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INTERACTION OF PLASMA, PARTICLE BEAMS, AND RADIATION WITH MATTER

Application of a Thin Organic Scintillator to Study 3α Fragmentation of ^{12}C Nuclei in Interactions with Relativistic Muons and Hadrons

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Abstract—The analysis of amplitude spectra from a thin polystyrene-based scintillation counter on muon-enriched and hadron beams of channel 18 of the U-70 accelerator complex in Protvino has been presented. On the basis of statistics of 150 million events on the Hyperon-M setup, the contribution of the 3α-fragmentation processes are highlighted and the cross sections of these processes on hadron and pion beams with a momentum of 7 GeV/*c* have been measured. In the future, the obtained result may be of interest for the method of analyzing the age of gas fields based on the concentration of helium in natural gas, the formation of which is possible in the reaction of 3α fragmentation of carbon nuclei in $\mu^{12}C$ interactions induced by high-energy cosmic muons.

Keywords: 3α fragmentation, nucleus C12, relativistic hadrons, cosmic muons, nuclear emulsions, Birks effect, organic scintillator, helium concentration, natural gas, Hyperon-M experiment, GEANT4

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INTRODUCTION

The study of inelastic interactions of muons in the energy range of several GeV began in the 1960s with longitudinal exposure of stacks of nuclear track emulsions (NTEs) on a secondary muon beam of an AGS BNL proton synchrotron. Along with the results obtained here on muon scattering, a description of the observed nuclear stars was also given, represented by tracks of the lightest fragments and mesons produced in this case [1, 2]. In the early 70s, a beam of muons at the momentum range up to 40 GeV/c was created at the U-70 accelerator in Protvino [3], where a number of scattering experiments were carried out, including polarized muons, see [4,5]. In the second half of the 70s, a muon beam was formed at the SPS at CERN, but with a momentum of 160 GeV/c. This made it possible to continue experiments with muons at higher energies with NTEs. The possibility of detecting in NTE short-range α particles produced in the reaction of nuclear fragmentation of the nucleus ^{12}C under the action of relativistic muons is of primary interest:

$$\mu + {}^{12}\mathrm{C} \to \mu' + 3\alpha. \quad (1)$$

The presence of the isotope ^{12}C in the composition of NTE and organic scintillators makes it possible to use these materials as active targets. The aforementioned μ-scattering reaction is due to the exchange of a virtual photon with the transition of the latter into a vector meson (vector dominance) or a pair of pseudoscalar mesons (Fig. 1). Despite the apparent simplicity of this reaction (a purely electromagnetic process), a clear anomaly is observed in the experiment, since the measured distributions over the set of fragments and the transverse momentum of the system indicate,

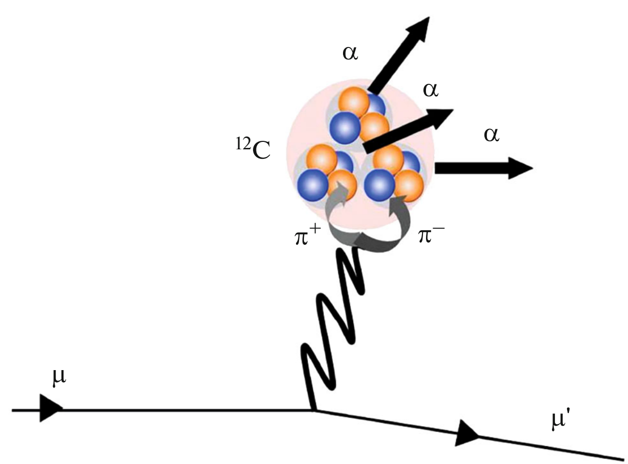

Fig. 1. Diagram of the ^{12}C nuclear disintegration into three α particles under the action of a relativistic muon (vector dominance) see [6].

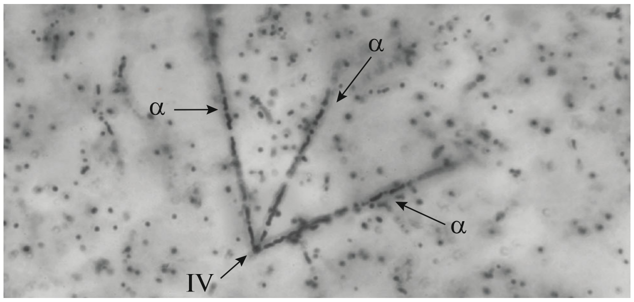

Fig. 2. Macrophotography of a 3α event observed during transverse exposure of the NTE layers by muons at 160 GeV at CERN. IV is the interaction vertex. The image was obtained using an MBI-9 optical microscope with a lens magnification of 60×. The characteristic size of the developed grain is 0.5 μm.

rather, the strong nature of the interaction of muons with the carbon nucleus in reaction (1), for more details, see [6, 7].

The reaction cross section (1) is fundamentally also in practical terms for geological estimates associated with natural gas fields. Apparently, it was mentioned for the first time in [6]. Traditionally, the radioactive decay of uranium, thorium, and their daughter radionuclides is indicated as a source of helium, and the analysis for the presence of helium in the rock serves to search for their deposits. At the same time, reaction (1) can serve as a mechanism for generating helium in natural gas fields at kilometer depths, where cosmic muons with an energy of hundreds of gigaelectronvolts can penetrate. The muon flux at the Earth's surface is formed as a result of bombardment by primary cosmic radiation of the Earth's atmosphere. As a result, the nuclear electromagnetic cascades of secondary particles, some of which certainly disintegrate into muons and neutrinos, are formed in the atmosphere. Muons are produced at an altitude of about 10–15 km in the atmosphere and lose about 2 GeV of energy before reaching the Earth's surface. The average muon energy at sea level is about 4 GeV. High-energy muons have a high penetrating power: they can penetrate deep underground and cause nuclear reactions there, including in natural gas. The average depth of a gas field is about 3 km. Since the natural gas contains carbon atoms in its composition, the high-energy muons can interact with ^{12}C nuclei with subsequent excitation and decay of the latter into 3 α particles. Thus, the muon mechanism of helium production in gas fields arises. At the same time, it is possible to determine the age and volume of a gas field by the concentration of helium. However, for this assessment, it is necessary to know the reaction cross section (1) fairly accurately.

Determining the cross section of this reaction directly from the flow of transversely directed tracks of relativistic particles and the stars observed in NTE is practically impossible. The primary tracks of the beam particles are represented by points of about 0.5 μm in size with a distance of several microns between them extending deep into the NTE layer. An additional difficulty in interpreting the results is also the multicomponent composition of NTE.

The above difficulties can be overcome by carrying out special measurements of the reaction cross section (1) on an active carbon-containing target, which allows simultaneous recording of beam particles and triples of α particles. The first such measurements were performed on channel 18 (Hyperon-M setup) of the U-70 accelerator complex. For this purpose, the muon beam with an energy of 7 GeV formed as a result of the passage of a secondary hadron beam through one or two closed collimators of channel 18, each of which is made of brass 75 cm thick, was used. The muon beam was directed to a 0.5-mm-thick polystyrene scintillation counter, which recorded, using a special photomultiplier, ionization losses in the counter's scintillator, starting with the minimally ionizing particles of the beam and up to 3α stars that are formed in reaction (1).

1. OBSERVATIONS OF μ EVENTS IN A NUCLEAR TRACK EMULSION

As part of the BECQUEREL experiment [7], the NTE experimental samples exposed transversely with muons at an energy of 160 GeV were analyzed [8]. The NTE layer samples were placed in front of the COMPASS experiment target at a distance of about 25 cm from the beam axis (halo) where the intensity reached 10^6 particles/cm^2 per cycle. The exposure time was about 9 h. The set of observed events of the interaction of relativistic muons with NTE nuclei begins with single *b*(black) and *g*(gray) tracks of the recoil protons followed by *b* triples. The most probable source of the latter can be the split $^{12}\mathrm{C} \to 3\alpha$ through the levels from 7.65 to 16 MeV lying below the threshold of separation of single nucleons. The statistics of more frequent 3α stars allows us to estimate the relative cross sections of events observed in parallel with them with a greater multiplicity of tracks. For analysis, 154 events were selected (an example of an event is shown in Fig. 2) with the observed three tracks of *b* particles that meet the criteria for conducting the planar measurements. Figure 3b shows the distribution of the measured total ranges of the α particles in the NTE layers. The values of the kinetic energy of the α particles depending on the track length were approximated by the empirical relation

$$E_{\mathrm{kin}}(L) = -0.677 \cdot \log(L) + 1.746 \cdot \sqrt{L} - 1.638 \ \mathrm{MeV}, \quad (2)$$

where L is the track length of the α particle in micrometers.

The kinetic energies of the α particles calculated in this way have an average value of 5.5 ± 0.2 MeV. The

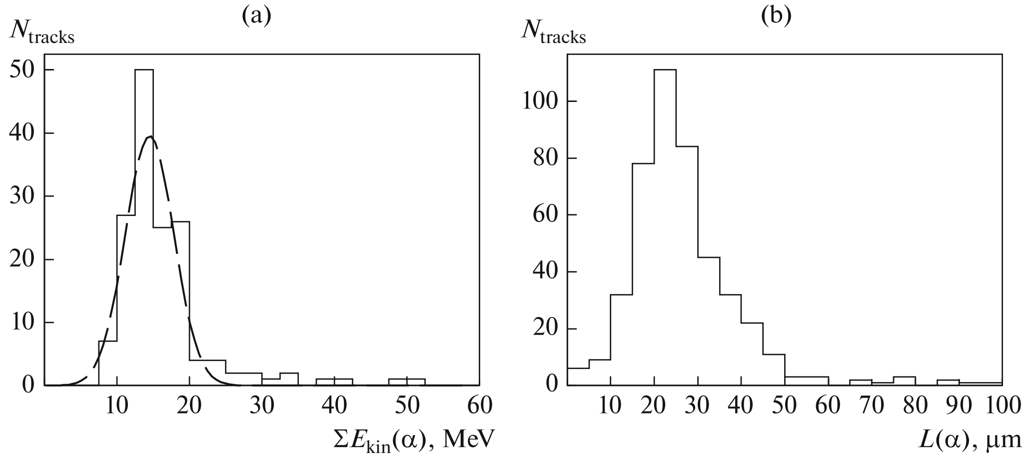

Fig. 3. Distribution by (a) total kinetic energy and (b) total path length of α particles for 154 events $\mu + ^{12}C \rightarrow \mu' + 3\alpha$ at an energy of 160 GeV. The dotted line in the left figure is the fitting by a Gaussian function.

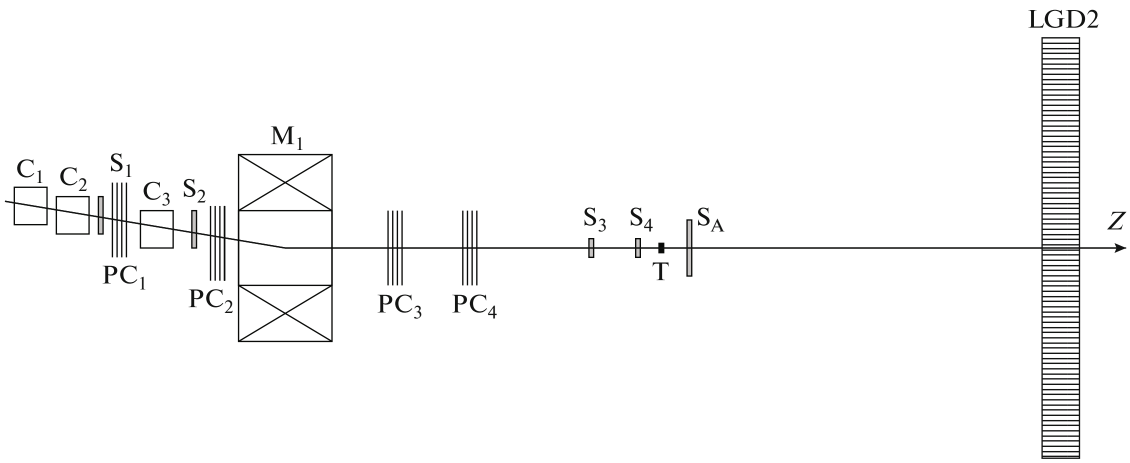

Fig. 4. Schematic of the experimental Hyperon-M setup: S_{1-4} are beam scintillation counters, C_{1-3} are Cherenkov counters, T is the setup target, S_A is a trigger scintillation anticounter, M_1 is a dipole beam magnet, LGD2 is a Cherenkov electromagnetic full absorption spectrometer with lead glass radiators.

resulting distribution of the total energy of the α triples (Fig. 3a) was fitted by a Gaussian function with an average value of 14.5 ± 0.3 MeV and a standard deviation of 3.3±0.2 MeV. These values can be considered as reference values when searching for the 3α-fragmentation effect in an organic scintillator. It is also worth noting that the spectra of emission angles of α particles and their energies were analyzed in [8] according to modeling and measurements in NTEs. It was found that the difference between the experimental data and the simulated data is that, in the case of modeling, there is an obvious signal from ^{8}Be in the energy distribution of 2α particles, which is absent in the measurements. At the same time, the average measured transverse momentum of α triples in reaction (1) was 241 ± 28 MeV/c, which corresponds not to electromagnetic, but rather to nuclear diffraction. Thus, the measurements carried out in [8] indicate a more complex mechanism of 3α fragmentation of the ^{12}C nucleus in a muon beam compared to that used in modeling, which further stimulates interest in reaction (1).

2. HYPERON-M SETUP

Given the interest in reaction (1) both from an applied and from a physical point of view, the experiments to measure the cross section of the 3α fragmentation of the ^{12}C nucleus in a muon beam were also carried out at the experimental setup Hyperon-M (the schematic is shown in Fig. 4) located on channel 18 of the U-70 accelerator complex. For a detailed description of the setup, see [9]. This channel potentially provides the formation of a secondary beam of positively

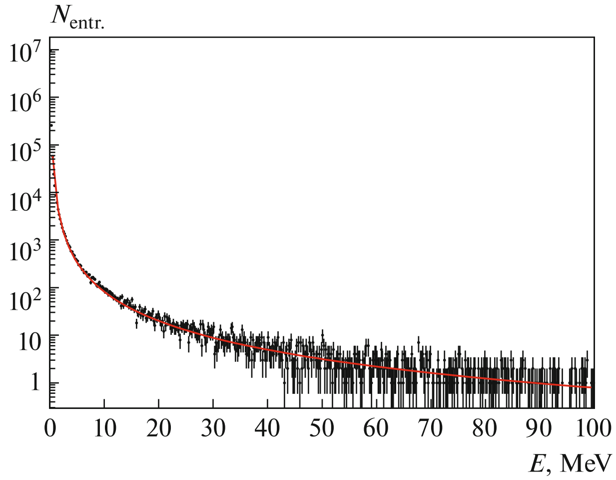

Fig. 5. MC spectrum of total energy losses of the muons with an energy of 7 GeV when passing through a 0.5-mm-thick polystyrene counter.

charged hadrons with a momentum in the range from 5 to 10 GeV/c, for the generation of which ^{9}Be or ^{12}C targets installed in the accelerator vacuum chamber are used. The energy of the proton beam in U-70 was 50 GeV. The first dipole magnet of the channel provides the initial deflection of the secondary particles produced on the inner target in the direction of channel 18, whose axis is oriented at an angle of about 30° relative to the direction of the primary proton beam. Further, a spectrometric magnet, two doublets of quadrupole lenses, vertical and horizontal collimators are sequentially placed on the channel. The latter are shiftable absorbers made of brass with a beam thickness of 75 cm, which is approximately 5 nuclear lengths. The collimators are located at a distance of ≈15 m from the inner target of the channel.

Channel 18 beam contains mainly pions, protons, and K^+ mesons, whose fractions are approximately 65%, 30%, and 4%, respectively. The proportion of muons is about 1%. It should be noted that the actual partial beam composition a particular run depends on the energy of the primary protons in the U-70, the type and position of the internal target, and the momentum of the secondary beam output in the direction of channel 18. The closure of one of the collimators provides a significant suppression of hadrons in the beam with respect to muons. The simulation of the beam passing through one closed collimator using the GEANT4 package [10] showed that the intensity of the hadron beam output to the beam telescope of the Hyperon-M setup counters drops by ≈100 times with respect to the muon beam intensity. In the case of two closed collimators, the specified ratio falls quadratically. Therefore, at the muon fraction of 1% in the primary beam, we should expect up to 50% of muons in a beam that has passed through one collimator, and in a beam that has passed through two collimators, the muon fraction is already almost 100%.

The Hyperon-M setup (see Fig. 4) includes a beam telescope of scintillation counters S_1, S_2, S_3, and S_4, the first three of which provide a trigger for the passage of a relativistic charged particle through the setup; Cherenkov counters C_{1-3} for the identifying the type of beam particle; a target T with a diameter of 4 cm; a scintillation trigger anticounter S_A; and an electromagnetic Cherenkov full absorption spectrometer LGD2. The counter S_4 was used in the experiment to measure the amplitude spectrum when the relativistic muons and hadrons passed through it. It is made on the basis of a round polystyrene scintillator $(C_8H_8)_n$ with a diameter of 120 mm and a thickness of 0.5 mm, as well as a special photomultiplier KS-PMT with a slit photocathode developed by IHEP. The pulses from the PMT are fed to an ADC with a dynamic range of 12 bits and are read by the experimental data acquisition system. The distance between the scintillator edge and the photocathode is 28 mm. The light from the passage of the charged particles of the beam through the scintillator of counter S_4 is collected by an aerial trapezoidal light guide. The light guide surface is pasted on the inside with mylar with a light reflection coefficient of about 80%. The scintillator is suspended inside the light guide on three threads. Other detectors of the setup were not used in the measurements described below.

3. MODELING IN GEANT4

The simulation of the passage of the muons through a thin scintillator was carried out by the Monte Carlo method using the GEANT4 package. This package is actively used in a number of fields, including nuclear, particle, space, and medical physics. The simulation of the passage of 10^7 positively charged muons with an energy of 7 GeV through a homogeneous polystyrene counter $(C_8H_8)_n$(the parameters of the substance are taken from the standard database G4_POLYSTYRENE 1.06 g/cm^3) with a thickness of 0.5 mm. The model took into account the muon energy losses associated with ionization (including the production of high-energy electrons and δ electrons), direct formation of e^+e^- pairs, bremsstrahlung, and photonuclear reactions. To do this, a standard package of electromagnetic processes included in GEANT4 was used: G4MuIonization, G4MuBremsstrahlung, G4MuPairProduction, and G4MuNuclearInteraction. A detailed description of these processes can be found in [11].

Figure 5 shows the obtained MC distribution over the total energy left by the muons in the polystyrene counter described above. The spectrum of ionization losses was fitted by the Landau function included in

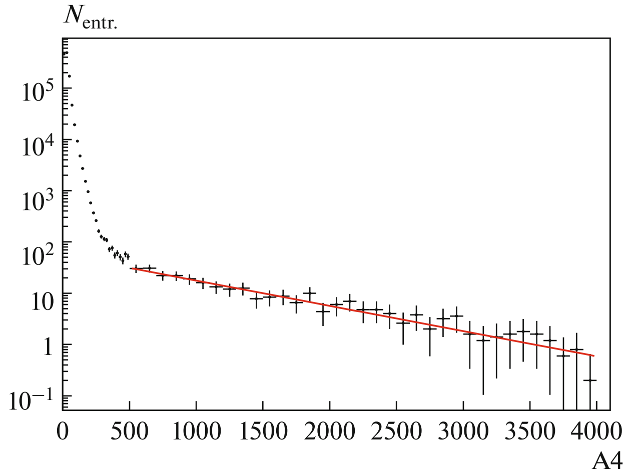

Fig. 6. The amplitude spectrum of the hadron events from the counter $S4$. The binning of the histogram is defined as follows: in the range of amplitudes [0, 500], the sum in 20 channels is shown in each bin, and in the range [500, 4000], the sum in 100 channels, factorized by 5. The red line shows the fit of the spectrum by an exponential in the range of amplitudes [500, 4000] in the ADC samples.

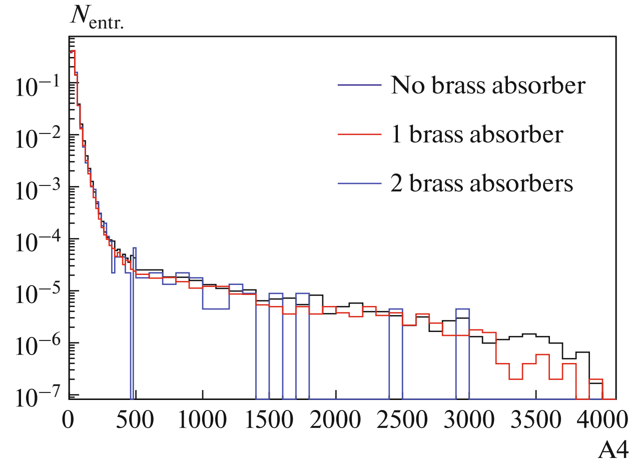

Fig. 7. Normalized amplitude spectra of the hadron and muon events sampled by one (K1) and two (K2) collimators. The binning of the histogram is defined as in Fig. 6.

the standard ROOT software package. The fitting curve is shown in the figure with a red line. The most probable value of muon ionization losses MPV = 0.107 ± 0.001 MeV (σ = 0.0119±0.0001 MeV) corresponds to the distribution peak associated with the losses of the particles having minimum ionization (minimum ionizing particle—MIP). This is followed by the distribution tail, the main contribution to which is the formation of δ electrons and, possibly, the ionization losses of recoil protons formed in elastic μ scattering on the nuclei of the hydrogen included in polystyrene.

4. DATA COLLECTION AND ANALYSIS

To study the amplitude spectra from the scintillation counter S_4 at the Hyperon-M setup, a special data collection with a trigger was carried out:

$$\text{trig} = S_1 * S_2 * S_3, \quad (3)$$

where S_1, S_2, and S_3 are the beam counters (see Fig. 4). The counter S_4 was in this case in the beam, but it was not included in the trigger. The beam momentum was chosen to be 7 GeV/c. During the exposure of the setup on the beam, about 1 million hadrons selected by the trigger (3) were passed through the counter S_4, while both collimators were opened at the same time. The muon exposures were carried out with the same trigger, but with one (K1) or two (K2) closed collimators. The corresponding ensembles contain 1 million and 40000 muon events.

Figure 6 shows the amplitude spectrum from the counter S_4 in a hadron beam. It is not described by a Landau distribution, which can be explained by the finite resolution of the conversion of ionization energy in the scintillation counter into the PMT signal pulses. Nevertheless, starting from 500 ADC samples, the amplitude spectrum in Fig. 6 is well described by an exponential. The amplitude spectra in the muon beams, K1 and K2, look similar. As in the case of the hadron spectrum in Fig. 6, the maxima of the amplitude distributions also lie in the region of the ADC channel 25 for the selected operating mode of the S_4 counter in these measurements.

The specific ionization losses of the relativistic muons with energy E = 7 GeV are equal to 2 MeV cm^2/g. In the case of a polystyrene scintillator (density of 1.06 g/cm^3) with a thickness of 0.5 mm, the most probable ionization losses of muons, which can be considered as MIP, are on the order of 0.1 MeV. The same estimate of the most probable energy release for the muons was also obtained in the MC modeling, described above in Chapter 4. This makes it possible to recalculate the scale of the amplitude spectrum in Fig. 6 from the ADC readings into energy units, e.g., in MeV, normalizing to the spectrum maximum in the MIP region. In particular, the energy scale maximum in the figure corresponds to 16 MeV.

In this regard, it should be noted that the hadron spectrum in Fig. 6 in the range of amplitudes up to 2800 ADC samples (11 MeV) hardly differs from the obtained muon spectra, which is especially clearly seen in Fig. 7, where the amplitude spectra of hadrons and muons (K1, K2) superimposed on each other are given, normalized to the number of entries in the histogram.

Returning to the 3α fragmentation of the ^{12}C nucleus in the muon beam (see Fig. 3), it can now be argued that the amplitude region corresponding to the expected 3α-ionization energy of 14.5 ± 3.3 MeV in

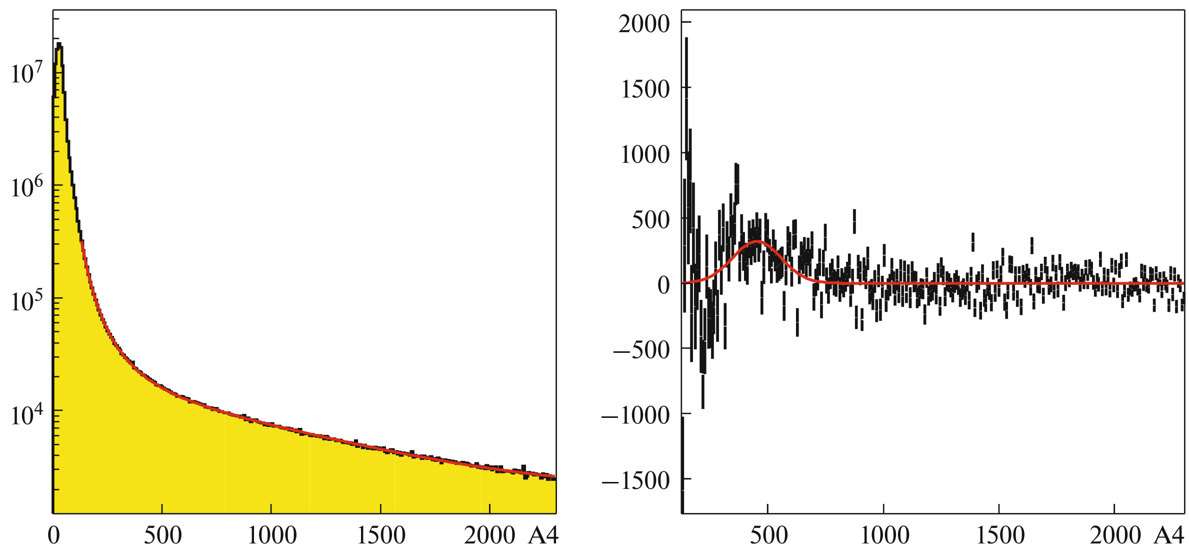

Fig. 8. On the left: the amplitude spectrum from the counter S_4 in the hadron beam of the 2021 run. A solid line shows the spectrum description by the empirical function of ionization losses (the first two terms in Eq. (5)). On the right: the amplitude spectrum from the counter S_4, but minus the ionization loss function in each bin. The solid red line shows the fit of the spectrum considering the 3α fragmentation of the ^{12}C nucleus in the form of the third term in Eq. (5).

Figs. 6 and 7 should lie at 3625 ± 850 ADC samples. However, for organic scintillators, including polystyrene, it is also necessary to take into account the inhibition effect of scintillation light at high ionization densities, characteristic for α particles of MeV energies. For example, in the case of α and β particles with energies below 5 MeV, the scintillation light pulses can differ by 5–10 times at the same particle energy. The dependence of the specific light output on the specific ionization energy losses is established by Birks' law [12]. With regard specifically to polystyrene, a semiempirical method for calculating inhibition factors in organic scintillators is presented in [13] and, in particular, the Birks factor for polystyrene equal to $kB = 9.0 \times 10^{-3}$ g MeV^{-1} cm^{-2} was calculated. The inhibition coefficient of the scintillation light for α particles is related to the Birks factor by the equation:

$$Q_\alpha(E) = \frac{1}{kB \cdot (dE/dx)_\alpha}, \quad (4)$$

where $(dE/dx)_\alpha$ is the stopping power of the α particles in the substance, which in polystyrene for the particles with an energy of 5 MeV is $(dE/dx)_\alpha = 8.75\times10^2$ MeV cm^2/g. As a result, the inhibition coefficient for α particles in polystyrene is $Q_\alpha(E) = 0.127$. Taking into account this factor, the signal from three α particles of megaelectronvolt energies formed in reaction (1) on the counter S_4 should be expected in the range of amplitudes of ≈460 ± 80 ADC samples in Figs. 6 and 7. By a long stretch of the imagination, one can notice in these figures some irregularity in the amplitude spectra in this area, but an attempt to get some kind of quantitative assessment of the expected effect is drowned in statistical errors. For a meaningful analysis, it is necessary to increase the statistics of the muon events by at least two orders of magnitude.

At the same time, the analysis carried out above showed that the amplitude spectra from the counter S_4 when the muons and hadrons with a momentum of 7 GeV/c pass through hardly differ in the region of ionization energies up to 11 MeV, which corresponds to 2800 ADC samples (see Fig. 7). Therefore, the hadrons, but especially pions, as particles dominating in the particle beam of channel 18 and in addition having a mass close to that of the muons can be used in the first approximation instead of the muons to study the characteristic features of indicated amplitude spectra (ionization losses) in thin scintillation counters of the type S_4, as well as to develop an up-to-date methodology for possible contribution of 3α-fragmentation processes to the amplitude spectra from such counters. For this purpose, the processing of the amplitude spectra from the counter S_4 obtained at the Hyperon-M setup in the methodical runs of 2021 and 2022 was carried out, in which, on one hand, the operating mode of the counter S_4 was the same as that in the run whose data were analyzed above, and, on the other hand, the data of each of these runs are two orders of magnitude greater: ≈110 million events in the 2021 run and ≈40 million in the 2022 run. As an illustration, the amplitude spectrum in the the hadron beam $h^+ = \{\pi^+, K^+, p\}$ from the counter S_4 in the 2021 runs is presented in Fig. 8 on the left. The presence of such statistics makes it possible to differentiate the beam particles using the Cherenkov beam counters C_{1-3} of the setup (see Fig. 4), separating the ensemble of the pions (π^+) from the ensemble of the hadrons (h^+). The analysis of these events was carried out separately for these ensembles and illustrated below by the example of the amplitude spectrum from the counter S_4 obtained in the hadron beam in the 2021 run (Fig. 8).

The purpose of the analysis was an attempt to isolate the contribution of events the 3α fragmentation of the ^{12}C nuclei to the amplitude spectrum from the counter S_4 when the hadrons pass through it and measure the cross section of this process. To do this, the obtained amplitude spectrum from the counter was fitted by a function $f(x)$ describing the ionization losses of charged particles in conjunction with the Gaussian function describing the distribution of the total kinetic energy of three α particles in the 3α-fragmentation process in a muon beam, as was done in Fig. 3 in the framework of the BECQUEREL experiment. The explicit form of the fitting function is given below:

$$f(x) = C + \exp(P_n(x)) + A_{3\alpha}\exp\left(-\frac{(x - x_{3\alpha})^2}{2s_{3\alpha}^2}\right), \quad (5)$$

where C is a constant, $P_n(x) = \sum_{k=-n}^{n} p_k x^k$ is the Laurent polynomial, $A_{3\alpha}$ is the normalization of the Gaussian distribution, $x_{3\alpha}$ is the average value of the 3α-fragmentation amplitude, and $s_{3\alpha}$ is the standard deviation relative to the mean. It should be noted here that the shape of the distribution of the total kinetic energy of alpha particles in the processes of fragmentation of the carbon nucleus should not depend on the type of beam particles, since it is determined by the set of excitation levels of the nucleus, located on the one hand above the fragmentation threshold into three alpha particles, and on the other—below the levels of knockout of individual nucleons, i.e. in fact, it is completely determined by the properties of the carbon nucleus.

The fitting of the amplitude spectra from the counter S_4 was carried out in two stages. At first, the fit was carried out without considering the possible contribution of the 3α fragmentation, i.e., without the third term in Eq. (5). At the same time, the constant C, coefficients p_k, and order n of the Laurent polynomial were varied in order to obtain a good description of the spectrum in the range of amplitudes [110, 2300] in the ADC samples. The fitting was carried out by the maximum likelihood method. If, as a result of spectrum fitting, one of the fitted parameters had a value within the standard deviation from zero, such a parameter was omitted in subsequent spectrum adjustments. As a result, it was found that, for a statistically good description of all the measured spectra, it is sufficient to limit the order of the Laurent polynomial from above to a value $n = 3$. As an illustration, the description of the spectrum by the ionization loss function with the specified eight fitted parameters according to the data of the 2021 run on the hadron beam is shown in Fig. 8 on the left by a solid line.

At the second stage, the third term of Eq. (5) was added to the fitting function $f(x)$, however, with only two parameters to be fitted: normalization $A_{3\alpha}$ and the average value $x_{3\alpha}$ of the 3α-fragmentation amplitude. At the same time, the following value was used as the standard deviation $s_{3\alpha}$ in the Gaussian function:

$$s_{3\alpha} = \sqrt{(\kappa x_{3\alpha})^2 + \delta^2(x_{3\alpha})}, \quad (6)$$

where $\kappa = 0.208$ is the ratio of the standard deviation of the 3α energy release (minus the hardware energy resolution in NTE, which is $\approx 10\%$) to the average value of the 3α-fragmentation energy obtained for the events $\mu + ^{12}C \rightarrow \mu' + 3\alpha$ according to the BECQUEREL experiment (Fig. 3), and $\delta(x_{3\alpha})$ is the expected hardware resolution of the counter S_4 in amplitude, for parameterization of which, in turn, the following expression was used:

$$\delta(x_{3\alpha}) = \sigma_{\mathrm{MIP}} \cdot \sqrt{x_{3\alpha}/x_{\mathrm{MIP}}}, \quad (7)$$

where x_{MIP} is the average amplitude of the MIP in the counter S_4 and σ_{MIP} is its standard deviation from the average. The described ten-parametric function Eq. (5) was used to fit the amplitude spectra from the counter S_4 when a hadron beam (h^+) and separately the pions (π^+) passed through it in the 2021 and 2022 runs. In all spectra with a confidence level from 5 to 10 standard deviations in the parameter $A_{3\alpha}$, the contribution of the Gaussian distributions used to describe 3α events was determined in accordance with Eq. (5). The resulting function (5) minus in each bin the ionization loss function, obtained in this case and described in Eq. (5) by the first two terms, is shown as an example by the red solid line on the hadron beam on the right in Fig. 8 according to the data of the 2021 run. As can be seen from the figure, the resulting function describes the observed spectrum of ionization losses in the counter S_4 quite well. An equally good description of the spectra from the counter S_4 was achieved according to other data from the 2021 and 2022 runs. The resulting values of the parameters of the 3α-fragmentation contribution to these spectra, as well as the physical quantities derived from them, are shown in Table 1, where $N_{3\alpha} = A_{3\alpha}(2\pi)^{1/2}s_{3\alpha}$ is the number of observed 3α events, $E_{3\alpha}$ is the average energy of the 3α systems, and $\sigma_{3\alpha}$ is the cross section of the 3α-fragmentation process of ^{12}C nuclei. The table shows only statistical errors of the parameters. As can be seen from the table, the average energy $E_{3\alpha}$ and cross sections $\sigma_{3\alpha}$ of the processes for the 2021 and 2022 runs are consistent within one to three standard

Table 1. Contribution of 3α fragmentation in terms of the parameters of Eq. (5) to the amplitude spectra from the counter S_4, as well as related physical quantities on the hadron h^+ (π^+, K^+, p) and pion π^+ beams according to the 2021 and 2022 runs at the Hyperon-M setup. Statistical errors are shown

Parameter	2021		2022	
	h^+ beam	π^+ beam	h^+ beam	π^+ beam
$A_{3\alpha}$	110.2 ± 12.4	76.8 ± 13.1	69.1 ± 6.7	50.9 ± 7.1
$x_{3\alpha}$	423.4 ± 16.0	397.5 ± 21.5	435.7 ± 13.1	439.5 ± 22.0
$N_{3\alpha}$, thous.	14.8 ± 1.7	10.0 ± 1.7	9.3 ± 0.9	7.1 ± 1.1
$E_{3\alpha}$, MeV	11.8 ± 0.5	11.2 ± 0.6	12.2 ± 0.4	13.0 ± 0.7
$\sigma_{3\alpha}$, mb	55.2 ± 6.4	56.0 ± 9.8	79.5 ± 8.4	85.3 ± 12.6

deviations without considering the systematic errors. This allows one to statistically average the obtained parameters for both runs. The results for the averaged physical parameters are shown in Table 2, where, along with the statistical errors, the systematic errors are also given.

The systematic errors were determined by the root-mean-square deviations of the parameters of the fit from the nominal values at the variations in the upper and lower limits of the fitting region of the amplitude spectra from the counter S_4 and by the variations in the parameterization of spectra used in the form of function (5) by adding other terms to the function of description of ionization losses and changing the parameterization of the root-mean-square width Eq. (6) of the Gaussian distribution of the energy $E_{3\alpha}$, as well as changes in the bin of the histograms being fitted. It turned out that the step-by-step fit procedure described above is quite stable. The values of the systematic errors are 2–3 times higher than the statistical ones. At the same time, considering the statistical and systematic errors, the measured average energies of the 3α systems and the cross sections of the 3α-fragmentation processes of ^{12}C nuclei are in good agreement with each other in the hadron and pion beams at a momentum of 7 GeV/c. Although the obtained cross section of the 3α-fragmentation process in the pion beam several orders of magnitude higher than the expected cross section 3α fragmentation of ^{12}C nuclei in a muon beam, as a purely electromagnetic process, it is, nevertheless, of interest as an independent upper bound estimate of the muon cross section 3 alpha for the fragmentation of a carbon nucleus, taking into account the anomalous observed nature of the latter process, see [6,7].

Table 2. Physical parameters characterizing the 3α fragmentation of the ^{12}C nucleus in hadron and pion beams with a momentum of 7 GeV/c according to the data of the 2021 and 2022 runs on the Hyperon-M setup. The statistical and systematic errors are shown

Parameter	h^+ beam	π^+ beam
$E_{3\alpha}$, MeV	$11.9 \pm 0.3_{st} \pm 1.0_{sys}$	$11.7 \pm 0.5_{st} \pm 1.5_{sys}$
$\sigma_{3\alpha}$, mb	$64.1 \pm 5.2_{st} \pm 17.8_{sys}$	$64.4 \pm 7.8_{st} \pm 21.6_{sys}$

5. CONCLUSIONS

At the Hyperon-M setup, the amplitude spectra from a 0.5-mm-thick polystyrene $(C_8H_8)_n$ beam scintillation counter S_4 when the hadrons and muons with a momentum of 7 GeV/c passed through it were measured in order to determine the cross section of the reaction $\mu + {}^{12}C \rightarrow \mu' + 3\alpha$. The average energy released in the counter by a minimally ionizing particle is ≈0.1 MeV, which corresponds to the channel 26 of the 12-bit ADC used to digitize the amplitudes of the pulses from the counter S_4 when charged particles pass through it. The upper limit of the amplitude spectra, which is determined by the ADC dynamic range, corresponds to the maximum measurable ionization energy equal to 16 MeV. The measurements carried out on the statistics of ≈1 million events showed that the amplitude spectra from the counter S_4 when the muons and hadrons (π^+, K^+, p) pass through it hardly differ in the range of energies of ionization losses up to ≈10 MeV.

The data of the BECQUEREL experiment on the 3α fragmentation of ^{12}C nuclei in a muon beam with a momentum of 160 GeV/c were used to parametrize the distribution of the total kinetic energy of the 3α particles in the form of a Gaussian distribution with an average value of 14.5 MeV and a standard deviation of 3.3 MeV. This distribution, considering the Birks effect, was used to describe the contribution of the 3α-fragmentation processes to the amplitude spectra from the counter S_4 on the hadron beam as a small addition to the dominant amplitude spectrum of the ionization losses when passing through the charged particle counter. On the basis of the total statistics of ≈150 million events, the contribution (≈0.015%) of the 3α-fragmentation processes of the ^{12}C nucleus was identified and the cross sections of these processes were measured on the hadron and pion beams at a momentum of 7 GeV/*c*. Within the limits of measurement errors, the cross sections on these hadron beams do not differ and amount to ≈64 mb. This value can be considered as the independent upper limit of the 3α-fragmentation cross section of the ^{12}C nucleus in the reaction $\mu + ^{12}C \rightarrow \mu' + 3\alpha$ at a momentum of 7 GeV/*c*, taking into account the experimentally observed anomalous nature of this process [6, 7].

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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