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Cross-Section Measurement near 50 Bev*

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An experiment to measure the cross section for high-energy cosmic-ray protons and neutrons to interact with the Fe nucleus has been carried out at 3250 m elevation. The detector had a relatively good energy resolution, and was designed to select nucleons in the vicinity of 50 Bev. The purpose was to obtain a single interaction cross section with good accuracy in order to compare it with results obtained with accelerators in the 1- to 5-Bev region. This comparison yields a value for the elementary meson-production cross section [the average of $\sigma(pp)$ and $\sigma(np)$] near 50 Bev. The Fe results are: neutrons, $\sigma_{\text{Fe}}=0.61\pm0.03$ barn; protons, $\sigma_{\text{Fe}}=0.61\pm0.04$ barn. The corresponding average nucleon-nucleon "inelastic" (presumably meson production) cross section is $\sigma_{\text{nucleon}}=21\pm4$ millibarns.

I. INTRODUCTION

Cosmic rays provide the only source of nucleons with energies above ~10 Bev that is presently available. The flux of such particles—about 10^{-4} cm^{-2} sec^{-1} at mountain altitudes—is adequate for measurements of the gross properties of nuclear cross sections at energies in the 10 Bev–100 Bev region; many investigations have been carried out, with the result that the relative probabilities for different processes are now known in a general way. Absolute values of nuclear cross sections have also been measured, though with less precision; they are interesting because they indicate the general trend of the elementary, i.e., (np) and (pp), cross sections with energy. Using the results of nuclear cross-section measurements obtained with Bev-range machines, one can infer the elementary cross sections for meson production from measured values of the nuclear cross sections.

We report on a measurement of the collision cross section[1] of iron for cosmic-ray neutrons, and also protons, of about 50 Bev. Our purpose was to do a relatively simple experiment, on a single substance, using well-known techniques, but to obtain high statistical accuracy at high energy by means of a large apparatus and long observing time. The interest in such a measurement was stimulated by the observation that existing cosmic-ray cross sections tended generally to be higher than the corresponding cross sections measured with Bev-range machines; an attempt to interpret this as an increase in elementary cross section[2] indicated that a surprisingly large increase in cross section would be needed.

The present experiment finds a cross section for iron which is slightly lower than those measured with ~1-Bev protons and neutrons by the Brookhaven groups. We therefore do *not* confirm the results quoted in reference 2, but find that the elementary cross sections (for meson production by protons or neutrons) decrease somewhat, or at most remain constant, with energy.

II. EXPERIMENTAL METHOD

The basic experiment for a "total" cross section of some kind—in our case the inelastic or collision cross section, since we necessarily have "poor" geometry in which scattering goes unnoticed—is the attenuation experiment, comparing the counting rate of a detector with and without an absorber in the beam. Techniques for doing this in the cosmic-ray beam were worked out by Cocconi and others,[3–6] following the scheme of Rossi and Regener[7]: (1) One chooses a detector which (ideally) responds only to nucleons (and, in practice, pions, which are present in the cosmic-ray beam and which we shall lump with the protons) and only above a certain energy. (2) When the absorber is placed above the detector, one makes provision to exclude counts from those very-high-energy particles which lose some energy by interacting in the absorber but still exceed the detector threshold.

The detector used in this experiment depends on the fact that mesons are produced when a high-energy nucleon collides with a nucleus in a local layer of iron. The energy measurement is based on the electronic cascade arising from the neutral mesons. The amount of ionization near the maximum of the shower is proportional to the amount of energy in the shower, which in turn is, on the average, about $\frac{1}{3}$ of the energy in all the mesons, charged and neutral.[8] The detector is also designed to require the presence of at least two highly-penetrating particles among the secondaries, since otherwise the electromagnetic processes of high-energy muons (whose flux greatly exceeds that of the nucleons)

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[1] The terms collision, absorption, inelastic, or reaction cross section are used by different authors to describe the nonelastic part of the total cross section. At high energies an experimental definition is implied, since one cannot hope to separate cleanly all inelastic events from the elastic ones. For the present experiment the problem is discussed in Sec. II, where it is shown that what is measured is the particle-production cross section.

[2] R. W. Williams, Phys. Rev. **98**, 1393 (1955).

[3] G. Cocconi, Phys. Rev. **75**, 1074 (1949).

[4] W. D. Walker, Phys. Rev. **77**, 686 (1950).

[5] K. Sitte, Phys. Rev. **78**, 714 (1950).

[6] J. Tinlot and B. Gregory, Phys. Rev. **75**, 519 (1949).

[7] B. Rossi and V. Regener, Phys. Rev. **58**, 837 (1940).

[8] G. Salvini and Y. Kim, Phys. Rev. **88**, 40 (1952).

would contribute an undesirable background by causing cascade showers similar to those caused by the π^0's.

Figure 1 shows the arrangement actually used at Echo Lake, Colorado, elevation 3260 m. The collision whose secondaries are detected occurs in the 6 in. ×36 in.×48 in. block of iron labeled "producing layer." The ionization measurement is made by the large double ionization chamber [9] directly beneath the producing layer; essentially it is two parallel-plate chambers, one above the other. One inch of lead (about 5 radiation lengths) above the sensitive volume of the upper chamber causes most of the cascades in the energy range of interest that originate in the producer to be near their maximum development as they cross the chamber. The $\frac{1}{4}$-in. lead plate between upper and lower chambers does not affect the cascade markedly (since it is near its maximum development), but prevents heavily-ionizing nuclear particles from traversing both chambers. Thus a coincidence between the two chambers assures us that an electronic cascade is present. With suitable calibration, the pulse height is a quantitative measurement of the number of electrons traversing the chamber.[10] Pulse-height discrimination therefore affords a relatively sharp energy threshold. The known properties of cascade showers, plus the assumption that the cascades when measured are near their maximum, then yield directly the energy of the initiating gamma rays. The energy measurement is much more definite than that obtainable from the usual device, which relies on the multiplicity of penetrating particles.

Minimum energy loss in each chamber was set at 8 Mev (actually 1.5 times the Po-alpha end point), which corresponds to 142 electrons. Heavily-ionizing particles from secondary nuclear disintegrations occurring in the ionization-chamber walls will occasionally increase the amount of ionization in one chamber (for example, a proton at the end of its range can lose up to 5.7 Mev in traversing the chamber vertically). We minimize this error by relying on the smaller of the two ionization-chamber pulses for the energy estimate. The probability that an event below the threshold energy be recorded because of secondary nuclear events in *both* chambers is estimated to be small, of the order of one percent.[11]

The minimum shower of 142 electrons corresponds to an energy of 9.2 Bev in the initiating gamma rays, or about 30 Bev in the secondaries of the interaction. The energy of the incident nucleon is greater by the ratio $1/(1-K)$, where K is the "elasticity" of the interaction; K is nearly zero in the Fermi statistical theory, but high-energy cosmic-ray results require that the nucleons retain an appreciable fraction of the energy—a recent determination[9] suggests the average value $K\sim\frac{1}{3}$, and other workers have proposed even larger values.[12] However, no direct determination is available, and we shall not put in a correction for elasticity; our energy values are therefore subject to upward revision by up to a factor of two.

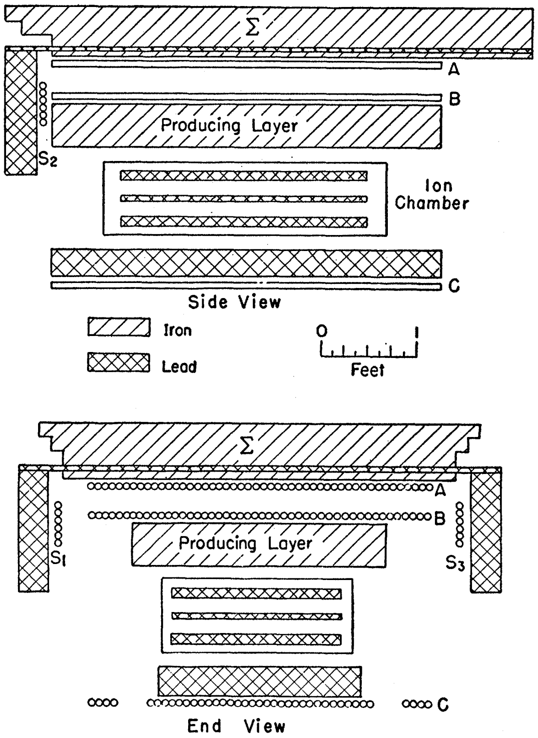

FIG. 1. Diagram of experimental arrangement. Trays A and B each consist of 44 Geiger tubes 48 in. long and 1 in. in diameter, which are hodoscoped as are the 38 similar tubes of Tray C. Trays S_1, S_2, and S_3 each contain Geiger tubes, in parallel, also 48 in.×1 in. The removable absorber, Σ, consists of 6 in. of iron, with base dimensions of 48 in.×60 in. The producing layer is of iron 6 in.×36 in.×48 in. Between Σ and Tray A there is a 1-in. layer of iron and a $\frac{1}{2}$-in. layer of lead permanently in place. The effective plan dimensions of the ionization chamber are 32 in. ×22 in. The plates of the ionization chamber are 1 in., $\frac{1}{4}$ in., and 1 in. lead. The material between the ionization chamber and Tray C is of lead 4 in.×27 in.×48 in.

In Fig. 1, the trays labeled A, B, and C contain 1 in. ×48 in. Geiger tubes connected to a hodoscope which was photographed each time an ionization chamber coincidence indicated that a high-energy collision had occurred. Tray C served to enforce the requirement that two penetrating particles be present: to be counted

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[9] This chamber was developed by H. S. Bridge and L. Altman, and is described more fully elsewhere [L. Altman, Ph.D. thesis, Massachusetts Institute of Technology, 1956 (unpublished)].

[10] The calibration procedures, depending ultimately on a polonium alpha source, are similar to those described by H. S. Bridge and R. H. Rediker, Phys. Rev. **88**, 206 (1952). This method of measuring number of electrons has been checked by direct comparison with a cloud chamber in connection with experiments of W. E. Hazen and collaborators [e.g., Hazen, Williams, and Randall, Phys. Rev. **93**, 578 (1954)].

[11] Since the number-energy curve of cosmic-ray nucleons is fairly steep there will undoubtedly be some subthreshold events included in our sample. However, it will be seen below that the cross-section curve is not changing rapidly in this energy region, so that no correction need be applied.

[12] It is shown below, however, that at least one argument for large K is based on a false assumption.

TABLE I. Counting rates for various events. Errors are standard deviations from counting statistics, with the exception of the correction error discussed in the text.

Event	Energy band, in terms of Po alpha ionization equivalent	Counting rate, hr^{-1}, no absorber	Counting rate, hr^{-1}, with absorber
neutron	$1.5\alpha-3\alpha$	1.79 ± 0.05	0.75 ± 0.03
neutron	$3\alpha-6\alpha$	0.61 ± 0.04	0.26 ± 0.02
neutron	$6\alpha-18\alpha$	0.14 ± 0.02	0.05 ± 0.01
proton	$1.5\alpha-3\alpha$	1.31 ± 0.05	0.58 ± 0.03
proton	$3\alpha-6\alpha$	1.15 ± 0.05	0.51 ± 0.02
proton	$6\alpha-18\alpha$	0.39 ± 0.03	0.16 ± 0.01
"meson"	$1.5\alpha-3\alpha$	0.69 ± 0.03	0.57 ± 0.03
"meson"	$3\alpha-6\alpha$	0.51 ± 0.03	0.42 ± 0.02
"meson"	$6\alpha-18\alpha$	0.13 ± 0.02	0.13 ± 0.01
proton, corrected	$1.5\alpha-3\alpha$	1.80 ± 0.05	0.77 ± 0.03
proton, corrected	$3\alpha-6\alpha$	1.55 ± 0.05	0.64 ± 0.03
proton, corrected	$6\alpha-18\alpha$	0.42 ± 0.04	0.13 ± 0.03
Total counting rate, 2-fold coincidences:		32.50	22.06

an event must discharge at least two nonadjacent tubes in tray C, and therefore at least two particles must have traversed 180 g cm^{-2} of Pb. The record of the two top trays is used to select the beam; only neutron events (no tubes discharged in A and B) or "clean" proton events (essentially a single tube in each tray, with the common line headed for the producing layer) were accepted.

A record was also made of the ionization-chamber pulse heights, and of discharges of the trays S which guard against particles incident at very large angles.

The experiment then consisted of repeatedly recording the counting rate of accepted events with and without the absorber—the 6 in. layer of iron labeled Σ in the figure. A collision in the absorber removes a particle from the beam either by dropping its energy below threshold or by causing extra discharges in A and B. It is clear that the cross section measured in this way is just the high-energy meson-production (or in general particle-production) cross section, and that non-meson-producing inelastic collisions will be lumped with elastic collisions as unobservable. One would expect on kinematic grounds that the transition between the two is abrupt, and there is some experimental evidence that this is so.[13]

To obtain the cross section from the measured attenuation, one must take into account the nonparallel character of the beam. We approximate the angular distribution of the cosmic-ray nucleons around the vertical[14] by $I(\theta)=I_v\cos^7\theta$, and find the appropriate average path length, which proves to be 12% greater than that for particles incident vertically.[15]

There are several small corrections which will not be discussed in detail, such as accidental coincidences, barometric corrections, and inefficiencies of the Geiger trays. An important precaution against spurious effects consisted in leaving a large slab of iron (actually 1 in. of iron plus $\frac{1}{2}$ in. of lead) permanently in place above tray A. This assured us that (a) knock-on electrons ejected from the absorber Σ could not reach tray A; and (b) the low-energy electrons which accompany some high-energy nucleons are at least partly removed. These electrons could give rise to a spurious effect, since with no absorber they would cause extra discharges in tray A, therefore excluding the accompanying nucleon from the sample, whereas with Σ present the electrons would be filtered out.

III. RESULTS AND DISCUSSION

Table I shows the counting rates obtained in 1500 hours of operation. Only $\frac{1}{6}$ of the total rate of ionization chamber coincidences satisfied the criteria for a "pure" nucleon beam (even less with absorber in place). Most of the discarded events were multiple discharges in trays A and B, but there is one class of events which is readily recognizable—the knock-on or bremsstrahlung-initiated showers due to high-energy muons. These events resemble proton events except that only the parent particle survives below the apparatus, so that only one tube of tray C is discharged. The rate of such "meson" events is displayed in Table I; the interpretation is confirmed by the fact that the rate is almost unaffected by the addition of absorber. This affords a direct method of estimating the number of spurious "proton" events caused by muons. These events arise because a low-energy gamma ray from such a meson-induced shower may occasionally penetrate the 25 radiation lengths of material below the ionization chambers and set off a counter in tray C. We have used the results of Greisen[16] to subtract these spurious events; the last rows of Table I show the corrected proton rates. We have arbitrarily assigned a relative error of 50% to the correction, which is itself an energy-dependent quantity, amounting to 5% of the whole sample. In thus assigning a larger error

TABLE II. The cross sections for penetrating-particle production by high-energy neutrons and protons on iron nuclei. Errors are standard deviations, with the exception of the correction error discussed in the text.

Energy range (Bev)	Median energy (Bev)	Neutron cross section (barns)	Proton cross section (barns)
28– 58	37	0.60 ± 0.04	0.59 ± 0.05
58–121	77	0.62 ± 0.05	0.61 ± 0.06
121–387	178	0.67 ± 0.13	0.79 ± 0.25
28–387	50	0.61 ± 0.03	0.61 ± 0.04

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[13] Walker, Duller, and Sorrels, Phys. Rev. **86**, 865 (1952).

[14] See, for example, E. P. Todd, thesis, University of Colorado, 1955 (unpublished).

[15] Useful results for simple geometries have been tabulated by E. Whitmer and M. Pomerantz, J. Franklin Inst. **246**, 293 (1948).

[16] K. Greisen, Phys. Rev. **75**, 1071 (1949).

to the proton data we have taken into account two small adverse effects in addition to the correction described. One is the internal consistency of the data: the proton data were subject to a long-term drift outside of statistics, an effect which is however averaged out by the frequent placing and removal of absorber. The other is the pion contamination, which depends on elasticity and is of the order of 10% (although pions may well have properties very similar to nucleons at this energy).

The cross sections for meson production by neutrons and protons on iron nuclei are given in Table II, for the various energy ranges. In each case, and for the aggregate, we quote the median energy, on the basis of a $dE/E^{2.3}$ spectrum.[2] Three points should be noted:

(1) The neutron and proton results agree.

(2) There is only slight indication of an increasing cross section with energy, not significant within the statistics. We lump all the data, obtaining the numbers in the last row, with a median energy of 50 Bev.

(3) The iron cross section, $\sigma=0.61\pm0.03$ barn (1 barn $=10^{-24}$ cm^2), is not greatly different from the cross sections measured at the cosmotron for 1.4-Bev neutrons[17] and 0.87-Bev protons[18]; it is lower by about 10% (the Cosmotron measurements were on other elements; a value for iron has been obtained by interpolation).

Taking the usual viewpoint that for high-energy events the nucleons in the nucleus can be considered to be independent, we therefore conclude that the effective *elementary* cross section for the occurrence of measurable events—the average of σ_{np} and σ_{pp}, which, following custom, we shall call $\bar{\sigma}$—cannot be very different at 50 Bev from what it is at 1 Bev.[19] We have pointed out that for our experiment a "measurable event" means particle production. For the Cosmotron experiments a wide-angle scattering also would be a measurable event, so that the effective elementary cross section $\bar{\sigma}$ would be intermediate between the meson-production and total cross sections. In the original papers[17,18,20] $\bar{\sigma}$ was tentatively identified with the *total* elementary cross section, about 43 millibarns at those energies. However, the elastic part of the total cross section is strongly peaked in the forward direction, at least for (pp) collisions[21] [it has not been measured for (np)], suggesting that in the nucleus such collisions are relatively ineffective, or in many cases inhibited by the Pauli principle. It therefore appears that $\bar{\sigma}$ should be closer to the meson-production cross section, which is about 25 mb near 1 Bev.[22] This assertion is supported by consideration of the magnitude of the absorption cross sections measured at Brookhaven, and their interpretation in terms of the nuclear density distribution found from electron scattering: the cross sections correspond to a $\bar{\sigma}$ of $\sim$30 mb rather than the 43 mb assumed in the original papers.[23]

Our cosmic-ray measurement therefore indicates a $\sigma_{\text{meson production}}$ somewhat smaller than the $\bar{\sigma}=30$ mb which fits the Cosmotron data. To be more quantitative, we must calculate the transparency curve which relates the observed inelastic cross section to a function of the mean free path in nuclear matter, and therefore (with a known nuclear density distribution) to the effective elementary cross section $\bar{\sigma}$.

This is readily done, once the nuclear density distribution $\rho(r)$ is known. Hofstadter and his collaborators[24] have measured the *charge*-density distribution $\rho_{\text{ch}}(r)$ for a large group of undistorted nuclei. They find an essentially constant region surrounded by a surface region in which the density drops smoothly to zero. The "radius" to the point of 50% of central density, c, scales approximately as $A^{\frac{1}{3}}$, $c=r_1A^{\frac{1}{3}}$, with values of r_1 from 1.05×10^{-13} cm to 1.096×10^{-13} cm; while the region of dropping density stays constant. The latter is conveniently measured by the distance for 90% to 10% density change, t, and they find $t=(2.4\pm0.3)\times10^{-13}$ cm. We shall assume that for a given nucleus the nucleon density is proportional to the charge density; that is, that the spatial distribution of neutrons is the same as that of protons. A recent experiment with high-energy pions[25] has shown this to be true even for the heaviest elements. We therefore could take $\rho(r)$ directly from Hofstadter's work, except that the transparency calculation ignores the finite range over which the elementary interaction can take place. This effect can be treated approximately by using an "effective" density distribution $\rho_e(r)$ which extends somewhat farther out than $\rho(r)$.[20] We have taken, for the parameters of $\rho_e(r)$, $t=2.6\times10^{-13}$ cm; $r_1=1.15\times10^{-13}$ cm. The latter, which is 7% larger than Hofstadter's mean value for the charge distribution, gives the best fit to the Cosmotron experiments,[17,18,26] when $\bar{\sigma}=30$ mb is used as the effective elementary cross section.

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[17] Coor, Hill, Hornyak, Smith, and Snow, Phys. Rev. **98**, 1369 (1955).

[18] Chen, Leavitt, and Shapiro, Phys. Rev. **99**, 857 (1955).

[19] This is contrary to conclusions drawn in reference 1 from previous cosmic-ray data.

[20] R. W. Williams, Phys. Rev. **98**, 1387 (1955).

[21] Smith, McReynolds, and Snow, Phys. Rev. **97**, 1186 (1955).

[22] R. P. Shutt in *Sixth Annual Rochester Conference on High-Energy Nuclear Physics* (Interscience Publishers, Inc., New York, 1956), p. IV-6.

[23] This discrepancy was overlooked in the original analysis in terms of a realistic density distribution (reference 20) because the emphasis then was on the heaviest nuclei, whose cross sections are relatively intensitive to $\bar{\sigma}$. When the density distribution for lighter nuclei became available it became clear that $\bar{\sigma}$ would have to be reduced. These arguments will be elaborated in a summary of transparency curves and relevant cross-section measurements, to be published elsewhere.

[24] Hahn, Ravenhall, and Hofstadter, Phys. Rev. **101**, 1131 (1956).

[25] Abashian, Cool, and Cronin, Phys. Rev. **104**, 885 (1956).

[26] Abashian, Cool, and Cronin (to be published). Dr. Cool has pointed out to us that there is another effect which also makes r_1 appear larger than the extent of the true density distribution:

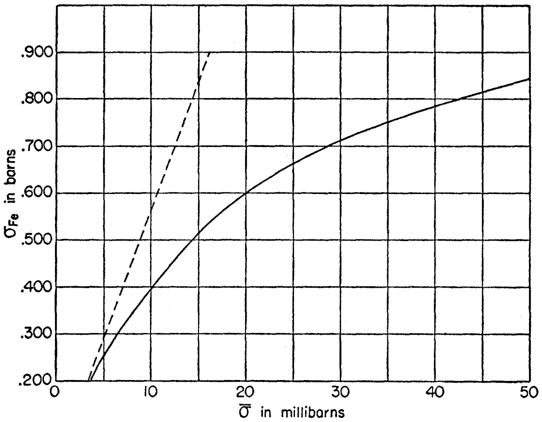

FIG. 2. Transparency curve for Fe, calculated by using for the parameters of the effective density distribution $\rho_e(r)$: $t=2.6\times10^{-13}$ cm and $r_1=1.15\times10^{-13}$ cm. For $\sigma_{Fe}=0.61$ b it is seen that $\bar{\sigma}=21$ mb. The dashed curve represents $A\bar{\sigma}$, the cross section for a completely transparent nucleus.

The calculation of the inelastic cross section for any nucleus, as a function of $\bar{\sigma}$, now is a simple generalization of the standard nuclear transparency theory.[27] It differs from the results of reference 20 only because the taper of the nucleus, t, is not assumed to scale as $A^{\frac{1}{3}}$ but is held constant, with the result that there is no universal transparency curve. The transparency curve for Fe is shown in Fig. 2.

Our result for the interaction cross section in Fe, $\sigma_{Fe}=0.61\pm0.03$ barn, corresponds, on the curve of Fig. 2, to an elementary meson production cross section $\bar{\sigma}=21\pm2.5$ mb. The error corresponds to the statistical error in σ_{Fe}. In fact, however, the Fe curve itself depends on the value assumed for $\bar{\sigma}$ for the ~1-Bev Cosmotron experiments; we are in effect determining $\bar{\sigma}$ at 50 Bev relative to that at 1 Bev, and our error should include the uncertainty in $\bar{\sigma}$ at 1 Bev, which we estimate to be 15%. Compounding the error which this causes in $\bar{\sigma}$ with the statistical error, we find $\bar{\sigma}=21\pm4$ mb as the average cross section for meson or particle production in *np*, *pp*, and *nn* collisions at ~50 Bev.

The meson-production cross section therefore has not changed greatly as one goes from 5.3 Bev, where the (*pp*) inelastic cross section is[22] ~25 mb to an energy around 50 Bev. There remains the puzzle of the previous cosmic-ray measurements of collision mean free paths at energies probably in the 5–50 Bev region; some of these, cited in reference 1, correspond to cross sections considerably larger than our measurement would indicate. The only measurement quoted for Fe is $\sigma_{Fe}=0.81\pm0.12$ b; this was apparently not corrected for the deviation from vertical of the cosmic-ray beam, but still seems high compared to our 0.61 b. The Pb results offer more difficulty—they are much larger than the cross section one would calculate from the transparency curves and $\bar{\sigma}=21$ or 25 mb, so large in fact that they led, in reference 2, to the incorrect inference that the elementary cross section must be very large, over 100 mb. We have no convincing explanation for these very short mean free paths. We can find other results which do agree with our expectations (mean free path ~210 g cm^{-2}) but there is no reason to select them from the whole sample. The results in reference 2 for carbon are closer to our expectations, though still somewhat high.[28]

IV. CONCLUSIONS

The average (*np*) and (*pp*) cross section for meson production at ~50 Bev, which we find to be ~21 mb, is not very different from that in the 1–5 Bev range. This, combined with the fact that meson multiplicity does not change much with energy[29] and that curious-particle production does not seem to be copious,[30] suggests that the gross features of collision processes in this energy region will not prove to be qualitatively different from those at energies now accessible to machines.

The small value of the cross section has an interesting consequence for the analysis of cosmic rays in the atmosphere: the collision mean free path in the 10–100 Bev range must be 100–110 g cm^{-2}, far larger than the 70 g cm^{-2} usually assumed.[31] This means that the observed absorption length of cosmic-ray nucleons in the atmosphere (125 g cm^{-2}) can be explained without invoking a very large degree of elasticity (energy retention by the bombarding nucleon) in the average collision in air. A smaller elasticity is in better harmony with the spirit of the Fermi or Landau statistical models of meson production. The absolute value of the cross section is much less than the $\pi(\hbar/m_\pi c)^2=62$ mb which Fermi assumed.[32] It corresponds to a smaller volume of interaction ($R\sim0.8\times10^{-13}$ cm) and therefore somewhat lower multiplicity.[33]

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the Fermi statistics cause similar nucleons in the nucleus to tend to stay apart. They therefore are more likely to be hit by a passing particle than one would infer from the usual transparency calculation. See R. J. Glauber, Physica **22**, 1185 (1956).

[27] Fernbach, Serber, and Taylor, Phys. Rev. **75**, 1352 (1949).

[28] Recent extensive unpublished results of Todd [E. P. Todd, thesis, University of Colorado, 1955] on carbon do agree with our predicted values.

[29] W. D. Walker and N. M. Duller, Phys. Rev. **93**, 215 (1954).

[30] M. Kaplon and D. Ritson, Phys. Rev. **88**, 386 (1952).

[31] In calculating the cross sections of C, N, and O, we have used the data on the charge density distribution in C given by Jerome H. Fregeau, Phys. Rev. **104**, 225 (1956).

[32] E. Fermi, *Elementary Particles* (Yale University Press, New Haven, 1951), p. 81.

[33] Professor B. T. Feld has pointed out to us that this distance corresponds to the "radius of the proton" as inferred by R. Hofstadter from electron-scattering measurements.

in analyzing the film. The experiment was performed at the Inter-University High-Altitude Laboratory, Echo Lake, Colorado, where we enjoyed the cooperation of Professor Byron Cohn and Professor Mario Iona. We have profited from conversations with Dr. R. L. Cool and Dr. J. Cronin of the Brookhaven National Laboratory, and are grateful to them for communicating their results before publication.

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Nuclear Interactions of Cosmic Rays in Aluminum*

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A method is described in which cosmic-ray nuclear interactions occurring in thin aluminum foils and argon gas within a cloud chamber can be detected and the tracks of the emitted charged particles observed. The observed ratio of the number of nuclear interactions per atom of argon to that of aluminum is 1.4±0.2, in agreement with the ratio of the nuclear areas of these atoms, 1.3.

THE rate of occurrence of cosmic-ray nuclear interactions in aluminum at sea level has been compared with that in argon by a cloud chamber method. The interactions were observed in the argon gas and in five horizontal aluminum foils suspended inside the chamber. The foils were held in an electrically insulated framework. The framework, maintained at minus 1000 volts, and eight 3-mil diameter tungsten wires strung between the foils, as shown in Fig. 1, form a proportional counter system. The eight wires were connected in parallel to a linear amplifier, the bias of which was set, by means of a retractable polonium alpha source, to pass pulses corresponding to the release of 5 Mev or more in the chamber gas. The pulses were used to trigger the expansion mechanism of the chamber and to cut off the high voltage on the counter rapidly enough so that track formation could take place on the positive ions of the pulse producing particles (see Fig. 2). When the gas is saturated with isoamyl alcohol vapor the counter has a multiplication of about 60 and track formation in the cloud chamber can take place at an expansion ratio of 1.15. A stereo camera was used for both photographing the tracks and later projecting them on a screen.

Except for a few instances in which extensive air showers released enough energy in the counter the expansions were triggered by the particles resulting from the nuclear interactions of cosmic rays in the aluminum foils or argon gas. The numbers and places of origin of the interactions that have one or more emitted charged particles are listed in Table I. Of the interactions involving just one charged particle only those

TABLE I. Cosmic-ray nuclear interactions (mg^{-1} cm^2) occurring in the aluminum foils and argon gas inside the cloud chamber.

Point of origin	Thickness mg cm^{-2}	Observed number of interactions	Interactions mg^{-1} cm^2
Foil No. 1	67.8	32	0.48
2	11.5	32	2.8
3	5.1	31	6.1
4	9.9	22	2.1
5	67.8	7	0.10
1 and 5	67.8	39	0.58
2, 3, and 4	26.5	85	3.2±0.3
Argon (in the 4 interfoil spaces)	65	194	3.0±0.2

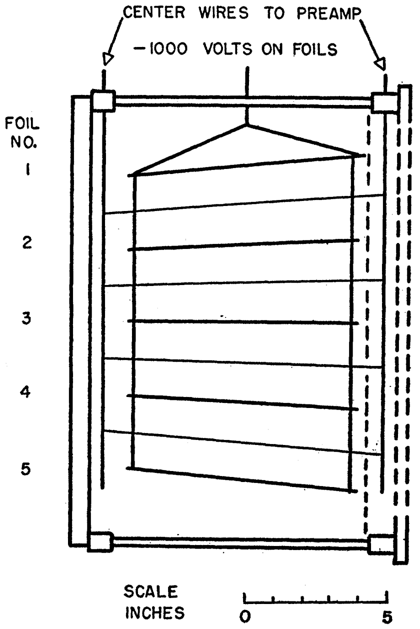

FIG. 1. Arrangement of five aluminum foils to form a proportional counter system inside the sensitive volume of the cylindrical cloud chamber. The foils are clamped in rectangular aluminum frames that are held in position by verticle rods at their corners.

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† Now at Atomics International, Canoga Park, California.