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Coherent dissociation of relativistic ^{9}C nuclei in nuclear track emulsion

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Abstract. For the first time nuclear track emulsion is exposed to relativistic ^{9}C nuclei. A systematic pattern of the distributions of charge combinations of fragments in the peripheral interactions of ^{9}C nuclei in a nuclear track emulsion has been obtained. The main conclusion is that the contribution of the channel $^9C \rightarrow {}^8B + p$ and $^9C \rightarrow {}^7Be + 2p$ is most important in events that do not involve the production of target-nucleus fragments or mesons (coherent dissociation). It can be concluded that in the peripheral ^{9}C dissociation the picture hitherto obtained for ^{8}B and ^{7}Be with the addition of one or two protons, respectively, is reproduced. Three coherent dissociation events $^9C \rightarrow 3{}^3He$ accompanied by neither target fragments of the nucleus target nor charged mesons are identified.

Keywords: relativistic, radioactive, nuclei, clustering, nuclear, track, emulsion, topology.
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INTRODUCTION

Beams of relativistic radioactive nuclei open up qualitatively new possibilities for studying the structural features of such nuclei and their excited states. This investigation relies on the potential of the JINR Nuclotron for creating beams of relativistic light nuclei including secondary ones. Of particular interest are peripheral nuclear interactions at energy of about 1A GeV per nucleon since they are optimal in measurement conditions and interpretation. Among all variety of the nuclear interactions the peripheral dissociation bears uniquely complete information about the excited nucleus states above particle decay thresholds.

A peripheral dissociation is revealed as a narrow jet of relativistic fragments the total charge of which is close to the charge of the primary nucleus. In spite of the relativistic velocity of fragments the relative velocities inside the jet are non-

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relativistic. The challenging task for a detection technique is to provide the completeness in the observation of relativistic fragments.

The difficulty of the principle is the following. An increase in the dissociation degree of a relativistic nucleus leads to a decrease in the fragment detector response. This circumstance makes the wholesome analysis, which is necessary up to the *He* and *H* isotopes, hardly accessible.

Then, the excited state of the produced fragment system is defined by the invariant mass of the relativistic fragment jet. Therefore the most accurate measurements of the emission angles of fragments are needed. The accuracy of momentum measurements isn't so demanding. It is enough to assume that the fragments conserve the primary momentum per nucleon. In addition, the selection of most peripheral collisions requires the detection threshold to be as low as possible for the target fragments.

The most peripheral processes of the fragmentation of relativistic nuclei on heavy nuclei of the emulsion composition (i. e., Ag and Br) proceed without production of target fragments and mesons (i. e., coherent dissociation). They are called "white" stars aptly reflecting the images of events [1-3]. The fraction of such events that are induced by electromagnetic exitation and nuclear interactions is a few percent of inelastic interactions. The statistics of various configurations of relativistic fragments reflects the cluster features of light nuclei due to minimal transferred excitation [4-10]. The use of emulsion provides a complete monitoring of relativistic fragments with an excellent angular resolution.

The BECQUEREL Project (<u>Be</u>ryllium (Boron) <u>C</u>lustering <u>Que</u>st in <u>Rel</u>ativistic Multifragmentation) at the JINR Nuclotron is devoted systematic exploration of clustering features of light stable and radioactive nuclei. A nuclear track emulsion is used to explore the fragmentation of the relativistic nuclei down to the most peripheral interactions - nuclear "white" stars. This technique provides a record spatial resolution (0.5 μm) and allows one to observe the 3D images of peripheral collisions. The analysis of the relativistic fragmentation of neutron-deficient isotopes has special advantages owing to a larger fraction of observable nucleons.

This approach to the study of the nucleon clustering is used by the BECQUEREL collaboration [11] for the study of light nuclei at the proton drip line. Exploration of the dissociation of lighter nuclei ^{7}Be [8] and ^{8}B [9] formed the basis for the progress in the study of the following nucleus - ^{9}C. Recently, search of the electromagnetic dissociation of the ^{8}B nucleus is successfully performed in a nuclear track emulsion at a projectile energy of 1.2 GeV per nucleon [9].

The ^{3}He clustering plays an equally important role in these nuclei as the α-particle one. For the ^{9}C nucleus a cluster excitation 3^{3}He with a relatively low threshold (around 16 MeV) becomes available. In this case, a rearrangement of a neutron from the α-particle cluster into the emerging ^{3}He nucleus should occur. The search for the dissociation ^{9}C → 3^{3}He without accompanying fragments of the target and mesons, i. e. "white" stars becomes the main task of this study. In principle, this bright channel could be identified by a trident of doubly charged fragments. But the real situation with emulsion exposure in the secondary beams of relativistic radioactive nuclei is more complicated. There should be a detailed analysis of events of the "white" star type as the most clearly interpreted interactions for a reliable determination of the used beam composition. In what follows, first results on ^9C identified interactions are described.

EXPERIMENT

The fragmentation of 1.2A GeV ^{12}C nuclei, accelerated at the JINR Nuclotron, was used to form a secondary beam with low magnetic rigidity for the best selection of ^9C nuclei [12]. The momentum acceptance of the separating channel was about 3%. An amplitude spectrum of a scintillation monitor of the secondary beam is presented on Fig. 1. It shows that the major contribution comes from C nuclei. The main background was an admixture of nuclei ^3He, which have the same ratio of the charge Z_{pr} to the atomic mass A_{pr}, as ^9C ones have. ^4He nuclei could not penetrate into the channel because of a much greater magnitude of this ratio. A small admixture of fragments ^7Be and ^8B with slightly higher magnetic rigidity than that of ^9C entered the beam. These spectrum features indicate the correctness of the channel tuning.

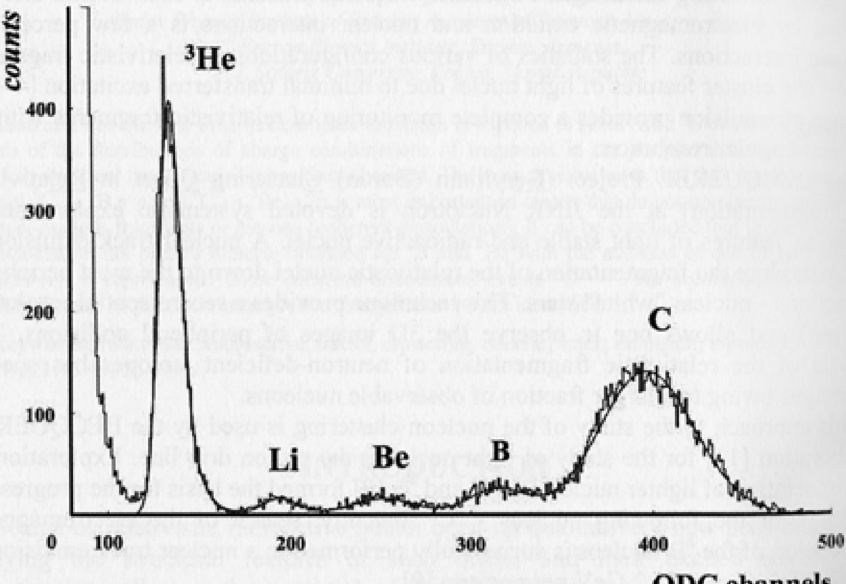

FIGURE 1. Charge spectrum of nuclei produced in the fragmentation of $^{12}C \rightarrow {}^9C$ at secondary beam tuning $Z_{pr}/A_{pr} = 2/3$.

The exposed stack consisted of 19 layers of nuclear track emulsion of the BR-2 type with a relativistic sensitivity. The layer was about 0.5 mm thick and 10×20 cm^2 in area. Stack exposure was performed in a beam directed in parallel to the plane of the stack along the long side. The presented analysis is based on a complete scanning of all layers along the primary tracks with charges visually assessed as $Z_{pr} > 2$. ^3He nuclei were rejected at the primary stage of selection. The ratio of intensities $Z_{pr} > 2$ and $Z_{pr} = 2$ was about 1: 10. The presence of particles $Z_{pr} = 1$ in the ratio $Z_{pr} > 2$ 1: 1 was also detected. The $Z_{fr} = 1$ fragments were separated visually from the $Z_{fr} = 2$

fragments, because their ionization was four times smaller. Over the viewed length of 253.7 m traces one found 1746 interactions mostly produced by C nuclei. Thus, it was obtained that the mean free path was equal to λ_C = 14.5 ± 0.5 см. This value corresponds to the estimate based on the data for the neighboring cluster nuclei.

The relativistic fragments H and He can be identified by their values $p\beta c$, derived from measurements of multiple scattering, where p is the full momentum, and β the speed. It is assumed that the projectile fragments conserve their momentum per nucleon, i. e., $p\beta c \approx A_{fr}p_0\beta_0 c$, where A_{fr} the fragment atomic number. To achieve the required precision one needs to measure the deflection of the track coordinates in more than 100 points. Despite the workload, this method provides a unique completeness of the information on the composition of the systems of few lightest nuclei.

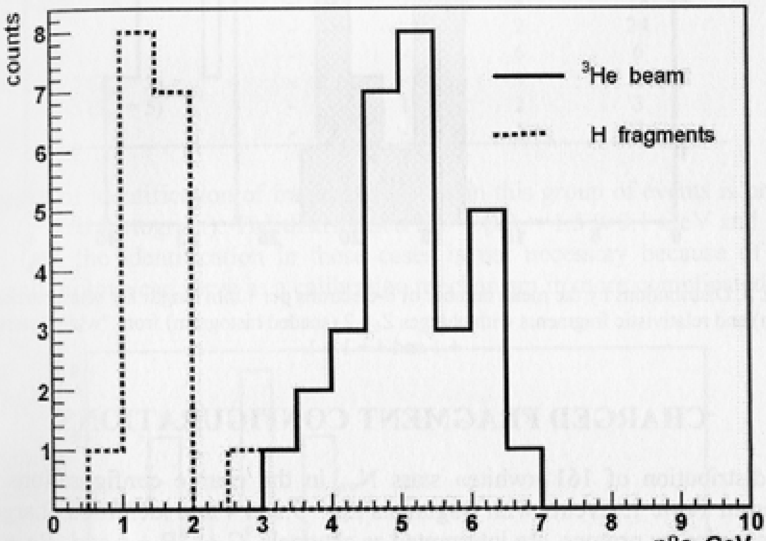

FIGURE 2. Distribution of the measurements $p\beta c$ for beam ^{3}He nuclei (30 tracks, solid histogram), singly charged fragments of the "white" stars $\sum Z_{fr}$ = 5 + 1 and 4 + 1 + 1 (17 tracks, dot histogram).

The presence of ^{3}He nuclei in the beam composition was found to be helpful to calibrate the identification conditions for secondary fragments. The distribution of the $p\beta c$ measurements for 30 nuclei ^{3}He from the beam is presented in Fig. 2 (solid histogram). The average value of the distribution is $\langle p\beta c\rangle$ = 5.1 ± 0.2 GeV in the mean scattering σ = 0.8 GeV. The absolute value is consistent to the expected value of 5.4 GeV for ^{3}He nuclei (for ^{4}He - 7.2 GeV) and is defined by the traditionally used constants. The σ value can be assumed to be satisfactory for the separation of isotopes ^{3}He and ^{4}He, and especially their systems.

The contribution of the C, Be and B isotopes was separated via the charge configurations of secondary fragments $\sum Z_{fr}$ in "white" stars and subsequent measurements of the primary charges Z_{pr}. The charges of the projectile nuclei and fragments $Z_{fr} > 2$ were determined by counting of δ-electrons on tracks. The measurement of the charges of the primary nuclei and fragments of the events $\sum Z_{fr}$ = 5

+ 1 and 4 + 1 + 1, presented in Fig. 3, allows one to conclude that all the events are originated from nuclei Z_{pr} = 6. There is an expected shift in the distribution for interaction fragments.

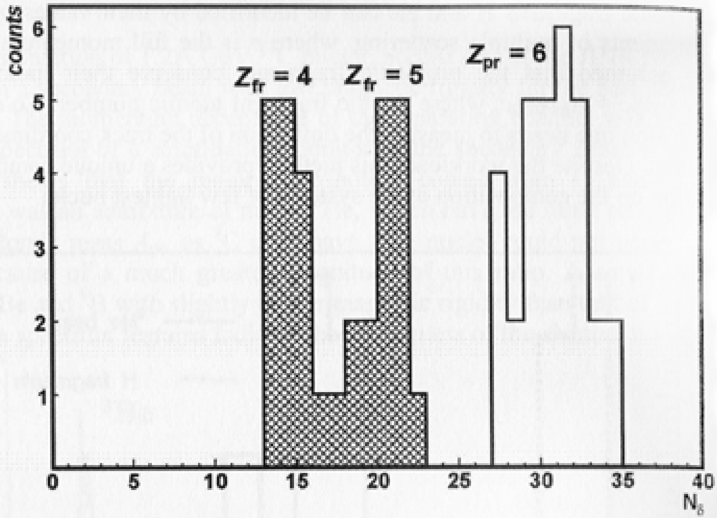

FIGURE 3. Distributions by the mean number of δ-electrons per 1 mm length for beam particles (solid histogram) and relativistic fragments with charges Z_{fr}> 2 (shaded histogram) from "white" stars $\sum Z_{fr}$ = 5 + 1 and 4 + 1 + 1

CHARGED FRAGMENT CONFIGURATIONS

The distribution of 161 «white» stars N_{ws} in the charge configurations $\sum Z_{fr}$ is presented in Table 1. Events with fragments Z_{fr} = 5 and 4 and identified charges Z_{pr} = 6, accompanied by protons, are interpreted as channels $^9C \rightarrow {}^8B + p$ and $^7Be + 2p$, due to the absence of stable isotopes ^9B and ^8Be. These two channels are relative to the most low-threshold dissociation of the nucleus ^9C and constitute about 30% of the events of $\sum Z_{fr}$ = 6. The ratio of ^8B "white" stars with heavy fragments ($^8B \rightarrow {}^7Be + p$) and stars containing only H and He are shown to be approximately equal [9]. Therefore, one can expect that the statistics of the table 1 contains a large fraction of events produced exactly by the ^9C nuclei.

TABLE 1. Distribution of "white" stars N_{ws} in charge configurations $\sum Z_{fr}$.

$\sum Z_{fr}$	Z_{fr} 6	5	4	3	2	1	N_{ws}
7	-	-	-	-	-	7	1
7 (Z_{pr} = 7)	-	1	-	-	-	2	1
7	-	-	-	-	1	5	3
7	-	-	-	-	2	3	5
6 (Z_{pr} = 6)	-	1	-	-	-	1	15
6 (Z_{pr} = 6)	-	-	1	-	-	2	16
6	-	-	-	-	3	-	16
6	-	-	1	-	1	-	4
6	-	-	-	1	1	1	2
6	-	-	-	1	-	3	2
6	-	-	-	-	1	4	28
6	-	-	-	-	2	2	24
6	-	-	-	-	-	6	6
5 (Z_{pr} = 5)	-	-	1	-	-	1	2
5 (Z_{pr} = 5)	-	-	-	1	-	2	3
5	-	-	-	-	-	5	2

The result of identification of fragments Z_{fr} = 1 in this group of events is presented in Fig. 4 (dotted histogram). The distribution has $\langle p\beta c\rangle$ = 1.5 ± 0.1 GeV and σ = 0.4 GeV. In fact, the identification in these cases is not necessary because of limited options, and protons can serve as a calibration mechanism in more complicated cases.

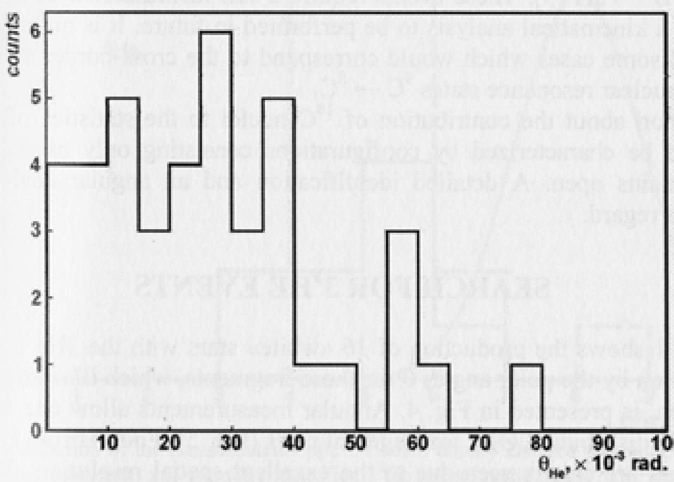

FIGURE 4. Distribution by polar angles θ for doubly charged fragments in the "white" stars C → 3He.

Table 1 allows one to derive useful indirect conclusions about the composition of the beam. For example, there is only one event $\sum Z_{fr}$ = 4 + 2, which might arise from the dissociation $^{11}C \rightarrow {}^{7}Be + {}^{4}He$ having the lowest threshold for the isotope ^{11}C. Thus, a possible presence of ^{11}C in the secondary beam is negligible. Ten «white» stars with the total charge $\sum Z_{fr}$ = 7 are associated with ^{12}N nuclei, captured in the beam. ^{12}N nuclei were produced in charge exchange processes $^{12}C \rightarrow {}^{12}N$ in the producing target.

The distribution of «white» stars produced by ^{7}Be, ^{8}B and C nuclei of the charge configurations $\sum Z_{fr}$, which consist only of the nuclei H and He, is presented in the table 2. One excluded from the sum $\sum Z_{fr}$ one H nucleus for the ^{8}B cases and 2H – for the C cases. There are similar fractions of the channels 2He and He + 2H, which corresponding to the appearance of ^{7}Be as a core of ^{9}C.

TABLE 2. Distribution of the numbers and fractions of "white" stars of ^{7}Be, ^{8}B and C nuclei, over H and He configurations

Channel	^{7}Be	Fraction, %	^{8}B (+ H)	Fraction, %	^{9}C (+ 2H)	Fraction, %
2He	41	43	12	40	24	42
He + 2H	42	45	19	47	28	44
4H	2	2	4	13	6	10
Li + H	9	10	3	0	2	4

Besides, it is possible to note the production of six "white" stars C → 6H (table 2). Events of this type in the cases of the ^{12}C and ^{11}C isotopes, requiring a simultaneous collapse of three He clusters, could not practically proceed without target fragments due to a very high threshold. Being related to an extremely high threshold, they could not proceed without the production of target fragments. In contrast, similar processes related to the breakups of cluster He pairs, were observed for the "white" stars $^{7}Be \rightarrow$ 4H [8] and $^{8}B \rightarrow$ 5H [9]. These events require a full identification of the He and H isotopes and a kinematical analysis to be performed in future. It is quite possible that one will find some cases which would correspond to the cross-border stability in the direction of nuclear resonance states $^{9}C \rightarrow {}^{8}C$.

The question about the contribution of ^{10}C nuclei to the statistics of the table 1 which would be characterized by configurations consisting only of the He and H isotopes, remains open. A detailed identification and an angular analysis will be crucial in this regard.

SEARCH FOR 3^{3}HE EVENTS

The table 1 shows the production of 16 «white» stars with the 3He configuration. The distribution by the polar angles θ for these fragments, which illustrates the degree of collimation, is presented in Fig. 4. Angular measurements allow one to derive the opening angle distribution Θ_{2He} for fragment pairs (Fig. 5). Four narrow He pairs with $\Theta_{2He} < 10^{-2}$ rad are clearly seen due to the excellent spatial resolution. The obtained statistics permits to begin the search for the channel $^{9}C \rightarrow 3^{3}He$ as the most interesting challenge. The ^{10}C admixture could also lead to the events of a deep nucleonic regrouping $^{10}C \rightarrow 2^{3}He + 4He$.

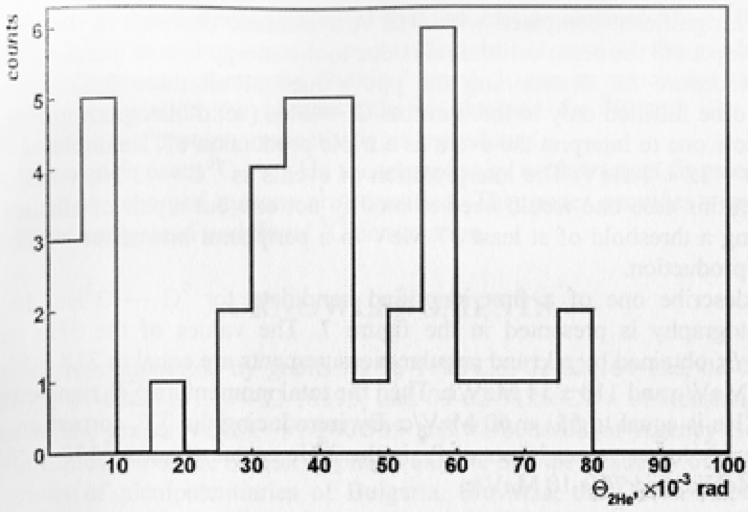

FIGURE 5. Distribution by opening angles Θ_{2He} between fragments in the "white" stars C → 3He.

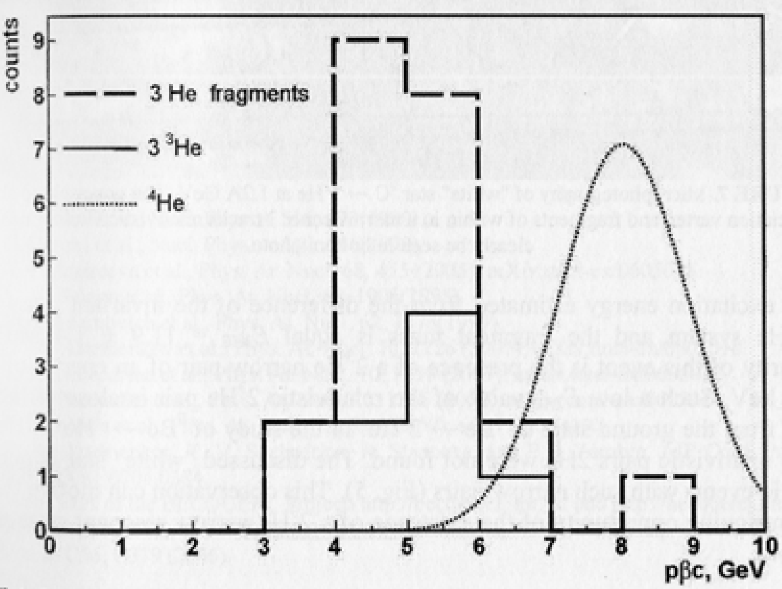

FIGURE 6. Distribution of the measurements pβc for beam doubly charged fragments of the "white" stars 3He (dashed histogram) and from the identified 3^{3}He events (solid histogram); dotted line shows possible distribution of ^{4}He fragments.

The method of the multiple Coulomb scattering was used to determine *pβc* values of He fragments. Such measurements were implemented only for 22 tracks because of the characteristics of the stack used and because of the fragment angular dispersion s (dashed histogram in Fig. 6). The average value ⟨*pβc*⟩ was found to be equal to 4.6 ± 0.2 GeV, with σ = 0.6 GeV. The fraction of the fragments that could be defined as ^{4}He nuclei is insignificant compared with ^{3}He. A systematic decrease in the value $\langle p\beta c\rangle$ with the respect to the beam calibration is due to the energy loss in interactions.

The procedure for determining the pβc values of all three fragments became possible to be fulfilled only in three events C → 3He (solid histogram in Fig. 3). The values allow one to interpret the event as a triple production of ^{3}He nuclei with a total value $p\beta c$ = 12 ± 1 GeV. The interpretation of events as $^{10}C \rightarrow 3^3Ne + n$ is unlikely, because in this case one would need to modify not one but a pair of clusters ^{4}He by overcoming a threshold of at least 37 MeV in a peripheral interaction without target fragment production.

Let's describe one of a first identified candidate for $^9C \rightarrow 3^3He$. Its mosaic microphotography is presented in the figure 7. The values of the 3He transverse momenta P_t, obtained by $p\beta c$ and angular measurements are equal to 318 ± 53 MeV/c, 128 ± 20 MeV/c and 110 ± 14 MeV/c. Then the total momentum $\sum P_t$ transferred to the system 3^3He is equal to 551 ± 60 MeV/c. By introducing the $\sum P_t$ correction, one can get noticeably lower values lower of P_t^* in the 3^3He center of mass - 138 ± 23 MeV/c, 66 ± 10 MeV/c, and 74 ± 10 MeV/c.

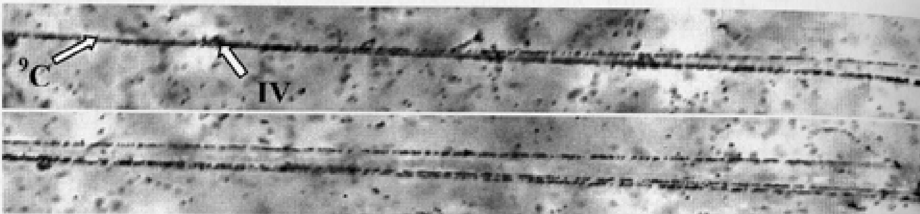

FIGURE 7. Microphotography of "white" star $^9C \rightarrow 3^3He$ at 1.2A GeV. The upper photo shows dissociation vertex and fragments of within in a narrow cone. 3 tracks relativistic He fragments can clearly be seen in bottom photo.

The excitation energy estimated from the difference of the invariant mass M_{eff} of the 3^3He system and the fragment mass is equal E_{3HE} = 11.9 ± 1.4 MeV. The peculiarity of this event is the presence of a 2^3He narrow pair of an energy of E_{2HE} = 46 ± 8 keV. Such a low E_{2HE} value of the relativistic 2^3He pair is close to the decay energy from the ground state of $^8Be \rightarrow 2^4He$. In the study of $^7Be \rightarrow {}^3He + {}^4He$ [8] so narrow relativistic pairs 2He were not found. The discussed "white" star is one of the four 3He events with such narrow pairs (Fig. 5). This observation can motive the study of an intriguing opportunity of the existence of a 2^3He narrow resonant state near the threshold.

CONCLUSIONS

For the first time nuclear track emulsion is exposed to relativistic ^{9}C nuclei. The entire body of experimental data the charge topology of peripheral collisions suggests the dominance of beam tracks predominantly ^{9}C nuclei. Thus, it has been confirmed that the problem of irradiating nuclear track emulsions with relativistic ^{9}C nuclei has been successively solved for the first time with the JINR Nuclotron.

A systematic pattern of the distributions of charge combinations of fragments in the peripheral interactions of ^{8}B nuclei in a nuclear track emulsion has been obtained. The main conclusion is that the contribution of the dissociation channel $^9C \rightarrow {}^8B + p$ and $^9C \rightarrow {}^7Be + 2p$ is most important in events that do not involve the production of target-nucleus fragments or mesons ("white" stars). It can be concluded that in the peripheral ^9C dissociation the picture hitherto obtained for ^8B and ^7Be with the addition of one or two protons, respectively, is reproduced.

Three dissociation event $^9C \rightarrow 3\,{}^3He$ accompanied by neither target fragments of the nucleus target nor charged mesons are identified. This paper provides a ground for further detailed analysis of peripheral ^9C dissociation.

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