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ANALYSIS OF COSMIC RAYS WITH Z > 50 REGISTERED IN METEORITE MINERALS

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Cosmic rays with $Z > 50$ captured in olivine meteorite crystal (Marjalahti) is analyzed. The lenght distribution of such cosmic ray traces ($R > 100\,\mu m$) at 6 and 9 cm from the meteorite surface is determined. Utilizing the dependency curve between trace length and charge, the relative contribution of nuclei with $Z > 50$ is ascertained and compared with similar experimental results from the literature. We estimate the energy spectrum decay index of cosmic rays for nuclei from $50 < Z < 70$, $70 < Z < 90$ and $Z > 90$.

1. Introduction

Investigation of the charge distribution and energy spectra of components of cosmic rays at $Z > 50$ is a difficult task due to low intensity of these nuclei, which is $2 - 4 \times 10^{-4}$ times less intense than the iron nuclei. Thus far, research concerning the components of cosmic rays has developed along two lines:

(i) Direct registration of heavy and superheavy nuclei using solid state detectors of charged particles and electronic detectors exposed to higher atmospheric layers, either from terrestrial satellites or interplanetary stations. Most data in regard to cosmic rays with $Z > 50$ has been obtained via nuclear emulsion stackes and polymeric solid-state detectors[1–4]. To attain statistical significance, it is necessary to expose large surface areas of detectors (approximately $100\,m^2$) for long periods of time.

(ii) Utilization of silicate and phosphate minerals from meteorites which register and preserve traces from cosmic nuclei $Z > 20$[5] for several hundred million years. The advantage of this line of research is clear from the fact that the fact that the minerals have been exposed for periods of 10 to 100 million years. Simple calculation reveals that $1\,cm^3$ of silicate obtained from 5 cm depth from meteorite surface aged $10^7 - 10^8$ years deposits $10^2 - 10^4$ traces from nuclei of the uranium-torium group[6].

Systematic investigation of heavy nuclear traces from galactic cosmic rays in meteorite minerals has not yet been fully elaborated due to various difficulties inherent to that field of research. These problems include: choice of appropriate material for study, necessity of etching of the entire trace length in the crystal paucity of data in regard to mineral calibration with accellerated ions of $Z > 36$, and partial regression of traces in cosmic space. Because of these obstacles, thus for only a limited number of nuclei from cosmic rays with $Z > 50$ has been examined.[7,8]

2. *Experimental methods*

Olivine crystals from palasite-type meteorites have been the most favorable and thus most widely utilized for trace analysis of heavy and super-heavy nuclei of cosmic rays compared to other extraterrestrial minerals[9,10]. During the first phase of our investigation, the trace length of elements from the iron group in olivine was measured from 14 different meteorites in order to choose the optimal meteorite. Here in this study, olivine Marjalahti from the Natural History Museum in Helsinki was employed for analysis of cosmic rays with $Z > 50$. Olivine crystal in palasite is found in a iron — nickel matrix and its extraction is extremely complicated. A portion of the olivine crystal is extracted mechanically, in addition, the iron — nickel matrix was corroded using nitric acid solution and electrolysis. During extraction careful attention was given to orientation of the crystal in relation to the melted meteorite core in order to ensure optimal conditions for etching the cosmic ray traces. Here, we analyzed olivine crystal of 6 ± 0.6 cm and 9 ± 1 cm depth in relation to the meteorite's outer surface. Selected crystals were then mounted on epoxide resin such that one side of the crystal was upon the resin surface. These mounted crystals were subsequently polished.

The solution suggested by Krishnaswami et al.[11] modified by the addition of 3% oxalic acid was employed for trace etching[12]. In order to etch the entire length of traces which were situated inside crystal, artificial microfissures were created within the crystal to facilitate diffusion of solution. To achieve this end, a portion of the polished crystal surface was irradiated with Xe, Ar and Ca ion beams at an energy of 300 MeV, with a flux of $10^{14}\,cm^{-2}$ (*TINT* method Fig. 1a).

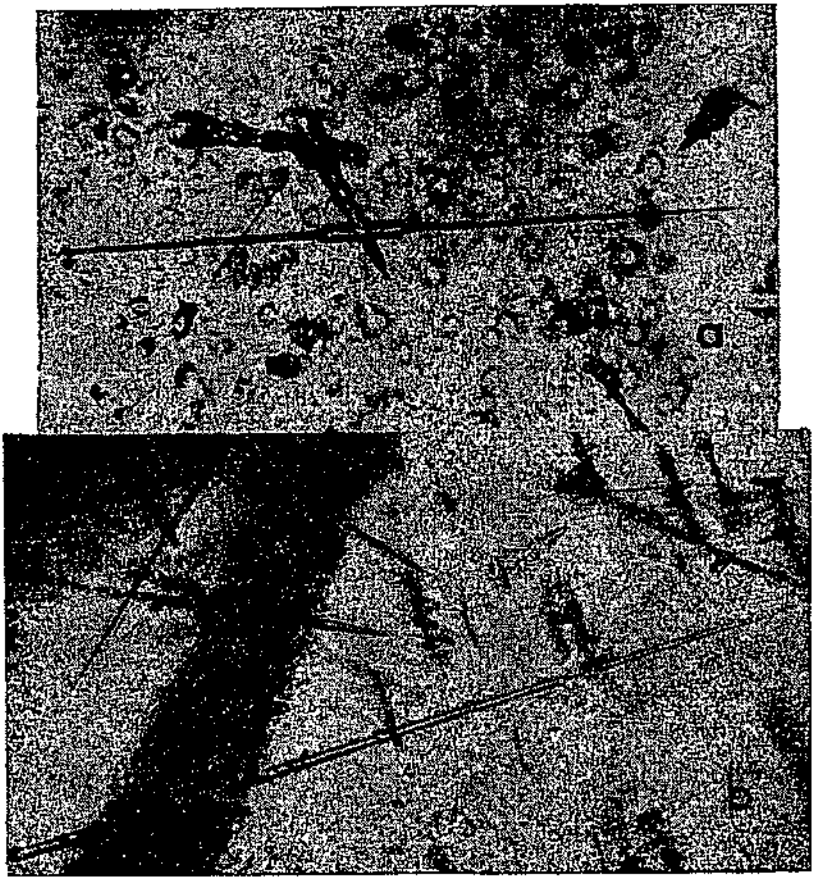

Fig. 1. Heavy nuclear cosmic rays traces in olivine Marjalahti meteorite (480 times magnification)
a. Trace etched using the *TINT* method.
b. Traces etched by means of the *TINGLE* method.

Another portion of the crystal was irradiated with a focused laser beam which also forms microfissures within the crystal through which solution can penetrate (*TINGLE* method Fig. 1b). The crystals were examined and trace range measured using an optical microscope with 500—1500 magnification. Some 540 mm^3 of crystal from 6 cm depth and 640 mm^3 from 9 cm depth were examined.

3. *Results and discussion*

Figures 2 and 3 reveal the trace length distribution from cosmic ray nuclei in olivine mineral taken at 6 and 9 cm depth from the Marjalahti meteorite surface.

The principal difficulty in interpreting the trace length distribution of cosmic rays lies in determining the precise dependency relation between the measured

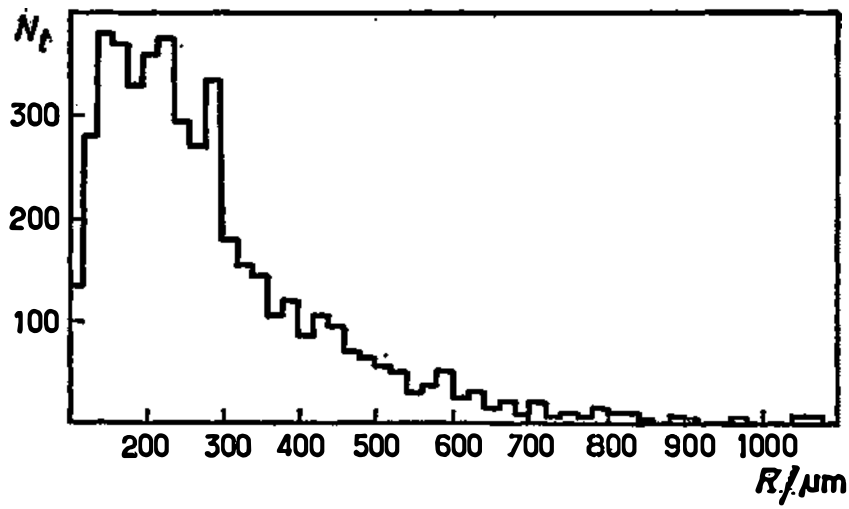

Fig. 2. Cosmic ray trace lenght distribution in olivine crystal taken at 6 cm depth.

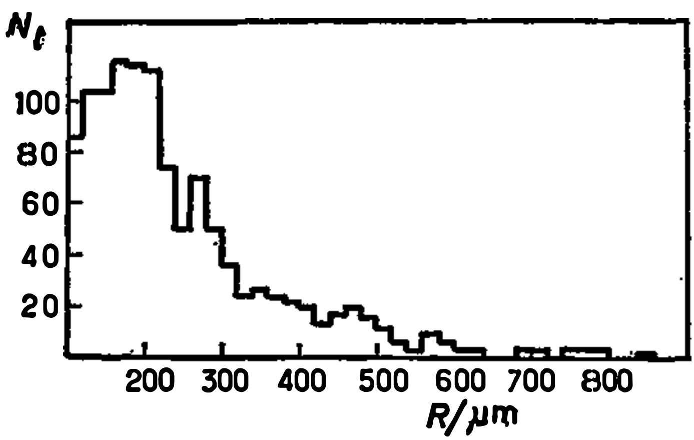

Fig. 3. Cosmic ray trace length distribution in olivine crystal taken at 9 cm depth.

trace lenght and atomic number Z, due to lack of crystal olivine calibration with accellerated ions for $Z > 36$. In order to identify traces of individual charge groups, the dependency of trace length and charge Z for selected nuclei for $Z = 23 - 36$ was utilized. For nuclei of charge $Z > 36$, data was extrapolated using the model of Katz and Kobetich[16] (Fig. 4 curve a). In analyzing the length distribution of cosmic ray nuclei, it is essential to consider trace regression in cosmic conditions and the change of the primary spectrum of cosmic rays, because of the nuclear interaction with interstellar gases and with meteorite substances[10]. This inter-

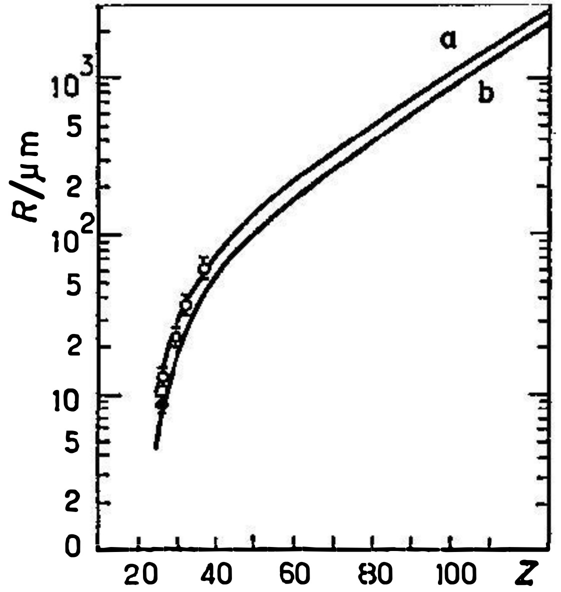

Fig. 4. Semi-empirical dependency of the trace lenght of atomic number Z
a. Olivine crystal.
b. Calculated partial regression of traces in the olivine meteorite under cosmic conditions.

action can lead to spreading of peak distribution. According to estimates from the literature[6,13], regression in cosmic conditions generates shortening of trace length for nuclei with $Z > 36$ of approximately 20—30% (Fig. 4, curve b).

As seen in Fig. 4, curve b, etched trace lengths for $Z = 50, 70, 80, 90$ are 130, 270, 560 and 710 μm, respectively. Trace length of super-heavy nuclei ($Z >$ > 110) is predicted to be 1400 μm. The relative contribution of individual charge groups for $Z > 50$ is displayed in Table 1, together with data regarding distribution for specific groups of elements in the solar system. In Table 1 the distribution of specific groups of elements obtained by nuclear emulsion and polymer detection is presented as well. The general agreement obtained between the dis-

TABLE 1

Olivine form the Marjalahti meteorite			Nuclear emulsion and polymer		
Charge groups	Trace Number N_t	$N_Z/_{Fe}$	Trace Number N_t	Refs. 1—3 N_Z/N_{Fe}	Solar Sistem Ref. 17 $N_Z/_{Fe}$
≥ 50	4391	$1,4 \cdot 10^{-5}$	477	$1.8 \cdot 10^{-5}$	$3.4 \cdot 10^{-5}$
≥ 70	2170	$5.5 \cdot 10^{-6}$	195	$7.5 \cdot 10^{-6}$	$8.7 \cdot 10^{-6}$
≥ 86	—	—	23	$8.0 \cdot 10^{-7}$	$1.1 \cdot 10^{-7}$
≥ 90	103	$2.0 \cdot 10^{-7}$	—	—	$1.1 \cdot 10^{-7}$
≥ 98	1	$2.0 \cdot 10^{-9}$	—	—	—

Distribution of elements $Z > 50$ in cosmic rays compared to iron-group nuclei.

TABLE 2

Charge grups	9 cm Depth Trace density N_t/cm^2	9 cm Depth Mean energy of nuclei E (GeV/u)	6 cm Depth Trace density N_t/cm^2	6 cm Depth Mean energy of nuclei E (GeV/u)	Relative density of the traces N_{6cm}/N_{9cm}	Energy Spectrum decay index
$23 \leq Z \leq 30$	$5{,}10^6$	$0{,}8 \pm 0{,}12$	$1.62.10^6$	$1{,}1 \pm 0{,}17$	3,08	$2{,}54 \pm 0{,}45$
$50 \leq Z \leq 70$	2201	$1{,}3 \pm 0{,}20$	599	$1{,}8 \pm 0{,}28$	3,42	$2{,}20 \pm 0{,}70$
$70 < 4 \leq 90$	2079	$1{,}6 \pm 0{,}24$	394	$2{,}2 \pm 0{,}35$	4,90	$2{,}50 \pm 0{,}60$
$Z > 90$	91	$1{,}8 \pm 0{,}27$	11	$2{,}5 \pm 0{,}39$	7,69	$2{,}80 \pm 0{,}90$

Energy spectrum data of cosmic rays.

tribution of various nuclei from the uranium group with those of actinide in the solar system at the end of nuclear-synthesis demonstrates the validity of extrapolating dependency curves derived for $Z > 36$. Data is shown in Table 2 concerning the energy spectrum of cosmic nuclei averaged over a period of 176 million years, which enables one to develop an energy spectrum decay index for certain groups of nuclei. In calculating such an index, the energy fluctuation of nuclei is taken into account. This is, in itself, determined by the specific geometry of the crystals exposed to cosmic radiation. In Fig. 5 the trace distribution which is de-

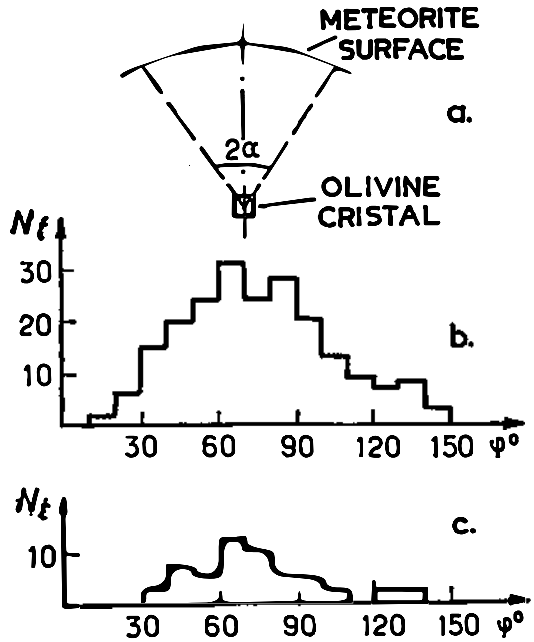

Fig. 5. Angular distribution of cosmic ray traces in olivine crystal
a. Geometric exposure of olivine crystal to cosmic rays
b. Angular distribution of cosmic ray traces at 6 cm depth.
c. Angular distribution of cosmic ray traces at 9 cm depth.

pendent upon the azimuthal angle as well as the geometry of the exposed crystals is revealed. The half-length of the azimuthal trace distribution causes a 10—12% fluctuation of the energy spectrum for galactic cosmic nuclei for each given localization. In addition, in ascertaining the rate of energy spectrum decline we consider the following: (i) differences in the relation between range and the energy of various group of nuclei, and (ii) nuclear interaction processes during the passage of moderate and heavy nuclei through the 3 cm meteorite matrix. Inclusion of fragmentation processes yields the largest indeterminacy for the group of fission active nuclei ($Z > 90$). In this case, some 70% of the interaction originates from the fission of incoming nuclei. Furthermore, in approximately 20% of cases the nucleus loses several protons forming groups of lighter element. Thus, from the data provided in Table 2 one can conclude that galactic cosmic nuclei with $Z > 50$ possess energy spectra similar to those of the iron group.

Further examination of the spectra of atomic numbers and energy spectra of heavy nuclei of galactic cosmic rays should be performed in meteorites of various radiation age. In such cases, one could potentially observe the variations in content and intensity of galactic cosmic rays originiating from possible explosions of *super nova* stars. In these instances, short-lived trans-uran nuclei from atomic number 96 to super-heavy nuclei might be observed.

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ANALIZA KOSMIČKOG ZRAČENJA SA Z > 50 REGISTROVANOG U MINERALIMA METEORITA

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U ovom radu su dati rezultati ispitivanja kosmičkog zračenja sa $Z \geq 50$, zaustavljenog u kristalima olivina meteorita Marjalahti. Određena je distribucija dometa tragova kosmičkog zračenja ($R > 100$ μm) na dubini 6 cm i 9 cm od doatmosferske površine meteorita. Koristeći krivu zavisnost razvijene dužine tragova jezgara i naelektrisanja, određen je relativni prinos jezgre $Z \geq 50$ i upoređen sa odgovarajućim rezultatima dobijenim u drugim eksperimentima. Procjenjen je indeks opadanja energetskog spektra kosmičkog zračenja za jezgra sa $50 \leq Z \leq 70$, $70 < Z \leq 90$ i $Z > 90$.