SOVIET PHYSICS - JETP VOLUME 1, NUMBER 1 JULY, 1955

The Proton Component of Cosmic Rays at 3200 Meters Above Sea Level

N. M. KOCHARIAN
Physical Institute, Academy of Sciences, Armenian SSR

(Submitted to JETP editor February 8, 1954)
J. Exper. Theoret. Phys. USSR 28, 160-170 (February, 1954)

The momentum spectrum of protons at an altitude of 3200 meters above sea level was obtained in the range of momenta $0.4 \leq p \leq$ BeV/c. The absorption lengths of the protons in air and in lead are determined. The spectrum of protons generated in lead is investigated.

1. DESCRIPTION OF THE APPARATUS

THE results reported in this paper are based on measurements made with two versions of a magnetic spectrometer. The first was described in detail previously[1]. The second, which provides great accuracy, will be described briefly here.

The particle momenta were measured in a field produced by an electromagnet, of strength 5800 oersteds, vertical length 80 cm, width 20 cm, and gap 10 cm (Fig. 1). Four trays of coordinate counters, K_1, K_2, K_3 and K_4, were used to determine the radii of curvature of the particle trajectories. The counters in trays K_1, K_3 and K_4 determined the radius of curvature, while those in tray K_2 served to check the accuracy of these determinations. In order to improve the accuracy of determination of the particle paths the counters were distributed in two layers in the trays[2]. These counters were 10 cm long and were of inside diameter $d = 4.6$ mm. From the point of view of specifying the path of the particles, these counters were equivalent to counters of diameter $^1/_3 d = 1.53$ mm distributed in a single layer. The counters in trays K_2 and K_3 were made of aluminum to reduce multiple scattering effects. The other counters had copper cathodes.

So that particles scattered from the poles of the magnet could be rejected, the counters, T, 1 cm in diameter, were placed on the poles at intervals of 3 cm, as indicated in Fig. 1. Two plates of lead, Π and Π', 5 cm in thickness, and 1 cm in thickness respectively, a total of 68 gm/cm^2, were placed above the magnet. These were removed for some of the measurements.

Seven double layer trays of copper-walled counters were located underneath the magnetic field, with absorbers Π_1, Π_2, Π_3, Π_4, Π_5 and Π_6 placed between these, as shown in Fig. 1. The first of these, Π_1, consisting of 4 cm of lead, was for the purpose of absorbing electrons, while the other absorbers were, respectively, 1, 4.2, 1.8, 6 and 2 cm of copper. Thus the total thickness of absorbers was $0.28\,\lambda_{Pb} + 1.23\,\lambda_{Cu}$, where λ_{Pb} and λ_{Cu} are the nuclear interaction lengths, assumed to be 160 gm/cm^2 and 108 gm/cm^2, respectively.

All of the counters, with the exception of those in K_{11} and T were individually connected to neon bulbs. The system was actuated only when a particle passed through counters in each of the trays K_1, K_3 and K_4. When this occurred the appropriate neon bulbs indicated through which particular counters the particle had passed. The mean square error of momentum determination in this assembly, due to the finite size of the counters and to multiple scattering in the counter walls, is given by

$$\sigma = \sqrt{(0.035p)^2 + \left(\frac{0.018}{\beta}\right)^2}. \qquad (1)$$

where β is the particle velocity in units of the velocity of light and p the particle momentum in units of BeV/c.

2. MOMENTUM SPECTRUM OF THE PROTONS

Using the arrangement described previously[1], 6085 protons were observed which had momenta ≥ 0.4 BeV/c and which were stopped in copper and lead absorbers of an equivalent thickness for ionization of 198 gm/cm^2. Of these 6085 protons, 1740 had momenta $\geq$ BeV/c and were stopped in the absorbers by nuclear collisions. Table 1 shows the distribution of these particles by range.

The protons and mesons were well separated in each of the range intervals of Table 1. For this rea-

[1] N. M. Kocharian, M. G. Aivazian, Z. A. Kirakosian and S. D. Kaitmazov, Doklady Akad. Nauk Armenian SSR 17, 33 (1953)

[2] N. M. Kocharian, P. S. Saakian, M. G. Aivazian, Z. A. Kirakosian and S. D. Kaitmazov, J. Exper. Theoret. Phys. USSR 23, 532 (1952)

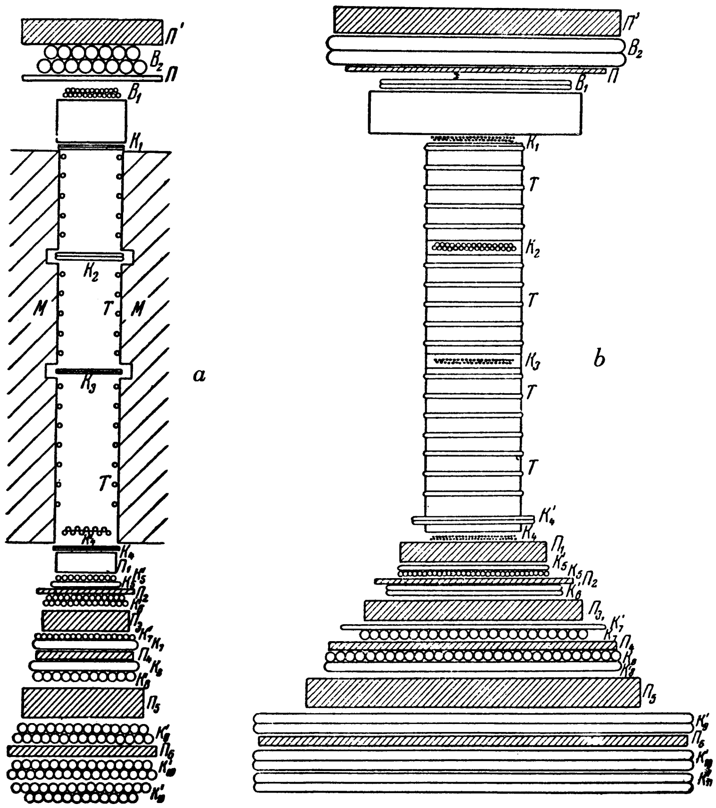

Fig. 1. Layout of the magnetic spectrometer, *a)* in the vertical plane parallel to the magnetic field, and *b)* in the vertical plane perpendicular to the field.

Table 1

Number of Protons Stopped in the Indicated Range Intervals

Range in gm/cm^2	Number of Stopped Particles		
	Ionizing	Nuclear	Total
11.3 Pb $\leq R \leq$ 57 Pb	1867	901	2768
57 Pb $\leq R \leq$ 57 $\leq$ Pb + 22 Cu	636	473	1109
57 Pb + 22 Cu $\leq R \leq$ 57 Pb + 48.4 Cu .	480	415	895
57 Pb + 48.4 Cu $\leq R \leq$ 57 Pb + 101.7 Cu	661	652	1313

son it was possible to derive the momentum spectrum of the protons stopped in the absorbers. This spectrum would not necessarily be the true spectrum of the vertical proton flux, however. In order to obtain the true specturm it is necessary to divide the observed numbers in the differential spectrum by the probability of the particles stopping in the system of absorbers. Let "w" represent this probability. Involved in w is the probability that all of the products of nuclear interactions of protons with $p \geq 1$ BeV/c terminate in the absorbers, and hence do not set off counters in the last tray underneath all of the absorbers. This probability is a function of the energy of the particles.

Since protons of momentum $p \leq 1$ BeV/c necessarily will stop in the absorbers because of ionization loss, in such a case $w = 1$, and the observed spectrum is the true one.

In order to evaluate w for $p > 1$ BeV/c a careful analysis was performed of the nuclear showers produced by the protons in the absorbers underneath the magnet. This analysis led to the conclusion that in most cases penetrating showers were produced by protons of $p > 3$ BeV/c. Penetrating showers were here defined to be those events in which more than one counter was set off in one of the trays situated between absorbers, and in which at least one of the products penetrated at least one of the following absorbers. In cases of momentum $p \leq 2$ BeV/c only very rarely was more than one counter in a tray set off. This implies that for such momenta the star products had little energy and so were usually absorbed in the same absorber wherein they were formed. In the rare cases at these momenta that such an event did occur, the star products were almost always absorbed in the next following absorber. Hence, it can be asserted with great confidence that particles with momenta $p \leq 2$ BeV/c are not capable of producing any appreciable number of fast secondaries able to penetrate all of the absorbers. From this it follows that the number of protons with momenta $1 \leq p \leq 2$ BeV/c which are not stopped in the absorbers by ionization is equal to the number of stars produced by particles in this range of momenta. Here, by stars are meant those inelastic collision events that give rise to more than one secondary. Thus, in the momentum range $1 \leq p \leq 2$ BeV/c the probability of stopping, w, approaches the probability of nuclear interaction, since at these momenta practically all protons suffering inelastic collisions are

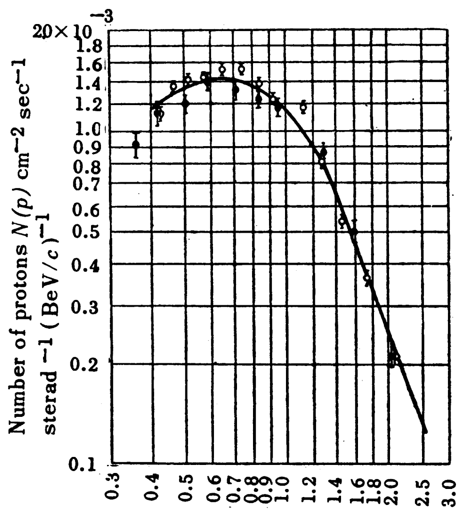

Fig. 2. Momentum spectrum of the vertical flux of protons in air at 3200 meters above sea level.

stopped in the absorbers along with their secondaries. Consequently, for $1 \leq p \leq 2$ BeV/c,

$$w = 1 - e^{-x_0/\lambda}, \tag{2}$$

where x_0 is the total thickness of absorbers and λ the inelastic nuclear scattering length.

Laboratory experiments on the scattering of fast neutrons[3] at energies of several tens of MeV show that the inelastic scattering length λ_a, increases with increasing energy. It first increases rapidly, but then at about 200 MeV approaches a constant value, $2\lambda_0$, where λ_0 is the inelastic scattering length corresponding to the geometrical cross section of the nuclei. Recent experiments[4,5] show that this constancy holds up to proton energies of 2.2 BeV. Thus, in the momentum range under discussion, $1 \leq p \leq 2$ BeV/c, it is correct to take $\lambda_a = 2\lambda_0$, and, for the experimental arrangement used,

$$w = 1 - e^{-x_0/2\lambda_0} = 0.48. \tag{3}$$

On the basis of Eq. (3) the deduction of the true differential spectrum from the observed numbers of protons stopped in the absorbers can be extended to momenta of the order of 2 BeV/c. For momenta $p \geq 2$ BeV/c, the probability, w, will not have the simple form of Eq. (3).

In Fig. 2 is shown the differential momentum spectrum of protons on a log-log plot. The abscissa is labeled in units BeV/c, while the ordinate indicates the intensity of the vertical flux of protons in air per unit momentum interval. The circles plotted are the results of the experiment described above, while the dots represent the results of the second version of the measurements. As is evident in the Figure, the spectrum can be approximated in the region $1.2 \leq p \leq 2$ BeV/c by a function of the form

$$N(p)\,dp = \frac{a}{p^{\gamma}}\,dp \tag{4}$$

with $\gamma = 2.65 \pm 0.23$, and $a = 1.46 \pm 0.16 \times 10^{-3}$, where p is in units of BeV/c. For values of $p \leq 1.2$ BeV/c the inclination of the curve de-

---

[3] V. I. Gol'danskii, A. L. Liubimov, and B. V. Medvedev, Usp. fiz. nauk 49, 3 (1953)

[4] L. W. Smith, C. P. Leavitt, A. M. Shapiro, C. E. Schwartz and M. Wotring, Bull. Am. Phys. Soc. 28, 15 (1953)

[5] G. A. Snow, T. Coor, D. A. Hill, W. F. Hornyak and L. W. Smith, Bull. Am. Phys. Soc. 29, 54 (1954)

creases, and becomes zero at $p = 0.7$ BeV/c.

The intensities of the vertical proton flux are $J_0 = 0.806 \pm 0.012 \times 10^{-3}$, $0.606 \pm 0.013 \times 10^{-3}$ and 0.281×10^{-3} cm^{-2} sec^{-1} sterad^{-1} in the momentum intervals $0.4 \leq p \leq 1$ BeV/c, $1 \leq p \leq 2$ BeV/c, and $p \geq 2$ BeV/c, respectively.

In order to increase the accuracy of the above determinations additional measurements were made, using the apparatus described in Sec. 1, which permitted more precise determination of particle momenta. In 267 hours 1581 particles of $p \geq 0.35$ BeV/c were observed. Of the total number of stopped particles, 492 had momenta $p \geq 1.11$ BeV/c and were stopped by nuclear collision. Within the limits of error the results of the two experiments are in agreement.

The author is not familiar with other work in which the proton component was studied at mountain altitudes with sufficient care and attention to detail. An attempt has been made[6] to determine the proton spectrum with a cloud-chamber. Not included in this spectrum was the momentum interval $p \geq 1.2$ BeV/c, for which we found the power law dependence with exponent $\gamma = 2.65$. In the work cited the particles were identified by their ionization, and for this reason it was difficult, for $p \geq 0.5$ BeV/c, to separate unambiguously the protons from the mesons (as was noted by the authors). For this reason the shape of the spectrum is strongly distorted. There the maximum occurs at about $p = 0.4$ BeV/c and then falls off at higher momenta, as compared with our spectrum where the maximum is at about $p = 0.7$ BeV/c and begins to fall off above a value of p of about 0.8 BeV/c.

The proton spectrum at 3400 m was carefully investigated by others[7]. The spectrum was calculated by an analysis of the positive excess in the hard component of cosmic rays. For $p \geq 2$ BeV/c the spectrum obeys a power law with exponent $\gamma = 2.5 \pm 0.5$. Although the general features of this spectrum resemble ours, the intensity of protons is approximately one-and-a-half times larger. Perhaps the explanation lies in the insufficient accuracy of the method used. It should be noted, however, that the intensity of the proton flux calculated in that paper[7] from experimental data of the paper previously cited[6] agrees well with our results.

[6] C. E. Miller, J. E. Henderson, D. S. Potter, J. Todd, Jr. and W. Wotring, Phys. Rev. 79, 459 (1950)

[7] W. L. Whittemore and R. P. Shutt, Phys. Rev. **86**, 940 (1952)

Now the intensity of the total flux of protons with $p > 1$ BeV/c can be calculated. The total intensity for such particles is given by

$$I = 2\pi \int_0^{\pi/2} J(\theta) \sin\theta \, d\theta \tag{5}$$

$$= 2\pi J_0 \int_0^{\pi/2} \exp\left[\frac{x}{z}(1 - \sec\theta)\right] \sin\theta \, d\theta,$$

where J_0 is the intensity of the vertical proton flux. We have, above, that $J_0 = 0.887 \times 10^{-2}$ cm^{-2} sec^{-1} sterad^{-1}. From the angular distribution of protons obtained in a previous work[8] we had $L = 120$ gm/cm^2. Substituting these quantities into Eq. (5), one obtains

$$I = 0.69 \times 10^{-3} \text{ cm}^{-2} \text{ sec}^{-1}$$

3. THE ABSORPTION LENGTH OF PROTONS IN AIR

The absorption length in air of the proton component can be calculated from comparison of the observed intensity of protons at 3200 m with the intensities at other altitudes. By the absorption length we mean here the reciprocal of the absorption coefficient for protons of greater than the given energy. We assume that the absorption of particles is according to an exponential law

$$n(p, s_2) = n(p, s_1) e^{-(s_2 - s_1)/L}, \tag{6}$$

where $n(p, s_1)$ and $n(p, s_2)$ are the intensities of the vertical flux of protons with momenta greater than p, at depths s_1 and s_2 measured from the top of the atmosphere, while L is the absorption length for protons of momenta greater than p.

Solving Eq. (6) for L gives

$$L = \frac{s_2 - s_1}{\ln n(p, s_1) - \ln n(p, s_2)}. \tag{7}$$

Since the integral spectra at the depths s_1 and s_2 have the form

$$n(p, s_1) = \frac{a_1}{\gamma_1 - 1} p^{1-\gamma_1};$$

and

$$n(p, s_2) = \frac{a_2}{\gamma_2 - 1} p^{1-\gamma_2},$$

[8] N. M. Kocharian, M. T. Aivazian, Z. A. Kirakosian and S. D. Kaitmazov, J. Exper. Theoret. Phys. USSR **25**, 364 (1953)

respectively, then Eq. (7) can be re-written

$$L = \frac{s_2 - s_1}{\ln\left(\frac{a_1}{a_2}\right) + \ln\frac{(\gamma_2 - 1)}{(\gamma_1 - 1)} + (\gamma_2 - \gamma_1)\ln p}. \quad (9)$$

At the same time one may consider a differential absorption length, which can be defined by the following expression:

$$l = \frac{s_2 - s_1}{\ln N(p, s_1) - \ln N(p, s_2)}, \quad (10)$$

where $N(p, s_1)$ and $N(p, s_2)$ are the ordinates of the differential momentum spectra at depths s_1 and s_2.

In another work[9], the values of the differential momentum spectrum at sea level was found to be $N(p, 1030) = 0.91 \pm 0.19 \times 10^{-4}$ and $1.21 \pm 0.23 \times 10^{-4}$ cm^{-2} sec^{-1} sterad^{-1} (BeV/c)$^{-1}$ for momenta $0.59 \leq p \leq 0.77$ BeV/c and $0.77 \leq p \leq 0.93$ BeV/c, respectively. For the same momentum intervals at a depth $s = 705$ gm/cm^2, the corresponding quantities were found here to be $1.52 \pm 0.03 \times 10^{-3}$ and $1.38 \pm 0.04 \times 10^{-3}$ cm^{-2} sec^{-1} sterad^{-1} (BeV/c)$^{-1}$. Inserting these values into Eq. (10), one obtains

$$l(p) = \begin{cases} (116 \pm 9) \text{ GM}/\text{CM}^2 & \text{for } p \approx 0.7 \text{ BeV}/c, \\ (133 \pm 10) \text{ GM}/\text{CM}^2 & \text{for } p \approx 0.85 \text{ BeV}/c. \end{cases} \quad (11)$$

Measurements have been made previously[9] of the proton intensities at 2750 m (depth $s = 750$ gm/cm^2). The results reported were that $N(p, 750) = 0.96 \pm 0.12 \times 10^{-3}$ and $0.79 \pm 0.12 \times 10^{-3}$ cm^{-2} sec^{-1} sterad^{-1} (BeV/c)$^{-1}$ for $0.59 \leq p \leq 0.77$ and $0.77 \leq p \leq 0.93$ BeV/c, respectively.

These can be compared with the results of the present study. Using Eq. (11) to correct the latter to the same depth: viz.,

$$N(p, 750) = N(p, 705)\, e^{-x/L}$$

$$= \begin{cases} (1.05 \pm 0.11) \cdot 10^{-3} & \text{for} \quad p = 0.68 \text{ BeV}/c, \\ (1.00 \pm 0.11) \cdot 10^{-3} & \text{for} \quad p = 0.85 \text{ BeV}/c, \end{cases}$$

where $x = 750 - 705 = 45$ gm/cm^2. The two sets of results are seen to be consistent within the experimental errors.

In another study[10] the proton spectrum at sea level was measured with a magnetic spectrometer, and it was found that the intensity at $p = 0.7$ BeV/c was about 10^{-4} cm^{-2} sec^{-1} sterad^{-1} (BeV/c)$^{-1}$. Comparison with the results of this work at 3200 m leads to

$$l(0.7) = 119 \text{gm/cm}^2.$$

The expected error in this result is large, as the statistical errors in the results of the work[10] were appreciable.

Now let us consider the absorption length of protons and the comparison of the integral spectra at different atmospheric depths. At sea level it was found[10] that the intensity of protons of momenta $p \geq 1$ BeV/c was 0.55×10^{-4} cm^{-2}sec^{-1} sterad^{-1}, while at 3200 m we obtained n (1705) $= 0.887 \pm 0.01 \times 10^{-3}$ cm^{-2} sec^{-1} sterad^{-1}, which results imply an absorption length $L = 118$ gm/cm^2. This value appears to be low. In the work cited[10] the number of protons observed to stop in the absorbers had to be divided by the probability of their being stopped; viz., by $1 - e^{-x/L}$, where L was taken to be 160 gm/cm^2. According to our method of calculation it would have been necessary to use instead $1 - e^{-x/320}$. Since the total thickness of absorbers in that experiment was 226 gm/cm^2, one should correct the observed intensities by $(1-e^{-x/160})/(1-e^{-x/320}) = 1.5$. Consequently, the sea level intensity of protons with $p \geq 1$ BeV/c would be $0.55 \times 1.5 = 0.83 \times 10^{-4}$ cm^{-2} sec^{-1} sterad^{-1}, and from this value one obtains $L = 137$ gm/cm^2.

It is of interest to compare the intensity of the primary component with that of the protons at the depth $s = 705$ gm/cm^2. We shall proceed from the results of Vernov et al[11]. It was found that the energy spectrum of the primaries can be approximated by a power law with $\gamma = 2$ and that their flux at 31° latitude was 1.8 min^{-1} cm^{-2} sterad^{-1}. At that latitude the cutoff energy for protons is about 6.8 BeV, while at the geomagnetic latitude of 35°, where our experiments were conducted, cutoff occurs at about 5.3 BeV energy, or 6.2 BeV/c momentum; from the 31° flux one can derive the flux at 35°, which comes out to be 0.0383 particle cm^{-2} sec^{-1} sterad^{-1}. On the other hand one can calculate from the spectrum observed

[9] A. Z. Rosen, Phys. Rev. **93**, 211 (1954)

[10] M. G. Mylroi and J. G. Wilson, Proc. Phys. Soc. **64A**, 404 (1951)

[11] S. I. Vernov and A. I. Charakhchian, Doklady Akad. Nauk SSSR **91**, 487 (1953)

Table 2

Spectra of protons above and below 68 gm/cm^2 of lead, and the absorption lengths in lead.

Momenta in BeV/c	$N_1(p)\times 10^3$	$N_2(p)\times 10^3$	$n_1(p)\times 10^3$	$n_2(p)\times 10^3$	$l(p)$	$L(p)$
0.502	1.15	0.740	1.59	1.17	154	222
0.587	1.22	0.744	1.49	1.11	137	230
0.707	1.22	0.786	1.34	1.02	155	252
0.826	1.16	0.830	1.05	0.824	204	280
0.977	1.05	0.798	0.884	0.701	247	293
1.14	0.99	0.764	0.713	0.576	258	318
1.30	0.85	0.673	0.574	0.463	290	316
1.57	0.504	0.411	0.419	0.338	333	316
2.04	0.212	0.172	0.273	0.220	325	315

at 3200 m for protons with $p < 2$ BeV/c that the flux of those with $p \geq 6.2$ BeV/c is 4.33×10^{-5} particle cm^{-2} sec^{-1} sterad^{-1} if it is assumed that the observed power law holds for the higher momenta. One should compare the primary flux with the total number of nucleons at 3200 m, or twice the number of protons; viz., 8.66×10^{-5} particle cm^{-2}sec^{-1}sterad^{-1}. Using these values, one obtains for the absorption length in air of protons with $p \geq 6.2$ BeV/c the value $L \approx 115$ gm/cm^2.

4. ABSORPTION LENGTH OF PROTONS IN LEAD

Using the second version of the spectrometer with 68 gm/cm^2 of lead above the magnet, 2742 protons with $p \geq 0.35$ BeV/c were observed in 523 hours. The spectrum obtained under lead was compared with that in air, and the results of this comparison are shown in Table 2. In this table $N_1(p)$ and $N_2(p)$ are the values of the differential spectra in air and under lead, respectively, and $n_1(p)$ and $n_2(p)$ the number of protons with momenta greater than p. In the last two columns the differential, l, and the integral, L, absorption lengths in lead are given as functions of the momentum.

It has been seen from Table 2 that both l and L increase with momentum, the latter reaching a constant value of

$$L = (315 \pm 49)\ \text{GM}/\text{CM}^2. \qquad (12)$$

for $p \geq 1$ BeV/c. These measured values of the absorption lengths are not immediately comparable with those obtained by others, as, for example, the photographic emulsion measurements [12-14] of the absorption lengths of the N-component of cosmic rays. In these studies the absorption length of the N-component was found to be appreciably (sometimes three times) larger than the interaction length λ_0 corresponding to the geometrical cross section, while in the present work it was found that the absorption length of protons was only 1 1/2 to 2 times larger. The reason for the difference between the proton and the N-component results may be due to the inclusion in the latter of meson, deuteron and heavier particle interactions, which tend to increase the absorption lengths.

5. SPECTRUM OF THE PROTONS PRODUCED BY NEUTRONS IN A THIN PLATE OF LEAD*

In the second arrangement of the experiment, two lead plates, 5 and 1 cm in thickness were placed above the magnet. Between these, as indicated in Fig. 1, was a double layer of counters whose detection efficiency for charged particles was practically 100%. In this way we were able to study protons and Π-mesons produced in a thin (11.3 gm/cm^2) layer of lead.

[12] J. C. Barton, Proc. Phys. Soc. 64A, 1042 (1951)

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

[14] S. A. Azimov, N. A. Dobrotin, A. L. Liubimov and K. P. Ryzhkova, Izv. Akad. Nauk SSSR, Ser. Fiz 42, 80 (1953)

* *Note added in proof:* The spectrum of protons generated by neutrons in thick plates of lead has been studied by Dadaian and Mirzon [e.g., see A. G. Dadaian and G. I. Mirzon, Doklady Akad. Nauk SSSR 86, 259 (1952)].

In 523 hours 146 protons were observed that originated in the 1 cm lead plate and were absorbed in the absorbers underneath the magnet. Of these, 114 particles had momenta $p \geq 0.35$ BeV/c, and 17 protons with $p \geq 1.13$ BeV/c stopped as a result of nuclear interaction. In order to derive the true spectrum of the protons produced in lead it is necessary to consider the ionization losses of the particles in the absorbers in which they were born. This was done approximately by assuming that the protons were generated uniformly throughout the thickness of the plate.

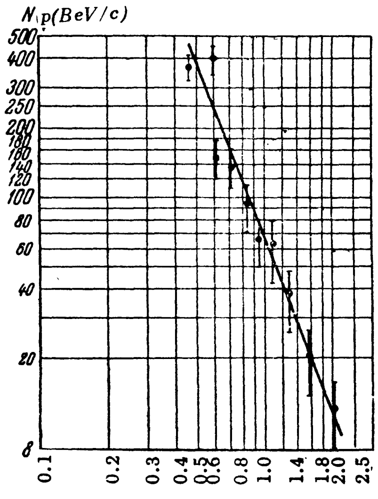

Fig. 3. Pulse spectrum of protons produced by neutrons in lead of thickness 11.3 gm/cm^2.

The curve of Fig. 3 was obtained by analyzing the data as described in Sec. 2. It is seen that the spectrum of the generated protons can be approximated by the power law

$$N(p)\,dp \sim p^{-\gamma} dp$$

where $\gamma = 2.55 \pm 0.3$. The number of protons of momentum $1.0 \leq p \leq 2.33$ BeV/c was 34, and those of $p \geq 1$ BeV/c (430 MeV) was 46. Assuming that the same law holds for $p \geq 2.33$ BeV/c, one obtains that the number of these is 12. In order to calculate the number of protons with momentum $p \geq 1$ BeV/c produced in 1 cm of lead, one must divide the number 46 by $s\,\omega\,t\,x\,k = 3.38 \times 10^7$ cm^2 sterad sec gm/cm^2, where $s = 140.8$ cm^2 is the area of the coordinate counters, $\omega = 0.0144$ sterad the solid angle of the apparatus, $t = 523$ hours $= 1.88 \times 10^6$ sec the time of observation, $x = 11.3$ gm/cm^2 the thickness of the lead plate, and $k = 0.78$ the overall counting efficiency. Since these observations of the production of protons were made under 5 cm of lead, the number observed must be multiplied by a factor $e^{62/315}$, where 315 is the absorption length of protons in lead. Thus one obtains

$$n = 1.66 \times 10^{-6} \text{ protons cm}^{-2} \text{ sec}^{-1} \text{ sterad}^{-1} (\text{gm/cm}^2)^{-1}.$$

Π-mesons are created in the lead as well as protons. In this experiment it was assumed that observed particles were mesons if they were negatively charged, or if, though positively charged, they exhibited a greater deflection than that of protons stopping in the same absorbers. There were 17 negatively charged and 12 positively charged particles with deflections greater than that of the protons, implying that in this range of the spectrum the ratio of negative to positive mesons was 1.5. However, 3 negative particles were observed with deflections about the same as that of the protons, so that if the same ratio holds there must also have been two positive mesons. Thus, the total number of Π-mesons observed was 34 and their momentum was $p \geq 0.16$ BeV/c ($E \geq 73$ MeV), if we assume that the mesons were produced, on the average, at a depth of 5.6 gm/cm^2 in the lead. Considering the efficiency of the apparatus one concludes that the number with $E \geq 73$ MeV was 54. Assuming that the spectrum of the mesons produced is the same as that previously reported[15], one can calculate that the number that penetrated through all of the absorbers without stopping was about 4. Consequently, there were 58 mesons and 46 protons with $E \geq 430$ MeV, and from the spectrum of the protons produced one concludes that there were about 40 protons with $E > 500$ MeV.

From this it may be concluded that in lead the ratio of mesons to protons in nuclear stars is 1.5, as compared with about 3 in photographic emulsions[16]. The explanation of this difference may be that in lead the mesons created may suffer secondary interactions in the nucleus, thus losing a considerable part of their energy, or perhaps being completely absorbed. In the course of these investigations there occurred instances where several of the coordinate counters in a tray were set off simultaneously in a way which precluded an unambiguous interpretation of the particle momenta, but this happened in less than 7% of the cases. Conse-

[15] J. G. Wilson et al, Progress in Cosmic Ray Physics, Amsterdam (1952), pp. 358 and 360

[16] W. O. Lock and Yekutieli, Phil. Mag. **43**, 231 (1952)

quently, the number of shower particles observed was for all practical purposes the total number of shower particles that were produced in the layer of lead during the time of observation (523 hours).

Translated by V. A. Nedzel
25

SOVIET PHYSICS - JETP VOLUME 1, NUMBER 1 JULY, 1955

On the Theory of Energy Losses of Charged Particles Traversing a Ferromagnetic Material

D. IVANENKO AND V. N. TSYTOVICH
Moscow State University
(Submitted to JETP editor March 5, 1954)
J. Exper. Theoret. Phys. USSR 28, 291-296 (March, 1955)

An investigation of the effect of saturation of the energy losses of a charged particle passing through a ferromagnetic material is presented[1-3]. An analysis of the separation of the losses into ionization losses and Cerenkov radiation losses is also given.

THE energy losses of a charged particle passing through a ferromagnetic material has been investigated in a series of papers[1-3].

It is known[4,5] that when high velocity charged particles traverse a dielectric the energy losses approach saturation. These energy losses do not increase without limit as the energy of the charged particle increases but they are higher in materials which have a lower electron density. In addition to this, at higher velocities the losses by Cerenkov radiation play a special role[6-8].

For the case of a charged particle traversing a dielectric the analysis of the separation of the losses into ionization losses and Cerenkov radiation losses showed the essential dependence of this separation on the value of the damping coefficients in the dispersion formulas, which coefficients must not be assumed equal to zero[8,9].

The analogous situation can be expected to occur in the analysis of the separation of the losses into ionization losses and Cerenkov radiation losses when a particle traverses a ferromagnetic material.

[1] D. Ivanenko and B. C. Gurgenidze, Doklady Akad. Nauk SSSR 67, 997 (1949)

[2] D. Ivanenko and B. C. Gurgenidze, Vestn. Moscow State University 2, 69 (1950)

[3] Ch. Weizsäcker, Ann. Physik 17, 869 (1933)

[4] E. Fermi, Phys. Rev. 53, 485 (1940)

[5] N. Bohr, Atomic Particles Traversing Media (1950)

[6] P. A. Cherenkov, Doklady Akad. Nauk SSSR 2, 451 (1934)

[7] I. M. Frank and I. E. Tamm, Doklady Akad. Nauk SSSR 14, 107 (1937)

[8] M. Schönberg, Nuovo Cim. 8, 159 (1951)

[9] P. Budini, Nuovo Cim. 10, 236 (1953)

In addition, in a ferromagnetic material as in a dielectric, the question of this separation cannot be calculated correctly if the effect of damping is not considered finite[9].

When a high velocity charged particle traverses a substance, the loss of its energy depends essentially on the interaction between the atoms of the substance. In a ferromagnetic material the magnetic properties are determined, first, by an exchange interaction of the electrons of the substance (exchange energy) and secondly, by a magnetic interaction of the elementary magnetic moments (energy of magnetic anisotropy(see, for example, Vonsovskii and Shur[10]). In the following discussion, however, it will be shown the exchange interaction is not essential for the energy losses of charged particles which pass through a ferromagnetic material. A relatively small energy of magnetic isotropy, however, gives a contribution to the energy losses, but it is negligibly small in comparison to the ionization losses and Cerenkov radiation losses associated with the dielectric constant ϵ of the ferromagnetic material. Also included are some unexpected results of the analysis of the energy losses in a ferromagnetic material. We note also that the effect of saturation of the losses in a ferromagnetic material is analogous to the effect of saturation of the losses in a dielectric, where the losses in the ultra relativistic region depend only on the number of electrons, but not on the character of their coupling in the material.

If point charged particles, moving in a medium characterized by values of dielectric constant and

[10] S. V. Vonsovskii and Y. S. Shur, *Ferromagnetism*, Moscow (1948)