The Disintegration of Mesotrons

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The variation of the hard cosmic-ray component with zenith angle and the temperature effect suggest that the cosmic mesotrons decay with a lifetime of about 3×10^{-6} sec. The other phenomena so far considered (variation with height, barometer effect, shape of the energy spectrum, number of secondaries, etc.) do not provide any evidence for the decay, but are not inconsistent with the above assumption. On the contrary a considerably smaller lifetime, less, for instance, than 1×10^{-6} sec., would be inconsistent with most of the experimental results. There is no evidence that the mesotrons which have been stopped actually disintegrate into an electron and a neutrino.

A NUMBER of well-established experimental facts show that the penetrating component of the cosmic radiation is composed of particles of mass intermediate between those of electron and proton. These particles, now called mesotrons, have been tentatively identified with the heavy particles predicted by Yukawa's theory of nuclear forces. From the interaction between the field of Yukawa particles and the electron-neutrino field, postulated in order to account for the emission of β-rays, it follows that the Yukawa particles are unstable, and disintegrate spontaneously each into an electron and a neutrino. It is consequently assumed that the cosmic-ray mesotrons are also unstable, and it then follows that they cannot be of distant origin, but must be generated by some primary agents in the earth's atmosphere.[1]

Let τ_0 be the lifetime of the mesotrons at rest. It then follows from the relativistic transformation formula of time intervals that the lifetime of a mesotron moving with a velocity βc is $\tau=\tau_0/(1-\beta^2)^{\frac{1}{2}}$ and so the probability of decay per unit length of path is

$$\frac{1}{\beta c}\frac{(1-\beta^2)^{\frac{1}{2}}}{\tau_0}=\frac{\mu}{\tau_0 p}, \qquad (1)$$

p being the momentum and μ the mass of the mesotrons.

A. Direct Test of the Decay of Mesotrons

When a mesotron stops in the gas of a cloud chamber, we should expect to find a decay electron of about 40 Mev energy starting from the end of the mesotron track. Actually only two cloud-chamber photographs in which a mesotron is seen to stop in the chamber are available (Neddermeyer and Anderson;[2] Nishina, Takeuchi and Ichimiya.[3] Neither shows any sign of an electron track. Some photographs obtained by Maier-Leibnitz[4] seem to show the expected effect, but the interpretation is doubtful due to the possibility of disturbances arising from a radioactive preparation inside the chamber.[5]

Quite recently Montgomery, Ramsey, Cowie, and Montgomery[6] made an attempt to detect the decay of the mesotrons investigating whether electrons are emitted from a metal plate shortly after a mesotron had fallen on it. The result was negative.

In conclusion, the present experimental evidence is against rather than in favor of the emission of electrons by mesotrons which have effectively stopped.

B. Indirect Test of the Decay of Mesotrons

Several consequences of the disintegration hypothesis can be investigated experimentally, thus allowing an indirect test of this hypothesis.

In the following discussion we shall assume that the mass of the mesotron is 160 times the

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[1] H. J. Bhabha, Proc. Roy. Soc. **164**, 257 (1938); H. Yukawa, Proc. Phys. Math. Soc. Jap. **20**, 319 (1938).

[2] S. H. Neddermeyer and C. D. Anderson, Phys. Rev. **54**, 88 (1938).

[3] Y. Nishina, M. Takeuchi and T. Ichimiya, Phys. Rev. **55**, 585 (1939).

[4] Maier-Leibnitz, Naturwiss. **29**, 677 (1938).

[5] Maier-Leibnitz reported lately (Zeits. f. Physik **112**, 569 (1939)) some more photographs showing tracks, which are interpreted as due to mesotrons stopping in the gas. No sign of decay electrons is visible in these photographs.

[6] C. G. Montgomery, W. E. Ramsey, D. B. Cowie and D. D. Montgomery, Phys. Rev. **55**, 1117 (1939).

electron mass; the rest energy is therefore 8×10^7 electron volts. From the experimental evidence we expect this estimate to be correct within 20 percent.

We assume further that all the mesotrons are generated at the same distance, measured as the mass of air traversed, say y_1 g/cm² from the top of the atmosphere. The distance y_1, of course, is to be measured in the direction of the actual path of the mesotrons, so that mesotrons coming from an inclined direction have been generated at a higher level than the mesotrons coming vertically (Blackett[7]).

It is convenient to characterize the energy of a mesotron by its momentum p, which is directly connected with the radius of curvature ρ measured in a magnetic field H by the formula: $(1/e)pc=H\rho$. We measure pc in electron volts; pc is practically equal to the actual energy of the mesotron when the energy itself is large as compared with the rest energy μc^2.

The atmospheric pressure h and the height z are connected by the barometer formula:

$$h=h_0e^{-z/z_0}, \tag{2}$$

where $z_0=7$ km. We measure h, which also measures the depth of material from the top of the atmosphere, in g/cm².

We refer to the absorption due to the energy loss alone, i.e., neglecting decay, as the *true absorption*. Screens of different materials, in which a mesotron beam undergoes the same true absorption, will be called equivalent.

I. Atmospheric density effects

The spontaneous disintegration of the mesotrons can only remove an appreciable number of particles, before they are brought to rest by ordinary energy loss, in a gaseous absorber. The number of mesotrons will be therefore more reduced by a gas layer than by a solid or liquid screen of the same stopping power. Again, the apparent mass absorption of a gas will increase as the density decreases.

The above density effect, as pointed out by Heisenberg and Euler,[8] must play an important role in the absorption of the mesotrons in the atmosphere. We shall briefly describe the most important phenomena to be expected.

(a). *Variation with height.*—Let us compare the vertical intensity at the depth $h+\delta h$ with the vertical intensity at the depth h, under a screen of dense material equivalent to δh. We expect to find a smaller number of mesotrons in the former than in the latter position, and the difference $-\delta N$ is due to the mesotrons disintegrating in the air layer. The probability of decay in an air layer of 1 g/cm²—i.e. over a path of $1/\rho$ cm, where ρ is the density of the air—is $\epsilon_1=-(1/N)(\delta N/\delta h)$. It follows from (1) that

$$\epsilon_1=\mu/\tau_0\rho p. \tag{3}$$

A more exact calculation (see Appendix) leads exactly to the same expression (3). It will be noted that the height where the mesotrons are generated does not occur in that formula, and that p is the momentum in the position where the mesotrons are observed.

If we do not select a monochromatic beam of mesotrons, but observe all mesotrons above a certain momentum, $1/p$ is to be understood as the average reciprocal momentum over the whole momentum spectrum. The lower limit of the spectrum is determined by the thickness of the screen that has to be used in order to cut off the soft component. Taking as lower limit 2.5×10^8 electron volts (corresponding to a screen of about 8 cm lead) and averaging over the momentum spectrum at sea level (see II (a)) we get:

$$cp=1.2\times10^9 \text{ electron volts.} \tag{4}$$

Hence:

$$\epsilon_1=1.7\times10^{-9}/\tau_0. \tag{3'}$$

Experimentally, ϵ_1 can also be defined as the difference between the absorption coefficient μ_1 in air and the coefficient μ of the true absorption

$$\epsilon_1=\mu_1-\mu. \tag{5}$$

(b). *The barometer effect.*—A given change of the atmospheric pressure, due to a variation of the meteorological conditions, may be considered exactly as in the previous Section I (a), provided that the atmosphere may be regarded in a state of equilibrium.

Thus the "barometer effect" is described by the same formulae (3), and (5) which describe the altitude effect and μ_1 is now to be understood as the barometer coefficient of the intensity of the

[7] P. M. S. Blackett, Nature **142**, 992 (1938).
[8] W. Heisenberg and H. Euler, Ergeb. der exakten Naturwiss. **17**, 1 (1938).

hard cosmic-ray component in the vertical direction (see also Rathgeber[9]).

(c). *Variation with zenith angle.*—We compare the intensity at the depth h and at a small zenith angle θ with the vertical intensity at a depth $h+\delta h$ where:

$$\delta h = h(1/\cos\theta - 1),$$

that is, where the distance in g/cm² from the top of the atmosphere is in both cases the same. The actual distance, however, from the place where the mesotrons are formed is greater for the mesotrons coming inclined at the depth h than for the mesotrons coming vertically at the depth $h+\delta h$. An easy calculation shows that the difference between the two distances is: $\delta l = z_1(\delta h/h)$ where $z_1 = z_0 \log (h/y_1)$ is the height at which the vertical mesotrons are formed.

The intensity will, therefore, be smaller in the former position than in the latter (Kulenkampff;[10] Blackett;[7] Rossi,[11] etc.). The difference δN, due to the decay of mesotrons over the difference of path δl, is given by:

$$\delta N = N(\mu/\tau_0)(z_1/P)(\delta h/h)$$

and hence, putting $\epsilon_2 = (1/N)(\delta N/\delta h)$,

$$\epsilon_2 = \frac{\mu z_1}{\tau_0 h P}. \tag{6}$$

In (6) P is not the actual momentum p of the mesotrons in the place where they are observed, but an average momentum along their path; the exact treatment (see Appendix) gives for P the value:

$$P = \frac{pc+ah}{c\left[1+\left(\log\dfrac{pc+a(h-y_1)}{pc}\right)\Big/\left(\log\dfrac{h}{y_1}\right)\right]}, \tag{7}$$

where a is the energy loss in air per g/cm².

Formulae (6) and (7) contain y_1—the depth at which the mesotrons were formed—thus the zenith angle variation may provide information about this depth. The observed quantities, however, are very little sensitive to the value of y_1.

Tentatively we shall take $y_1 = 100$ g/cm², which corresponds to a height above sea level $z_1 = 16$ km.

If our observations are made upon the whole mesotron spectrum we must use an average value of $(1/P)$. With the same assumed spectrum as in I (a), and putting $a = 2\times10^6$ ev per g/cm², we have at sea level

$$cP = 2.8\times10^9 \text{ electron volts} \tag{7'}$$

and hence

$$\epsilon_2 = 1.5\times10^{-9}/\tau_0. \tag{6'}$$

The decrease of intensity of mesotrons, as the zenith angle is increased, can formally be described by an "absorption coefficient" $\mu_2 = -(1/N)(\delta N/\delta y)$ where $-\delta N$ is the difference between the vertical intensity and that for the (small) zenith angle θ, and where $\delta y = h[(1/\cos\theta)-1]$ is the corresponding variation of the thickness of the atmosphere. It is easy to see that ϵ_2 is the difference between μ_2 and the "absorption coefficient" μ_1 of the vertical intensity defined above:

$$\epsilon_2 = \mu_2 - \mu_1. \tag{8}$$

Finally, we can also compare, at a given height, the intensity at the angle θ with the vertical intensity under a screen of thickness $\delta y = h[(1/\cos\theta)-1]$. If δN is the difference of the two intensities, $\epsilon_3 = (1/N)(\delta N/\delta y)$ is obviously equal to the difference between the absorption coefficient μ_2 and the true absorption coefficient μ. Therefore

$$\epsilon_3 = \mu_2 - \mu \tag{9}$$

and hence

$$\epsilon_3 = \epsilon_1 + \epsilon. \tag{9'}$$

From (3′) and (6′) it follows (at sea level):

$$\epsilon_3 = 3.2\times10^{-9}/\tau_0. \tag{9''}$$

(d). *The temperature effect.*—When the temperature increases the atmosphere extends upwards and the mesotrons are generated at a higher level. A larger number of mesotrons will, therefore, disintegrate before reaching our apparatus. If the atmosphere is taken as at a uniform temperature T, then a variation δT of the temperature will produce a variation $\delta z_1 = z_1(\delta T/T)$ of the height where the mesotrons are formed, and a variation $-\delta N = N(\mu/\tau_0)(z_1/P)(\delta T/T)$ of the number of mesotrons observed at the level h.

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[9] H. D. Rathgeber, Naturwiss. **26**, 842 (1939).
[10] H. Kulenkampff, Verh. Dtsch. physik. Ges. (1938).
[11] B. Rossi, Nature **142**, 993 (1938).

Thus we expect (Blackett[12]) for the hard component of cosmic ray a temperature coefficient:

$$\alpha = -\frac{1}{N}\frac{\delta N}{\delta T} = \frac{\mu z_1}{\tau_0 T P}, \qquad (10)$$

where P is the same function of the momentum p as used in (6) and given in (7). Averaging over the spectrum at sea level and taking $T = 250°\text{K}$ we have

$$\alpha = 6.1 \times 10^{-9}/\tau_0. \qquad (10')$$

Comparing the above results with the experimental data, difficulty is encountered in the definition of equivalent screens. Experiments seem to show that different materials absorb mesotrons according to mass, but they are not accurate enough to remove any doubt on this law; especially since the theory (Bloch) would predict a rather considerable deviation from pure mass absorption. This fact is the more disturbing since the most accurate absorption measurements have been carried out on elements (lead, iron) having a much higher atomic number than air. Taking into account the uncertainty of the reduction factor, as well as the probable error of the measurements, we estimate the true absorption coefficient in air at sea level to be

$$0.7 \times 10^{-3} < \mu < 1.5 \times 10^{-3} \text{ cm}^2/\text{g}.$$

There are at present comparatively few data on the variation of the vertical intensity of the hard component with height, and the measurements available are only of moderate accuracy. These data are represented in Fig. 1 where the logarithm of the intensity is plotted against the depth. The intensities observed with different screens have been reduced to a standard screen thickness of 8 cm lead.

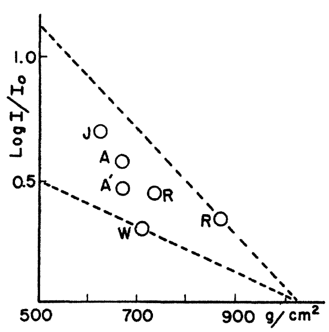

FIG. 1. Intensity of the hard component as a function of the depth. *A*, Auger, Ehrenfest, Fréon, Fournier, Comptes rendus **204**, 257 (1937). *A'*, Auger, Leprince-Ringuet, Ehrenfest, J. de phys. et rad. **7**, 58 (1936). *J*, Johnson, Phys. Rev. **47**, 318 (1935). *R*, Rossi and De Benedetti, Ric. Scient. **5**, 119 (1934). *W*, Woodward and Street, Phys. Rev. **49**, 198 (1936).

[12] P. M. S. Blackett, Phys. Rev. **54**, 973 (1938).

TABLE I. *Barometer effect (sea level).*

Author	Experimental Condition	μ_1(10^{-3} cm²/g)
Barnóthy and Forró[1]	Vertical counter train	
	no screen	2.6
	36 cm Pb	2.3
Stevenson and Johnson[2]	Vertical counter train	
	no screen	2.8
Kolhörster[3]	Vertical counter train	
	no screen	2.0
	140 g/cm² wood	1.15
Messerschmidt[4]	Ionization chamber	
	no screen	1.4
	10 cm Pb	1.35
	20 cm Pb	0.77
Steinmaurer[5]	Ionization chamber	
	10 cm Pb	2.0
Compton and Turner[6]	Ionization chamber	
	12 cm Pb	1.2

[1] J. Barnóthy and Forró, Zeits. f. Physik **100**, 742 (1936).
[2] E. C. Stevenson and T. H. Johnson, Phys. Rev. **47**, 578 (1935).
[3] W. Kolhörster, Physik Zeits. **40**, 142 (1939).
[4] W. Messerschmidt, Zeits. f. Physik **78**, 688 (1932).
[5] R. Steinmaurer, Gerl. Beitr. **45**, 148 (1935).
[6] A. H. Compton and R. N. Turner, Phys. Rev. **52**, 799 (1937).

The points in Fig. 1 are widely scattered, and it is only possible to make a rough estimate of the absorption coefficient μ_1 at sea level,

$$1.0 \times 10^{-3} < \mu_1 < 2.2 \times 10^{-3} \text{ cm}^2/\text{g}.$$

As we have already seen, another method for determining μ_1 is to measure the *barometer coefficient* of the vertical intensity of the hard component. A certain number of counter measurements on the barometer effect are available. They are collected in Table I, where some ionization chamber measurements are also given. The agreement between the various results is not very satisfactory, besides, only the measurements of Barnóthy and Forró have been carried out with a sufficient screening to exclude the soft component.

Altogether, neither the variations with height, nor the barometer effect provide at present a reliable value of the absorption coefficient μ_1. The value of μ_1 seems to lie between 1.5×10^{-3}

and 2×10^{-3} cm²/g and to be, therefore, slightly higher than the coefficient μ of true absorption. The experimental evidence, however, is not strong enough to let appear this difference as a proof of the disintegration hypothesis.

Some counter measurements by Kolhörster give directly the difference $\mu_1-\mu$, the variation of atmospheric pressure being compensated by altering the thickness of a wood screen so to maintain constant the amount of matter above the counters. The residual barometer effect was $\epsilon_1=\mu_1-\mu=1.15\times10^{-3}$ cm²/g, which put into (3′) gives $\tau_0=1.5\times10^{-6}$ sec. We cannot, however, give too much weight to this result, especially since Kolhörster found the same barometer effect with a constant amount of wood (140 g/cm²) above the counters.

The absorption coefficient μ_2, calculated from the measurements of the *variation with zenith angle* now available, are given in Table II. Only

TABLE II. *Variation with zenith angle.*

Author	Depth in mH_2O	Screen between the counters	$\mu_2(10^{-3}$ cm²/g)
Bernardini and Bocciarelli[1]	10	no screen	1.8
Johnson[2]	10	no screen	2.9
Clay, Jonker, Wiersma[3]	10	no screen	2.0
Jánossy[4]	10	no screen	2.1
Auger, Ehrenfest, Fréon, Fournier[5]	10	6 cm Pb	1.6
Bernardini and Bocciarelli[1]	10	10 cm Pb	1.9
Bernardini and Bocciarelli[1]	10	30 cm Pb	2.9
Clay,[3] etc.	10	30 cm Pb	1.3
Johnson[2]	8.0	no screen	2.7
Ehmert[6]	7.3	no screen	3.6
Auger,[5] etc.	6.8	6 cm Pb	3.5
Ehrenfest and Fréon[7]	6.8	10 cm Pb	3.6
De Benedetti[8] (equator)	7.85	9 cm Pb	2.3

[1] G. Bernardini and D. Bocciarelli, Ric. Scient. 6 I, No. 1 (1935).
[2] T. H. Johnson, Phys. Rev. **43**, 307 (1933).
[3] J. Clay, K. H. J. Jonker, J. T. Wiersma, Physica **6**, II, 174 (1939).
[4] L. Jánossy, Zeits. f. Physik. **99**, 369 (1936).
[5] P. Auger, P. Ehrenfest, A. Fréón, A. Fournier, Comptes rendus **204**, 257 (1937).
[6] A. Ehmert, Physik. Zeits. **35**, 20 (1934).
[7] P. Ehrenfest and A. Fréon, J. de phys. et rad. **9**, 529 (1938).
[8] S. De Benedetti, Phys. Rev. **45**, 214 (1934).

the measurements taken with a lead screen can be directly compared with the theory, although the angular distribution *at sea level* (not at high altitude) seems to be almost the same for the hard and for the soft component.

In evaluating the above results we must consider that almost every systematic source of error tends to smooth the actual anisotropy of the radiation; this would be the effect, for example, of a too big solid angle subtended by the counters or of coincidences due to air cascade showers. We incline, therefore, to attach greater weight to the measurements showing a more rapid decrease of the intensity with zenith angle and, accordingly, to ascribe to μ_2 at sea level a value not far from 2×10^{-3} cm²/g.

It follows that μ_2 is almost certainly larger than the coefficient of true absorption μ. Thus the variation with zenith angle provides a more convincing support to the disintegration hypothesis than the variation with height or with atmospheric pressure.

Moreover, in many cases measurements of the angular distribution and absorption measurements in dense materials were carried out under exactly the same conditions, thus allowing a more direct comparison between μ_2 and μ. In such a way De Benedetti[13] [see also Rossi[11]] found at 2400 m: $\epsilon_3=1.7\times10^{-3}$ which gives, taking into account the height at which the experiments were performed, $\tau_0=2.4\times10^{-6}$ sec. and Bernardini and Bocciarelli, at sea level: $\epsilon_3=1.14\times10^{-3}$ which gives $\tau_0=2.8\times10^{-6}$ sec.

In the above calculations, air and lead are supposed to have a true absorption coefficient proportional to their mass; using the Bloch formula we would obtain respectively:

$$\epsilon_3=1.4\times10^{-3},\quad \tau_0=3\times10^{-6}\text{ sec.};$$
$$\epsilon_3=0.74\times10^{-3},\quad \tau_0=4.3\times10^{-6}\text{ sec.}$$

Johnson[14] compared at sea level the intensity at 58° with the vertical intensity under 8.9 m H_2O. Measurements were made with 17 and 38 cm Pb. The ratio between the vertical and the inclined intensity is 2.5 for the mesotrons with range between 17 and 38 cm Pb. The average momentum of this mesotron group is $pc=4.5\times10^8$ electron volts. It follows (see appendix formula (14)): $\tau_0=3.3\times10^{-6}$ sec.

Finally a direct comparison between the absorption of air in vertical and in inclined direction can be deduced from Auger's measurements in Paris and at the Jungfraujoch. The result is

$$\epsilon_2=1.33\times10^{-3},\quad \tau_0=1.1\times10^{-6}\text{ sec.}$$

As to the *variation with atmospheric temperature* at a constant pressure, the effect itself, irrespective of magnitude, as compared with other

[13] S. De Benedetti, Phys. Rev. **45**, 214 (1934).
[14] T. H. Johnson, Phys. Rev. **55**, 104 (1939).

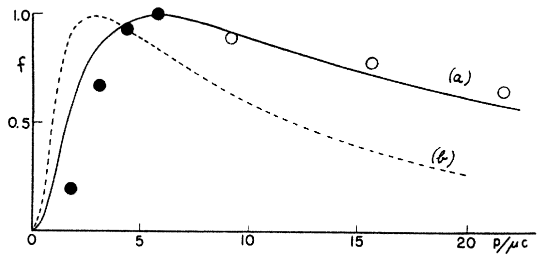

FIG. 2. Differential momentum spectrum of the mesotrons at sea level. (a) $\tau_0 = 2.7 \times 10^{-6}$ sec. (b) no decay.

effects, provides a test of the disintegration hypothesis. In this effect, however, the interference of unknown meteorological factors may be particularly troublesome.

A negative correlation between temperature and cosmic-ray intensity, as predicted by the disintegration hypothesis, seems to be experimentally established. Some experimental results are collected in Table III. The most accurate observations have been carried out with ionization chambers and cannot, therefore, be easily compared with the theory; on the other hand the results of the counter measurements of Barnóthy and Forró are not consistent enough to allow any definite conclusion. Taking tentatively Compton and Turner's value of the temperature coefficient $\alpha = 1.8 \times 10^{-3}$, we obtain from (10′)

$$\tau_0 = 3.4 \times 10^{-6} \text{ sec.}$$

II Other phenomena

(a). *The energy spectrum.*—The disintegration of the mesotrons not only reduces the total number of mesotrons observed at sea level, but also modifies the shape of the energy spectrum, owing to the different life time of mesotrons of different energy.

The energy spectrum of the mesotrons at sea level has been calculated by Heisenberg and Euler assuming that the mesotrons are formed with an energy spectrum $f_1(pc) \propto (pc)^{-2.9}$ and taking $\tau_0 = 2.7 \times 10^{-6}$. The results for the high energy part of the spectrum are in agreement with Blackett's[15] measurements. The above assumption on the original energy distribution of the mesotrons, however, is more or less arbitrary, and with a different choice of the original spectrum it would be possible to account for the experimental results without allowing for any decay.

The situation is different for the low energy end of the spectrum, which is very little affected by the shape of the original energy distribution. In that region Heisenberg and Euler's approximation (constant ionization loss) does not hold, and a more exact treatment is required, including both the decay and the decrease of the energy loss with decreasing energy. This has been done recently by Hartree.[16] Curve (*a*) Fig. 2 represents the differential momentum spectrum calculated for $\tau_0 = 2.7 \times 10^{-6}$ sec., while curve (*b*) represents the differential spectrum neglecting the decay, in order to show the influence of this factor. In both curves an original spectrum $f_1(pc) \propto (pc)^{-2.9}$ is assumed and the intensity factor is so adjusted as to give $f = 1$ at the maximum.

We see that the decay makes the initial slope of the curve less steep and, consequently, shifts the maximum to larger momenta. These conclusions are, to a large extent, independent of any particular assumption concerning the original spectrum. For example, the mesotrons observed at sea level with momentum between, say, 0 and $2\mu c$ originate in a portion of the original spectrum in which the momentum only varies by 2.7 percent. In Fig. 2 some experimental results of Blackett[15] (open dots) and of Wilson (black dots) are also plotted.[17] Measurements in the low energy end of the mesotron spectrum are very difficult and, therefore, not very exact. The experimental points, however, fit better to curve (*a*) than to curve (*b*).[18]

TABLE III. *Temperature effect (sea level).*

AUTHOR	EXPERIMENTAL CONDITION	$\alpha(10^{-3}$ per °C)
Barnóthy and Forró[1]	Vertical counter train, no screen	4.2
	36 cm Pb apparatus II.	−1.0
	idem. apparatus III.	4.6
Steinmaurer[2]	Ionization chamber 10 cm Pb	1.0
Compton and Turner[3]	Ionization chamber 12 cm Pb	1.8

[1] J. Barnóthy and Forró, Zeits. f. Physik **104**, 534 (1937).
[2] R. Steinmaurer Gerl. Beitr. **45**, 148 (1935).
[3] A. H. Compton and R. N. Turner, Phys. Rev. **52**, 799 (1937).

[15] P. M. S. Blackett, Proc. Roy. Soc. **159**, 1 (1937).

[16] D. R. Hartree, unpublished (1939).

[17] J. G. Wilson, unpublished (1939). The Wilson's points refer to measurements with a counter controlled chamber, for which a 2-cm gold plate in the chamber is used to discriminate between mesotrons and electrons. The observed number of mesotrons below 2 μc is appreciably reduced by scattering in this plate.

[18] I am very indebted to Professor Hartree and to Dr. Wilson for giving me their results, which are not yet published.

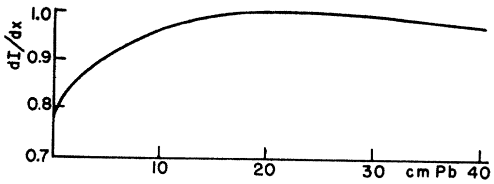

FIG. 3. Differential absorption curve of the mesotrons at sea level.

(b). *The absorption curve.*—Another possibility of testing the influence of the decay on the energy spectrum would be to measure very exactly the differential absorption curve in some dense materials, i.e., the number of mesotrons stopping between x and $x+dx$ as a function of x.

The differential absorption curve is easily obtained from the differential momentum spectrum. In Fig. 3 we give the result for lead, assuming for high energy mesotrons an energy loss of 1.4×10^7 electron volts/cm. We note in that curve a flat maximum at about 20 cm, which is directly connected with the maximum of the momentum spectrum. Here, however, not only the position, but the very existence of the maximum, would be strong evidence of the decay. As a matter of fact, a differential absorption curve like Fig. 3 could only be explained by very special assumptions on the original spectrum, unless the spontaneous decay or other processes occurring only in gases removed the slowest mesotrons coming from the air.

The experimental results, now available, are not accurate enough to allow any definite conclusion on this point.

(c). *Number of secondary electrons.*—As pointed out by Heisenberg and Euler, the number of secondary electrons and photons accompanying the mesotrons ought to be larger in gases than in dense materials. In the latter, of course, the production of a secondary shower can probably only be initiated by a close collision between a mesotron and an atomic electron (Bhabha's ionization showers), whilst in gases some electrons arise also from the decay of the mesotrons themselves.

Actually, experiments show that the proportion between the soft and the hard group is larger in air than under a layer of dense material. It is difficult, however, to draw from this fact any definite conclusion because the experimental results are not yet consistent enough, and because an unknown part of the soft component in the open air arises from primary cascade processes and not from cascade processes initiated by mesotrons.

APPENDIX

A mesotron beam coming at the zenith angle θ is observed at the depth h; let the distance from the top of the atmosphere in the given direction be $(h/\cos\theta)=y$, let ρ be the density of the air, p the momentum of the mesotrons hitting the apparatus. Let the same quantities referred to another arbitrary point of the path be h', y', ρ', p'.

The probability for the mesotron to penetrate to the depth y' without decay satisfies the differential equation.

$$-\frac{1}{w}\frac{dw}{dy'}=\frac{\mu}{\tau_0 p'\rho'}. \qquad (11)$$

Now $\rho'=(h'\rho/h)$; and if we assume that the energy loss of the mesotrons per g/cm² is constant and equal to a over the whole path,

$$p'=p+(a/c)(y-y').$$

Hence

$$-\frac{1}{w}\frac{dw}{dy'}=\frac{b}{y'[p+(a/c)(y-y')]}, \qquad (12)$$

where

$$b=\frac{\mu h}{\tau_0\rho\cos\theta}=\frac{\mu y}{\tau_0\rho}. \qquad (13)$$

We assume that the mesotrons are formed at the depth y_1 from the top of the atmosphere. Then $w(y_1)=1$, and the integration of (12) gives

$$-\log w$$

$$=\frac{b}{p+(a/c)y}\log\left[\left(\frac{y}{y_1}\right)\frac{pc+a(y-y_1)}{pc}\right]. \qquad (14)$$

Let $f_1(p)$ be the differential spectrum at y_1. Then the differential spectrum at the depth h and zenith angle θ is

$$f(p,y,\theta)=f_1(p+(a/c)(y-y_1))w(p,y,\theta). \qquad (15)$$

Formula (15) is identical with that given by Euler and Heisenberg except for the factor $(1/\cos\theta)$ in b, which takes into account the variation with zenith angle.

The quantities ϵ_1, ϵ_2, α, defined in the paper can easily be obtained by differentiation of (15). They all refer to experiments in which the variation, if any, of y is compensated by screens of equivalent thickness; $pc+ay$ has, therefore, to be taken as a constant. Hence $\delta(\log f)=\delta(\log w)$.

If we select a *monoenergetic* portion of the mesotron spectrum we have

$$\epsilon_1=-\frac{\delta(\log w)}{\delta y}, \qquad \text{(a)}$$

where $pc+ay=\text{constant}$, $(\delta p/\delta y)=-(a/c)$, $\theta=0$, $y=h$, $b=\text{constant}$.

Hence

$$\epsilon_1=\frac{b}{p+(a/c)y}\left[\frac{1}{y}-\frac{1}{p}\frac{\delta p}{\delta y}\right]=\frac{b}{yp},$$
$$\epsilon_1=\mu/\tau_0 p\rho. \qquad (16)$$

Again

$$\epsilon_2=\delta(\log w)/\delta h, \qquad \text{(b)}$$

where $p=\text{constant}$, $y=\text{constant}$, $(h/\rho)=\text{constant}$. Then

$$\epsilon_2=-\frac{1}{p+(a/c)y}\left[\log\frac{h}{y_1}+\log\frac{pc+a(h-y_1)}{pc}\right]\frac{\delta b}{\delta h}$$

or, putting $(h/\rho)=z_0$ and

$$\frac{1}{P}=\frac{1}{p+(a/c)h}\left[1+\left(\log\frac{pc+a(h-y_1)}{pc}\right)\Big/\left(\log\frac{h}{y_1}\right)\right], \qquad (17)$$

$$\epsilon_2=\frac{\mu}{\tau_0}\frac{z_0}{h}\log\frac{h}{y_1}\frac{1}{P}.$$

Finally

$$\alpha=-\delta(\log w)/\delta T, \qquad \text{(c)}$$

where $y=h=\text{constant}$, $p=\text{constant}$, $\theta=0$. Hence

$$\alpha=\frac{1}{p+(a/c)y}\left[\log\frac{h}{y_1}+\log\frac{pc+a(h-y_1)}{pc}\right]\frac{\delta b}{\delta T}$$

and since

$$\frac{\delta(1/\rho)}{\delta T}=\frac{1}{\rho T}, \qquad \alpha=\frac{\mu}{\tau_0}\frac{z_0}{T}\log\frac{h}{y_1}\frac{1}{P}.$$

If we observe a continuous mesotron spectrum from, say, p_0 to ∞ and put

$$N=\int_{p_0}^{\infty}f(p)dp$$

we have:

$$\epsilon_1'=-\frac{1}{N}\frac{\delta N}{\delta y}=\frac{-\int_{p_0}^{\infty}f(p)\frac{\delta(\log w)}{\delta y}dp}{\int_{p_0}^{\infty}f(p)dp},$$
$$\epsilon_1'=\frac{\mu}{\tau_0}\frac{1}{\rho}\overline{\left(\frac{1}{p}\right)}, \qquad (18)$$

where:

$$\overline{\left(\frac{1}{p}\right)}=\frac{\int_{p_0}^{\infty}\frac{1}{p}f(p)dp}{\int_{p_0}^{\infty}f(p)dp}. \qquad (19)$$

Again

$$\epsilon_2'=\frac{1}{N}\frac{\delta N}{\delta h}=\frac{\int_{p_0}^{\infty}f(p)\frac{\delta(\log w)}{\delta h}dp}{\int_{p_0}^{\infty}f(p)dp},$$
$$\epsilon_2'=\frac{\mu}{\tau_0}\frac{z_0}{h}\log\frac{h}{y_1}\overline{\left(\frac{1}{P}\right)}, \qquad (20)$$

where:

$$\overline{\left(\frac{1}{P}\right)}=\frac{\int_{p_0}^{\infty}\frac{f(p)}{p+(a/c)h}\left[1+\left(\log\frac{pc+a(h-y_1)}{pc}\right)\Big/\left(\log\frac{h_1}{y}\right)\right]dp}{\int_{p_0}^{\infty}f(p)dp}. \qquad (21)$$

Finally

$$\alpha'=-\frac{1}{N}\frac{\delta N}{\delta T}=\frac{-\int_{p_0}^{\infty}f(p)\frac{\delta(\log w)}{\delta T}dp}{\int_{p_0}^{\infty}f(p)dp},$$

$$\alpha'=\frac{\mu}{\tau_0}\frac{z_0}{T}\log\overline{\left(\frac{1}{P}\right)}.$$