Vector is built from center at angle which is obtained in Monte-Carlo generator with constant length. Ends of these vectors are on a sphere. Uniformity of points on the sphere can be checked if one can separate the surface of the sphere on equal parts. This was realized by obtaining spherical sectors – section of sphere by two planes passing through one axe. These planes clip part of surface as petal. If angles between these planes will be equal areas of petals will be equal too. As example two such petals are shown in Fig.5. Here angles between two planes are ten degrees.

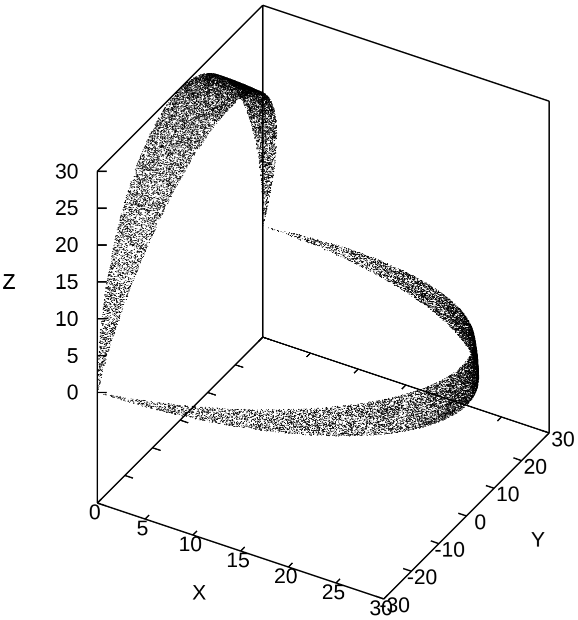

Fig.5. An example of two surfaces from spherical sectors. Planes go through Y axe. Angles between planes are equal ten degrees.

For checking of uniformity of spherical Monte-Carlo events sphere was cut on 360 sectors with the angles between two planes of one degree. Statistics in each petal is shown in Fig.6. In this picture planes pass through Z axe.

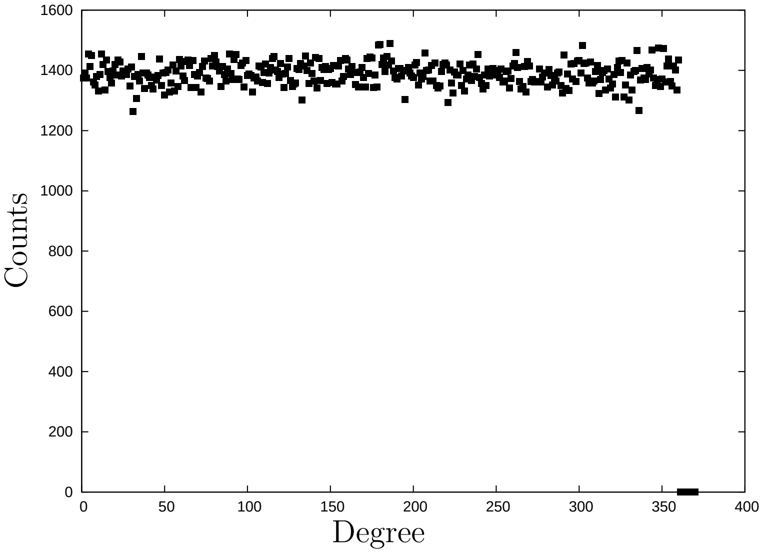

Fig.6. Statistics of Monte-Carlo events in each of 360 petals with the angles equal one degree (see text).

Such pictures were obtained with planes which go through X axe and Y axe and statistics had similar view. This demonstrates uniformity of spherical Monte-Carlo generator.

As α-particles in our experiment suffer energy loss in Al foils and ΔE detectors with summing loss about 7 MeV all α-particles in Monte-Carlo simulations with energy lower 7 MeV were cut off.

After dissociation of ^{7}Li ^{3}H suffer energy loss and in Monte-Carlo simulation all events with energy lower 2.7 MeV were cut off.

Some words about detection of ^{3}H is need to say. As thicknesses of Timepix detectors were 300 μm stopping power of ^{3}H was 9.4 MeV. All ^{3}H with energy more than this energy suffer loss of only part of their energy and with more energy less energy loss. Hence energy of detected ^{3}H can be from 2.7 MeV to 9.4 MeV. As energy of α-particles can be from 7 MeV events of ^{3}H have energy less than energy of α-particles. All events with energy less 7 MeV are events of ^{3}H.

5. Results and discussion

Monte-Carlo calculations of opening angles between two light charged particles from the "pseudo"-quaternary fission of ^{252}Cf were provided by us. Six modes of dissociations which were shown in Tab.1 were analyzed. Distributions of opening angles for three modes of ^{8}Be dissociations are shown in Fig.7. Result of Monte-Carlo calculation of sensitivity of our system with two telescopes is plotted by smooth line in this Fig.

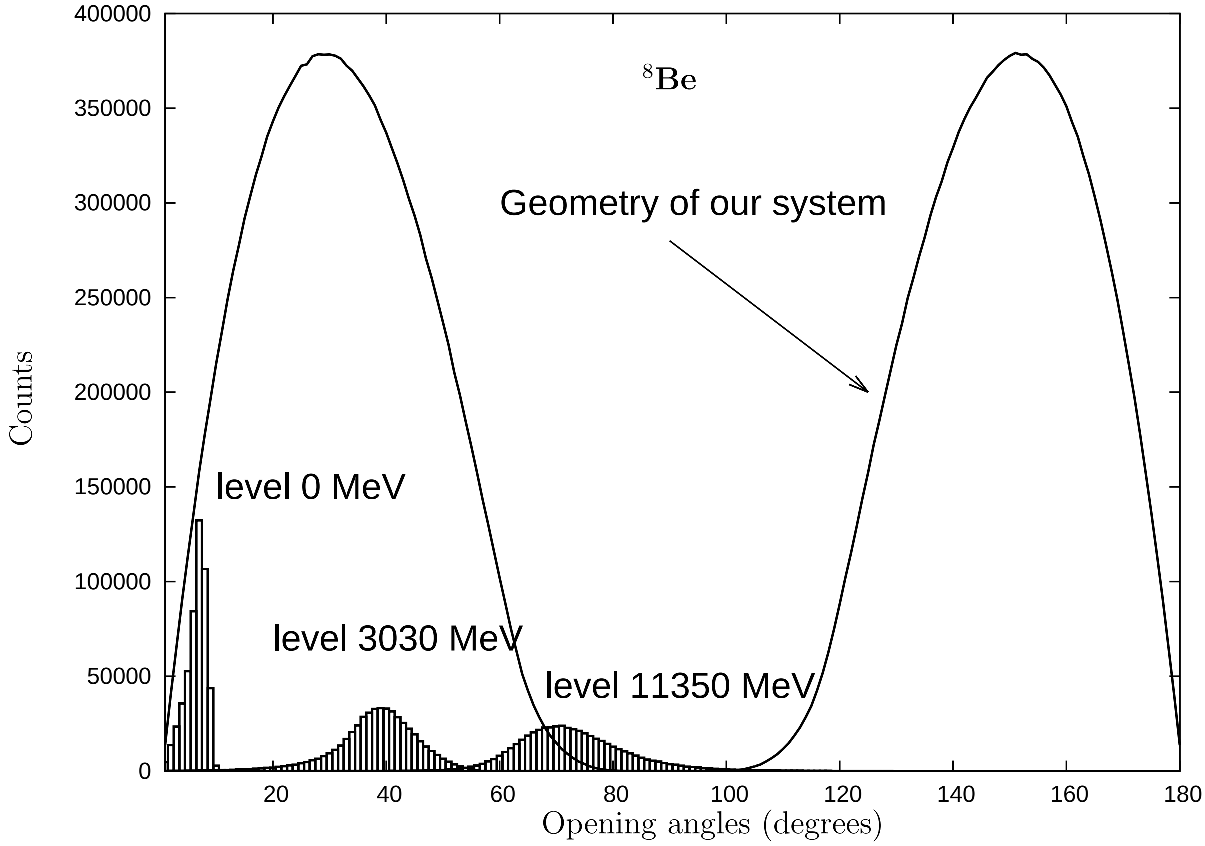

Fig.7. Opening angles for three modes of ^{8}Be dissociation are plotting by boxes. Smooth line showes our calculated geometry for two telescopes.

It can be seen from this Fig. that detection of events from mode 3 (dissociation of ^{8}Be from the level 11350 keV) is strongly forbidden from sensitivity of our system. Practically only the first and the second modes can be detected. A total of 63 (α,α) coincidences were registered in our experiment with two telescopes up to now. This statistics is not enough for comparing with Monte-Carlo calculations.

Results from ^{7}Li dissociation are shown in Fig.8. One can see that three modes of ^{7}Li dissociation can not be isolated and only summing yield can be obtained. In addition yield of these modes very small compared with three modes of ^{8}Be dissociation. In our experiment only 9 events of (α,t) coincidences were registered up to now.

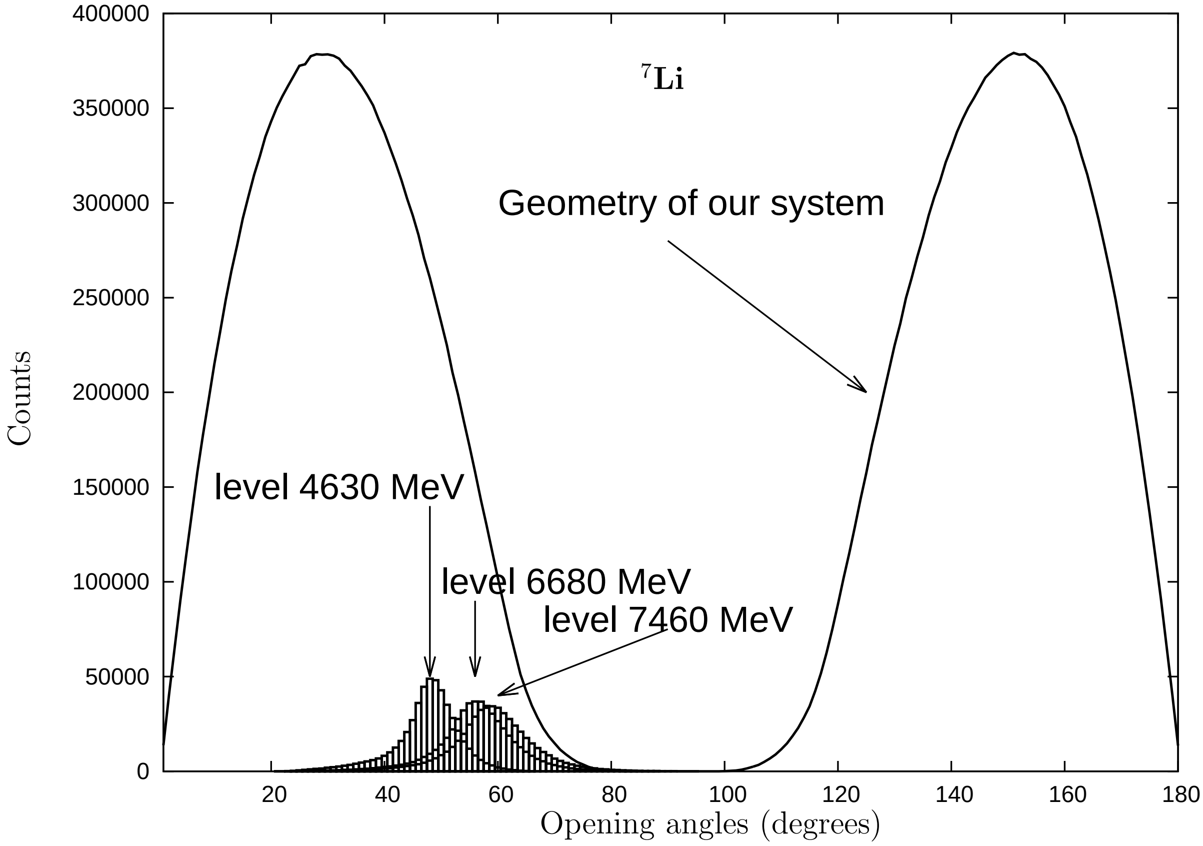

Fig.8. Opening angles for three modes of ^{7}Li dissociation are plotting by boxes. Smooth line showes our calculated geometry for two telescopes.

It was said in part 2 of this report that there must be two scenarios of dissociation of unstable particle. The first when dissociation take place after full acceleration of particle and the second when dissociation is before full acceleration. From analyzing of data in Tab.1 it was noted that the second mode of ^{8}Be dissociation and two modes of ^{7}Li dissociation can be before full acceleration. Now it can be emphasized that this scenario can not change results of our calculations because of the fact that such events are not registered in view of energy loss of α-s and ^{3}H in ΔE detectors and Al foils. As result of our Monte-Carlo calculations: minimal energy of ^{8}Be which can give registered events is 14 MeV, and minimal energy of ^{7}Li is 10 MeV.

Our experimental work in progress.

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