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The Anomalous Absorption of the Hard Component of Cosmic Rays in Air

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The anomalously large absorption of mesotrons in air has been confirmed by a comparison of the vertical intensity of mesotrons at two different altitudes (500 m and 3460 m). At 3460 m the vertical intensity has also been compared with the intensity under a zenith angle of 45°. If the results obtained are interpreted according to the hypothesis of the instability of the mesotron, they are found to be consistent with the assumption of a proper lifetime of 4 or 5 microseconds for the mesotron.

A COMPARATIVE study of the absorption of cosmic radiation in air and other media by several experimenters has revealed the striking fact that the hard component of cosmic radiation undergoes an anomalously large absorption in air.[4]

Apart from small secondary effects, like the barometer effect, most determinations of the absorption coefficient in air and most comparisons of air with other media are based on the variation of the intensity with zenith angle. Their validity *depends on the hypothesis of an isotropic distribution* of the primary rays which produce the effects observed at sea level. Small deviations from isotropy due to geomagnetic effects are to be expected even at latitudes as high as 50°. The effect of penumbra at these latitudes has not yet been investigated.[5]

For these and other reasons it seemed of interest to determine the absorption in air in a manner independent of that hypothesis, that is, by comparing the intensity of the hard component from *one* given direction at *two different altitudes*. An experiment of this kind was planned by two of us (M. A and B. F.) and some preliminary results were obtained on the Gran Sasso in May, 1939. Then it was decided to take up the work again under more favorable conditions near Cervinia; This was done in August and September, 1939. A preliminary report has been published.[6]

Meanwhile an experiment very similar to ours has been reported by Rossi, Hilberry and Hoag.[7] Since our arrangement differs from theirs in some important respects and since also our results are somewhat different from a quantitative point of view, we intend to give here a short description of our apparatus and results. A possible origin of the difference between our result and theirs is also suggested.

In our experiment the vertical intensity of the hard component has been measured at two different altitudes: Chatillon (500 m; 700 mm

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[4] For a general survey of these experiments see B. Rossi, Rev. Mod. Phys. **11**, 296 (1939).
[5] At lower latitudes by R. Albagli Hutner, Phys. Rev. **55**, 15 and 614 (1939).
[6] Ricerca Scient. **10**, 1073 (1939).
[7] B. Rossi, H. Van Norman Hilberry and J. Barton Hoag, Phys. Rev. **56**, 837 (1939).

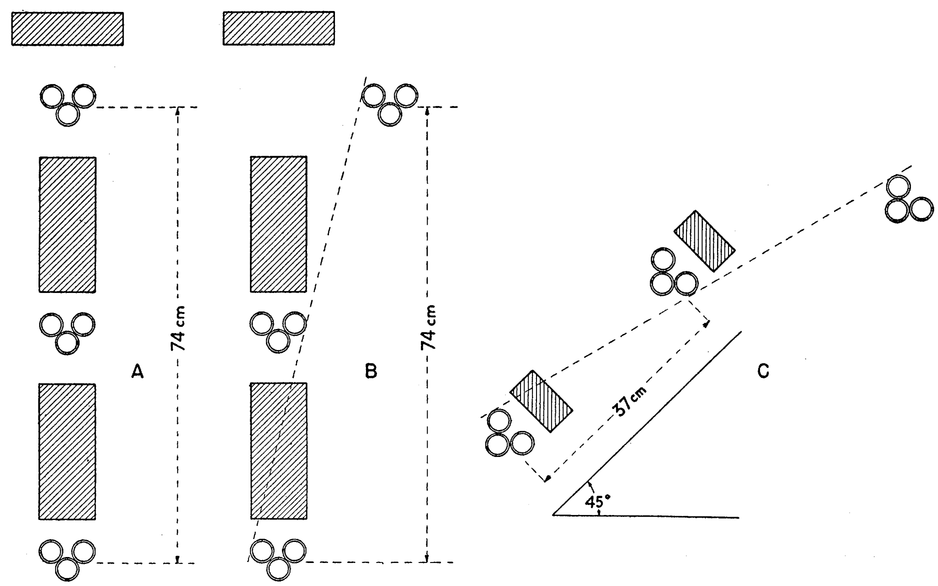

FIG. 1. Arrangement of counters. A, normal position; B and C, displaced for determining the effect of showers.

Hg) and Pian Rosà (3460 m; 495 mm Hg) by means of a counter telescope with a lead screen 10 cm thick permanently interposed between the counters. At Pian Rosà we interposed a further lead screen 39 cm thick, which was regarded as equivalent to the air layer between the two altitudes (see next section). We found a lower intensity at Chatillon; this indicates that lead absorbs less than air, in accordance with previous results.

At Pian Rosà the measurements of vertical intensity were alternated with measurements at a zenith angle of 45° *without the additional lead screen* of 39 cm thickness. Since cos 45° is about equal to the ratio of the pressures at 3460 m and at 500 m, we may compare the intensity at 45° with the vertical intensity either at Chatillon or at Pian Rosà (in the last case with the additional lead screen). *Thus our measurements also include a new comparison of air and lead by the older method.*

1. The Anomalous Absorption

The great interest of the absorption anomaly in air is connected with the fact that it is a density effect. Until very recently it was regarded as evident that all true absorption processes are density independent. Hence the absorption anomaly was interpreted as a decisive proof of the hypothesis of the disintegration of the mesotron.[8] In a paper which has just come to our notice Fermi throws considerable doubt on this conclusion.[9] We shall refer to it again in the last section.

In comparing different media, each of the following criteria has been used in the past: (a) the mass absorption law; (b) the Z-absorption law; (c) the Bethe-Bloch-Bhabha stopping power formula.[10] If air is compared with a medium of nearly equal atomic number, then all three criteria are equivalent. Any deviation from them has to be regarded as a density effect.

In comparing media of widely different atomic number, as in our case, the mass absorption law (a) is of little theoretical significance. Criterion (b) has to be regarded as merely a rough approximation to criterion (c). If the mesotrons were absorbed by ionization only, according to (c), then in comparing air with lead by the mass absorption law one should find that air is more absorbing than lead. If, on the other hand, an effect of this kind be found in a comparison based on criterion (c), then it could not be due to

[8] H. Euler and W. Heisenberg, Ergeb. d. exakt. Naturwiss. **17**, 1 (1938).
[9] E. Fermi, Phys. Rev. **56**, 1242 (1939). We are thankful to Professor Fermi for an advance copy of his full paper.
[10] See H. J. Bhabha, Proc. Roy. Soc. **A164**, 257 (1938).

anything but a true density effect, since it is very likely that any additional absorption process (like nuclear collisions or radiation) would give an effect in the opposite direction. Hence the third criterion is not only the most theoretically significant, but is also the most suitable one for our purpose.

The thickness of the lead absorber equivalent to the atmospheric layer between 495 and 700 mm Hg has been accordingly evaluated by means of the theoretical formula for ionization losses. On the Z-absorption law it would be about 32 cm of lead, which becomes 39 cm with the more correct formula. It may be remarked that an error of 1 or 2 cm in the evaluated thickness would probably affect the measured intensity by 1 or 2 percent which is much less than the effects observed.

2. Apparatus

The telescopic counter system (Fig. 1A) consisted of three trays of three counters each, filled with a 91 percent-argon: 9 percent-alcohol mixture, at a pressure of 11 cm Hg. The cathodes of the counters were brass tubes 1.5 mm thick, enclosed in a glass tube 1 mm thick. The useful length of the counters was 27 cm, the diameter 3 cm.

The counters in each tray were connected in parallel; by means of a Neher circuit (resolving power about 10^{-4} sec.) the triple coincidences and the double coincidences from the upper and lower trays were recorded at the same time. The directional intensity of radiation was supposed to be proportional to the number of triple coincidences, while the slight excess of the double on the triple coincidences was mostly due to chance coincidence. The approximate constancy of this excess was used as a check on the constancy of the apparatus. As a further check the number of single pulses from each counter was determined after every hour of counting.

Table I. *Summary of results.*

	Pressure mm Hg	Zenith Angle	Lead Absorber cm	Triple Coincidences/hour First run	Triple Coincidences/hour Second run	Showers First run	Showers Second run
Pian Rosà	495	0°	10+39	280.7±4.27	297.6±4.10	26.4±2.2	34.6±2.6
Pian Rosà	495	45°	10	213.7±4.31	230.4±3.31	19.8±2.7	26.8±2.3
Chatillon	700	0°	10	250.6±2.87	253.1±3.51	9.5±1.1	11.6±1.1

It was found necessary, however, to bring two corrections to the intensity of the hard component as given by the triple coincidences. The first was due to the effect of air showers, which was, of course, larger at the greater altitude, where it amounted to about 10 percent. The second correction was due to a slight decrease in the efficiency of the counter system, when the number of single pulses in a counter was increased. The effect of showers was determined in the usual way: the upper counter tray was displaced laterally until it was out of line as in Fig. 1B, C. The change of efficiency was determined by artificially increasing the number of single pulses in the counters with a radioactive source. The correction amounted only to 3 percent. (This is the change of efficiency for triple coincidences from 500 m to 3460 m altitude.)

3. The Measurements

The intensities of the hard component at Chatillon and Pian Rosà have been compared in two alternative runs. In the first run the intensity was measured first at Chatillon, then at Pian Rosà; in the second run it was measured first at Chatillon, then at Pian Rosà, and again at Chatillon. At Chatillon the measurements were made under a thin roof, about 7 g/cm^2 thick. At Pian Rosà the apparatus was placed in a hut with thin wooden walls; the roof was lined with sheet-iron and had a thickness of about 3 g/cm^2. Alternating current was available in the hut, and the temperature was controlled by means of a stove.

Our results are summarized in Table I; root mean square errors are given. We discuss the results from the two runs separately. First we deduct the showers from the triple coincidences. Then we have to remember that the data at Pian Rosà have to be raised by 3 percent with respect to those at Chatillon, because of the

Table II. *Comparison of experimental results with those expected for various values of mesotrons proper lifetime,* τ_0.

	Expected with τ_0 = 2	3	4	5×10^{-6} sec	Found
$\frac{J_0(500)}{J_0(3500)}$	0.78	0.85	0.88	0.90	0.91 ±0.015
$\frac{J_{45}(3500)}{J_0(3500)}$	0.65	0.72_2	0.77	0.80_5	0.769±0.016

change in the efficiency of the counter system. Indicating by $J_\zeta(h)$ the directional intensity at altitude h under a zenith angle of ζ degrees, we find after the above corrections:

$$\frac{J_0(3500)-J_0(500)}{J_0(500)}=\begin{cases}8.5 \text{ percent in the first run}\\ 11.9 \text{ percent in the second run.}\end{cases}$$

Similarly the comparison between the vertical intensity and the intensity under 45° both at Pian Rosà (no correction for the change of efficiency is necessary this time) gives:

$$\frac{J_0(3500)-J_{45}(3500)}{J_0(3500)}=\begin{cases}(23.7\pm 2.4) \text{ percent in the first run}\\ (22.6\pm 2.1) \text{ percent in the second run.}\end{cases}$$

Both these results show that lead absorbs less than air in accordance with previous results. The consistency of our results in the two different runs can be judged from the above table. As a matter of fact the measurements in the second run seem to be systematically somewhat higher than in the first run. The difference between the vertical coincidences at Pian Rosà in the two runs, for instance, amounts to about 6 percent which is larger than can be imputed to statistical errors. Such small inconsistencies were not unexpected, since some of the counters had to be replaced between the first and the second run. The difficulties involved in such work, when measurements have to be made at different places and times are, of course, well known and were fully realized from the beginning. On the other hand the greatest precautions were taken to insure the constancy of the apparatus during each run, and the effects found in the two different runs are, in fact, fairly consistent with each other. We think therefore that the difference observed between Chatillon and Pian Rosà is real and affords a new proof of the absorption anomaly in air, a proof which is independent of the hypothesis that the angular distribution of the primary rays at the top of the atmosphere is isotropic.

The comparison between 0° and 45° zenith angle, both at Pian Rosà, is of course much simpler, since the effect is larger and the two measurements could be frequently alternated. The difference observed confirms the results previously obtained by the same method.

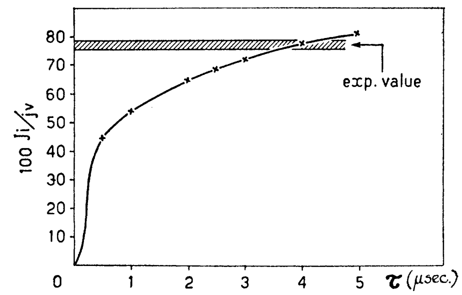

FIG. 2. Determination of proper lifetime of mesotron. The curve gives the expected ratio between inclined and vertical intensity at 3460 m, as a function of the proper lifetime τ_0 (in microseconds) of the mesotron, when $\mu/m=160$ and the energy loss is $J=2\times 10^6$ ev cm²/g. The horizontal strip represents the experimental value; the breadth of the strip is twice the statistical error.

4. DISCUSSION

We shall first discuss our results on the usual hypotheses:

(a) The mesotrons are formed at a height corresponding to about 0.1 NP. Direct evidence in favor of this assumption is afforded by recent results of Schein, Jesse and Wollan[11] and of Dymond.[12] The energy spectrum at the top of the atmosphere is assumed to follow a power law: $W^{-2.9}dW$.

(b) The mesotrons lose energy at a constant rate J per g/cm² of matter traversed, corresponding to a loss of 2×10^9 ev in the whole atmosphere; moreover they disintegrate with a proper lifetime τ_0.

(c) The rest mass of the mesotron is $\mu=160$ electronic masses.

Actually it can be easily seen that when our or similar experiments are discussed on the above hypotheses, the quantity which is measured directly is the ratio:

$$\mu/J\tau_0,$$

so that corrections for any change in the hypotheses on J or μ are easily made. We have evaluated the effects to be expected with several values of τ_0 and found the results given in Table II.

[11] M. Schein, W. P. Jesse and E. O. Wollan, Phys. Rev. **57**, 68 (1940).
[12] E. G. Dymond, Nature **144**, 782 (1939).

Our first result is consistent with a proper lifetime of about 5 μsec. We need not stress the fact that the precision of this value is low. The statistical error is indicated; an estimate of the true error could only be attempted after a greater number of alternative runs. The importance of this determination, however, lies in the fact that it is independent of the isotropy hypothesis.

The second determination of τ_0 is of course much more reliable quantitatively, provided the hypotheses for its validity are granted. The value of about 4 μsec. which can be deduced from it (see also Fig. 2) is in accord with the results of other authors. Especially an experiment of M. A. Pomerantz which has just become known to us[13] may be compared with our second determination. Pomerantz finds $\tau_0=3$ or 4 μsec. if he makes the same assumptions about ionization loss and mesotron mass as we have made. The agreement is very satisfactory. He also makes a direct comparison between the absorption in lead and water which justifies our evaluation of the lead thickness equivalent to the air layer.

Let us now compare our results with that of Rossi *et al.*[7] They find a lifetime of 2 microsec. which is considerably less than the values found by us. This can be seen even more directly from the fact that they find an intensity ratio 11.0/9.7 $=1.13$ due to disintegration on a path of 1.06 km, while we find in the comparison between Chatillon and Pian Rosà nearly the same ratio (1.10) due to disintegration on a 3-km path. The discrepancy is not quite so large as it seems at first sight since we have verified by computation that the difference effect due to disintegration does not quite increase proportionally to the path difference and since the above data of Rossi *et al.* refer to a greater height and therefore to mesotrons which should have a somewhat smaller energy than in our experiment.

The most trivial source of the discrepancy may be sought for in the fact that both experiments are liable to systematic errors, since the measurements to be compared were made at different places and could not therefore be frequently interchanged. Since moreover the effects are small such a source of discrepancies cannot be entirely excluded. If the lifetime were 2 microseconds, however, we should expect a ratio 1.28 in our comparison between vertical intensities, instead of 1.10. It seems very unlikely that the error is so great.

Another explanation may be sought for in the difference in the absorbers used, or in the different arrangement of the absorbers. As already mentioned, our evaluation of the lead thickness equivalent to a layer of some light element, like the carbon used by Rossi *et al.* is directly confirmed by the experiments of Pomerantz. In our apparatus the lead absorber was put between the counters and could hence give rise to an additional absorption due to scattering. This would tend to mask the effect of disintegration, and thus give an error in the lifetime in the direction sought for. The scattering of mesotrons, however, has been measured by Blackett and Wilson, and by Wilson[14] and found in agreement, roughly, with pure Coulomb scattering as evaluated by E. J. Williams. The correction for scattering due to small angle scattering is a differential correction, since particles can be scattered out of, as well as into, the effective solid angle of the apparatus. The effect should not amount to more than a few percent. Scattering through large angles seems to be a rare phenomenon; it has been observed in one case over a total thickness of lead traversed of 50 m. It does not seem, therefore, that scattering in the lead absorber can account for the high value of the lifetime of the mesotron found by us.

In our apparatus a correction for air-showers had to be made (this was avoided by Rossi *et al.*). This correction is somewhat arbitrary, since it is not certain that the number of showers observed with one of the trays displaced as in Fig. 1*B*, *C* is the same as when the trays are in line. We have found approximately the same shower frequency with 0° and 45° zenith angle; this may afford some justification for the assumption that the frequency does not depend critically on the position of the upper tray. Neglecting the shower correction we would find a ratio 1.15 between Chatillon and Pian Rosà, or 1.18 taking into account the correction for change of efficiency. The air showers increase with altitude faster

[13] M. A. Pomerantz, Phys. Rev. **57**, 3 (1940).

[14] P. M. S. Blackett and J. G. Wilson, Proc. Roy. Soc. **A165**, 209 (1938). J. G. Wilson, Proc. Roy. Soc. **A174**, 73 (1940).

than the hard component; it is difficult to see how the shower correction might help to *raise* the ratio from 1.18 to 1.28 as would be expected assuming a lifetime of 2 μsec. The presence of lead between the counters as in Fig. 1 at the greater altitude does not alter this conclusion materially.

We shall now briefly consider our results in connection with the density effect of ionization losses recently discovered by Fermi.[9] This effect becomes important only at high energies. A mesotron having a residual range of 280 g/cm^2 of air (the path between Pian Rosà and Chatillon) has an energy of 5 or 6×10^8 ev. At these energies Fermi's effect is small and cannot account for the effects we have observed. Fermi himself states in his paper that the experiments with comparatively thin absorbers cannot be explained by the density effect alone. It seems therefore that the instability hypothesis is still necessary to explain these effects. A striking confirmation of this hypothesis is afforded by a photograph recently published by E. J. Williams.[15]

On the other hand it has been shown by Fermi that the existence of a density effect on ionization means that the value of the lifetime which Euler and Heisenberg have derived from the experiments of Ehmert (with large absorbing thicknesses) must be increased by about a factor 2. It is indeed remarkable that both our measurements and those of Pomerantz, which were made also with comparatively small absorbing thicknesses, indicate a rather large value of the proper lifetime of the mesotron. In another paper we shall describe evidence which we have collected on this problem by a different method, that is, by a detailed study of the soft component which accompanies the mesotrons near sea level. Here also we have not found indication of the presence of "disintegration electrons" in the number that would be expected if the lifetime of the mesotron were as low as 2 microseconds. This also is in partial agreement with experiments made on somewhat similar lines by Pomerantz,[13] who finds a value of 6 μsec. from the intensity of the "disintegration electrons."

In conclusion we wish to acknowledge our indebtedness to the "Comitato per la geofisica e meteorologia del Consiglio Nazionale delle Ricerche" for financial assistance.

[15] E. J. Williams and G. E. Roberts, Nature **145**, 102 (1940).

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The Missing Heavy Nuclei

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Considerations of the regularities in the distribution of isotopes lead to the following conclusions. (1) Rn, AcA, ThA, and RaA should all be somewhat beta-active but the branching ratios would be too small for detection of the activity except for Rn and RaA. (2) $_{93}$EkaRe^{239} should be beta-active with a roughly estimated half-life of about 1 month, $_{93}$EkaRe^{237} should be an alpha-emitting nucleus, and $_{92}$U^{237} should be beta-active. (3) The heaviest beta-stable isotopes of transuranic elements should be as follows: $_{93}$EkaRe^{237}, $_{94}$EkaOs^{244}, $_{95}$EkaIr^{243}, $_{96}$EkaPt^{250}. It is shown that isotopes of transuranic elements should undergo fission upon exposure to slow neutrons, which may account for their absence in nature. Their presumable greater probability for spontaneous fission might also account for their absence. The relative abundance of U^{235} and U^{238} is in fair agreement with the hypothesis that the amount of U^{235} was determined by a balance between production from U^{239} and loss by fission. The probable chain of disintegrations of $4n+1$ nuclei is discussed. The estimated half-lives of all are too short for them to have survived. Their absence is to be attributed to the absence of a possible long-lived transuranic ancestor. Either the hypothetical irradiation by neutrons or spontaneous fission of a transuranic ancestor will account for the low abundance of Bi^{209}.

In a letter to the editor[1] it has been pointed out that the absence in nature of atoms of atomic number greater than 92 can be accounted for on the basis of a hypothetical exposure of all matter to irradiation by neutrons in some early phase of

[1] L. A. Turner, Phys. Rev. **57**, 157 (1940).