Momentum Spectra of Cosmic-Ray Mesons and Protons at Sea Level and 3.4-km Altitude*

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A cloud-chamber experiment has been performed at sea level and 3.4-km altitude to collect data on the momentum and scattering distributions of 15,000 mesons and protons. The momentum spectra and derived conclusions are discussed here. The meson momentum distribution at sea level is in accord with the results of others. A comparison of the sea-level and altitude spectra indicates that, for momenta between 0.7 and 3 Bev/c, 0 to 15 percent of the mesons observed at sea level are produced below 3.4 km. Assuming that production of the fast mesons observed takes place within the top 125 g/cm^2 of the atmosphere, the differential momentum distribution of mesons at production can be represented adequately as an inverse power law with an exponent equal to 2.75 ± 0.07, in good agreement with previous published results. The relative numbers of positive and negative particles at sea level agree well with those of other workers. At altitude the $+/-$ ratio becomes quite large for the lower momenta (up to 2.5 as against 1.2 at sea level), while it approaches the sea-level ratio (1.3) for high momenta. Assuming that the difference between the sea-level and altitude ratios is due to protons, one can compute that above 0.3 Bev/c protons form 19 ± 2 percent of all ionizing particles (excluding electrons) at 3.4 km. From the observed $+/-$ ratios the proton momentum spectrum has been calculated.

I. INTRODUCTION

BY means of a cloud-chamber experiment carried out both at sea level and at 3.4-km altitude, data have been obtained on the momentum and scattering distributions of mesons and protons. 15,000 meson and proton tracks have been measured. The purpose of this article is to make available the data concerning the momentum spectra, particularly those obtained at 3.4 km, to present the information which can be deduced concerning the production of mesons and the spectrum of protons, and to compare the results with some already existing in the literature.[1–6]

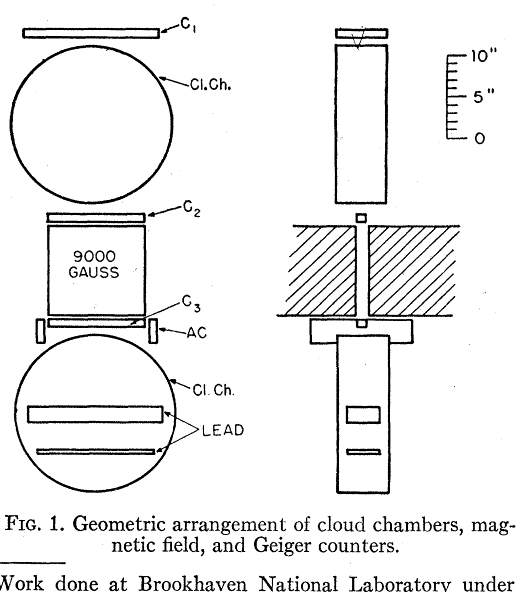

FIG. 1. Geometric arrangement of cloud chambers, magnetic field, and Geiger counters.

II. APPARATUS

The equipment consisted of two nineteen-inch cloud chambers mounted one above and one below the air gap of a permanent magnet which provided a field of 9000 gauss. Figure 1 shows the geometrical arrangement with the location of Geiger counters. The two chambers were triggered by a simple threefold counter telescope $C_1C_2C_3$ if no particles set off the anticoincidence counters AC. The AC were used only during the altitude run in an effort to reduce the number of expansions which showed no counter-controlled track in the bottom chamber. Some of these expansions were caused by side showers while most were caused by particles of low momentum which triggered all the coincidence trays but were deflected away from the bottom chamber by the magnetic field. The AC were not as necessary at sea level because of the presence of relatively fewer particles of low momentum. Stereoscopic pictures were taken of both chambers. A system of mirrors was used to allow a single camera to photograph both cloud chambers simultaneously. One camera viewed the cloud chambers along the axis of each, while another camera viewed each chamber with a stereoscopic angle of 20°. At the top and bottom of the top chamber were sets of fiducial wires which could be used together with a third set of wires in the bottom chamber to ascertain the path of the particles through the cloud chambers and the air gap of the magnet. The equipment had a small vertical aperture of only 20° in the east–west direction and 6° in the north–south direction. The roof of the trailer housing the equipment was the only absorber over the apparatus and amounted to only one or two g/cm^2 of wood and steel.

The angle between the tracks produced in the upper

* Work done at Brookhaven National Laboratory under the auspices of the AEC.
[1] M. Sands, Phys. Rev. **77**, 180 (1950).
[2] J. C. Street, J. Franklin Inst. **227**, 765 (1939).
[3] B. G. Owen and J. G. Wilson, Proc. Phys. Soc. (London) **A64**, 417 (1951).
[4] Caro, Parry, and Rathgeber, Australian J. Sci. Research **A4**, 16 (1951).
[5] B. Rossi, Revs. Modern Phys. **20**, 537 (1948).
[6] Miller, Henderson, Potter, Todd, and Wotring, Phys. Rev. **79**, 459 (1950); Miller, Henderson, Potter, and Todd, Phys. Rev. **84**, 981 (1951).

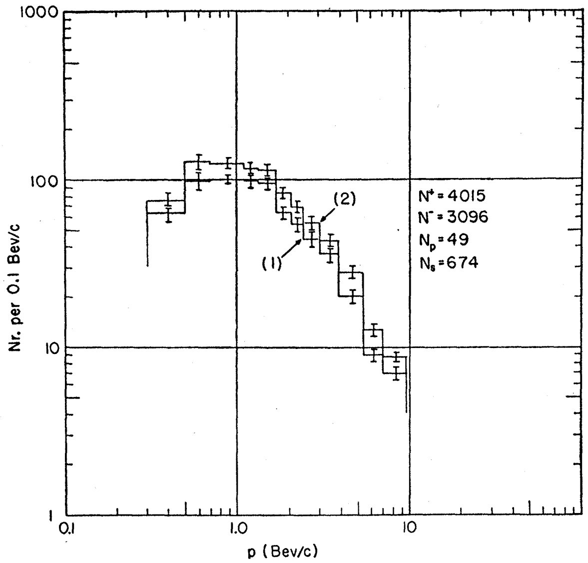

FIG. 2. The differential momentum distributions of positive and negative particles observed at sea level. No electrons are included. (1) refers to negative particles, (2) to positive particles after subtraction of identified protons. For absolute intensity multiply ordinate by 1.07×10^{-8} cm^{-2} sec^{-1} sterad^{-1} (Mev/c)$^{-1}$.

chamber and that in the top half of the bottom chamber was used to determine the momentum in a manner already described.[7-9] The lower section of the bottom chamber contained a 5-cm and a 1-cm lead plate and thereby gave information on the projected angle of scattering in lead for a particle whose momentum was also measured. The plates also aided in the identification of electrons and slow protons. The momentum p was measured in the range 0.300 ± 0.006 to 11 ± 4 Bev/c. The errors are caused mainly by distortion in the chambers. Scattering in the two cloud-chamber walls and four Geiger counter walls (total thickness $\frac{3}{16}$-in. Lucite, 0.006-in. aluminum[10]) caused an error of less than one percent for mesons. For some tracks of exceptional quality the momentum could be measured up to 30 Bev/c, both at sea level and at altitude. The "cut-off" effect of the magnetic field on the momentum distribution at low momenta has been investigated and found to be negligible for momenta larger than 0.5 Bev/c. For smaller momenta the spectrum must be increased by a factor which increases with decreasing momentum to 1.15 for $p=0.3$ Bev/c. This correction is not included in the histograms discussed in the next section but is included later on.

III. MOMENTUM DISTRIBUTIONS

The differential momentum spectra are given in Figs. 2 and 3 for runs made at sea level and altitude, respectively. N^+ and N^- refer, respectively, to the total number of positive and negative particles after all recognized electrons are deducted; the appropriate values are stated in each histogram. At sea level 42 electrons were recognized by the showers produced in the 5-cm and 1-cm lead plates. At altitude 43 electrons were similarly observed. The ratio of these numbers of electrons has no significance because the anticoincidence counters were used at altitude and not at sea level. On each histogram the number of particles N_s whose momenta were too large to be measured is also included. N_p refers to the number of protons which were identified by their absorption in the 6 cm of lead in the lower cloud chamber and also by their heavy ionization in the gas. Protons which are stopped by ionization losses in 6 cm of lead must produce in the gas an ionization density I greater than 2.2 times the minimum rate. Hence, N_p should include all protons for which $I/I_{\min}>2.2$. It was not possible to separate, on the basis of ionization alone, other protons whose ionization was less than 2.2 $I_{\min}$. Therefore, the distribution (2), Fig. 3, represents data for particles ionizing in the range 1 to 2.2 times the minimum rate. In what follows these particles will be referred to as ionizing at the minimum rate.

No accurate record of running time was kept; hence the absolute intensity is not plotted in these histograms. However, if Greisen's value[11] of 0.82×10^{-2} cm^{-2} sec^{-1}

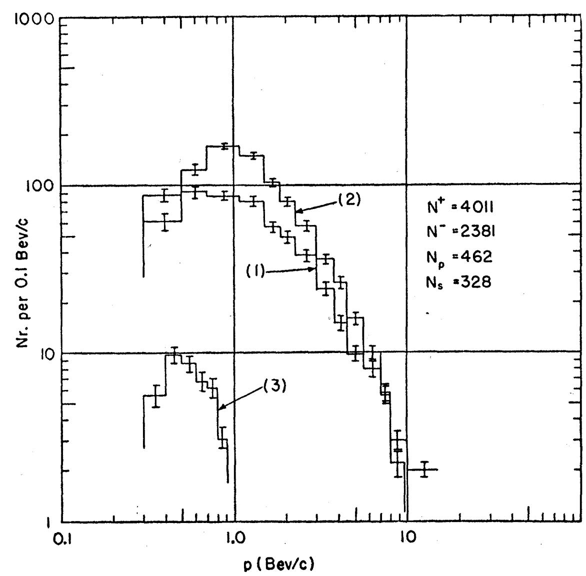

FIG. 3. The differential momentum distributions of positive and negative particles observed at 3.4-km altitude. No electrons are included. (1), (2), as in Fig. 2; (3) refers to identified protons. For absolute intensity multiply ordinate by 2.41×10^{-8} cm^{-2} sec^{-1} sterad^{-1} (Mev/c)$^{-1}$. For simplification of the graph the ordinate of (3) has been divided by 10.

[7] R. B. Brode, Revs. Modern Phys. **21**, 37 (1949).
[8] Glaser, Hamermesh, and Safanov, Phys. Rev. **80**, 625 (1950).
[9] R. P. Shutt and W. L. Whittemore, Rev. Sci. Instr. **22**, 73 (1950).
[10] The counters C_2 and C_3 were especially constructed in order to minimize scattering in their walls. The top and bottom walls consisted of 0.0015-in. aluminum foils while the effective counting volume was limited at the sides by a series of fine wires spaced $\frac{1}{2}$-in. from the solid side walls. The counters were operated at atmospheric pressure by means of "Q"-gas passed through the counters at the slow rate of 1 cm^3/sec. The "Q"-gas was obtained from the Matheson Company, East Rutherford, New Jersey.

[11] K. Greisen, Phys. Rev. **61**, 212 (1949).

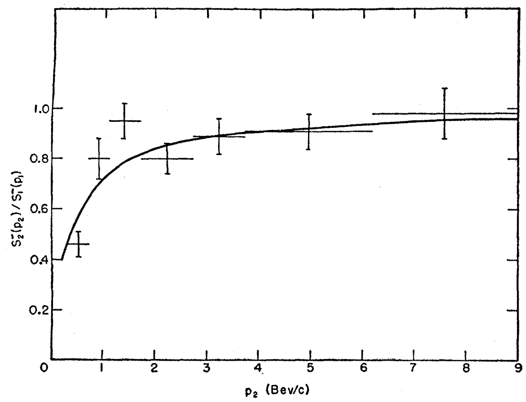

FIG. 4. Experimental and theoretical variation of $S_2^-(p_2)/S_1^-(p_1)$ with momentum.

sterad^{-1} for the total intensity of the penetrating component at sea level is used to normalize the combined data for positive and negative particles ionizing at the minimum rate, the ordinate in Fig. 2 should be multiplied by 1.07×10^{-8} cm^{-2} sec^{-1} sterad^{-1} (Mev/c)$^{-1}$ to give the absolute differential intensity at sea level. If this change of scale is made, the resulting differential momentum spectrum agrees very well with that of Wilson as exhibited by Rossi.[5] In particular, for low momenta the present spectrum follows closely that of Wilson rather than the one Rossi has deduced from counter absorption measurements. The ordinate of Fig. 3 should be multiplied by $2.25\times1.07\times10^{-8}$ cm^{-2} sec^{-1} sterad^{-1} (Mev/c)$^{-1}$ to give the absolute differential momentum spectrum at 3.4 km. The factor 2.25 by which the spectrum obtained at altitude must be increased to take account of the different running times used at sea level and altitude will be derived in the next section.

IV. PRODUCTION OF MESONS BELOW 3.4 KM

The momentum distributions obtained at sea level and at 3.4 km can be compared so as to reveal any production of mesons which may take place below 3.4 km. This comparison, which will be described below, gives no evidence that a large fraction of mesons observed at sea level is produced below 3.4 km. For this comparison only the data for negative particles are used since the data for positive particles include a number of protons, unrecognizable because they ionized at the minimum rate. Since electrons were not included, the data for negative particles pertain solely to mesons.

Let $S_1^-(p)dp$ and $S_2^-(p)dp$ represent the differential momentum distributions for negative particles at 3.4-km altitude and at sea level, respectively. Let $P_1(p_2)$ be the probability that a meson with momentum p_1 at 3.4 km will arrive at sea level with momentum p_2, suffering a momentum loss p_1-p_2 due to ionization. The quantity $P_1(p_2)$ is evaluated from data given by Sands.[1] Except for mesons produced below 3.4 km, the following relation holds between the two spectra

$$S_2^-(p_2)(dp)_2=S_1^-(p_1)(dp)_1P_1(p_2). \qquad (1)$$

Divide both sides of (1) by dx and rearrange to obtain the equation

$$S_2^-(p_2)/S_1^-(p_1)=\left[\left(\frac{dp}{dx}\right)_1\Big/\left(\frac{dp}{dx}\right)_2\right]P_1(p_2). \qquad (2)$$

The term in brackets in (2) takes into account the changes in the rate of momentum loss with increasing momentum. The theoretical quantity on the right can be evaluated on the basis of ionization theory, since the half-life of mu-mesons is known. This quantity represents essentially the probability that a meson known to be present at 3.4-km altitude will survive to sea level, since the quantity in brackets ranges from 1.08 to 1.03 for the momentum interval under consideration. The quantity on the left, $S_2^-(p_2)/S_1^-(p_1)$, can be evaluated from the spectra in Figs. 2 and 3. This ratio cannot be compared directly with the theoretical expression but must be decreased by a factor K to take into account the fact that the running times at altitude and sea level were different. Since it can be shown from different considerations that only a few percent of the radiation at 3.4 km consist of protons with momenta greater than 5 Bev/c, one can reasonably conclude that only few mesons with momenta larger than 5 Bev/c are produced below 3.4 km. Under these circumstances the experimental and theoretical curves should agree at high momenta even if production should occur for smaller momenta. Figure 4 shows the theoretical curve and experimental points together with the standard errors. The value $K=2.25$ was chosen to make the best over-all fit with particular attention paid to high momenta. This choice of K implies that the intensity at 3.4 km as measured by a Geiger counter telescope containing 167 g/cm^2 of lead would increase by a factor of 1.9 over that at sea level. Rossi[5] has shown that the increase as measured by such a counter telescope is 2.0. The discrepancy may be due to statistical fluctuations, due to a residual effect of side showers on the counter telescope, or due to the fact that the counter experiment covered a larger solid angle than covered in the present experiment.

A comparison of the experimental points and theoretical values of $S_2^-(p_2)/S_1^-(p_1)$ in Fig. 4 shows that two experimental points fall considerably above the theoretical curve in the range from about 0.7 to 3 Bev/c. Except for mesons produced below 3.4 km, the two functions should agree everywhere. Hence, the difference between the theoretical curve and the curve determined by the experimental points, unless wholly due to statistical fluctuations, indicates the magnitude of meson production. A computation based on this difference shows that of the 1600 negative sea-level mesons between 0.7 and 3 Bev/c about 120 ± 90 or between 0 and 15 percent were produced below 3.4 km. Therefore

260 ± 200 mesons of both signs could have been produced. The experimental point at 0.5 Bev/c falls below rather than above the theoretical curve. The detection of sea-level particles in this momentum range ($0.3 < p_2 < 0.7$ Bev/c) is made somewhat uncertain by magnetic cutoff and also by increased scattering, while the corresponding high altitude particles are not so affected due to their higher momenta ($1.0 < p_1 < 1.4$ Bev/c). Thus the latter discrepancy is understandable. We conclude that the experimental data are mainly in agreement with the assumption advanced by other workers that mesons observed at sea level are largely produced in the upper atmosphere; however, there is some evidence that a few of the sea-level mesons with momenta less than 3 Bev/c are produced in the lower one-third of the atmosphere. As shown later there are about 200 protons and probably about as many neutrons present in the altitude spectrum, possessing sufficient energy to produce one or more mesons in the indicated momentum range. Thus, a small amount of meson production, as indicated here, is entirely feasible.

V. DERIVATION OF THE DIFFERENTIAL PRODUCTION SPECTRUM FOR MESONS

Using a method similar in principle to that used first by Euler and Heisenberg[12] and later by Janossy and Wilson,[13] one can derive a spectrum for mesons at production, assuming that production of mesons takes place near the top of the atmosphere. The method for deriving the production spectrum follows closely the material presented in Sec. IV. Equation (2) can be rewritten to represent the spectrum observed at sea level, $S_2^-(p)dp$, in terms of the production spectrum $S_0^-(p)dp$. For particles starting with momentum p_0 one has

$$S_0^-(p_0)=S_2^-(p_2)\bigg/\left[\left(\frac{dp}{dx}\right)_0\bigg/\left(\frac{dp}{dx}\right)_2\right]P_0(p_2). \quad (3)$$

In this case the momentum at sea level and at the place of production differ by an amount p_0-p_2, which is the momentum loss in traversing the atmosphere between these two depths. Furthermore, $P_0(p_2)$ has the same significance as before but different values since it now represents the probability that a meson with momentum p_0 at the place of production will survive to sea level. When $S_0^-(p)dp$ is evaluated by means of (3) and plotted as a function of p, it is found that it follows a power law $p^{-\gamma}dp$ (except for a scale factor) where $\gamma=2.92\pm0.08$ for $2<p<10$ Bev/c. A similar calculation using the spectrum of negative particles observed at 3.4 km together with the appropriate changes in the momentum loss and survival probabily leads to $\gamma=2.61 \pm0.15$. These values of γ differ by more than the standard errors. If no production occurs except near the top of the atmosphere, the two values of γ should agree. On the other hand, if some production does occur down through the atmosphere, the two values of γ obtained would not necessarily agree, the production process having been over-simplified. The results of Sec. IV indicate that some production may indeed take place in the lower atmosphere and, in particular, that up to 15 percent of the mesons with momenta lower than 3 Bev/c could be produced below 3.4 km. If these mesons are subtracted from the spectrum observed at sea level a value of $\gamma=2.82\pm0.08$ is found, in better agreement with the altitude value. By averaging the two values for γ in the appropriate manner one finds $\gamma_{Av}=2.75\pm0.07$. However, it must be kept in mind that the power law is only an approximation because some production takes place through the whole atmosphere, particularly, of course, at the lower momenta as shown by Sands.[1] It is interesting to note that this value agrees with the value $\gamma=2.87$ deduced by Euler and Heisenberg,[12] but is less than the value $\gamma=3.3$ cited by Janossy and Wilson.[13]

If the observed momentum spectra are first transformed to range distributions expressed in g/cm² of air and the above computations are repeated, it is found that $S_{0R}^-(R)dR\sim R^{-\gamma_R}dR$ where $\gamma_{RAv}=2.90\pm0.07$ for $900<R_0<4100$ g/cm² of air. This value is in good agreement with $\gamma_R=2.92$, cited by Sands.[1]

VI. DIFFERENTIAL PROTON SPECTRUM AT 3.4 KM

The ratio of the number of positive particles to the number of negative particles observed at any given altitude and momentum, defined as r, has been investigated previously by several workers.[3,4,6,8,14–17] Each of the given references includes many additional ones. Several detailed studies of the variation of r with momentum have been performed at sea level. The results of the present study obtained at sea level and also at 3.4 km are shown in Table I.

Protons with momenta >0.7 Bev/c cannot be stopped by ionization losses in 6 cm of lead. However, in

TABLE I. Ratio (r) of number of positive particles to number of negative particles and proton fraction (f) of total number of mesons and protons at 3.4 km. Values for $r=r_m$ in parenthesis pertain solely to mesons.

Range of momentum Bev/c	r Sea level	r 3.4 km	f 3.4 km
0.30–0.70	1.38±0.09 (1.24±0.08)	2.50±0.14 (1.35±0.10)	0.34[a]±0.06
0.70–1.10	1.22±0.07	2.10±0.12	0.28±0.06
1.10–1.9	1.21±0.07	1.87±0.10	0.22±0.05
1.9 –3.5	1.28±0.07	1.52±0.07	0.11±0.04
3.5 –9.6	1.32±0.06	1.41±0.08	0.06±0.04
0.3 –9.6			0.19±0.02

[a] Observed directly.

[12] H. Euler and W. Heisenberg, Ergeb. Exact. Naturwiss. **17**, 1 (1938).

[13] L. Janossy and J. G. Wilson, Nature **158**, 450 (1946).

[14] W. R. Brode, Phys. Rev. **78**, 92 (1950).

[15] M. G. Mylroi and J. G. Wilson, Proc. Phys. Soc. (London) **A64**, 404 (1951).

[16] M. Correll, Phys. Rev. **72**, 1054 (1947).

[17] Quercia, Rispoli, and Sciuti, Phys. Rev. **74**, 1728 (1948).

histogram (3), Fig. 3, "stopped" protons with apparent momenta up to 0.9 Bev/c are shown. Near 0.7 Bev/c the criterion for proton identification based on ionization density becomes quite uncertain while the criterion based on the stopping power of lead also becomes uncertain since some of the protons that normally would emerge from the lead with low energies may well be scattered out of the field of view, may be stopped by the greater effective path length caused by scattering, or may be absorbed by nuclear interaction.[18] On the other hand, a slow ($p<0.7$ Bev/c) heavily ionizing proton is more subject to scattering than a meson with the same momentum, and its track is relatively wide. These facts combined with still other sources of small errors may lead to slightly falsified proton momentum measurements. A rough estimate shows that about one half of the particles in question may actually belong in the range 0.3 to 0.7 Bev/c. With this correction the values for r have been calculated as given in Table I. (Without this correction the directly observed value for f in the range $0.3<p<0.7$ Bev/c would be 0.31 instead of 0.34.)

The values of $r(=r_m)$ for mesons alone are shown in parenthesis for the momentum interval 0.3 to 0.7 Bev/c, since here protons could be identified directly. The other values of r include the effects of protons. However, at sea level, Mylroi and Wilson[15] have shown that for $p>0.7$ Bev/c less than four percent of all ionizing particles at sea level are protons and that for higher momenta the fraction is much less. Hence the values of r at sea level for $p>0.7$ Bev/c pertain mostly to mesons. In addition, the following argument indicates that essentially no energetic protons are left at sea level. The intensity of primary protons at the top of the atmosphere is about twenty times the mu-meson intensity at sea level.[19] For a mean free path of 125 g/cm^2 (see reference 5) one would have [20 exp(−1030/125)] or about 0.5 percent of the sea-level intensity left as protons of high energy. Of course, secondary protons would increase somewhat this number, which is a lower limit; however, one would expect that most secondary protons have relatively low energy.

The present experimental data at sea level (Table I) also represent adequately the results of other workers. The results of Owen and Wilson[3] and Caro *et al.*[4] indicate that there is a flat maximum for r at about 5 Bev/c. Our results are consistent with this view, although there are not sufficient data above 10 Bev/c to check this point quantitatively. The good agreement between the present data and those of others obtained at sea level leads one to have confidence in the values of r obtained with the same equipment at 3.4-km altitude.

Concerning the variation of r with momentum at 3.4 km (Table I), the first important point to notice is the large excess of positive particles observed at low momenta. Except for the small positive excess known to be characteristic of mesons at sea level, this large excess of positive particles must be caused by protons. This idea has been previously used by Miller *et al.*[6] and by Adams *et al.*[20] for results obtained at airplane altitudes. Practically all the pi-mesons which are produced will quickly decay into non-interacting mu-mesons. These mu-mesons will be removed by decay or by ionization losses regardless of the sign of their charge; therefore, any r_m inherent in the production of the mesons must be maintained through all altitudes thereafter, provided, of course, that no measons are produced below 3.4 km with a different positive to negative ratio. In particular, if a certain r_m exists at 3.4 km this same value should exist at sea level for mesons having a momentum reduced by the ionization loss. If this reasoning is correct, the large values of r observed at 3.4 km must be caused by a component of cosmic rays which is positively charged and almost completely absorbed in the atmosphere below 3.4 km. Thus one is justified in identifying this component with protons since they have the required properties and are known to be much more abundant at high altitudes than at sea level. Furthermore, the values of r_m at sea level and altitude for $0.3<p<0.7$ Bev/c agree within the limits of error (see Table I, values in parenthesis). Finally, the values of r at sea level and altitude approach each other for large momenta. This would imply that there are relatively few energetic protons at 3.4-km altitude, a result in agreement with what one expects on the basis of the following computation. Since the intensity of primary protons at the top of the atmosphere is about ten times the intensity of the hard component observed at 3.4 km, [10 exp(−670/125)] or only 5 percent of the observed high energy intensity at altitude consist of high energy protons. Of course this number will be increased somewhat by secondary protons, as mentioned previously.

Before calculating the proton spectrum from the variation of r with altitude and momentum, some results of other workers will be examined. Miller *et al.*[6] (1950) observed 950 particles at 3.4 km under 5 cm of lead for which $r=1.50\pm0.05$ in the range $0.05<p<2.5$ Bev/c. A value can be deduced in the following manner for the present data and compared with that of Miller. Miller observed all particles below 5 cm of lead. This is roughly equivalent to the present results when we deduct all particles which stop in 5 cm of lead from the total observed for $0.3<p<2.5$ Bev/c. For this case, $r=1.68\pm0.06$, in fair agreement with Miller. For mesons having ranges >60 cm of iron and momenta of $1.0<p<2.5$ Bev/c Brode[14] reports values of $r_m=1.32\pm0.02$ near sea level and $r_m=1.30\pm0.03$ at 3.65 km. The present results agree sufficiently with these values. In Brode's experiment protons are practically eliminated

[18] The effects of nuclear interaction of the protons in the lead will be considered in detail in a later paper.

[19] Winckler, Stix, Dwight, and Sabin, Phys. Rev. **79**, 656 (1950).

[20] Adams, Anderson, Lloyd, Rau, and Saxena, Revs. Modern Phys. **20**, 334 (1948).

by ionization losses, scattering, and nuclear interactions in the interposed iron. Correll[16] has observed r_m for slow mesons at 3.4 km and found for about 350 particles that $r_m=1.0$. Considering the poor statistics, this value is in agreement with the value $r_m=1.35\pm0.10$ deduced from the present work. It is interesting to compare our value with a value of $r_m=1.26$ which Quercia *et al.*[17] have deduced from counter experiments at altitude for the region of low momenta. Identification of the charge was made in this case by deflecting the charged particles through magnetized iron plates. This experiment was operated at sea level, at 5.1 and 7.3 km.

In order to determine the proton spectrum at 3.4 km we proceed as follows. As just described, for mesons we must have

$$S_2^+(p_2)/S_2^-(p_2)=r_{m2}(p_2)=r_{m1}(p_1)=S_1^+(p_1)/S_1^-(p_1), \quad (4)$$

where the subscripts were defined for Eq. (1) and S_1^+, S_1^-, S_2^+, S_2^- refer to mesons only. Because of the presence of only few protons with momenta >0.7 Bev/c at sea level we may put the sea-level values of r equal to r_{m2}. If $S_{T1}^+(p)dp$ is the differential spectrum of the total positive component at 3.4-km altitude, then the proton component $S_{P1}(p)dp$ is given by

$$S_{P1}(p_1)=S_{T1}^+(p_1)-S_1^+(p_1)$$
$$=S_{T1}^+(p_1)-S_1^-(p_1)r_{m2}(p_2). \quad (5)$$

The results obtained by performing this computation are shown in Fig. 5, where both the total spectrum $[S_{T1}^+(p)+S_1^-(p)]dp$ and the proton spectrum are exhibited. The spectrum of protons for $p>2$ Bev/c can be represented fairly well as $S_{P1}(p)dp\sim p^{-\alpha}dp$, where $\alpha=2.5\pm0.5$. From these spectra one can find the fraction f of the protons in the total spectrum as shown in the last column of Table I. One also finds that protons form 19 ± 2 percent of all ionizing particles with $p>0.3$ Bev/c. The value of about 6 percent for high momenta agrees with the approximate value of 5 percent calculated from the proton primary intensity.

Figure 5 includes from the data of Miller *et al.*[6] (1951) three points which fall somewhat below the proton spectrum derived here. Protons of momenta <0.7 Bev/c are quite subject to multiple Coulomb scattering in the 2.5 cm of lead located above Miller's cloud chamber, and some of them may have been scattered out of the field of view. Furthermore, a number of protons ($\sim$10 percent) may have been removed by nuclear interaction in the same lead. From the results of Miller *et al.* one infers the value for the total intensity near 0.5 Bev/c shown in Fig. 5. This value agrees well with the present result. The data of Winckler *et al.*[19] obtained at high altitudes have been used to compute the expected number of protons at 3.4 km for high momenta. The point entered at 5 Bev/c is in agreement with the present results, taking into account the large experimental errors in this momentum range.

The proton spectrum at 3.4 km consists of a small number of high energy primaries and a larger number of lower energy secondaries produced in the atmosphere by nuclear interaction of the primaries. Particularly the number of secondaries is modified by ionization losses in the atmosphere. Messel[21] has calculated several values for the integral spectrum of the proton component at different altitudes, making use of an interaction model first proposed by Heitler and Janossy,[22] including a mean free path of 65 g/cm² for interaction and of 130 g/cm² for absorption. An energy power law for the primaries with an exponent of -2.7 was chosen. From these calculations one expects that at 3.4 km the ratio of the number of protons with $p>0.78$ Bev/c to the number of protons with $p>2.9$ Bev/c should be 5, in rough agreement with a value of 7 ± 2 found from our data.

Most of the protons observed at 3.4 km disappear before reaching sea level in the following manner. In

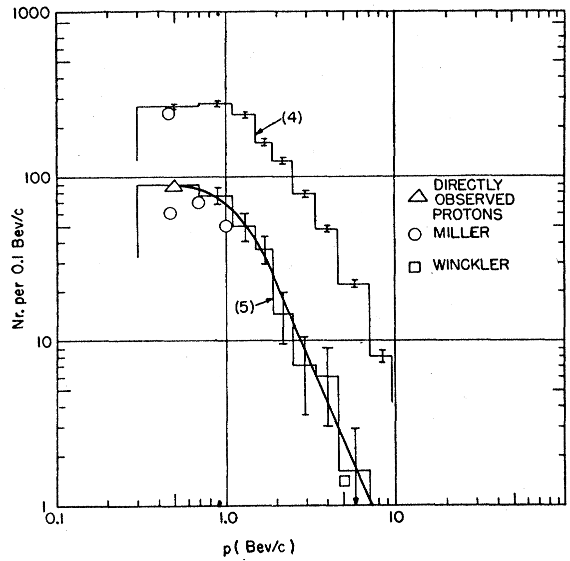

FIG. 5. The spectrum for combined negative and positive particles, including protons, observed at altitude (4) and the deduced spectrum for protons (5). Multiply ordinate by 2.41×10^{-8} cm^{-2} sec^{-1} sterad^{-1} (Mev/c)$^{-1}$ for absolute intensity.

the first place, a proton must have a momentum of at least 1.67 Bev/c to arrive at sea level. 19 ± 2 percent of all ionizing particles (excluding electrons) at altitude are protons, but the spectrum of Fig. 5 shows that only one quarter of these have $p>1.67$ Bev/c and hence can reach sea level. Furthermore, since the 353 g/cm² of air between 3.4 km and sea level correspond to about 2.8 mean free paths for interaction, these remaining protons become reduced to about $[\exp(-2.8)]$ or 0.06 of those initially present. Finally, the proton component capable of reaching sea level becomes $(19)\times(0.25)\times(0.06)$ or 0.3 percent of all ionizing particles observed at altitude. Since the total intensity of the hard component at sea level is only half that at altitude, the above predicts

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[22] W. Heitler and L. Janossy, Proc. Phys. Soc. (London) **A63**, 374 (1949).

that 0.6 percent of the penetrating component at sea level should consist of protons, a value comparable to what has already been deduced. Of course, many of the protons absorbed between 3.4 km and sea level produce nuclear stars, the products of which are secondary protons, neutrons, and mesons, all with energies still lower than those of the incident protons. These secondary protons will be absorbed in the atmosphere for the most part. Some of the mesons produced below 3.4 km should penetrate to sea level, although many should be absorbed or arrive with too little momentum to be measured by the present apparatus. The results of Sec. IV indicate that up to 15 percent of the mesons observed at sea level with momenta less than 3 Bev/c could be produced below 3.4 km.

Finally, one can deduce from the positive to negative meson ratio r_m something concerning the multiplicity with which mesons are produced. The ratio r_m depends on a number of poorly understood factors. The specific mechanism by which mesons are produced is not known. Whether mesons are produced multiply or plurally in several acts all occurring in one nucleus is not yet clear. However, one can make some very simple assumptions about the production of mesons by saying that in half of all cases the extra charge due to the protons is not projected forward but goes off as some low or medium energy proton instead of a high energy meson. Then $r_m=1.32\pm0.06$ implies an average multiplicity of 4 for meson production by high energy protons which agrees with other arguments. For instance, see the discussion of Owen and Wilson.[3]

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Radioactivities of Platinum and Iridium from Photonuclear Reactions in Platinum*

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The products of photonuclear reactions induced in platinum by a 70-Mev synchrotron x-ray beam have been studied. No osmium activities were found. The iridium fraction included Ir^{192} and Ir^{194} and two new isotopes: a 140-min, 1-Mev β^- emitter, probably Ir^{195}, and a 7-min activity, probably Ir^{197}. Pt^{193}, Pt^{197}, and the 88-min isotope which decays by isomeric transition were found in the platinum fraction. Some evidence is presented to question the assignment of the 88-min activity to Pt^{195}. Relative yields of all these radioactive isotopes have been measured.

INTRODUCTION

In this investigation, platinum was irradiated in the x-ray beam of the Iowa State College 70-Mev synchrotron in order to identify and characterize the osmium, iridium, and platinum activities produced and to determine their relative yields.

Prior to this work an 87-min platinum activity and the 18-hr Pt^{197} had been reported from photonuclear reactions in platinum.[1,2] Also, Butement[3] reported a new 66-min activity and the well-known 19-hr Ir^{194} in the iridium fraction from $PtCl_4\cdot xH_2O$ which had been irradiated with x-rays.

EXPERIMENTAL DETAILS

Irradiations

Samples of 1 to 5 grams to be irradiated were contained in test tubes of 1-cm diameter. The tubes were mounted close to the synchrotron doughnut by a plastic holder which was carefully aligned in the x-ray beam of the synchrotron. The intensity of the beam was monitored by an ionization chamber whose current was continuously recorded. All of the samples for yield determinations were irradiated at nearly constant beam intensities at the maximum energy of the synchrotron unless otherwise indicated. In early experiments, platinum metal was irradiated. However, dissolving the platinum metal was time consuming and in subsequent irradiations, $PtCl_4\cdot xH_2O$ was used. In spectroscopic analyses of the platinum and $PtCl_4\cdot xH_2O$ no osmium or iridium was found. The principal impurity was copper estimated at about 0.01–0.1 percent.

Chemical Separations

The various components of the irradiated samples were separated by the chemical methods outlined below.

1. Chlorine. A small fraction of the $PtCl_4\cdot xH_2O$ was fused with Na_2CO_3. The melt was extracted with water, and silver nitrate was added to precipitate AgCl.

2. Osmium. The $PtCl_4\cdot xH_2O$ was dissolved in concentrated HNO_3. Osmium and iridium carriers were

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[3] F. D. S. Butement, Nature 165, 149 (1950).