ISSN 1547-4771, Physics of Particles and Nuclei Letters, 2011, Vol. 8, No. 6, pp. 562–565. © Pleiades Publishing, Ltd., 2011.
Original Russian Text © V. Bradnova, D.A. Artemenkov, L.A. Goncharova, E.D. Donets, E.E. Donets, P.I. Zarubin, I.G. Zarubina, A.D. Kovalenko, N.V. Kondrat'eva, N.K. Kornegrutsa, A.I. Malakhov, P.A. Rukoyatkin, V.V. Rusakova, N.G. Polykhina, A.S. Rusetskii, N.I. Starkov, 2011, published in Pis'ma v Zhurnal Fizika Elementarnykh Chastits i Atomnogo Yadra, 2011, No. 6(169), pp. 936–942.

PHYSICS OF ELEMENTARY PARTICLES AND ATOMIC NUCLEI. EXPERIMENT

Experimental Exposure of Nuclear Emulsion by Xenon Nuclei at the JINR Nuclotron

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Abstract—Nuclear emulsion was exposed to xenon nuclei accelerated at the JINR Nuclotron. Visual and automated scanning of the extracted beam profile was performed using the exposed emulsion film.

DOI: 10.1134/S1547477111060033

In March 2010 during the run of the Nuclotron, $^{124}Xe^{42+}$ ions produced by the KRION source were accelerated to about 1 GeV/nucleon; this corresponds to a magnetic field strength in the accelerator ring of 7.9 kG. Accelerated nuclei were extracted from the Nuclotron through a flange foil; this made it possible to extract totally stripped Xe^{53+} ions. For the accelerated beam diagnostics, MR nuclear emulsion films with a thickness of 20 μm (produced by the Scientific Research Cinema and Photo Institute (NIKFI)) placed perpendicular to the beam direction and "thick" layers of nuclear emulsion with a thickness of about 450 μm placed along the beam were irradiated at the focus F3 of the extracted beam channel. The main objective of this methodical study was to demonstrate the fact of the successful acceleration of ^{124}Xe nuclei. It turned out to be possible to estimate some aspects of digital processing presented below using the exposure by nuclei with a high ionizing power. Macrophotos of Xe nuclei passage and interaction in the emulsion obtained using a NIKON D70 camera and a MBI-9 microscope can be found at the Becquerel site of collaboration [1].

"Crests" of tracks of strongly ionizing particles with a layer-penetration depth of about 4 cm can be clearly seen on the surface of the longitudinally irradiated emulsion layers. Several interaction events with high multiplicity were found upon microscopic scanning. One of the examples is shown in Fig. 1. Several tracks could be seen within one emulsion layer before stopping. A photo of such a nucleus stopping is shown in Fig. 2. The average track length for this track type was $\lambda_{exp} = (38 \pm 15)$ mm. The range of $^{124}Xe^{42+}$ with an initial energy of 1 GeV/nucleon calculated using the SRIM program with account for the substance before the emulsion, 100 μm of iron and 15 mm of the scintillator, is in agreement with the small experimental value of λ_{exp}.

The trace of the flux of Xe^{53+} nuclei on the developed emulsion film represents a weakly visible darkened spot with a diameter not exceeding 1 cm. Figure 3 shows a macrophoto made with a 20-fold enlargement in the region of the highest intensity; cross sections of particle tracks with high ionization can be clearly seen in this photo. A segment of this region is shown in Fig. 4 with a 90-fold enlargement. This figure also shows a 40% transparent photo of a human hair with a thick-

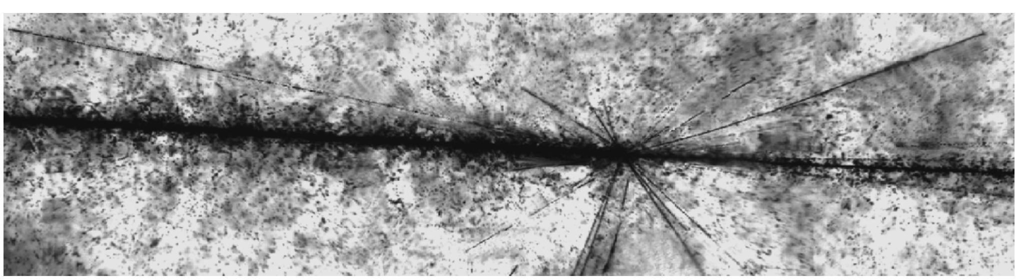

Fig. 1. Macrophoto (60-fold enlargement) of the interaction of the Xe nucleus in emulsion with the formation of a highly charged fragment.

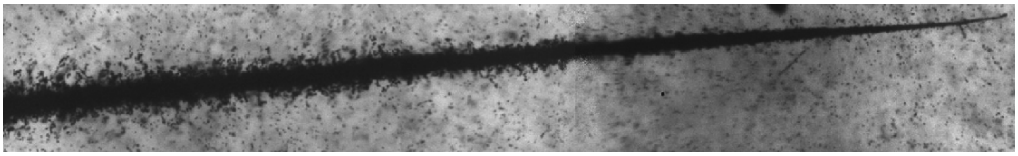

Fig. 2. Macrophoto (60-fold enlargement) of a segment of Xe nucleus stopping.

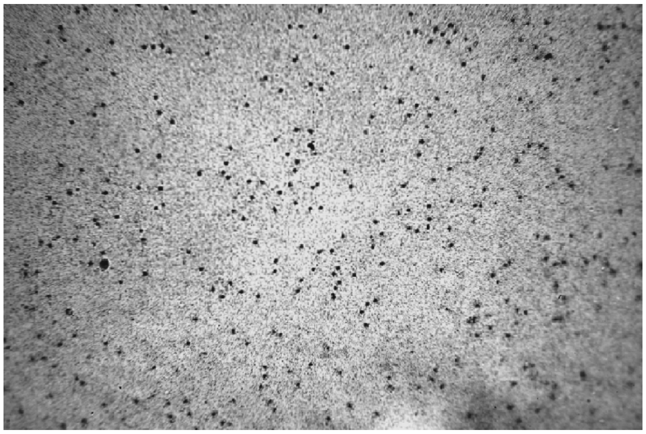

Fig. 3. Macrophoto (20-fold enlargement) of emulsion film irradiated by a Xe nuclear beam in the region of the maximum beam density.

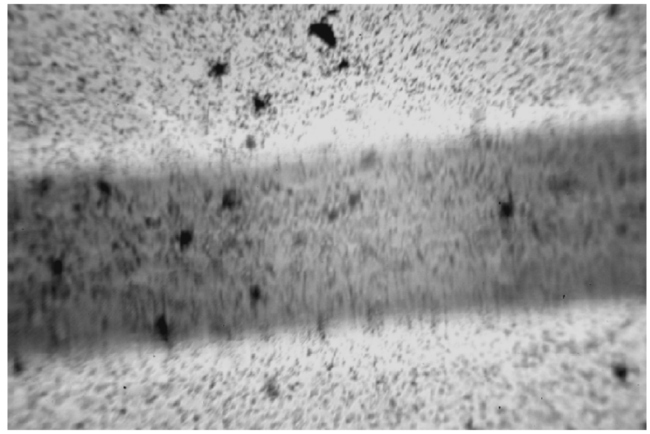

Fig. 4. Macrophoto (90-fold enlargement) of an emulsion film irradiated by a Xe nuclear beam in the region of the maximum beam density; a photo of a human hair is superposed for comparison.

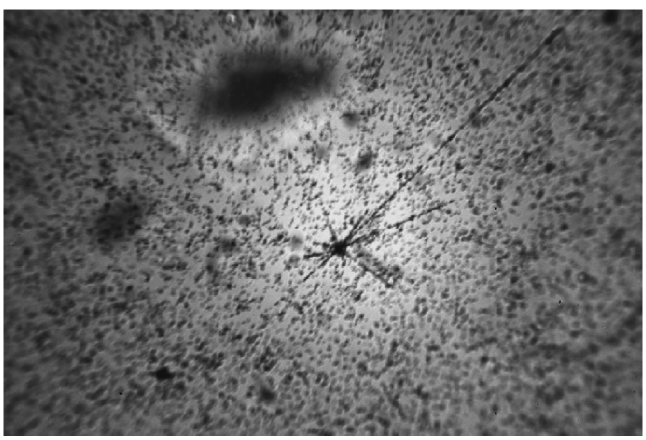

Fig. 5. Macrophoto (90-fold enlargement) of a nuclear star in emulsion film irradiated by a Xe nuclear beam.

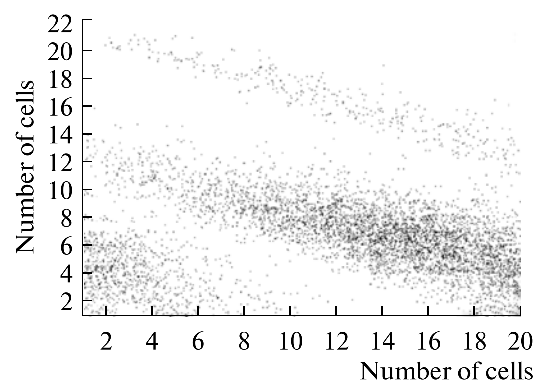

Fig. 6. Xe nuclear beam profile with a step of 0.36 mm obtained by visual track counting.

ness of about 60 μm for comparison. Figure 5 shows the star of disintegration of the heavy target nucleus into at least seven fragments; this proves the fact of exposure by high energy nuclei. The transverse beam profile was measured using the coordinate grid of the ocular with a step of 0.36 mm by counting about 7000 tracks of Xe nuclei. A typical profile inhomogeneity is observed (Fig. 6).

The dark spot on the emulsion from the beam was photographed by a digital camera (without a microscope). The image was saved as a one-bit map; this map provided the distribution of pixels above a certain threshold. The calculated number of such pixels resulted in approximately the same number of track marks from Xe nuclei. The two-dimensional image (Fig. 7) was constructed based on the obtained map; this image reproduces the specific features of the profile obtained by visual calculation (Fig. 6). Some difference is connected with the difference in the boundaries of the analyzed regions and the track selection criteria in the photo processing.

For a detailed investigation of Xe nuclei tracks, the emulsion film was scanned using the PAVICOM-2 microscope (Fig. 8), which is part of the PAVICOM

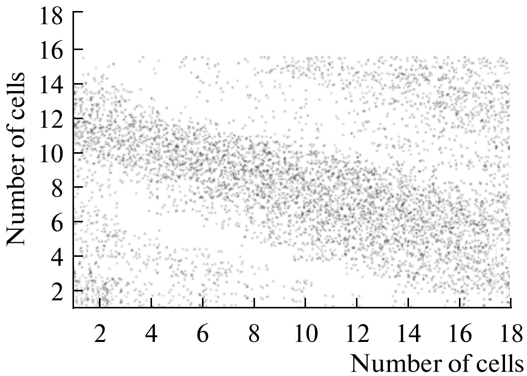

Fig. 7. Xe nuclear beam profile with a step of 0.36 mm obtained by photographing.

Fig. 8. PAVICOM-2 automated complex (Lebedev Physical Institute) created based on the MPE-11 microscope with controllable table, video camera, and image capture board; an image of a fragment of irradiated emulsion film is shown on the screen.

automated complex (Lebedev Physical Institute) [2–6]. Programs of automatic processing for PAVICOM for the recognition and estimation of the beam profile were adapted for this methodical study. Note that the PAVICOM complex was initially created for processing events registered using nuclear photoemulsions irradiated by a lead nuclear beam with an energy of 158 GeV/nucleon at the SPS accelerator (CERN) in the framework of the EMU-15 experiment. The main direction of investigation in this experiment is the search for possible signals of quark–gluon plasma formation at superhigh temperatures in superdense matter states. The universal character and potentially great capabilities of the PAVICOM complex made it possible to use it for a much broader range of problems. In particular, this complex is used to process data of the

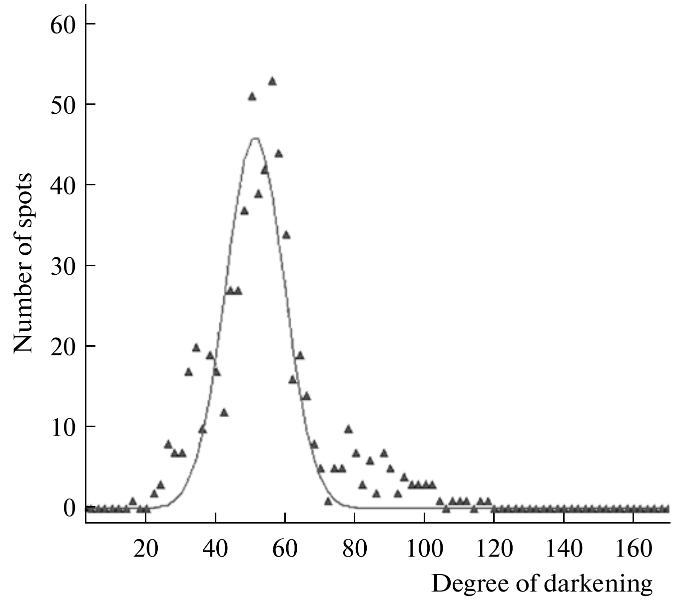

Fig. 9. Spot distribution with respect to the degree of darkening in the region of accumulation of heavy nuclei.

Becquerel experiment. The setup is also used for emulsion processing in the OPERA experiment [7]. At present, PAVICOM is used to process data from practically all types of track detectors (photoemulsions, X-ray films, mylar, plastic, and crystals). Actually, PAVICOM operates in the regime of a center for the collective use of equipment. Researchers from approximately 10 Russian and several foreign institutes, together with the PAVICOM service group, process and analyze experimental data. The members of the PAVICOM service group actively participate in the creation of a specialized software, scanning, and the physical analysis of results.

The film was scanned with 8-fold enlargement at PAVICOM-2 and, after adaptation to this type of emulsion of the standard software created at the Lebedev Physical Institute, processed in an automated regime. It was discovered that the particle tracks can be divided into two groups. One of these groups includes rather dark (degree of darkening ~60 in terms of a pixel scale in which 0 denotes black and 255 denotes white) and large spots (~4 μm) belonging to a heavy nucleus; the second group includes smaller (~2 μm) and lighter (degree of darkening ~100) spots belonging to a fragment of a heavy nucleus. These features make it possible to reliably separate nuclei with respect to their charge. The spot distribution over the degree of darkening in three regions was obtained as an example: in the region of accumulation of heavy nuclei (Fig. 9), light fragments (Fig. 10), and in the intermediate region (Fig. 11). The distribution peaks are approximated by the Gaussians.

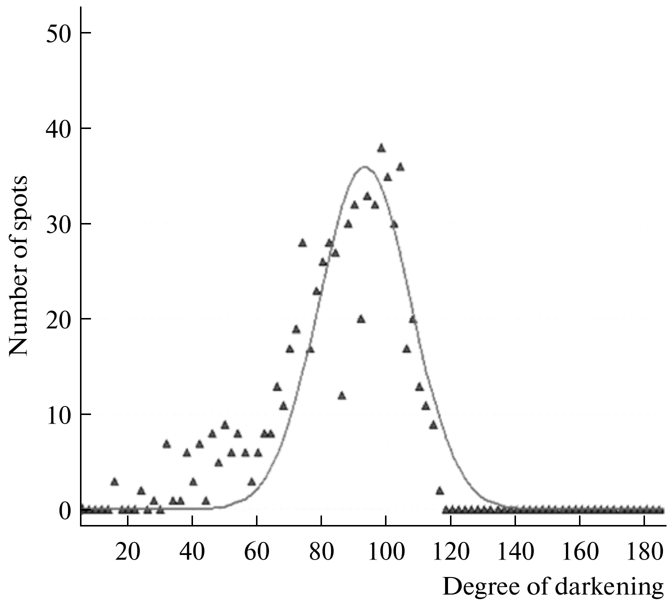

Fig. 10. Spot distribution with respect to the degree of darkening in the region of accumulation of light fragments.

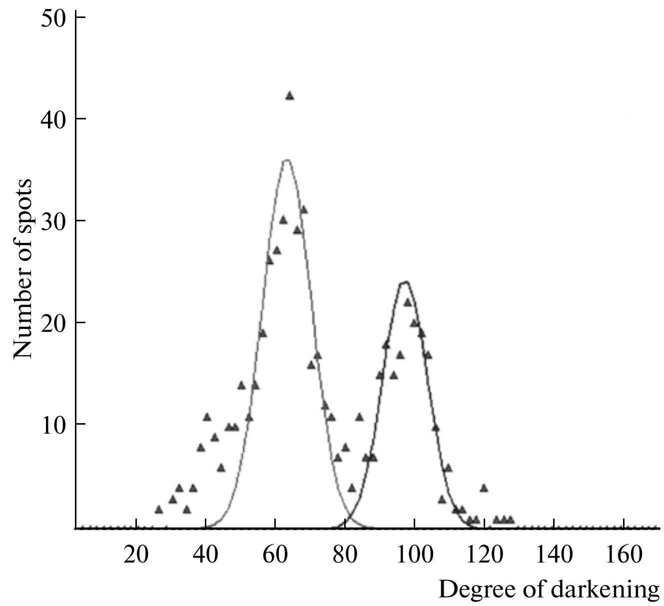

Fig. 11. Spot distribution with respect to the degree of darkening in the intermediate region.

Thus, the study demonstrated that there is a successful acceleration of xenon nuclei at the JINR Nuclotron. In order to overcome the uncertainty in the energy of the primary nuclei due to their deceleration in the emulsion, it is necessary to essentially increase the beam energy. A comparison of methods of the emulsion-film study indicates the possibility of obtaining detailed information on the profiles of low-intensity beams of relativistic nuclei using an automated microscope. A two-component (with respect to the nuclear charge) beam with the spatial splitting of the main beam and the accompanying fragments is observed; these fragments should have a close charge-to-mass number ratio. This fact indicates the potential possibility of using the main segment of the Nuclotron extraction channel as the separator of secondary nuclei. Currently, the whole irradiated emulsion region is being scanned. The adaptation of the PAVICOM software will make it possible to use it in an analysis of other transverse exposures of an emulsion film by relativistic nuclei. The PAVICOM service group developed an algorithm of automatic focusing and tracking for long tracks in the case of the longitudinal exposure of thick emulsions by nuclei, the detection of the interaction vertex, and the determination of charges of relativistic particles by the geometric characteristics of their tracks [8]. The use of the capabilities of the PAVICOM complex opens up prospects for an automated analysis of newly irradiated nuclear emulsions by heavy relativistic nuclei.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research, project no. 09-02-9126 ST-a.

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