the high photoelectric absorption coefficient in sodium iodide below this energy.[4]

The stilbene beta-pulses were shaped with a shorted delay line to a width of 0.03 μsec, and an over-all resolving time of 0.11 μsec was obtained in the coincidence circuit.

The angular correlation measured is shown by the open circles in Fig. 2.

The theoretical angular correlation as given by Wang Chang and Falkoff is

$$d\Phi(v,\,\theta,\,\omega)/d\Omega=2\beta^2\sin^2\theta/2\pi\omega(1-\beta\cos\theta)^2,$$

the probability per unit solid angle for an electron with velocity v to emit a quantum of a frequency ω at an angle θ.

This was averaged over an experimental beta-distribution and over the range of detection of the gamma-ray:

$$\frac{d\Phi}{d\Omega}=c\int_0^{E_{\beta\max}}\int_{40\text{ kev}}^{E_\beta}\frac{N(E_\beta)}{E_\gamma}\frac{\beta^2\sin^2\theta}{(1-\beta\cos\theta)^2}E_\gamma dE_\beta$$
$$=c\int_0^{E_{\beta\max}}\ln(E_\beta/40\text{ kev})N(E_\beta)\frac{\beta^2\sin^2\theta}{(1-\beta\cos\theta)^2}dE_\beta,$$

the probability per unit solid angle for a quantum of energy greater than 40 kev to be detected at an angle θ.

The result of numerical integration of the above expression was normalized to the experimental result at 30°. It can be seen that the data are in excellent agreement with the theory.

A recent article[5] on the intensity and energy distribution of inner-bremsstrahlung mentioned a preliminary experimental affirmation of the angular correlation as found in this work.

[1] T. B. Novey, Phys. Rev. **78**, 66 (1950).

[2] J. K. Knipp and G. E. Uhlenbeck, Physica **3**, 425 (1936). See also F. Bloch, Phys. Rev. **50**, 272 (1936).

[3] C. S. Wang Chang and D. L. Falkoff, Phys. Rev. **76**, 365 (1949).

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[5] L. Madansky and F. Rasetti, Phys. Rev. **83**, 187 (1951).

On the Interaction in Pb of the Secondaries Produced in Penetrating Showers*

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DURING the months from August, 1949, to January, 1950, the cloud-chamber assembly sketched in Fig. 1 was operated at Echo Lake, Colorado (altitude 3260 m, average pressure 706 g cm^{-2}), in order to measure the collision mean free path (m.f.p.) in Pb of the secondary particles produced in penetrating showers and to investigate the nature of the penetrating particles in extensive air showers.

Here we give the results of the first experiment. The two chambers, 24 in.×12 in.×12 in., were filled with argon at about atmospheric pressure, and each contained five ½-inch Pb plates; they were located one above the other and separated by a slab of Pb 6 in. thick. Stereoscopic pictures were taken with a single camera on 70-mm film. The master pulse triggering the expansions was generated whenever a coincidence $2A+3B$ among two or more of the counters of tray A and three or more of the counters of tray B was registered.

In the analysis of the pictures obtained, only the cases were considered in which a penetrating shower was generated either in the plates inside the upper chamber or in the 6-in. absorber between the chambers, showed in the lower chamber penetrating particles recognizable as coming from a common center, and was not accompanied by dense air showers. Among the particles belonging to the showers thus selected, the ones considered for the measurement of the collision mean free path were required to fulfill the following conditions: (a) to be minimum ionizing and to be scattered less than 1° in crossing any plate (except for cases judged to be nuclear scatterings, when the particles were deflected less than 1° in every plate but one, and more than 10° in that one plate) and (b) to cross at least the middle three plates of the lower chamber in the case of non-interacting particles. In the case of interacting particles the direction of the particle in the space was determined by reprojection on translucent screens, and was required to be such as to cross the middle three plates in the illuminated region. Since particles ionizing 2 times minimum would have been recognized, and since scattering angles larger than 1° were measurable, condition (a) ruled out particles of momentum smaller than ∼Mc or ∼2 Bev/c, whichever is larger.

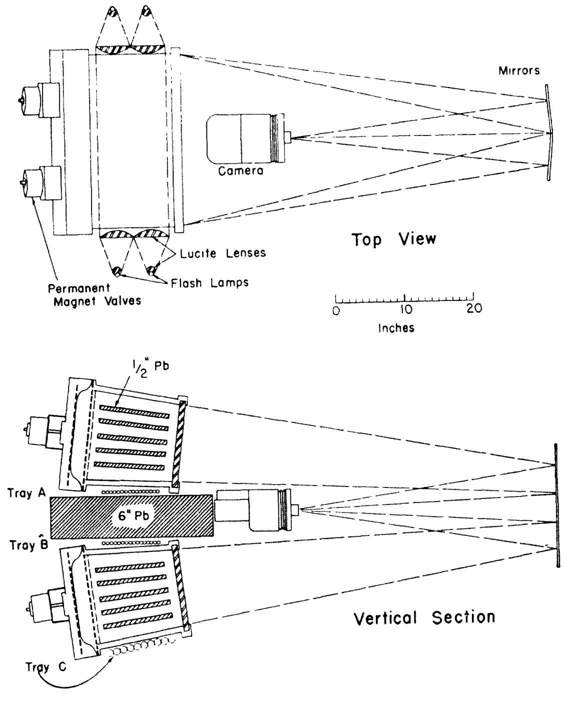

FIG. 1. Diagram of dual cloud-chamber assembly.

The observed number of plate traversals without interaction by particles fulfilling the conditions (a) and (b) was $N=1977$, while the number of interactions observed was $\Delta N_0=91$. If the condition (b) is modified so as to consider the traversals and interactions in one plate only if the particle is observed to traverse at least the preceding plate,[1] the total number of such traversals without interaction is $N=2568$, and the number of observed interactions $\Delta N_0=111$. The observed collision m.f.p. Λ is then

$$\Lambda=h/\ln(1+\Delta N_0/N)=\begin{cases}354\pm39\text{ g cm}^{-2}\text{ of Pb,}\\376\pm40\text{ g cm}^{-2}\text{ of Pb,}\end{cases}$$

where $h=15.9$ g cm^{-2} is the thickness of the Pb plates averaged over the zenith distribution of the particles. The errors given are the statistical ones. The two values practically coincide.

Λ is certainly larger than the real collision m.f.p., λ, because an appreciable number of interactions occurring inside the plates do not give rise to secondaries of energy sufficient to escape from the plates and be seen.

The correction can be evaluated with the aid of Fig. 2, where is plotted the number of interactions observed to start at various depths inside the plates.[2] The point where the interaction occurred inside the plates was identified with the common point of origin of the secondary tracks. From Fig. 2 it clearly appears that many of the interactions occurring inside the plates were lost. An examination of the particles emitted shows that the ratio of the number of heavy prongs to that of light prongs sharply decreases when the interaction occurs more deeply inside the plate; this indicates that the less energetic interactions are more likely

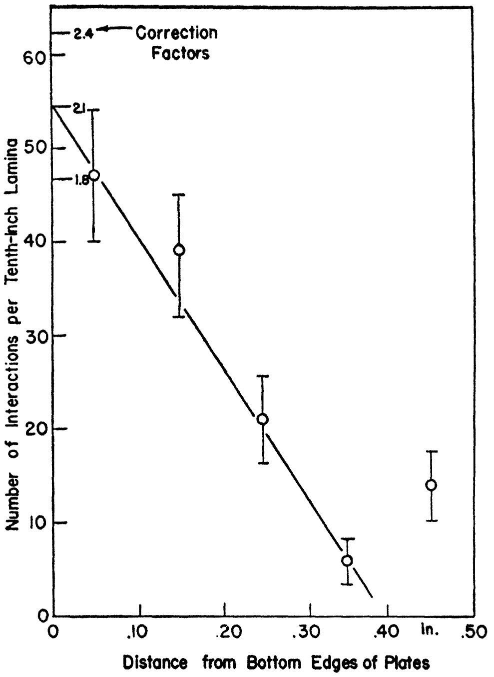

FIG. 2. Distribution of observed nuclear interactions in the lead plates.

to be lost. The factor K by which it is necessary to multiply ΔN_0 in order to obtain the real number of interactions, ΔN, in our case turns out to be $K=2.1\pm0.3$. The uncertainty in K arises from both the statistical errors and the extrapolation. With this correction we deduce λ to be

$$\lambda=172\pm29 \text{ g cm}^{-2} \text{ of Pb},$$

a value quite close to the geometric m.f.p.

The value of K is expected to decrease strongly when the thickness of the absorber is decreased. With plates of $\frac{1}{4}$-in. Pb one can anticipate a value $K=\sim1.1$. In fact, Gregory and Tinlot[3] with plates of $\frac{1}{4}$-in. Pb found $\Lambda=172\pm20$ g cm^{-2}.

In the past years several authors (see bibliography in the paper of Gregory and Tinlot) obtained much higher values for λ in Pb; probably the reason for the discrepancy with the present determination is due to the fact that generally they used thick absorbers inside the chambers and did not select energetic secondaries, hence making the number of missed interactions too high to permit accurate correction. The same conclusion was reached by Lovati *et al.*,[4] who found a value $\Lambda=200\pm50$ g cm^{-2} Pb using plates 0.5 mm thick.

* This work was supported in part by a grant from the Research Corporation.

[1] This prevents consideration of interactions and traversals in the top plate of the lower chamber, but makes the discrimination against electrons and low energy particles more effective than if all single traversals and interactions were counted.

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[3] B. P. Gregory and J. H. Tinlot, Phys. Rev. **81**, 675 (1951).

[4] Lovati, Mura, Succi, and Tagliaferri, Nuovo cimento **8**, 271 (1951).

A Dual Cloud-Chamber Study of Extensive Air Showers*

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DURING the fall of 1949 the dual cloud-chamber assembly described in the preceding letter was operated at Echo Lake, Colorado, to obtain photographs of penetrating particles in extensive air showers. The counter tray A, indicated in Fig. 1 of the previous letter,[1] was removed; and two unshielded trays, X and Y, each of about 500-cm^2 area, were placed at distances of about two meters from the cloud-chamber assembly. About 400

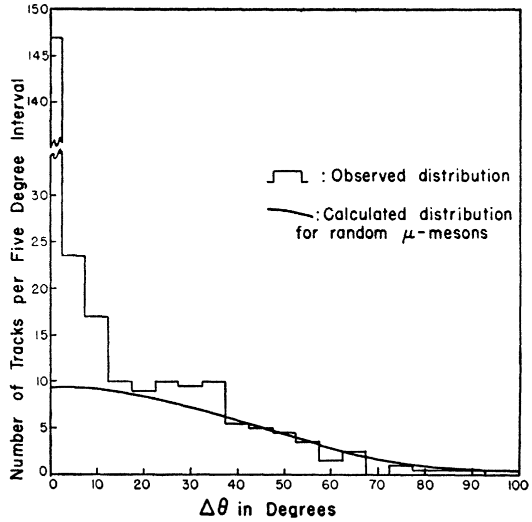

FIG. 1. Distribution of deviations, Δθ, between the projected zenith angles of penetrating particles and their respective extensive air shower axes. Note that the ordinate scale has been broken to show the relatively high peak at small deviations.

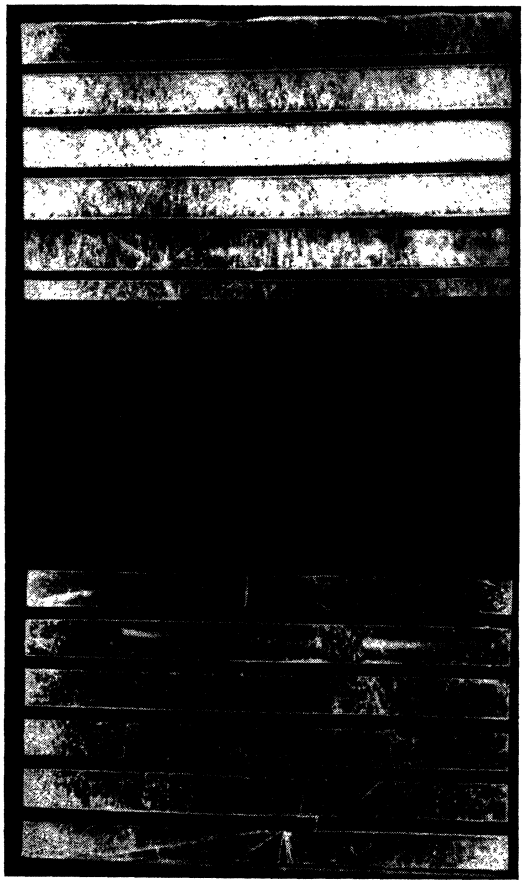

FIG. 2. An extensive air shower containing a coherent particle generating the nuclear cascade beginning in the fifth plate of the upper chamber.