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Current status and prospects of nuclear physics research based on tracking techniques

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Abstract. Results of nuclear physics research made using track detectors are briefly reviewed. Advantages and prospects of the track detection technique in particle physics, neutrino physics, astrophysics and other fields are discussed on the example of the results of the search for direct origination of tau neutrino in a muon neutrino beam within the framework of the international experiment OPERA (Oscillation Project with Emulsion-tRacking Apparatus) and works on search for superheavy nuclei in nature on base of their tracks in meteoritic olivine crystals. The spectra of superheavy elements in galactic cosmic rays are presented. Prospects of using the track detection technique in fundamental and applied research are reported.

1. Introduction

Track detectors have been widely used in particle physics over many decades. The track detector registration of elementary particles is accompanied by the emergence of observable traces (tracks) corresponding to the elementary particle trajectories. This principle applies in bubble and spark chambers, nuclear emulsions, silver chloride crystals and etchable solid state track detectors [1]. The popularity and long life of the track technique are not accidental and owe to a range of detectors' merits: the unique spatial resolution, obviousness of the reconstructed spatial pattern of the particles' interaction, relative design simplicity and low cost, capability of information accumulation over long periods of time, and others. Majority of nuclear decays and reactions, as well as new elementary particles (positron, muon, charged pions, strange and charmed particles), were discovered owing to the track detectors.

Thus, the track detectors play an outstanding role in the development of nuclear physics due to high visualization and possibility of obtaining an exhaustive spatial pattern of the processes studied. This exclusivity is confirmed by quite a number of Nobel prizes – from H. Becquerel (1903) up to G. Charpak (1992).

Development of the method was conditioned by the emergence of automated measuring systems that radically changed the approach to data processing of track detectors. Previously the particle tracks had to be discovered visually and measured manually. This procedure required large expenditures of labor and time, and probability of the occurrence of hardly detectable errors was rather high. The



advent of charge-coupled devices (CCDs) and the use of CCD cameras for recording and digitizing optical images led to the development of microprocessor-oriented systems for the automatic processing and recognition of the particle tracks in detectors.

The two most well-established approaches to the automation of measurements proposed by Japanese and European researchers are currently used. The first one provides a high speed of data processing, while the second one is more flexible and adaptable to new challenges. In the world there are over 50 automated systems for track detector data processing, and the first Russian measuring complex of the world level has been created at Lebedev Physical Institute, Russian Academy of Sciences (LPI).

The completely automated measuring complex PAVICOM was created in 2000 in the LPI Fundamental Particle Laboratory. Its main difference and advantage in comparison with the other ones is that it allows to process almost all known types of track detectors. The complex consists of three automated microscopes made by analogy with to the European scanning system and equipped with the appropriate software. The three microscopes differ mostly in the ranges of the scanning table movement. The technical capabilities of the equipment and strategy of its most effective use has allowed to create a mode of multi-purpose use of PAVICOM for at least 10 institutions, including foreign ones. Almost all the known types of solid-state track detectors, such as nuclear emulsion, olivine crystals, x-ray films, plastic detectors CR-39 and others, are processed. This article discusses the current status of data-handling of the nuclear track detectors, particularly, on the example of the studies performed on PAVICOM.

2. PAVICOM main research lines

The most significant experiments processed on PAVICOM are presented below (the details are given in [9]).

2.1. Experiment EMU-15

The experiment EMU-15 was aimed at the study of the peculiarities in the scattering of the secondary charged particles in nucleus-nucleus interactions with energy of 158 GeV/nucleon. The presence of collective effects in these interactions could indicate the possible existence of quark-gluon plasma.

The results of EMU-15 data processing showed circular structures in the secondary charged particle escape. For recognition of these structures, analysis and localization of the peculiarities of the charged secondary particle angular distributions, for the first time in high energy physics the wavelet analysis was used, since becoming a practice of processing of experimental nuclear physics data [10].

2.2. Experiment RUNJOB

The data of Russian-Japanese balloon experiment RUNJOB for investigation of the nuclear composition and energy spectrum of primary cosmic radiation [11] was processed on PAVICOM. Results on proton, helium and CNO group spectra have been obtained. Experiment RUNJOB is considered one of the most successful balloon experiments and is widely cited in world scientific literature.

2.3. The BECQUEREL Project

The BECQUEREL Project (Beryllium (Boron) Clustering Quest in Relativistic Multifragmentation) carried out at the Joint Institute for Nuclear Research (JINR) Nuclotron was devoted to systematic exploration of clustering features of light stable and radioactive nuclei. Nuclear track emulsion was used to explore the fragmentation of the relativistic nuclei down to the most peripheral interactions - nuclear "white" stars. This technique provided a record spatial resolution and allowed to observe the 3D-images of peripheral collisions. A principal experimental task consisted in provision of a complete spectroscopy of final fragments - observation of dissociation events, determination of various channel probabilities, and fragment identification and velocity measurement. Observations of the

fragmentation of light relativistic nuclei opened up new opportunities to explore highly excited nuclear states near multiple particle decay thresholds [12].

2.4. The Energy-Transmutation Project

The PAVICOM facility was used to analyze data of Energy-Transmutation experiment, performed in Joint Institute of Nuclear Research. The aim of this experiment was an investigation of possibility of an electro-nuclear method to get energy. The assemble of a radiator (Au, Pb and other nuclei) and plastic (lavsan) was used as a detector. The plastic part of the detector registered the fragments of radiator, activated with neutrons after uranium decay in the main part of a device. At large neutron flux many fragment traces cross each other and the direct count of the cluster number in the image of the plastic does not coincide with the number of tracks. The special method based on fuzzy logic was worked out to estimate the neutron flux even at large load [13, 14, 15].

2.5. The investigation spectra of inner conversion electrons of lanthanide nuclei (ITEP-JINR project)

PAVICOM was used to investigate spectra of inner conversion electrons of lanthanide nuclei. The emulsion layer covered on to glass base of 40 cm length was used as a detector. It was necessary to create special methods of the images cleaning because there was large noise on the emulsion layer surface. The special automatic method of vertical summing of digitized images was proposed. As a result of the investigation several new lines absent in the World atlas of lines were explored [16, 17].

2.6. Study of Halo-Nucleus Structure using Neutron Transfer Reaction - experiment of Institute for Nuclear Research of the RAS

Investigations of neutron rich nuclei ${}^6\text{He}$ were performed with the use of emulsion chamber including several thick (600 mcm) nuclear emulsion. The aim of this experiment was the search for configuration of two additional neutrons which could occur near each other (dineutron) or in opposite points relative to alpha particle (cigar-like configuration). The event reconstruction in the tree-dimensional space and the total kinematic analysis were carried out. According to obtained results, both configurations have almost equal probabilities to occur in ${}^6\text{He}$ nucleus [18, 19].

2.7. The automated charge measurement in nuclear photoemulsions

In PAVICOM group the methodology of automatic estimation of relativistic nuclei charges in nuclear emulsion was created. The derived special calibration curves used the track characteristics (number of delta electrons, track area, etc) to perform the assessment. The use of multiple characteristics allowed to improve the estimation accuracy. The accuracy of measurements based on several parameters is about two percent for three millimeter scanning length [20, 21].

2.8. Work with polymer detector CR-39

In the last decade serious efforts were focused on evaluation of the possibility to use nuclei beams in medicine. The reason for this interest lies in the fact that in the beams of nuclei, in contrast to beams of protons, a large portion of the energy is released in a certain definite area. As a result, a healthful tissue is less damaged. Thus, the treatment occurs in more favourable conditions and requires a smaller dose of irradiation. Currently, the Institute of Experimental and Theoretical Physics (ITEP, Moscow) carries out works on simulation of the carbon beam settings and on testing various substances for human phantom imitation. The irradiation dose in these studies is determined by the plastic detector (CR39) subsequently processed on PAVICOM. A special program for PAVICOM was designed and successfully tested in the analysis of calibration irradiation of CR39 films. This program can also be used in the future by an operator-medic, non-professional programmer, to process the optical microscope images of particle tracks in the etched plastic and can later be used as a part of a medical complex [22].

Currently, successful researches based on track methods and automated data processing on PAVICOM are going on, among them the following directions can be emphasized.

3. The OPERA experiment

Neutrino oscillations has been mostly studied via the disappearance channel by many experiments with atmospheric and accelerator neutrinos. The OPERA experiment is designed to observe ν_μ to ν_τ oscillations in appearance mode. This is a very important step forward to establish conclusively the neutrino oscillation framework. The OPERA experiment identifies tau neutrino charged current interactions by observing tau lepton decays in the nuclear emulsion detector on event by event basis.

The main part of OPERA detector consists of almost 150000 unit cells, called emulsion bricks, arranged in walls, a total mass of nuclear emulsion was about 1.25 kton. The Emulsion Cloud Chamber technique uses lead as neutrino target and emulsion films as high precision trackers, capable of observing the tau-decay with a space granularity better than 1 μm . The electronic detectors provide the time stamp of neutrino interactions, identifying the brick where the interaction took place and measuring the muon charge and momentum. In five years of run, from 2008 to 2012, the CNGS beam has provided a neutrino flux equivalent to 18×10^{19} protons on target and the OPERA experiment has collected more than 19500 neutrino interactions. During the period of data accumulation and an analysis, more than 200 OPERA bricks was scanned with Russian scanning stations (LPI, JINR and SINP MSU), reconstructed with EDAEventDisplay, decay searched and written from local Russian data bases to central data base OPERA experiment. Moreover, the PAVICOM team in collaboration with the Neapolitan group of the Italian National Institute of Nuclear Physics developed an algorithm of continuous saw tooth motion [23]. The development of the clustering algorithm (separation of regions of darkening of a given level) using the GPU computational power became a new direction in constructing the high-speed image processing system. The algorithm of continuous motion increases the effective scanning speed more than twice even without equipment replacement. Taking into account the progress achieved in the use of the GPU for data processing, it is also planned to develop a hybrid CPU–GPU tracking algorithm, which will allow real-time reconstruction of microtracks during scanning, using a fast motion algorithm; at the PAVICOM, the development of the software for the next-generation scanning stations is in progress [24].

The analysis chain of neutrino interactions in the OPERA target has been fully simulated and the efficiencies for all the tau- decay channels obtained. A detailed analysis of all the background sources has been performed. In particular, the background from charmed hadron production and decay has been studied (see table 1).

Table 1. Expected signal and background events for the analysed data sample.

Channel	Expected background				Expected signal	Observed
	Charm	Had.reiterations	Large μ scat.	Total		
$\tau \rightarrow 1h$	0.017 ± 0.003	0.022 ± 0.006		0.04 ± 0.01	0.52 ± 0.10	3
$\tau \rightarrow 3h$	0.17 ± 0.03	0.003 ± 0.001		0.17 ± 0.03	0.73 ± 0.14	1
$\tau \rightarrow \mu$	0.004 ± 0.001		0.0002 ± 0.0001	0.004 ± 0.001	0.61 ± 0.12	1
$\tau \rightarrow e$	0.03 ± 0.01			0.03 ± 0.01	0.78 ± 0.16	0
Total	0.22 ± 0.04	0.02 ± 0.01	0.0002 ± 0.0001	0.25 ± 0.05	2.64 ± 0.05	5

They have been fully analysed and the results of the topological reconstruction as well as the kinematical analysis have been reported. The statistical significance of the observation of five candidates has been evaluated with a simple counting method based on the background yield in the different channels. The result gives a significance 5.1σ [25].

4. The OLYMPIA Project

The issue of the existence of super heavy nuclei is of utmost importance for understanding the properties of nuclear matter. First and foremost, of interest is to verify the prediction of a significantly

increasing stability of nuclei in the vicinity of the magic numbers $Z = 114$ and $N = 184$ (N , the number of neutrons), which could lead to the existence of “Stability Islands” of the relatively stable super heavy nuclei [26]. At the Joint Institute of Nuclear Research (JINR), work on the search for tracks of superheavy cosmic ray nuclei in olivine crystals from meteorites was undertaken under G N Flerov's and Yu Ts Oganessian supervision [27].

Track analysis of Galaxy cosmic ray (GCR) nuclear component charge spectrum has been carried out by LPI Fundamental Particle Laboratory and GEOKHI Cosmology Laboratory since 2005 in the frame of OLIMPIA project [28, 29]. Olivine crystals extracted from iron-nickel meteorites were used as GCR particle track detector and processed on PAVICOM. Method of the nucleus charge identification is based on empirical dependence of the longitudinal track etching velocity from the track residual path and calculated (and checked in accelerator calibration exposure) nuclei charge-track length dependence [30].

Figure 1 shows the charge distribution of nucleus tracks obtained in the implementation of the project OLIMPIYA, as compared with the abundance of galactic nuclei obtained in UHCRE, HEAO and Ariel experiments [31-34]. The charge distribution was obtained for more than 11500 galactic nuclei.

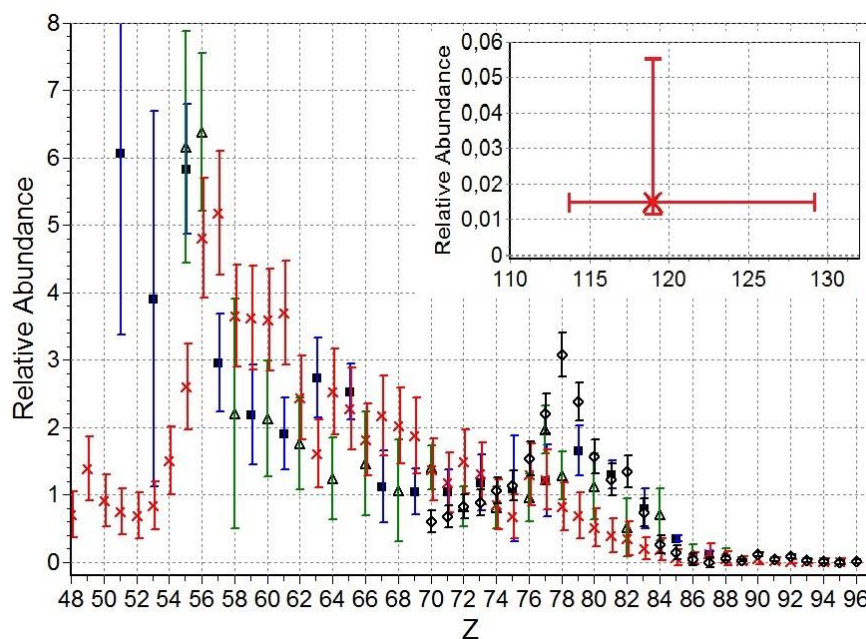


Figure 1. Relative abundance (the data were normalized by the content of iron nuclei $A(^{26}\text{Fe}) = 106$) of GCR heavy nuclei registered in the OLIMPIYA experiment (crosses, with statistical errors) as compared with the results of other experiments: ARIEL-6 (triangles), HEAO-3 (squares), and UHCRE (diamonds). The inset shows three transuranic nuclei registered in the experiment. The abundance evaluation of these 3 nuclei is $A=0.015+0.042-0.003$ with level of confidence 95% on base of rare event processing method Gehrels (1986).

As the most distinguished result, the tracks of three transuranic nuclei of galactic cosmic rays have been found and identified in meteoritic olivine crystals studied. In the first approximation, the charge of these nuclei is estimated as $Z = 119^{+10}_{-6}$. Detection of such nuclei in nature confirms the adequacy of theoretical predictions and justifies efforts on synthesis of super heavy elements under terrestrial conditions.

5. Proposal for new experiment at the CERN to search for Hidden Particles

The SHiP Experiment is a new general-purpose fixed target facility at the SPS CERN to search for hidden particles as predicted by a very large number of recently elaborated models of Hidden Sectors which are capable of accommodating dark matter, neutrino oscillations, and the origin of the full baryon asymmetry in the Universe [35]. Specifically, the experiment is aimed at searching for very weakly interacting long lived particles including Heavy Neutral Leptons - right-handed partners of the active neutrinos; light super symmetric particles - sgoldstinos, etc; scalar, axion and vector portals to the hidden sector. The high intensity of the SPS accelerator at CERN and in particular the large production of charm mesons with the 400 GeV beam allow accessing a wide variety of light long-lived exotic particles of such models and of SUSY. Moreover, the facility is ideally suited to study the interactions of tau neutrinos. Part of future SHiP detector named neutrino detector will be completely repeated OPERA detector design. It will be use emulsion bricks as main detector for neutrino registration and tau lepton investigation. SHiP is currently a collaboration of 46 institutes from 16 countries.

6. Nuclear emulsion application for muon radiography

The muon radiography is an innovative image technique that can be applied to inspect the inner structure of large size natural and industrial objects. Based on the same principle as the standard medical radiography except for the usage of cosmic ray muons instead of X-ray sources, the method provides a complementary approach to the geophysical research, geological exploration, mining geophysics, alternative geophysical methods of seismic process analysis, the study of volcanoes (information about the internal cavity of the crater and lava movements). Muon radiography method has been already successfully used for nondestructive testing of large industrial facilities, such as bridges, dams, blast furnaces, etc., for radiation monitoring of nuclear power facilities and for large archaeological object radiography. The first successful archaeological research of Khafre pyramid in Egypt was carried out in the 70s of the 20th century by a group of scientists under the leadership of Nobel laureate Luis Alvarez and remain topical today [36, 37].

Russian scientific groups, Lebedev Physical Institute, Russian Academy of Sciences (LPI RAS) and the Skobeltsyn Institute of Nuclear Physics, Moscow State University (SINP MSU) in collaboration with the INFN (Naples scanning laboratory, Italy), about two years engage of the development and testing of the muon radiography method based on emulsion track detectors. Emulsion track detectors, in addition to small size and design simplicity, have today's best spatial resolution (<1 micron), large information capacity. They are easy to transport and easy to operate in difficult conditions, for example, in the mountains. In the period of data accumulation these detectors require no power supply and electronic reading systems, as well as direct human intervention. Progress in the development of automated systems for scanning and processing of nuclear emulsions, allowed to implement a number of ambitious successful nuclear physics experiments with usage of tons of nuclear emulsion, and to begin large-scale applied research using the muon radiography method. In recent years production of nuclear emulsions with characteristics required for relativistic particle registration was organized at the Slavich JSC in Pereyaslavl-Zalessky, Yaroslavl Region, in particular, - to put the first test experiments to master the method [38, 39, 40]

Our scientific group made few test exposures of nuclear detectors, last of them was carried out at a depth of 30 m in an underground mine, located on the territory of the Geophysical Survey RAS, Obninsk [41]. During this experiment it was registered a 50 times difference of flow of the atmospheric muons on the earth's surface and at depth, for what on both observation levels two detector sets were installed. In addition, the experiment objectives included the estimation of opportunities of the vertical cavity (elevator shaft) "discovery" in the soil by the muon radiography detector with nuclear emulsions located at a depth of 30 m. To reveal the density variations from the above to ground layers the comparison of the observed and the expected muon angular distribution, the muon spectrum parametrization [42] from was used. To obtain possibly realistic spectrum on the exposure depth the muons generated on the surface were traced in 30 m depth layer of standard rock

using the GEANT4 package. After track reconstruction and efficiency correction procedure, clearly seen the elevator shaft in the data [43].

The first test experiments carried out by the authors demonstrated the potential of the muon radiography method, distributions of the muon flux measured show good agreement with computational predictions for inhomogeneities in the studied structure. Advanced innovation in electronics in the field of image processing [44, 45] open large perspectives of implementation of the method in various fields of research, such as nondestructive testing of large industrial facilities, monitoring of nuclear reactors, geological exploration, alternative method of seismic process analysis, volcanology.

7. Conclusions

All the above demonstrates the track technique opportunities to provide answers to many topical questions of modern physics, as well as to derive real practical benefit in modernizing the approaches to the solution of a broad range of important applied problems.

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