interaction is consequently

$$V_1 = -\frac{g^2}{9\kappa^2}\left[J_z s_z{}^A s_z{}^B + J_\perp(s_x{}^A s_x{}^B + s_y{}^A s_y{}^B)\right].$$

Introduce the unit vector $\hat{\mathbf{r}}$ along the line joining the two systems (in the z direction). Then

$$V_1 = \frac{-g^2}{9\kappa^2}\left[J_\perp \mathbf{s}^A\cdot\mathbf{s}^B + (J_z - J_\perp)(\mathbf{s}^A\cdot\hat{\mathbf{r}})(\mathbf{s}^B\cdot\hat{\mathbf{r}})\right].$$

The integrals J_z and $J_\perp$ are given by (84). Letting $\kappa d = x$, we have

$$V_1 = \frac{g^2\kappa e^{-x}}{9(4\pi x)}\left[(1/3)\mathbf{s}^A\cdot\mathbf{s}^B + \{(\mathbf{s}^A\cdot\hat{\mathbf{r}})(\mathbf{s}^B\cdot\hat{\mathbf{r}}) - (1/3)\mathbf{s}^A\cdot\mathbf{s}^B\}\left\{\frac{3}{x^2} + \frac{3}{x} + 1\right\}\right]. \quad (92)$$

Aside from the factor $\frac{1}{9}$, this is precisely the interaction between two heavy particles derived from the same Hamiltonian by perturbation methods.

Acknowledgments are due Professor W. Pauli and Professor J. R. Oppenheimer for illuminating discussions on all parts of this work.

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Cloud-Chamber and Counter Studies of Cosmic Rays Underground

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A counter controlled cloud chamber and two counter coincidence sets were used to study the nature of the cosmic rays observable underground. The experiments were performed in a copper mine at depths of 71, 141, 582, and 657 meters water equivalent. The data are easily interpreted, if one assumes that underground the primary rays are mesotrons and that the soft rays and showers are electronic secondaries produced by the penetrating mesotrons.

INTRODUCTION

At the time of the cosmic-ray symposium[1] held at Chicago in June, 1939, it was evident that there was as yet much unknown about the nature of cosmic rays underground as well as considerable disagreement concerning the known material. The shape of the total intensity *vs.* depth curve seemed to be quite well established. When plotted on a log log scale, the data fall on a line composed of two straight portions, the change in slope occurring at about 250 to 400 meters water equivalent. However, concerning the nature of the rays responsible for the two parts of the curve, there was a diversity of opinion. Several observers had found evidence for the non-ionizing character of the rays which carry the energy down to great depths; Wataghin and Santos[2] at 250 and 400 m,[3] Barnothy and Forro[4] at 1000 m. However, Wilson's[5] experiments at 30 m and 300 m indicated that the penetrating rays responsible for the observed intensity at both these depths are ionizing. Clay's[6] interpretation was that protons are predominant below the break in the intensity curve.

Neither data nor interpretation were clear-cut on the matter of shower production and the abundance of soft particles. The ratio of soft to hard components, as measured by counter absorption experiments, varied greatly, and it was quite evident that much of this disagreement

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[1] V. C. Wilson, Rev. Mod. Phys. **11**, 230 (1939).

[2] G. Wataghin and M. Damy de Souza Santos, Ann. Acad. Brasil. Sci. **11** (March 11, 1939).

[3] m means meters water equivalent of rock calculated on a density basis.

[4] J. Barnothy and M. Forro, Phys. Rev. **55**, 870 (1939).

[5] V. C. Wilson, Phys. Rev. **55**, 6 (1939).

[6] J. Clay, Rev. Mod. Phys. **11**, 128 (1939).

was caused by differences in geometry of counters, absorbers, and surrounding material. Thus, Wilson had found a 7 percent soft component, Nielsen and Morgan 24 percent, and Auger 9 percent, all at 30 m depth. Both Wilson and Clay found that the ratio of soft to hard rays increases with depth at moderate depths, and Clay observed a marked decrease below 400 m. Auger's data showed a constant decrease with depth. According to these observers, shower intensities vary with depth in about the same way as the soft component although it is difficult to distinguish between variation in shower intensity and possible variation in the nature of the showers themselves, such as size, angular spread, etc.

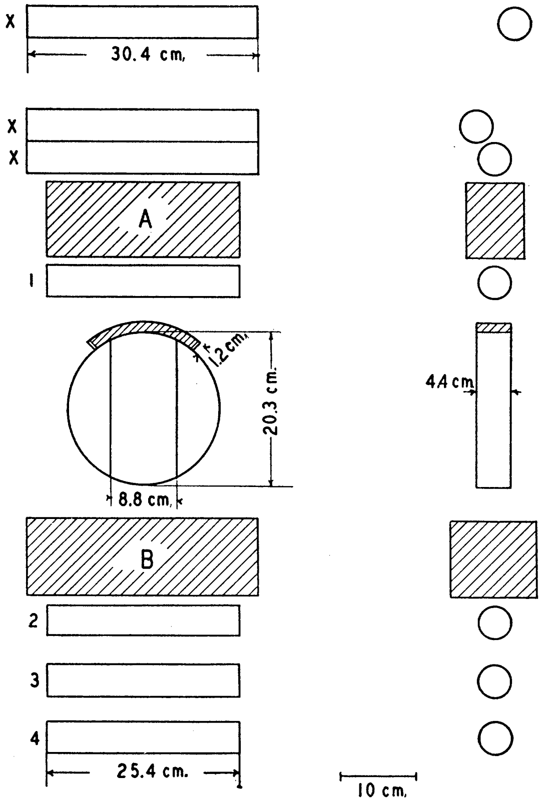

FIG. 1. Cloud chamber and Geiger-Mueller tube arrangement to study the nature of cosmic rays at 71 m.

The question of the nature and production of the showers is intimately related to the study of the nature of the penetrating rays at different depths. The experiments of Auger, Wilson, Janossy, Nielsen, and Morgan indicated that the showers at moderate depth are ordinary electronic multiplicative ones, accompanying the ionizing primaries which produce them. Barnothy and Forro felt that the great bulk of the ionization at depths below the break in the intensity curve is made up of soft particles, secondaries of a penetrating non-ionizing radiation. Wataghin also found a production by non-ionizing primaries at both moderate and great depths, it being the only method of production at the great depths. The interpretation of Clay, however, was that at great depths, the secondary showers, few in number, are progeny of the protons which are the particles penetrating to such depths.

Thus, it was realized that much more experimental work was needed to help clear up this diversity of fact and interpretation. Clear-cut data were needed to show the kinds of rays present at a particular location and the processes taking place there, and to show the way in which these things vary as the cosmic-ray energy is carried downward to greater depths. It was decided, therefore, to perform a series of experiments which might aid in the resolution of some of the difficulties mentioned. The work was carried on in the fall and winter of 1940–41, at the Isle Royale copper mine near Houghton, Michigan. Although it was necessary to terminate the experiments at the end of December, enough data were obtained in the time available to give results of definite value.

CLOUD-CHAMBER EXPERIMENTS

Since the interpretation of counter tube experiments underground is often difficult and uncertain, it seemed desirable to supplement them by the use of a cloud chamber. The immediate phenomena recorded in the chamber are more obvious than interpretation of counter readings, but quantitative results are, of course, much more uncertain. It was felt, however, that cloud-chamber results combined with counter data would give a good picture of the complex of rays present underground. The chamber would show directly what was being measured quantitatively with the counters; the latter would give some idea of the frequency of occurrence of the processes seen in the former.

The chamber was of the conventional diaphragm type, 20 cm in diameter, automatic in operation, and counter-controlled. It was mounted between the poles of a 600-lb. Alnico permanent magnet, which produced a field of 1250 gauss in the plane of the chamber. Illumination was provided by two 36-volt coil-coil line filament bi-post lamps, which, when flashed in parallel on 110 volts and focused with cylindrical lenses, produced a brilliant sheet of light of chamber depth. It was found possible to let the apparatus run continuously in the mine. It was visited daily to check adjustments, remove film, etc.[7]

The cosmic-ray intensity in the mine, and hence, rate of expansion of the chamber, was so low that in the time available it was felt best to get as many pictures as possible at one depth, the "1st level," 71 m, and use the counter data alone to infer the variation of phenomena with depth. The counter control and lead absorbers used to obtain a general picture of the rays and processes present at this depth are shown in Fig. 1. Three general arrangements were used:

I. Coincidences of tubes 1, 2, 3, and 4 controlling the expansions, no Pb absorber present.
II. Same counter control as I but with 10 cm Pb at *B*.
III. Coincidences of tubes 1, 2, 3, and 4 controlling expansions; 3 to 10 cm Pb at $A+1.2$ cm on chamber; tubes *X*, in parallel, light a neon lamp when they discharge coincidently with 1, 2, 3, and 4.

The purpose of I is to give a cross section of the rays in equilibrium with the rock at this depth undistorted by Pb absorbers. Arrangement II shows the effect of the usual method of removing the soft component in a counter absorption experiment—the lead under the chamber allowed only penetrating rays to be observed without the addition of rays produced in the absorber itself. In III the more complicated picture of penetrating rays plus secondaries produced in the lead above the chamber is observed, the neon lamp indicating whether secondary production was by ionizing or non-ionizing primaries. For these three groups, with an expansion rate of about two per hour, a total of 1248 pictures was obtained. A shower arrangement of tubes was also tried, but the counting rate was prohibitively low, power line failures causing more expansions than showers.

For the single tracks, visible in both of the stereoscopic views, passing through the control counters, and long enough for curvature measurement, the pc value (300 $H\rho$) was determined by use of the micrometer device described by Jones and Hughes.[7] There were 364 such tracks, divided among the three groups as shown in Table I with momentum spectra as in Fig. 2. The momentum range shown does not extend above 10^9 ev. The tracks with higher measured values are classified with the "straight" tracks.

The table and momentum spectra show that for group I (no Pb absorber), there is an excess of negative particles of low energy. These are, of course, secondaries and are undoubtedly knock-on electrons separated sufficiently from their primaries to appear singly. Aside from this explicable excess, there seems to be a positive-negative equality. A proton with an energy low enough to be measured in this apparatus would be quickly absorbed by its great ionization loss. Therefore, this is not evidence against the presence of positive protons in the penetrating group. Incidentally, except for a few contamination alphas, no particles with heavier ionization than electronic were observed in any of these pictures.

TABLE I. Rays photographed with the three counter arrangements at 71 m depth.

Group	+	−	Straight (>10^9 ev)	Total	$\frac{10^8-10^9}{\text{total}}$
I. No Pb	22	35	117	174	33%
II. 10 cm Pb below chamber	5	3	23	31	26%
III. 3–10 cm Pb above chamber	18	23	118	159	26%
				364	

The expansion rate of the chamber was 2.10 per hour in I and 1.98 in II, a 5 percent decrease in counting rate with 10 cm Pb. The last column

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[7] The chamber resembled closely that described by H. Jones and D. Hughes, Rev. Sci. Inst. **11**, 79 (1940). The magnet was an enlarged version of the one described by Herzog, Phys. Rev. **59**, 117 (1941). We wish to thank Dr. Herzog also for the use of an electronic timing circuit.

of Table I, which is a rough measure of the "shape" of the spectrum, indicates that the rays absorbed are of low energy. Comparison of the momentum spectra of I and II (Fig. 2) shows this even more clearly, for the low energy group of I does not appear in II. There are now no rays of momentum less than 2.1×10^8 ev, which checks well with the fact that the momentum value for mesotrons of range 10 cm Pb is 2.3×10^8 ev. The eight rays still present in II with measurable momentum are almost certainly mesotrons; electrons of such momentum could never penetrate the absorber because of radiation loss; nor could protons because of the increased ionization loss at these momentum values (a proton of momentum 8.2×10^8 ev has a 10 cm range). The uncertainty in curvature measurement for the higher momentum particles in this group would perhaps permit their interpretation as protons of actually higher momentum; however, of the three over 5×10^8 ev, two are negative. Of the five most certain mesotrons, of momentum under 5×10^8, four are positive. Protons of such momentum value also would show increased ionization, which is not the case.

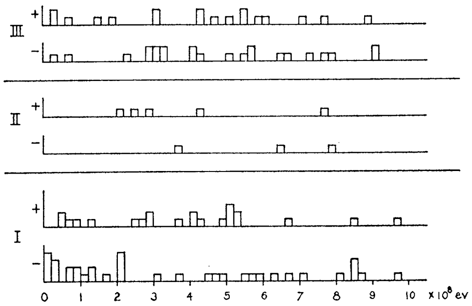

FIG. 2. Momentum spectra taken from cloud-chamber photographs at 71 m.

Those secondary rays which travel close to their penetrating primaries are not revealed by a decreased counting rate when Pb is interposed in a counter experiment. It follows that for this particular geometrical arrangement (roof 80 cm above upper counter) 5 percent of the total are soft rays separated enough from their primaries to set off a counter train missed by the primary rays. The actual soft component is of course greater than 5 percent by an amount which will be larger the greater the coherence of the secondaries to the primaries. A rough estimate can be made by an actual count of the secondary rays observable in the chamber accompanying the penetrating rays of group II—the resulting figure is 13 percent, which should be increased somewhat to allow for those secondaries which pass out of the illuminated area. Thus, in a rough way, we see that an actual 13 percent soft component would be measured as 5 percent—or even less if the counter train were nearer the overlying rock. This point is, of course, closely related to the counter absorption experiments described below.

Group III concerns the more complicated case in which the Pb block absorbs some particles but also creates others, which are observed in the chamber. In this sense, the phenomena observed are a combination of those in I and II, and it is seen in the momentum spectra and Table I that the results lie between those of the first two groups. Under the Pb block there is an approximate positive-negative equality—as would be expected from multiplication of those soft rays in the absorber which are not absorbed. Of more interest in this group than the momentum spectra are the nature and mode of production of the showers observed.

The secondaries and showers observed with the three arrangements are shown in Table II. Again, the relative number of coincidences caused by showers to those due to single rays is not the ratio of occurrence of these phenomena, but depends on the geometry and the surrounding material. Still another reason is seen here for the fact that the decrease in counting rate with insertion of 10 cm Pb gives a low value for the soft component, for an appreciable number of showers present in I are removed by the Pb, each of which would be counted as only one soft ray by the counter absorption method. The difference in size distribution of showers for the three arrangements is quite marked. The Pb-produced showers in III seem to contain a greater number of larger size than the rock-produced ones in I; this would be expected from the difference in material but, of course, can be due simply to the proximity of the producer in III. The large production of showers in a few cm of Pb as shown in III and their complete absorption by the Pb in II indicate their nature as ordinary multiplicative showers—at least, no evidence is present of an unusual shower type. The additional, admittedly subjective, but important fact can be added that the showers look just like all those photographed at sea level with the same apparatus.

The neon lamp data in group III give definite information on the mode of production of the ionizing rays created in the Pb, which set off the counters below the Pb and are seen in the chamber. A lamp flash on the film signifies that coincident with the expansion an ionizing ray has passed through the counters X above the chamber. On 11 of 251 coincidences, there were no neon flashes. Without the cloud chamber evidence, we might conclude from this that under the Pb $4\frac{1}{2}$ percent of the ionizing rays were produced by non-ionizing primaries; furthermore, the primaries were unaccompanied by ionizing rays, hence were not photons—an important finding. But there would always be the question in such a result as to whether there might be an error in interpretation. Perhaps side showers, scattering, or insufficient coverage by counters X could explain the apparent production by non-ionizing penetrating rays. Here, however, we have the additional evidence of the chamber, and, seeing the actual ionizing rays in the chamber, we can project them upwards to see if their ionizing primaries would have fired the counters X. When this is done, it is found that in none of the 11 pictures showing no neon flashes is there a ray visible whose projection passes through X. In 7 of these pictures no rays are visible (a ray can miss the chamber and fire the counters); inclined showers are present in 2 of them; and the final 2 show single rays inclined so as to hit the ends of the control counters but not counters X. So, of the 162 rays photographed with arrangement III, there is no evidence of production by a non-ionizing agent which is unaccompanied by ionizing rays. Photons are not ruled out by this evidence, but production by any penetrating non-ionizing ray (which would not be accompanied by numerous secondary ionizing rays), as suggested by several experimenters, must be extremely rare.

TABLE II. Secondaries and showers accompanying the counter control rays.

Group	Rays	Single secondaries	Shower size						Total
			2–5 rays	6–10	11–20	21–30	31–40	>40	
I	174	29%	15	4	2	1	0	1	23
II	31	13%	11	0	0	0	0	0	11
III	159	11%	11	2	1	2	2	2	20

A number of knock-on electrons created in the gas of the chamber were observed. The great majority of these have ranges lying entirely in the chamber; hence, their energies can be estimated even when scattering prevents curvature measurement. The probability of ejection of a knock-on of energy E electron volts is given by[8]

$$p(E)dE = 0.3\frac{z}{A}\frac{mc^2}{\beta^2}\frac{dE}{E^2}dx,$$

provided E is small as in the cases considered here. The electronic rest energy is mc^2 and dx is measured in g per cm^2. If the momentum of the primary particles is high enough so that $\beta = 1$, then this probability is independent of the momentum and mass of the primaries. As all the rays recorded were of electronic ionization density (hence with $\beta = 1$), a study of the distribution in energy of the knock-ons in the gas will give no information on the mass of the primary particles. Nevertheless, it is interesting to check the validity of the above formula by counting the observed total number of knock-on electrons. For 390 rays there are 48 knock-on electrons with range greater than 0.5 cm in the chamber, i.e., of energy greater than 18 kev. Integrating the formula with respect to E between the limits 18 kev and infinity, we find 3.89 per g/cm^2 of argon or per 516 cm track length in the chamber. Thus, for 390 tracks of average observable length of 18 cm, or 7030 cm track length, we would expect $7030/516 \times 3.89$ or 53 knock-on electrons as compared to the 48 observed. The number of cases is too small to allow any significant comparison between the observed and expected distributions in energy.

Contrasted to statistical data on their energy distribution, cases of individual knock-on elec-

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[8] B. Rossi and K. Greisen, Rev. Mod. Phys. **13**, 240 (1941).

trons, where angles and momenta can be measured, furnish excellent methods of mass determination. In order to estimate the mass of the primary with any accuracy, the collision must be almost head-on and the primary momentum must be relatively low, as can be seen from the formula

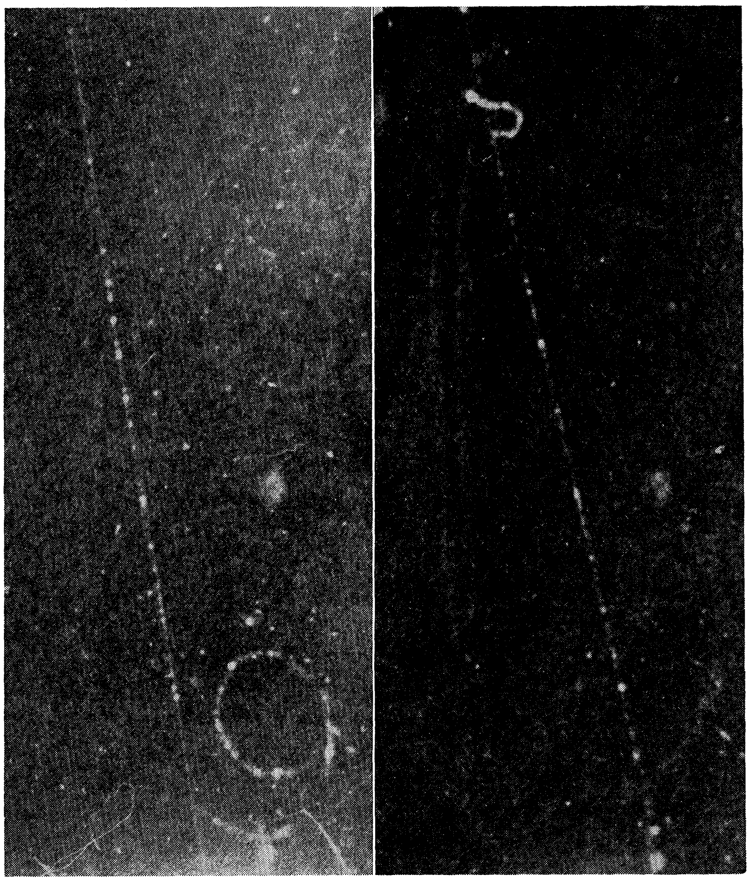
$$E=\frac{2mc^2(\mu_0/k)^2\cos^2\theta}{\{[(\mu_0/k)^2+1]^{\frac{1}{2}}+1/k\}^2-(\mu_0/k)^2\cos^2\theta}$$

which gives knock-on energy E (electron volts) in terms of the angle of ejection θ of the knock-on electron by the primary, of mass km, of momentum μ_0 mc. For the knock-on electrons observed, θ, μ_0, and E could be measured at least approximately, but in most of these cases the values were such (θ large, μ_0 large) that k could not be determined with any accuracy. The two knock-on electrons shown in Fig. 3 illustrate this.

All in all, the cloud-chamber data show that at 71 meters depth the kinds of rays and interactions which are observed are just those well-known at sea level. There are penetrating ionizing rays, soft secondaries (with an excess of negatives), and ordinary multiplicative showers. The penetrating rays of high energy may be mesotrons or protons, there being definite evidence only for the presence of mesotrons. A soft component, composed of low energy rays, is present. The fraction of soft rays is greater than would be indicated by counting rate ratios in an absorption experiment. The soft rays apparently are largely produced by well-known knock-on processes; the number of electrons ejected in the chamber gas checking with theoretical knock-on probability, and the greater number of absorbable secondary rays being negative. Under a shower producer of moderate thickness the number and size of the showers increase just as observed at sea level, and the energy of the individual rays is likewise similar. The mode of production of showers at this depth seems to show nothing unusual; in particular, there is no evidence of production by penetrating non-ionizing primaries. The evidence is mainly qualitative, the more quantitative data and the important change of the phenomena with depth can be obtained from the counter data.

ABSORPTION EXPERIMENT

It was mentioned in the introduction that some observers think the penetrating rays are ionizing and others believe that below 250 m the energy is carried down by a non-ionizing ray that produces softer ionizing secondaries. The cloud-chamber work shows that at 71 m, most of the rays are penetrating and ionizing. There might be, however, a small fraction of secondaries created by non-ionizing primaries. If, as the rays pass to greater depths, the ionizing rays are absorbed, the majority of the remaining rays observed might be secondaries from these non-ionizing primaries. If this is the case, the absorption of rays present at great depths would be greater with material between the counters than with material above the counters. Material between the counters would give the absorption curve for the secondaries produced in the rock, and material above would give the absorption for the primaries. Figure 4 shows a Geiger-counter arrangement used under exactly similar conditions at 71 m and at 657 m. Each group of three tubes was connected together to form one large tube. Lead surrounding the second and third tubes shielded these tubes from side showers. The upper four tubes were connected to one coincidence circuit and the lower four to another in order to take two sets of data simultaneously. The coincidences were recorded by two pens on a moving tape. The ceiling was one meter from the top group of tubes, and the same vein of rock was overhead at the two locations. Figures 5 and 6 show the absorption curves obtained. It is immediately apparent that at both depths, the observed rays are very penetrating. The comparatively rapid decrease in the counting rates in the first 10 cm of lead was caused by the absorption of the soft rays. As pointed out when discussing the cloud-chamber data, this initial drop cannot be used to calculate the relative number of soft to hard rays, but if this ratio should increase with depth, then the initial drop would be greater at 657 m. The similarity of the curves indicates that the ratio of soft to hard rays is about the same at the two depths. This also suggests that the rays at 657 m are similar to those at 71 m. Certainly any possibility of a large fraction of non-ionizing



(a) (b)

FIG. 3. Two knock-on electrons observed at 71 m. (a) *Counter arrangement* I. The primary is negative, of momentum 4.7×10^8 ev ($\mu_0=940$). The energy of the knock-on electron is 215 kev ($\epsilon=0.43$, where energy$=\epsilon mc^2$) and θ is about 60°. For proton mass, the measured values for μ_0 and θ give $\epsilon=0.094$, thus definitely ruling out this possibility. For $k=200$, the resulting ϵ is 0.62, which becomes 0.45 for $\theta=64°$, agreeing very well with the measured value. But assumption of electronic mass results in almost the same values ($\epsilon=0.48$ for $\theta=64°$). Here then elimination of the proton is definite but no distinction is possible between the mesotron and electron as the primary particle. (b) *Arrangement* II. Primary momentum 2.9×10^8, $\epsilon=0.08$, $\theta\geqq60°$. For $k=200$ the observed ϵ is obtained for $\theta=78°$ while for protonic mass, θ would have to be 45°. θ is certainly greater than 45° so the primary is not a proton. Also the ionization density is too low for a proton which at this momentum value would ionize five times as heavily as an electron. As for (a), distinction between $k=1$ and 200 is impossible for large θ values ($\theta=79°$ gives the correct ϵ for $k=1$), but here, the fact that the primary penetrates 10 cm of Pb eliminates the electron. Thus, in this case, identification as a mesotron is certain, but quantitative mass determination is impossible.

primaries is ruled out. With Pb only in A, a non-ionizing ray to be detected would need to produce two secondaries—one in the ceiling and one in A. With the same amount of Pb divided and placed in A and B, three secondaries would need to be produced to cause a coincidence. This probability would be much lower. However, the points L_{10-5} (10 cm Pb in A and 5 cm Pb in B) and L_{23-10} do not fall below the curve, thus further ruling out the non-ionizing primaries.

SHOWER EXPERIMENT

Showers detected by counter tubes are produced in the material surrounding the tubes.

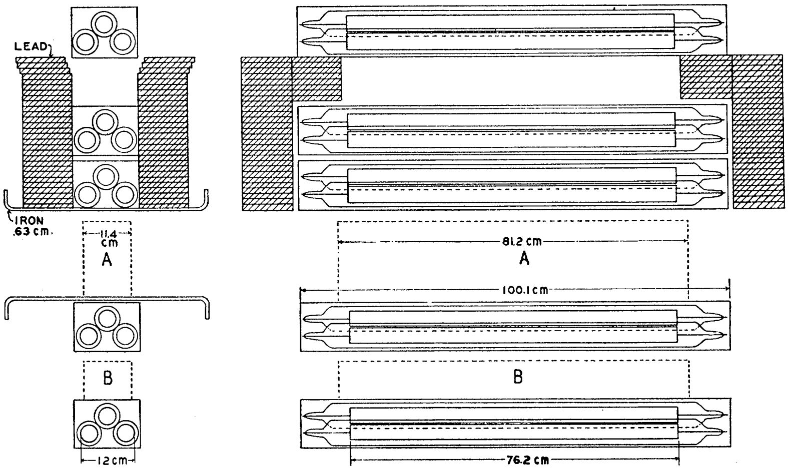


FIG. 4. Experimental arrangement used at 71 m and 657 m to measure absorption and relative numbers of soft and hard cosmic rays.

Therefore, to make a comparison of the shower properties at various depths, the counter tube arrangement used (Fig. 7) was completely surrounded by Pb. The Pb was 15 cm thick on the top, 10 cm on the sides and ends, and 2.5 cm on the bottom. It was thought that these thicknesses would be sufficient to insure that all shower particles observed in the cavity would have originated in the Pb and not in the surrounding rock. By moving this entire arrangement from one depth to another, any change observed in the nature of the showers should be caused by a change in the rays producing the showers and not by the geometry of the surrounding material.

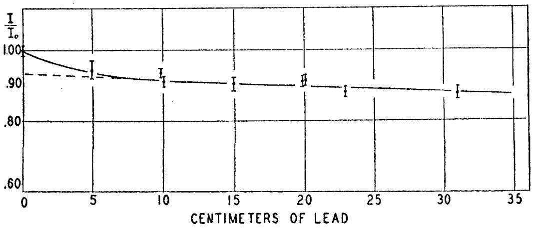


FIG. 5. Absorption of cosmic rays at 71 m.

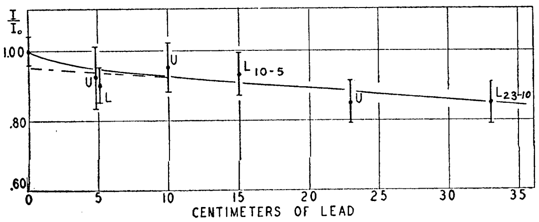


FIG. 6. Absorption of cosmic rays at 657 m.

The five tubes marked X were electrically connected in parallel to operate as one tube. Similarly, the Y tubes were connected together to form one large tube. Figure 8 is a block diagram of the circuits, each block representing a standard coincidence circuit. The counts from each were recorded upon a telephone message counter driven by a multivibrator. The threefold circuits $X12$, $X23$, $X34$, $X45$, $X24$, and $X15$ recorded showers of two or more particles. Small condensers coupled the plates of the threefold output tubes to the twofold coincidence circuits $X123$, $X234$, and $X345$. In this way, showers of three or more particles were recorded. Similarly, the outputs from $X123$ and $X345$ were combined in $X12345$ to count showers of five or more particles. The outputs from the above ten circuits were combined with the pulses from the Y tubes in ten more twofold circuits ($XY12$————————$XY12345$). This arrangement made it possible to obtain twenty sets of data simultaneously. Combining the outputs not only reduced the number of vacuum tubes needed, but also reduced the capacity connected to each Geiger-Mueller tube, thus short resolving times could be maintained.

This apparatus was first taken to the 29th level, 2100 m, and operated from the same power line as was used for the experiment. No coincidences were observed in fourteen hours. Apparently surges in the power line would not cause false counts. Tests showed that there was no intercoupling of the circuits which would cause a circuit to count falsely even when the other nineteen circuits were activated. Measurements of individual counting rates and of twofold coincidences were made, and from these values, the time constants of the threefold circuits were found to be 3×10^{-6} min. The calculated threefold chance counts were one in 2000 days. At the surface, where both the Y and the $X12$ etc. counting rates were much greater, the estimated Y–$X12$, etc. chance counts were one in three days. All other chance counts were much lower. Data were taken at the surface, at 71 m, 141 m, and 582 m.

The function of the Y counters was to furnish some information on the mode of production of the observed showers. As mentioned above, it was thought that cascade showers could not penetrate the 15 cm of Pb above the X tubes, and the showers observed would have originated in the lead. Therefore, if a Y tube was discharged simultaneously with an observed shower, one should conclude that the shower was caused by an ionizing ray. Only about 40 percent of the area and solid angle above the X counters was covered by the Y tubes, and no measurements were made of the efficiency or sensitive area of the counter tubes; therefore, this arrangement was used not to determine the actual fraction of showers caused by ionizing rays, but rather to see if there is any change in this fraction with depth.

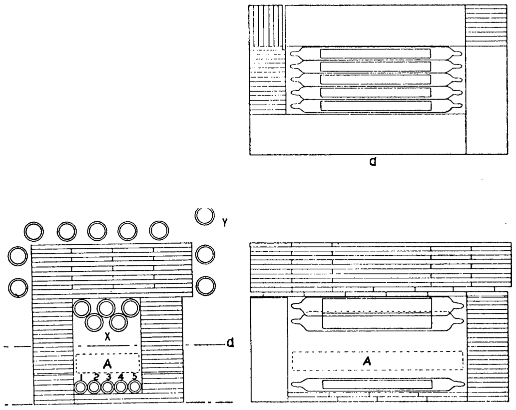


FIG. 7. Shower apparatus used at various depths.

Table III shows that the percentage of showers produced by ionizing rays does not change with depth. Since it is generally assumed that most of the showers at sea level are produced by mesotrons and since the cloud-chamber work at 71 m depth gave no evidence of a non-ionizing shower producer, one may assume that practically all showers down to 582 m are produced by ionizing primaries.

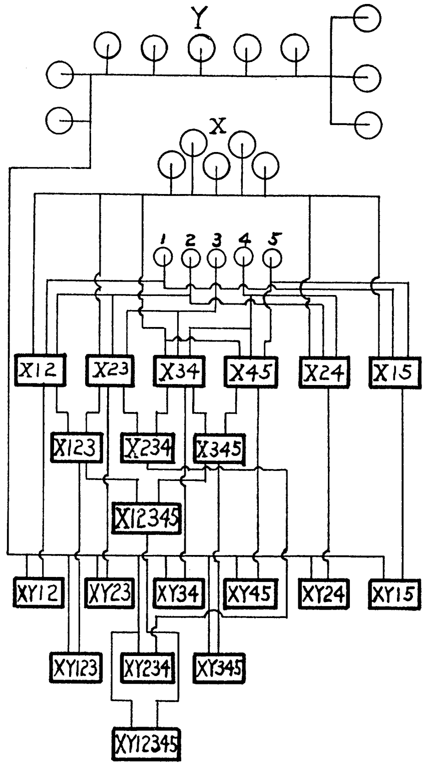


FIG. 8. Circuit diagram for shower apparatus.

Concerning now the size of showers, it is seen that the threefold circuits, $X12$, $X23$, etc. counted all sized showers; i.e., two or more particles. The $X123$, $X234$, and $X345$ circuits recorded showers of three or more particles. If a shower discharged $X12$ but not $X123$, one cannot say that that shower consisted of only two particles, but rather that the shower was small and particles penetrated only two of the lower counters. Similarly, a coincidence $X12345$ represented a shower of five or more particles. It is more probable that such a coincidence was caused by a very large shower than by one of only five particles. One can only say that the

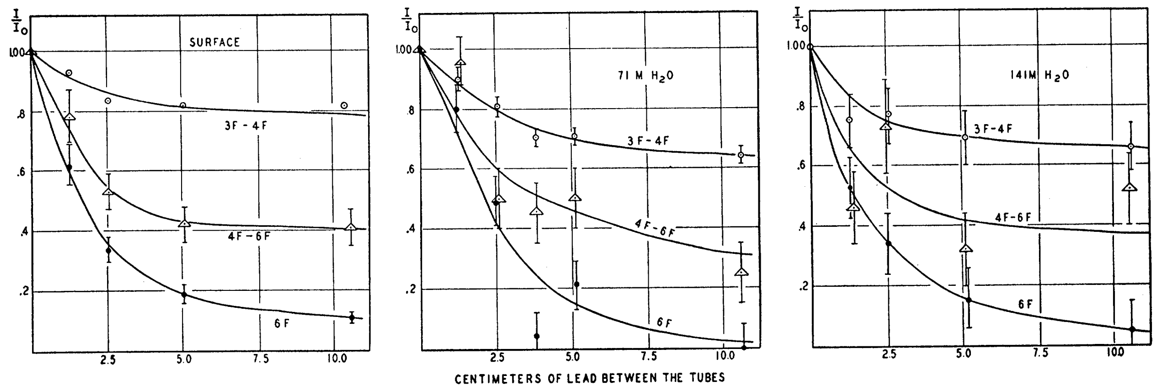


FIG. 9. Absorption of the individual particles in showers at different depths.

TABLE III. Percentage of showers accompanied by a discharge of a *Y* counter.

Depth	Percentage
Surface	36.6±0.4
71 m	31.1±1.5
141 m	30.8±2.0
582 m	38.6±6.0

density of shower particles was sufficiently high for at least one particle to pass through each tube. We shall call the showers which tripped two of the lower tubes but not three (3*F*–4*F*) small showers; showers which tripped three but not five lower tubes (4*F*–6*F*) medium-sized showers; and showers which tripped all the lower counters (6*F*) large showers.

The percentage of small, medium, and large showers at the different depths is shown in Table IV. The data show quite consistently the steady increase in the relative number of large showers with depth. Furthermore, as the third column shows, the increase in the relative number is greater for the large showers than for the medium-sized showers. At the extreme position, 582 m, it is interesting to note that the number of showers large enough to set off at least three of the lower tubes is actually larger than the number of small showers. Since the *Y* data show that there is no significant change in the nature of the shower-producing rays, this increase of size is most probably a manifestation of the increase in mean energy of the penetrating rays with depth.

Table V gives the absorption data for various sized showers.

Table IV shows that the large showers are relatively more abundant at greater depths. Table V states the same thing in a different way; namely, that the rays producing the large showers are more penetrating. This is to be expected, since the more energetic a ray, the larger is the shower it can produce, and also the greater is its probable penetration.

These tables explain why shower absorption experiments performed by various observers can give such different results. For example, an experiment designed to measure shower intensity *vs.* depth will also be affected by the change in shower size with depth.

To measure the absorption of the individual particles in the showers, counts were taken with various thicknesses of Pb at *A*, between the *X* counters and counters 1, 2, 3, 4, and 5.

TABLE IV. Percentage of small, medium, and large showers at different depths.

Depth	Small	Medium	Large
Surface	75	19	06
71 m	58	22	20
141 m	53	23	24
582 m	45	($M+L=55$)	*

* At 582m the *X*12345 circuit did not record because of a faulty vacuum tube.

TABLE V. Ratio of $\frac{\text{counts/hour}}{\text{counts/hour at surface}}$.

Depth	3*F*	4*F*	6*F*	3*F*–6*F*	4*F*–6*F*
Surface	1.00	1.00	1.00	1.00	1.00
71 m	0.11	0.19	0.37	0.08	0.13
141 m	0.04	0.08	0.18	0.03	0.05
582 m	0.003	0.008	—	0.002	—

Figure 9 shows these absorption curves. It is apparent that at all three depths the individual particles in the large showers are less penetrating than in the medium-sized showers, and these, in turn, are less penetrating than the particles in the small showers. This is probably because in the larger cascade showers the energy of the original particle has been divided many more times, and so the average energy of the individual particles is less than in the small showers. Of course, there is no way to prevent showers from being formed in the Pb absorber *A*. These, moreover, would be confined to a narrow bundle in the Pb; and so would have a greater probability of being detected as small showers than as large showers. These showers formed in *A* will not reduce in number with increasing thicknesses of *A*. This explains why the particles in the small showers appear to be hard. The difference at any one depth in the absorption curves for particles of various sized showers thus can be interpreted simply and probably is not of great significance. But the fact that these groups of curves are very similar at several depths indicates that the showers are also similar in nature at the different depths. At sea level, the showers are known to be cascade showers; apparently, this is also true at the other depths.

Showers are produced by knock-on electrons or radiated photons. If protons are present and are more penetrating than the mesotrons, at the greatest depth the protons alone will remain. Clay has pointed out that at high energies, the protons do not radiate as efficiently as the mesotrons. Thus, if the most penetrating primaries are protons, as one goes to the greatest depths, the relative number of showers will decrease. These data do not show any decrease; however, there may be a maximum between 141 and 582 m, or the ratio may fall off at still greater depths. Plans have been made to continue these experiments to detect the presence of protons underground.

CONCLUSIONS

The results of the various experiments of the present series are all consistent with the interpretation that the cosmic rays underground are mesotrons accompanied by electronic secondaries (knock-ons and their progeny). No evidence could be found for a non-ionizing primary. The data at the greatest depths are not sufficient to rule out the possible existence of high energy protons underground.

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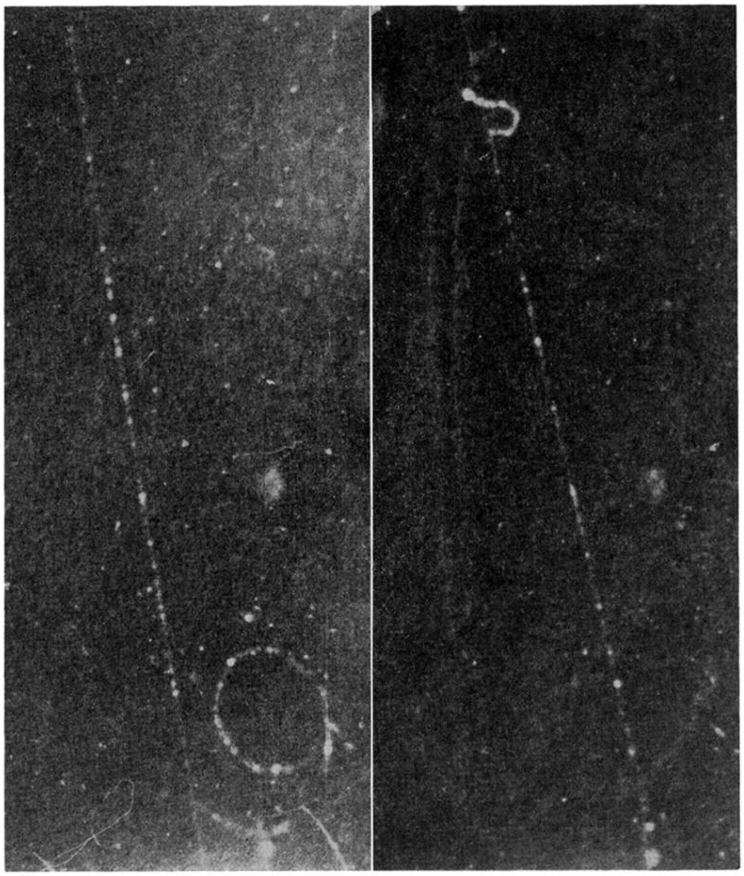

(a) (b)

FIG. 3. Two knock-on electrons observed at 71 m. (a) *Counter arrangement* I. The primary is negative, of momentum 4.7×10^8 ev ($\mu_0=940$). The energy of the knock-on electron is 215 kev ($\epsilon=0.43$, where energy$=\epsilon mc^2$) and θ is about 60°. For proton mass, the measured values for μ_0 and θ give $\epsilon=0.094$, thus definitely ruling out this possibility. For $k=200$, the resulting ϵ is 0.62, which becomes 0.45 for $\theta=64^\circ$, agreeing very well with the measured value. But assumption of electronic mass results in almost the same values ($\epsilon=0.48$ for $\theta=64^\circ$). Here then elimination of the proton is definite but no distinction is possible between the mesotron and electron as the primary particle. (b) *Arrangement* II. Primary momentum 2.9×10^8, $\epsilon=0.08$, $\theta\geqq60^\circ$. For $k=200$ the observed ϵ is obtained for $\theta=78^\circ$ while for protonic mass, θ would have to be 45°. θ is certainly greater than 45° so the primary is not a proton. Also the ionization density is too low for a proton which at this momentum value would ionize five times as heavily as an electron. As for (a), distinction between $k=1$ and 200 is impossible for large θ values ($\theta=79^\circ$ gives the correct ϵ for $k=1$), but here, the fact that the primary penetrates 10 cm of Pb eliminates the electron. Thus, in this case, identification as a mesotron is certain, but quantitative mass determination is impossible.