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Determining the Characteristics of Cosmic-Radiation Nuclei in the Sileye Experiment on Board the Mir Orbital Station

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Abstract—An algorithm for reconstructing the characteristics (charge, mass, and energy) of cosmic-radiation nuclei with 20- to 200-MeV/nucleon energies is described. The detector is a telescope of three two-coordinate planes with two 1-mm-thick iron filters inserted between them. Each plane is composed of two strip silicon detectors with 3.6-mm-wide orthogonally oriented strips, an effective area of 6×6 cm^2, and a thickness of 380 μm. The algorithm for reconstructing the nuclei characteristics is based on the analysis of how the specific ionization losses change as the nuclei pass through the filter material. The results of the Monte Carlo simulation are presented for the energy dependence of the telescope acceptance and the energy deposited in the detectors by different nuclei in view of the detector calibration on the nuclear beams of the accelerator. The mass resolution of the telescope is ~30, 12, and 5% for He, N, and Al nuclei, respectively. The energy resolution, which is ~20%, is much the same for all nuclei.

A most important objective of the Sileye experiment, conducted on the Mir orbital station, was to determine the characteristics and types of particles which give rise to the phenomenon of light flashes (LF) observed by cosmonauts during orbital flights. This phenomenon—suddenly arising sensation of a bright light signal—was first observed during the flight of Apollo-11 to the Moon [1]. The interest in this phenomenon has been fueled by its possible influence on the radiation safety and reliability of complicated operations performed by a cosmonaut in the conditions of a space flight. The causes of LF are sought in numerous investigations, including those in space [2]. Until the present time, these experiments, mainly consisting in the statistical correlation analysis of the frequency of LF occurrence with fluxes of different cosmic-radiation particles, have failed to provide an unambiguous answer to the question of the causes of their appearance. The Sileye experiment is aimed at providing an answer to this question.

This problem can be solved if the type and characteristics of cosmic-ray particles are determined during their passage through the recording system before they hit the cosmonaut's eye (or, perhaps, his head). This scenario appears possible now, first, owing to the progress in semiconductor strip detectors engineering and, second, through the high ionizing power of the particles that are presumably responsible for this phenomenon.

A charge-particle parameter whose value and variation allows one to determine the physical characteristics of particles is their ionization loss. Within the zero approximation, the ionization loss dE/dX is proportional to $(Z/\beta)^2$, where Z is the particle charge, and β is its velocity. Taking into account that we are dealing with energies of a few megaelectronvolts per nucleon, we can write

$$dE/dX \sim Z^2/(2T/M),$$

where T is the kinetic energy of the particle, and M is its mass. After passage through a substance of thickness

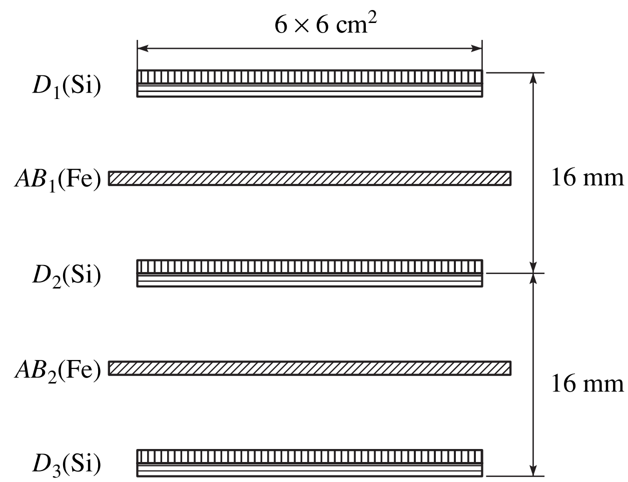

Fig. 1. Schematic diagram of the telescope of the Sileye apparatus.

ΔX, the specific ionization loss changes approximately by a value $(dE/dX)\Delta T/(T/M)/M$ (ΔT is the change in the kinetic energy of particles). If two isotopes fly into the system with equal velocities (the T/M ratio is the same) and, hence, equal specific ionization losses, then, after traversing a thickness ΔX, the difference between these losses is defined by a value

$$\Delta X(dE/dX)^2\{1/M_1 - 1/M_2\}/(T/M).$$

Since dE/dX is proportional to Z^2, the mass resolution of the instrument, working on the principle of measuring a change in dE/dX, is improved as the mass increases; i.e., this technique is efficient for heavy particles. This circumstance is very useful in a study of the LF phenomenon, which was the prime objective of the experiment.

A schematic diagram of the telescope from the Sileye system is shown in Fig. 1. The telescope is composed of six individual strip silicon detectors (for details, see [3]). Two separate semiconductor junctions with an orthogonal strip orientation, when connected together, form double position-sensitive detectors (D_1–D_3). The gap between the outer position-sensitive detectors is 32 mm, and their area is 6 × 6 cm^2. The thickness of each silicon semiconductor junction is 0.38 mm. A separate strip of silicon semiconductor junction is 3.6 mm wide. In view of the gap between the outer position-sensitive detectors, the strip width governs the angular accuracy in determining the particle direction, which is ~6° for this apparatus. For the dynamic energy range of the telescope sensitivity to be extended, 1-mm-thick iron plates AB_1 and AB_2 are inserted between the position-sensitive detectors. Aluminum plates, placed at the top and bottom of the telescope, are its structural elements: top and bottom "covers."

The physical characteristics of the telescope were determined for different nuclei by the Monte Carlo method using the GEANT 3.21 software package [4]. The initial parameters of the particles were simulated either for an isotropic angular distribution of incoming particles or for a fixed angle of incidence; the acceptance and effective area of the telescope were computed in accordance with these conditions. The simulated positions of incidence were uniformly distributed over an area of 7 × 7 cm^2 on a level of the top telescope "cover." The simulated initial energies of incident particles were uniformly distributed within the margins of E_{min} to E_{max}. The lower limit E_{min} of this energy range was taken to be 20 MeV/nucleon, which was slightly below the energy of protons with which they could travel through the entire substance of the telescope. In the majority of cases, the upper limit E_{max} was 200 MeV/nucleon. This value corresponded to energies at which separation of nuclei was still possible, and changes in the specific ionization of particles at the "entrance" and "exit" of the telescope were noticeable. The energy dependence of the effective area (acceptance) was represented by histograms with a step ΔE.

Under the specified simulation conditions, the average telescope acceptance in the given histogram channel is defined by the formula

$$\Gamma(E) = \Gamma_0(E_{max} - E_{min})N_+(E)/N_\Sigma\Delta E,$$

where $\Gamma_0 = \pi S_0 \sin^2(\theta_m) = 135.2$ cm^2 sr is the acceptance of an area $S_0 = 49$ cm^2 for isotropic radiation within a space angle with a maximum value of the polar angle $\theta_m = 69^\circ.71$; N_Σ is the total number of incoming particles in the E_{min} to E_{max} range; $N_+(E)$ is the number of "detected" particles, satisfying the selection criterion, in the specified histogram channel; and ΔE is the width of this histogram channel.

The effective area of the telescope $S(E)$ is defined by a similar formula:

$$S(E) = S_0(E_{max} - E_{min})N_+(E)/N_\Sigma\Delta E.$$

The criteria for event selection in the analysis of the simulation results are important in the determination of $\Gamma(E)$ and $S(E)$. Those events are neglected, if (1) the specific ionization loss in D_2 is above the maximum or under the minimum value in the outer detectors D_1 and D_3; (2) the difference in the ionization losses in each of the three pairs of semiconductor detectors exceeds 20%; and (3) the difference of the total energy release in the position-sensitive detectors D_1 and D_3 is under 2 MeV.

The type and characteristics of incident particles are found by minimizing the functional

$$R = \mathrm{sqrt}[\Sigma(E_i - T_i)^2],$$

where E_i and T_i are the experimental and theoretical values of energy release in the ith strip semiconductor detector.

The experimental energy release in the telescope detectors takes into account the their calibration results

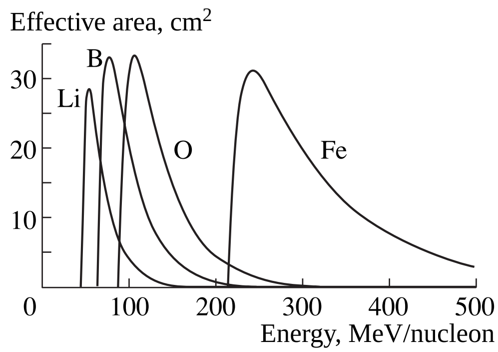

Fig. 2. Energy dependence of the effective telescope area for a set of nuclei at normal angle of incidence.

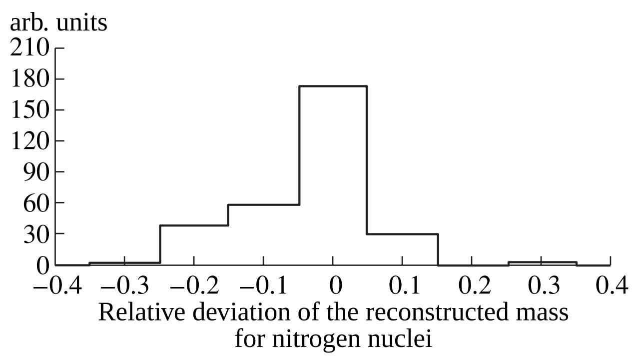

Fig. 3. Mass resolution for nitrogen nuclei.

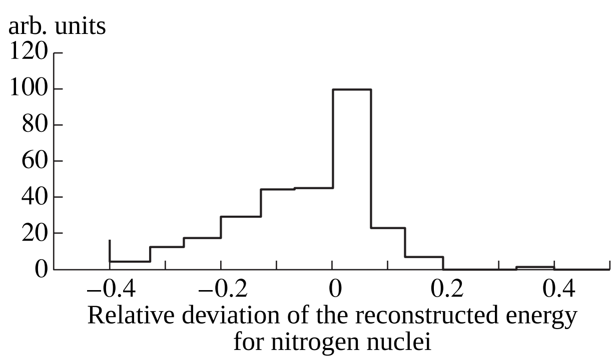

Fig. 4. Relative energy resolution for nitrogen nuclei.

on the nuclear beams of the Uppsala accelerator [3]. The theoretical values of the energy deposited in the detectors were computed by the Bethe–Bloch formula. The functional R is minimized by the following parameters: charge, mass, and energy of incident particles. In this case, the charge and mass are selected from the fixed list of nuclei from protons to nickel. Note that the computations take into account the angle and direction (up or down) of the incoming particles.

Dependences $S(E)$, obtained for some nuclei at normal angle of incidence, are shown in Fig. 2. The lower bound of efficiency is defined by the particle range; the fall in the efficiency at higher energies is determined by the selection of events according to the difference in the total energy deposited in the outer telescope detectors (D_1 and D_3). Note that, for the selection criteria in use, the probability of an error in determining the particle direction (up or down) is below 10^{-4}, and the maximum mass of detected nuclei extends up to Fe nuclei and is governed by the dynamic ranges of the amplifiers and analog-to-digital converters.

Figure 3 presents the mass resolution, obtained by minimizing the functional R for normal incidence of nitrogen nuclei over the entire range of the initial particle energies and using the above selection criteria. The mass resolution for N nuclei throughout the energy range of sensitivity is ~12%; for He and Al nuclei, this value is ≈30% and ≈5%, respectively.

The relative energy resolution $\delta = (E_r - E_0)/E_0$ (E_r is the reconstructed particle energy, and E_0 is the energy of the incident particle), averaged over the energy range of telescope sensitivity, is shown in Fig. 4 for nitrogen nuclei. The energy resolution is equal to ~20% and is approximately constant for all nuclei.

The results presented demonstrate the potentialities of the Sileye apparatus in determining the characteristics of cosmic-radiation nuclei. We see that, despite the fact that the mass resolution obtained is worse than that for other known methods (e.g., for the measurement of dE/dX and the total absorbed energy), this method is completely applicable to cosmophysical research. As noted, it is very important that the nuclei characteristics are determined during their flight through the apparatus, before they reach an area where their interactions are to be investigated. Note that this energy range (somewhat exceeding 100 MeV/nucleon) is of interest for solar physics [5], since it makes possible measurements of fluxes of partially ionized nuclei, accelerated in solar flares, even in the orbit of the Mir station.

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