Instruments and Experimental Techniques, Vol. 48, No. 1, 2005, pp. 32–36. Translated from Pribory i Tekhnika Eksperimenta, No. 1, 2005, pp. 46–51.

NUCLEAR EXPERIMENTAL TECHNIQUE

A New Method for Determining Particle Energy in the Range 10^{11}–10^{15} eV and Results from a Beam Test at 180 GeV/*c*

G. L. Bashindzhagyan*, A. G. Voronin*, S. A. Golubkov, V. M. Grebenyuk***, N. N. Egorov**, A. M. Kalinin***, D. E. Karmanov*, K. A. Kon'kov**, N. A. Korotkova*, Yu. F. Kozlov**, Z. V. Krumshtein***, M. M. Merkin*, M. I. Panasyuk*, A. Yu. Pakhomov*, D. M. Podorozhnyi*, E. B. Postnikov*, T. M. Roganova*, A. B. Sadovskii**, L. G. Sveshnikova*, A. I. Sidorov**, L. G. Tkachev***, and A. N. Turundaevskii***

* *Skobel'tsyn Institute of Nuclear Physics, Moscow State University, Vorob'evy gory 1, str. 2, Moscow, 119992 Russia*
** *Research Institute of Materials Science, Zelenograd, Moscow oblast, Russia*
*** *Joint Institute for Nuclear Research, ul. Joliot-Curie 6, Dubna, Moscow oblast, 141980 Russia*
Received June 3, 2004

Abstract—A method for measuring the energy of the nuclear component of cosmic rays is described. The principle of the method consists in determining the energy of a primary nucleus from the space density of secondary particles produced in a thin target in the initial event of inelastic interaction. The results from testing the method on an ejected 180-GeV pion beam are presented. Analysis of the experimental data and simulation show that, using this method, it is possible to measure the particle energy with a relative error of ~67%. The method is being developed for the direct detection of cosmic rays over wide ranges of energy (10^{11}–10^{15} eV/particle) and charge (Z = 1–30) during a cosmic experiment in near-Earth space.

INTRODUCTION

An ionization calorimeter method for measuring the energy of high energy particles was first proposed in work [1]. This method is now widely used in direct investigations of cosmic rays at energies of $>10^{12}$ eV for nuclei with Z = 1–30 over a wide energy range. Though reliable and well-studied, this method does have one significant drawback: a great amount of dense material is needed for a nuclear cascade to develop. Therefore, the requirement that a considerable mass of detecting equipment be placed in orbit hinders the study of cosmic rays with energies above $>10^{14}$ eV during cosmic experiments.

In this paper, we analyze the results from testing a new method for measuring primary particle energy by the space density of secondary particles produced in a thin target in the first event of inelastic interaction [2]. Detailed simulations show that this method may be used over a wide range of energies (10^{11}–10^{15} eV/particle). This method differs from the ionization calorimeter technique mainly in that it dispenses with the massive absorber that is required for the development of a cascade. As a result, it is possible to design instruments for scientific studies such that their mass is relatively low while their luminosity is high.

PHYSICAL PRINCIPLES OF THE METHOD

The proposed method is based on the fact that secondary pions produced during hadron–hadron interactions fly apart symmetrically, forward and backward, in a center-of-mass system, and their transverse momentum depends only slightly on the primary energy [3]. The mean value of pseudorapidity $\eta = -\ln\tan(\theta_i/2)$ (where θ_i is the exit angle of a secondary particle in the laboratory system of coordinates) appears to be proportional to the logarithm of the primary energy of the incident particle; i.e., the shape of the space distribution of the secondary particles in their pseudorapidity $dN/d\eta$ turns out to be sensitive to the primary energy. This method has been applied in various experiments on cosmic rays in which nuclear emulsions and spark chambers were used as particle detectors. In these cases, it is impossible to detect secondary photons from the decays of neutral pions; this reduces the statistics on secondary particles and may affect the accuracy of assessing the energy. Moreover, the observed distributions of secondary particles may be heavily distorted by the contribution of slow particles produced during subsequent interactions of the incident particle and the products of its first interaction with the target's nucleons. This can lead to an increase in the fluctuations of $\langle\eta\rangle$ in individual events and, consequently, in the error of determining the particle energy. These factors, as well as the experimental difficulties in detecting all of the backward cone's slow particles, have been responsible for an extremely great error in determining the energy in cosmic ray experiments.

We propose using a combined method that includes simultaneous measurements of the exit angles of both charged and neutral particles and suppression of the

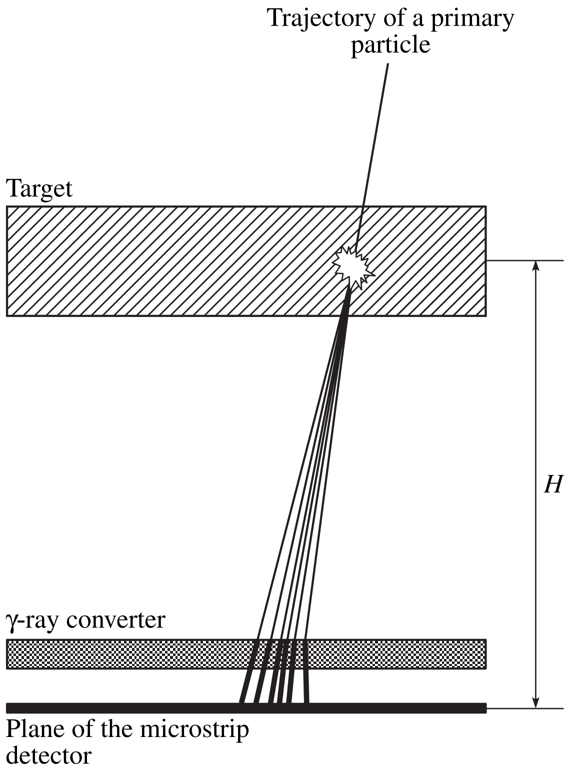

Fig. 1. Diagram of the proposed setup.

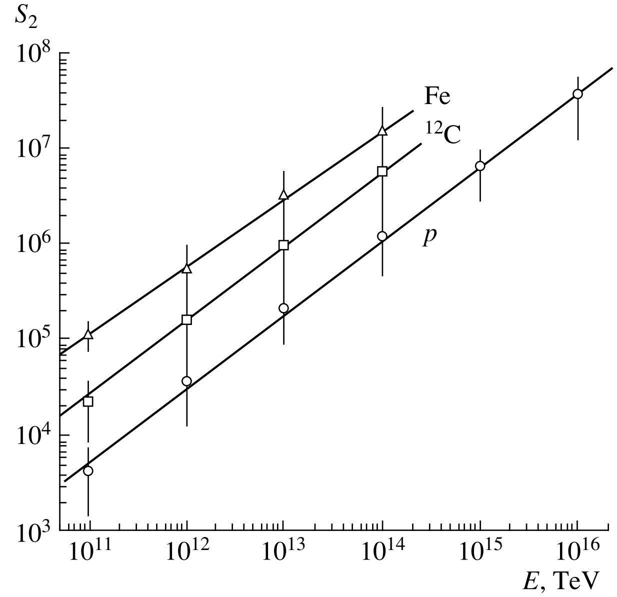

Fig. 2. Calibration dependences of the mean value of $S_2(E)$ for different primary nuclei (protons, carbon, and iron). The straight lines correspond to the exponents $\beta_2(p) = 0.78$, $\beta_2(^{12}C) = 0.79$, and $\beta_2(Fe) = 0.71$.

effect of the slow particles generated by secondary interactions.

A simplified diagram of the setup for testing this method of measuring the energy of high-speed particles is shown in Fig. 1. A primary particle interacts with nuclei of a relatively thin (<20 g/cm^2) target made of a light material, e.g., carbon. This interaction produces secondary charged particles (mostly π^+ and π^-) and γ rays (during decays of π^0 and η mesons). A thin layer of a heavy material (lead or tungsten), which acts as a γ-ray converter into electron–positron pairs, lies at distance H from the target. A layer composed of silicon microstrip detectors is placed directly behind the converter to record the distribution of secondary charged particles.

To characterize the pseudorapidity distribution of the flux density of secondary particles, we introduce parameter S, which depends on the primary particle energy E_0:

$$S(E_0) = \sum \eta_i^2 N_i.$$

In this expression, $\eta_i = -\ln\tan(\theta_i/2) \approx -\ln(r_i/H/2)$, where r_i is the distance from the shower axis to the ith position-sensitive detector, in which N_i particles were registered; and H is the distance from the interaction point.

The energy dependence of parameter S, which is obtained using this method over a wide range of energies (10^{11}–10^{15} eV) for nuclei with Z = 1–30, is expressed by a power function. The error in determining energy E is $\sigma(E) \sim 0.6$–0.7 [2].

The simulation is based on the assumption that a position-sensitive detector will comprise two layers of silicon microstrip detectors placed with a pitch of 50 μm such that their strips are perpendicular to one another. Each strip measures the total ionization, which actually indicates the number of secondary particles that hit the strip. The use of microstrip detectors allows the integration of the function that represents the space distribution of secondary particles along X and Y axes. On average, the distributions of secondary particles in the X and Y coordinates are symmetrical. Therefore, two detector layers provide two independent measurements of the transverse density; as a result, the energy can be determined with a higher accuracy. With this in mind, we modified parameter S: instead of the secondary-particle angle, we used its projection onto the plane of observation. Since $\eta_i = -\ln\tan(\theta_i/2) = \ln(2H/r_i)$, quantity $\varphi_i = \ln(2H/X_i)$ is taken as a new variable. Hence, parameter $S_2 = \Sigma \ln^2(2H/X_i)N_i$ is considered to be an analog for parameter S. In this expression, H is the distance from the point of the first interaction to the detectors' plane; r_i is the distance between the coordinate of a secondary particle in the plane of the detector and the shower axis; X_i is the distance between the middle of the strip and the shower axis; and N_i is the num-

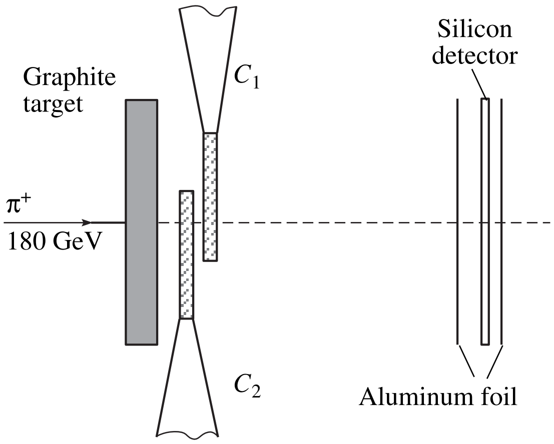

Fig. 3. Layout of the experiment.

ber of particles that hit the strip. The shower axis is defined as the line that separates all the particles into halves. The position of the strip's center is used as a coordinate. It was found that modified parameter S_2, averaged over coordinate X, also had the power-law energy dependence $\langle S_2\rangle(E)$. This function is shown in Fig. 2 for various primary nuclei.

Exponents β_2 of the power function for the energy dependence $S_2(E)$ turned out to be very close to the values obtained for the energy dependence of parameter S in the case when the coordinates of each secondary particle were measured: $\beta_2 = 0.78$ and $\beta = 0.82$ for protons, $\beta_2 = 0.79$ and $\beta = 0.82$ for carbon nuclei, and $\beta_2 = 0.71$ and $\beta = 0.74$ for iron nuclei. The reconstructed-energy distribution functions $W(E_{meas}/E)$ also differ little in both cases. The expected accuracy of energy determination is in both cases approximately $\sigma(E) \sim 0.7$ [2].

The GEANT 321 and PAW software packages were used to simulate the events and to process the results of simulation and the experimental data.

SETUP FOR TESTING THE METHOD ON AN ACCELERATOR BEAM

The method was tested on an ejected pion beam in the SPS accelerator at CERN. A diagram of the experimental setup is presented in Fig. 3. The beam of 180-GeV pions was incident on a carbon target; secondary particles were registered by one plane of microstrip detectors. An electron beam of the same energy was used to calibrate the system. The target-to-detector distance was 75 mm. Two trigger scintillation counters C_1 and C_2 were located immediately past the target.

A converter was not included in the setup because of engineering difficulties, and the target's thickness was reduced to 5 mm in order not to introduce distortions in the pion beam. A trigger signal was generated when the signals from both of the scintillation counters coincided.

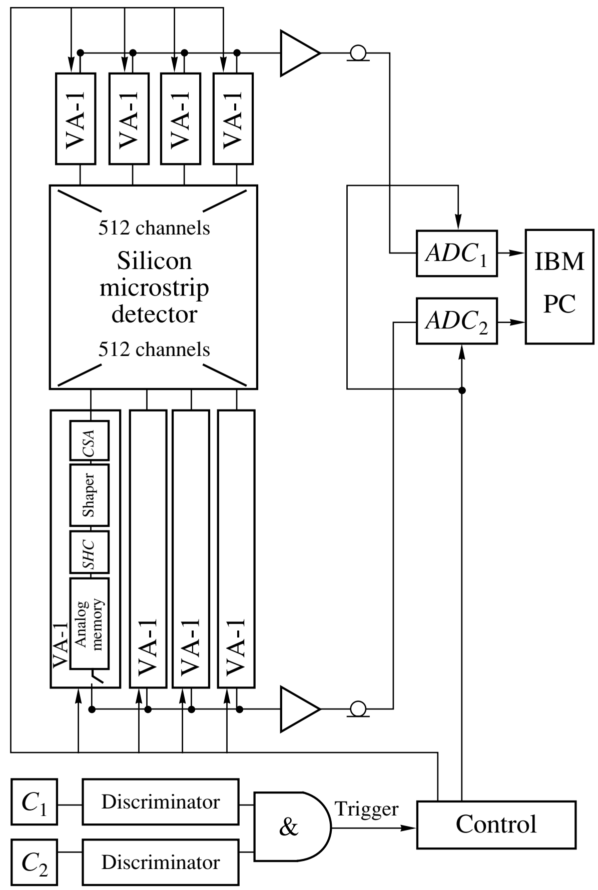

Fig. 4. The detector and the readout electronics.

The microstrip detectors and a readout device were mounted on a common board. The entire unit was shielded with aluminum foil against electromagnetic radiation and light. All components were erected on a mobile steel platform, which readily inserted the setup into the beam.

Each microstrip detector, which was made of high-resistivity n-type silicon, contained 1024 strips separated by 50 μm. The sensitive area was 51 × 50 mm. Each channel was connected to an individual readout input. A flowchart of the electronics is shown in Fig. 4.

Eight 128-channel VA-1 chips (Viking) [4] were used for data readout from each of 1024 strips. Each channel comprised charge-sensitive preamplifier *CSA*, a pulse shaper, sample-and-hold circuit *SHC*, and an analog commutator. Analog signals were transmitted via a ~25-m-long coaxial cable to the IBM PC computer that contained two built-in analog-to-digital converters *ADC*. The mean delay time taken to receive, process, commutate, and transmit data on one event was around 500 μs. Data were recorded in files, each of which contained 256 events. At a beam intensity of 10^5 particle/cycle, approximately one file was recorded during each accelerator cycle (16.8 s).

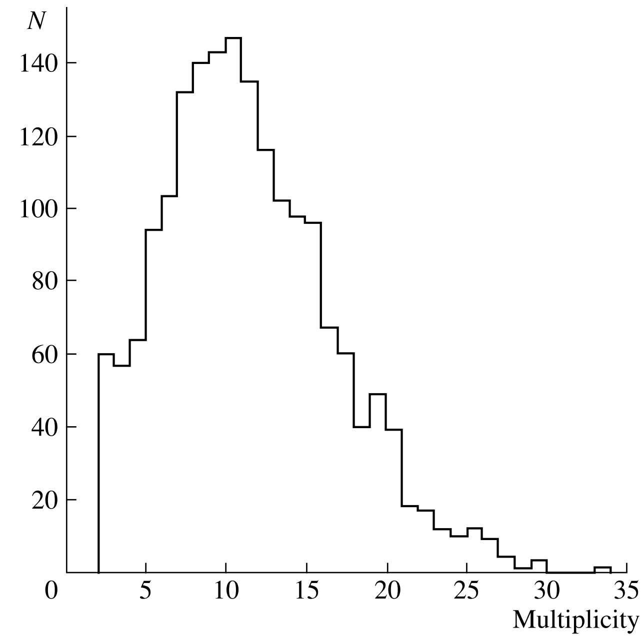

Fig. 5. Distribution of events by multiplicity. The data were obtained by simulating interactions between 180-GeV pions and carbon nuclei.

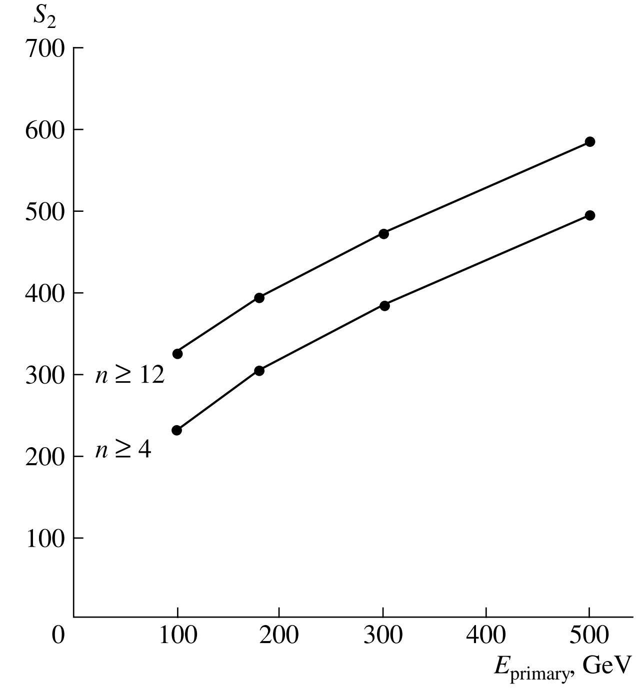

Fig. 6. Energy dependence of parameter S_2, obtained by the simulation at different threshold multiplicities.

To produce a trigger signal, pulses from the scintillation counters first arrived at the discriminators–shapers and then were fed into the AND-to-OR logic circuit. A trigger pulse was generated when signals came from both of the scintillation counters. The threshold of the trigger pulse formers was set at a level corresponding to one minimum-ionizing particle. Owing to the use of a very low threshold, those particles traveling without interaction were also detected, along with nuclear interactions. These particles were rejected during subsequent processing. Noninteracting particles were used to calibrate the electronics and determine the beam profile.

EXPERIMENTAL DATA AND HOW THEY COMPARE TO THE SIMULATION RESULTS

The main objective of the test was to verify the results of the simulations by the experimental data. Although these measurements did not allow us to test the method at operating energies ($1–10^4$ TeV), the good agreement between the experimental data and the results of simulation under the given conditions offered additional confidence that the simulation was also correct for high energy particles.

Separating the hadron interactions inside the target (as was mentioned, only about 1% of pions interacted with the target's nuclei) from the high flow of background events was complicated by the use of a high-intensity beam in combination with a slow readout device, which was designed for experiments with cosmic rays and, hence, with low-intensity events. This led to a large number of random coincidences of several particles, imitating interaction inside the target. In addition, the high level of noise and interference complicated the taking of measurements. Therefore, we had to find a way of discriminating between the real particle interactions and the background events. A distribution of the events by multiplicity of secondary particles is presented in Fig. 5. This distribution was obtained by simulating the interactions between 180-GeV pions and carbon nuclei (i.e., real particle interactions) against the background. Analysis of the experimental data and the results from simulations showed that distinguishing events by their multiplicity is the best method for extracting those caused by pions.

Choosing a threshold involves a trade-off: a high threshold multiplicity causes the statistics to decrease, whereas, at a low threshold, the contribution of background events is too large. After a comprehensive analysis of the results from simulations and the experimental data obtained at different thresholds, we selected a threshold multiplicity of $n \geq 12$. It is seen from Fig. 5 that, at this threshold, ~60% of secondary particles are detected, while the background suppression is virtually total. Note that, in this case, the functional dependence of the mean pseudorapidity on the particle energy is unaltered, while the accuracy of reconstructing the energy is independent of the threshold level. This is demonstrated in Figs. 6 and 7.

Figure 6 shows the energy dependence of S_2 at threshold multiplicities $n \geq 4$ and $n \geq 12$. We see that the

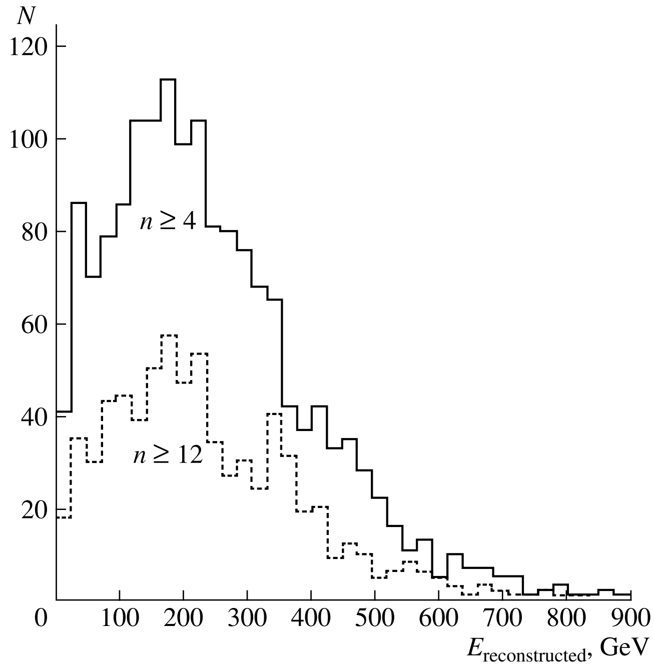

Fig. 7. Reconstructed energies of 180-GeV pions, obtained by simulation at threshold multiplicities $n \geq 4$ and $n \geq 12$. The respective values of the reconstructed energies, their errors, and the numbers of events are as follows: for $n \geq 4$, $\bar{E}$ = 242.1 GeV, σ = 156.8 GeV, and N = 1714; for $n \geq 12$, $\bar{E}$ = 239.5 GeV, σ = 154.5 GeV, and N = 756.

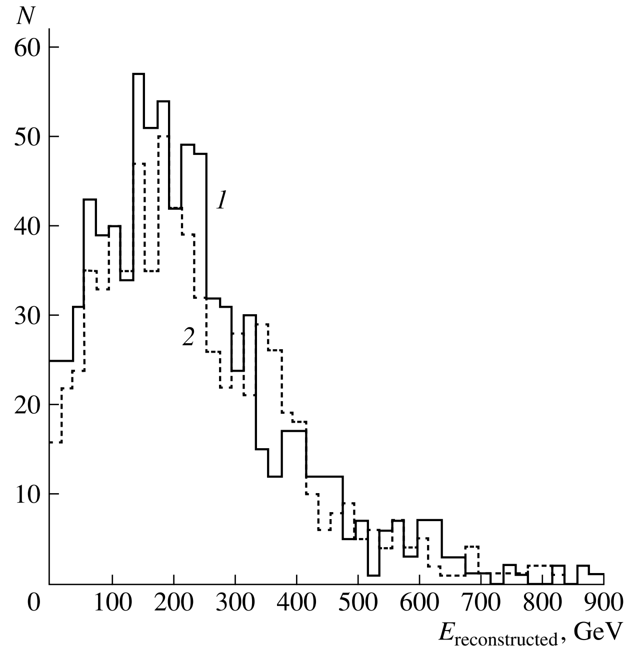

Fig. 8. Comparison of the results from reconstructing the energy (*1*) by the experimental data and (*2*) by the simulation at a pion energy of 180 GeV and a threshold multiplicity $n \geq 12$.

energy sensitivity (i.e., the slope of the curve) is approximately constant.

Figure 7 presents the reconstructed energy distributions obtained by simulating the interactions of 180-GeV pions at threshold multiplicities $n \geq 4$ and $n \geq 12$.The respective mean values of the reconstructed energy and its rms deviation are as follows: $\bar{E}$ = 242.1 GeV and σ = 156.8 GeV; $\bar{E}$ = 239.5 GeV and σ = 154.5 GeV. As a result, neither the mean energy nor the accuracy of its reconstruction are affected by the threshold level, which is selected from the given range.

The energy distributions of incident 180-GeV pions, which were reconstructed using experimental data and the results from simulations at threshold multiplicity $n \geq 12$, are presented in Fig. 8. The figure demonstrates that there is good agreement between these distributions.

CONCLUSIONS

The results of our experiment showed that the method proposed in this paper worked properly at energies of about 200 GeV. In this case, the pion energy can be measured with a relative error of ~67%, very close to the simulation results (65%). It should be noted that these results were obtained with only one array of microstrip detectors and without resorting to a γ-ray converter. It could be expected that the accuracy of measuring the particle energy would be higher using a γ-ray converter and both of the detector arrays.

ACKNOWLEDGMENTS

We would like to thank our colleagues for their assistance in preparing and carrying out our experiment. We especially thank N. Shalanda for his help in adjusting the apparatus; R. Leitner, I. Minashvili, and R. Stanek for their patience; and B. Di Girolamo for his cooperation and patronage. Separate thanks are due G. Moorhead for his care at all stages of carrying out the experiment.

This work was supported by the Russian Foundation for Basic Research, grant no. 01-02-16611.

REFERENCES

1. Grigorov, N.L., Murzin, V.S., and Rapoport, I.D., *Zh. Eksp. Teor. Fiz.*, 1958, vol. 34, p. 506 [*Sov. J. Exp. Theor. Phys.*, 1958, vol. 7, p. 348].
2. Korotkova, N.A., Podorozhnyi, D.M., Postnikov, E.B., *et al.*, *Yad. Fiz.*, 2002, vol. 65, no. 5, p. 884 [*Phys. At. Nucl.*, vol. 65, no. 5, p. 852].
3. Nishimura, J., *Soryusi-ron Kenkyu*, 1956, no. 12, p. 24.
4. Masciocchi, S., Nygard, E., Tocker, O., *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. A*, 1994, vol. 340, p. 572.