Cosmic Rays as a High-Energy Particle Source*

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A large cloud-chamber-ion-chamber stack has been designed and operated to measure the properties of the interactions in light materials of cosmic-ray protons and pions in the energy range greater than 140 GeV. The usable flux of these particles at sea level is limited to the measured value of $(1.3\pm0.1)\times10^{-4}$ m^{-2} ster^{-1} sec^{-1} by the requirement that each particle be unaccompanied by time-coincident particles in the aperture of the apparatus of 0.22 m^2-ster. With the use of this flux and the apparatus described, an interaction cross section for protons in carbon can be measured for energies up to 300 GeV in about a year. In the use of the ionization spectrometer, large fluctuations in the absorption curve have been observed that preclude the use of the shape of the curve alone to measure the energy of individual events.

COSMIC rays represent the only available source of particles with energies in excess of those produced by machines, presently at a maximum of about 3×10^{10} eV. The cosmic rays are a "beam" of particles with energies extending at least up to 10^{20} eV at the top of the atmosphere, but with extremely low flux and poor angular collimation. At any appreciable depth in the atmosphere, each high-energy particle is part of an essentially time-coincident shower of many particles of different types and energies. The use of such a beam in the study of individual high-energy interactions presents several unusual problems not encountered with machines, where the identity energy and direction of the particles can be controlled. Several large-scale experiments[1,2] have been proposed to cope with these problems. The experiment to be described here uses apparatus on an intermediate scale that has provided information that may be helpful in the design of future experiments.

The apparatus consists basically of an array of 12 flat cloud chambers and 8 flat ion chambers that can be interleaved with flat slabs of absorbers in various combinations. Each cloud chamber has a sensitive volume $152\times76\times10$ cm and expands vertically in the direction of the small dimension in about 25 msec. The horizontal top and bottom surfaces are of aluminum with a total surface density of 5.4 g/cm^2 per cloud chamber. Each ion chamber has a sensitive volume $156\times92\times10$ cm filled with a mixture of 98% argon and 2% CO$_2$ to a total absolute pressure of 2.0 atm, and the iron horizontal top and bottom surfaces have a mass per unit area of 40.0 g/cm^2 total for each chamber. Additional slabs of iron absorber, each of 40.6 g/cm^2, are interleaved between the eight ion chambers to form an ionization spectrometer of the general type used by several other groups.[3-6]

The entire array of total height 6 m is photographed from the side by two cameras taking stereoscopic photographs from a distance 11.8 m with a demagnification of 24:1. The photographs record the cloud chamber tracks as well as the size of the pulse from each ion chamber, the total of the pulses from all of the chambers, and miscellaneous information concerning the electrical and mechanical operation of the equipment.

An initial arrangement of the array to study the details of high-energy interactions in carbon is shown in the photograph in Fig. 1. At the top of the stack, a cloud chamber (No. 0) locates the track of a charged high-energy particle, which then passes through a carbon target of 111 g/cm^2. If the particle interacts in the carbon, the charged secondary particles leave tracks in successive cloud chambers (No. 1 through No. 10) in the stack below the block of carbon. Between cloud chambers 8 and 9, there are two radiation units of lead. These layers of lead serve to start electron showers along the paths of the γ rays from the decay of any π^0 mesons among the secondary particles of the interaction. Beneath cloud chamber 10 is a hodoscope, which is discussed in connection with the cross section measurements, and then the stack of 8 ion chambers and their interleaved absorbers. The total mass in the spectrometer is 604 g/cm^2 of iron. At the bottom of the stack, cloud chamber 11 gives information about any charged particles that may pass completely through the spectrometer and emerge from the bottom.

The cloud chambers are triggered and a photograph taken of the chambers and the associated meters whenever

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[1] Proceedings of Conference on the Interaction Between Cosmic Rays and High Energy Physics, Case Institute of Technology (Sept. 1964).

[2] L. W. Jones, Univ. Mich. Tech. Rept. No. 21 (Oct. 1965).

[3] N. L. Grigorov, V. Nurzin, and I. Rapoport, Soviet Phys. JETP (English Transl.) 7, 348 (1958).

[4] N. L. Grigorov, N. A. Kondratiev, A. J. Savelieva, V. A. Sobinyakov, A. V. Podgurskaya, and V. Ya. Shestoperov, Moscow Conference 1, 130 (1960).

[5] V. V. Guseva, N. A. Dobrotin, N. G. Zelevinskaya, K. A. Kotelnikov, A. M. Lebedev, and S. A. Slavatinsky, J. Phys. Soc. Japan **17**, Suppl A-111, 375 (1962).

[6] P. V. R. Murthy, B. V. Sreekantan, A. Subramanian, and S. D. Verma, Nucl. Instr. Methods **23**, 245 (1963).

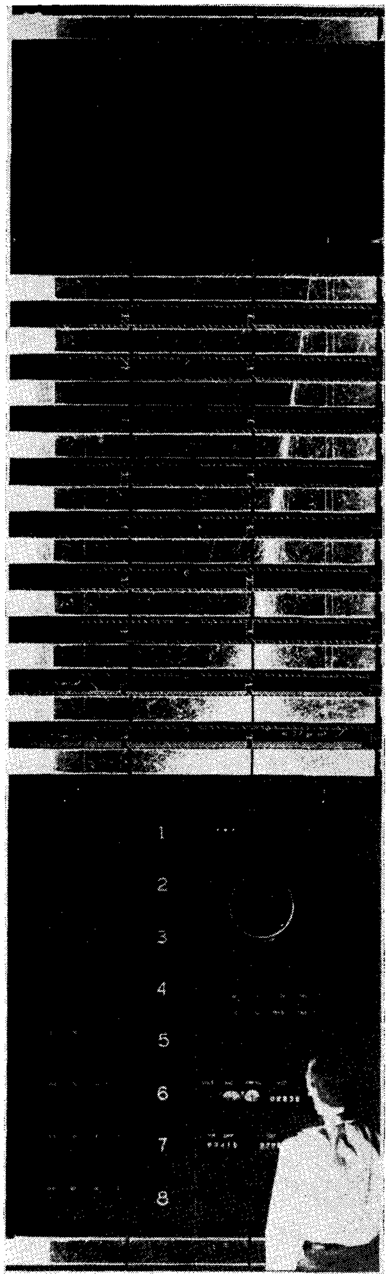

FIG. 1. The cloud-chamber-ion-chamber stack, showing a 3000 GeV penetrating shower initiated by an interaction in the 111 g/cm^2 carbon block beneath the top cloud chamber. The ion chambers lie behind the numbers 1 through 8 in the lower third of the photograph and read respectively 2050, 855, 211, 22.8, 0, 28.5, 28.5, and 0 GeV. A person has been added to show the scale.

a preset bias is exceeded (corresponding to about 140 GeV for most of the past operation) in coincidence with at least one charged particle passing through an area of 50 by 100 cm immediately above the first ion chamber. With a minimum energy requirement of 140 GeV, the triggering rate for the apparatus, which is at 250 m above sea level, averages about 1.8/h. In about 20% of the pictures, the nature of the particle or particles initiating the pulses in the ion chamber is not indicated by tracks in the cloud chamber, either because the particle is neutral or because the path of the particle makes a large angle with respect to the vertical and misses all of the cloud chambers. About 40% of the pictures show a diffuse rain of electrons without any identifiable strongly interacting particles. Many of the higher energy readings recorded corresponded to such electron showers, with various numbers and densities of cores. It is not possible to identify penetrating particles in these cores with the exception of μ mesons that may pass completely through the spectrometer and be visible in chamber 11. Another 20% of the pictures show mixed showers that contain a strongly interacting particle, but also contain associated particles that contribute an unknown amount of energy to the ion chamber readings. The remaining 20% of the pictures show single particles that may or may not have interacted above the ion chambers, but which appear to be responsible for the ion chamber pulses. This last group of pictures is further reduced by the selection of particles with paths in an aperture such that there is no "leakage" of energy from the sides of the ionization spectrometer. The following usable particle fluxes remain, and these are expressed in absolute terms.

The average flux of protons and pions singly traveling in the aperture 0.22 m^2 ster (centered on the vertical) and with energy greater than 140 GeV is measured to be $(1.3\pm0.1)\times10^{-4}$ m^{-2} ster^{-1} sec^{-1}. The fact that this number is considerably lower than estimates currently being made in conjunction with plans for more elaborate apparatus may be a consequence of the requirement that there be no accompanying particles within the 0.22 m^2 ster aperture.

An estimate of the proportion of protons and charged pions in the sample has been made by the following method. A separate experiment using a cloud chamber with 11 iron plates containing a total of 254 g/cm^2 of material was used to count the number of charged and neutral primary particles that transferred more than 50 GeV (estimated from the shower particles) in interactions in the iron. A total of 138 charged primary particles (protons and pions) and 47 neutral primary particles (neutrons) was observed. Strange particles contributed a negligible number. For the energy range and elevation being considered, the ratio of charged pions to nucleons (neutrons and protons) has been calculated[7] to be 0.29. These two results combine to give an answer of approximately 70% protons and 30% charged pions in the pion-proton component of sea-level cosmic rays of energy greater than 140 GeV. The calculated ratio of protons to neutrons under these conditions is about 2 to 1.

The high proportion of one type of particle is fortunate for the present apparatus, since no distinction can be made between protons and pions. A special camera is being added to photograph chamber 0 with sufficient resolution to count droplets and obtain some lower limit on the velocity

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[7] L. T. Baradzei, V. I. Rubtsov, Y. A. Smorodin, and M. V. Solovyov, *Proceedings of the International Conference on Cosmic Rays, Jaipur* (1963), p. 283.

of the primary particle from the shape of the ionization vs velocity curve at relativistic velocities, but the success of this method of identification is questionable.

It is interesting that there is an appreciable flux of singly traveling high-energy electrons at sea level. These are identified by their interaction in the two layers of lead and by the nature of the absorption curve as measured by the ionization chambers. In the energy range above 140 GeV, the flux measured by the apparatus in the 0.22 m^2-ster aperture is approximately $5\times 10^{-6}\ \mathrm{m}^{-2}\ \mathrm{ster}^{-1}\ \mathrm{sec}^{-1}$. These electrons presumably come from the decay of high-energy μ mesons in the air within a few radiation units of the apparatus, and the number is roughly that obtained by calculation. This represents a possibly overlooked source of single electrons in an energy range well beyond that of present machines.

Initially the apparatus has been used to look at the secondary particles coming from the interaction of high-energy particles in the carbon target. In many photographs, the charged particles in the cone of secondary particles can be resolved. However, in a surprisingly high percentage of the interactions, such as the one shown in Fig. 1, the particles in the forward cone cannot be resolved, and it is therefore not possible to obtain useful statistical results on the multiplicity or angular distribution of the secondary particles. (It has not usually been found possible to resolve the γ rays from the decay of π^0 mesons by means of the showers developing in the layers of lead.)

In order to reduce the material that might produce further multiplication of particles along the path of the secondary particles from the initial interaction, cloud chambers 2 through 7 were removed from the stack. The narrow cone of particles from the target then spreads out in the 1.5 m of free air below chamber 1. Under these conditions, occasional shower cores still contain as many as 100 or more particles, which are impossible to resolve. These dense showers may result from fluctuations in the multiplicity, which has an average value only of the order of 10 for energies near 300 GeV. In addition, fluctuations in the proportion of charged and neutral mesons may produce an unusually high proportion of π^0 mesons among the secondaries.[8] The γ rays from the decay of these mesons produce electron secondary particles in the carbon and aluminum that is unavoidably present in the upper section of the stack. Such electrons have paths very close to the shower axis even though they are of comparatively low energy. A magnetic field of large extent appears to be essential in the design of future apparatus, both to separate out such electrons and to measure the momentum of individual secondary particles.

A second type of experiment that is presently in progress with this apparatus is the measurement of the interaction cross section of protons in light materials as a function of the energy. If photographs are selected that show an interaction of a penetrating particle, then a maximum likelihood procedure can be used with the location of the point of interaction to determine the cross section. This type of measurement has the disadvantage of giving the cross section only for transfer of large amounts of energy (the energy transfer is required to identify the energetic particle) and of being limited to heavy materials that can give a depth of several interaction lengths in a reasonable geometry. The maximum likelihood procedure becomes increasingly difficult when the total target thickness becomes comparable to the interaction length or if any bias is introduced in the location of the point of interaction in the target. These appear as competing difficulties when light material is used in a thick target.

A somewhat different procedure appears to be more feasible with the present form of the apparatus. A search is made in all of the photographs for individual particles of high energy, as indicated by the ionization spectrometer, whether or not these particles interact in the target material. (This unfortunately excludes as primary particles the neutrons, which are the only type of primary that can be identified with reasonable certainty, and which can be used with the maximum likelihood procedure.) If all high-energy particles that traverse the target can be identified, an interaction length can be calculated directly from the total length of material traversed by all of the primary particles and the total number of interactions. A small correction may be necessary for those particles that interact twice in a single thickness of the target, since this would ordinarily not be detected. The feasibility of this procedure with the present apparatus has been confirmed in a preliminary experiment using the aluminum walls of the cloud chambers as the target.

The main difficulty in this type of cross section measurement arises in separating the tracks of noninteracting high-energy particles from the clutter of unrelated but nearly time-coincident tracks in the cloud chambers. This problem was alleviated by the addition of a hodoscope that displays the horizontal coordinates of the Geiger tubes triggered in two crossed trays directly above the ion chambers. This device was helpful when only a few tubes were triggered, but of less use when large numbers of tubes were triggered by stray time-coincident particles of low energy that might not enter the cloud chambers. In the latter case, the picture was often removed from consideration by the presence of multiple particles from a distant interaction, and this removal was done irrespective of the presence of a local interaction. Although the number of aluminum interactions to date is insufficient to yield a reliable value for the aluminum cross section, it appears to

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[8] Z. Buja, B. Heller, J. Massalski, and B. Niziol, Acta Phys. Polon. 27, 609 (1965).

be possible to single out nearly all of the high energy particles.

Another possible source of error that must be considered in a cross section measurement of this type results from including in the sample of strongly interacting particles the high-energy muons that transfer sufficient energy by multiple pion production in the spectrometer to exceed the bias level. Calculations based on recent theoretical and experimental values for muon interactions[9] indicate a rate of fewer than 8 muon triggers per year, or less than 1% of the rate of single, nuclear-active particles above 140 GeV.

Since it is clear that the apparatus is better suited to cross section measurements than to statistical studies of multiplicity and angular distribution of secondaries, the carbon target has been redistributed to facilitate a carbon cross section measurement. The stacking arrangement now consists of alternating carbon slabs and cloud chambers, beginning with a cloud chamber on top, followed by 24 g/cm^2 carbon, etc., until there are 6 cloud chambers and 5 slabs of carbon. Beneath the sixth cloud chamber are 4 radiation units of lead, the seventh cloud chamber, the Geiger trays, the spectrometer, and a final cloud chamber as before. The run time required to measure a carbon cross section as a function of energy with this arrangement has been estimated on the basis of the flux and energy spectrum of particles previously measured by the apparatus. Figure 2 shows the estimated time required to record 100 carbon interactions (protons on carbon) within an energy band $\Delta \log_{10} E = 0.30$ at various energies. It has been assumed for the estimate that the interaction length in carbon remains constant at 92 g/cm^2 for all energies $>$140 GeV. At mountain altitudes (of the order of 4000 m) the flux of protons is increased by roughly tenfold over that at sea level, but the number of particles unaccompanied in a given aperture may not change by the same ratio.

The following information on the performance of the ionization spectrometer may be of interest, since the general principle is being incorporated into the design of a number of high-energy cosmic-ray experiments. Twenty-one events have been selected due to singly traveling particles in the energy range 210±70 GeV, none of which had an interaction before entering the spectrometer. For the purpose of the following comparison, the ion chamber readings were normalized for each of the 21 events so that the total of the eight ion chambers equalled the mean total energy (200 GeV). From the average normalized readings of the individual ion chambers, the numbers of electrons in the chambers were calculated and plotted as circles in Fig. 3 to be compared with curves calculated by Pinkau and Thompson[10] for the numbers of electrons as a function of depth of iron for a particular model of the nuclear interaction. Several curves with different values of inelasticity, multiplicity, and energy appear in the figure.

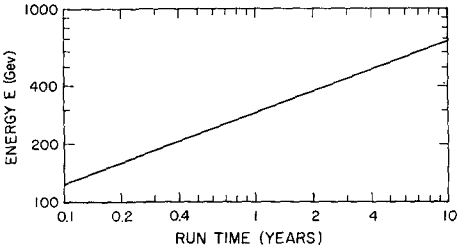

FIG. 2. Estimated run time required to record 100 proton interactions in carbon in an energy band $\Delta \log_{10} E = 0.3$, as a function of proton energy.

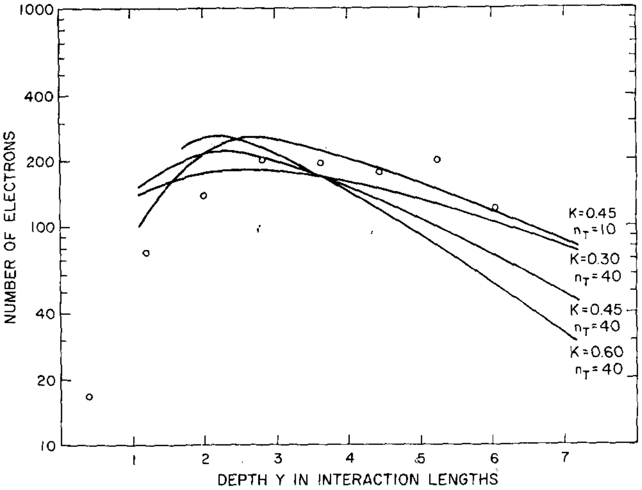

FIG. 3. The average distribution of ion-chamber readings for 21 strongly interacting particles in the energy range 210±70 GeV is shown by circles. The continuous curves were calculated by Pinkau and Thompson for particles of energy 210 GeV with interactions of inelasticity K and multiplicity n_T.

The shape of the average distribution is seen to be in closest agreement with the curve for $K = 0.45$ and $n_t = 10$, which are reasonable values of the inelasticity and multiplicity.[11] Although the average of the 21 events is consistent with these values, the number of events is too small to draw conclusions concerning the average inelasticity and multiplicity. Individual distributions fluctuate widely from the average curve as seen from some of the more extreme cases plotted in Fig. 4. The deviations are due in part to the infrequency of sampling (every 6 radiation units), but another effect seems to be important and less easily avoided. There are fluctuations from the calculated curves corresponding to widely separated maxima in the measured curve, such as shown in Fig. 4(c), that appear to correspond to unusually wide separations between the interactions of the primary particle. For example, a particle that interacts to produce the first of the two maxima has a probability of 1/20 of going three interaction

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[9] S. Higashi, T. Kitamura, Y. Mishima, S. Miyamoto, Y. Watase, and H. Shibata, Nuovo Cimento **38**, Series 10, 107 (1965).

[10] K. Pinkau and K. V. Thompson, Rev. Sci. Instr. **37**, 302 (1966).

[11] L. F. Hansen and W. B. Fretter, Phys. Rev. **118**, 812 (1960).

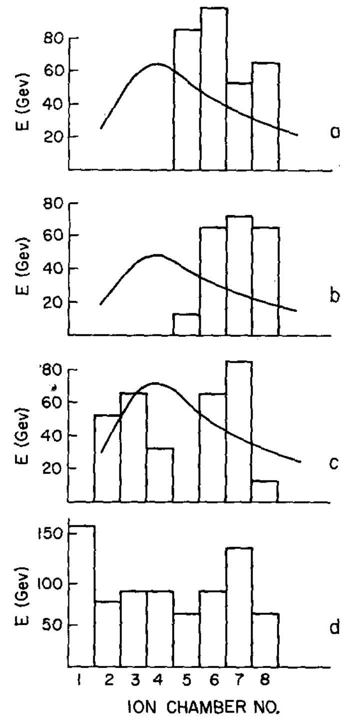

FIG. 4. Large fluctuations in the distribution of ion-chamber readings for individual events. The curves in (a), (b), and (c) are those of Pinkau and Thompson for $K=0.45$, $n_T=10$, and $E=210$ GeV, normalized in each case to the total energy recorded by the spectrometer. In (d), a particle that interacts high in the stack loses 690 GeV in the spectrometer. There is no indication from the shape of the distribution of the amount of energy lost through the bottom.

lengths (about 4 chambers and plates) before interacting again to produce the second maximum. The secondaries from the initial interaction have a high probability of being completely absorbed before the second interaction. The probability of 1/20 is consistent with the number of such events observed. There is a similar probability for a delayed maximum as in Figs. 4(a) and 4(b). A significant number of events has also been observed in which the readings of the lower ion chambers are zero, but, nevertheless, one or more high energy particles are observed in the lower cloud chamber to have escaped from the bottom of the spectrometer. In the event shown in Fig. 1, for example, such particles are visible (in the original negative) in the lower cloud chamber. For an accurate energy measurement of a single event, it is therefore not possible to rely on measurements based on the shape of the absorption curve. It is necessary to stop *all* of the particles in the spectrometer. This requires a much thicker spectrometer than that used here, even though its depth is calculated to be sufficient to stop most of the particles in the energy range being considered.

Several types of errors may enter into the spectrometer measurements, that is, actual errors in measurement rather than fluctuations in the true ionization curve in the iron. Heavily ionizing particles that run the long dimensions of the chambers in the gas may contribute an appreciable reading. A stopping proton with a range of 100 cm in the argon can contribute 30 GeV to the reading of that chamber. The number of such protons visible in showers in the cloud chambers would indicate, however, that their presence in the ion chambers is rare except in very energetic events where they do not constitute a major source of error. Leakage of particles out of the sides of the ion chambers does not appear to be significant for the aperture used. A more important effect is the entrance *into* the sides of the ion chambers of time-coincident shower particles that are not observed in the cloud chambers at the top and bottom of the spectrometer. The energy contributed by such particles is mistakenly attributed to another particle. Since an anticoincidence blanket around the sides of the spectrometer would nearly always be activated by stray low energy particles, the best solution is to provide some information about the spatial location of the cores of particles in the spectrometer, either by subdividing the ion chambers or by inserting near the center of the stack a detector of shower cores with coarse spatial resolution. (One of the flat cloud chambers is being inserted in the present arrangement.) The probability of this type of error decreases for particles near the vertical, and for the 0.22 m^2 ster aperture used, the effect does not seem to be large. There is no significant correlation between particles with double-maximum absorption curves and particles at a large angle from the vertical.

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