Search for superheavy elements in galactic cosmic rays

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Abstract

An original method of studying chemically etched tracks of heavy nuclei in olivine from pallasite meteorites was used to obtain a charge distribution of approximately 6000 nuclei with charge more than 55 in galactic cosmic rays. Three superheavy nuclei were detected whose charge is within the range of $105 < Z < 130$. Regression analysis enabled amending the charge of one of those three nuclei to 119^{+10}_{-6} with the probability of 95%. Exactly such nuclei should form islands of stability; their occurrence in nature supports the validity of theoretical predictions and justifies efforts for their synthesis under the Earth conditions.

1 Introduction

Registration of heavy and superheavy nuclei in cosmic rays and search for trans-Fermi nuclei with charge $Z > 100$ in them is among the most significant and topical tasks of modern nuclear physics and astrophysics [1].

The issue of the existence of superheavy nuclei is of prime importance for understanding the properties of nuclear matter. First and foremost, of interest is to verify predictions [2] of a tangible increase in the stability of nuclei near magic numbers Z = 114 and N = 184 (N, the number of neutrons), which could lead to the existence of islands of stability of superheavy nuclei in this range.

Confirmations of this prediction were obtained in experiments led by G. N. Flerov and Yu. Ts. Oganessian at the accelerator of the Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research [3], where the nuclei of elements from 105 to 118 were discovered. The lifetimes of some of those nuclei are several seconds and even minutes, which is tens of thousand times greater than the lifetimes of nuclei with smaller charges. However, according to theoretical estimates, nuclei in the zone of islands of stability should have lifetimes many orders of magnitude greater.

Thus, the results of experiments at the JINR accelerator inspire one to continue the search for and registration of trans-Fermi nuclei in nature. Such nuclei can be detected, primarily, by way of investigating cosmic rays.

Registration of superheavy elements in cosmic rays using artificial detectors is made difficult by the negligibility of their fluxes near the Earth. This difficulty can be overcome in two ways: either significantly (several orders of magnitude) increasing the area of detectors, which is rather difficult to do under the space conditions, or increasing the detector exposure times in outer space. Experiments at balloons, Earth satellites and space stations are continued for several years, which, however, proves insufficient for efficient registration of superheavy nuclei. At the same time, there are solid state detectors in nature that have been irradiated for protracted periods of time with particles of cosmic origin crystals of silicate minerals in meteorites.

2 Search for nuclei of galactic cosmic-ray superheavy elements in olivine crystals from meteorites

The chemical composition of galactic cosmic rays (GCR) started to be studied using meteorites in mid-1960s. GCR heavy nuclei of the iron group ($Z \approx 26$) were first found in meteorites in 1964 [5]. Nuclei of heavier elements were registered in 1967 [6]. Since 1970s, works on the search for tracks of GCR superheavy nuclei in olivine crystals from meteorites were initiated at JINRs Laboratory of Nuclear Reactions under the guidance of G. N. Flerov [7].

Search for relic tracks formed by cosmic ray particles in crystals of silicate minerals in meteorites [8, 9] makes use of the ability of these crystals to register and preserve for prolonged times ($>$ 108 years) tracks of nuclei with $Z > 24$ [6]. The most suitable for track studies of GCR chemical composition are pallasite meteorites, about 60% of the volume of which is occupied by crystals of olivine.

3 OLIMPIYA experiment

In 2005, the authors started the OLIMPIYA experiment at the Lebedev Physical Institute of the Russian Academy of Sciences. To search for and measure the parameters of tracks of heavy and superheavy GCR nuclei in olivine crystals from meteorites, the project made use of the modern highly efficient measuring complex PAVICOM [10]. The complex is based on the use of CCD cameras to register and digitize images of heavy nuclear tracks in the microscope, and a proprietory software package for recognition of track images and reconstitution of track positions in space.

The radiation ages of investigated pallasites and, therefore, times of their exposure to the GCR flux are approx. 185 million years for Marjalahti and 300 million years for Eagle Station.

3.1 Methodological bases for track studies of olivine crystals from pallasites

Pallasite meteorites consist of an ironnickel matrix, in the bulk of which there are numerous inclusions of crystals of olivine, a slightly yellowish transparent mineral of up to 12 cm in size (Fig. 1). However, only specimens of no more than 23 mm in size are available for track studies, which is due to numerous cracks that emerged, probably, during shock impacts on the substance of the meteoroid in its formation and during the entire history of its existence.

Figure 1: A specimen of the Eagle Station meteorite used for studies in OLIMPIYA project.

The through channel in the area of damage caused in olivine crystals by heavy nuclei has a transverse size of (37) nm. Herewith, a significant factor is a huge (up to 200-fold) difference in the etch rate of the olivine substance along the trace of the nucleus as compared with the crystal region undamaged by radiation. Etching is done by means of a specially chosen chemical solution at certain temperature and pressure [8, 9].

As the result, a hollow channel whose length and width depend on the extent of crystal lattice damage is formed during the etching of the olivine crystal surface in sites of heavy nucleus passage. The extent of damage mainly depends on specific ionization losses of energy by the stopping nucleus.

Figure 2 presents the results of calculating specific energy losses by nuclei with charge $Z > 26$ for interaction with olivine stopping-medium electrons as a function of the residual path length, obtained using SRIM2006 program [11].

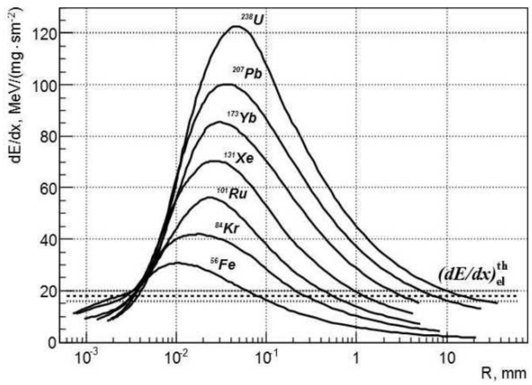

Figure 2: Ionization losses of the energy of nuclei in olivine from the Marjalahti pallasite vs their residual path lengths.

The peaks of ionization losses shown in Fig. 2 are called Bragg peaks. The horizontal lines mark the threshold value $(dE/dx)_{th} \approx 18MeV/(mg \cdot cm^2)$ and the interval $\Delta(dE/dx)_{th} = 18 \pm 2MeV/(mg \cdot cm^{-2})$. The diameter of the etched channel, corresponding to this interval $\Delta(dE/dx)_{th}$ of ionization losses, is significantly lower than the channel diameter in the region of the Bragg peak.

A more graphic representation of the size and geometry of chemically etched tracks in olivine is given in Fig. 3.

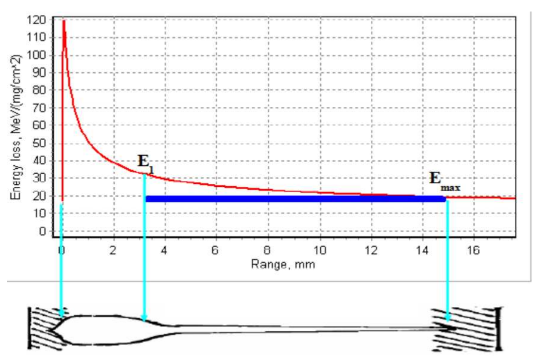

Figure 3: Formation of an etched part of track in olivine. Upper, specific ionization losses of nucleus energy. Lower, geometry of various parts of a track.

With the energy of the particle decreasing, starting from energy max, when specific energy losses become greater than the threshold value, the etch rate along the track begins to exceed the etch rate of undamaged parts of olivine. A narrow needle-like channel corresponds to this part of the track (Fig. 3).

During its further stoppage ($< E1$), the energy losses of the particle sharply increase. As the result, the etched region of this main cylindrical section also acquires a large diameter. In the end of the track before the particle is stopped, the energy losses sharply drop again below the threshold value, and the channel ends with a narrow sharp tip (Fig. 3). Thus, completely etched channels of various stopping path sections of heavy nuclei before their stoppage are shaped as syringes.

The hollow channel formed during the etching becomes visible in an optical microscope at a magnification of $600 - 900$.

Figure 4 presents optical microscope micrographs of really observed tracks of superheavy nuclei etched in olivine crystals from the Marjalahti meteorite.

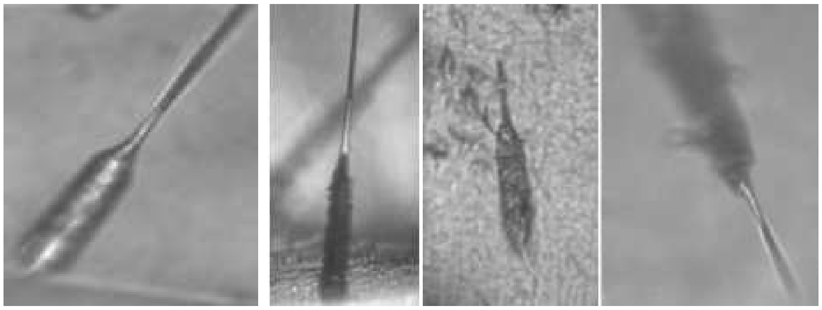

Figure 4: Micrographs of GCR superheavy-element nuclear tracks etched in olivine crystals from pallasites. Fields of view on all micrographs, $(60 - 100) \times 140$ microns.

The geometry and parameters of etched tracks (Fig. 4) confirm the above-described mechanism of crystal structure-damage formation along the traces of the stopping nuclei.

3.2 Identification of nuclear charges of GCR superheavy elements

To identify nuclear charges by track parameters, the authors proposed, in addition to track length, to use an additional parameter the lengthwise etch rate (VL). Figure 5 shows a dependence of the etch rate for tracks obtained during a controlled irradiation at the GSI accelerator (Darmstadt, Germany) on the residual path length (RRZ) of Fe, Kr, Xe and U nuclei with respective measuring error limits. Herewith, the stopping path length of nuclei with charge Z from the point of the trajectory of motion with energy Ei to complete stoppage is taken as the value of RRZ [12].

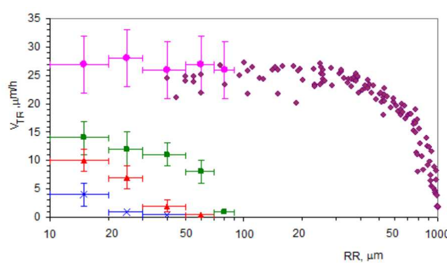

Figure 5: Dependences of track etch rates on residual path lengths (RRZ,i) of Fe, Kr, Xe and U nuclei.

Comparison, in particular, of track lengths of Au ($77 \pm 5 \mu m$) and U ($91 \pm 5 \mu m$) nuclei with energy 11.4 MeV/nucleon obtained in our experiment, with the values of track lengths calculated using SRIM and GEANT4 programs ($69 \pm 6 \mu m$ and $89 \pm 5 \mu m$, respectively) shows a rather good convergence of the results. The dependence of the lengthwise track etch rate (VL) on charge Z and residual nuclear path length (RR) can be presented in a three-dimensional form (as a surface indicating the dependence of VL on Z at certain RR).

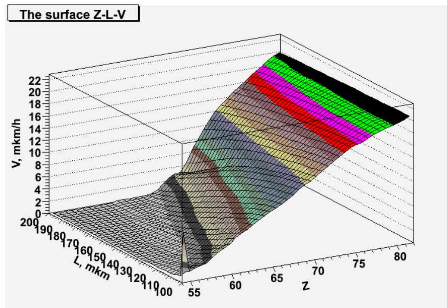

Figure 6: A correlation between nuclear charge, residual path length and track etch rate obtained in this work.

Thus, the method of assessing the value of charge in our studies is based on a three-dimensional interpolation of the surface (Fig. 6) plotted by the values of V and RR measured in calibration experiments for tracks (etched in olivine crystals) from nuclei with charge Z.

In early 2011, in the course of the OLIMPIYA project we found three superlong tracks whose etch rate was Vetch > 35 $\mu m/h$. If we take into consideration that the experimentally measured maximal etch rate of tracks in olivine for uranium nuclei before their stoppage is equal to Vetch,U = 261 m/h, it becomes clear that the charges of these nuclei significantly exceed Z = 92. As in this range of charges the function Z(RR, Vetch) is unknown, to assess the charge preliminarily in the first approximation we extrapolated it to the region of trans-Fermi nuclei. Thus, we assessed in the first approximation the boundaries of the identified charge of three superheavy GCR nuclei we registered; they were in the interval $105 < Z < 130$ [18]. Regression analysis we performed made it possible to amend the charge of one of those nuclei to 119^{+10}_{-6} with the probability of 95%.

It is such nuclei that should form islands of stability, and their finding in nature confirms the validity of theoretical predictions and justifies efforts for their synthesis under the Earth conditions.

Apart from stable nuclei with $Z < 92$, we registered single tracks of particles with charge within the interval of $94 < Z < 100$. Particles with such a charge may not be part of primary cosmic radiation due to their very small lifetimes. In our opinion, events with $Z > 92$ emerge not due to methodological inaccuracies or instrumental failures, but are the result of fragmentation of heavier nuclei from the region of an island of stability.

3.3 Charge distribution of nuclei

Figure 7 shows the results of a conducted track investigation of nuclear distribution by charges. To date, a total of more than 9000 tracks left by nuclei with charge greater than 40 have been processed in olivine crystals from Marjalahti and Eagle Station meteorites. About 2500 of them have been assigned to nuclei with charge greater than 55.

To be compared with data of other studies, the data of this work were normalized with account for the relative abundance of Fe nuclei. It is seen that within the specified error limits there is a good correspondence between the data obtained in our studies and the results of [13, 14].

4 Conclusion

A charge distribution of about 9000 GCR nuclei with charge greater than 55 was obtained in the course of the OLIMPIYA project. The ratio of the abundance of nuclei with $Z > 88$ to the abundance of nuclei with $74 < Z < 87$ is equal to 0.045 ± 0.015 (Marjalahti) and

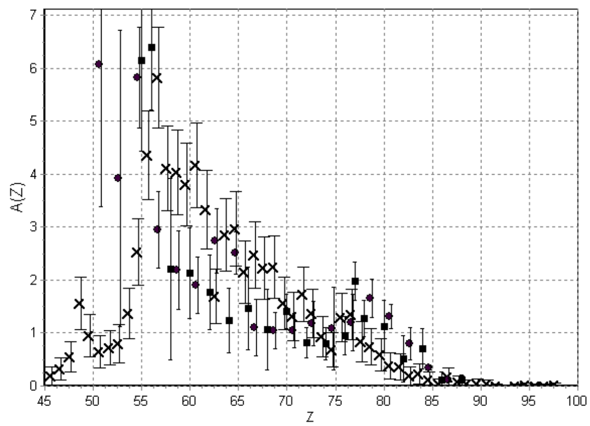

Figure 7: Nuclear charge distribution obtained in this work (filled squares) in comparison with experimental data from HEAO-3 (triangles) [13] and ARIEL-6 (circles) [14]. The galactic nuclei abundance A (AFe= 106) totally 9173 nuclei; Maryalakhty - 5654, Eagle Station 3519

$0.025pm0.02$ (Eagle Station). These values are slightly larger than in the UHCRE experiment (0.0147 ± 0.0032) [19], but are well consistent with the data of the HEAO-3, ARIEL-6 and TREK experiments [13, 15, 17]. The OLIMPIYA charge distribution obtained in processing detectors exposed in outer space for 185300 million years has much heavier nuclei, too [16]. In addition to stable nuclei with $Z < 92$, single signals from particles with charge numbers in the range of $94 < Z < 100$ were detected in experiments. Particles with such charge numbers cannot enter into the composition of primary cosmic radiation because their lifetime is very short. The other authors did not discuss the nature of these particles. We believe that events with $Z > 92$ are due to the fragmentation of heavier nuclei from the stability island, rather than to methodical inaccuracies or fault of instruments. Several such events have also been revealed in our studies of tracks of superheavy particles in olivines from meteorites

Besides the distributions of galactic nuclei we observed three events having very large charges (our estimations are $Z > 105$). Their lengths are large (700-900 μm) but their minimal etching rates are more then 35 $\mu m/h$. It is very large as compared with the uranium maximum etching rate (25 $\mu m/h$). So, the boundaries of the identified charge of these three tracks of GCR superheavy nuclei we registered, liying within the interval of $105 < Z < 130$, were assessed. The superheavy nuclei in olivine crystals evidently lived long enough to fly from the place of their origin to the meteorite. At present, it is believed that the main source of the nuclear component of GCRs are supernovae, in which the nuclei of superheavy and transuranium elements are generated and accelerated. To reach the solar system and form the tracks registered in our meteorites, the average lifetime of these nuclei must be equal to at least the time of their propagation from the source to our solar systems asteroid belt. In estimating the lifetime of superheavy nuclei, we must consider that in order to form tracks in olivine crystal the nuclei must have an input energy in the meteorite of several gigaelectron volts per nucleon, and supernovae in our Galaxy can occur at distances of 18 kiloparsecs from the solar system. A rough estimate of the minimum lifetime of such GCR nuclei thus yields a value of 3000 years.

Thus, the track method makes it possible to obtain results very important for understanding of the physical picture of the world. The results obtained within the OLIMPIYA project show that the study of tracks of galactic cosmic rays in olivine crystals from meteorites opens new capabilities for the investigation of fluxes and spectra in cosmic rays in the region of heavy and superheavy nuclei. This information is of great importance for nuclear physics, physics of elementary particles, and astrophysics.

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