Bulgarian Chemical Communications, Volume 54, Special Issue B1 (pp. 81-85) 2022 DOI: 10.34049/bcc.54.B1.0401

Possibility of measuring the angular characteristics of the primary and secondary tracks of relativistic nuclear fragmentation by the nuclear track emulsion method

R. Stanoeva[1,2]*, A. A. Zaitsev[3,4], P. I. Zarubin[3,4]

[1]South-West University, Ivan Michailov Str. 66, 2700 Blagoevgrad, Bulgaria
[2]Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, BG-1784, Sofia, Bulgaria
[3]Joint Institute for Nuclear Research, Joliot-Curie 6, Dubna, Moscow region,141980, Russia
[4]P. N. Lebedev Physical Institute of the Russian Academy of Sciences, Leninskij Prospekt 53, Moscow, 119991, Russia

Received: October 27, 2021; Accepted: March 21, 2022

In this study the application of the nuclear track emulsion technique (NTE) in radioactivity and nuclear fission studies is used. As an example, some results for determining the angular characteristics of the primary and secondary tracks of relativistic fragmentation of ^{28}Si nuclei with a momentum of 4.5 A GeV/c are presented. Angular measurements only for fragments are performed. The invariant mass approach based on angular emission measurements of secondary fragments and approximation of the momentum conservation per nucleon of the parent nucleus is applied.

Keywords: nuclear track emulsion technique, relativistic fragmentation, angular measurements.

INTRODUCTION

Providing a record spatial resolution, the nuclear emulsion method makes it possible to very effectively conduct survey studies on newly formed beams. A et of relativistic fragments can be observed entirely in a single emulsion layer with a thickness of only about 500 μm in 3 spatial dimensions with a resolution of better than 0.5 μm [1, 2]. The accuracy of the reconstruction of the vertex makes it possible to get rid of secondary interactions, since the thickness of the substance before the start of observing individual tracks in such a detector does not exceed several mg/cm^2. The limitation on the analyzed statistics is compensated for by the inaccessibility for complete observation of fragment et composition in other methods. The content in a nuclear emulsion in close concentrations of heavy nuclei Ag and Br, a group of light nuclei C, N, and O, and hydrogen turns out to be useful when comparing peripheral interactions of various types. Under the same conditions, one can observe both the breakup of the nucleus by the electromagnetic field of the heavy target nucleus and in collisions with the target protons. The fragmentation pattern of emulsion nuclei includes a multiplicity of strongly ionizing target fragments, including -particles, protons with energies below 26 MeV, and light recoil nuclei - n_b (b-particles), as well as non-relativistic protons with energies above 26 MeV - n_g (g-particles). In addition, the reactions are characterized by a multiplicity of produced mesons n_s (s-particles). Using these parameters, one can draw preliminary conclusions on the character of the interaction.

* To whom all correspondence should be sent:
E-mail: rstanoeva swu.bg

An example of the interaction of pro ectile nuclei in a nuclear track emulsion is shown in Fig. 1.

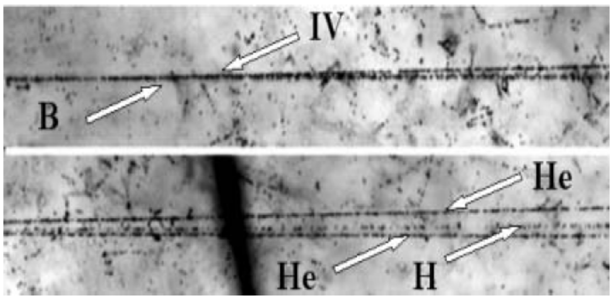

Fig. 1. Example of peripheral interaction of a 1.2 A GeV ^{8}B 2He H in a nuclear track emulsion (white star). The interaction vertex (indicated as IV) and nuclear fragment tracks (H and He) in a narrow angular cone are seen on the upper microphotograph. Following the direction of the fragment et, it is possible to distinguish 1 singly (the central track) and 2 doubly charged fragments on the bottom microphotograph.

Angular measurement conditions

Fragments of the relativistic nucleus fly out in a narrow front cone, the angle of which can be approximately estimated by:

$$_{fr} \quad \sin\ _{fr} \quad P_F/P_0,$$

where P_F is the average momentum of the Fermi motion of nucleons in the pro ectile nucleus, and P_0 is the momentum per nucleon of the pro ectile nucleus. It can be seen from the above formula that the greater the pro ectile energy, the smaller the emission angles of the pro ectile-nucleus fragments. For a pro ectile-nucleus momentum of 4.5 A GeV/c and a Fermi momentum of P_F 200 MeV/c, we obtain $_{fr}$ 2.5°. Most sensitive to the structural features of the nuclei under study are the angular distributions of relativistic fragments and their angular correlations.

The search and collection of material in a nuclear photographic emulsion is carried out at the stage of viewing, preceding direct measurements, sometimes with the aim of isolating certain types of events. Analysis of angular distributions plays an important role in describing the physical picture of the reaction under study. The emulsion technique makes it possible to measure the track angles, both of primary particles and those formed with a high accuracy of 10^{-3} radians. Measurements of the angular characteristics of the tracks are carried out in a coordinate system associated with the Cartesian coordinates of the microscope.

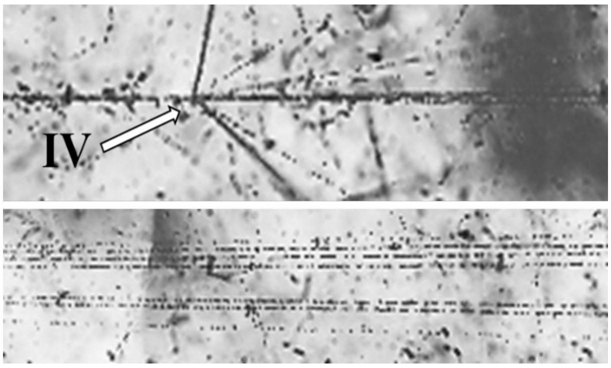

Fig. 2. Example of peripheral interaction of a 4.5 A GeV/c ^{28}Si 5He 2H in a nuclear track emulsion. The interaction vertex (indicated as IV) and nuclear fragment tracks (He and H) in a narrow angular cone are seen on the upper microphotograph. Following the direction of the fragment et, it is possible to distinguish 2 singly and 5 doubly charged fragments on the bottom microphotograph.

EXPERIMENTAL

A stack of NTE layers was exposed to a beam of ^{28}Si nuclei with a momentum of 4.5 A GeV/c. An example of the interaction of pro ectile nuclei in a nuclear track emulsion is shown in Fig. 2.

The NTE layer with the plate number 34 is randomly selected. Viewing the plate was aimed at searching for nuclear interactions of ^{28}Si nuclei with nuclei from the emulsion. We can use three methods for searching for events, including trail, area, and strip. In our study the search was carried out by scanning by stripes with a step of 1 mm.

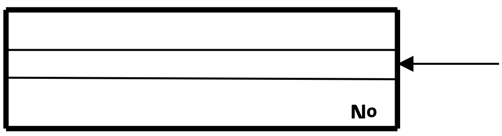

Fig. 3. A schematic representation of the emulsion layer, where is the plate number.

The NTE layer has a size of 10 20 cm^2, and its primary thickness is 579 m. During irradiation, the beam was directed as shown in Fig. 3.

To view the emulsion layer, an MBI-9 type microscope was used with a 60 ob ective lens and 15 eyepieces. In total, about 60 squares were viewed. Eight different types of interactions of beam nuclei were found, in which the formation of more than two -particles in the fragmentation cone is observed. The fragmentation cone was determined visually.

In our experiment, the coordinate method of angular measurements was used. The emission angles of secondary relativistic particles relative to the primary particle (polar and azimuthal) were measured using a special measuring microscope for nuclear research KSM-1 from Zeiss. Since the microscope is designed to measure momentum of high-energy particles by multiple Coulomb scattering, then the noise of the microscope when measuring the coordinates of the tracks can be ignored. It is worth noting that there are situations where angular measurements cannot be taken. This is most often associated with the location of the event in the emulsion. For example, the star is too close to the edge of the record, etc. Further, we assume that the conditions for the measurement are favorable. The angles of secondary particles measured in emulsions and their designations are shown in Fig. 4.

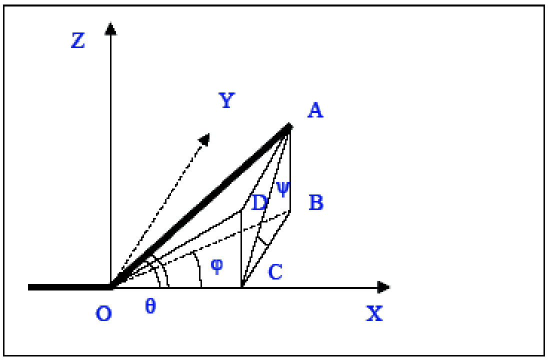

Fig. 4. Determination of the angles of secondary particles: - direction of the primary particle; - direction of the secondary (measured) particle; $\angle AOC$ - polar angle ( ); $\angle ACB$ - azimuth angle ( ); $\angle BOC$ - angle in the plane of the emulsion ( ); $\angle DOC$ - depth angle ( ).

The emulsion layer glued to the glass is fixed on the microscope stage. In this case, the plate is turned in such a way that the direction of the primary particle best coincides with the OX axis of the microscope stage with an accuracy of 0.1–0.2 m. Before starting measurements, select a rectangular Cartesian coordinate system as follows.

The OX axis is directed along the beam along the pro ection of the primary track. The OZ axis is perpendicular to the plane of the emulsion and is directed from the glass on which the emulsion is fixed to the surface. The OY axis is directed so that a right-handed coordinate system is obtained. In this coordinate system, it is possible to determine the coordinates of points, both of the track of the primary particle and the tracks of fragments. The coordinate method is based on the measurement of three coordinates (x, y, z) of the track point in the emulsion, on the basis of which the track angles are calculated. The transition to the system associated with the primary particle uses the angular measurement of the primary track.

Angular measurements were performed only for fragments in 6 events with the formation of target fragments. Two of them are ^{28}Si 5 ..., 1- ^{28}Si 6 ..., 1- ^{28}Si 4 ... and 2 - ^{28}Si 3 ... The track point coordinates were measured sequentially in one direction (from left to right and from the layer surface to) along the beam starting from the primary track and further for all tracks of fragments simultaneously. To measure the angles of fragments with a narrow angular cone of fragmentation, it was necessary to shift the measurement from the center of the event at a distance 200 µm, since the fragments cannot be distinguished. The offset for each event was selected individually. For all tracks, 10 triplets (x, y, z) of coordinates of points were measured with a step of 100 µm, with a total track length used for measurement of 1 mm. In one event, 15 triplets (x, y, z) with a step of 100 µm were measured for the secondary tracks (Fig. 5). Below are the primary results of angular measurements.

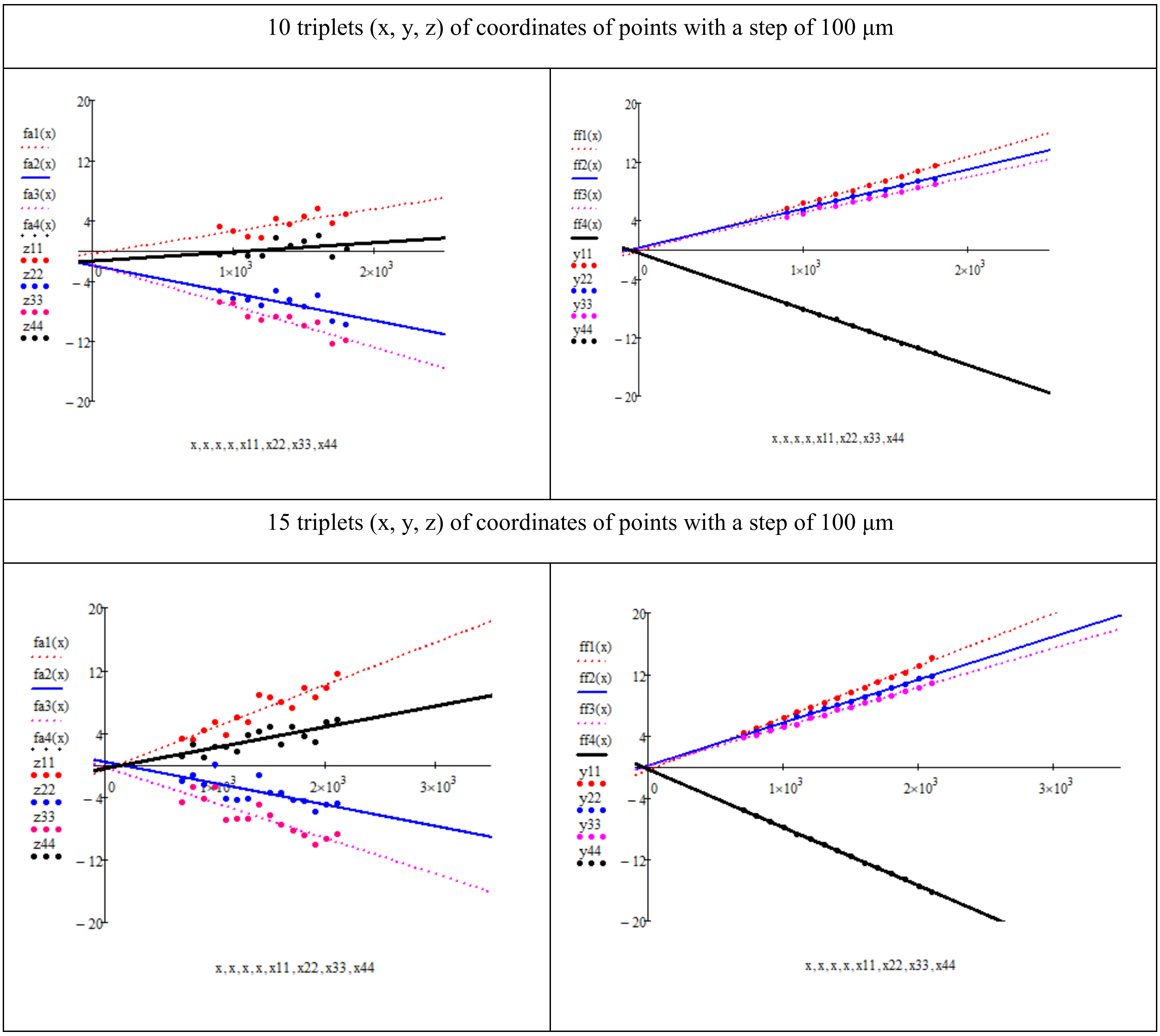

Fig. 5. Examples of observed triplets (x, y, z) of coordinates of points with a step of 100 µm. The left-side pictures are pro ections of tracks to the XOZ plane, on the right side – to the XOY plane. Dots are the measured points, lines – approximated directions of tracks.

Some results of angular characteristics of fragments of the ^{28}Si nucleus

The emission angles of particles with Z_{fr} 2 (Fig. 6) are measured up to the value   3° with mean value   12 10^{-3} rad (RMS   9 10^{-3} rad) for 26   fragments. Measurements of the angle   make it possible to calculate the transverse momenta P_T of relativistic fragments with a mass number A_{fr} according to the approximate relation P_T $A_{fr}P_0$ sin , where A_{fr} is the mass number of a fragment,   its emission angle and P_0 the momentum per ^{28}Si nucleon (P_0 4.5 A GeV/c).

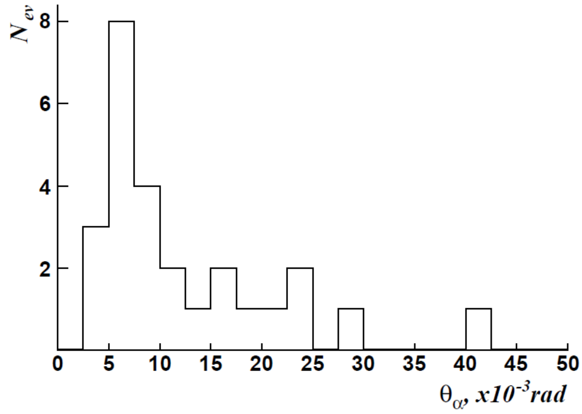

Fig. 6. Distribution of the   -particle polar angle .

As the next step in the analysis of events, the spectrum of pair angles was obtained. Figure 7 shows the opening angle distribution   2 of   -particle pairs with mean value   2   16 10^{-3} rad (RMS   10 10^{-3} rad) (47 pairs of alpha particles). Associated with the distribution over the pair angle is the invariant mass of the system of fragments: $M^{*2}=(\Sigma P_j)^2=\Sigma(P_i P_k)$. Knowing its value allows you to calculate the excitation energy   M*-M, where   is the mass of the ground state of the nucleus corresponding to the charge and weight of the analyzed system.

Figure 8 presents the energy distribution   2 of   -particle pairs with mean value   2   8 MeV (RMS   9 MeV) for 47 pairs of   -particles. In the interval   2   1 MeV, a grouping of events is observed. A more detailed histogram in this interval presented in the inset shows an increased distribution of   2   1 MeV of pairs of   -particles, which includes 17% (8   -particle pairs) of   -particle pairs with an average value   2   3 10^{-3} rad (RMS   2 10^{-3} rad). The relativistic fragmentation of the ^{28}Si nuclei in a nuclear track emulsion can help us to identify decays of ^{8}Be, ^{9}B nuclei and Hoyle state in the invariant mass distributions of 2 -pairs. As an example, the values of   2a   0.1 MeV indicate decays of the unstable ^{8}Be nucleus.

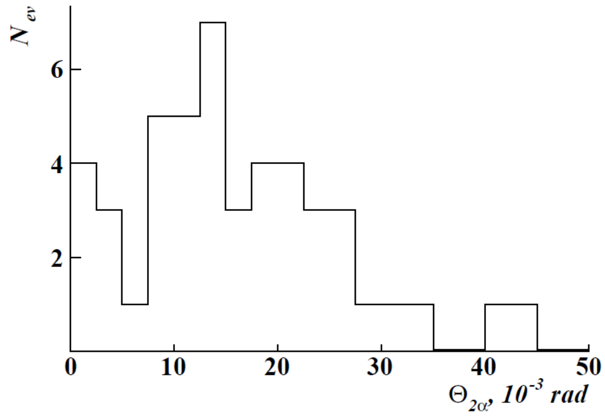

Fig. 7. Distribution over angle   2 of   -particle pairs

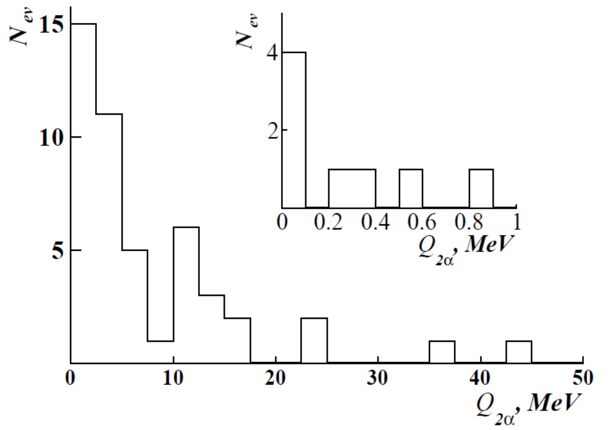

Fig. 8. Energy distribution   2 of   -particle pairs. The inset shows an increased distribution of   2   1 MeV of pairs of   -particles.

CONCLUSIONS

Possessing a record space resolution, the nuclear emulsion method keeps unique possibilities in studying the structure particularities of light nuclei. The traditional task of the nuclear track emulsion method is to outline the nuclear-interaction pattern on the basis of a limited statistical data sample in order to plan better future complicated experiments featuring various detectors. Limitations on the statistics sub ected to analysis are compensated to some extent by the impossibility of completely observing the composition of fragments within other methods. The macro photos of the experiments under discussion and the corresponding videos are available on the website of the BEC   UEREL pro ect [3].

The results of this work can form the basis for planning future experiments with radioactive relativistic nuclei with higher statistics and detail of fragment identification, as well as higher complexity and variety of detectors. The described option for measuring angles is not the only one.

The choice of technique depends on the specific task and the resources available.

Acknowledgement: *The scientific publication was realized as a result of the provided funding from the Ministry of Education and Science under the project "Joint Institute for Nuclear Research (JINR, Dubna)", object of the National Roadmap for Scientific Infrastructure 2020 – 2027.*

REFERENCES

1. C. F. Powell, P. H. Fowler, D. H. Perkins, The Study of Elementary Particles by the Photographic Method, London - New York, Pergamon Press, 1959.
2. W. H. Barkas, Nuclear Research Emulsions. New York – London, Academic Press, 1963.
3. The BEC UEREL Pro ect, http://becquerel. inr.ru/.