Speed Measurement of Cosmic-Ray Particles Using Millimicrosecond Timing Circuit*

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The speed of cosmic-ray particles was measured using a three-channel time-interval-measuring modified chronotron circuit. Results concerning mu-mesons agree with those theoretically expected. For cosmic-ray particles of speeds higher than 0.64 times that of light, about 1.5±0.8 percent of high-speed ionizing particles (excluding electrons) at sea level are protons.

WITH the use of cloud chambers operated in uniform magnetic fields, many measurements have been made on the momentum of cosmic-ray particles.[1] If one has also knowledge of the specific ionization, or range, or momentum loss of the particle itself, or the direction and momentum of a collided particle, one can also determine the speed of the particle. However, frequently, especially for the purpose of selecting or discriminating against special events, it is highly desirable to be able to measure the speed of high-speed particles directly, and preferably by electronic means.

In the following we describe an experiment in which the speed of cosmic-ray particles was measured making use of a millimicrosecond timing circuit.

I. EXPERIMENTAL APPARATUS

The fast timing circuit used was a three-channel time-interval-measuring modified chronotron circuit.[2,3] The two signal pulses, whose time delay was to be measured, were fed into two transmission lines, between which at regular intervals diode detectors were connected. Also, the width of the input signals was made much smaller than the RC time constant of each detector.[4]

A block diagram of the recording circuit is shown in Fig. 1. S_1 and S_2 were two anthracene-in-polystyrene plastic scintillators.[5] They were shaped at both ends to be coupled optically to two RCA 5819 photomultiplier tubes. The pulse from one phototube coupled to each scintillator was separately amplified by a Hewlett-Packard 460A distributed amplifier and then by another fast amplifier. This pulse was then shaped to a width of 1.4 mμ sec. The two pulses thus obtained from the two scintillators were fed into the two input ends of the two transmission lines in the chronotron circuit. These portions of the circuit dealt with pulses in the working range of the order of mμ sec and are labelled as "fast" in the diagram with heavy black lines. The outputs of this circuit were then amplified, delayed, and mixed, to be mixed again with the pulses corresponding to the energy losses of the particle in the two scintillators and detected by the other two coupled phototubes.

The pulse from each of these other two phototubes coupled to the two scintillators was separately amplified, delayed, shaped, and attenuated. The two pulses thus obtained from the two scintillators were then mixed. Part of the output was delayed and amplified for better exhibition of small pulses. These pulses were

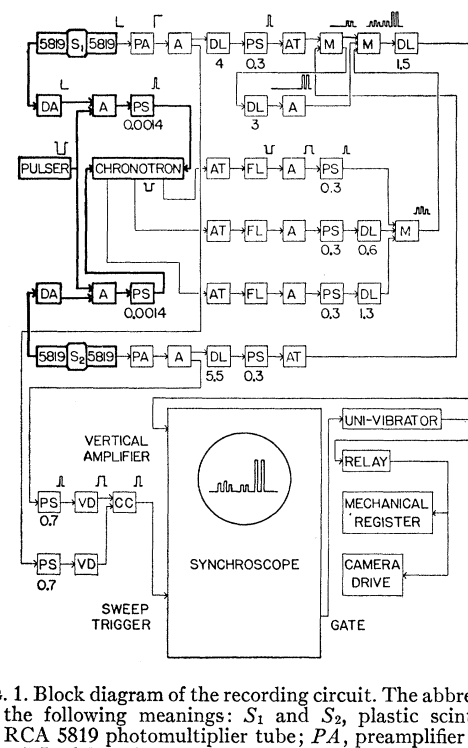

Fig. 1. Block diagram of the recording circuit. The abbreviations have the following meanings: S_1 and S_2, plastic scintillators; 5819, RCA 5819 photomultiplier tube; PA, preamplifier; A, amplifier; DL, delay line unit; PS, pulse shaping unit; AT, attenuator; M, mixing unit; DA, distributed amplifier; FL, feedback amplifier loop; VD, voltage discriminator; CC, coincidence circuit. The approximate wave forms at various points are indicated. The numbers below PS and DL give the width of the pulse and the time of delay, respectively, in μsec. "Fast" portions of the circuit are shown in heavy black lines.

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[1] See, for example, W. L. Whittemore and R. P. Shutt, Phys. Rev. **86**, 940 (1952).

[2] Neddermeyer, Althaus, Allison, and Schatz, Rev. Sci. Instr. **18**, 488 (1947).

[3] J. W. Keuffel, Rev. Sci. Instr. **20**, 197 (1949).

[4] H. K. Ticho, University of California at Los Angeles Technical Report (unpublished).

[5] C. N. Chou, Phys. Rev. **87**, 376 (1952); Phys. Rev. **87**, 903 (1952).

then mixed with the original pulses (before being amplified and delayed) and also with the pulses from the output of the chronotron as described above. They were now fed into the vertical amplifier of the synchroscope and were ready to be displayed on the scope provided that the sweep of the latter was triggered by the following coincidence circuit.

Part of the output of the amplified pulse due to energy loss in each scintillator was separately shaped and fed into a voltage discriminator. The outputs of these discriminators were fed into a coincidence circuit, whose output triggered the synchroscope.

The displayed tracing of pulses was photographed by a camera. A gate pulse from the synchroscope then actuated a univibrator and relay and hence a mechanical register and a camera drive to advance the film forward by one frame and to wait for the next event.

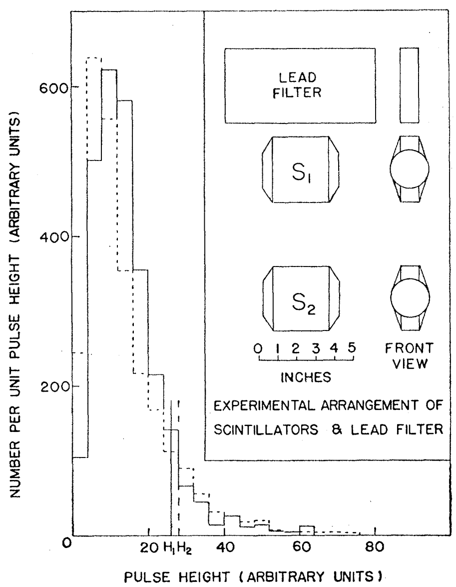

FIG. 2. Pulse-height distributions of pulses due to energy losses in the two scintillators. The solid-line histogram is for scintillator S_1, and the dotted-line one for scintillator S_2.

A fast-pulse generator of the discharge-line type was used for calibration purposes. It fed fast signals of known time delays into the two transmission lines of the chronotron.

During the experiment, a lead block 10 cm thick used as a filter was placed above the scintillators as shown in the inset of Fig. 2.

The experiment was carried out about 600 ft above sea level at 51°N geomagnetic latitude. About 3000 events were recorded and analyzed.

II. PROCEDURE AND ANALYSIS

When a fast particle passed through the two scintillators successively, two pulses from the scintillators met in the chronotron and produced in the output three pulses of different heights (corresponding to the three channels), depending upon the time delay between the two pulses. This time lag gave the speed of the particle since the distance between the scintillators was known. For calibration purpose, various known lengths of transmission line were introduced into one branch of the circuit connecting the pulser to the chronotron. We label the three pulses of the chronotron record as the left-hand pulse P_L, the middle pulse, and the right-hand pulse P_R, as they appear on the film. The height of the middle pulse is normalized to 100 units, and the pulse heights of P_L and P_R are expressed in terms of this "normalized unit." The results of the calibration of the chronotron are shown in the inset of Fig. 3, in which the pulse heights of pulses P_L and P_R are plotted *vs* the known time delay.

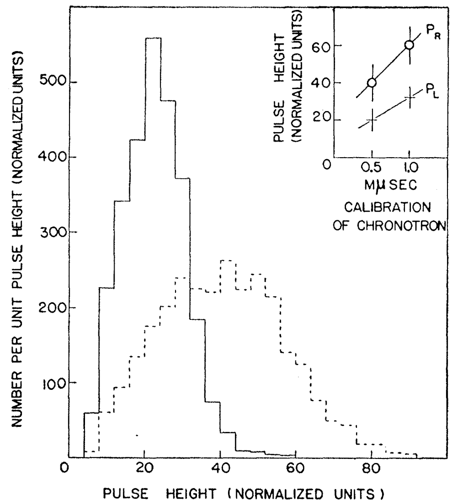

FIG. 3. Chronotron pulse-height distributions for particles of group I. The solid-line histogram is for the left-hand pulse P_L, and the dotted-line one for the right-hand pulse P_R. The unit pulse height used in the ordinate is equal to four times the normalized unit used in the abscissa.

For each ionizing particle recorded, its energy loss in each scintillator was also measured and recorded on the synchroscope display as explained above. In Fig. 2 are plotted the distributions of these pulses due to energy losses in the two scintillators. They are of the approximately Landau type. For scintillator S_1 the line H_1 is drawn such that the area of the solid histogram at the right-hand side of it is 0.1 of the total area of the solid histogram. Similarly, for scintillator S_2, the area of the dotted histogram at the right-hand side of the line H_2 is 0.1 of the total area of the dotted histogram.

We separate all the observed particles into two groups. In group I are particles whose energy losses in the two scintillators were less than H_1 *or* H_2, respectively. In group II are particles whose energy losses in the two scintillators were greater than H_1 *and* H_2, respectively. The distribution of the chronotron pulses, P_L and P_R for particles of group I is plotted in Fig. 3. A similar distribution for particles of group II is plotted in Fig. 4.

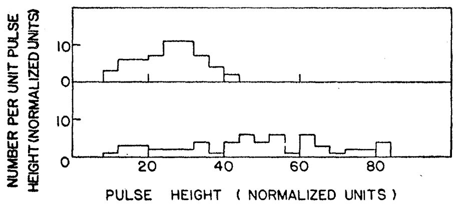

FIG. 4. Chronotron pulse-height distributions for particles of group II. The upper histogram is for the left-hand pulse P_L, and the lower one for the right-hand pulse P_R. The unit pulse height used in the ordinate is equal to four times the normalized unit used in the abscissa.

III. RESULTS AND DISCUSSION

Since 10 cm of lead was placed above the scintillators as filter, we assume that only mu mesons and protons were recorded in the present experiment. From the consideration of range, the particles observed were limited to mu mesons of β equal to 0.93–1.00, and protons of β equal to 0.64–1.00, where β represents the ratio of the speed of the particle to that of light. The lower limits of the value of the momentum measured were $2.4m_0c$ (or 257 Mev/c) and $0.83M_0c$ (or 779 Mev/c), respectively, where m_0 and M_0 denote the rest masses of mu-mesons and protons, respectively. With the separation between the scintillators equal to 17.8 cm, the time delay between the time of traversing the upper scintillator and that of traversing the lower one were 0.64–0.59 mμ sec for mu mesons and 0.92–0.59 mμ sec for protons, respectively. From Fig. 3 and the chronotron calibration in the inset, we see that the maxima of P_L and P_R for particles of group I fall in the time interval 0.6–0.7 mμ sec, within the statistical fluctuations. This group of particles should consist mostly of relativistic mu mesons.

We have 57 events in group II of the particles. From the criteria of selecting the particles of this group, we expect that $0.1\times0.1\times2700$, or 27 events were mu-mesons of large energy losses in both scintillators. The remaining 30 events should be due to protons, since we assume that only mu mesons and protons were recorded. We know that the energy loss of protons of speeds around 0.6 that of light is about twice its minimum value at higher speeds. This is in agreement with the shift of the maxima of P_L and P_R for particles of group II in Fig. 4, as indicated by the chronotron calibration given in the inset of Fig. 3.

We now proceed to estimate the contribution of high-speed protons to the spectrum of high-speed ionizing particles at sea level. We make use of the empirical momentum spectrum of the particles penetrating 10 cm of lead at sea level,[6] and normalize it to the data of the present experiment. We also make use of the fact that while the intensity of primary protons at the top of the atmosphere is about twenty times the mu-meson intensity at sea level,[7] only about 0.5 percent of the sea-level intensity is left as protons of high energy because of the loss through nuclear interactions in the atmosphere. From these and our data we find that for particles of speeds higher than 0.64 times that of light about 1.5 ± 0.8 percent of high-speed ionizing particles at sea level are protons. This result can be compared with the result of momentum measurement[8] that for momenta higher than 0.7 Bev/c less than four percent of all ionizing particles at sea level are protons and that for higher momenta the fraction is much less.

For a fixed distance between the scintillators, let v and t denote the speed of the particle and the time of traversal between the two scintillators, respectively. We then have the relation

$$\Delta v/v = \Delta t/t.$$

While Δt is a more or less fixed quantity in a particular experimental setup, the accuracy of individual speed measurement can be increased by increasing the value of t, i.e., by increasing the distance between the scintillators.

The spread of the individual measurements about the most probable value in the chronotron records can be improved considerably by more careful selection of diode detectors and by more efficient temperature control of the surroundings.

Also, if higher accuracy is desired, a greater number of channels for the chronotron is desirable.

Obviously, with suitable modifications, this circuit can be combined with other accessory circuits for the purpose of selecting or discriminating against special events in cosmic-ray or high-energy phenomena, based upon the speed distributions of the primary or secondary particles.

IV. ACKNOWLEDGMENTS

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[6] Caro, Parry, and Rathgeber, Nature **165**, 689 (1950).

[7] Winckler, Stix, Dwight, and Sabin, Phys. Rev. **79**, 656 (1950).

[8] M. G. Mylroi and J. G. Wilson, Proc. Phys. Soc. (London) **A64**, 404 (1951).