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Nuclear track detection: advances and potential in astrophysics, particle physics, and applied research

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Results of nuclear physics research made using track detectors are briefly reviewed. Advantages and prospects of applying the track detection technique in particle physics, neutrino physics, astrophysics, and other fields are discussed for the example of the results of works at the PAVICOM facility of the Lebedev Physical Institute (LPI), Russian Academy of Sciences (PAVICOM: the Russian acronym for Completely Automated Measuring Complex). A unique facility PAVICOM satisfies the best world standards for track detectors and has been successfully operated for about 10 years now. The review covers the results of studies on the search for direct origination of the tau neutrino in a muon neutrino beam within the framework of the international experiment OPERA (Oscillation Project with Emulsion-tRacking Apparatus). LPI's PAVICOM made the possibility of scanning nuclear emulsions from OPERA's detector a reality, enabling the participation of Russian physicists in processing and analyzing the data of this experiment. The spectra of superheavy elements in galactic cosmic rays are presented; the spectra were obtained in measurements of the nucleus tracks in crystals of olivines from meteorites, and nuclei with charges within the range $105 < Z < 130$ *were registered. The prospects for using the track detection technique in, for example, neutrino physics studies (the search for double beta decay) and applied research into muon radiography (nondestructive testing of large construction sites, the search for mineral resources, etc.) are reported.*

Track detectors have been widely used in particle physics for very many decades. In track detectors, registration of elementary particles is accompanied by the emergence of observable traces (tracks) repeating the mechanical trajectory of an elementary particle. These are bubble and spark chambers, nuclear emulsions, silver chloride crystals, and etchable solid state track detectors [1–14]. The popularity and long lifetime of the track detection technique are not by chance and are due to a range of merits of the detectors: uniquely high spatial resolution, obviousness of the reconstructed spatial pattern of particle interaction, relative simplicity and low cost, capability of accumulating information over long periods of time, and some other advantages.

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The technique started to develop with the work by Becquerel [1–3] in 1896. The first track detectors were common photographic plates — Becquerel discovered natural radioactivity when finding fogged (exposed) photoplates that were wrapped in an opaque material together with fluorescent potassium uranyl sulfate.

The so-called Wilson chamber makes use of the condensation of liquid from supersaturated vapor (under suitable conditions ionization produced in a substance by a traveling charged particle can cause a phase transition in it). The instrument was invented in 1912 by Wilson [4], who for many years had studied the physics of cloud formation in the terrestrial atmosphere. The bubble chamber was invented and improved in the early 1950s by Glaser [6] [a superheated liquid is used, which boils near the nucleation centers — local energy-release sites ($\geqslant 0.1$ keV) in the trajectory of a particle in the superheated liquid]. Wilson chambers and bubble chambers also make it possible to directly observe tracks of particles. This means that the position of a particle can be determined accurate to the size of a drop or a bubble, i.e., to approximately 1 mm.

One of the first applications of track detectors was to determine the charge spectrum of the nuclear component of primary cosmic radiation [15, 16]. Studies of the heavy component of primary cosmic rays made use of stacks of nuclear emulsions [17]. The advantages of track detectors as integral instruments accumulating information under conditions of minor particle fluxes were employed not only in balloon experiments but also in satellite experiments with cosmic rays [18]. Stacks of polymer track detectors were subjected to long-time irradiation in a satellite to investigate the energy spectra of cosmic nuclei with the view of obtaining information on nucleosynthesis processes and mean free paths of cosmic nuclei in the interstellar medium [19]. In the 1970s, bubble and spark chambers were the most widespread track detectors [20]. For instance, many properties of strange particles — their mass, lifetime, spin, parity — were determined using these types of detectors [21]. A large number of experiments with chambers studied resonant states of particles and weak interactions [22–25]. Owing to track detectors, many nuclear decays and reactions were discovered, as were new particles (positron, muon, charged pions, strange and charmed particles).

Thus, track detectors have played an outstanding role in the development of nuclear physics due to visualization and the possibility of obtaining an exhaustive spatial pattern of the processes studied. This is confirmed by quite a number of Nobel Prizes in Physics awarded sequentially to:

1903 — A H Becquerel, in recognition of the extraordinary services he has rendered by his discovery of spontaneous radioactivity;

1927 — C T R Wilson, for his method of making the paths of electrically charged particles visible by condensation of vapor;

1936 — V F Hess, for his discovery of cosmic radiation. His apparatus included photoplates and stroboscopes;

1950 — C F Powell, for his development of the photographic method of studying nuclear processes and his discoveries regarding mesons made with this method;

Table 1. Characteristics of various track detectors.

Detector	Spatial resolution, μm	Time resolution	Recovery time
Nuclear photoemulsion	1	—	—
Wilson chamber	1000	10 ms	10 s
Bubble chamber	10 – 150	10 μs	50 ms
Spark chamber	100	1 μs	1 ms
Proportional chamber	50 – 300	2 ns	200 ns
Streamer chamber	300	2 μs	100 ms
Drift chamber	50 – 300	2 ns	100 ns
Semiconductor detector	2	10 ns	10 ns

1960 — D A Glaser, for the invention of the bubble chamber;

1968 — L W Alvarez, for his decisive contributions to elementary particle physics, in particular the discovery of a large number of resonance states, made possible through his development of the technique of using hydrogen bubble chamber and data analysis, and

1992 — G Charpak, for his invention and development of particle detectors, in particular the multiwire proportional chamber.

For comparison, the characteristics of track detectors are given in Table 1. It is worth noting that thermodynamic detectors (Wilson cloud chamber and bubble chamber) are barely in use these days, but new types of track detectors are appearing instead, e.g., semiconductor detectors whose spatial resolution is inferior to nuclear emulsions alone. Nuclear emulsion has been used in particle physics experiments for many decades now. This long lifetime of the technique is, certainly, due to the above-mentioned uniquely high spatial resolution and the possibility of separating particle tracks. None of the known particle detectors are capable of providing the spatial resolution given by emulsion: at a grain size of 0.3–1.0 μm, the deflection of grains from the reconstructed mechanical trajectory of a particle does not, on average, exceed 0.8 μm and under certain conditions can be 0.2 μm. The use of double-sided emulsion makes it possible to achieve an angle determination accuracy of better than 1 mrad. In addition, nuclear photoemulsion enables determining quite a number of other particle characteristics, such as energy, charge, mass, and momentum, and enables exposures in the absence of the experimentalist and studies of reactions with complex topologies of decays. Nuclear photoemulsion represents an extremely 'capacious' detector. Our colleagues from Nagoya University [26] noticed that a DVD can store up to 8.5 GB of information, whereas a double-sided nuclear photoemulsion plate can hold 556 GB of data (the body of information on a 10 cm by 12 cm plate was assessed: 50-micrometer layers of emulsion are applied to a mylar base 200 μm thick on both sides; such plates are used in the OPERA experiment detector). A disadvantage of nuclear track emulsion is the absence of time reference — all particles that pass through it are registered. This leads to the registration of a large number of background particles and reduces the time of admissible exposure, e.g., in an accelerator.

It is hard to find a field of science and technology where track detectors are not used nowadays. These detectors found a wide utility in high-energy physics, cosmic ray physics, reactor physics, metallurgy, geology, archeology, medicine, biology, and studies of meteorites and lunar soil samples.

For instance, data on the energy spectrum of reactor neutrons are gathered by means of neutron dosimeters that contain fissionable layers and track detectors [27]. Using track detectors, information is obtained on the distribution of radiologically essential α-emitting natural nuclei of inert gases ^{222}Rn and ^{230}Rn (from, respectively, decays of ^{238}U and ^{232}Th), which, diffusing from a solid (rocks or structural materials) get into the Earth's atmosphere and may create a hazardous level of radiation [28]. Radon irradiation time in uranium mines is controlled by employing strips of cellulose nitrate fixed on miners' helmets [29]. Registration of α particles from radon gas has been used in attempts to predict earthquakes, because an increase in seismic danger before earthquakes is often noted to be accompanied by the emergence of cracks and stresses; herewith, a large amount of radon is released from uranium and thorium occurring in Earth's crust [30]. The track detection technique is also applied in studies of the exchange processes in the troposphere, where radon is used as an indicator [31]. Track detectors are also employed in beams of negative pions in radio therapy to study events with high linear losses of energy [32, 33].

The simplicity of track detectors exemplifies their significant advantage. However, this advantage can be implemented only if efficient means of retrieving the information they contain are available. Processing of track detector data manually by operators with the aid of optical microscopes required vast amounts of labor and time. The measurement rate proved to be not high, which determined the low statistics of processed events. Moreover, the probability of hard-to-catch errors in such measurements was high, so the measurement results yielded poorly to checks of possible failures occurring in the processing of material (e.g., losses of particle tracks by operators and other errors). For this reason, measurement automation methods were developed simultaneously with the advancement of the detection technique [34–42].

Complete automation of measurements with track detectors became possible after the advent of charge-coupled devices (CCDs). CCD cameras find use for registration and digitization of optical images, which enables microprocessor-oriented systems for automatic processing of particle tracks in detectors. The recognition of particle tracks and reconstruction of their spatial position in these systems are done by computers utilizing specially developed programs. All this made possible the complete automation of processing, obviating the exhausting visual labor of microscopists. In the course of measurements in such an automated mode, digitized images of tracks of charged particles and nuclei in emulsion, obtained by means of CCD cameras, are entered into computers whose software enables the search for, recognition of, and study of tracks. This automated method of measurements with track detectors greatly accelerates the process, enabling the processing of large arrays of experimental data and significantly increasing the statistics of events for a wide range of experiments. This had not been attainable earlier.

The advantages of nuclear track emulsion — the main one being unique spatial resolution — and complete automation of measurements have led to many experiments making use of large amounts of emulsion. These are, for example, CHORUS (CERN Hybrid Oscillation Research apparatUS) — 770 kg; DONUT (Direct Observation of the NU Tau) — 200 kg, and OPERA (Oscillation Project with

Emulsion-tRacking Apparatus) — 100 tons of nuclear photo-emulsion.

None of the industrially produced systems for automatic analysis of images were designed specially for processing images obtained by means of track-etch detectors. This made researchers either develop their own processing systems or else refine or adjust commercial systems for their purposes. Two major tasks had to be solved. The first was to single out objects with darkening levels greater than preset values, and the second reduced to recognizing the features of object shapes. Note that automatic recognition of tracks in emulsion differs significantly from the similar procedure for other visual detectors. For emulsions, penetrating tracks of particles are automatically reconstructed based on several tomographic images at different depths [43]. There are two different approaches — European and Japanese — to the automation of measurements. In the Japanese system, many image processing and recognition stages are put into a special chip, so that emulsions (e.g., from the OPERA experiment detector) can be processed with a rate of up to 75 cm^2 h^{-1}. Extremely fast and highly efficient in track recognition, the Japanese system has a significant disadvantage: expensive R&D and fabrication of another processor are required if experimental conditions and/or emulsion characteristics were changed. In contrast, most of the image processing (at a rate of 20 cm^2 h^{-1}) in the automated systems for processing the data of track detectors used in Europe is done by special software, which makes these systems more flexible in the sense of their adaptation to different statements of the problems.

There are more than 50 automated microscopes in the world for processing the data of track detectors. A world-level automated facility like this — PAVICOM — is available at LPI, too. The facility consists of three microscopes (one of the three PAVICOM microscopes is shown in Fig. 1) which, in the same way as those in European systems, were designed mainly in a software potential-oriented manner. None of the PAVICOM microscopes was a completely industrially-fabricated product; many structural elements were designed and fabricated at LPI or assembled from components of various manufacturers (high-precision German mechanical parts, Swiss video components, Japanese optics). The running accuracy of the microscope stage is 0.5 μm at a displacement range of up to 80 cm, and the processing rate reaches 500 frames per second. To appreciate such a high accuracy of mechanical displacement of the stage, it is sufficient to recall that the thickness of a human hair is 50 μm. From the outset, the facility was established for processing materials from EMU-15 (EMU: the English acronym for EMUlsion) — LPI's experiment at CERN [39, 44–49], in which the emulsion chamber including a lead target 0.4 mm thick followed with a stack of 38 photoemulsion layers, was irradiated with a beam of lead nuclei with an energy of 158 GeV/nucleon. However, the versatility and large hardware potential of the PAVICOM facility, envisaged in the course of its development, enabled its use for a much broader range of problems [49]. PAVICOM is used to process practically all known types of solid-state track detectors: nuclear track emulsions, X-ray films, CR-39 polymer detectors, and others. Staff members of approximately ten Russian and several foreign institutes, together with LPI's PAVICOM group, perform the processing and analysis of experimental data. In fact, PAVICOM is employed as a shared-use center, and in this sense it has no analogs in the world. Below, the review briefly discusses the results obtained at PAVICOM and gives a more detailed account of two main avenues of current research and plans for the future.

Figure 1. PAVICOM-3 automated microscope: Nikon optical system; miCOS precision stage (displacements along axes: $X = 120$ mm, $Y = 120$ mm, $Z = 30$ mm; coordinate measurement accuracy, 0.5 μm); Mikrotron MC-1310 CMOS video camera (color depth, up to 10 bit; image size, 1280×1024 pixels; frame rate, up to 500 frames per second), and Matrox Odyssey XPro workstation, image digitization and processing board.

EMU-15 experiment. In LPI's EMU-15 experiment performed at CERN, where nuclear photoemulsion was used as a detector, the main purpose was to search for possible signals of quark–gluon plasma formation at superhigh temperatures and superdense states of matter. The EMU-15 experiment made use of 16 emulsion chambers shaped as cylinders 260 mm long and 95 mm in diameter. Each chamber contained a thin (400 μm) lead target and 38 layers of nuclear photoemulsion (each 50 μm thick) applied to a mylar substrate 25 μm thick. One emulsion layer was placed immediately before the target; the others were placed behind the target. The total thickness of each chamber was a mere 0.07 cascade lengths, which is very important for the registration of central collisions of very high-energy lead nuclei, in which several thousand secondary particles are generated. The chamber was fixed transversely to a 2 T magnetic field and was positioned such that the planes of the target and nuclear photoemulsions were perpendicular to the beam. The total number of Pb nuclei at the irradiation of each of the 16 emulsion chambers was approximately 10,000. Each chamber was found to register about 10 central Pb–Pb interactions with the secondary particle multiplicity of over 1000 (the selection criterion for such events is a large multiplicity of secondary charged particles and the absence of fragments with charge $Z \geqslant 2$).

Image processing and microtrack search methods developed for this experiment enabled the first Russian automated search for tracks of secondary charged particles produced in central nucleus–nucleus interactions with a multiplicity of > 1500 in nuclear track emulsion [50]. The automated processing of tracks in nuclear emulsion required software to be developed for monitoring the displacement of the microscope stage, video shooting of images, their analysis, and the reconstruction of the geometric pattern for bouncing apart secondary charged particles. The result of the restoration of particles' dispersion geometry after nucleus–nucleus interactions was a pseudorapidity distribution of secondary particles, which then was analyzed in detail applying various mathematical methods.

Analysis of the distribution of secondary particles in phase space was the main task of the study, because it enabled making a conclusion about the dynamics of the process. This was not an easy thing to do, even if only angles (polar and azimuthal) of particle divergence were measured, because the number of secondary particles sometimes exceeds 1000. The problem was reduced to the recognition of images made up in the plane of a target diagram by this number of points. The solution to this problem was found applying wavelet analysis. When processing the EMU-15 data, the Daubechies wavelet was used for the first time for two-dimensional wavelet analysis of particle spectra. The result of this analysis was demonstrated by the example of the internal structure study of secondary particle dispersion locally and on different scales. It was evidenced that correlated groups in the distribution of secondary charged particles by pseudorapidity have a tendency to be arranged in the form of a ring around the center of the diagram. This corresponds to groupings of particles at a constant polar angle, i.e., to a fixed pseudorapidity. The mechanism of the emergence of these structures in strong interactions can be explained either by an analog of Cherenkov radiation (gluons act as an analog of photons) or else by the emergence of Mach shock waves [39, 51, 52]. Both mechanisms are of a similar nature — the radiation emerges upon the movement of a body in a medium with a velocity exceeding the phase velocity of the disturbance propagation in this medium.

The most significant indicator of the existence of ring structures is the occurrence of two peaks in the pseudorapidity distribution (Fig. 2). Ring structures are seen on the plane of the target diagram in this case [51]. Thus, the results of EMU-15 data processing confirmed the asymmetric character of the distribution of secondary charged particles by the azimuthal angle in combination with pseudorapidity peaks in an individual event. This is indicative of particle dispersion features caused by many-particle correlations whose occurrence, notably, was expected in a comparatively small number of emitted Cherenkov gluons in each ring. It is worth noting that wavelet transformation was first used in high-energy physics in processing EMU-15 data for the analysis of the features of the distribution of secondary charged particles and their localization [39, 48, 52].

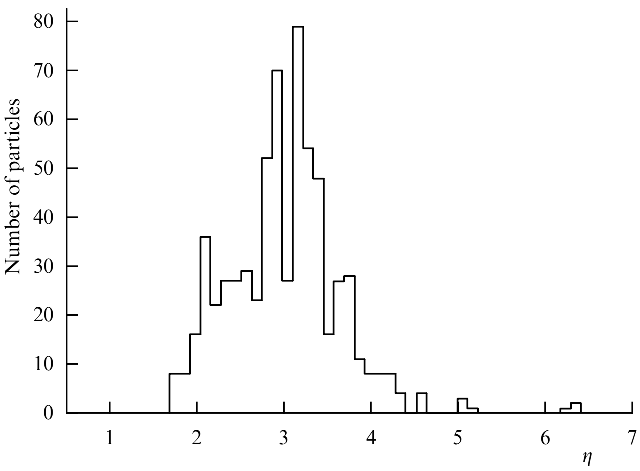

Figure 2. Pseudorapidity distribution of secondary charged particles, $\eta = -\ln(\mathrm{tg}\,\theta/2)$, where θ is the angle between the direction of the track and the axis of the event, in one of the events (designated as 5c15e) of the EMU-15 experiment after automated processing.

RUNJOB (RUssia–Nippon JOint Balloon) experiment. One of the users of the PAVICOM facility was the RUNJOB Collaboration [Skobeltsyn Institute of Nuclear Physics of Moscow State University (SINP MSU), LPI, seven Japanese universities]. Ten successful flights of high-altitude automatic balloons with on-board emulsion chambers of a total duration of 1440 h at a height of 32 km on average were carried out from 1995 to 1999 within the framework of the Russian–Japanese RUNJOB experiment to investigate elementwise energy spectra of primary cosmic radiation [53–58]. The chambers had a complex lamellar structure with tens of layers of photosensitive detectors (X-ray film and nuclear emulsion), layers of carbon or steel in the target, as well as layers of lead in a thin calorimeter. Processing the photosensitive layers was done by four groups in Russia and Japan. The use of PAVICOM facility enabled Russian physicists to participate on a par with their Japanese colleagues in the processing of experimental material. The developed software for automatic scanning and analysis of microimages made it possible to process large areas (0.5 m^2) of photosensitive materials with high spatial resolution (7 μm/pixel and higher) and large rate (16 cm^2 min^{-1}). The RUNJOB Collaboration produced results on the spectra of protons, helium nuclei, nuclei of the CNO group, and Fe nuclei in the spectra of all particles; the data obtained were compared with the data of other experiments, including those of the ATIC (Advanced Thin Ionization Calorimeter) experiment; no noticeable discrepancies were found in the intersecting range of energies. It was shown that the spectra of protons and helium nuclei had close values and did not indicate any noticeable steepening in the range of energies up to 1 PeV/particle. RUNJOB is acknowledged to be one of the most successful balloon experiments and has been rather widely cited around the world.

BECQUEREL (BEryllium/boron Clustering QUEst in RELativistic multifragmentation) project. Studies of fragmentation processes in light radioactive nuclei, as well as review information on the charge states of secondary particles in fragmentation of intermediate and heavy nuclei, were the aim of research within the framework of the BECQUEREL experiment [Joint Institute for Nuclear Research (JINR)]. Processing (at the PAVICOM facility) of nuclear track emulsions irradiated with light relativistic nuclei of ^{4}He, ^{6}Li, ^{7}Li, ^{7}Be, ^{10}B, ^{12}C, ^{14}N, ^{16}O, ^{22}Ne, ^{24}Mg and ^{28}Si, produced at the JINR nuclotron, with energies greater than 1 GeV/nucleon, made it possible to reveal clusters of secondary particles formed in the diffraction dissociation processes and to investigate the characteristics of particles even inside closely collimated clusters. This work determined the fragmentation features of light nuclei and measured the ratios and probabilities of their decays via different channels [44, 59–65].

Energy Plus Transmutation project. The major international Energy Plus Transmutation project was also carried out at the Joint Institute for Nuclear Research (Dubna) on the basis of the Nuclotron accelerator. Accelerators of charged particles with energies on the order of $\gtrsim 1$ GeV, developed in their time for basic nuclear physics research, can be used for creating pulsed intense neutron sources and experimental facilities based on them to study the electronuclear method of energy production and the transmutation of radioactive waste from the nuclear power industry. In 1999, a model of a uranium–lead assembly was constructed and tested at JINR on the proton beam of the synchrophasotron within the framework of the Energy Plus Transmutation project [66, 67]. Experiments on the U/Pb assembly and its model were conducted with the view of directly measuring the energy release rate both by the number of fissions of natural uranium nuclei and by the amount of heat liberated in the blanket bulk [67]. Studies of the neutron spectrum in the bulk of the blanket were of exceptional importance. Extensive application of solid state track detectors (SSTDs) based on lavsan (polyethylene therephthalate) in this experiment for studying the neutron spectra was caused by their specific features: high efficiency of the registration of fission fragments, low intrinsic background, and simplicity of the processing technology. SSTDs were used in the calorimeter of the facility for monitoring and determining the beam's profile; for studying the distribution of fission events in the blanket; for investigating the fission of uranium nuclei by thermal, resonant, and fast neutrons, and for determining the averaged fission cross section in the blanket.

Track detectors fabricated in the form of solid strips with various radiators were positioned during irradiation sessions in a line perpendicular to the axis of symmetry of the facility at several angles. Based on the track count results, the partial integrals for the fission of natural uranium nuclei by thermal, resonant, and fast neutrons were determined as functions of the radius of the uranium blanket model. To measure the threshold nuclear reaction rates, use was made of a set of targets from 23 chemical elements, including ^{232}Th and ^{197}Au. The values obtained of the reaction rates were utilized to analyze the numbers of fissions in radiators with various fission thresholds, which were placed on the surface of the Energy Plus Transmutation facility and between the sections of the assembly. They made it possible to retrieve the spectrum of fast neutrons for the U/Pb assembly model, as well as to calculate the induced activity of chemical elements that can be employed as structural materials in developing electronuclear and other nuclear physics facilities. The method of determining the absolute number of fission events in uranium nuclei by means of SSTDs makes it possible to measure the distribution of the number of reactions in relation to the radius and, thereby, the energy release rate in the blanket.

However, the visual count of tracks on a large number (tens or hundreds) of detectors is a rather labor-intensive and time-consuming procedure. Automated data processing for such film detectors at the PAVICOM facility was made possible after developing appropriate software [68] which enabled digitization of optical images of tracks on films in a completely automated mode, the recognition of traces of fission fragments, and the calculation of their concentration. The possibility of automatic measurements in SSTDs significantly facilitated the data processing and increased both the number of processed detectors and their effective area. In particular, from the results of the automated processing of track detectors irradiated in the November 1999 session, the number of fissions by (separately thermal, resonant, and fast) neutrons was determined in relation to the distance from the axis of symmetry of the uranium–lead assembly. The contribution of slow neutrons was observed to tend to rise with an increase in the radius. The main contribution to the fission of ^{238}U nuclei was made by fast neutrons [67].

Spectra of internal conversion electrons of rare-earth elements. Physicists at the Alikhanov Institute for Theoretical and Experimental Physics (ITEP) and the Joint Institute for Nuclear Research experimentally studied the spectra of internal conversion electrons (ICEs) by the nuclear spectroscopy method, which makes it possible to gather information on the properties of nuclear states — energies, spins, parities, isotopic spins, and other characteristics. By studying the ICE spectra, one can investigate transitions between nuclear energy levels. Comparison of the experimental values of internal conversion coefficients or the relative intensities of conversion electron spectral lines with their respective theoretical values makes it possible to determine the nuclear transition multipolarity and, therefore, the data on the spin and parity of nuclear states. Knowing the internal conversion coefficient, in a number of cases (at a mixed multipolarity of gamma radiation) it is possible to find correlations between matrix elements and arrive at conclusions regarding the character of nucleus excitations and nuclear wave functions. Conversion studies are the main way to investigate 0–0 transitions in nuclei and to obtain experimental values of nuclear matrix elements. Precision measurements of ICE intensity provided by modern nuclear emulsion equipment give us the opportunity of studying anomalies in the values of the internal conversion coefficients and other phenomena.

Moving from the microphotometry technique to that of microscopic emulsion measurements in studies of the ICE spectra of rare-earth isotopes opens the possibility of revealing the multipolarity of nuclear transitions whose intensities are 3–4 orders of magnitude lower than those of the known transitions.

In joint work done by ITEP and JINR, emulsion layers 25×450 mm^2 in size and 600 μm thick were irradiated with internal conversion electrons emitted by rare-earth isotopes at a JINR beta spectrometer. The quantity to be determined at the stage of processing the experimental ICE spectral data accumulated in photoemulsion strips at the PAVICOM facility was the blackening intensity of the photographic layer applied to the glass substrate, as a function of the distance from the electron source to the observation point.

To single out the spectral lines in scanning emulsions at PAVICOM, original software was developed, being relied on the idea of summing up the degree of blackening in a given direction for digitized images in an effort to enhance the singled-out effect and to detect weak lines against a large background. Measurements at the PAVICOM facility made it possible to determine the intensities of the ICE spectral lines, as well as to obtain the intensities of 0–0 transitions inaccessible with the common gamma spectroscopy technique [69, 70]. The results obtained in this data processing revealed that some rare-earth isotopes experience tens of earlier unknown nuclear transitions which supplemented the world database of ICE lines.

In particular, the intensity of L_2 and L_3 lines of the γ transition with an energy of 148.16 keV could not be measured in studies of the spectrum of internal conversion electrons by means of the microphotometry technique [71]. This is due to the occurrence of an intensive γ transition with an energy of 195.5 keV in isotope $^{158}_{68}$Er in this energy interval, giving the K line of internal conversion electrons ($E_e = 139.9$ keV). The sought-for lines L_2 and L_4 of $^{161}_{68}$Er get to the right and left slopes of this K line of $^{158}_{68}$Er and 'sink' in background fluctuations. Still, using a correct approximation of the spectral line, attempts to single out lines L_2 and L_3 against a huge background (effect/background $\sim 1/100$) proved successful (Fig. 3).

Study of neutron-excess nuclei. An experiment by the Institute for Nuclear Research of the Russian Academy of

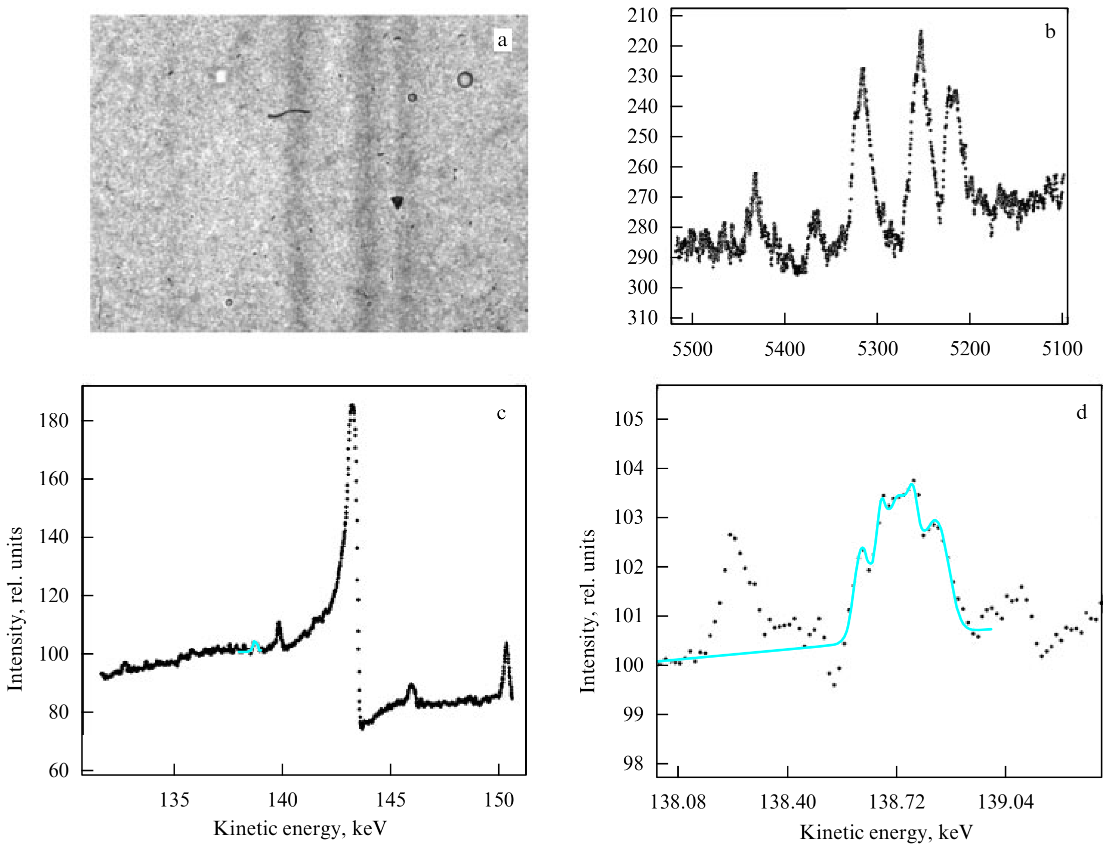

Figure 3. The results of processing the spectra of $^{158}_{68}$Er isotope internal conversion electrons. (a) An image of one field of vision 3×4 mm in size in an emulsion irradiated by internal conversion electrons. (b) The same field of vision after computer processing: on the ordinate the total degree of blackening (the blackening changes within the limits of 0 to 255 bytes: 0 corresponds to black color, and 255 to white color) is plotted; on the abscissa the conventional units of splitting the frame in summation are plotted, with the total length of the frame being 4 mm. (c) A segment of the spectrum plotted in terms of electron energy. (d) An enlarged part of figure c: the fine structure of the spectrum — lines L_2 and L_3 – is seen.

Sciences to study the structure of light neutron-excess nuclei is aimed at obtaining information on the possibility of the existence of neutron clusters in exotic nuclei, e.g., in the helium-6 nucleus. Several stacks of 4–6 substrate-free nuclear emulsions with each layer 400 μm thick were irradiated with a beam (directed perpendicular to the surface of the stack) of light nuclei of ^{6,8}He, ^{11}Li, and other elements with energies in the range $3 < E < 15$ MeV/nucleon at the accelerator of the Flerov Laboratory of Nuclear Reactions at the Joint Institute for Nuclear Research. Nuclei of the elements occurring in the emulsion (^{12}C, ^{14}N, ^{79,81}Br, ^{107,109}Ag) served as targets. As the energy of reaction products in the given energy interval is totally absorbed in an emulsion stack 1600–2000 μm thick, the photoemulsion in this experiment registers all particles in the range of angles extending over 4π. This significantly increases the efficiency of the method as compared with that of the technique based on electronic instruments. Emulsions were scanned at the PAVICOM facility, for which purpose additional equipment was fabricated and special software developed.

Using an example of 50 reconstructed events of the ^{6}He nucleus scattering on the proton to form T and D nuclei, information was obtained on two cases of the expected reaction: with the transfer of two neutrons to the proton, and with the transfer of one. Using the results of a draw of the reactions with two-neutron and one-neutron transfer, the reconstructed events were shown to cover both kinematic regions, thus confirming the occurrence of both neutron configurations in ^{6}He [72, 73].

Automated nuclear charge determination technique. A technique for automated determination of charges of relativistic nuclei in photoemulsion was developed and implemented at the PAVICOM facility. To choose an optimal determination procedure, all known methods of deducing charges of particles from the characteristics of their tracks were considered and tested. Thus, when deducing charges within the range of $Z = 3-7$, use is made of the method of counting the number of breaks (gaps) between blobs of developed grains on the track. For particles with charges $Z > 7$, whose tracks have almost no breaks, use is made of the method of measuring the number and/or length of the traces of delta electrons formed in the medium ionization along the track of a charged particle. The method is substantiated by the fact that the distribution of delta electrons by their energy and range depends on charge Z of the ionizing particle [74]:

$$\frac{d^2N}{dT\,dx} = \frac{1}{2}\,4\pi N_A\, r_e^2\, m_e\, c^2 Z^2\, \frac{z}{A}\,\frac{1}{\beta^2}\,\frac{F}{T^2}\,,$$

where T is the kinetic energy of delta electrons, x is the amount of matter passed by the ionizing particle, N_A is the Avogadro constant, A is the atomic weight of atoms in the medium, z is the charge of atoms in the medium, and $\beta = v/c$, with v being the velocity of the ionizing particle, and c the

Table 2.

Cell number	Charge determined by a microscopist		Charge determined by automated processing	
	Primary	Fragment	Primary	Fragment
174-43/153 90-39	12	10	$12/2 \pm 0.4$	10.2 ± 0.3
174-43/174 80-48		5		4.9 ± 0.3
174-43/180 67-52	12		12.2 ± 0.4	10.2 ± 0.3
174-43/88 44-55	12	6	12.2 ± 0.4	6.6 ± 0.5
174-43/169 75-48	10		9.7 ± 0.6	4.2 ± 0.9
174-43/129 48-39	10	6	9.3 ± 0.6	5.9 ± 0.4
174-43/59 08-68	14	13	14.0 ± 0.5	13.3 ± 0.5

speed of light in vacuum. Parameter F depending on the spin of the ionizing particle is considered to be constant at relativistic energies, and m_e and r_e are the mass and classical radius of the electron, so that the factor $4\pi N_A r_e^2 m_e c^2 = 0.3071$ MeV cm^2 g^{-1}.

The work carried out at the PAVICOM facility made use of an integrated nucleus-charge determination method combining the advantages of all known techniques. As a result, an algorithm was developed that enabled the measurement of the nuclear charges with $Z > 3$ [75]. Given that the scanned track of a nucleus is 3 mm long, the accuracy in determining its charge by our method, which considers several parameters, approaches 2%. What is more, there were cases when the nuclear charge could not be determined manually, but the program did this rather successfully. Table 2 presents the results of test measurements, where emulsions irradiated and labelled at JINR were utilized (the number of the cell in the first column of the table designates the region on the emulsion plate in which the track of the investigated nucleus is located).

Medical carbon beam dosimetry. Adjustment of the medical carbon beam at ITEP was done using CR-39 polymer detectors for the dosimetry of the irradiated human phantom. Detectors of this type provide acquisition of data not only about the mean values of the particle energies and energy release of particles in the object, but also about the distribution of the density of the beam over its cross section, the number and place of particle entries, and the spread in particle energies. Processing these detectors was also carried out at PAVICOM. The diameter of the beam field was 45 mm and the size of the plates was 2×2 cm^2. To calculate the number of particles, as well as to measure the size of clusters, part of a plate 5×5 mm^2 in size was scanned. An objective lens with a 100-fold magnification was used (the size of each frame measured 420×350 μm^2).

All the above is only a brief outline of some of the work done at the PAVICOM facility over 10 years. That said, the involvement of the LPI group was not reduced to the mere lease of equipment. It has always been a joint activity: together with their colleagues from other institutes, members of the PAVICOM group did scanning, developed software, additionally procured required equipment, and carried out physical data analysis. Three CandSc theses were defended (two at SINP MSU, and one at LPI), as were two DSc theses (both at LPI) relying on the results of this work lasted for a decade at PAVICOM.

The efforts of LPI's PAVICOM group are at present concentrated mainly on two projects: the OPERA experiment and the OLIMPIYA project.

OPERA experiment. OPERA is a major international experiment aimed at the search for neutrino oscillations.

We live in a virtually neutrino Universe; there are very many of these particles, and one of their main sources is the Sun. Each second, 60 to 100 billion of these particles pass through a square centimeter on Earth's surface, with an interaction involving neutrinos occurring in the body of each human approximately once every 70 years. Neutrinos interact very weakly, and there are quite a number of unclarified questions about their nature. Studies of the properties of neutrinos are of fundamental significance for particle physics, astrophysics, and cosmology. In this context, it is appropriate to recall the words uttered more than 40 years ago by M A Markov, who made a great contribution to studies of this 'enigmatic' particle: "For the contemporary, it is hard to guess what true place the neutrino will occupy in physics in the future. However, the properties of this particle are so elementary and peculiar that it is natural to think that the Nature created the neutrino with some profound purposes that are not yet clear for us" [76].

Despite evident progress, difficulties in experiments with neutrinos led to a situation, where many of their essential characteristics, such as the masses of the many kinds (flavors) of neutrinos and mixing angles, as well as the nature of massive neutrinos have not yet been determined. There are no fundamental reasons to consider neutrinos massless particles, but for a long time (according to the 'scientific public opinion') it has been accepted to think that the neutrino masses at rest are equal to zero. The zero values of neutrino masses were consistent with the results of many experiments, where those masses were determined proceeding from the kinematics of weak decays, the probability of neutrinoless double-beta decay, and from the analysis of neutrino signals detected from the SN-1987A supernova. By the same token, each of the lepton numbers determining the type of neutrino (L_e, L_μ, L_τ) was assumed to be preserved in all processes. If, however, the masses of neutrinos are not zero, the eigenstates of neutrinos with a given mass do not coincide with the eigenstates of neutrinos with a given lepton number. Therefore, a 'mixing' of neutrinos should occur, similar to the mixing of quarks described by the Kobayashi–Maskawa matrix. Neutrino mixing should lead to the phenomenon of neutrino oscillations. A possibility of neutrino oscillations was hypothesized by B M Pontecorvo in 1957. Neutrino oscillations represent a periodic process of the total or partial change of flavor of a neutrino beam moving in a vacuum or in matter.

The issues of neutrino oscillations and neutrino masses are so important that very many quite diverse experiments are being conducted throughout the world to elucidate them. The success of 'oscillation' experiments is largely determined by the involvement of so-called far neutrinos, i.e., those that pass a significant distance L from the source to the detector. The sensitivity of experiments to the small value of the difference between neutrino mass squares $\Delta m_{ij}^2 = m_i^2 - m_j^2$ is determined by the path length L of the experiment, i.e., the distance between the neutrino source and the detector. To observe oscillations, it is necessary that the path length be close to the so-called length of oscillations, $L = 4\pi E_\nu/\Delta m_{ij}^2$, which, at small values of Δm_{ij}^2, can be very large. Thus, theory requires that experiments in which neutrino oscillations are assumed to be directly registered have a large path length, and high energy and intensity of the beam. Until now, all oscillation experiments have investigated 'disappearance'. That is, it is assumed that a certain number of neutrinos of one flavor should be registered, and if a smaller number of them arrives, the conclusion is made that oscillations have occurred. The first experiment for neutrino 'appearance' was the OPERA experiment started in 2006, whose detector enables the emergence of a tau neutrino in a beam of muon neutrinos to be directly registered by the direct registration of a short-lived tau lepton (the lifetime of tau lepton is 2.9×10^{-13} s).

To perform this experiment on the search for neutrino oscillations, a special kilometer-long channel was constructed at CERN to bring the neutrino beam to the largest underground laboratory at Gran Sasso (Italy). A practically pure beam of muon neutrinos (the contribution of other types of neutrinos to the ν_μ beam does not exceed the following values: $\nu_e/\nu_\mu = 0.8\%$, $\bar{\nu}_\mu/\nu_\mu = 2.0$, $\bar{\nu}_e/\nu_\mu = 0.05\%$) having a mean energy of 17 GeV passes a distance of 732 km; as a result of their oscillations, tau neutrinos may emerge. The number of interactions that occurred in 1 kt of detector mass per proton delivered to the target is about $5.44 \times 10^{-17}\,\nu_\mu$ events in charged-current channel per proton per kiloton.

The OPERA detector, 1.25 kt in mass, consists of two independent supermodules which include target blocks and muon spectrometers. The main component of the detector compresses an emulsion 'brick' consisting of 56 one-millimeter-thick lead plates and 57 emulsion plates. The emulsion brick is 12.8×10.2 cm^2 in area and 7.9 cm thick (about 10 radiation units). Beyond each wall of target blocks are strip electronic detectors used to pinpoint the emulsion brick in which an interaction took place [77]. The OPERA experiment considers several types of events, but the main goal is to search for charged current interactions, when a tau lepton can be born. The aim of the experiment consists in singling out interactions of tau neutrinos against the predominant background of interactions of other flavor neutrinos based on the topology inherent in this sort of events. The features of the topology are due to decays of the short-lived taon. The tau lepton is identified by the decay forming one visible trace of a particle (an electron, muon, or hadron) or three visible particles. Upon the decay of the tau lepton, according to one of these protocols, a characteristic inflection of the track is formed, which is the main indicator of tau lepton formation in studies of the topology of the event. After the target is pinpointed from the system of electronic detectors and this event is confirmed by the scanning of two special changeable layers, emulsion bricks are sent for processing to various laboratories (in Italy, Japan, and Switzerland; in Russia, to date only to PAVICOM).

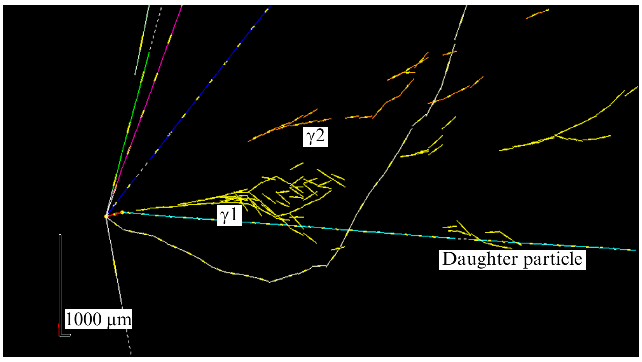

Figure 4. Observation of the first candidate for charged-current interaction of ν_τ in the OPERA detector in the underground laboratory at Gran Sasso [Laboratori Nazionali del Gran Sasso, Instituto Nazionale di Fisica Nucleare (INFN), Italy]. The candidate was identified in a selection of events corresponding to 1.89×10^{19} protons on target (pot) in a beam of ν_μ from the CERN accelerator towards Gran Sasso. The assumed τ^- lepton decays into $h^-(n\pi^0)\,\nu_\tau$.

In 2010, the OPERA Collaboration reported on the results of registering the first tau lepton in the OPERA detector. This event was processed twice: a large area of nuclear track emulsion was independently scanned in two laboratories, which made it possible to completely reconstruct the interaction pattern (Fig. 4). One event was found in the hadron channel of tau lepton decay. If only the channel with the production of the hadron ($\tau^- \to h^-(n\pi^0)\,\nu_\tau$) is considered, the probability of observing one event with respect to background fluctuations is 1.8% at a confidence level of 2.36σ. If all modes of tau lepton decay are taken into consideration, the probability of observing one event with the background allowed for is 4.5%. This corresponds to 2.01σ [78]. Thus, the OPERA Collaboration detector registered the production of a tau lepton with a probability of 98.2% at a confidence level of 2.36σ and its subsequent decay through the hadron mode (see Fig. 4).

To be certain, the fact of registering the first direct appearance of a tau neutrino in a beam of muon neutrinos stages an event for world physics, which was noted in a special letter by Rolf-Dieter Heuer, CERN Director General (31 May 2010) and in quite a number of publications in scientific journals. The experiment continues, and direct registration of new cases of neutrino oscillations will make it possible to move forward in understanding the properties of these unusual particles omnipresent around us in vast amounts. As of March 2012, according to the processing results, 3054 events of charged-current neutrino interactions were singled out and are being analyzed. Of them, 55 events were identified as those with the production of charmed particles, 24 events with ν_e, and one event was the registration of a tau lepton. The search for more cases of the appearance of tau leptons continues; from the results of processing, a report is in preparation for the International Conference on Neutrino Physics in Japan in June 2012.

OLIMPIYA project. A rather important part of the work carried out at PAVICOM is the project OLIMPIYA (the Russian acronym for OLIvines from Meteorites — Search for

Figure 5. Specimens of meteorites used for studies in the OLIMPIYA project. The upper one, larger in size, is part of the Marjalahti meteorite (Finland, 1 June 1902): size of the whole meteorite, ≈ 30 cm; weight, ≈ 45 kg; age, 185 mln years (Geological Museum at the University of Helsinki, Finland). The lower specimen, smaller in size, is part of the Eagle Station meteorite (USA, 1880): size of the whole meteorite, ≈ 25 cm; weight, ≈ 38 kg; age, 300 mln years.

Heavy And superheavy Nuclei) — the search for heavy and superheavy nuclei in Nature. This problem is associated with the issue of the existence of stability islands in Mendeleev's Periodic Table. Vitaly L Ginzburg considered the search for superheavy nuclei in Nature a very significant issue for the physics of the 21st century and included it in his famous list of priority issues. On his initiative, LPI scientists started to deal with the search for traces of heavy and superheavy nuclei in crystals of olivines from meteorites [79] (Fig. 5). The work is carried out jointly with colleagues from the Vernadsky Institute of Geochemistry and Analytical Chemistry (GEOKHI) and is supported by JINR Laboratory of Nuclear Reactions.

In 1869, Dmitri Mendeleev compiled the Periodic Table of elements, entering into it the 63 elements known at that time. The periodicity with which the chemical properties change reflects the periodicity of filling the electron shells in the atoms. The development of the Table made it possible to predict and discover gallium (1875), scandium (1879), and germanium (1886). In 2009, the official boundaries of the Periodic Table were expanded to include the 113th element, and now elements 114 and 116 are undergoing the certification procedure, and the first nuclei of element 118 have already been obtained in accelerator experiments. How many elements can the Table contain? Where is its boundary? The greater the charge of a nucleus, i.e., the larger the serial number of an element, the more strongly the innershell electrons are attracted to the nucleus. Ultimately, a moment should come when they begin to be captured by the nucleus. Preliminary calculations have shown that no elements can exist with a serial number greater than 170–180 — capture of a negatively charged electron decreases the charge of the nucleus. Still, the subsequent development of nuclear physics has shown that the boundary of the Table is determined not by the instability of an atomic electron shell but by the instability of the nucleus itself — a source of an electric field in which electron shells are formed. The most stable nuclei are those that contain the so-called magic number of neutrons or protons (2, 8, 20, 50, 82, 126). As atomic electrons, nucleons in nuclei form shells. Shells are successively filled up as the number of particles in the nucleus increases. Just as the inert gases are most stable in the Periodic Table, so the most stable are those nuclei in which the neutron and proton shells are fully built up. It is to such closed nuclear shells that magic numbers (calcium, tin, lead) correspond. The issue of the existence of superheavy nuclei is of uttermost significance for understanding the properties of nuclear matter. First and foremost, it is of interest to check the prediction [80] of the considerable increase in the stability of nuclei near the magic numbers $Z = 114$ and $N = 184$ (N is the number of neutrons), which could lead to the existence of superheavy nuclei in this region of 'stability islands'.

In transuranic nuclei, even for nuclear forces of attraction it is hard to restrain huge electrostatic forces of repulsion between protons. Therefore, the greater the serial number of the nucleus, the shorter its lifetime. For example, plutonium-244 lives 100 mln years; californium-250, about 10 years, and fermium-252, about 20 hours. Alpha decay and spontaneous fission are to blame. The heavier the nucleus, the greater the role of fission. The nucleus of uranium ($Z = 92$) is the heaviest of those found on Earth. The next nuclei were synthesized artificially.

Nuclear theory predicts that an element with a charge of 110 and an atomic mass of 294 should live a hundred (and maybe a billion) years. But, if the number of neutrons or protons is changed by 2–3, i.e., by a mere 1%, the atomic lifetime should be decreased 10 mln times. This effect is observed, for example, in the double magic nucleus of lead: 82 protons and 126 neutrons. This lead-208 is so stable that nobody has observed its decay yet. But lead with 127 neutrons decays in 3.3 hours.

Scientific interest in determining the boundary of the Periodic Table is quite understandable, but why are artificial superheavy elements needed?

The most 'hard-working' of all synthesized elements proved to be plutonium-239. Nuclear reactors burn uranium-235, whose content in natural uranium is only 0.7%; the bulk of uranium mass is made up of uranium-238, which is not a nuclear fuel. Fast neutron reactors, after burning 1 kg of uranium-238, produce 1.6 kg of plutonium-239, which is a better-quality nuclear fuel than uranium-235. At present, applications of synthetic elements are huge in space, medicine, etc. Their production has increased from several billion fractions of a gram up to many kilograms and even tons.

Predictions of theory say that there should be so-called stability islands of superheavy elements beyond uranium. It is for this reason that work on the artificial synthesis of superheavy elements has never been discontinued.

The first artificial elements were synthesized by the so-called reactor method — by the direct addition of neutrons to the nucleus. However, the potential of this synthesis on Earth was sufficiently quickly exhausted. The last element produced by this direct neutron synthesis was element 100, fermium, which was found in the ground after a nuclear explosion. This method of synthesis requires too high a density of neutron fluxes and high energies. Nowadays, elements can be synthesized in this way only in astrophysical processes, and under terrestrial conditions in accelerators superheavy nuclei are synthesized in collisions of two different nuclei.

According to the existing views, chemical elements from carbon and to heavier ones are formed in the stars' interiors and in supernova explosions [81]. Heavy and superheavy elements located in the Periodic Table beyond bismuth are formed as a result of proceeding r processes (rapid neutron capture processes) that occur at a high concentration of neutrons and can lead to the formation of superheavy nuclei with the number of neutrons up to $N = 184$. Besides these traditional mechanisms, the possibility of the formation of very heavy nuclei (with the mass number up to 500) at a high density of neutrons (on the order of 10^{30} cm^{-3}) and moderate temperature $T < 10^8$ K is also discussed [82]. Such a situation can be realized in nonequilibrium shells of neutron stars, ejections from which can lead to the emergence of superheavy elements in the interstellar medium, stars, and planets [83, 84].

One of the world leaders in the synthesis of new chemical elements under terrestrial conditions is JINR's Laboratory of Nuclear Reactions. Staff members of the Laboratory succeeded in synthesizing 12 out of 18 trans-Fermi elements [102, 103, 104, 105 (dubnium), and 106 under the leadership of G N Flerov; 112, 113, 114, 115, 116, 117, and 118 under the leadership of Yu Ts Oganessian].

Experimental data on superheavy nuclei in Nature are extremely scarce; such nuclei are precious few — they are a mere 1–2 nuclei per m^2 a year; for trans-Fermi nuclei, sufficiently reliable data are not available at all. In the same way, there are no data either on the possible existence of exotic superheavy nuclei. For this reason, nuclear track detectors of very large areas and long exposure times are required to search for them in Nature.

Measurement of the fluxes and energy spectra of heavy and superheavy nuclei in cosmic rays is an efficient way to study the composition of cosmic ray sources, processes occurring in the sources themselves and in the interstellar medium, in which cosmic rays propagate, and models of retaining cosmic rays in the Galaxy. According to an estimate by G N Flerov, who proposed considering a meteorite as a natural detector of cosmic rays, at the age of a meteorite of a few hundred million years, the study of its matter with a volume of 1 cm^3 is equivalent to an experiment with 1 t photoemulsion in space for a year. The employment of the factor of prolonged exposure of meteorites in space gives an enormous advantage to the method of searching for superheavy elements in crystals of olivines from meteorites over methods based on the application of various satellite and balloon detectors. The search for relic tracks left by particles of cosmic rays in minerals appearing in some meteorites relies on the ability of silicate crystals occurring in meteorites (olivines, pyroxenes) to register and preserve for a long time ($> 10^8$ years) tracks of nuclei with $Z > 20$. A typical age of meteorites and, therefore, the time of their exposure to the flux of cosmic rays is estimated to be $10^7 - 10^9$ years. Therefore, they can contain a large number of cosmic ray tracks. Estimates show that $10^2 - 10^3$ tracks of nuclei with $Z > 90$ can be formed in 10^8 years in 1 cm^3 of such crystals located at a depth of < 5 cm from the preatmospheric surface of a meteorite; and in crystals taken from the surface regions of a meteorite (< 1 cm in depth), up to 10^4 tracks. By measuring the parameters of the tracks, it becomes possible not only to identify particles, but also to determine their energy spectra. Pallasite type meteorites consist of an iron–nickel 'matrix' in the bulk of which there are inclusions of crystals of olivine — a yellow semitransparent mineral up to 1–2 cm in size. As with previous studies involving olivines, the OLIMPIYA experiment is based on applying the method of solid state track detectors, where particles are registered by radiation damage they cause in the bulk of detector material.

Specimens of two meteorites — Marjalahti (185 mln years) and Eagle Station (300 mln years) — are being studied. Both these meteorites are pallasites. They represent an iron–nickel matrix in which there are inclusions of olivine.

The technique developed in the OLIMPIYA project makes it possible for the first time to examine the entire bulk of the crystals, thus significantly increasing the volume of statistics collected from processed tracks. The software developed at PAVICOM enables singling out isolated regions in crystals, finding and measuring the geometric parameters of nuclear tracks, and performing spatial cross-linking of traces. The main goal of the OLIMPIYA project reduces to determining the charge composition of cosmic rays in the range of heavy and superheavy nuclei. The magnitude of the charge is related to the characteristics of an etched track. The main one is the etchable length L_{etch}; however, it exceeds the size of olivine specimens for very heavy nuclei. As a way out of this situation, it was proposed to utilize an additional quantity, the etching rate. This quantity changes during the etching and increases as the stop point of the particle is approached [85, 86].

About 170 crystals have been processed; the size of the crystals does not exceed 2 mm. A charge distribution of about 6000 nuclei of galactic cosmic rays with charges greater than 55 has already been examined. The ratio of the abundance of nuclei with $Z \geqslant 88$ to that with $74 \leqslant Z \leqslant 87$ equals 0.045 ± 0.015 (Marjalahti) and 0.025 ± 0.020 (Eagle Station). These values are slightly larger than in the UHCRE (Ultra Heavy Cosmic Ray Experiment) (0.0147 ± 0.0032) [87], but are well consistent with the data of the TREK (Time Reversal Experiment with Kaons), HEAO (High Energy Astrophysics Observatory), and Ariel experiments [88–90]. However, the charge distributions deduced in the OLIMPIYA project in the processing of detectors with observation times of 185–300 mln years include much heavier nuclei [91].

Three superlong tracks ($L_{\mathrm{etch}} > 700$ μm), whose etching rate was $V_{\mathrm{etch}} > 35$ μm h^{-1}, were found in the course of the OLIMPIYA project in early 2011. If it is taken into account that the experimentally established maximal rate of etching the tracks in olivine for uranium nuclei before their stop is $V_{\mathrm{etch,U}} = (26 \pm 1)$ μm h^{-1}, it becomes clear that the charges of these nuclei significantly exceed $Z = 92$. Because the function $Z(\mathrm{RR}, V_{\mathrm{etch}})$ (RR is the residual range) is unknown over this region of charges, to assess the charge of the transuranium element nuclei in the first approximation the function $Z(\mathrm{RR}, V_{\mathrm{etch}})$ was extrapolated to the nuclear charge range for which the experimental data of calibration measurements are available. To a first approximation, an estimate of the charge boundaries for three ultraheavy nuclei occurring in galactic cosmic rays was obtained within the interval $105 < Z < 130$. This result was presented at the 32nd International Cosmic Ray Conference held in Beijing in August 2011 [92]. The conducted regression analysis made it possible to adjust the estimate for the charge of one of the three nuclei: it is equal to 119^{+10}_{-6} with the probability of 95% (Fig. 6). Exactly such nuclei should compose stability islands; their detection in Nature confirms the validity of theoretical predictions and justifies the efforts went to their synthesis under terrestrial conditions.

Thus, the nuclear track method makes it possible to obtain priority results of extreme significance for understanding the physical picture of the world.

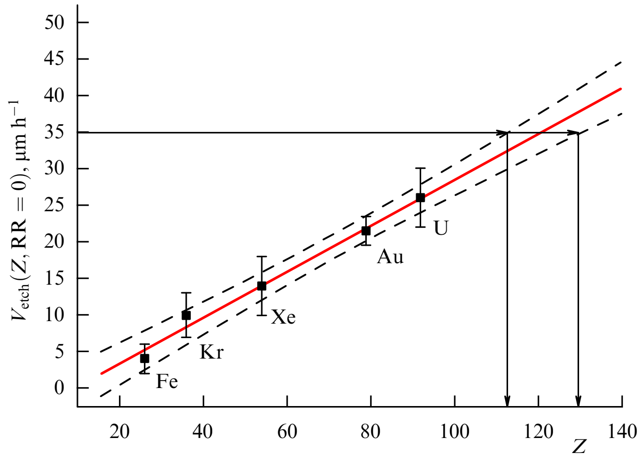

Figure 6. A result of regression analysis-based assessment of the charge of one of three ultraheavy nuclei: at the significance level of 95%, the charge of the nucleus that left the track whose etching rate near the stop point was 35 μm h^{-1} is $Z = 119(+10, -6)$. Solid straight line passes through the experimental points; dashed lines show the error corridor at the significance level of 95%. The vertical lines single out the possible interval of the charge at the significance level of 95% at the etching rate near the stop point.

In addition, as was mentioned above, this technique is successfully utilized in many applied studies. First and foremost are those on muon radiography. The Nobel Laureate Luis Alvarez proposed well back in the last century 'raying' Egyptian pyramids by fluxes of muons — particles possessing a high energy and penetrability, with a mass 200 times greater than that of the electron, which make up about 70% of secondary cosmic radiation particles reaching Earth. The density of the muon flux depends on the amount of matter on its way, and if there are hollow spaces on the way, as in the pyramids, then more particles will come from this direction. Using a bubble chamber, Alvarez rayed by the method of muon radiography about 10% of the volume of two Egyptian pyramids. The limited portion of volume he examined was due to the complexity of processing the bubble chamber data. Automation of measurements in nuclear track emulsion and its exceptionally high spatial resolution determined a sharp increase in the amount of work on muon radiography in the world using the emulsion technique. Muon radiography is actively used at present in Japan and Italy for nondestructive testing of various industrial sites (e.g., the state of nuclear reactors, blast furnaces of steel mills, and supports of bridge conduits) and to study the internal structure of volcanos. The structures of the Asama and Unzen volcanos in Japan, and Stromboli and Vesuvius in Italy are being investigated. Apparently, the only acceptable way for Japanese physicists to ray the severely damaged Fukushima reactor is to use emulsion stacks and muon radiography. Indeed, under conditions of enhanced radiation background, the impossibility of providing a proper power supply and the restricted space, the best way to reconstruct the reactor internal structure with the highest spatial accuracy is to use emulsion stacks.

The University of Bern is carrying out a study of a mineral deposit in Canada by means of muon radiography and the track technique. At a density ratio of 1 to 3, the efficiency of applying namely this technique was demonstrated.

At present, work is underway to advance the prospects of using PAVICOM and the accumulated experience of automated recognition of images to study neutrinoless double beta decay [93], to investigate the internal structure of industrial sites by muon radiography methods, to extend the potential of the PAVICOM facility for the recognition of objects on images in various innovations, e.g., in the automation of medical measurements of blood parameters.

Thus, it is evident that the nuclear track technique opens possibilities to get answers to many topical questions of modern physics, as well as to derive real practical benefit by virtue of modernizing the approaches to the solution of a broad range of important applied problems.

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High-temperature superconductors in high and ultrahigh magnetic fields

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1. Introduction

High-temperature (or high-T_c) superconductors (T_c being the superconducting transition temperature) compose a family of materials with a generic structural peculiarity which consists in the presence of relatively well-separated copper–oxygen (Cu–O) planes. They are also termed as cuprates. Some compositions in this family exhibit the highest T_c among all known superconductors. The current record is held at $T_c = 135$ K ($T_c = 165$ K if the sample is kept under pressure). High-temperature superconductivity results from doping a Mott insulator with charge carriers and exists in a narrow carrier concentration range. Figure 1 demonstrates a

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