Bacher in the ^3D terms of the analogous Tl II spectrum.

Conclusion

It has been assumed throughout the preceding discussion that the even isotopes have no spin and the line due to each of them falls undisplaced and unresolved at the center of gravity. These assumptions seem to be established within the limits of the resolution attained. The spectra of the two odd isotopes are also assumed to fall together and to have the same nuclear moment, as happens in most known similar cases. The evidence given on the basis of the separation of the components from the center of gravity, on the basis of the spacing, and on the basis of the patterns of the various lines, while not absolutely conclusive, when taken with the intensity measurements of Murakawa, seem to point quite convincingly to a value of $I=1\frac{1}{2}$ for the nuclear moment of the odd isotopes of barium.

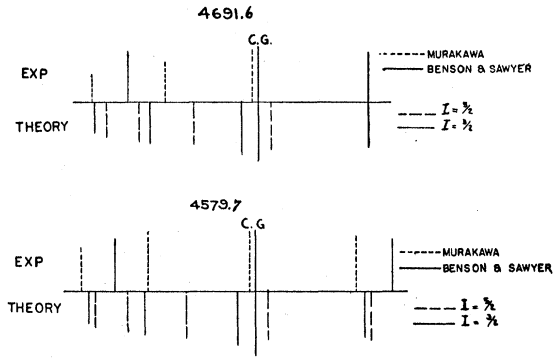

FIG. 4. The observed and expected structures are shown for $6s6p\,^3P_2-5d6d\,^3P_1$, 4691.6, and for $6s6p\,^3P_2-5d6d\,^1D_2$, 4579.7, on the assumption that the structure is due to the $^3P_2$ term. The calculated structures are given both for $I=1\frac{1}{2}$ and for $I=2\frac{1}{2}$ and are drawn to have the same over-all width as the observed patterns.

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The Production of Cosmic-Ray Showers at Great Depths

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Experiments are described which prove the existence of cosmic-ray showers consisting of at least three particles, at depths down to 30 meters of water below sea level. The experiments also show that the number of showers decreases in much the same way with depth as the number of vertical coincidences. Even in the first few meters of water there is no marked falling off in the relative number of showers. The effect of lead on the showers at great depths is also discussed.

EXPERIMENTS by various observers[1] have shown that as one ascends towards the top of the atmosphere the cosmic-ray showers measured by three Geiger counters placed below a thin lead plate, increase much more rapidly than the general radiation. The rate of increase is approximately exponential with an absorption coefficient of about 0.5 per meter of water. If an absorption at this rate continued below sea level, it is clear that a comparatively thin layer of water above the counters would eliminate the showers almost completely. Measurements of the showers at points below sea level have been made by Rossi,[2] Follett and Crawshaw,[3] Pickering,[4] and others. The published results, however, are not in good agreement, and in an attempt to clear up the matter further experiments have been performed by the writer.

As in the previous work, the counters were placed in a tunnel in the Morris Dam of the city of Pasadena. This tunnel goes straight down a 45° slope to the bottom of the lake behind the dam. At the top of the arch of the tunnel the minimum thickness of reinforced concrete varied from about 8 in. to 18 in. as one went down the

[1] Woodward, Phys. Rev. **49**, 711 (1936); Braddick and Gilbert, Proc. Roy. Soc. **156**, 570 (1936); and many others.

[2] Rossi, Ricerca Scient. **5**, 93 (1934).

[3] Follett and Crawshaw, Proc. Roy. Soc. **155**, 546 (1936).

[4] Pickering, Phys. Rev. **47**, 423 (1935).

TABLE I. *Observed counting rates; counts per minute.*

Arrangement of Counters	Position of Counters			
	Water level	9 m water	13 m water	30 m water
Vertical	19.0 ±0.1	14.9 ±0.1	11.8 ±0.1	5.40±0.02
Shower, no lead	1.98±0.03	1.17±0.04	1.10±0.07	0.44±0.01
Shower, 0.6 cm Pb	1.80±0.06	1.1 ±0.13	—	0.51*±0.01
Shower, 1.6 cm Pb	1.92±0.04	1.21±0.02	—	0.49±0.01
Shower, 2.8 cm Pb	—	—	—	0.39±0.03
Horizontal, no lead.	—	—	0.41±0.01	0.18±0.01
Horizontal, 0.6 cm Pb	—	—	—	0.18±0.02
Horizontal, 1.2 cm Pb	—	—	0.33±0.01	0.21±0.03

* For this reading the area of the lead plate was larger than usual.

tunnel. For the experiments two sets of counters were used. One set, measuring showers, was placed with the counter axes horizontal and approximately in the center line of the tunnel. The other set, measuring the vertical intensity, was nearer the side of the tunnel, hence the radiation reaching this set, after passing through the same thickness of water, had to penetrate perhaps twice as much concrete as the radiation reaching the shower set. Readings were taken at four elevations: (1) just above the water level, (2) under about 9 meters of water, (3) under about 13 meters of water, and (4) under about 30 meters of water. At this last station a complication was introduced by the fact that an unknown quantity of rock had fallen on to the top of the tunnel from a slide above the tunnel entrance. Because of the depth of water at this point no attempt was made to estimate the amount of this rock.

The apparatus used in this work was that used in a sea-level study of the variation of the showers with latitude, and has been described elsewhere.[5] Although this equipment worked well on a long ocean voyage, the extreme humidity in the tunnel caused some trouble. The tunnel is primarily for drainage purposes and a great deal of water is carried through it. Under certain wind conditions a thick mist was formed, and this deposited moisture on all parts of the apparatus. The use of a heater helped matters somewhat, but even then trouble occurred. The arrangement of the counters and the lead was the same as that used in the sea level work. At two depths some readings were also taken with one set of counters arranged in a horizontal plane with about 25 cm separation between the outside counters. With this arrangement a thin lead plate could be put over the whole effective area of the counters.

[5] Neher and Pickering, Phys. Rev. (In preparation.)

In Table I the results are summarized. The counting rates in each case are counts per minute. The probable errors have been computed from the total number of counts in each reading. The accidental counting rate is very low, and furthermore it seemed to change with depth in roughly the same manner as the real coincidences, so that no effort has been made to correct for this. In order to show the effects of depth more clearly the readings have been adjusted with those at the highest elevation 1.00 in each case. These relative values are shown in Table II.

We first note that these results show definitely the existence of showers beneath great depths of water. Thus at the greatest depth, where a counting rate of about 0.5 per minute was obtained with the counters in the shower position, removing one of the counters to a great distance so lowered the counting rate that only one count was obtained in a 35 minute run. To exclude the possibility that the coincidences in this shower position were due to ordinary secondaries, for two particles could cause a coincidence with this arrangement, readings were taken with the counters in a horizontal plane. For a single particle to cause a coincidence in this case it has to make an angle of less than 20° with the horizontal. Because of the location of the dam in a deep canyon, such a ray would have to penetrate an enormous thickness of rock, and hence it can be definitely asserted that no single ray could pass through the three counters. There is still the possibility that two particles could cause a coincidence, but again, because of the geometry of the arrangement, this process can be excluded as being too rare to be significant. Hence (with this arrangement of the counters) all real coincidences must be due to showers of three or more particles originating in the material above the counters. Experimentally it was found that at the greatest depth the counting rate with two counters in the horizontal position and the third far removed was

TABLE II. *Relative counting rates.*

Arrangement of Counters	Position of Counters			
	Water level	9 m water	13 m water	30 m water
Vertical	1.00	0.78	0.62	0.28
Shower, no lead	1.00	0.59	0.55	0.22
Shower, 0.6 cm Pb	1.00	0.6	—	0.28
Shower, 1.6 cm Pb	1.00	0.63	—	0.25

0.014 ± 0.003 per minute. With the three counters in position the rate was 0.18 ± 0.02 per minute, about 13 times the chance count. In view of this result it seems reasonable to ascribe most of the coincidences observed with the counters in the usual shower position, to real showers.

With the experimental evidence that showers exist at great depths conclusive, it follows that the shower producing radiation below sea level is not absorbed as fast as the absorption coefficient 0.5 per meter of water would indicate. The above experiments do not allow an accurate estimate of the rate of absorption of the radiation because of the irregular distribution of matter around the counters. However, the data do show that at depths somewhat below sea level the showers vary in much the same way as the vertical radiation. The ratio of vertical counting rate to the maximum shower counting rate at sea level is about 12, and at these points below sea level it is not very different from this value. If it is valid to make this comparison, then support is given to the results of Follett and Crawshaw,[3] rather than to those of Clay.[6] The latter found that the ratio went to twice its sea-level value, while the former observed no marked change.

An obvious feature of these measurements is the fact that the lead caused practically no change in the counting rates at all stations. In a previous paper the writer reported a similar result.[4] However, at that time this was interpreted as meaning that there were very few showers below sea level. The counting rates without lead were tacitly assumed to be solely due to the chance coincidences. The new data show that this was not correct, and that the number of showers produced in the lead is apparently not proportional to the intensity of the shower producing radiation. The reason for this lies in the fact that the concrete above the counters was heavily reinforced so that it could almost be regarded as an iron plate. That this is significant is beautifully shown by Schindler's transition curves,[7] which indicate that with large thicknesses of iron above an electroscope, the addition of lead between the iron and the electroscope causes an immediate decrease in the ionization. At intermediate thicknesses of iron no change is produced with small thicknesses of lead, and with very little iron, the addition of a thin lead plate increases the ionization. Since these transition effects are surely connected with the shower phenomena, one would expect the shower effects measures with Geiger counters to behave in the same way. A direct experiment with counters does indeed show a similar result. Thus, with a certain shower arrangement, the addition of lead above the counters caused a maximum increase in the counting rate of about 5 counts per hour. With 2 cm of iron above the lead the maximum increase was only 2 counts per hour, and furthermore, the thickness of lead required to produce this increase was about half the initial thickness. From these results it is easy to see that at the Morris Dam with the thickness of iron above the counters perhaps 20 cm, the addition of lead above the counters could cause no increase in the counting rate. It is perhaps worth noting that this explanation must almost certainly account for Rossi's results.[2]

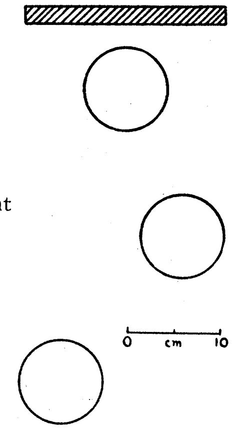

FIG. 1. Arrangement of counters.

Having shown that at depths somewhat below sea level the showers vary in much the same way as the vertical radiation, there still remains the interesting question: what happens in the first few meters of water? Earlier in this paper it was noted that the evidence seemed to indicate that the ratio of showers to vertical rays remained essentially constant at all points below sea level, but the validity of this conclusion rested on a somewhat doubtful comparison. In order to gain further information on the matter the following experiment has been performed.

Three counters were grouped as shown in Fig. 1. The whole arrangement could be rotated about

[6] Clay, Physica **2**, 1042 (1935).
[7] Schindler, Zeits. f. Physik **72**, 625 (1931).

TABLE III. *Observed counting rate; counts per minute.*

Zenith Angle	Counters in Line	Counters in Shower Position		
		No lead	With lead	Due to lead
0	25.6	1.34	3.00	1.66
30°	18.1	0.91	2.07	1.16
60°	6.12	0.44	0.88	0.44
90°	0.87	0.52	0.64	0.12

TABLE IV. *Relative counting rates.*

Zenith Angle	Counters in Line	Counts Due to Lead with Counters in Shower Position
0	1.00	1.00
30°	0.71	0.70
60°	0.24	0.26
90°	0.03	0.07

a horizontal axis parallel to the axes of the counters. By alternately finding the counting rates with and without the 1.6 cm lead plate above the counters, the number of showers from a direction making a given angle with the vertical could be found. By displacing the two lower counters laterally until the three were in a straight line, the corresponding distribution of the single rays about the vertical was readily obtained. The ratio of showers to single rays then gives the relative shower producing efficiencies of rays which have traveled through different thicknesses of air. This assumes of course, that in this case, with only air above the apparatus the number of showers emerging from a 1.6 cm lead plate gives a true picture of the intensity of the shower producing radiation.

The results of these measurements are given in Table III. The counting rates in each case are counts per minute. Again, to show the results more clearly, the relative values are shown in Table IV.

In considering these results due regard must be paid to the fact that the geometrical arrangements in the two cases are different. Undoubtedly the solid angle from which showers are received is larger than the angle from which the straight rays must come, however, the exact size of this angle is difficult to estimate, and for the present investigation it is not necessary. The effect of the larger solid angle is to make the intensity at the larger zenith angles seem larger, and the magnitude of the addition to the intensity is, to a first approximation, proportional to the sine squared of the zenith angle (see, for example, Janossy).[8] Hence in our case the correction is quite small, and will not affect the validity of our conclusions.

At Pasadena the water equivalent thickness fo the atmosphere is about 10.0 meters, so that the additional air at zenith angles of 30° and 60°, is equivalent to 1.5 and 10.0 meters of water respectively. The above data show that with these additional thicknesses of air above the apparatus, the decrease in intensity of the showers measured as described above, is almost exactly equivalent to the decrease in intensity of the single particles. This result again implies that the radiation that can penetrate to depths far below sea level is just as efficient at producing showers as the whole radiation at sea level.

The results of these experiments may be summed up as follows.

(1) The existence of showers at great depths below sea level is well established. The positive result obtained with three counters in a horizontal line is clear evidence of the presence of showers of at least three particles. Furthermore the comparatively large separation of the counters in this case shows that the shower particles are spread over a large solid angle.

(2) The negative result obtained when lead is added above the counters does not show an absence of showers, but is due to the presence of a considerable thickness of reinforced concrete above the apparatus.

(3) At all depths below sea level the decrease in the number of showers is almost exactly equivalent to the decrease in the number of vertical coincidences. Therefore, at a depth below the top of the atmosphere of 10 meters of water, or perhaps a little less than this, the absorption coefficient of the shower producing radiation changes quite rapidly from a value of about 0.5 per meter of water, to a value of about 0.07 per meter of water.

In conclusion I wish to thank the water department of the city of Pasadena for their generous cooperation in making possible the experiments at the Morris Dam. I also wish to acknowledge my appreciation of the financial assistance rendered by the Carnegie Corporation.

[8] Janossy, Zeits. f. Physik 99, 369 (1936).