PHYSICAL REVIEW VOLUME 89, NUMBER 2 JANUARY 15, 1953

Further Results from the Study of Sea-Level Penetrating Showers

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(Received August 21, 1952)

Thirty-five non-ionizing link showers (produced at a 17-g/cm² Pb plate) associated with sea-level penetrating showers are presented. These have their axes oriented toward the origins of the penetrating showers and are believed to be cascade electronic showers initiated by high energy photons, which are probably produced from the decay of π^0 mesons among the penetrating shower particles. The size distribution of these showers is given showing a spread from 2 to 20 particles per shower. The angular distribution of their axes with respect to the penetrating shower axes is also approximately determined.

Showers particles (of the penetrating showers) scattered by Be and Pb at angles greater than 10°, 15°, 20°, 30°, and 40° have been observed. The mean free path against scattering, and the corresponding scattering cross section per nucleon have been estimated in each case. The total scattering cross section per nucleon is of the order of magnitude of several millibarns. This figure may be compared with the total theoretical meson-nucleon scattering cross section calculated from pseudoscalar or scalar theory for meson energy equal to several times its rest energy. Perhaps, it is several times smaller than the total experimental nucleon-nucleon scattering cross section for, say, 300-Mev proton energy. Our experimental cross section probably represents the combined effect of meson-nucleon and nucleon-nucleon scattering.

1. INTRODUCTION

In previous communications[1] we have presented our experimental results obtained at sea level for (1) the multiplicity distribution of the penetrating showers produced in Be, C, and Pb, (2) the angular distribution of the shower particles, and (3) the mean free path against total absorption in Be and Pb of the shower particles. In order to complete our preliminary study, we should like to report from further analysis, the following two more types of results: (*a*) the non-ionizing link showers associated with penetrating showers and (*b*) the scattering of the penetrating shower particles. These two types of events are very rare and, consequently, the statistics are bound to be poor. It is hoped, however, that they may help to throw some light into the nature of the penetrating-shower particles produced at sea level.

2. NON-IONIZING LINK SHOWERS ASSOCIATED WITH PENETRATING SHOWERS

Electronic components associated with penetrating showers have been observed by several workers.[2] These have been interpreted as due to the decay in flight, into two photons, of neutral pi-mesons which are assumed to be produced among the particles of the penetrating showers. However, in most of these cases the pictures are so complicated that it is not possible to decide whether the electrons arise from gamma-rays. The electrons very often appear to have come from the same place as the penetrating-shower particles. In the study of penetrating showers produced in Be, C, and Pb at sea level, we have found, in addition to the mixed showers of the above type, 35 missing-link showers at the bottom Pb plate (17 g/cm²) from about 350 penetrating showers.[1] Each of these showers has its approximate axis pointing toward the origin of the penetrating shower with no observable producing particle. A few pictures similar to these have also been reported recently by other workers.[2] The shower particles in all of the 35 cases have wide angular spread (most of the cases around 60°, some as large as 150°). In each shower all of the tracks show minimum ionization and some suffer from multiple scattering in the gas. Therefore, it is believed that these non-ionizing link showers are electronic showers.[3]

Table I. Size distribution of the non-ionizing link showers. N is the number of charged particles per shower.

Picture quality \ N	2	3	4	5	6	7	8	9	10	13	14	17	20
A showers	1	4	2	1	3		1	1	1			1	1
B showers	1	3	3	3	2	1		2	1	1	1		1
Total	2	7	5	4	5	1	1	3	2	1	1	1	2

Figures 1 and 2 are two examples of these events. Figure 1 shows a penetrating shower of three particles produced from the second Be plate. The two particles on the left-hand side pass through the Pb plate, while the one on the right suffers from backward scattering, moving upward to the front glass plate of the chamber. A missing-link shower of four particles is seen from the

* Supported in part by the Purdue Research Foundation and Institute Nacional de la Investigacion Cientifica, Mexico.

[1] Chang, Del Castillo, and Grodzins, Phys. Rev. 84, 582, 584 (1951). In the 11-month study approximately 8000 pictures were taken. About 350 showed penetrating showers from the desired substances, of which 220 were suitable for analysis and have been published. More than 20 percent of the 350 showers are seen to contain electronic components, as determined by the multiplication at the Pb plate. Out of these, 35 are the missing link showers produced at the bottom Pb plate, 10 each associated with C and Pb showers and 15 with Be showers.

[2] For earlier references, see G. D. Rochester and W. G. V. Rosser, Repts. Progr. Phys. (London) **14**, 249 (1951). Also Gregory, Rossi, and Tinlot, Phys. Rev. **77**, 299 (1950); **81**, 675 (1951).

[3] As estimated roughly from the cascade-shower theory, the energy of the initiating photons varies from about 50 Mev to about 10 Bev. The best way would have been to count the number at maximum but, with only one thick Pb plate in the chamber, this could not be done.

TABLE II. Distribution of approximate projected angle in degree (at the origin of the penetrating shower) between the axes of the non-ionizing link and the penetrating showers.

Picture quality \ Degree	0–3	4–7	8–11	15	20
A showers	10	5		1	1
B showers	11	6	1		
Total	21	11	1	1	1

Pb plate, with its approximate axis pointing toward the origin of the penetrating shower. Figure 2 is a similar picture having a much larger electronic shower of at least 17 particles. The penetrating shower is produced again in the second Be plate, and all the three shower particles pass through the Pb plate. The large electronic shower with no observable initiating particle appears under the Pb plate on the left of the penetrating shower. The apex of this electronic shower is clearly separated from all of the particles of the penetrating shower, as can easily be seen in an enlarged print. It is to be noted that in both cases no heavily ionizing particles are seen among the particles of the missing-link showers, that the thin tracks have large angular spread, and that some show multiple scattering in the gas. It is, therefore, extremely unlikely that they are nuclear events.

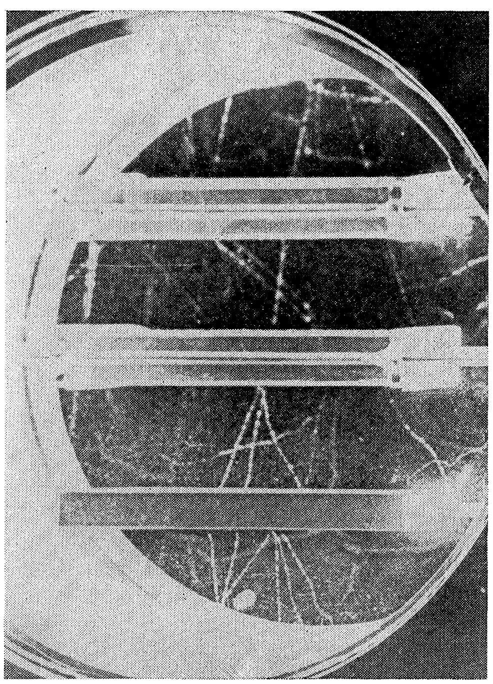

FIG. 1. A penetrating shower of 3 particles produced in Be_2. One of the 3 particles is scattered upwards to the glass window, and the other two pass through the Pb plate (17 g/cm²). A non-ionizing link shower of 4 particles occurs at the Pb plate (on the right), which may be interpreted as due to decay of a neutral pi-meson into 2 photons. One of the two photons is converted into the cascade shower.

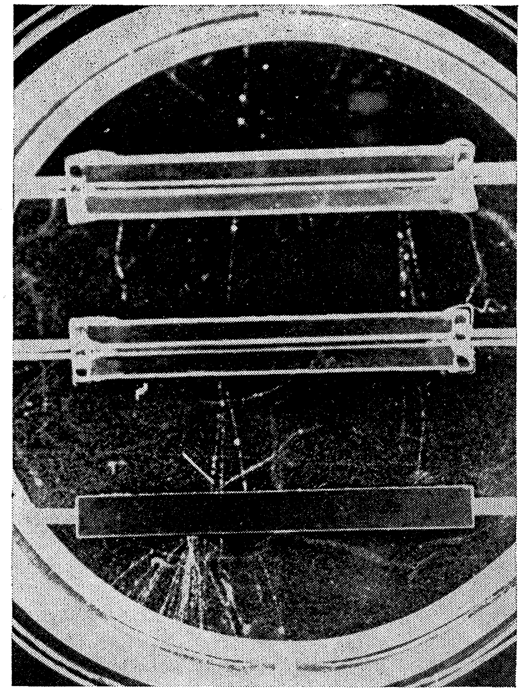

FIG. 2. An event similar to that shown in Fig. 1. All of the three penetrating-shower particles pass through the Pb plate. A missing link shower of at least 17 particles appears under the Pb plate (on the left) which may be similarly interpreted as in Fig. 1.

The size distribution of these showers is shown in Table I. The size of a shower may represent the energy[3] of the initiating photon, though for a given energy there is a large fluctuation in the number of the particles. It is seen that some showers have particles as many as 20. Table II shows the angular distribution of the missing-link shower axis from the penetrating-shower axis. The figures for the projected angles were only approximately determined because of the difficulty in defining the two shower axes. However, these two tables are good enough to indicate the angular (with respect to penetrating-shower axes) and energy spread of the initiating photons.

Because of the relatively small surface of the Pb plate in our arrangement, the chance to observe both photons from each decay is small.[4] This was particularly true when the penetrating showers and hence the neutral mesons were produced in the Pb or C which was placed above the chamber. So far, we have observed only one case where two missing-link showers are associated with a penetrating shower produced in Be with both their approximate axes pointing toward the origin of the penetrating shower. Unfortunately this picture is of poor quality. Several pictures have also been observed, where the non-ionizing link showers do

[4] For discussion on neutral mesons and related problems, see C. F. Powell, Repts. Progr. Phys. (London) **13**, 402 (1950), and B. Rossi, *High Energy Particles* (Prentice-Hall, Inc., New York, 1952).

TABLE III. Scattering cross section of penetrating-shower particles at different angles.[a] θ=projected angles of scattering in degrees larger than specified; N=No. of particles scattered at angles larger than specified; L=mean free path in g/cm²; σ=cross section per nucleon in millibarns.

Showers	Scat-terer	θ	>10°	>15°	>20°	>30°	>40°	No. of traversals
C−Pb		N	5	4	2	0	0	405
	Be	L	780	980	1950			
		σ	2.1	1.7	0.8			
		N	12	9	9	7	2	302
	Pb	L	430	570	570	740	2580	
		σ	3.9	2.9	2.9	2.3	0.7	
Be		N	9	8	3	0	0	142
	Pb	L	270	300	810			
		σ	6.2	5.6	2.1			

[a] The theoretical total cross section for meson-nucleon scattering at meson energy $\sim 5\mu c^2$ is as follows.
Pseudoscalar theory: $\sigma\sim 1$ millibarn, for $g^2/\hbar c\sim 1$.
Scalar theory: $\sigma\sim 3$ millibarn, for $g^2/\hbar c=2.39\mu/M$ as determined from deuteron binding energy.

not have their axes oriented toward the origins of the penetrating showers. These could be due to decay at a distance (of very fast π^0 mesons) from the penetrating-shower origins. No attempt has been made to correlate these showers with the observed penetrating showers, because in each picture only one such non-ionizing link shower has been found.

From the solid angle of detection and probability of conversion of the photons, a crude estimate shows that the number of π^0 mesons is of the same order of magnitude as (though smaller than) that of the charged shower particles.

3. THE SCATTERING OF THE PENETRATING-SHOWER PARTICLES

Measurement has been carried out of the large angle scattering of the penetrating-shower particles previously reported,[1] in the hope that more knowledge may be obtained about the nature[5] of the shower particles produced particularly at sea level. The showers produced in C and in Pb have been grouped together to form the "C−Pb showers," because in these two elements they have been produced and propagating dowanwards under similar conditions. Some of the shower particles have been scattered by the two Be plates (9.6 g/cm² all together) and others by the Pb plate (17 g/cm²). The showers produced in the two Be plates have been put together as the "Be showers"; in this case, scattering greater than ten degrees has not been observed at the second Be plate but only at the Pb plate.

The particles scattered at angles larger than 10°, 15°, 20°, 30°, and 40° have been observed. The mean free path against scattering and the corresponding scattering cross section per nucleon have been estimated in each case from the number of particles so scattered and the number of traversals. The number of traversals in each element does not include those particles which are absorbed catastrophically. The results are presented in Table III. It is seen that all the cross sections lie between 10^{-26} and 10^{-27} cm²/nucleon. The figures for the mean free path and hence those for the cross section must not be taken too seriously because of low statistics. The angles for the two particles of C−Pb showers scattered by Pb at angles greater than 40° as listed are actually about 50° and 70°, respectively. We have also observed two events of backward scattering. One particle of a 3-particle Be shower has been scattered at about 130° and another of a 2-particle Pb shower at about 150°, both occurring at the Pb plate. These last two events have not been included in Table I.

It is very probable that the scattering events at the plates as described above are due to single nuclear scattering (by Coulomb or nuclear force) instead of multiple Coulomb scattering as may be judged from the fact that the scattering angles are fairly large yet the ionization of the scattered particles is only about minimum. Most of the particles of the penetrating showers must be nonelectronic, except those electrons found in the mixed showers as identified by the multiplications at the 17 g/cm² Pb plate. It may also be noticed that none of the particles of the C−Pb showers, which had been already scattered by Be, produces any multiplication at the Pb plate. Furthermore, nearly all the scattered particles, including those two backward scattered ones, do not show appreciable multiple scattering in the gas. Therefore, most of the charged shower particles as observed in the chamber must be either protons or π-mesons (or some other mesons) or both. For these particles, if the scattering process in the plates were multiple, the energies of the particles scattered at such angles must be low enough that their tracks should have ionization much greater than the minimum value. However, all the scattered particles (in fact, all the shower particles) appear to have minimum ionization. This seems to indicate, therefore, that most, if not all, of the scattering events are due to single nuclear scattering (more probably by nuclear force) instead of multiple Coulomb scattering, unless the charged shower particles were electrons which as mentioned above are improbable.

It may be interesting to see how the scattering cross sections obtained in our experiments are compared with some theoretical values for meson-nucleon scattering and with that of nucleon-nucleon scattering. Our results for scattering in Be at angles larger than 10° and 15°, respectively, are of the same order of magnitude as those obtained at high altitude by Green[6] for carbon at the corresponding angles. However, our results for scattering in Pb at angles larger than 15° are 10 to 20 times larger than that (at high altitude, too) of Fretter[7] for the same material and angular range. The results from our experiments at sea level seem to be in closer

[5] O. Piccioni, Phys. Rev. 77, 1 (1950).

[6] F. R. Green, Phys. Rev. 80, 832 (1950).

[7] W. B. Fretter, Phys. Rev. 76, 511 (1949).

agreement than Fretter's with the theoretical meson-nucleon scattering cross sections calculated from certain meson theories for reasonably estimated meson energies. For example, our experimental cross sections are roughly comparable with the theoretical values of the pseudoscalar theory[8] for meson energies several times its rest energy, when the coupling constant (or the nucleon area for mesons) is properly chosen.[9] Moreover, they are also compatible with the values obtained from the scalar theory for similar meson energies, if in this latter case the coupling constant is determined from the binding energy of the deuteron. On the other hand, the total scattering cross sections obtained from experiment for nucleon-nucleon scattering at several hundred Mev proton energies would probably be several times larger than the values obtained from Table I. Closer comparison is not very meaningful at present because of the unknown momentum spectrum of the shower particles and because of the poor statistics. All one can say at present is: The sea-level penetrating-shower particles are very probably both mesons (of some kind) and protons.

Experiments with two large rectangular cloud chambers (16 in.×16 in.×14 in. each), one above the other, are being started at Purdue, in which efforts are being made to identify the shower particles, to reduce discriminations in the measurements of the multiplicity and angular distributions, and to observe multiplicity of penetrating showers produced from liquid hydrogen to be put above the top chamber.

In conclusion, we are grateful to Princeton University for the apparatus used in this work, which one of us (W. Y. C.) and his co-workers built at Princeton, and to our colleagues at Purdue, particularly R. M. Whaley, K. Lark-Horovitz, and R. Haxby, for their interest and support in these experiments.

[8] M. Peshkin, Phys. Rev. **81**, 425 (1951).
[9] H. A. Bethe and R. R. Wilson, Phys. Rev. **83**, 690 (1951).

PHYSICAL REVIEW VOLUME 89, NUMBER 2 JANUARY 15, 1953

Production of Negative Ions and Noise in Negative Ion Beams*†

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(Received October 7, 1952)

In a search for high current sources of low energy (≈100 ev) negative atomic ions of hydrogen and oxygen, five types of sources were examined. The most promising practical source for both H^- and O^- was found to be the dc glow discharge from which beams of 10^{-7} ampere of either ion could be drawn. Hot cathode arc discharges yielded H^- currents of 7×10^{-8} ampere. Rf discharges, hollow cathode discharges, and sources involving the Arnot effect seem inferior as high current sources.

Two results were found which are of interest both for the mechanism of the discharge and for the production of negative ions. First, the most copious source of negative ions seems to be the anode side of well-formed striations such as are present in the two superior sources. Second, when either of these sources is used, the beam noise in the low audiofrequency range is much greater than shot noise and is related to fluctuations in the striations.

I. INTRODUCTION

IN the past twenty years, considerable attention has been given to certain negative ions. The theory of the opacity of the solar atmosphere, evolved primarily by Wildt and Chandrasekhar, has as its major thesis the absorption of light by negative atomic hydrogen ions (H^-). It is calculated that the absorption spectrum of these ions is a broad continuum in the visible and infrared light regions and that the presence of these ions in the sun's atmosphere would slightly alter the continuous spectrum of the sun from a blackbody spectrum to one such as is actually found.[1]

In the realm of upper atmosphere physics, attention has been directed to the negative atomic oxygen ion (O^-). The assumption of the presence of these ions in the ionosphere has been used in the past to account for the apparent coefficient of recombination between positive ions and electrons, the night-time persistence of the ionized layers, and the appearance of the green and red lines of the atomic oxygen spectrum in the air-glow or night sky spectrum.[2] For the most part, information about these ions has been acquired from theory. In the case of H^-, calculations appear to be trustworthy; for here the arbitrarily accurate Hylleraas wave function for the ion in the ground state can be used. In the case of O^-, exact calculations of quantities relevant to upper atmosphere physics are frequently replaced by little more than considered guesses.

It is clear that direct laboratory measurements on negative ions are desirable—in the case of H^-, to check

* The material in this paper is a portion of a thesis submitted to Harvard University in partial fulfillment of the requirements for the Ph.D. degree.
† This work was supported in part by the Office of Naval Research and by the Milton Fund of Harvard University.
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[1] S. Chandrasekhar, Revs. Modern Phys. **16**, 301 (1944); A. J. Deutsch, Revs. Modern Phys. **20**, 388 (1948); H. S. W. Massey, *Negative Ions* (Cambridge University Press, Cambridge, 1950), second edition, p. 122.

[2] H. S. W. Massey, reference 1, pp. 107–122; S. K. Mitra, *The Upper Atmosphere* (Royal Asiatic Society of Bengal, Calcutta, 1947), Chapters VI, X.

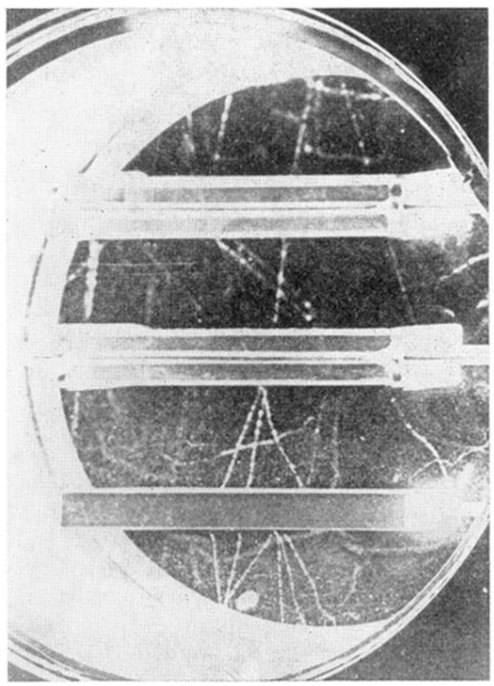

FIG. 1. A penetrating shower of 3 particles produced in Be_2. One of the 3 particles is scattered upwards to the glass window, and the other two pass through the Pb plate (17 g/cm²). A non-ionizing link shower of 4 particles occurs at the Pb plate (on the right), which may be interpreted as due to decay of a neutral pi-meson into 2 photons. One of the two photons is converted into the cascade shower.

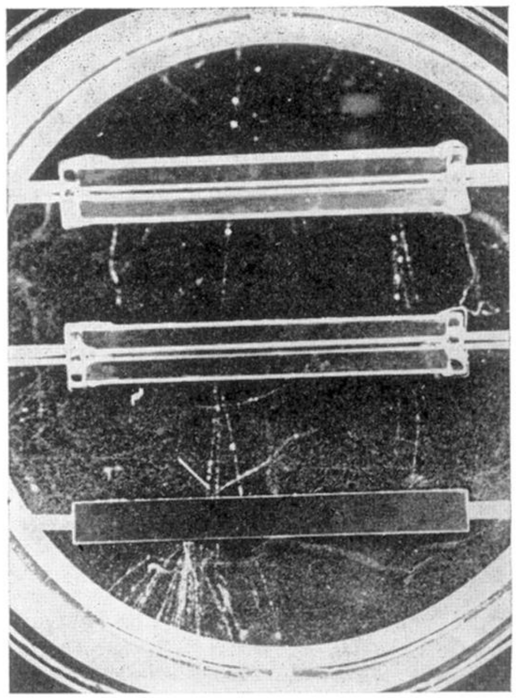

FIG. 2. An event similar to that shown in Fig. 1. All of the three penetrating-shower particles pass through the Pb plate. A missing link shower of at least 17 particles appears under the Pb plate (on the left) which may be similarly interpreted as in Fig. 1.