Results of a calibration of olivines from meteorites by means of ^{238}U nuclei at the Bevalac accelerator

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The results of a calibration of the sensitivity of olivine crystals from meteorites by means by ^{238}U nuclei at the Bevalac accelerator are reported. The spectra of etchable lengths of the accelerated ^{238}U nuclei and of "ancient" tracks in these olivines show that the group of ancient tracks $\sim 210\,\mu m$ long found in 1980 in the Nuclear Reactions Laboratory of the Joint Institute for Nuclear Research was caused by galactic cosmic rays of the Th–U group. The possibility of an unambiguous identification of a group of anomalously long cosmic-ray tracks, 340–360 μm long, is discussed.

Experiments were carried out in 1980–1987 in the Nuclear Reactions Laboratory of the Joint Institute for Nuclear Research to study ancient tracks from galatic cosmic-ray nuclei in olivine crystals from meteorites. The purpose of this study was to search for and to identify anomalously long tracks caused by nuclei with $Z \geqslant 110$ (Refs. 1–3).

Crystals from the Marialachti and Eagle Station meteorites were used in these experiments. Most of the work was carried out on samples from the Marialachti meteorite (radiation age $\sim 180 \times 10^6$ yr).

Before the etching, the olivine crystals were annealed at 430 ± 1 °C for 32 h in order to eliminate the background of tracks of cosmic-ray Fe (10^{10}–10^{11} tracks/cm^3) and also to shorten by a factor of 6–8 and to flatten out the spectrum of nuclear track lengths at $Z \geqslant 54$ (Ref. 3). The analytic expression given in Ref. 3 for the etchable track lengths as a function of the atomic number (Z) of the nuclei was based on a single calibration point, for ^{132}Xe: $L = 26.5 \pm 2.5\ \mu m$.

The very first experiments[1] clearly revealed track groups 120–140 μm and 190–210 μm, in the length spectrum (Fig. 1a) which could be classified as tracks of cosmic-ray nuclei in the Pt–Pb and Th–U groups. An anomalously long track, with a length of 365 μm, was also found.

The number of tracks $\sim 210 \mu m$ long which have been found in recent years[2] has exceeded 1100; the number of tracks 340–360 long has reached 11 (Fig. 1b).

It can be seen from the spectra in Fig. 1, a and b, that the track length groups 120–140 μm and $\sim 210\ \mu m$ are clearly distinguishable, evidently because of an absence of sufficiently stable nuclei between Bi and Th($T_{1/2} \geqslant 10^5$ yr).

The anomalously long tracks are approximately 1.7 times as long as the tracks which have been assigned to nuclei of the Th–U group.

The latter circumstance is of much interest in connection with the hypothesized existence of nuclei of superheavy elements in the galactic cosmic rays.

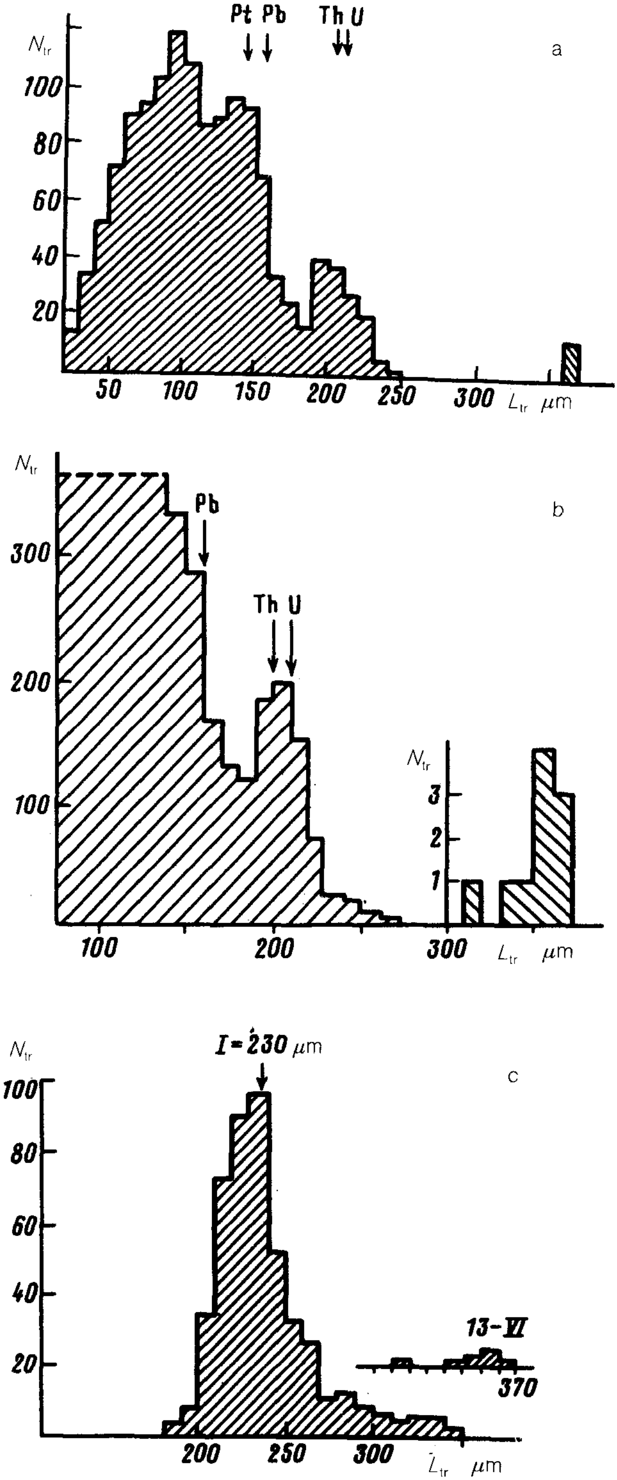

FIG. 1. a—Spectrum of lengths of "ancient" tracks of galactic cosmic-ray nuclei in olivine crystals from meteorites according to the data of the 1980 study[1] (the crystals were annealed at 430 °C for 32 h); b—total length spectrum of ancient tracks of galactic cosmic-ray nuclei in olivine crystals (the crystals were annealed at 430 °C for 32 h; 90% of the tracks were measured in crystals from the Marialachti meteorite, and the rest in crystals from the Eagle Station meteorite[2]); c—length spectrum of tracks of accelerated ^{238}U nuclei in olivine crystals from the Marialachti meteorite (annealed before etching at 450 °C for 32 h).

Note that these studies are unique from the standpoint of the sensitivity with which the heaviest component of the cosmic rays has been studied. The sensitivity here is many times that of other methods, both track and electronic.[2] However, resolving the question of identifying cosmic-ray tracks $\approx 210\ \mu m$ long and determining the origin of the anomalously long tracks required a calibration of the olivine crystals from the meteorites by means of relativistic Au, Pb, and U nuclei with energy > 25 MeV/nucleon.

The first calibration experiment was carried out at the Bevalac accelerator (Lawrence Berkeley Laboratory, Berkeley, California) in November 1987. The energies of the ^{238}U nuclei in that experiment were ≈ 30 and ≈ 70 MeV/nucleon; the ions entered at an angle of 25° or, for some of the samples, $\sim 10°$ with respect to the polished surfaces of the olivine crystals from the meteorites. The fluence of uranium ions was $\approx 10^4$ nuclei/cm^2 ($\pm 20\%$). It was determined with the help of mica detectors, which were bombarded at the same time as the olivine crystals, and at the same angles.

The annealing, the etching, and the visualization of the tracks were carried out under conditions which were completely identical to those of the earlier experiments.[1,2]

Figure 1c shows the results of the measurements of the track lengths of the accelerated ^{238}U in 83 crystals from the Marialachti meteorite.

It follows from Fig. 1c that the peak in the spectrum of ^{238}U track lengths for the olivines from the Marialachti meteorite corresponds to $230^{+25}_{-20}\ \mu m$. The shape and half-width of this spectrum agree well with the length spectrum of the "ancient" tracks: $210 \pm 20\ \mu m$ (Fig. 1, a and b).

The track lengths of the accelerated uranium are systematically somewhat ($\sim 10\%$) higher, apparently because of some effects which have been disregarded and which stem from the heating of the olivine crystals under the conditions prevailing in space over the 180×10^6-yr radiation history of the Marialachti meteorite. Furthermore, some additional information was obtained from measurements of the length spectra of ^{238}U tracks in 32 olivine crystals from the Eagle Station meteorite. It was found that the length spectrum of the ^{238}U tracks obtained from the olivine crystals from the Eagle Station meteorite agrees essentially completely with the length spectrum of the corresponding group of ancient tracks (≈ 220 and $\approx 210\ \mu m$). It thus follows from the results of this experiment that the group of ancient tracks with a length $\approx 210\ \mu m$ was caused by galactic cosmic-ray nuclei of the Th–U group. It is not possible to separate the peaks corresponding to thorium and uranium ($\Delta Z = 2$), since the difference between the etchable track lengths of these nuclei does not exceed 5%, and the resolution which we achieved was $\Delta Z = 4$–5.

Let us consider separately the long tracks in the length spectrum for ^{238}U, with lengths up to 350 and even up to 370 μm. These tracks constitute 1–2% of the total number of tracks for the crystals from the Marialachti meteorite and are not found in the length spectrum for the Eagle Station meteorite. Comparing the tail on the ^{238}U calibration spectrum (Fig. 1c) with the longest ancient tracks (Fig. 1b), we note that their numbers, divided by the number in the main peak, are approximately the same. Even this analysis of such a limited number of crystals containing long ^{238}U tracks has

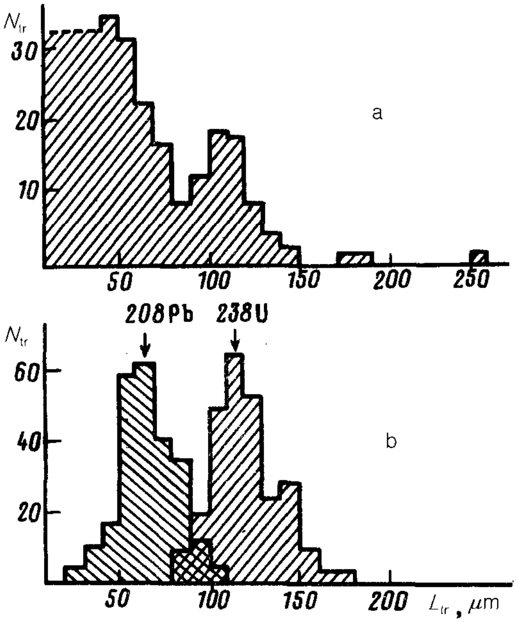

FIG. 2. a—Length spectrum of ancient tracks of galactic cosmic-ray nuclei in olivine crystals from the Marialachti meteorites (the crystals were annealed at 450 °C for 32 h); b—length spectrum of tracks of ^{238}U nuclei in olivine crystals from the Marialachti meteorite (annealed at 450 °C for 32 h).

shown that such tracks are generally close in terms of orientation to the main crystallographic planes of the olivine.

For the ancient tracks 340–360 μm long, on the other hand, this correlation was not found. The origin of the group of anomalously long tracks of cosmic-ray nuclei thus remains an open question. Resolving it will require more-detailed studies.

We also carried out some experiments in which we examined 1.2 cm^3 of olivine crystals from the Marialachti meteorite which had been annealed at 450 °C for 32 h. Figure 2, a and b, compares the measured length spectra of the ancient tracks in these crystals with data from the annealing of tracks left by accelerated ^{238}U under the same conditions.

It follows from Fig. 2, a and b, that the group of ancient tracks ≈ 115 μm long corresponds to tracks of accelerated ^{238}U which are ≈ 120 μm long. The length of the ^{238}U tracks do not exceed 180 μm, while in the length spectrum of the ancient tracks (Fig. 2a) there are tracks about 250 μm long.

It seems to us that for future studies of this type the olivine samples from the Eagle Station meteorite are more promising. They contain regions which lie at a depth of 1.5–2.5 cm from the original (preatmospheric) surface.

The density of tracks of the heaviest cosmic-ray nuclei in these crystals is several times that in the samples from the Marialachti meteorite.

It can be concluded from the results of this experiment that Ref. 1 did indeed constitute the first report of tracks of nuclei of the Th–U group of galactic origin. The new direction for studying galactic cosmic-ray nuclei (in the region Z) which was pointed out in that paper—the use of crystals from meteorites—has a sensitivity which is substantially better than that of other methods.

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[1]V. P. Perelygin and S. G. Stetsenko, Pis'ma Zh. Eksp. Teor. Fiz. **32**, 622 (1980) [JETP Lett. **32**, 608 (1980)].

[2]V. P. Perelygin, S. G. Stetsenko, and G. N. Flerov, Brief Communication No. 7-85, Joint Institute for Nuclear Research, Dubna, 1985, p. 5.

[3]D. Lhagvasuren, O. Otgonsuren, V. P. Perelygin, *et al.*, in: Solid State Nuclear Track Detectors (ed. Francaus *et al.*), Pergamon Press, New York, 1980, p. 997.

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