On the Knock-On Secondaries of Penetrating Particles

W. W. Brown, A. S. McKay, E. D. Palmatier*
Cornell University, Ithaca, New York

(Received March 29, 1949)

The knock-on secondaries of penetrating particles emerging from Pb plates (15 g cm^{-2}) have been investigated by cloud chamber and by counter telescope. The frequency of occurrence and the observed spatial distribution of the secondaries with respect to the primary penetrating particles have been found to be in agreement for the two different methods. Further data are presented on the back scattering of secondaries in Pb plates and on the emergence of secondaries from thin pieces of wood and counter walls. The possible effects on counter experiments are discussed briefly.

INTRODUCTION

During the course of a recent measurement by one of us on the total intensity of cosmic radiation, it was observed that a large fraction of the so-called side shower correction (obtained by the usual method of displacing the center counter out of the solid angle of the telescope) appeared to originate in the walls (0.11 g cm^{-2} of Al) of the top counter of the telescope and in the thin wooden roof (0.4 g cm^{-2}) over the telescope. In order to correct for this effect, we have investigated the frequency of occurrence and the spatial distribution, relative to the primary penetrating particle, of secondaries emerging from various materials. The investigation was made with both cloud chamber and counter telescope in an attempt to reduce the possibility of misinterpretation of the data.

A. CLOUD-CHAMBER MEASUREMENT

1. Experimental Method

A cylindrical argon-filled cloud chamber of 11-inches diameter and $3\frac{1}{4}$-inches depth was operated at 1.2 atmospheres and contained five lead plates (7 inches $\times 3\frac{1}{4}$ inches$\times\frac{1}{2}$ inch) in which the production of the secondaries was observed. The expansion of the chamber was counter controlled by a threefold coincidence telescope consisting of one counter (A) immediately above the chamber, a second counter (B) immediately below the chamber and a tray of counters (C) under five inches of lead placed below the second counter. The disposition of the chamber, counters, and lead is shown to scale in Fig. 1. The effective areas of the counters A, B, and the tray C are 1 inch$\times$5 inches, 1 inch$\times 2\frac{3}{4}$ inches, and 3 inches$\times$16 inches respectively. The telescope defines a beam of penetrating particles, mostly mesons at sea level, lying within the well illuminated portion of the cloud chamber. The photographs were not stereoscopic, hence only the projection of each track on the plane of the cloud chamber could be observed. The small maximum angular deviation of a meson path from the plane of the chamber, indicated by the dashed lines in the side view (Fig. 1) ensures that all secondaries making true angles of 75° or less with their primary will have visible tracks of sufficient projected length for a good measurement of the projected angle between primary and secondary. Furthermore it allows us to consider the primaries as lying in this plane without introducing any appreciable error.

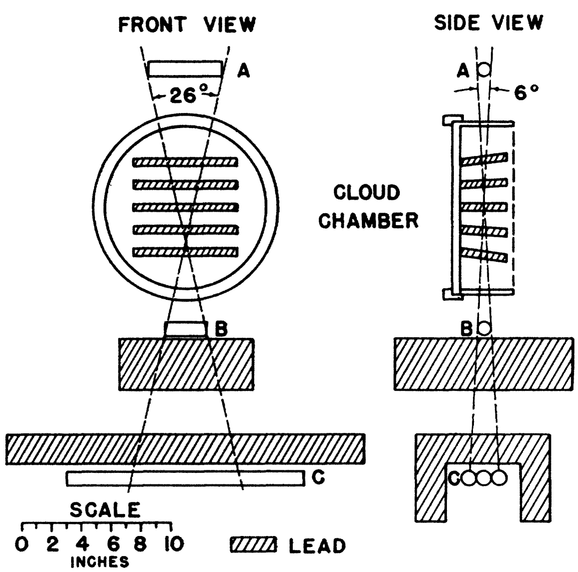

Fig. 1. Arrangement of cloud chamber and triggering telescope used in Part A.

It is expected that secondaries lying in a small cone around the line of sight of the camera and making an angle greater than 75° with the primary will be missed, as well as secondaries whose projections are superimposed on that of the primary. However, it will be apparent from the observed distribution and the geometry of the telescope that these effects are insignificant.

2. Results and Discussion

Out of 1200 photographs taken at an elevation of 260 m, 900 showed single mesons free from the extraneous electrons of local or extensive showers and suitable for measurement. The events observed were classified in accordance with the headings of Table I, the arbitrary division into high and low energy secondaries (columns 4 and 5 of Table I) being arrived at by defining as a low energy secondary any secondary which in the interval between two plates deviated by 10° or more from

* Now at University of North Carolina, Chapel Hill, North Carolina.

its initial direction of emergence. Since an electron with an r.m.s. projected deviation of 10° has about 1 Mev energy, this may be taken as the energy boundary between the two groups.

The observed total number of knock-ons accompanying mesons emerging from lead is in close agreement with the results of Hazen who used 0.7 cm of Pb.[1] Hazen has shown that of the secondaries emerging from 0.7 cm of Pb only a few percent are capable of penetrating an additional 0.7 cm of Pb; hence equilibrium has essentially been reached at this thickness and the comparison is valid.

Whenever a secondary did occur, the projected angle between its direction and that of its primary was measured to the nearest degree. The latter data are summarized (by 10° intervals) for penetrating particles emerging from or entering into a $\frac{1}{2}$-inch lead plate, in Figs. 2 and 3 respectively. The histograms do not represent the angular distribution at the point of production, but rather the distribution resulting after each secondary has undergone an amount of scattering in the lead, depending on its initial energy, direction, and position of production. If $N_1(\theta)d\omega$ is the probability that a knock-on will emerge from the lead into the solid angle $d\omega$, making an angle θ with its primary, then the probability of its occurring in the projected angular interval β to $\beta+d\beta$ is given by

$$N_2(\beta)d\beta=4\int_0^{\pi/2} N_1(\theta)\cos\alpha d\alpha d\beta$$

where $\cos\theta=\cos\alpha\cos\beta$ (see Fig. 4A). If we assume that $N_1(\theta)\sim\cos^n\theta$ then $N_2(\beta)=k\cos^n\beta$ where k is a constant depending on n. The curves of Fig. 2 are plots of $\cos^n\beta$ for $n=2$, 2.5, and 3, normalized so that the area

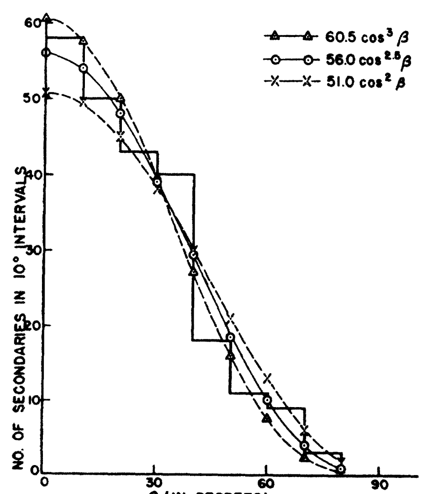

FIG. 2. Distribution in projected angle, β, between mesons (of energy > 200 Mev) and the knock-on secondary electrons they produce in a $\frac{1}{2}$-inch lead plate which are capable of emerging in the forward direction.

[1] W. E. Hazen, Phys. Rev. 64, 7 (1943).

TABLE I. Knock-on electrons of mesons observed in cloud chamber.

Event	Number of events observed	Number of accompanying knock-ons observed	High Energy knock-ons per meson	Low Energy knock-ons per meson	Total number of knock-ons per meson
Emergence of a meson from a lead plate	3364	232	0.065	0.004	0.069±0.005*
Entry of a meson into a lead plate	3304	59 (back scattered)	0.014	0.004	0.018±0.002
Traversal of gas between 2 lead plates	3523	119	0.0035	0.0305	0.034±0.003

* Errors quoted are statistical standard deviations only.

under each curve is equal to that under the histogram. It is apparent that $n=2.5$ gives a satisfactory fit for an empirical relationship of this form.

Some further observations concerning the nature and behavior of the secondaries follow.

(a) The 232 knock-ons observed, occurred as 201 singles, 11 pairs emerging from the same plate and 3 triplets, a distribution not differing significantly from what would be expected if the events were independent of one another.

(b) Three of the singly occurring knock-ons had sufficient energy to produce a small cascade through the next three plates with a maximum of 3 to 6 electrons after traversing $\frac{1}{2}$ to $1\frac{1}{2}$ inches of Pb. In one of the triplet cases, an electron produced a small cascade containing 4 electrons after $\frac{1}{2}$ inch of lead. In all of these instances the direction of the shower-producing electron made a projected angle of less than 10° with that of its primary.

(c) 140 of the knock-ons produced by emerging mesons were observed to impinge on the next lead plate and of these, 43 were scattered back into the gas. The large number of back-scattered knock-ons occurring when a meson enters a lead plate is thus understandable.

(d) Of the knock-ons produced in the gas, the shortest delta-ray tracks counted were of about 3-mm length (equivalent to 0.59 g cm^{-2} of Al). Since a beta-ray of this range in aluminum has an energy of about 20 Kev[2] we have this rough lower limit of the energies of the secondaries produced in the gas that were counted. In traversing the gas between two plates a meson travels through approximately 3.0 cm of argon at 90 cm Hg and 30°C. The 119 knock-ons produced in the total observed path length (21.0 g cm^{-2} of argon) is, in view of the uncertainty of the low energy limit, in agreement both with Seren's[3] value of 143 knock-ons with tracks longer than 2 mm produced in 24.2 g cm^{-2} of argon and a value of 3.4 knock-ons per g cm^{-2} with tracks longer than 3 mm calculated from the Rutherford formula.

B. COUNTER TELESCOPE MEASUREMENT

1. Experimental Method and Results

The arrangement of counters, counter shields and material (S) for the production of secondaries is shown in Fig. 5. All the counters were of a standard construction described elsewhere,[4] h, b and c were of brass, while the remainder were of aluminum with a wall thickness of 0.11 g cm^{-2}, an external diameter of one

[2] F. Rasetti, *Elements of Nuclear Physics* (Prentice-Hall, Inc., New York, 1936).
[3] L. Seren, Phys. Rev. 62, 204 (1942).
[4] D. R. Corson and R. R. Wilson, Rev. Sci. Inst. 19, 225 (1948).

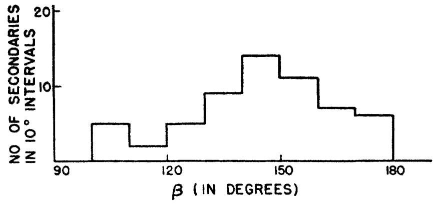

FIG. 3. Distribution in projected angle, β, between mesons (of energy > 200 Mev) and the knock-on secondary electrons they produce in a $\frac{1}{2}$-inch lead plate which, through scattering, emerge in the backward direction.

inch and an effective length of sixteen inches. Counters labelled identically in the diagram were connected in parallel. In the main series of measurements the following coincidences were recorded concurrently.

Fourfold—abch (referred to as T from now on)—arising mainly from passage of single mesons through the telescope.

Fivefolds—Td, Te, Tf, Tg—arising mainly from mesons and accompanying secondaries generated in S.

Sixfolds—Tde, Tef—arising mainly from showers (local as well as extensive).

With no material at S the 5 fold and 6 fold rates were found to be appreciable, and arose apparently from showers (local and extensive) as well as secondaries of mesons generated in the counter walls and in the air. These rates ($S=0$) were decreased considerably by:

(a) housing the telescope in a wooden hut with thin walls (0.4 g cm^{-2}) and a thin plastic roof (0.0125 g cm^{-2}).

(b) placing the bottom of the curved collecting tray d, e, f, and g on the same level as the top counter of the telescope rather than below it.

A further effect which is highly undesirable is that of secondaries being scattered in the counter walls so as to pass through more than one counter of the tray. Since the magnitude of this effect will depend on the material and dimensions of S in an unknown manner, we have attempted to eliminate it by inserting strips of lead and iron as indicated in the diagram. Very few of the secondaries scattered through large angles in the counter walls would be expected to traverse these strips (thickness of approximately 0.3 cm). Now the presence of this shower generating material between counters may well introduce further local effects, but these new effects may be considered as remaining constant as S is changed.

From the observed number of the coincidences listed above, the number of 5 folds per 4 fold, and the 6 folds per 4 fold can be calculated. These results, obtained with various absorbers at S and in some cases with shields over the counters d, e, f, and g, are shown in Table II.

2. Discussion of Results

The 5 fold coincidences without S are interpreted as background effects and these rates (coincidences per event T) are subtracted from the observed 5 fold coincidences rates with S present. The remaining 5 fold events are assumed to be due to mesons accompanied by knock-ons generated in S. The corrected 5 fold coincidences per meson are shown in Table III. The subtraction of the 5 fold rates with S absent is justified by the following arguments.

(a) The equality of all 6 fold counting rates (within the statistical error) in columns 9 and 10 of Table II, in the cases where shields are absent, shows that the 6 fold counting rates, taken concurrently with the 5 folds in each case, are independent of the presence of S and show no marked dependence on the angular position β of the counters (see Fig. 4B). When S is present, the expected contribution of multiple knock-ons from S to the 6 fold rate, calculated from the cloud chamber observations, is only 4 percent of the observed rate. This indicates that the 6 fold rate is due to air showers.

(b) In the cloud chamber with considerably smaller counters and a slightly greater thickness of lead over the bottom counter, the rate for events observed in the small thickness of the cloud chamber and appearing as showers originating outside the cloud chamber was 0.4 per hour. In view of the differing geometry this may be considered as in rough agreement with the shower rate of 0.65 per hour indicated by the 6 fold coincidences.

(c) The five fold coincidences (Td, Te, Tf, Tg) for S of zero thickness, after subtracting the average 6 fold shower background of 0.0044 ± 0.0002 per T event then appear as 0.0043 ± 0.0008; 0.0013 ± 0.0007; 0.0013 ± 0.0006; 0.0000 ± 0.0005 per T event, respectively. These residual counts may be attributed to the following causes: (i) the production of knock-ons in the air by mesons passing through the telescope (the cloud chamber re-

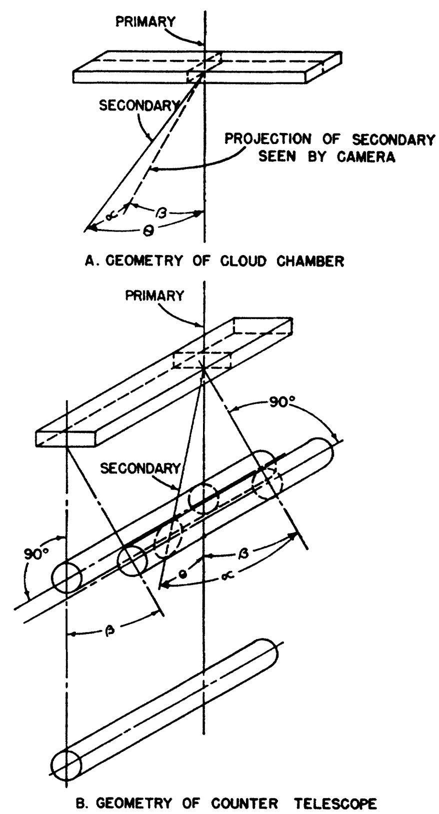

FIG. 4. Meaning of the angles α, β, and θ in the cloud chamber and counter telescope experiments.

TABLE II. Observed 4 fold coincidences T, 5 folds per T, 6 folds per T, for various materials at S. (Fig. 5).

				5 Folds per T				6 Folds per T	
Case	Material at S	Shields***	T	$(Td/T)\times 10^3$	$(Te/T)\times 10^3$	$(Tf/T)\times 10^3$	$(Tg/T)\times 10^3$	$(Tde/T)\times 10^3$	$(Tef/T)\times 10^3$
1	None	absent	15236	8.7±0.8*	5.7±0.7**	5.7±0.6	4.4±0.5	4.0±0.6**	3.9±0.6**
2	15 g cm^{-2} Pb	absent	17348	28.3±1.3	18.6±1.0	12.1±0.8	7.4±0.65	4.4±0.5	5.6±0.6
3	15 g cm^{-2} Pb	2.0 g cm^{-2} Pb	4782	24.4±2.3	12.1±1.6	9.8±1.4	6.9±1.2	6.1±1.1	7.3±1.2
4	3.8 g cm^{-2} Pb	absent	14379	22.3±1.2	13.1±1.0	9.2±0.8	5.2±0.6	3.3±0.5	4.2±0.5
5	3.8 g cm^{-2} Pb	2.0 g cm^{-2} Pb	3986	17.3±2.1	7.0±1.3	6.8±1.3	6.0±1.2	5.0±1.1	5.3±1.1
5a	3.8 g cm^{-2} Pb	0.4 g cm^{-2} Al	4862	21.8±2.1	12.7±1.6	7.6±1.3	6.4±1.1	4.3±0.9	4.7±1.0
6	0.45 g cm^{-2} Pressed wood	absent	8006	16.0±1.4	10.1±1.1	7.2±1.0	6.5±0.9	4.1±0.7	4.1±0.7
7	2 Al counters (identical to a) placed side by side	absent	8102	14.2±1.3	9.0±1.1	7.3±0.95	6.0±0.9	3.3±0.6	3.8±0.7

* Errors quoted are statistical standard deviations only.
** Te, Tde, and Tef in this case obtained with only 11900 coincidences in T as e counters were inoperative during a portion of the run. Chance coincidences in the worst case above were less than 2 percent of the observed rate and have been neglected.
*** In some instances small strips of Pb and Al were placed over counters d, e, f, and g as indicated.

corded .0035 high energy knock-ons per meson in traversing 3 cm of argon at 1.2 atmospheres—see Table I), (ii) the production of electrons in the material around the counters coincident with a T event.

The data of Table III, with the standard statistical errors, are shown in Fig. 6. It is apparent from this figure that quite small thicknesses of material may be the source of relatively large numbers of secondaries which are able to penetrate thin counter walls, while a considerable fraction of the secondaries produced may penetrate quite thick counter walls. It is of interest to note that the large angle secondaries are more markedly reduced than the small angle secondaries by the presence of a Pb shield over the counters.

A comparison of the results obtained by the cloud chamber and counter coincidence methods has been made for a Pb thickness of 15 g cm^{-2} and is shown in Fig. 7. The blocks indicate the statistical error and counter widths as well as the number of secondaries per meson for the counters of the counter telescope. The

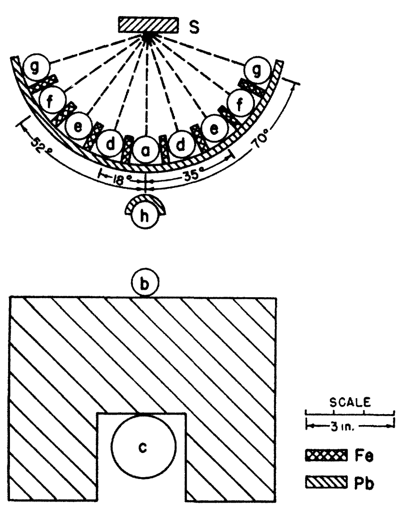

FIG. 5. Arrangement of meson counter telescope $ahbc$, secondary detecting counter pairs d, e, f, and g, and counter shields used in Part B. The production of secondaries in S is observed.

TABLE III. Single knock-ons generated in S per meson and counted by the counter pairs d, e, f, and g.

	Knock-ons per meson detected by counter pair			
Case	$d\times 10^3$	$e\times 10^3$	$f\times 10^3$	$g\times 10^3$
2	19.6±1.5*	12.9±1.2	6.4±1.0	3.0±0.9
3	15.7±2.4	6.4±1.8	4.1±1.5	2.5±1.3
4	13.6±1.5	7.4±1.2	3.5±1.0	0.8±0.8
5	8.6±2.2	1.3±1.5	1.0±1.5	1.6±1.3
5a	13.1±2.2	7.0±1.8	1.9±1.3	2.0±1.2
6	7.3±1.6	4.4±1.3	1.5±1.2	2.1±1.0
7	5.5±1.8	3.3±1.3	1.6±1.2	1.6±1.0

* Errors quoted in table are statistical standard deviations only.

solid line is the calculated distribution in β for the counter telescope (see Fig. 4) based on the results of Part A where a total number of 0.069 knock-ons per meson and an angular distribution of $\cos^{2.5}\beta$ for the secondaries were observed. An end loss of 10 percent was estimated for this particular counter geometry. The curve has been plotted without normalization at any point. It can be shown in a manner similar to the treatment of the projected distribution for the cloud chamber that the distribution in $\beta\sim\cos^n\beta$ if the distribution in θ follows the same law. The agreement of the two methods is perhaps better than might be expected in view of small factors which we have neglected in the interpretation of the counter telescope data, e.g., absorption in the counter walls, materialization of photons, increase in the effective widths of the counters owing to the presence of the thin Fe strips between the counters. However, these effects are small, and as the first one will tend to compensate for the latter ones, it is possible that no appreciable error, outside the statistical error, has been introduced.

GENERAL CONCLUSIONS

(1) The cloud chamber and counter telescope methods both give a total number of 0.07 secondaries per meson emerging from a $\frac{1}{2}$-inch Pb plate in the forward direction and indicate a distribution of $\cos^{2.5}\theta$, where θ is the angle between a secondary and its primary. The

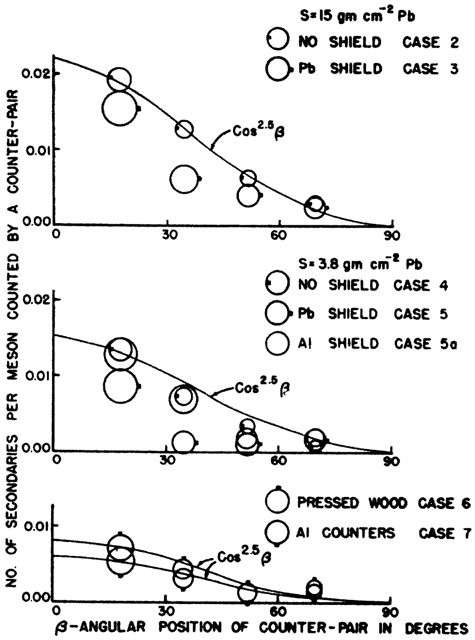

FIG. 6. Single knock-on secondaries generated in the material S per meson and counted by the counter-pairs d, e, f, and g.

results for the total number of secondaries per meson also agree, within statistical error, with the measurements of others where conditions were most similar to ours.[1, 5]

(2) Thin sections of material produce appreciable numbers of secondaries which appear to follow a similar distribution in θ.

[5] S. N. Nassar and W. E. Hazen, Phys. Rev. **69**, 298 (1946).

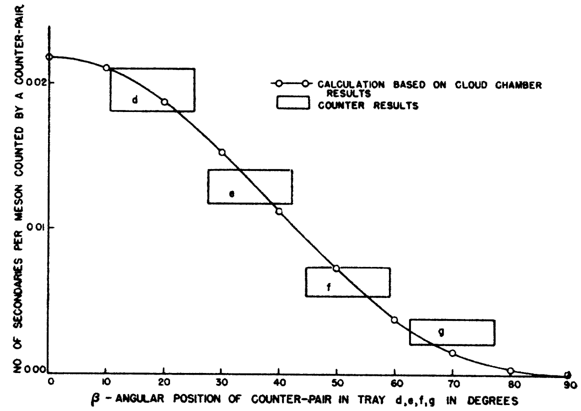

FIG. 7. Comparison of the expected number of knock-ons per meson counted by the counter geometry of Fig. 5 (calculated from the cloud chamber results) with the observed number counted.

(3) Some of the difficulties inherent in the interpretation of counter coincidence experiments are readily apparent; e.g., backscattering of secondaries, in the case of a tray of coincidence counters with absorber above and below, may introduce an appreciable contribution to 3 fold and higher coincidence rates, while the production of secondaries in the counter walls or in the surrounding air may also give rise to errors. We shall discuss these effects further at a later date, in their application to the correction of measurements on the total intensity of cosmic radiation.

The authors are indebted to Professor K. I. Greisen for helpful discussion and criticism of the work. The apparatus used had been built under a contract with the Office of Naval Research.