RATIO OF PIONS TO PROTONS AND RATIO OF NEUTRAL TO CHARGED INTERACTING PARTICLES AT MOUNTAIN ALTITUDE OF 800 gm/cm²

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Abstract

Using a combined set-up of a multiplate cloud chamber, an air Cerenkov counter and a total absorption spectrometer, the ratio of pions to protons not associated with large air showers has been determined to be $0 \cdot 50 \pm \cdot 07$ in the energy region 20–40 GeV at an altitude of 800 gm/cm². In the same energy region the ratio of neutral to charged particles is found to be $0 \cdot 66 \pm \cdot 07$. From the ratio of neutrons to protons deduced from these measurements (*i.e.*, $0 \cdot 99 \pm \cdot 11$), it is concluded that most of the charge excess of nuclear active particles of energies ≥ 20 GeV at mountain altitudes and sea-level is due to pions.

1. Introduction

Experimental determination of the relative proportion of neutral to charged particles among the nuclear interacting particles at mountain altitudes and sea-level and the determination of the ratio of pions to protons is of particular interest in understanding the development and absorption of the nuclear cascades initiated by high energy cosmic ray primaries in the atmosphere. These ratios depend on various characteristics of high energy collisions in air like inelasticity, multiplicity, interaction cross-section, the extent of regeneration of pions by pions, probability of charge persistence of nucleons and pions, etc.,—parameters which enter into the diffusion equations describing the development and absorption of the nuclear cascades in the atmosphere. Since many of these parameters are not yet determined at high energies from a direct study of nuclear interactions, knowledge of the ratio of neutral to charged interacting particles, the ratio of pions to protons and the variation of these ratios with energy and altitude would help considerably in fixing at least some *limits* on the values of some of the parameters.

While several experiments have been carried out before to determine the ratio of neutral to charged particles, there has been no experiment reported so far in which the proportion of *pions to protons* has been determined at mountain altitudes. There exists a considerable amount of disparity in the value that has been obtained for the ratio of neutral to charged particles by different workers.[1] The value varies from 0·04 to 1·0. In none of these experiments the energy of the nuclear interacting particles has been determined reliably.

Using a combined set-up[2] of a multiplate cloud chamber, an air Cerenkov counter and a total absorption spectrometer, we have determined the ratio of neutral to charged interacting particles and also the ratio of pions to protons at an altitude of 800 gm/cm^2.

2. Experimental Details

The experiment was principally designed to study the detailed characteristics of nuclear interactions produced by pions and nucleons of energy greater than 20 GeV and has been described elsewhere.[2] The experimental arrangement consisted of a multiplate cloud chamber with an air Cerenkov counter above and a total absorption spectrometer below. The cloud chamber was triggered with a selection system which selected only charged interacting particles for part of the run and made no distinction between charged and neutral interacting particles for the rest of the operating period. Triggering of the cloud chamber by nuclear interacting particles associated with large air showers or by particles in the cores of small air showers was prevented by a system of anti-coincidence counters of total effective area about a square meter placed by the side of the cloud chamber. The nuclear interacting particles were identified by the interactions they produced in the cloud chamber or by the characteristic development of nuclear cascades initiated in the spectrometer.* The air Cerenkov counter[3] which was operated at atmospheric pressure and had a threshold value of 45 for the Lorentz factor of the charged particles, enabled the classification of the charged interacting particles into *pions* and *protons* in the energy range 20–40 GeV. The energy of nuclear interacting particle was determined in individual cases to an accuracy of ± 20% with the total absorption spectrometer.[4]

* The latter criterion of selection was used only in the determination of the ratio of pions to protons (Sec. 3 *a*).

3. Experimental Results

(*a*) *Ratio of pions to protons.*—During the period (4500 hours) when the cloud chamber was triggered exclusively for nuclear interacting particles 427 events were recorded for which the charged primary was well within the solid angle of the air Cerenkov counter above the cloud chamber and for which the estimated energy from the total absorption spectrometer was in the energy range 20–40 GeV. Out of these, in 91 cases the air Cerenkov counter gave pulses indicating that the particles were pions. This number has to be corrected for spurious association of pulses from the Cerenkov counting system. A correction of about 1% arises from chance coincidence and another 1% from other background pulses due to knock-on electrons produced in the air column of the air Cerenkov counter passing through the front glass of the photomultiplier producing Cerenkov radiation there. This latter correction was determined by observing coincidences associated with the passage of μ-mesons through the Cerenkov counter while its photomultiplier was covered with black paper. These corrections reduce the number of pion events to 82. The air Cerenkov counter had an efficiency for extreme relativistic particles of 82 ± 6%; there was an additional inefficiency of about 10% due to saturation effects in the recording system. Taking account of these facts we finally obtain the number of pion events to be 113 in a total of 427 events. This gives the ratio of pions to protons as 0·50 ± ·07 in the energy region of 20–40 GeV.

(*b*) *Ratio of neutral to charged particles* (*N/C*).—During the period of 4650 hours when the chamber was triggered for both charged and neutral interacting particles 567 (above 20 GeV) nuclear interactions were recorded in the chamber for which one could unambiguously determine whether the interaction was produced by a charged or a neutral particle. Out of the 567 cases in 412 cases the energy of the interaction as determined with the total absorption spectrometer was in the range 20–40 GeV. In these 412 cases it was found that 248 were due to charged primaries giving a value of 0·66 ± ·07 for the N/C ratio at energies 20–40 GeV. In the remaining 155 cases for which the energy was higher than 40 GeV (median energy 60 GeV), 103 interactions were due to charged primaries leading to a value of 0·52 ± ·09 for the N/C ratio.

(*c*) *Ratio of neutrons to protons and probability of charge persistence.*—Using the ratio of neutral to charged particles and the ratio of pions to protons we could determine the ratio of neutrons to protons in the energy range 20–40 GeV. The value of this ratio comes out to be 0·99 ± ·11, Assuming that the cosmic ray primaries are all protons, the ratio of neutrons to protons at an atmospheric depth of X gm/cm² can be written as

$$\frac{N}{P} = \frac{1 - \exp.\left[-2\,\epsilon X\left(\frac{1}{\lambda_{int}} - \frac{1}{\lambda_{abs}}\right)\right]}{1 + \exp.\left[-2\,\epsilon X\left(\frac{1}{\lambda_{int}} - \frac{1}{\lambda_{abs}}\right)\right]} \tag{1}$$

where

ϵ = probability of charge exchange in an inelastic collision of a nucleon with an air-nucleus, assumed to be energy independent;

λ_{int} = interaction mean free path of nuclear interacting particles in air;

λ_{abs} = the absorption mean free path of nucleons in the atmosphere.

In Table I we have given the expected ratio of N/P at an altitude of 800 gm/cm² for various values of the parameters ϵ and λ_{int} using a value for λ_{abs} as 120 gm/cm².

If we take into account the presence of heavy nuclei in addition to protons in the primary cosmic ray beam and consider the fragmentation of these nuclei at the top of the atmosphere, then formula (1) needs to be replaced by the approximate formula (72% protons and 28% neutrons).

TABLE I

ϵ	Expected ratio N/P at 800 gm/cm²			
	λ_{int} = 72 gm/cm²	λ_{int} = 80 gm/cm²	λ_{int} = 85 gm/cm²	λ_{int} = 90 gm/cm²
0·5	0·98 (0·99)	0·94	0·87	0·80
0·4	0·94 (0·96)	0·88	0·80	0·71
0·3	0·87 (0·89)	0·78	0·68	0·58
0·2	0·71 (0·79)	0·60	0·50	0·43

$$\frac{N}{P} = \frac{0{\cdot}72\left[1 - \exp.\left(-2\,\epsilon X\left\{\frac{1}{\lambda_{int}} - \frac{1}{\lambda_{abs}}\right\}\right)\right] + 0{\cdot}28}{0{\cdot}72\left[1 + \exp.\left(-2\,\epsilon X\left\{\frac{1}{\lambda_{int}} - \frac{1}{\lambda_{abs}}\right\}\right)\right] + 0{\cdot}28}. \tag{2}$$

In Table I values for the N/P ratio calculated on the basis of formula (2) are given in the second column within brackets. It is seen that the values obtained according to formula (2) are always higher than those according to formula (1).

It is seen from Table I that the observed value of $0 \cdot 99 \pm \cdot 11$ for N/P excludes the probability of charge persistence, *i.e.*, $(1 - \epsilon)$ being higher than 80% and may as well be close to 50% if λ_{int} is taken $= 90$ gm/cm^2 for nucleons of energies ~ 100 GeV (nucleons in the observed energy range of 20–40 GeV are expected to arise from the collision of nucleons of energy ~ 100 GeV in the atmosphere).

4. Comparison with Other Experiments and Discussion

(*a*) *Ratio of pions to protons.*—There are no experimental results on the ratio of pions to protons at mountain altitudes with which we can compare our results. However, it may be pointed out that the evaluation by the Durham group[5] with magnetic spectrograph of the vertical intensity of pions and protons at sea-level indicates a ratio of $\pi/P = 0 \cdot 5 \pm \cdot 11$ at an energy of 27 GeV. This compares well with our value of $0 \cdot 50 \pm \cdot 07$ at 800 gm/cm^2.

(*b*) *Neutral to charged ratio.*—As stated in Section 1, the ratio of neutral to charged interacting particles has been determined earlier by many workers[1] at different altitudes. The experimental systems used by different workers to identify nuclear interacting particles are different (*see* Tables II and III). Brown *et al.* used nuclear emulsions; Greisen and Walker, and Farrow used ionisation chambers in conjunction with GM counter trays; Cervasi *et al.* and Khrimian used arrays of GM counters alone; Gottlieb, Deutschmann and Lal *et al.* have used multiplate cloud chambers.

In all experiments in which visual detectors like nuclear emulsions or cloud chambers have not been used, it must be emphasised that the identification of both the *charge* and the *interacting nature* of the particles are subjected to large uncertainties. The identification of charge in these experiments is based upon the presence or absence of a pulse from an array of hodoscoped GM counters placed over the apparatus meant for detecting nuclear interacting particles. Corrections due to (*i*) inefficiency of GM counter arrays, (ii) backward projected secondaries and (iii) association of air showers will be necessary and these corrections are quite appreciable (*see* Greisen and Walker). Since the association of air showers increases with energy, in these experiments, only part of the data will be useful for evaluating the N/C ratio. For example, in the experiment of Farrow at energies greater than 200 GeV, only $\sim 10\%$ of the interactions recorded could be used for the determination of the N/C ratio.

TABLE II

Authors	Altitude of observation gm/cm²	Detector for nuclear interacting particles	Criteria for classification (energy or multiplicity)	N/C
Greisen and Walker (1953)	680	Ion chamber	(a) $0{\cdot}5a$–$1{\cdot}4a$ $1{\cdot}4a$–$4a$ $4a$–∞ $a = 55$ GeV based on median energy estimate	0·82±0·17
Farrow (1957) ..	626 703 790	Ion chamber	200 GeV ,, ,,	0·74±0·15 0·65±0·15 0·56±0·36
Cervasi *et al.* (1955) ..	680	GM counters	10 GeV	0·77±0·035
Khrimian (1959) ..	720	GM counters	30 GeV	0·83±0·11
Brown *et al.* (1949) ..	670	Nuclear emulsions	$n_s \geqslant 3$	0·72±0·14
Gottlieb (1951) ..	650	Cloud chamber	$\gtrsim$100 GeV	0·04 to 0·16
Siddheswar Lal *et al.* (1962)	800	Cloud chamber	20-150 GeV (median energy 55 GeV)	0·69±0·13
Present experiment ..	800	Cloud chamber with total absorption spectrometer	20-40 GeV >40 GeV (median energy ~60 GeV)	0·66±0·07 0·52±0·09

TABLE III

Results obtained by Deutschmann[1]

Altitude: 730 gm/cm² (Cloud Chamber)

E_{π^0} GeV	0·0–0·4	0·5–0·9	1·0–1·9	2·0–2·9	3·0–3·9	4·0–4·9	5·0–9·4	9·5–16·4	16·5–29·9	30–∞
N/C	0·435 ±0·09	0·435 ±0·10	0·635 ±0·11	0·416 ±0·08	0·416 ±0·08	0·37 ±0·10	0·416 ±0·08	0·37 ±0·12	0·167 (2/12)	0·125 (1/8)

Because of these considerations, it is evident that particularly from the point of view of determination of the neutral to charged ratio of nuclear interacting particles and the variation of this ratio with energy, one cannot place much reliance on experiments in which visual detectors have not been used. Therefore, for purposes of discussion we consider only experiments in which either cloud chambers or nuclear emulsions have been used.

In experiments in which cloud chambers have been used, there is absolutely no uncertainty regarding the identification of the charge or the interacting nature of the particles. However, partial rejection of data due to air shower association will still arise either due to the selection system incorporating anti-coincidences to remove strong association with air showers (as in the present experiment) or due to the rejection of cloud chamber photographs in which associated particles are seen (as in the analysis of Gottlieb). It is to be expected that the ratio of neutral to charged particles determined by rejecting the *associated cases* will represent the *upper limit* of the ratio for *all* nuclear interacting particles since pions should be more in concentration if at all, in the associated than in the unassociated events.

In the experiment of Gottlieb no attempt was made to estimate the energy of the nuclear interacting particles using the cloud chamber photographs themselves. From considerations of the flux of nuclear interacting particles reported, Greisen and Walker have pointed out that the mean energy of the interactions recorded in Gottlieb's experiment should be higher than 100 GeV. Therefore, the value of less than 0·2 obtained by Gottlieb probably corresponds to energies above 100 GeV. In the experiment of Lal *et al.* the energy of nuclear interacting particles has been estimated using the angular distribution method of Castagnoli *et al.*[6] From our experiment in which we have compared the energy estimates obtained by the angular distribution method with that obtained from the total absorption spectrometer, we find that the energy estimates in the angular distribution method are overestimated by a factor of about 1·4 (at energies of the order of 50 GeV). Therefore, we feel that the ratio of $0{\cdot}69 \pm {\cdot}13$ reported by Lal *et al.* for a median energy of 55 GeV actually corresponds to a median energy of about 40 GeV and is therefore in agreement with the present experiment. In the experiment of Deutschmann, the events have been grouped according to the energy going into the π^0-component and the variation of N/C ratio with energy studied. It becomes therefore difficult to compare the results of Deutschmann with the present experiment. Nevertheless, there is a clear indication of a decrease of the neutral to charged ratio with increasing energy in the experiment of Deutschmann also. The low value of 0·435 reported by Deutschmann for energies of π^0-mesons less than 0·9

GeV is probably due to biases introduced in the triggering system. The triggering system required at least one charged penetrating particle to go through the array of shielded counters below the chamber. At very low energies the multiplicity is small and, therefore, there can be a preferential selection of interactions produced by charged primaries. The results of Brown *et al.* obtained with nuclear emulsions in which the criterion for selection was based on the multiplicity of fast particles (*i.e.*, $n_s \geq 3$) probably correspond to the ratio of nuclear interacting particles at energies of the order of a few tens of GeV. Since in this experiment there is absolutely no bias introduced by either the selection system or association with air showers, the ratio corresponds to that of the nuclear interacting particles at 670 gm/cm.[2]

It can, therefore, be concluded from a comparison of all the cloud chamber and emulsion experiments that the ratio of neutral to charged particles not associated with large air showers is about 0·7 at energies of the order of a few tens of GeV and decreases to a value perhaps of the order of 0·3 or less at energies more than 100 GeV.

Any model for the development and absorption of the nuclear interacting component should, therefore, account for this variation of the N/C ratio with energy. From our result that nearly 33% of the charged interacting particles are pions even at energies 20–40 GeV, it appears that the decreasing value of the N/C ratio is pobably due to an increasing proportion of pions with increasing energy. This increase in the contribution of pions with energy may perhaps be due to the regeneration of pions by pions as pointed out by Subramanian and Verma.[7]

(*c*) *Ratio of protons to neutrons and probability of charge persistence.*— There are no experimental results on the ratio of protons to neutrons at mountain altitudes or sea-level with which we can compare our results. The deduced value for the ratio of neutrons to protons is close to unity and suggests that the charge excess in the nuclear interacting particles is almost entirely due to pions. A further test of this conclusion would be to study the variation of the neutral to charged ratio with altitude. If the charge excess is due to the charge persistence of nucleons, then the neutral to charged ratio should increase with atmospheric depth and approach unity. If, on the other hand, the charge excess is due to pions, then one would expect the ratio to decrease with increasing atmospheric depth. A recent compilation of data by Hayakawa[8] indicates a decrease consistent with our findings regarding the composition of nuclear active particles.

The upper limit of 0·8 for the charge persistence probability of nucleons which we have deduced from the observed ratio of neutrons to protons can be compared with other observations. Vorobiev[9] has set a limit of 0·7 – 0·8 for the charge persistence probability in collisions of nucleons with air nuclei at energies 3–10 GeV; Daniel *et al.*[10] have reported from a study of nuclear interactions in emulsions that the charge persistence probability is not likely to be higher than 0·6 at 6 GeV, whereas at energies $\sim 10^{12}$ eV a figure of 0·74, (*i.e.*, 14/19) results from their data.[11]

5. Conclusions

From the present study the following conclusions may be drawn regarding nuclear interacting particles not associated with large air showers:

(*a*) The relative proportion of pions to protons is appreciable at mountain altitudes and sea-level at energies above 20 GeV; this ratio is as high as $0 \cdot 50 \pm \cdot 07$ in the energy region 20–40 GeV at 800 gm/cm^2.

(*b*) The ratio of neutral to charged particles seems to show a decrease with increasing energy of the particles. From our measurements in the energy region 20–40 GeV, it is found to be $0 \cdot 66 \pm 0 \cdot 07$ and at about 60 GeV it is $0 \cdot 52 \pm 0 \cdot 09$. Such a trend has been found more strongly in earlier measurements quoted. This feature suggests that at energies of about 100 GeV pions are comparable or even more than protons among the nuclear interacting particles at mountain altitudes and sea-level.

(*c*) The ratio of neutrons to protons in the energy region 20–40 GeV deduced from the ratio of neutral to charged particles is $0 \cdot 99 \pm 0 \cdot 11$ which leads to an upper limit of 80% for the probability of charge persistence of nucleons at energies ~ 100 GeV in collisions with air nuclei. This ratio of neutrons to protons which is close to unity implies that the charge excess among nuclear interacting particles at mountain altitude is almost entirely due to pions.

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References

1. Brown, R. H., Camerini, U., Fowler, P. H., Heitler, H., King, D. T. and Powell, C. F. *Phil. Mag.*, 1949, **40**, 862.

Gottlieb, M. B. .. *Phys. Rev.*, 1951, **82**, 349.

Greisen, K. and Walker, W. D. *Ibid.*, 1953, **90**, 915.

Deutschmann, M. .. *Zeitz. fur Nature*, 1954, **9** *a*, 477.

Cervasi, M., Fidecaro, G. and Mezzetti, L. *Nuovo Cimento*, 1955, **1**, 300.

Farrow, L. A. .. *Phys. Rev.*, 1957, **107**, 1687.

Khrimian, G. V. .. *Soviet. Phys. JETP*, 1959, **8**, 752.

Siddheshwar Lal, Yash Pal and Raghavan, R. *Nuclear Physics*, 1962, **31**, 415.

Schultz, H. .. *Zeitz. fur Nature*, 1954, **9** *a*, 419.

2 (i) Lal, S., Raghavan, R., Sreekantan, B. V., Subramanian A. and Verma, S. D. *Journ. of Phys. Soc. of Japan*, 1962, **17**, Suppl. A-III, 390.

(ii) ———, ———, Rangaswamy, T. N., Sreekantan, B. V., Subramanian, A., Tonwar, S. C. and Vatcha, R. H. Under publication in *Proc. Ind. Acad. Sci.*

3. Subramanian, A. and Verma, S. D. *Proc. Ind. Acad. Sci.*, 1966, **64**, Sec. A.

4. Ramana Murthy, P. V., Sreekantan, B. V., Subramanian, A. and Verma, S. D. *Nuclear Instruments and Methods*, 1963, **23**, 245.

5. Brook, G., Meyer, M. A. and Wolfendale, A. W. *Proc. Phys. Soc.*, 1964, **83**, 871.

6. Castagnoli, C., Cortini, G., Franzinetti C. F., Manfredini, A. and Moreno, D. *Nuovo Cimento*, 1953, **10**, 1539.

7. Subramanian, A. and Verma, S. D. .. *Ibid.*, 1959, **13**, 572.

8. Hayakawa, S. .. *Cosmic Ray Physics*, Wiley, Interscience, 1969, p. 342.

9. Vorobiev, V. A. .. *Soviet Phys. JETP*, 1958, **6**, 203.

10. Daniel, R. R., Kameshwara Rao, N., Malhotra, P. K. and Tzuzuki, Y. *Nuovo Cimento*, 1960, **16**, 1.

11. ———, Durgaprasad, N., Malhotra, P. K. and Vijayalakshmi, B. *Suppl. Nuovo Cimento*, 1963, **1**, 1169.