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Ratio of Neutral to Charged Particles in the Nuclear Interacting Component of Cosmic Rays

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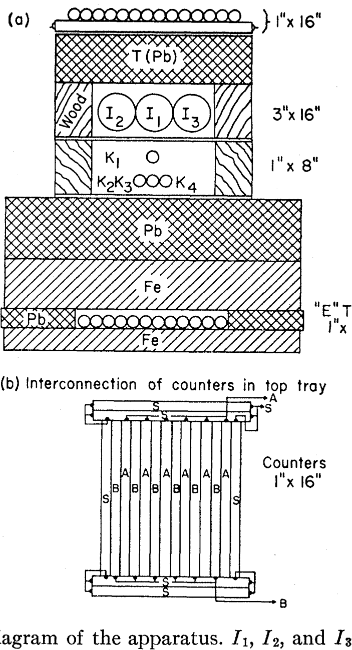
The ratio of neutral to charged primaries of nuclear interactions having a median primary energy around 10^{11} ev has been measured at 3250-m elevation, the result being $N/C \cong \frac{3}{4}$. This value indicates a high degree of elasticity in the nuclear collisions from which nucleons of 10^{11}-ev emerge.

INTRODUCTION

THE relative number of charged and neutral particles which produce nuclear interactions at mountain elevations is of interest in connection with the nucleonic cascade in the atmosphere, since the ratio depends on the elasticity of the collisions occurring at higher elevations and higher energies and on the properties of the secondaries produced in these collisions. In particular, it is interesting to know how the neutral/charged ratio varies with energy as one approaches the energy range where the multiplicity of meson production is high, where several kinds of secondaries are produced and where the pi-mesons can traverse a large fraction of the atmosphere without decaying.

From a comparison of the stars observed at different latitudes near the top of the atmosphere,[1] and from the weak latitude effect of small penetrating showers at airplane altitudes,[2] it is known that the penetrating showers and the stars with multiple relativistic secondaries are produced by particles with energy on the order of 10 Bev or more, the average value probably being 20–30 Bev. For such events occurring at mountain elevations or sea level, the ratio of neutral to charged primaries N/C has been observed with photographic emulsions,[3] cloud chambers,[4–6] and counters.[7–11] All but one of these experiments have yielded values of N/C between 0.5 and 1.5, but the cloud-chamber pictures of Gottlieb[4] indicated a much smaller ratio, between 0.04 and 0.16: practically all the unambiguous events seemed to be produced by charged particles. The explanation advanced by Gottlieb for his unusual results was based on the conclusion that the events selected by his apparatus were of exceptionally high energy, estimated to be above 15 Bev and hence of average value on the order of 40–50 Bev.[12]

The present report is of another experimental effort to obtain the ratio N/C for the primaries of nuclear interactions of comparatively high energy. The trigger requirement of Gottlieb's cloud chamber was that three particles be registered under 300 g/cm^2 of absorber. In the present experiment, the requirement was a burst in a shielded ionization chamber, with at least two secondary particles penetrating another 220 g/cm^2. The



(b) Interconnection of counters in top tray

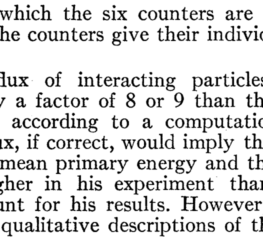


FIG. 1. Diagram of the apparatus. I_1, I_2, and I_3 are ionization chambers; the other circles represent Geiger counters. Figure 1 (b) shows the connection of the counters of the top tray in three groups, in each of which the six counters are in parallel. The numbers alongside the counters give their individual dimensions.

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[1] Reported by Camerini, Lock, and Perkins in *Progress in Cosmic Ray Physics* (Interscience Publishers, Inc., New York, 1951).

[2] T. G. Walsh and O. Piccioni, Phys. Rev. **80**, 619 (1950).

[3] Brown, Camerini, Fowler, Heitler, King, and Powell, Phil. Mag. **40**, 862 (1949).

[4] M. B. Gottlieb, Phys. Rev. **82**, 349 (1951).

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

[6] Lovati, Mura, Tagliaferri, and Terrani, Nuovo cimento **9**, 946 (1952).

[7] L. Janossy and G. D. Rochester, Proc. Roy. Soc. (London) **A182**, 180 (1944).

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

[9] K. Sitte, Phys. Rev. **78**, 721 (1950).

[10] Cocconi, Tongiorgi, and Widgoff, Phys. Rev. **79**, 768 (1950).

[11] Walker, Walker, and Greisen, Phys. Rev. **80**, 535, 546 (1950).

[12] The absolute flux of interacting particles estimated by Gottlieb was less by a factor of 8 or 9 than that found in the present experiment, according to a computation given below. This difference in flux, if correct, would imply that he may have underestimated the mean primary energy and that it may have been four times higher in his experiment than in ours. This might help to account for his results. However, the trigger requirements and the qualitative descriptions of the events in the two experiments do not seem to justify such a difference in mean energy of the initiating particles. Neither his estimate nor ours of the absolute flux was capable of accuracy to better than a factor of two.

TABLE I. Mixed showers with total burst pulse $\Sigma H \geqq 0.5\alpha$ and at least two penetrating particles, as a function of number of charged primaries detected, burst size ΣH, and number of shielded counters discharged. Units of burst size are the pulses due to Po-α particles.

Charged primaries detected		0 0	1 *A* or *B*	1 *S*	2 *AB*	2 *AS* or *BS*	3 *ABS*	Total
Burst size ΣH								
0.50–1.40	No.	112	149	19	29	10	22	341
	Percent	33	44	6	9	3	6	100
1.40–4.0	No.	97	149	18	36	14	40	354
	Percent	27	42	5	10	4	11	100
4.00–∞	No.	19	54	3	25	14	42	157
	Percent	12	34	2	16	9	27	100
Number of *E* counters discharged								
2–3	No.	96	170	19	24	10	32	351
	Percent	27	49	5	7	3	9	100
4–7	No.	104	131	12	45	21	32	345
	Percent	30	38	3	13	6	9	100
8–12	No.	28	51	9	21	7	40	156
	Percent	18	33	6	13	4	26	100
Totals	No.	228	352	40	90	38	104	852
	Percent	27	41	5	11	4	12	100

results are subdivided below, according to the size of the burst and the number of penetrating particles observed. These results contradict those of Gottlieb and agree instead with the other references quoted. Discussion of the interpretation is deferred until after a description of the experiment.

PRESENT EXPERIMENT

The main parts of the ionization chamber apparatus shown in Fig. 1 were constructed and have recently been described by Donald E. Hudson.[13] The modification for the sake of the present experiment was to add the tray of counters at the top of the apparatus in order to distinguish between events made by neutral, charged, and multiple incident particles.

Figure 1(b) shows how the 18 counters of the top tray were divided into three groups, *A*, *B* and *S*, of 6 counters each, with the group *S* distributed around the perimeter of the central area occupied by interspersed counters of *A* and *B*. Each of these groups was connected to a neon bulb, which indicated when a counter was discharged in coincidence with a recorded event. The most frequent cases showed either one bulb lit or none, and thus gave, in first approximation, the ratio of charged and neutral primaries. In addition, however, the relative frequency with which single charged primaries discharged the counter group *S*, as compared with groups *A* and *B*, provided an indication of the zenith angle distribution of the primaries and hence of the fraction that might miss the entire tray. The number of multiple coincidences assisted in evaluating the effects of air showers; while the relative number of double coincidences *AB*, as compared with *AS* and *BS*, made possible an estimate of the frequency with which the top counters were discharged by back-projected secondaries.

The "producing layer" of Pb, *T*, was made 4 inches thick, sufficient to absorb most of the electrons of incident air showers and to allow full development of most of the locally initiated cascades but not so great as to absorb fully the larger of the local cascades.

The pulses in the ionization chambers (which contained argon at 5-atmos pressure) were recorded by photographing the traces on three oscilloscopes. Neon bulbs appearing in the photographs indicated simultaneous pulses in the individual counters of tray *E*, in the three groups of counters of the top tray, and in the four counters, K_1 to K_4, located under the center ionization chamber.

The "master pulses," which intensified the oscilloscope traces, permitted the neon bulbs to ignite, and later advanced the camera film, were generated upon fulfillment of comparatively weak conditions. Therefore the records included many events which were useful only for setting limits on background effects. By examination of the records the following, more stringent requirements were imposed in order to select the energetic mixed showers to which our results pertain:

(1) The pulse height H_1 in the central chamber was required to be the greatest of the three pulse sizes. The purpose of this requirement was to minimize the number of events occurring near the edge of the apparatus and thus to decrease the chance that a primary particle should miss the top counter tray.

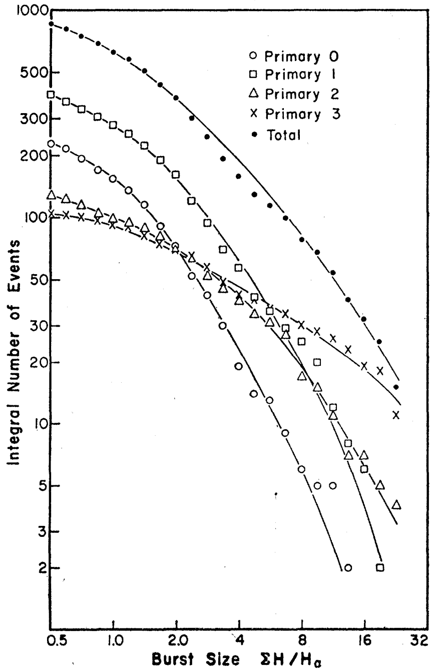

FIG. 2. Integral frequency distributions of the pulse sizes in units of a Po-α pulse, for the different types of primary.

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[13] D. E. Hudson, Phys. Rev. **86**, 453 (1952).

(2) The sum ΣH of the three burst sizes was required to exceed 0.5α, where α is the size of calibration pulses caused by polonium sources located at the chamber walls.

(3) The four counters K_1 to K_4 were required all to be discharged. This requirement discriminated strongly against low energy stars, and against events generated in the material under the chambers rather than in the layer T. It did not reduce significantly, however, the efficiency of detecting bursts of numerous electrons originating in T.

(4) At least two counters in the heavily shielded tray E were required to be discharged. This requirement discriminated against events with axes inclined at a large angle to the vertical direction, against low energy stars, and against purely electronic cascades generated by mu-mesons. From the number of rejected events with only one E counter discharged and the probability of knock-on electron production, we find the residual background of events produced by mu-mesons to be less than two percent and therefore negligible.

The apparatus was run for 544 hours at Echo Lake, Colorado, elevation 10 600 ft, pressure 0.7 atmos. In this time, 852 events were recorded which fulfilled the above conditions. These events are subdivided in Table I and Figs. 2 and 3, according to the total burst size ($\Sigma H = H_1 + H_2 + H_3$), the number of E counters discharged, and the number of charged primaries indicated by the counters A, B, S. Figure 4 shows how the total ionization was distributed among the three chambers.

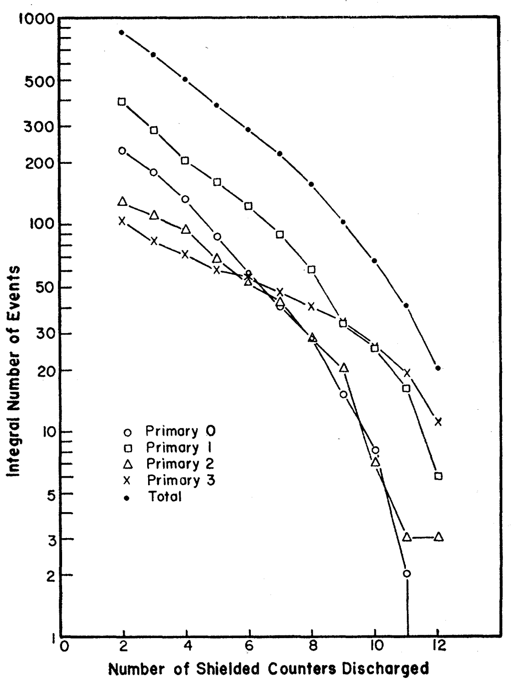

FIG. 3. Integral frequency distributions of the events with regard to numbers of counters discharged in the shielded tray E.

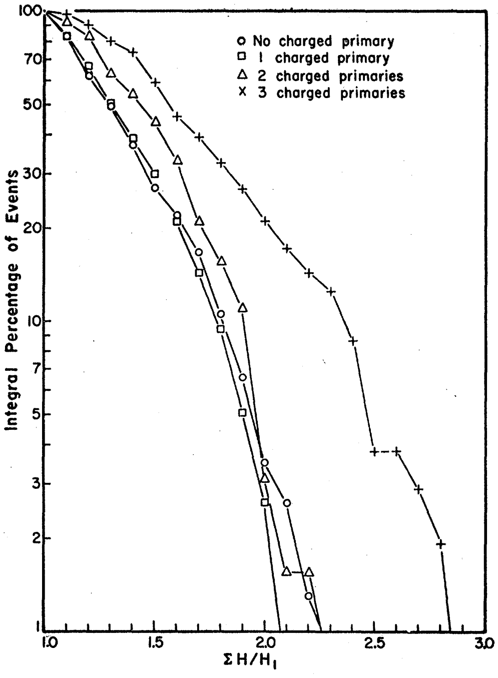

FIG. 4. Integral distributions of the events with regard to relative pulse size in the central chamber and the two side chambers. ΣH is the sum of the pulse sizes. For all the events included, $\Sigma H \geqq 0.5\alpha$ and H_1 exceeds the pulse sizes in both of the other chambers: the latter selection criterion strongly influences the shape of the graph.

CORRECTIONS

From the data in Table I one may compute the ratio N/C of neutral to charged primaries, in first approximation, as the ratio of the number of cases with zero detected primaries to the number with one. These crude results vary from 0.73 to 0.33 Three significant corrections must be considered, however, before quoting final results or concluding anything about the variation of N/C with energy.

(1) Efficiency of the Top Tray

The zenith angle distribution of the primaries of penetrating showers at Echo Lake is known to be approximately $\cos^7\theta$. With this distribution, the ratio was calculated between the number of primaries expected to strike the counters S distributed about the edge of the tray and the number expected to strike the central groups A and B. The calculated ratio was $\frac{1}{8}$, which agrees with the observed ratios and thus lends support to the method of calculation. By the same method, the fraction of the primaries inclinded so as to miss the entire tray ABS was calculated to be $4\frac{1}{2}$ percent. The fraction going through the dead spaces between the counter walls would be about 3 percent. Therefore the number of single charged primaries must be increased by about 8 percent, and the same number must be subtracted from the apparent number of neutral primaries.

TABLE II. Corrections of the observations. The increases in $(N+C)$ arise from the apportioning between neutral and charged primaries of the events in which two or more particles were registered in the top tray. The subdivision of the data marked thus $(++)$ is believed to have been affected by an unusual fluctuation in the small numbers of events that determined the corrections. Column b represents the inferred total probability of having a back-projected secondary emerge from the lead, and S is the inferred total probability of an associated air shower striking one or more counters in the top tray. Errors listed are standard statistical errors, including effects of the corrections. The statistical errors are believed to outweigh the systematic ones.

	Uncorrected		Corrected for primary missing the counters		Further corrected for back-projected secondaries		Further corrected for air showers		Final ratio		
Burst size	N	C	N	C	N	C	N	C	N/C	b	S
0.50–1.40	112	168	98	182	131	173	154	187	0.82±0.17	0.26	0.15
1.4–4.0	97	167	83	181	118	175	150	204	0.74±0.17	0.30	0.21
4.0–∞	19	57	14	62	25	68	50	107	0.47±0.24	0.43	0.49
No. of E counters discharged											
2–3	96	189	80	205	98	206	117	234	0.50±0.10	0.18	0.16
4–7	104	143	92	155	150	130	198	147	$(++)$ 1.35±0.37	0.39	0.24
8–12	28	60	23	65	41	65	63	93	0.68±0.30	0.45	0.35
Combined data	228	392	195	425	280	410	370	482	0.77±0.12	0.31	0.24

This correction alone leads to the results in columns 4–5 of Table II. The remaining corrections are less certain but can only increase the ratio N/C.[14]

(2) Back-Projected Secondaries

If the twofold coincidence AB, AS, and BS were all the result of air shower electrons accompanying the charged and neutral particles of the N component, a simple calculation shows the frequency $AB/(AS\times BS)$ would be about 0.7.[15] Experimentally, however, it is between 2 and 3. The excess coincidences of type AB are due to back-projected secondaries occurring close to each other and to the primary particle.

Such secondaries have been observed in photographic emulsions[1] and cloud chambers[16] and have been inferred in hodoscope experiments.[11] According to these references, about 15 percent of the lightly ionizing secondaries are emitted in the backwards hemisphere, and some of them are able to penetrate considerable thicknesses of lead. In the present experiment, the average number of shielded counters discharged was 5, implying the presence of about 10 penetrating particles, or approximately one regressive lightly ionizing particle per event. If $\frac{2}{3}$ of the fast regressive particles failed to emerge from the lead, the others could still account for the excess coincidences of type AB.

A minimum correction was made quantitatively by assuming that all the coincidences of type AS or BS were due to air showers and subtracting 0.7 times this number from the coincidences AB in order to obtain the number of twofold coincidences caused by regressive particles. With the further assumption that the regressive particles occurred independently of each other, it was then possible to calculate the probabilities of one or two regressive particles being registered in a given event initiated by a neutral or charged primary. Thus the excess coincidences of type AB could be divided in a reasonable manner between neutral and charged primaries, and also a more significant correction could be calculated, namely, the number of events with a neutral primary that appeared to have a single charged primary because of a back-projected secondary. The results of these corrections are shown in columns 6–7 of Table II.

(3) Corrections for Associated Air Showers

The distributions of ionization shown in Fig. 4, and particularly the auxiliary data in Table III, show that the events associated with triple coincidences ABS were mostly the result of complex air showers. It is interesting to observe, as has been noted before,[11,13,17–19] that the proportion of the events associated with dense air showers increases remarkably with the energy of the events (see Table I); while the high average degree of association attests to the high energy of the events selected in the present experiment.[20]

Most of the events involving twofold coincidences of type AS or BS, plus some of type AB, result from less dense air showers, which miss one or two of the three counter groups. Also, some of the events appearing to

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[14] Some of the events in which only the S group is discharged in the top tray are likely to be due to neutral primaries accompanied by low density air showers. This would imply that the correction for inefficiency of the top tray is an over-correction, and therefore that the true ratio N/C is slightly larger than is inferred.

[15] The calculation depends only weakly on the ratio N/C and on the relative probability of air showers that discharge two or one of the counter groups. Over a wide range of these factors, the predicted ratio lies between 0.6 and 0.8.

[16] W. W. Brown and A. S. McKay, Phys. Rev. **77**, 342 (1950).

[17] H. K. Ticho, Phys. Rev. **88**, 236 (1952).

[18] E. F. Fahy, Phys. Rev. **83**, 413 (1951).

[19] T. G. Stinchcomb, Phys. Rev. **83**, 422 (1951).

[20] These observations also show that even the most energetic particles in the lower atmosphere are more often secondaries than primaries that have escaped interaction. This in itself points to the same conclusion, significant elasticity of the collisions, which is derived below from the measurements of N/C.

have single-charged primaries must be due to neutral primaries accompanied by low density showers which discharge only one of the counter groups.

A priori, it seems just as likely for an air shower to accompany a neutron as to accompany a proton or a pi-meson; and previous measurements have indicated[11] that the nuclear interacting component in dense air showers has about the same ratio N/C as that found among the particles observed singly. Hence, this assumption is made in calculating the corrections.

Three probabilities enter in the corrections, namely, those of the occurrence of showers that discharge one, two or three counter groups. The following data help to supply the necessary values: the rate of events associated with a threefold primary coincidence ABS, the rate of associated twofold coincidences AS and BS, and the rate of single coincidences S, the last of which provides an upper limit to the number of neutral-initiated events accompanied by low density showers hitting only one counter group. Auxiliary information on the relative probabilities of associated showers discharging various numbers of counters were also available from other similar experiments.[11,13] By using all this information, self-consistent corrections were found as shown in columns 8 and 9 of Table II.

It will be observed that the uncertainties in the values of the ratio N/C have been greatly increased by the corrections. The large effects of air showers and regressive secondaries seem to be an inevitable consequence of selecting events of high primary energy and hence of considerable complexity.

Because of these errors, the variation of the ratio N/C with energy is not made clear by the data. N/C surely does not increase with energy, but it may remain almost constant or it may decrease appreciably. However, the average value is close to $\frac{3}{4}$, and the value is greater than $\frac{1}{4}$ even for the largest bursts and penetrating showers observed.

MEDIAN PRIMARY ENERGY OF THE EVENTS

The apparatus discriminated strongly against bursts caused by heavily ionizing particles, since these particles only contribute significantly to the ionization in the case of those penetrating showers that originate in the ionization chamber walls. Therefore, the most economical way to account for the ionization is with electrons. The medium burst size was 1.5α, which corresponds to about 80 electrons crossing the chamber, or (because of scattering and the lead-brass transition effect) to about 180 electrons in the cascade within the lead. Since the cascades were not all detected at their maxima, the median energy in the electronic component must have been somewhat greater than 2×10^{10} ev. Judging from the average number of shielded counters discharged and the energy lost by the secondary N component in nuclear interactions while traversing the filter, the average energy in the secondary heavy particles was roughly equal to that in the electronic component. Thus, the median total energy of the secondaries was 40–50 Bev, and the median primary energy presumably exceeded this by a small amount.

A second way of estimating the median primary energy is from the absolute frequency, as has been done before.[17] A geometric calculation based on a $\cos^7\theta$ zenith angle dependence indicates that the equivalent area times solid angle of the apparatus in the vertical direction was 100 cm^2 sterad. The thickness of lead in which bursts could be efficiently generated was about two inches; hence, about 0.3 of the particles capable of producing an event would do so. There were 852 events in 544 hours. Therefore, the absolute intensity was about 1.45×10^{-5} cm^{-2} sec^{-1} sterad^{-1}. Of these primaries half were above the median primary energy. Ticho[17] has shown that the nuclear interacting component of energy around 10^{11} ev is absorbed exponentially in the atmosphere, with a mean free path (after a small correction by means of a Gross transformation) equal to about 130 g/cm^2. The intensity at the top of the atmosphere, above the median primary energy, accordingly was about 1.67×10^{-3}; and with the primary spectrum published by Barrett *et al.*,[21] this corresponds to an energy of 1.2×10^{11} ev.

Within the accuracy of the methods used, both estimates of median primary energy are consistent with each other; and if one accepts the value 80 Bev, the error will be less than a factor of two.

DISCUSSION

From the work of the Bristol Laboratory,[22] the number of charged pi-mesons produced in high energy collisions is about six times the number of protons and hence also about six times the number of neutrons. If the collisions are of the catastrophic nature suggested

TABLE III. Comparison of the number of bursts in which the central chamber had the smallest pulse with the number in which it had the largest pulse. The most obvious way to account for cases in which $H_1<H_2$ and H_3 is in terms of incident air showers, though even these should produce $H_1\geqq H_2$ and H_3 more often than $H_1<H_2$ and H_3. The inference is that most of the events with primary ABS were due to complex air showers; while probably significant fractions of the types AS and BS, and possibly of type S, but not many of type AB, were also due to air showers.

Primary	Number of mixed showers with $H_1<H_2$ and H_3	Number of mixed showers with $H_1\geqq H_2$ and H_3	Ratio
0	3	228	0.01
1 A or B	2	352	0.01
1 S	2	40	0.05
2 AB	1	90	0.01
2 AS or BS	3	38	0.08
3 ABS	36	104	0.35
Total	47	852	0.055

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[21] Barrett, Bollinger, Cocconi, Eisenberg, and Greisen, Revs. Modern Phys. **24**, 133 (1952).

[22] Daniel, Davies, Mulvey, and Perkins, Phil. Mag. **43**, 753 (1952).

by Fermi, the mesons and the secondary protons and neutrons would have similar energy distributions. At 80 Bev, the fraction of the charged pi-mesons surviving to make nuclear collisions is 0.4; while for energies within a factor two of 80 Bev, the fraction varies between 0.25 and 0.57.[21] Therefore, considering only the secondary nucleons and pi-mesons, the ratio N/C for particles of the median energy in the present experiment should be 0.3 ± 0.1.

Two effects should further reduce this ratio. One is the presence, in the N component at 700 mb, of a residue of primary protons that have not interacted in the atmosphere. The other is the production of τ, χ, $V_0^{(1)}$, and $V_0^{(2)}$ particles, which contribute to the intensity of charged pi-mesons by decay in the atmosphere, but presumably (because of the short lifetimes of the neutral particles that have strong nuclear interaction) do not contribute comparably to the intensity of neutral N component.

Therefore, the average value of N/C predicted according to this picture is less than $\frac{1}{3}$, in marked contrast to the observed value of about $\frac{3}{4}$. A considerable difference exists independently of the corrections to our data, which may reasonably be viewed with some distrust.

It is suggested that our results, as well as the difference between the absorption and interaction lengths of the high energy N component in the atmosphere,[17] can be better explained if the collisions are less catastrophic, allowing the incident nucleons some "memory" after the interactions of their identity and energy beforehand. One must, of course, assume that charge exchange occurs freely—that is, that there is almost equal likelihood for a proton, after meson production, to emerge as a neutron or still as a proton; the "memory" must not include the initial charge to any great extent. However, we propose that one of the nucleons participating in the interaction may on the average retain a substantial fraction (half or more) of the initial energy, while the other particles emerge with considerably lower energies.

In this case, the neutrons would comprise a larger fraction of all secondary particles of a given energy than in the case of more violent interactions in which the initial identity is lost. Also, since the degradation of energy would be less per collision, the absorption length would exceed the interaction length considerably, as observed; and the particles arriving at mountain elevations would on the average have suffered more collisions, tending to equalize the N/C ratio.

These arguments may be illustrated with the following crude model, accurate enough for our purposes, of the diffusion of the N component in the atmosphere. Assume that the primaries have an integral energy spectrum following a power law with exponent $\gamma\cong1.5$; that λ_i is the interaction mean free path; and that in each collision, fractions f_j ($j=1, 2, \cdots$) of the primary energy are given to the various secondaries. Let g_j be the probability that the secondary designated by j survives to make further nuclear interactions, and set $g=0$ for noninteracting types of particles. Approximate λ_i and the multiplicities of secondary production as being independent of energy and of type of initiating particle, and the values of g_j as being independent of energy. Then the total N component will retain the form of the primary energy spectrum, and will be absorbed exponentially with an absorption length λ given by $\lambda_i/\lambda=1-\Sigma g_j(f_j)^\gamma$. The relative numbers of secondary and primary particles at any depth x in the atmosphere will be given by $\exp(x/\lambda_i-x/\lambda)-1$; and the relative numbers of neutral and charged particles among the secondaries will be given by the value of the sum $\Sigma g_j(f_j)^\gamma$ for the neutrons produced in the interaction, relative to the corresponding sum over all the charged particles produced.

To be more specific in applying this model, let us assume that in the collisions in which the secondaries have energies of 80 Bev, the following particles emerge: one proton and one neutron, for which $g=1$, four charged pi-mesons for which $g=0.4$, two neutral pi's for which $g=0$, and four heavy mesons of which two give half their energy to a charged pi. Assume that half of these particles are emitted backwards in the c.m. system and so have practically no energy in the laboratory frame of reference and that the other six particles are emitted forwards with equal energies. Such collisions would lead to $\lambda/\lambda_i=1.15$, or $\lambda=92$ g/cm^2 if $\lambda_i=80$; and to $N/C=0.22$. Now change only the assumption about the energy distribution among the forward-emitted particles, letting the nucleon (either proton or neutron with equal probability) retain half the primary energy and the other five particles each have $\frac{1}{10}$ of the energy. Then $\lambda/\lambda_i=1.62$ or $\lambda=130$ g/cm^2 for $\lambda_i=80$; and $N/C=0.80$.

Such a crude model, completely ignoring fluctuations, cannot be expected to produce accurate results, and the excellent agreement of the second set of values of λ and N/C with the observations must not be given too much weight. The calculation is only illustrative of how the data can be explained in terms of nuclear collisions that are on the average rather elastic, but not if one assumes an equipartition of energy among the secondaries.

The facilities of the Inter University High Altitude Laboratory at Echo Lake, Colorado were used in the performance of this experiment. Financial support was provided by the Research Corporation, and some of the apparatus was made available through a contract with the U. S. Office of Naval Research. We wish to thank Professor G. Cocconi for helpful discussions.