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The Hard Component of Cosmic Rays in the Upper Atmosphere*

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An experiment has been performed in the upper atmosphere to study charged cosmic-ray particles that penetrate 20 cm of lead. These particles were divided into two groups depending on whether or not they interacted on traversing the lead. The experimental equipment, which consisted of the lead absorber, G–M tubes in coincidence, and radio telemetering devices, was carried to high altitudes by an array of 36 balloons. The rate of occurrence of particles in the two groups was determined as a function of atmospheric depth from 16 g-cm^{-2} to 400 g-cm^{-2}. The experimental results can be interpreted in terms of high energy protons and μ-mesons, with corrections for low energy protons and primary alpha-particles. The results are consistent with a primary proton intensity equal to 0.19 cm^{-2} sec^{-1} sterad^{-1}, an absorption length in air of 110 g-cm^{-2} for high energy protons, and the μ-meson production spectrum given by Sands.

I. INTRODUCTION

MOST investigations of the development of high energy cosmic rays in the upper atmosphere have involved measurements of the altitude- and angular-dependence of the hard component. Work done prior to 1948 has been discussed in some detail by Rossi.[1] Since that time, hard component measurements in the upper atmosphere have been made by Winckler *et al.*,[2] Pomerantz,[3] Vidale and Schein,[4] and others.

Rossi,[1] using the results of experiments at mountain altitudes, has analyzed the results of the hard component experiments in terms of two groups of particles: those which readily undergo nuclear interactions (chiefly protons), and those which do not readily undergo nuclear interactions (μ-mesons).

In order to study more directly the composition of the hard component at high altitudes, a balloon-borne experiment has been performed, in which the essential difference between the protons and μ-mesons (i.e., their very different probability for nuclear interaction) was explicitly involved.

II. EXPERIMENTAL METHOD

The detecting equipment used is shown in Fig. 1. A telescope consisting of G–M tubes A and B in time coincidence defined the passage of charged particles through 20 cm of lead. The AB coincidences were divided into two groups, $(AB-C)$ and $(AB+C)$, depending on whether or not they were accompanied by a discharge of one or more G–M tubes in the C tray which covered both sides of the lead absorber. The absorber was 3.5 cm wide and extended 15 cm perpendicular to the plane of the diagram. The purpose of this arrangement was to differentiate between particles which traversed the lead without interacting, and therefore gave rise to $(AB-C)$ events, and particles which suffered nuclear interactions on traversing the lead, many of which gave $(AB+C)$ events. Mu-mesons, of course, belong to the first group, while a large fraction of the high energy protons belong to the second group. Mu-mesons having kinetic energy greater than 295 Mev and protons having kinetic energy greater than 500 Mev were able to traverse the 20 cm of lead in the telescope.

The balloon-borne telemetering system is shown in Figs. 2 and 3. The G–M pulses were passed through preamplifiers and blocking oscillator pulse-forming circuits to a diode coincidence circuit which provided pulses of different magnitudes corresponding to the $(AB-C)$ and $(AB+C)$ events. A time modulator converted pulses of different magnitudes to pulses of different durations. These pulses were then used to modulate the frequency of a 70-Mc radio transmitter. They were received on the ground, presented on an oscillograph, and recorded photographically.

Individual G–M tube counting rates were monitored periodically. For this purpose, a clock altered the form of the coincidence circuit for 40 seconds every seven minutes. In this way the operation of the equipment during a flight was checked, and the resulting data on

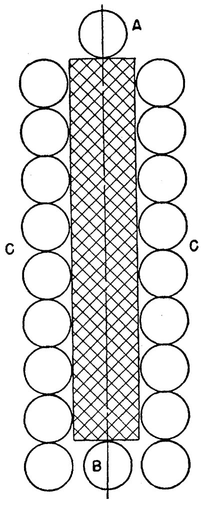

FIG. 1. The detecting instrument. The G–M tubes have an active volume 2.41 cm in diameter and 13.7 cm in length. The lead absorber is 20 cm by 3.5 cm by 15 cm.

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[1] B. Rossi, Revs. Modern Phys. **20**, 537 (1948).

[2] Winckler, Stroud, and Shanley, Phys. Rev. **76**, 1012 (1949).

[3] M. A. Pomerantz, Phys. Rev. **75**, 69 (1949).

[4] M. Vidale and M. Schein, Phys. Rev. **81**, 1065 (1951).

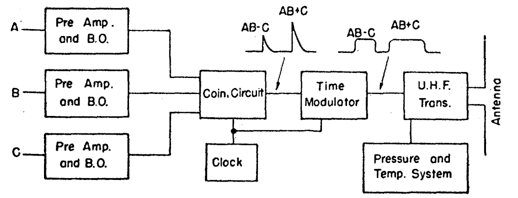

FIG. 2. Block diagram of the balloon-borne telemetering system.

single G–M tube rates were used to estimate accidental coincidence rates.

Atmospheric pressure was measured by means of an aneroid cell and switching device,[5] and temperature was measured by means of a thermistor located near the G–M tubes. The temperature and pressure data were transmitted to the ground over the same telemetering channel used for the coincidence data, modulating pulses of opposite polarity being used for the two types of data.

The complete balloon-borne equipment is shown in Fig. 4. It was about six feet in height and weighed 120 pounds. The equipment was carried to high altitudes by 36 Neoprene balloons.[6] Ten additional balloons,[7] filled to break at 25,000 feet, were used to lift the array rapidly in the lower part of the atmosphere. The flights were made from Lexington, Massachusetts (geomagnetic latitude 55 deg. N.).

III. EXPERIMENTAL RESULTS

Figure 5 shows an altitude-time curve for one of the balloon flights. Data were taken during the ascent. The results to be presented are based on two such flights, the data for the two being in agreement within the statistical errors. The combined results for two flights are given in Table I and by the experimental points in Figs. 6 and 7. In all cases, corrections for counting errors and accidental coincidences were less than the statistical errors in the data.

The shapes of the curves for the two events are considerably different.

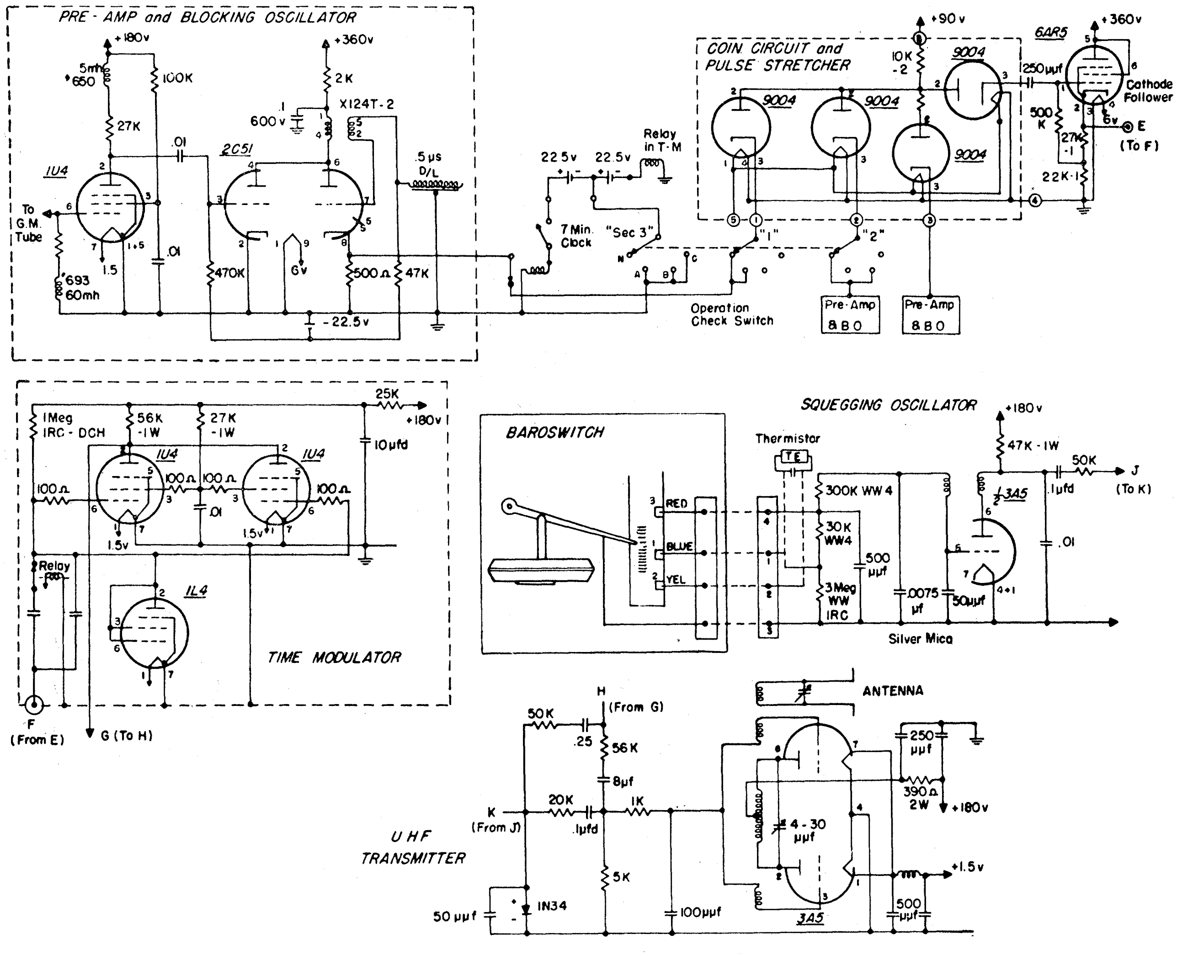

FIG. 3. Schematic diagram of the balloon-borne electronic circuits.

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[5] Baroswitch, Kollsman Instrument Company.

[6] J-8-18-800 balloons, Dewey and Almy Company.

[7] J-100 balloons, Dewey and Almy Company.

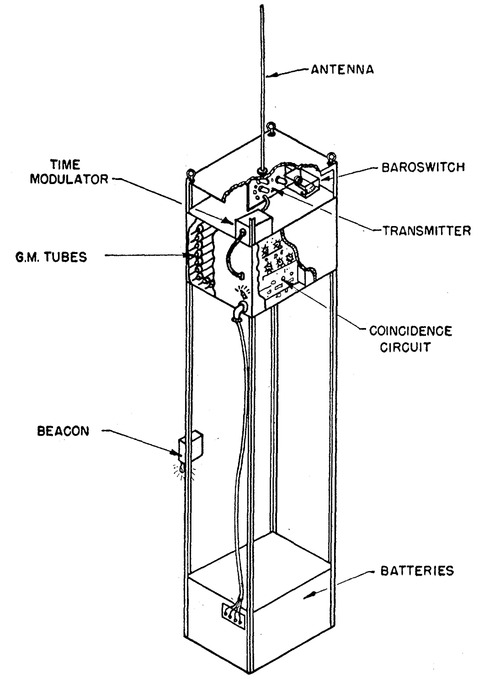

FIG. 4. The complete balloon-borne equipment.

TABLE I. The experimental results; all numbers in the body of the table are coincidences per hour.

Atmos. depth g-cm^{-2}	$(AB-C)$	Standard deviation $(AB-C)$	$(AB+C)$	Standard deviation $(AB+C)$
19	528	45	787	55
22.5	477	40	624	46
30	531	39	645	39
42	496	31	578	34
60	507	31	533	32
80	528	39	371	33
94	444	47	389	45
106	521	47	364	40
125	467	38	225	28
150	373	32	229	26
185	400	29	176	20
222	296	30	144	22
255	277	27	147	20
291	244	32	135	24
325	299	38	65	18
362	198	31	72	18
401	155	30	56	18

Some protons and most of the μ-mesons traversing the telescope contribute to the $(AB-C)$ curve. It is likely that the $(AB+C)$ coincidences are due primarily to high-energy protons. The slope of the $(AB+C)$ curve corresponds to an absorption length in air of about 110 g-cm^{-2}. This extends our knowledge of the altitude variation of the intensity of high-energy protons, which was previously known[8] only for atmospheric depths greater than about 300 g-cm^{-2}.

IV. ANALYSIS OF THE DATA

We have calculated the expected $(AB-C)$ and $(AB+C)$ counting rates, making the following assumptions: (a) the production spectrum for μ-mesons is that derived by Sands[9] from the results of Rossi's analysis of the hard component[1] and from measurements of the altitude dependence of the slow μ-meson intensity; (b) the primary cosmic-ray proton energy spectrum is that given by Peters;[10] (c) the absorption length in air of high energy protons (kinetic energy greater than 1000 Mev) is 110 g-cm^{-2};[11] (d) the mean free path for nuclear interaction of protons in the lead

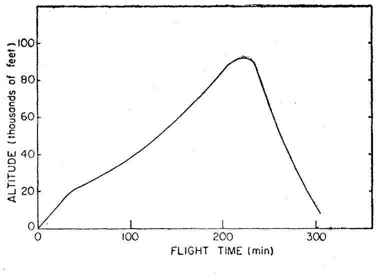

FIG. 5. Altitude-time curve for the flight of August 14, 1951.

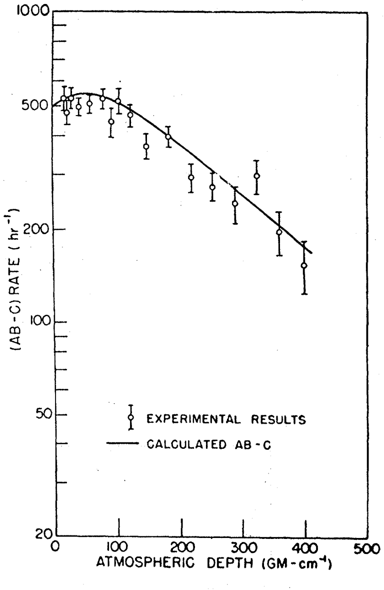

FIG. 6. The $(AB-C)$ results.

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[8] J. Tinlot, Phys. Rev. **73**, 1476 (1948); **74**, 1197 (1948).

[9] M. Sands, Tech. Report No. 28, LNSE, Massachusetts Institute of Technology (1949).

[10] B. Peters, *Progress in Cosmic Ray Physics* (Interscience Publishers, Inc., New York, 1951), Chapter IV.

[11] This value for the absorption length, which is a result of the combined effects of nuclear interactions and ionization losses, corresponds to an absorption length of 120 g-cm^{-2} resulting from nuclear interactions alone. The absorption length which includes the effects of ionization losses is, of course, dependent upon the proton energy spectrum. The minimum energy chosen for the "high energy proton" group coincides approximately with the geomagnetic cut-off energy at the latitude where the experiment was performed. Thus one should not expect any "transition effect" for the high energy protons on account of the geomagnetic cutoff. However, the primary radiation does not contain neutrons and for this reason one may expect the absorption length for high energy protons near the top of the atmosphere to be somewhat different from that observed at lower altitudes where the proton and neutron components are in approximate equilibrium with one another. No indication for this difference has been found in the present experiment.

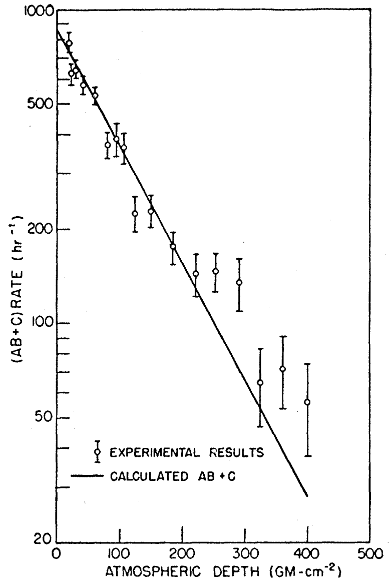

FIG. 7. The $(AB+C)$ results.

absorber is 168 g-cm^{-2} (geometric). Corrections were made for primary alpha-particles and for low-energy protons (500–1000 Mev kinetic energy). Effects of the electronic component were negligible except for the case of $(AB+C)$ events at large atmospheric depths.

The calculated results are given by the solid lines in Figs. 6 and 7. To obtain a fit to the experimental data, we made the following additional assumptions: (e) interactions in the lead of low energy protons (kinetic energy 500–1000 Mev) were unable to produce $(AB+C)$ events; (f) half the low energy protons which interacted in the lead were unable to cause either event; (g) 12 percent of the interactions in the lead of high energy protons (kinetic energy greater than 1000 Mev) caused $(AB-C)$ events; (h) 9 percent of the interactions of high energy protons in the lead were unable to cause either event. The calculations are described in some detail elsewhere.[12] In Fig. 8 are presented curves showing the contributions of various groups of particles to the $(AB-C)$ events, and in Fig. 9, similar curves for the $(AB+C)$ events.

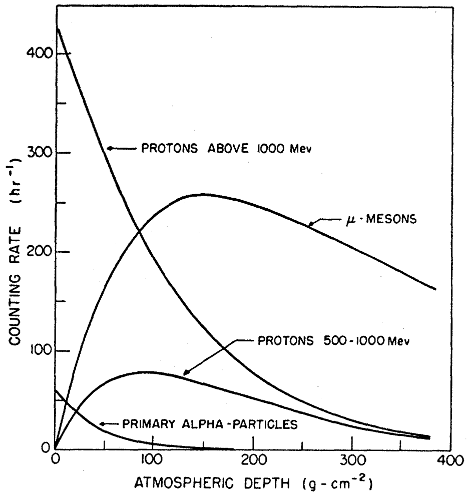

FIG. 8. The $(AB-C)$ calculated results.

V. DISCUSSION

The calculated $(AB+C)$ curve deviates from the experimental points for atmospheric depths greater than 225 g-cm^{-2}. The difference is very likely due to the effects of air showers, which are known to be unimportant for atmospheric depths less than about 200 g-cm^{-2}.[13]

Figure 9 shows that $(AB+C)$ events are due almost entirely to high energy protons. Thus the $(AB+C)$ results confirm the assumed absorption length (110 g-cm^{-2}) of protons in the upper atmosphere.

Figure 8 shows that at depths near 20 g-cm^{-2} most of the $(AB-C)$ events are due to high energy protons, while at depths greater than 250 g-cm^{-2} most of these events are due to μ-mesons. Thus the agreement between the computed curve and the experimental points in Fig. 6 provides some confirmation for the assumed dependence of meson production on depth. For example, our results would be in definite disagreement with the crude assumption that all mesons are produced at a depth of 100 g-cm^{-2}, an assumption sufficient to explain most of the observations on μ-mesons at lower altitudes.

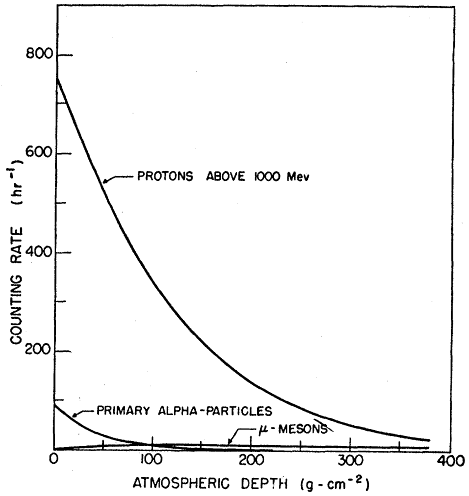

FIG. 9. The $(AB+C)$ calculated results.

It is estimated that one can vary by about 20 percent the contributions of high energy protons and μ-mesons to the computed counting rates before these are in serious disagreement with the experimentally observed rates. Thus, to an accuracy of about 20 percent, our results confirm the absolute intensity of primary protons as given by Peters and the absolute value for the rate of production of μ-mesons as given by Sands.

It is a pleasure to thank Professor Bruno Rossi for his help and encouragement, and Mr. Philip Zlochiver for his assistance with the experimental work.

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[12] M. A. Clark, Tech. Report No. 59, LNSE, Massachusetts Institute of Technology (1952).

[13] A. T. Biehl and H. V. Neher, Phys. Rev. **83**, 1169 (1951).