On the Production of Cosmic-Ray Mesotrons by Primary Protons*

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CALCULATIONS have been made on the difference between the number of mesotrons in the vertical direction at a geomagnetic latitude 40° N, and the number at the equator, as a function of altitude, on the basis of the following assumptions:

(1) The primary particles producing mesotrons are protons. The cut-off energies for vertically moving protons for geomagnetic latitude 40° and 0° are 6 and 16, respectively. Here, and in what follows, the rest mass is included, and proton energies E are given in units of the proton rest mass, mesotron energies ϵ in units of the mesotron rest mass.

(2) The differential energy spectrum of the primary protons is $(E-1)^{-2.8}$.

(3) The mesotrons are produced at a height X_0 by the collision of a primary proton with a nucleon.

(4) This collision, when viewed in its center of mass system, results in a complete stopping of the nucleons, and in the emission of N mesotrons of equal energy, uniformly distributed in space. N is assumed to be constant in the energy range between 6 and 16.

By using (4) and performing a relativistic transformation, it follows that the energy of the mesotrons produced by a primary proton of energy E will be initially distributed uniformly between the two limits:

$$\epsilon=\epsilon_0\pm\epsilon_0\left(\frac{E-1}{E+1}\right)^{\frac{1}{2}}\left[1-\frac{N^2\mu^2}{4M^2}\frac{1}{\left(\left(\frac{E+1}{2}\right)^{\frac{1}{2}}-1\right)^2}\right]^{\frac{1}{2}},$$

$$\epsilon_0=\frac{M}{N\mu}\{E+1-[2(E+1)]^{\frac{1}{2}}\}.$$

μ is assumed to be 200 times the mass of the electron. M is the proton mass.

In the calculations for primary energies between 6 and 16, the lower limit was approximated by 0 and the upper limit by $2\epsilon_0$.

According to Hamilton, Heitler, and Peng,[1] the number of mesotrons of energy ϵ at height x can be written as follows:

$$f(\epsilon,x)=\left(\frac{\epsilon}{X}\right)^{10.7/\epsilon+x}\int_0^x S(\eta,\xi)\left(\frac{\eta-\xi}{\xi}\right)^{-10.7/\eta}d\xi. \quad (1)$$

In this expression, 2×10^{-6} sec. was used for the lifetime of the mesotron at rest.

$S(\epsilon,x)$ is the expression for the number of mesotrons of energy produced at height x. In our case

$$S(\epsilon,X)=\frac{\mu}{M}\frac{N^2}{2}\int_{E_{\min}}^{16}\frac{(E-1)^{-2.8}}{E+1-[2(E+1)]^{\frac{1}{2}}}dE\,\delta(X-X_0), \quad (2)$$

where $E_{\min}$ is either 6, or $\frac{\mu N}{2M}\epsilon\left[\left(\frac{\mu N}{M}\right)\epsilon+1\right]^{\frac{1}{2}}$, depending on which one is the greater quantity, and X_0 is the height of the mesotron producing layer. $\delta(X-X_0)$ is a Dirac delta-function.

On substituting (2) into (1) we obtain:

$$f(\epsilon,X)=\left[\frac{X_0\epsilon}{(\epsilon+X-X_0)X}\right]^{10.7/\epsilon+X}\times\frac{N^2\mu}{2M}\int_{E_{\min}'}^{16}\frac{(E-1)^{-2.8}dE}{E+1-[2(E+1)]^{\frac{1}{2}}}, \quad (3)$$

where $E_{\min}'$ is either 6 or

$$\frac{\mu}{M}\frac{N}{2}(\epsilon+X-X_0)+\left[\frac{\mu N}{M}(\epsilon+X-X_0)+1\right]^{\frac{1}{2}},$$

depending on which one is the greater quantity.

The unit of distance X is that distance in which a mesotron loses an energy μc^2 by ionization.

Finally, by using (3), the total number of mesotrons capable of penetrating 20 cm of lead at a height X is given by:

$$I(X)=\int_4^\infty f(\epsilon,X)d\epsilon.$$

$I(X)$ has been calculated numerically for several values of N and X_0. The results, normalized to the experimental data of Gill, Schein, and Yngve,[2] at $X=4$ (138-mm Hg), are reproduced in Fig. 1 and Table I.

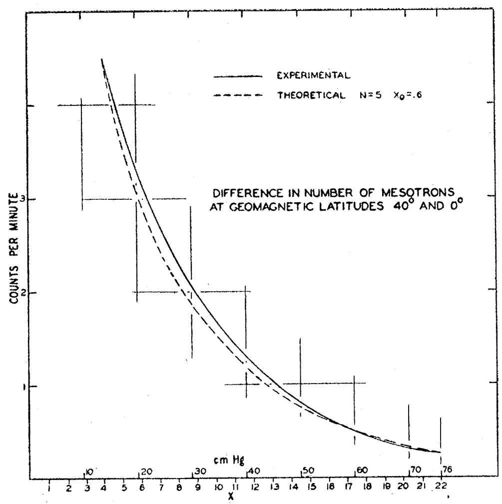

FIG. 1.

Figure 1 shows that the theoretical curve for $X_0=0.6$ (2-cm Hg) and $N=5$ is in satisfactory agreement with the experimental curve over the atmosphere between 35,000 feet and sea level.

The theoretical value of $X_0=0.6$ for the average altitude where mesotrons are produced corresponds to a cross section, ϕ, for multiple mesotron production of 5.8×10^{-25}

TABLE I. Shows that the values $N=5$, $X_0=0.3$ result in too large a latitude effect at sea level; the value $N=6$ gives too small a latitude effect at the lower altitudes.

		Number of counts per minute			
X	Experiment	$N=5$ $X_0=0.3$	$N=5$ $X_0=0.6$	$N=6$ $X_0=0.3$	$N=6$ $X_0=0.6$
4	4.5	4.5	4.5	4.5	4.5
8	2.31	2.22	2.07	1.88	1.66
12	1.22	1.25	1.10	0.95	0.80
17	0.53	0.64	0.53	0.40	0.31
22	0.25	0.30	0.25	0.13	0.11

TABLE II. $\frac{\text{(Total number of primaries of energy between 6 and 16)}}{\text{(Number of mesotrons at sea level at geom. lat. 40°N)}}$.

N	X_0	
5	0.3	6.8
5	0.6	4.08
6	0.3	8.34
6	0.6	4.61

cm^2 per air nucleus. This is in rough agreement with the experimental results on mesotron production in paraffin.[3]

The normalization also determines the number of protons in the energy range 6 to 16 which produce mesotrons. Table II gives the ratio of these protons to the hard component at sea level.

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[1] J. Hamilton, W. Heitler, and H. W. Peng, Phys. Rev. **64**, 78 (1943).
[2] P. S. Gill, M. Schein, and V. Yngve, Phys. Rev. **72**, 733 (1947).
[3] M. Schein and D. J. Montgomery, *Problems in Cosmic Ray Physics* (Princeton University Press, Princeton, New Jersey, 1946).

On the Generation in Paraffin of Ionizing Penetrating Particles by a Neutral Component of the Cosmic Radiation

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De Vos and du Toit[1] have recently found at sea level, with the counter-set drawn in Section *a* of Fig. 1, a ratio $R=1.03$ between the threefold coincidences $A+B+C$, recorded with a paraffin layer 1.3 cm thick in π, and the ones recorded with the same layer in π'. In their opinion the effect is outside the experimental uncertainty, and the increase in the frequencies when paraffin is in π is due to the generation in the paraffin layer of mesons or protons by some neutral component of the cosmic radiation.

This result is very interesting, because experiments[1,2] like the above-mentioned, performed at sea level also, but with layers of lead instead of paraffin, did not show the same effect; therefore one is compelled to think of a particular phenomenon characteristic of the low atomic number materials.

In order to look into this point the following experiments were performed:

Series 1: (see Section *b* Fig. 1) with the telescope $ABCD$ arranged under a thin deck (0.5-cm wood), the fourfold coincidences $A+B+C+D$ were recorded with 2 cm of paraffin alternatively in π and in π'. (Counter surface: 4×40 cm^2, counter walls: 1-mm brass, resolving time of the recording apparatus: 2.10^{-5} sec.) The penetrating particles were selected by 12.5-cm Pb and the side showers stopped by 5-cm Pb around the counters D.

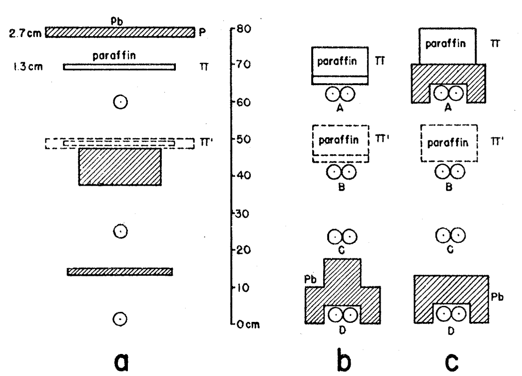

FIG. 1.

As the Table (series 1) shows, no changes in frequencies were recorded by changing the position of the paraffin.

TABLE I. Measurements on the generation of ionizing particles by a neutral component of cosmic rays.

	Lead			Paraffin			
Series	coinc.	min.	coinc./min.	coinc.	min.	coinc./min.	Ratio R
1	69,172	7836	8.827 ±0.034	61,016	6922	8.815 ±0.036	1.0013 ±0.0080
2	43,205	4940	8.746 ±0.042	45,792	5358	8.546 ±0.040	1.023 ±0.010
3	71,394	8225	8.680 ±0.033	68,708	7881	8.718 ±0.034	0.995 ±0.008
4	61,655	7784	7.922 ±0.033	66,219	8338	7.942 ±0.031	0.997 ±0.008

Series 2: counters and screens as in series 1, but paraffin layer: 10 cm.

As it appears in the Table (series 2), a ratio $R=1.02\pm 0.01$ was found in this case.

Series 3: with the arrangement drawn in Section *c* of Fig. 1, we tried to test whether or not the result of series 2 was a real effect, or a spurious one caused by soft secondary particles generated in the paraffin while in π; such particles could give rise to spurious coincidences in association with penetrating particles hitting only counters B, C, and D. This possibility was removed by arranging a screen of lead 5 cm thick around the counters A (paraffin layer: 10 cm).

As the Table (series 3) shows, in this case we found $R=1$ within the experimental uncertainty, which indicates that the positive result of series 2 was really caused by such a spurious effect.

Series 4: In order to make our data more comparable with De Vos and du Toit's result, we performed a last experiment arranging above the counter-set used in series 3 a layer of 2.5-cm Pb, like that (2.7 cm) placed above the counter-set in De Vos and du Toit's experiment (see Fig. 1a).

In this case also no changes in frequencies were recorded when the position of the paraffin was changed (see Table: series 4).

We think our experimental arrangements (series 3 and 4) afford the following advantages with regard to De Vos and du Toit's experiment: (a) screening against side showers (Pb screens surrounding D and A); (b) removal of soft secondary particles generated in the materials above the telescope (Pb screen surrounding A and shapes of paraffin layers so chosen to cover only the solid angle of the telescope); (c) large efficient surface of the telescope and therefore short recording times (our frequencies were about 17 times larger than De Vos and du Toit's); and (d) statistical errors in every series about one-half the error in the result of the above-mentioned observers.

The results obtained compel us to point out that our experiments do not confirm the effect found by De Vos and du Toit, both for thin and thick paraffin layers. Therefore we reach the conclusion that, at sea level, the phenomena of generation in paraffin of penetrating ionizing