The Radioactive Decay of Slow Positive and Negative Mesons*

G. E. VALLEY
Laboratory of Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received July 21, 1947)

Cosmic ray mesons, after passage through a cloud chamber situated in a magnetic field, were slowed down and allowed to decay in specimens of carbon, stainless steel, brass, water and beryllium. By means of delayed coincidence circuits the cloud chamber was actuated only when a meson decayed in the specimen. In stainless steel and in brass, only positive mesons decay; in carbon, water, and beryllium both positive and negative mesons decay in such numbers as to indicate that few, if any, of the negative mesons undergo nuclear capture in these substances. It is shown that the masses of the decaying mesons are approximately two hundred times the mass of an electron.

I. INTRODUCTION

IT has been established that a cosmic ray meson at rest can decay radioactivity into at least one high-speed charged particle, and that its half-life for radioactive decay is about 2 μsec. These results have been confirmed by a considerable number of experimenters all using essentially the same "delayed coincidence" technique.[1–7]

Conversi, Pancini, and Piccioni[8] have reported such an experiment in which the delay-coincidence Geiger counters were surmounted by an analyzing magnet so that alternatively only positive or only negative mesons could be brought to rest within range of the counters. They found that when the mesons were brought to rest in iron, only the positive ones decayed radioactively, whereas when brought to rest in carbon (graphite), mesons of both signs decayed radioactively.

This finding has excited considerable attention among theorists[9–12] since it seems to contradict predictions of the meson theories of nuclear forces. According to these theories, the meson, once within range of the nuclear binding force, should be absorbed in a time so short compared to its natural half-life that any particles emitted in the process could not be detected by the delayed coincidence method. Since, however, the electric field of the nucleus keeps the positive mesons from coming within range of the nuclear binding force, they alone should be able to decay radioactively. Thus, the findings of Conversi *et al.*, for the case of mesons stopped in iron, should be typical of all elements which might be used to stop mesons.

Sigurgiersson and Yamakawa[13] have measured the absolute rate of delayed coincidences in various elements and find values consistent with the results of Conversi *et al.*

The experiment described here was already begun when the results of Conversi *et al.* were made known in this laboratory. Their results have been confirmed and extended to other elements.

II. EXPERIMENTAL METHOD

Arrangement of Apparatus

A schematic diagram of the apparatus is shown in Fig. 1. Three G.M. counter trays labeled **1**, **2**, and **3** contained respectively four, three, and three counter tubes effectively in parallel, and

* A report of the results for carbon and iron was made to an informal group of members of the A.P.S. in Washington, D. C. on May 1, 1947.
[1] F. Rasetti, Phys. Rev. **59**, 613 (1941); **60**, 198 (1941).
[2] P. Auger, R. Maze, and R. Chaminade, Comptes rendus, **213**, 381 (1941).
[3] R. Maze and R. Chaminade, Comptes rendus **214**, 266 (1941).
[4] B. Rossi and N. Nereson, Phys. Rev. **62**, 417 (1942); **64**, 199 (1943).
[5] R. Maze, R. Chaminade, and A. Freon, J. de phys. et rad. **7**, 202 (1945).
[6] M. Conversi and O. Piccioni, Phys. Rev. **70**, 859, 874 (1946).
[7] H. K. Ticho, Phys. Rev. **71**, 463 (1947).
[8] M. Conversi, E. Pancini and O. Piccioni, Phys. Rev. **71**, 209 (1947).
[9] J. A. Wheeler, Phys. Rev. **71**, 462 (1947); **71**, 320 (1947).
[10] E. Fermi, E. Teller, and V. Weisskopf, Phys. Rev. **71**, 314 (1947).
[11] G. Gamow, Phys. Rev. **71**, 550 (1947).
[12] V. Weisskopf, Phys. Rev. **72**, 155 (1947).
[13] T. Sigurgiersson and A. Yamakawa, Phys. Rev. **71**, 319 (1947).

were connected in threefold instantaneous coincidence. They defined a beam of particles to pass through the cloud chamber CC and the magnetic field H. After passage through tray 3, these particles penetrated into specimen block S ann a few of them stopped therein. Surrounding specimen block S were sixteen counters connected effectively in parallel, and together comprising tray D. Plates L_1 and L_2 were of lead 1.5 and 0.5-inches thick respectively. They served to eliminate most of the soft component of the cosmic radiation and so lowered the counting rates. Attention is called to water jackets J_1 and J_2, each of which was equivalent to about $\frac{1}{8}$ inch of brass. One of these, J_2 had a useful effect upon the measured momentum spectrum as will be described below. All of the counters were electrically shielded; in cases where this shielding was of such a nature as to affect the experimental results, it is indicated as a dashed line in Fig. 1.

Whereas Conversi *et al.*[8] allowed alternatively only positive or only negative mesons to fall on the specimen material and then measured the resulting delayed coincidence rate, in the present experiment a different procedure was followed. All particles of either sign which could penetrate to it, were allowed to fall upon the specimen block S, the magnetic field H causing no discrimination against either positive or negative particles. Then, whenever tray D was discharged in an interval of from one to approximately ten microseconds after a coincidental discharge of trays 1, 2, and 3, the cloud chamber was tripped, and the curved track of the causitive particle photographed. Thus if negative tracks were observed it meant that negative mesons decayed radioactively. The half-life of the mesons was not measured.

Electronic Details

The counters of trays 1, 2, 3 and of the vertically arrayed portion of tray D had each an active length of ten inches. The seven counters forming the horizontal array of tray D had each an active length of twenty inches. All the counters were constructed of brass tubing of one-inch outside diameter with a wall thickness of 0.032 inch. The tubes were filled with the usual mixture of argon and ethyl alcohol vapor required for self-quenching.

The circuits employed were remarkable only for some special characteristics not of interest to this experiment. They are shown in block diagram form in Fig. 2.

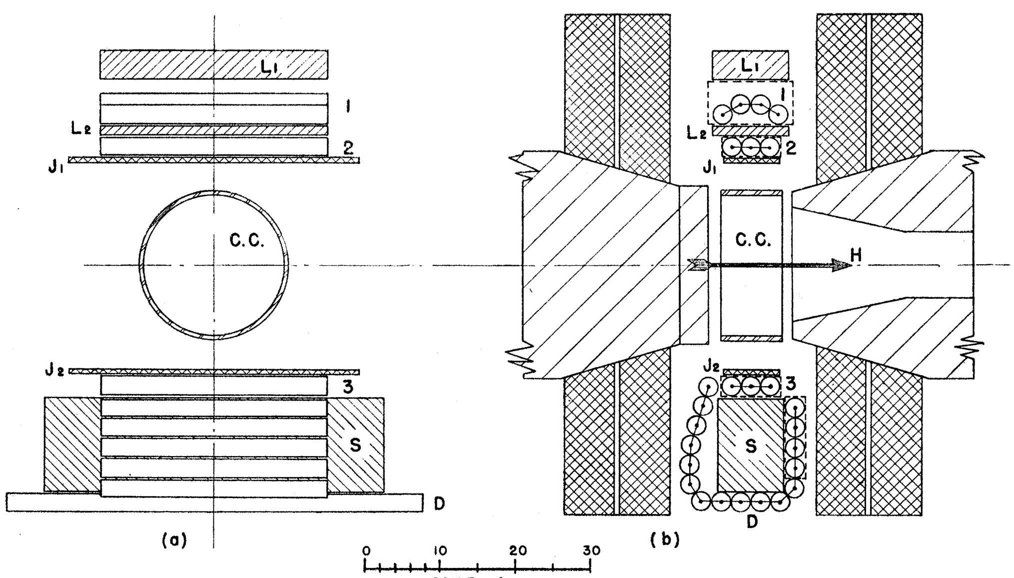

FIG. 1. Disposition of apparatus: 1, 2, 3 designate counters of the meson beam defining "telescope"; D designates the counters which surrounded the specimen and which responded to the product particle of the decaying meson; S is the specimen; L_1 and L_2 are lead slabs; J_1 and J_2 are brass-water-jackets. CC is the cloud chamber and the arrow H designates the magnetic field.

Each counter tray shown in Fig. 1 was divided into subgroups of three tubes or less, connected to common high voltage charging resistors. The members of each subgroup were chosen to have equal threshold voltages. The operating voltages of the several subgroups were separately adjusted so that all gave pulses of approximately equal amplitude. Each subgroup was connected to its own type 6AK5 pentode, operating at normal plate voltage, and upon firing, drove that tube's grid to a potential much below cut-off. All the type 6AK5 tubes of a given counter tray shared a common plate resistor, and together with an output cathode follower (type 6J6) comprised one of the preamplifiers *a*, *b*, *c*, and *d* (Fig. 2). The output pulses from these amplifiers rose to their maximum amplitude in 0.2 μsec. and appeared across an output impedance of a few hundred ohms. In effect, all the tubes of a particular tray functioned as one tube, because of the signal addition property of the common anode resistor circuit when the dynamic plate resistances are large. The charging resistors were of 2 megohms, the capacity of an individual counter tube was about 10 μμf, of its coupling condenser 50 μμf. In some cases, the restricted space of the apparatus made it necessary to have about 15 μμf capacity to ground due to cabling. The mean counter overvoltage was 125 volts.

The pulses from preamplifiers *a*, *b*, and *c* were applied to a triple coincidence circuit (*IIIC* in Fig. 2) whose resolving time was 1 μsec. In parallel with each input terminal of this coincidence circuit was connected an individual scale of four, whose function was to monitor the counting rates of the individual trays. Similarly and for the same reason, the output pulse of tray *D*, besides being applied to the delay-coincidence set (*DD* in Fig. 2) was applied also to a scale of thirty-two.

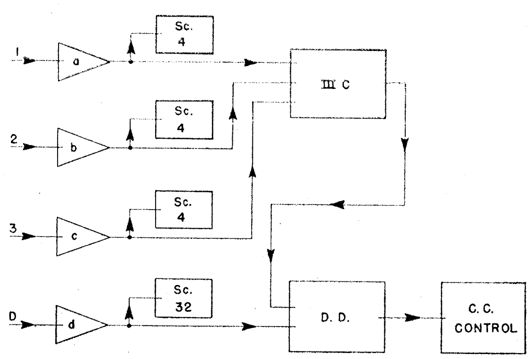

FIG. 2. Block diagram of circuits used; *a*, *b*, *c*, and *d* are preamplifiers used for counters 1, 2, 3 and *D* respectively; *IIIc* is a three-fold coincidence circuit; *DD* is a delayed-coincidence circuit which responded whenever it received a pulse from *d* within the interval from 1 to 10 μsec. after it had received an initiating pulse from *IIIc*; "cc control" is the cloud-chamber-control circuit.

The delayed-coincidence set** functioned in the following way: The pulse from the triple-coincidence set upon entering it was sharpened by a biased-off blocking oscillator circuit, delayed for 1 μsec. by means of a delay line, and then caused to initiate a positive pulse of 9 μsec. duration. This long pulse was applied to the third grid of a type 6AS6 pentode, to whose first grid was applied the positive pulse from preamplifier *d*, also after sharpening. The type 6A6S tube is designed to have short grid-bases for both No. 1 and No. 3 grids, and it functions very well as a double-coincidence element. Its plate current cannot flow unless both grids are simultaneously more positive than their cut-off voltages. The signal which appeared at the plate of this pentode was used to trip an electromechanical register and also the cloud-chamber control circuit (*CC* in Fig. 2).

By means of an auxiliary circuit in the delayed-coincidence set, the pulses from preamplifier *d* and from the threefold coincidence set could be applied directly to a simple-coincidence element. The resultant pulses marked the simple fourfold coincidences between trays 1, 2, 3 and *D*. Besides being continuously registered, these could also be used to trip the cloud chamber.

The Cloud Chamber and Associated Equipment

The cloud chamber was of the rubber diaphragm type filled with argon and the usual 70–30 solution of ethyl alcohol and water. Its illuminated volume was 7 inches in diameter and $2\frac{1}{4}$ inches deep. It operated at a mean absolute pressure of 93 cm of mercury.

The magnetic field was supplied by a cast-steel yoke*** one pole of which was hollow so

** Mr. M. L. Sands kindly loaned this piece of equipment, which he had originally constructed to measure the spontaneous delays of counter tubes.

*** This was patterned after a design of Professor R. B. Brode.

that photographs could be taken through it. The magnet was energized by an unregulated generator and over the several months' course of the experiment its field varied at most by plus or minus 200 Gauss around a mean value of 5800 at the center of the active volume of the cloud chamber. Over most of the volume of the cloud chamber, the field was uniform to ± 1 percent; near the hollow pole, however, the field rapidly became non-uniform, at its worst being non-uniform by ± 5 percent.

The use of an electromagnet in conjunction with a vertical cloud chamber for cosmic-ray studies has been noted to cause the tracks to be seriously distorted because of convection currents existing in the chamber prior to its expansion. These are due to unequal heating of the chamber.[14]

This problem arose during the present work. It was overcome by surrounding the cloud chamber with jackets through which water at controlled temperature was circulated. Six thermopiles were fastened to the cloud chamber at various points and by means of a recording potentiometer indicated temperatures to $\pm 0.1°C$. By judicious regulation of the water system, these six thermopiles could all be kept within $\pm \frac{1}{4}°C$ of the same temperature.

Scattering

The effect of coulomb scattering upon the measured curvature was calculated. From Eq. (153a) of Rossi and Greisen's paper,[15] the root-mean-square angular deflection of a particle of given velocity traversing 10 cm. in argon at 1.2 atmospheres pressure was calculated. This was divided by the angular deviation produced on the same particle by a field of 5800 Gauss over a 10-cm path. It is reasonable to take this fraction as the fractional error in radius of curvature produced by coulomb scattering. It is a number which increases with decreasing particle velocity and magnetic field. For the field intensity used, the error in radius due to coulomb scattering varied from 5.5 percent at the low end of the observed momentum spectrum, to 2 percent at the high end.

[14] P. M. S. Blackett and R. B. Brode, Proc. Roy. Soc. **154**, 573 (1936).

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

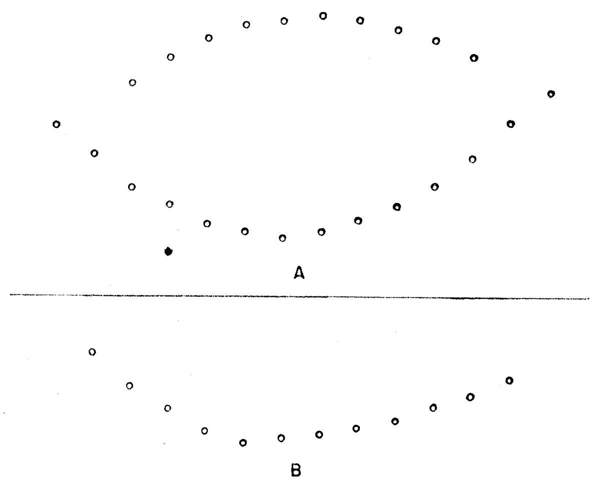

FIG. 3. In A and B are shown positive and negative tracks replotted with the vertical coordinate multiplied by ten so as to increase the apparent curvature; the tracks shown in Fig. 3(a) are Grade A tracks; the track shown in Fig. 3(b) is a poor Grade B track and shows the worst distortion allowed for a track whose apparent sign of curvature was believed.

Photography

Pictures were taken by means of a single 35 mm motion picture camera. The duration of exposure was fixed by the flash of the condenser-discharge lamps. Pictures were taken from 80 to 100 milliseconds after passage of the charged particle. Stereoscopic photographs were not taken. The probable difference between photographed and true radius of curvature due to optical effects was about 5 percent.

Analysis of Pictures

As soon as was convenient after their development, the photographs were inspected and all pictures bearing tracks which could possibly have had anything to do with the experiment were suitably marked for analysis. In this way, several percent of the pictures which bore tracks were eliminated. In general these were tracks due to small showers, knock-on electrons travelling in a markedly non-vertical direction, and tracks resulting from the nuclear radiation of neighboring laboratories.

The marked pictures were then mounted on the micrometer stage of a tool-maker's projector; they were so oriented that one of the two perpendicular micrometer screws lay parallel to the maximum chord of the circular track. The coordinates of the track were measured at intervals of about 1 cm along its chord.

These coordinates were replotted, the chordal coordinate to a scale about 30 percent larger than true size, and the sagittal coordinate to ten times this scale. The resulting curves were, for perfect tracks, elliptic arcs (see Fig. 3(a)). This process greatly accentuated the apparent curvature.

Although the primary purpose of the experiment was simply to ascertain the qualitative fact as to whether negative mesons decay in any substance, the tracks were measured to a precision commensurate with the other experimental errors for two reasons: first, this procedure, although laborious, is alone capable of giving an objective estimate of the reliability of the apparent sign of curvature; second, it was apparent after the apparatus was in operation, that it was capable of yielding a rough measure of the mass of the particles which caused the delayed coincidences.

Two methods were tried for determining the radii of curvature of the original tracks from the plots. In the first method, the tracks were compared with calculated ellipses each of which corresponded to a circular arc of a particular radius. The track plot was bracketed between that ellipse which was just too small and the one which was just too large. The average of the two values for the radius so obtained was taken as the radius of the original track and the difference of these two radii divided by their sum was taken as indicating the *quality* of the track.

This method took too much time. It was noticed that in most of the cases in which the track departed from a perfect circle, the deficiency consisted of a continuing increase or decrease in radius along the arc (see Fig. 3(b)). The second method made use of this fact. The maximum chord was determined and the sagitta at its midpoint measured. From these, one value of the radius could be calculated. The maximum sagitta was then determined and the half-chords to the right and left of this point were measured. From these, two more values of the radius could be calculated. The average of the three values was taken as the radius of the track and the fractional average deviation of the three values from their mean was taken as a measure of the quality of the track. By measuring a given group of tracks by both methods, it was shown that they were equivalent (most of the radii were less than 80 cm).

Neither method was completely objective: the first obviously required the exercise of judgment; in the second, the small fraction of tracks which were non-circular, but still symmetric, were assigned too good a quality number and these had then to be degraded by inspection. The second method was used because it was less tedious.

After being measured, the tracks were reprojected on a true scale copy of Fig. 1(a). The direction of curvature was noted, and also the tracks were examined to make sure they were "pertinent," i.e., that they lay within the solid angle determined by the counter arrays. Non-pertinent tracks were discarded. Also discarded, were a very few slow meson pairs.

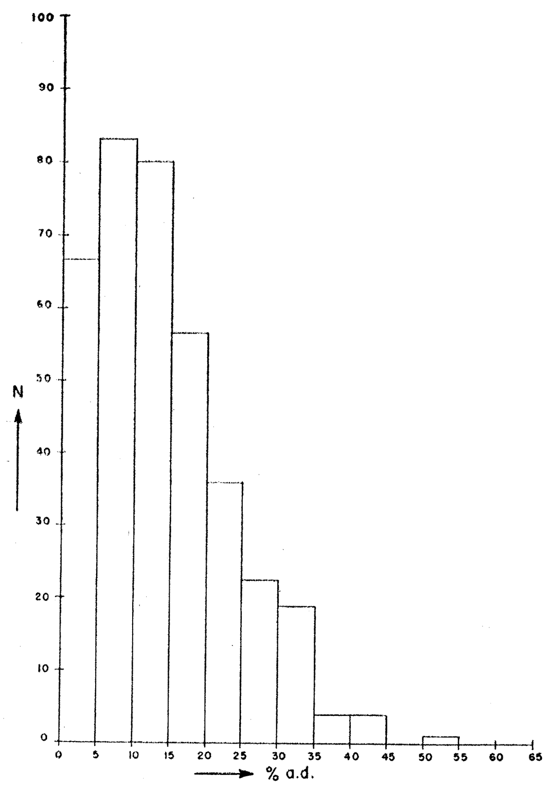

FIG. 4. Distribution of tracks in quality. The radius of curvature of each track was measured at three positions; this diagram shows the number of tracks plotted against the fractional average deviation from their mean of the three measurements on a given track. Tracks for all specimens are included.

The tracks were then graded: Grade A tracks are those whose quality number lies between 0 and 0.15; Grade B are those whose quality number is greater than 0.15 and less than or equal to 0.30; Grade C tracks are those whose quality number is greater than 0.30; Grade C^1 includes all those of insufficient contrast to be measured.

Tracks whose radii of curvature were greater than 250 cm were called "straight" and were not considered as being due to meson decay. This is a value considerably higher than the theoretical upper limit of the expected spectrum and it will be shown that it is also higher than the experimental upper limit. Such "straight" tracks were discarded. Figure 4 shows the distribution in quality of all the measurable curved tracks for all specimens together.

Testing Procedure

After the apparatus had operated for several days, controlled by delayed coincidences, it was stopped. The film was marked and then an additional set of pictures was taken on the same film strip, but with the cloud chamber controlled by simple four-fold coincidences between trays 1, 2, 3 and D. The particles whose tracks were thus photographed comprised a random sample of whatever in the cosmic radiation could penetrate the several absorbing blocks shown in Fig. 1. These particles were mostly fast mesons and thus nearly all of the tracks photographed by this second type of control had radii of curvature far greater than 250 cm.

From these simple-coincidence controlled pictures, the presence of any non-magnetic cause of track curvature, other than scattering, large enough to have invalidated the delayed-coincidence controlled pictures could easily have been detected. In addition, these pictures served to determine the recording efficiency of the cloud chamber. It will be seen from Fig. 1 that the counter tubes overhung the cloud chamber so that not every coincidence was necessarily produced by a particle which passed through the illuminated volume. The cloud-chamber efficiency was gotten by dividing the number of pictures bearing pertinent tracks by the total number of pictures taken, in a given run. A similar efficiency ratio could of course be gotten from the delayed-coincidence controlled pictures. Whenever these two values of efficiency departed widely from one another, the circuits were suspected of malfunction. Actually this happened only once.

The general idea is useful, however, because it is possible to study the performance of the apparatus as a whole when it is controlled by simple four-fold coincidences since they occur at the rate of about 500 per hour. Because of the few delayed coincidences (less than one per hour) the delay circuits can only be tested by artificial pulses. This, then, is a way to help ascertain that the cloud chamber has functioned properly over a long interval, even though at a very slow rate. At the beginning of the experiment, both efficiencies were about 45 percent. By improving the lighting system and the pressure-temperature controls, this was gradually increased to 75 percent, which is approximately the limit set by the counter geometry.

Now when the apparatus was controlled by delayed coincidences, there were recorded a certain number of "straight" tracks which were certainly not due to slow mesons. These averaged to 15 percent of the pertinent tracks recorded by delayed coincidence control. However, when the apparatus was controlled by simple four fold coincidences, more than ninety percent of the tracks were due to fast particles. This is additional proof that the apparatus functioned properly since the delayed coincidence control increased the relative number of slow particles about fifty fold. These numbers also show that only 1.5 percent of the slow particles whose tracks were photographed during delayed-coincidence control were not germane. The presence of the "straight" tracks has therefore no important bearing on the results.

Two additional tests were made. The duration of the long-gating pulse of the delay circuit was increased from 9 μsec. to 17 μsec. No increase in the rate at which slow meson tracks were obtained was noticed. Again, when the gating pulse was 9 μsec. in duration, the apparatus was exposed to sufficient gamma radiation to increase the counting rate of tray D by a factor of four. Again no increase was observed in the rate at which slow meson tracks were recorded. However, the presence of sufficient slow neutrons from the cyclotron, to increase the individual counting rates by a factor of ten, rendered the apparatus inoperable because of the large background in the cloud chamber.

Possible Causes of Spurious-Delayed Coincidence Tracks

It is necessary for completeness to investigate why 15 percent of the tracks observed when the apparatus was tripped by delayed coincidences were "straight" (i.e., had momenta in excess of 3.5×10^8 Mev/c).

It was possible that a meson could decay in the specimen without having passed through the cloud chamber. In fact, since the measured-cloud-chamber efficiency $\eta\cong75$ percent, it was possible for 25 percent of the slow mesons to do this. It was then possible that during or immediately before the resultant expansion of the cloud chamber, an independent fast particle could traverse the cloud chamber. Since such a particle has nearly unit probability of tripping the three-fold coincidence circuit, and since most of the penetrating particles are fast, it is possible to set the three-fold coincidence rate N_3 equal to the rate at which such particles traverse the cloud chamber. Then if γ_1 is the rate at which such spurious tracks are observed,

$$\gamma_1=\eta N_3 t N_D(1-\eta)\cong.01N_D, \qquad (1)$$

where N_D is the observed rate of delayed coincidences and t is the resolving time of the cloud chamber. For the rates observed, γ_1 amounts to only about 1 percent of the delayed-coincidence rate recorded.

Another source of such tracks arises because it was possible for a particle to penetrate trays 1, 2, and 3, and the cloud chamber without triggering a tube of tray D about 10 percent of the time. Such events would have no effect on the apparatus, unless within the 9 μsec. period defined by the gating pulse of the delay-coincidence circuit, a tube of tray D was triggered by another particle. The rate at which straight tracks would be observed due to this cause is,

$$\gamma_2=\eta(N_3-N_4)n_D\tau, \qquad (2)$$

where N_4 is the four fold coincidence rate, n_D is the separate counting rate of tray D and τ is 9 μsec. This can amount to less than 2 percent of delay coincidences recorded if there is no non-cosmic radiation. A recording counting-rate meter was kept in operation continuously to check the background of non-cosmic radiations. This indicated that this effect could actually have amounted to 3.5 percent of the delay coincidences recorded.

The imperfect anticoincidence efficiency can in principle contribute in another way to the spurious tracks recorded, for a moderately fast meson can penetrate the specimen without triggering the counters of tray D about 10 percent of the time. It can then decay in the material of the supporting framework and send back an electron to trigger tray D, thus establishing a true delayed coincidence. Only mesons whose range after penetrating the specimen S is less than that of a decay electron can do this. Solid angle calculations indicate the effect to be small. In this experiment the supporting framework was of wood. Since few if any negative particles appeared to decay in brass or in iron this estimate is confirmed because the wood would have allowed mesons of either sign to decay.

The charging-time constant for a subgroup of tubes which shared a common charging resistor and coupling condenser was at most 50 μsec. Now if one tube of such a subgroup was fired, the voltages applied to the other tubes of that subgroup were so lowered that they would yield smaller than normal pulses until the 50 μsec. circuit was recharged. The preamplifier-output pulses which ensued then rose to their limited maximum value more slowly. It is not probable that any of these abnormally low pulses contributed a delay of as much as one microsecond. However, even if it is assumed that the output pulses were delayed by one microsecond for a period of 100 μsec. after discharge of one tube, only about 0.3 percent of the delayed coincidences observed could be due to this cause.

After a self-quenching counter tube has fired, it is known to require several hundred microseconds to recover sufficiently to fire normally a second time. During approximately the last 100 μsec. of this "dead-time," the tube will give out pulses, but of less than the normal size.[16] If it is assumed that all of these abnormally small

[16] A. Trost, Zeits. f. Physik **105**, 399 (1937).

pulses contribute fictitious delays of one microsecond or more, this effect could contribute at most 0.3 percent of the observed delayed coincidences.

Aside from the above effects, the pulses from counter tubes do not issue immediately after passage of the charged particle but may be delayed on the average as much as several tenths of a microsecond. Mr. M. L. Sands has measured these spontaneous delays for tubes similar to the ones used in this experiment. He finds that not more than one pulse in 5×10^3 can be delayed by as much as one microsecond. If this finding is interpreted to mean that one in five thousand of the pulses actually is delayed by one microsecond, then 10 percent of the delays recorded would be fictitious due to this cause.

It is concluded that spontaneous counter delays and the effect described by Eq. (2) are chiefly responsible for the "straight" tracks.

Theoretical Limits of the Momentum Spectra

The arrangement shown in Fig. 1 imposes both an upper and a lower limit to the momentum spectrum of the observed tracks. No meson which passes through the specimen S and one of the counters D and then decays can cause a true delayed coincidence. This is so even if the decay electron comes back and triggers a D counter which is connected to a different preamplifier pentode, since the blocking oscillator peaking circuit in the delay-coincidence set has a recovery time of about 25 μsec., during which it cannot be triggered successfully. Thus the particle whose momentum is measured in the cloud chamber has a maximum permissible range. Therefore there is a maximum observable momentum for a given mass. The maximum amount of material which can be traversed includes the lower wall of the cloud chamber, water jacket J_2, the walls and shield can of tray 3, the specimen and, for positive mesons, the upper wall of the long counters of tray D. Obviously, this is to be computed for the trajectory which makes the greatest permissible angle with the vertical. There are in addition, a few particles which travel almost entirely in the brass walls of the vertical portions of tray D. These have a much longer permissible maximum range. For this reason and because of scattering within the specimen, the upper limit is not expected to be sharp. The *lower* limit to the spectrum is set by the fact that it is necessary to discharge a counter of tray 3 in coincidence with trays 1 and 2 before a delayed pulse from tray D can have any effect. Therefore, any meson whose momentum is measured in the cloud chamber must have at least enough energy to penetrate to the active volume of one of the counters of tray 3. Such a meson, if positive, must be able to penetrate the wall of the cloud chamber, the water jacket J_2, the upper part of the shield can of tray 3 and one wall of a tube of tray 3. If the meson is negative, it must penetrate the lower walls of tray 3 in addition, because it cannot disintegrate in brass. The lower limit to the momentum spectrum also depends on the meson mass and is not expected to be broadened by the factors which broaden the upper limit. This lower limit is not dependent upon the specimen used.

Now one would expect the momentum spectrum to fall at the low end anyhow if the original spectrum is uniform in range, because of the parabolic nature of the mean range-momentum law in the non-relativistic region.[17,18] It will be shown that the observed cut-off is much sharper than this, however. Furthermore, the minimum radius of a particle which can traverse the magnetic field and still trip all the counters is at least three times smaller than the minimum radius observed, so that the observed lower limit is not due to this cause.

TABLE I. Tracks of each category observed when specimen was carbon.

Sign	Grade A	Grade B	Grade C	Grade C^1	Non-perinent
+	49	30	7	5	6
−	34	22	13	8	3

III. RESULTS

Except for a daily test period, the apparatus was operated continuously for periods of several weeks duration with a given specimen material.

In the first experiment, the specimen was composed of carbon. This experiment indicated

[17] G. C. Wick, Nuovo Cimento **XXI**, 1 (1943).
[18] J. H. Smith, Phys. Rev. **71**, 32 (1947).

that negative mesons decay, in accord with the findings of Conversi *et al.* The apparatus was then refined, particular attention being given to improving the illumination and temperature control of the cloud chamber. A specimen of stainless steel was next employed and after negative mesons were found not to decay in it, the carbon experiment was repeated. It agreed with the first carbon experiment. Following this, water, brass and beryllium were tried. During part of each experiment the magnetic field was reversed. There was no possibility of the magnetic field being inadvertently reversed.

Carbon

The carbon used was in the form of pressed porous bricks whose specific gravity was 1.12. The different categories of tracks of each sign obtained when the specimen was composed of carbon are shown in Table I, which includes the results of both carbon experiments.

The ratio of positive to negative mesons of Grades A and B together was, when the magnetic field was directed toward the camera 33/14, and when the field was directed away from the camera 46/42. The dependence of this ratio upon the direction of the magnetic field was due to the fact that counter tray 3 was displaced horizontally (Fig. 1(a)). This was rectified before the water experiment was begun, and then no such dependence was discernable. The desired ratio is easily seen to be the geometric mean of these two values. It must be further corrected because the incident mesons are known to

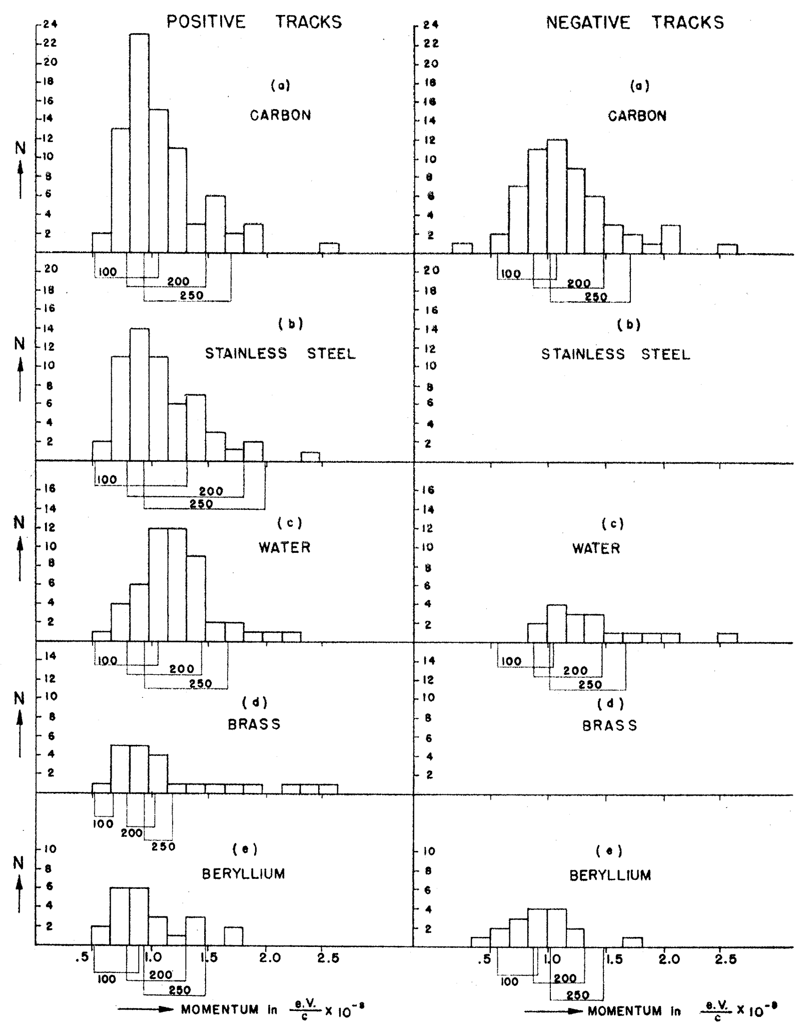

FIG. 5. Momentum distributions of positive and negative tracks for various specimens. The rectangular brackets underneath each distribution show the location and width of the main part of the expected distribution if the meson mass is 100, 200 or 250 times that of an electron. The ordinates are not corrected for the effect of the counter walls or of the copper can.

TABLE II. Tracks of each category observed when specimen was stainless steel.

Sign	Grade A	Grade B	Grade C	Grade C^1	Non-pertinent
+	42	17	10	12	1
−	0	0	1	1	1

comprise about 20 percent more positives than negatives.[19,20]

The observed positive to negative ratio, thus corrected, is for carbon: 1.33 ± 0.19. This does not give the relative number of positive and negative mesons which decay in carbon however, because some of the positive mesons could decay in the counter walls. The mass per unit length in the horizontal direction (Fig. 1(a)) was for carbon 82 gms/cm. and for the counters 49 gms/cm.; then if k is the fraction of negative mesons which disintegrate, we should set

$$(82+49)/82k = 1.33 \pm 0.19$$

on the assumption that the efficiency for detecting decay electrons from the carbon and from the brass is the same. Then $k = 1.2 \pm 0.17$. Since the maximum expected value for k is unity, the experiment indicates that all negative mesons decay in carbon and that none undergo nuclear capture.

Figure 5(a) shows the momentum distribution of the Grade A and Grade B tracks together with brackets which indicate the expected spectrum limits for several values of the meson mass. The registered delay-coincidence rate was 0.74 ± 0.04 per hour for 493 hours of operation. There were photographed 173 tracks of Grades A, B, and C together and also 22 "straight" tracks. The register data should be corrected for background, therefore, by 13 ± 3 percent. This gives for the counting rate 0.65 ± 0.04 per hour.

Figure 6 shows two contiguous pictures on the same film strip. It will be noted that the tracks curve in opposite directions.

Iron

The iron specimen comprised ten pieces of non-magnetic stainless steel each $\frac{1}{8}$-inch thick and separated from one another by $\frac{3}{8}$ inch. The

[19] H. Jones, Rev. Mod. Phys. 11, 235 (1939).
[20] D. J. Hughes, Phys. Rev. 57, 592 (1940).

FIG. 6. A positive and a negative meson track photographed on adjacent frames of the same film strip (carbon specimen). The sharply curved negative track at the top of the upper picture is known not to be contemporaneous with the meson track since its narrow width indicates that that particle passed through the cloud chamber after the expansion.

specimen was of about the same external dimensions as the other specimens (carbon, water, beryllium) but had somewhat more than twice their average density. Non-magnetic steel was used in order not to affect the magnetic field. Its composition was 73.8 percent iron, 18 percent chromium, 8 percent nickel, and 0.2 percent carbon. The mass of the specimem per unit length was 210 gms/cm.

The different categories of tracks of each sign

TABLE III. Tracks of each category observed when specimen was water.

Sign	Grade A	Grade B	Grade C	Grade C^1	Non-pertinent
+	37	17	1	2	2
−	10	8	3	2	1

obtained when the specimen was composed of stainless steel are shown in Table II.

It is obvious that very few, if any, negative mesons decay in stainless steel. The two Grade *C* tracks can easily be accounted for as having accompanied the 22 "straight" tracks which were also observed.

The registered delay-coincidence rate was, for 302 hours of operation, 0.74 ± 0.05/hr. The total number of Grade *A*, *B*, and *C* tracks photographed was 81, and there were in addition 22 straight tracks. From these numbers, the background is estimated to be 27 percent. Corrected for this background, the counting rate is 0.54 ±0.06/hr.

Figure 5(b) shows the momentum distribution of the Grade *A* and Grade *B* tracks together with brackets indicating the expected spectrum limits for several values of the meson mass.

Water

Water was used in order to study the behavior of mesons stopped in oxygen. It has been pointed out† that water should behave precisely like oxygen, the only effect of the hydrogen being to form "hydrogen meside," an electrically neutral system which can drift within range of the oxygen nuclear force in a time very small compared to the meson half-life. The water was contained in a copper can of approximately the same dimensions as the previous specimens. This can increased the mass per unit length of copper and brass to 71 gms/cm.; the mass per unit length of the water was 98 gms/cm.

The different categories of tracks of each sign observed when the specimen was composed of water are shown in Table III.

The ratio of positive to negative mesons of Grades *A* and *B* together was, when the magnetic field was directed toward the camera, 22/9; and when it was directed away from the camera, 32/9. The disagreement between these ratios is not statistically significant. The mean observed positive to negative ratio, corrected for the initial positive excess, is 2.46 ± 0.67.

Proceeding as in the case of carbon, the fraction of negative mesons which decay is found from

$$(71+98)/98k=2.46\pm0.67$$

which gives $k=0.7\pm0.19$.

Figure 5(c) shows the momentum distribution of the tracks observed.

The registered delay-coincident rate was, for 278 hours of operation, 0.87 ± 0.06/hr. There were photographed three "straight" tracks and eighty Grade *A*, *B*, and *C* tracks. If these numbers indicate the background rate, then the corrected counting rate is 0.84 ± 0.06/hr.

Brass

This specimen consisted only of the counter tubes themselves and the empty water can. The mass of the specimen per unit length was 71 gms/cm.

The different categories of tracks of each sign observed for this specimen are shown in Table IV.

The registered delay-coincidence counting rate was, for 160 hours of operation, 0.26 ± 0.04 per hour. A total of 23 tracks of Grades *A*, *B*, and *C* were photographed as well as two "straight" tracks. If these numbers indicate the background rate, the corrected delay coincidence rate was 0.24 ± 0.04/hr.

Figure 5(d) shows the momentum distribution of these tracks. Note that it has the narrow peak and long high momentum tail which would be expected from a hollow specimen.

Beryllium

The can previously used to hold water was packed with beryllium chips. The mass per unit

TABLE IV. Tracks of each category observed when specimen was brass.

Sign	Grade *A*	Grade *B*	Grade *C*	Grade C^1	Non-pertinent
+	19	2	2	0	1
−	0	0	0	0	0

TABLE V. Tracks of each category observed when specimen was beryllium.

Sign	Grade *A*	Grade *B*	Grade *C*	Grade C^1	Non-pertinent
+	9	14	7	4	0
−	11	6	1	0	0

† At the Conference on the Foundations of Quantum Mechanics held at Shelter Island, New York, June 1–3, 1947.

TABLE VI. Comparison of delayed coincidence rates.

Specimen	Carbon	Stainless steel	Brass and copper	Water	Beryllium
Rate per hr per gm/cm	0.0059 ± 0.0003	0.0018 ± 0.0002	0.0034 ± 0.0005	0.0061 ± 0.0007	0.002 ± 0.0015

length of beryllium was 70 gms/cm. and of brass and copper 71 gms/cm.

The different categories of tracks and each sign observed in this experiment are shown in Table V.

The positive to negative ratio corrected as in the cases of carbon and water for the initial positive excess is 1.13 ± 0.36. The fraction of positive mesons which decay is found from

$$(70+71)/71k = 1.13 \pm 0.36,$$

which gives $k = 1.76 \pm 0.56$. Since the maximum possible value of k, if all positive and all negative mesons decay, is unity, this figure does not indicate that any negative mesons are captured.

Figure 5(e) shows the momentum distribution of the beryllium tracks.

The registered delayed-coincidence rate was, for 369 hours of operation, 0.61 ± 0.04/hr. The total number of Grade A, B and C tracks photographed was 48, and in addition 18 "straight" tracks were recorded. If these numbers indicate the background, the corrected rate was 0.38 ± 0.26/hr.

Comparison of Counting Rates

By subtracting the counting rate for brass from those for the water and beryllium experiments, we arrive at the counting rate for the water and beryllium alone. Since the copper can was not used during the carbon and iron experiments, only 49/71 of the brass counting rate needs be subtracted from their rates to get the rates for carbon and iron alone. If each of these rates is divided by the linear density of its respective specimen, the resultant ratios should be comparable in the sense of Sigurgiersson and Yamakawa.[13] The results are shown in Table VI.

It should be remarked that the apparatus behaved poorly during the beryllium experiment which was terminated by its breaking down. The two sets of data for beryllium, if accepted at their face value, would indicate that positive mesons undergo nuclear capture in this element. Because of the known deficiencies of the apparatus during the time beryllium was being tested, this is not regarded as conclusive and the matter is being subjected to further test.

The results for carbon, steel, brass and water tend to validate the method used by Sigurgiersson and Yamakawa, especially in view of the great difference in electron absorption to be expected for the steel and for the brass specimens, due to their different geometries.

Professor Bruno Rossi suggested this problem. The writer is indebted to him for his constant advice and encouragement.

Mr. M. L. Sands was associated with the work during its early stages.

Much of the apparatus was constructed by Mr. R. Hewitt, technician. Mrs. T. Kallmes measured all the tracks and prepared plots of which Fig. 3 is an example.

The research reported in this document was made possible through support extended the Massachusetts Institute of Technology, Laboratory of Nuclear Science and Engineering, by the Navy Department (Office of Naval Research) under Contract N5ori-78, Task Order VI.

FIG. 6. A positive and a negative meson track photographed on adjacent frames of the same film strip (carbon specimen). The sharply curved negative track at the top of the upper picture is known not to be contemporaneous with the meson track since its narrow width indicates that that particle passed through the cloud chamber after the expansion.