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INSTRUMENTS AND METHODS OF INVESTIGATION

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Charge spectrum of galactic cosmic ray nuclei as measured in meteorite olivines

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Contents

Abstract. **This paper presents experimental results on galactic cosmic ray nuclei in olivine crystals from the Marjalahti and Eagle Station pallasites. The charge spectrum of the nuclei is measured to be in good agreement with the experimental data from the HEAO-3 and ARIEL-6 satellite missions.**

1. Introduction

The detection of heavy and superheavy nuclei of cosmic rays, and in particular the search for transfermium nuclei with $Z > 100$, is among the most significant and topical tasks of modern nuclear physics and astrophysics [1–5]. The earliest experiments in the search for such nuclei were carried out about 40 years ago with the use of thick nuclear emulsions exposed on balloons in the upper layers of the atmosphere [6]. Multilayer track detectors made of polymer materials in combination with Cherenkov counters were also used [7, 8]. The main drawback of these experiments was the short detector exposure time, which allowed detecting only single events under the low flux of the particles under study. The interest in the problem of the existence of superheavy nuclei has been considerably increasing over the last several years, to a large measure due to recent new accelerator results on the synthesis of transuranium elements. New satellite-borne experiments aimed at studying the abundance of superheavy nuclei in the Galaxy are under preparation [4, 5]. In many of them, the use of solid-state track detectors is planned.

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 supervision [9–12]. This technique relies on the capacity of silicate crystals (olivines, pyroxenes) to detect and retain the tracks of nuclei with $Z > 26$ for a long time ($> 10^8$ years). According to estimates, 100–1000 tracks of $Z > 90$ nuclei may form in 10^8 years in 1 cm^{-3} of these crystals located at the depth less than 5 cm from the preatmospheric meteorite surface, while small crystals from surface meteorite segments (at the depth less than 1 cm) may accommodate up to 10^4 tracks. Therefore, the factor of long-term meteorite exposure in space underlies the substantial advantage of this technique in comparison with the use of satellite- or balloon-borne instrumentation. Determining the track parameters and their density dependence on the depth of particle penetration into a meteorite permits studying the fluxes and spectra of the particles in the heavy component of galactic cosmic radiation. Among the $Z > 60$ nuclei track samples revealed by annealing and etching in the early work at the JINR, about 150 were ascribed to the tracks of uranium group nuclei (190–220 μm long annealed tracks). Also discovered were 5 tracks approximately 360 μm in length, which are conceivably the tracks of nuclei with $Z > 110$ [9–12]. However, the examination of large crystal volumes, typically at high magnification, was an arduous technical problem. The particle tracks had to be discovered visually and measured manually. This was time and labor consuming, and the 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 of particle tracks in detectors. The recognition of particle tracks and the

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recovery of their spatial position in these systems are performed by computers using purpose-oriented codes. All this has enabled replacing the exhausting visual labor of microscope operators by the fully automated procedure of track recognition. In the measurements in this automatic mode, the digitized images of the in-emulsion tracks of charged particles and nuclei acquired with CCD cameras are input into computers whose software is capable of seeking, recognizing, and studying the tracks. The new technique not only speeds up the measurements but also allows processing large data arrays and substantially improving the statistics of events for a broad spectrum of experiments, which was heretofore unrealistic. Currently, investigations of nuclear tracks in olivine crystals from meteorites are being jointly pursued by groups from the Lebedev Physical Institute, RAS (FIAN) and the Vernadsky Institute of Geochemistry and Analytical Chemistry, RAS (GEOKhI RAN) with the use of the highly efficient modern PAVIKOM facility (a fully automated measuring facility) made at FIAN [13].

2. Method of studying the characteristics of the tracks of galactic cosmic rays in meteoritic olivines and the resultant data

In the course of executing the OLIMPIYa Project (Olivines from meteorites: the quest for heavy and superheavy nuclei) [14], the groups of FIAN and GEOKhI staff members developed a new technique for identifying and measuring the parameters of the stopping tracks of nuclei in the bulk of olivine crystals [15]. The main difference between the new measurement technique and the previously used one [9–12] is that (i) the chemical etching of the tracks is performed without prior thermal annealing of the crystals; (ii) the measurement of dynamic and geometric parameters of the tracks (in the course of their sequential, step-by-step etching) is performed with high precision at the PAVIKOM facility; (iii) the search for tracks and their measurements are made throughout the crystal volume (the average crystal size is 2–3 mm), which entails a manifold improvement in the statistics of the detected stopping tracks of cosmic ray nuclei.

The energy losses of fast ions passing through a medium are caused primarily by the ionization of target atoms [16], and the ionization loss of the particles, in turn, affects the geometrical dimensions of the tracks being etched. By its crystallographic structure, the olivine mineral $(Mg_{0.88}Fe_{0.12})_2SiO_4$ belongs to silicates with an isolated, isle (unlike chain, layer, and framework silicates) arrangement of the silicon–oxygen tetrahedrons SiO_4, which are connected via Mg or Fe cations [17]. The individual silicon–oxygen radicals are isolated from each other. It can be expected that owing to this structure, the efficiency of chemical etching of the substance from the region of crystal lattice disturbance occurring along the heavy nucleus stopping track should not depend heavily on the orientation of the track relative to the symmetry axes of the olivine lattice. Furthermore, it is significant that the dimensions of the domain of radiation-induced lattice disordering along stopping paths of the nuclei exceed the elementary crystal cell size by a factor of several dozen (60–100 Å versus 2–3 Å). To investigate the orientation effect of olivine crystallographic axes on the parameters of the tracks produced, olivine crystals from the Marjalahti pallasite irradiated by accelerated ^{132}Xe nuclei were analyzed via X-ray diffraction [18, 19]. For the first time it was determined that the track lengths and the rate of track etching in natural olivine crystals from pallasites are independent of the track orientation relative to olivine crystallographic axes. The efficiency of the etching of these tracks was shown to remain invariable for olivine crystals with a polycrystalline, highly ordered regular texture, as well as for monocrystals.

In this investigation, the program package SRIM (Stopping and Range of Ions in Matter) and the program complex GEANT4 (GEometry ANd Tracking) were used for simulating the passage of fast particles through matter. The combined use of the programs permits comparing the results and thereby increases their reliability.

SRIM comprises a set of codes for calculating different ion–matter interaction parameters. The physical models for the calculation of energy loss used in the SRIM code are comprehensively described in monograph [20]. Also given in Ref. [20] are the codes of the first SRIM versions written in FORTRAN.

To calculate the ion energy loss in matter, the GEANT4 package allows the inclusion of all possible mechanisms; in particular, the stopping power is calculated by the Bethe–Bloch formulas and data borrowed from the ICRU (International Commission on Radiological Units and Measurements) tables are interpolated.

For simulations, the Hadr01 package was used, which was developed with the participation of the members of our group as a part of GEANT4, and its use was an official example of its application. The package permits simulating the passage of proton and ion beams through matter. The output of simulation is given by different parameter distributions (the energy deposition along the track, the energy and charge of the secondary particles, etc.) amenable to further analysis. Test calculations have been made of the passage of ^{131}Xe, ^{207}Pb, and ^{238}U nuclei through a variety of materials in a wide energy range. To within statistical errors, the results of simulations are in good agreement with the data tabulated in [21], which represent the stopping power and the range of ions with charges $2 \leqslant Z \leqslant 103$ in the energy range between 2.5 and 500 MeV per nucleon for different materials.

Therefore, to determine the charge of the VVH (very very heavy) group nuclei ($Z > 50$) of cosmic rays, two main parameters of the tracks chemically etched in olivine crystals from the Marjalahti and Eagle Station pallasites were used: the geometric parameter given by the measured length L, and the dynamic one, the etching rate $V_{\mathrm{tr}} = L/t$, where t is the etching time of a track at a given stage. The technique of charge determination in the OLIMPIYa Project is described in detail in Ref. [15]. A relation between three parameters characterizing the etched portion of the track was constructed: the charge Z, the track length L, and the average etching rate V_{tr} at a given etching segment. This relation was used to estimate the lower charge bound in our subsequent work; in Fig. 1, it is represented in the form of a Z–L–V surface.

The error in charge determination arising from coordinate measurements with the help of a microscope equipped with a high-precision mechanism [13] does not exceed 2%. The error mainly occurs because the overall etched track length exceeds the crystal dimensions. That is why the accuracy of charge measurement is determined primarily by the accuracy of etching rate measurement. The results of charge determination obtained at this stage of research rely on the data of L and V_{tr} track measurements in 48-hour etching intervals. The 48-hour etching interval was selected to

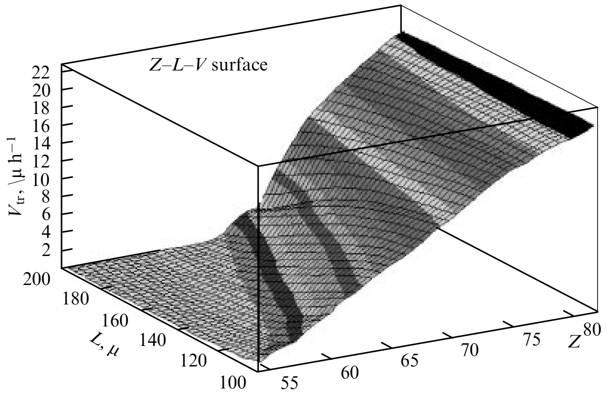

Figure 1. The three-dimensional surface obtained by generalizing the dependence of the average track portion etching rate V_{tr} on the etched track length L for several heavy nuclei with charges $55 < Z < 82$.

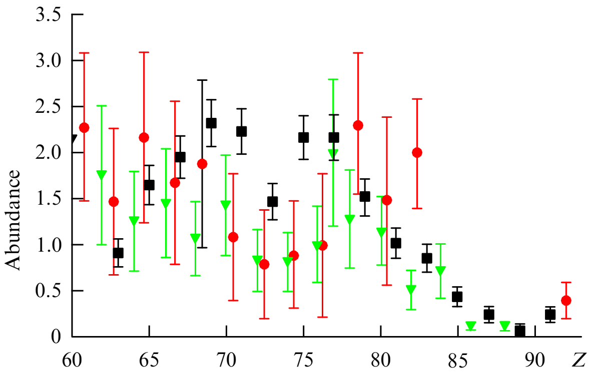

Figure 2. The charge distribution of nuclei obtained in our research (squares) in comparison with the experimental data acquired by the HEAO-3 (triangles) [23] and Ariel-6 (circles) [22] spacecraft.

absolutely guarantee the etching of the entire track length in crystals. For such a long etching time, the etching rate may be lower than the highest one, which determines the nuclear charge. A test evaluation of Z based on L and V_{tr}, which were measured in shorter (12 and 24 h) time intervals, showed that the greatest systematic error ΔZ on the underrating side is within 4–5 units. That is why at this stage, prior to the pursuance of accurate calibration experiments, our approach permits determining only the lower bound Z' of the estimated nuclear charge Z, i.e., $Z' \leqslant Z$; the accuracy of charge determination is Z^{+5}_{-1}.

Our data acquired in the processing of nuclear tracks in olivine crystals are consistent with the data of other authors. The characteristics of over 6500 tracks have been measured to date. Figure 2 shows the charge distribution (normalized to the abundance of Fe nuclei) of tracks for nuclei with $Z > 60$ obtained in our work (squares) with the systematic error $\Delta Z = 5$. The circles and triangles represent the data in Refs [22, 23].

3. Conclusions and projected work to continue this research

To determine nuclear charges from the measured track characteristics, a program package has been elaborated that simultaneously takes into account the length and etch rate of each track, which are measured with a high accuracy. In particular, the characteristics of 2761 superlong tracks have been determined, for which the lower charge bound is estimated as $Z > 50$. Olivine crystals with the total volume about 0.22 cm^3 have been processed up to now. The volume projected for processing is about 5 cm^3 of the olivines of two meteorites, Marjalahti and Eagle Station.

Continuation of this research requires the pursuance of calibrating irradiation of olivines on a heavy-ion ($Z = 50$, 82, 92, and so on) accelerator in several energy ranges (50, 260, and 400 MeV per nucleon) with the aim of verifying the simulation data in direct experiments and using additional track parameters (the diameter) in charge evaluation. The program of irradiation sessions has been tentatively agreed on with the governing body of the Darmstadt heavy-ion accelerator; olivine crystals were already calibrated with Au nuclei with the energy 11.4 MeV per nucleon in 2009 (Fig. 3).

The authors of this paper were the first to propose the idea of including the effect of heavy nucleus fragmentation. Before they reach olivine crystals, the charged particles traverse some distance (4–12 cm) through iron, of which meteorites primarily consist. In the process, the charge composition of primary cosmic rays changes owing to the interaction of the incident nuclei with target nuclei and fragmentation. The energy spectrum of the outgoing particles is simultaneously changed as a result of energy losses in the passage of heavy ions through the layer of the material. The elaborated program package for GEANT4-based simulations currently permits obtaining the charge (Fig. 4) and energy distributions for the heavy ions produced throughout the target depth

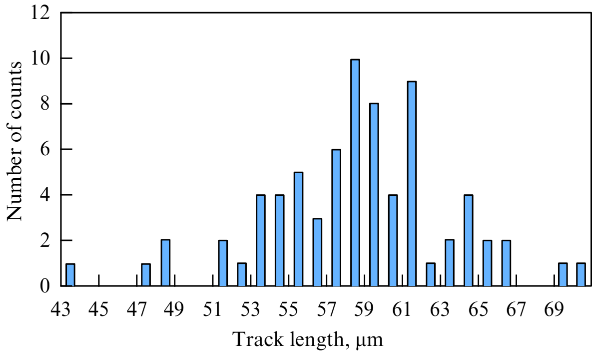

Figure 3. Track length distribution for Au nuclei with the energy 11.4 MeV per nucleon.

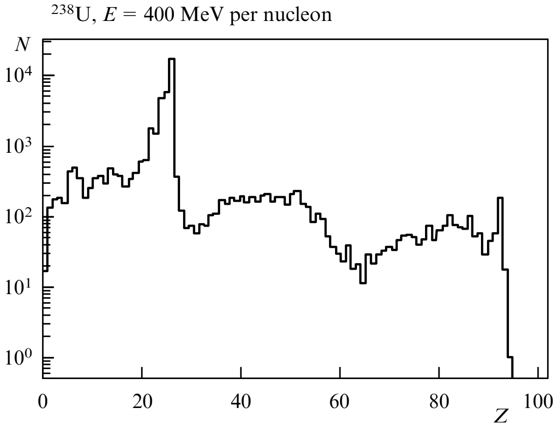

Figure 4. A model charge distribution for heavy ions produced in an iron target.

(material layer), as well as for those leaking from the target. The first data obtained suggest that fragmentation may have a significant effect on the spectrum of cosmic rays.

4. Summary

The findings made in the course of realization of the OLIMPIYa Project allow drawing the conclusion that studying the tracks of galactic cosmic rays in olivine crystals from meteorites opens up new avenues in the investigation of the fluxes and spectra of cosmic rays in the area of heavy and superheavy nuclei, which is very important in nuclear physics, elementary particle physics, and astrophysics.

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