The six curves are shown in Fig. 2 together with the three experimental values and their statistical errors. An examination of the curves shows that the different values of s do not seriously affect the theoretical values of R_1 and R_2. Since s almost certainly lies between 50 and 200 g/cm^2, it seems reasonable to conclude that the assumption $s=100$ g/cm^2 will not cause an error in $\tau/\mu c^2$ greater than 10 percent. Since we are here primarily interested in relative values this uncertainty will not appear.

With $s=100$ g/cm^2 we get for the first series of measurements

$$\tau/\mu c^2=(2.8\pm0.5)\times10^{-14}\text{ sec./ev.}$$

For the second series the two values

$$\tau/\mu c^2=(2.6\pm0.4)\times10^{-14}$$

and

$$(2.3\pm0.4)\times10^{-14}\text{ sec./ev.}$$

We therefore conclude that the value of $\tau/\mu c^2$ does not increase when the path traversed is increased from 23 to 43 km. (If anything there is a slight decrease.) We believe, therefore, that these measurements confirm what we have already stated[4] that $\tau/\mu c^2$ is independent of path traversed, at least within the experimental errors of the measurements to date.

The three measurements together give a mean value for $\tau/\mu c^2$ of $(2.6\pm0.3)\times10^{-14}$ sec./ev. This value agrees within experimental errors with that given by Bernardini[6] from an extensive analysis of all measurements to date. It also agrees with the recent careful direct measurements of M. Conversi and O. Piccioni[7] which gave $\tau=(2.30\pm7\text{ percent})\times10^{-6}$ sec.

[6] G. Bernardini, Zeits. f. Physik **120**, 413 (1943).
[7] M. Conversi and O. Piccioni, Nuovo Cimento **11**, 71 (1944).

PHYSICAL REVIEW VOLUME 70, NUMBERS 11 AND 12 DECEMBER 1 AND 15, 1946

On the Mean Life of Slow Mesons

M. CONVERSI AND O. PICCIONI*
Institute of Physics, University of Rome, Rome, Italy
(Received February 10, 1945)**

A new investigation on the spontaneous decay of mesons is performed by counting delayed coincidences between the impinging low energy mesons and the decay electrons. Four points of the decay curve of mesons are obtained for relative delay times ranging between −0.91 and 2.43 μsec. The results give an exponential curve which is evidence of the decay process. For the mean life we find $\tau=2.33$ μsec. ±6.5 percent. The effect disappears completely by inverting the sign of the delay.

1. INTRODUCTION

ACCORDING to current ideas, the particles which make up the hard component of cosmic rays have properties very similar to those of the particles first postulated by Yukawa[1] to explain the nuclear forces. This particle (meson, positive, or negative) having a mass of about 200 electron masses, undergoes spontaneous disintegration producing—according to the scheme generally accepted—one electron and one neutrino. The instability of mesons was assumed in order to explain the anomalous absorption of the hard component, upon which are based all the measurements performed up to now of the ratio $\tau/\mu c^2$ of the mean life τ to the rest energy μc^2 of mesons.[2–14]

* At the present Visiting Research Associate at Massachusetts Institute of Technology.
** The manuscript of the present paper was prepared in 1944. At that time no information was available in Italy on the experiment on the disintegration of mesons carried out by N. Nereson and B. Rossi (Phys. Rev. **64**, 199 (1943)). On account of wartime conditions the manuscript did not reach the Editor of *The Physical Review* until February 10, 1945.
[1] Yukawa, Proc. Phys. Math. Soc. Japan **20**, 319 (1938).
[2] Johnson and Pomerantz, Phys. Rev. **55**, 104 (1940).
[3] Rossi, Hilberry, and Hoag, Phys. Rev. **57**, 461 (1940).
[4] Ageno, Bernardini, Cacciapuoti, Ferretti, and Wick, Phys. Rev. **57**, 945 (1940).
[5] Pomerantz, Phys. Rev. **57**, 2 (1940).
[6] Cocconi, Ricerca Scient. **11**, 50 (1940).
[7] Rossi and Hall, Phys. Rev. **59**, 223 (1941).

The most reliable value of this ratio seems to be 3.0±0.3 sec./Mev.[14] One notes, however, that the results obtained by different authors do not agree very well, and that the deduction of the value of $\tau/\mu c^2$ from experimental measurements is based on special assumption about the generation of mesons. Moreover, a determination of τ based on the anomalous absorption is to be considered only an indirect proof of the assumption of the disintegration of mesons. Direct proofs of the instability of these particles have been supplied up to the present only by two cloud chambers photographs[15] and by two direct experiments, the first obtained by Rasetti[16] and the second attributed to Auger, Maze, and Chaminade,[17,18] which allow at the same time a direct measurement of the mean life of the decay process.

The first attempt at a direct measurement of τ is attributed to Montgomery Ramsey, Cowie, and Montgomery[19] who counted the delayed coincidences of two sets of G.M. counters between which could be inserted a lead plate 2 cm thick, where the slow mesons were stopped and in which they decayed. The mean life could be deduced by comparing the number of delayed coincidences with and without the lead absorber. These authors concluded that the experiment had given a strictly negative result; it is, however, to be noticed that they had evaluated the amount of the effect (to about ten times the experimental error) by taking into account only the geometrical condition under which the experiment was performed and overlooked the effect of the low value of the range of the decay electrons, which in their absorber of lead is 1.23 cm according to Bethe and Heitler.[20]

For this reason, and because of the uncertainties affecting measurements of absolute delay and the evaluation of the efficiency of delayed coincidences, the negative result of this experiment cannot be considered as definitive. In fact, as will be seen later, our experimental disposition gave a number of undelayed coincidences nearly equal to that of Montgomery and collaborators, and a slightly higher number of delayed coincidences. As an absorber, we used iron which is more convenient than lead for detecting the maximum number of decay electrons.

The second experiment of this type is attributed to Rasetti and was published in June, 1941.[16] Typical of this experiment was a very successful disposition of the counters: a fivefold coincidence set which by its geometry did not register particles following a straight line. In effect fivefold coincidences were simultaneously registered by means of three circuits having resolving times equal, respectively, to $t_2=15.0$; $t_3=1.95$; $t_4=0.95$ μsec.

Therefore the differences (with obvious correspondence in the labels) n_2-n_3 and n_2-n_4 gave the number of coincidences due to pulses separated one from the other by times ranging, respectively, between 1.95 and 15.0 μsec. and 0.95 and 15.0 μsec. The value of τ was determined by the ratio of these two differences not by their absolute values.

The result of this experiment was positive. In fact Rasetti found different values for the above-mentioned differences as would be expected if the meson decays with electron emission.

The value of τ deduced from two series of measurements, one performed with an iron, the other with an aluminum absorber, was $\tau=1.5\pm0.3$ μsec.

As a qualitative proof of the reality of the effect, Rasetti showed that almost no effect was observed without an absorber.

This result was considered a rather good proof of the decay of mesons, the more so as the experimental value of the mean life was in reasonable agreement with the values deduced at that time by the anomalous absorption of mesons on the assumption of $\mu c^2=100$ Mev.[9]

However, it seems to us that in his deduction

---

[8] Cacciapuoti and Piccioni, Ricerca Scient. **12**, 874 (1941).
[9] Nielsen, Ryerson, Nordheim, and Morgan, Phys. Rev. **59**, 547 (1941).
[10] Bernardini, Cacciapuoti, Pancini, and Piccioni, Nuovo Cimento **19**, 69 (1941).
[11] Festa, Santangelo, and Scrocco, Nuovo Cimento **1**, 71 (1942).
[12] Bernardini and Festa, Atti d. R; Acc. d'Italia **7**, 4 (1943).
[13] Conversi and Scrocco, Nuovo Cimento **1**, 372 (1943).
[14] Bernardini, Zeits f. Physik **120**, 413 (1943).
[15] Williams and Roberts, Nature **145**, 102 (1940).
[16] Rasetti, Phys. Rev. **59**, 613 (1941); **60**, 198 (1941).
[17] Auger, Maze, and Chaminade, Comptes rendus **213**, 381 (1941).
[18] Maze and Chaminade, Comptes rendus **214**, 266 (1941).
[19] Montgomery, Ramsey, Cowie, and Montgomery, Phys. Rev. **51**, 635 (1939).
[20] Bethe and Heitler, Proc. Roy. Soc. **A146**, 83 (1934).

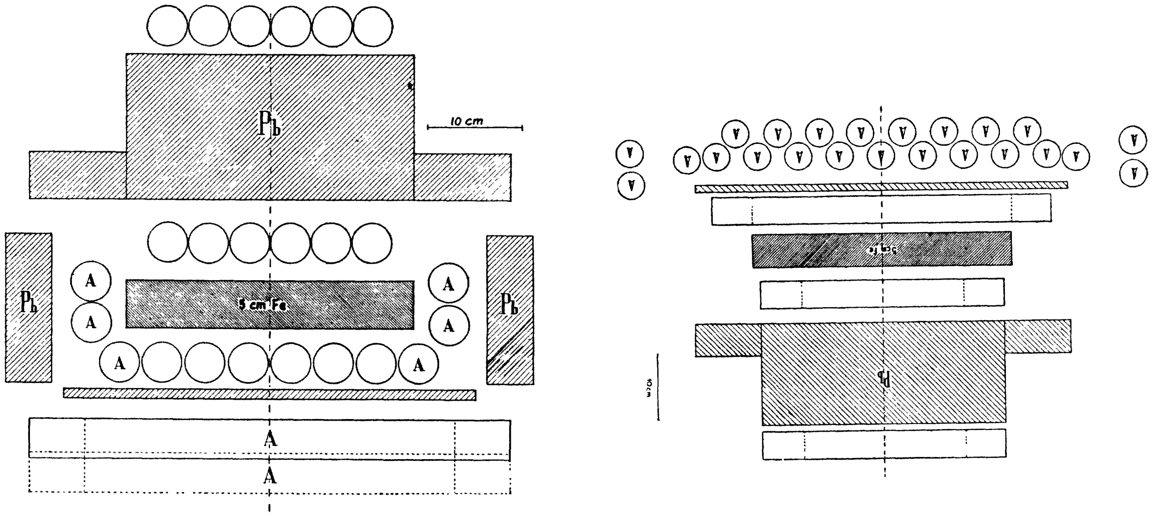

FIG. 1 (a) and (b). Vertical sections of the whole set of counters.

of the mean life of mesons, Rasetti makes the implicit assumption that, by using a circuit of resolving power θ, only the double coincidences due to pulses following one another by a time $\bar{t}$ smaller or equal to θ are registered.

On this point one can make the two following remarks: (a) Under the assumption that the two branches of the coincidence circuit give pulses of the same time length, Rasetti's procedure is correct only if the two branches introduce no delay or, at least, equal delays; otherwise $\bar{t}$ is larger than θ by the difference of the delays introduced by the amplifiers;

(b) Under the assumption that those delays are zero or equal, Rasetti's assumption is correct only if the effective coincidence-times θ_1 and θ_2 of the pulses in the two branches are strictly equal. In the general case, when θ_1 and θ_2 are not equal, a coincidence will be registered provided that the pulse of the second branch is delayed by no more than θ_1 over the pulse of the first branch, or the first pulse by no more than θ_2 over the second pulse. Calculating the resolving power from the number of random coincidences $N_c = N_1N_2(\theta_1+\theta_2)$, ($N_1$, N_2 being the zero-effect of each branch) according to the usual formula $\theta = N_c/N_1N_2$ we get for θ the mean value of θ_1 and θ_2.

Such a difference between θ_1 and θ_2, actually occurs, when circuits with too large values of RC are used that may obviously introduce a considerable error in the value of τ; therefore, we thought it desirable to make a direct measurement of τ by using a registering set appropriate for very short pulses whose behavior could be checked frequently during the measurements by means of a suitable disposition of the tubes. At the same time we had the purpose of giving new evidence of the instability of mesons, besides that based on the comparison "with and without absorber": (a) by obtaining many points of the decay curve in order to show its exponential shape, (b) by comparing measurements (that we shall call *normal*) in which were registered the coincidences of a set of counters (set 3) delayed with respect to two other sets (sets 1, 2); and measurements (that we shall call *inverted*) in which were registered the delayed coincidences of the two sets 1, 2 with respect to the set 3.

While we were arranging our experiment, we heard about the results obtained by Auger, Maze, and Chaminade[17,18] who had found three points of the decay curve, with an arrangement similar to that of Rasetti, although independently. The points obtained by these authors in the above mentioned paper[18] are not sufficient to prove the exponential shape of the decay curve nor allow an exact determination of τ. In the paper available to us, the authors do not state that the measurements for the different delays were made alternatively; this point is very important since the experiment took a rather long time because of the

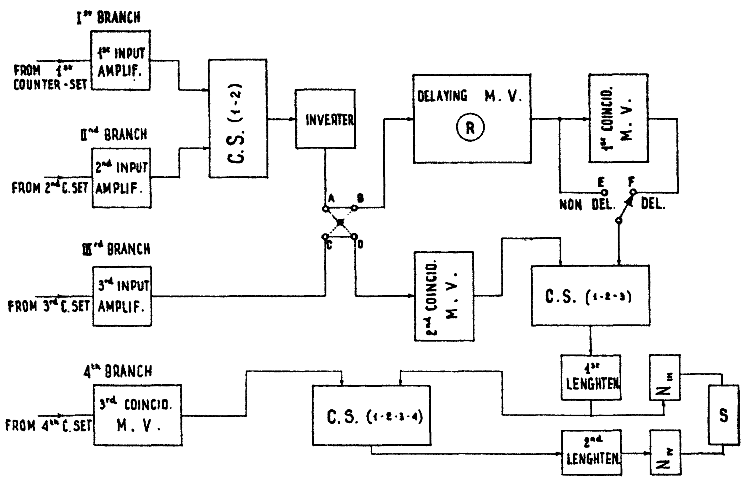

FIG. 2. Block diagram of the registering set.

low intensity of the effect. The authors claim to have found no effect for an inverted delay and give for τ the value (1.45 ± 0.44) μsec. We started to arrange our equipment in the autumn of 1941. The already considerable time, necessary to make and calibrate the above mentioned set, was much increased by the war conditions. The work was finished in February, 1943 and published in *Nuovo Cimento*.[21]

2. COUNTER SETS

Two vertical sections of the whole set of counters, lead plates, and iron absorber are shown in Figs. 1(a) and 1(b). Our arrangement is similar to that of Montgomery and collaborators from which it differs in the number of coincidence branches (3 instead of 2), and in the counter-set for anti-coincidence marked in Fig. 1 with a letter A. This set, which is formed by an unusual number of counters, is able to reach a rather large intensity (about 40 times greater than that of Rasetti).

The first and second set of counters define a solid angle to which belong all mesons stopped by the iron absorber in which they disintegrate. The third set detects the disintegration electrons, since its pulses are registered only if in delayed coincidence with the first two sets. Finally the fourth set of counters, i.e., the anti-coincidence, has as its purpose the cancellation of registration of the delayed coincidences between the first three sets of counters which are accompanied by a particle crossing the fourth set. Between the first and the second set of counters (each set consisting of 6 counters of 4×25 cm^2 area connected in parallel) were placed about 15 cm of lead in order both to absorb almost completely the soft component and to get the energy interval of mesons stopped in iron in a suitable region of the differential mesonic spectrum. In fact it is known that at the sea level the spectrum of the hard component, owing to the disintegration of mesons in air, has a very low intensity for the first few centimeters of lead.[22] To the 15 cm of Pb we had to add about 150 g/cm^2 because of the 3 floors above our equipment.

The third set of counters is composed of 6

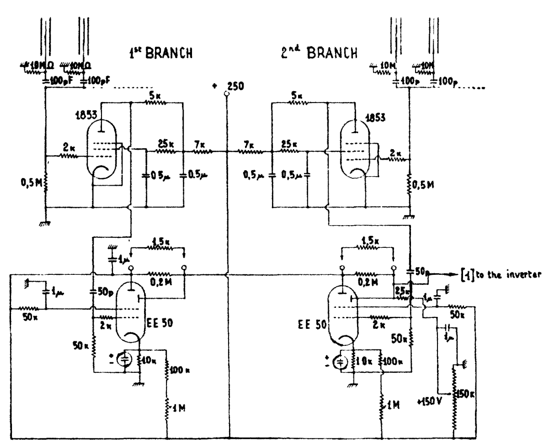

FIG. 3. Input amplifiers (first and second branches) and CS (1–2).

[21] M. Conversi and O. Piccioni, Nuovo Cimento 2, 40 (1944).

[22] Bruins, Proc. Roy. Soc. Amsterdam 17, 672 (1939); Cocconi, Ricerca Scient. 11, 58 (1940).

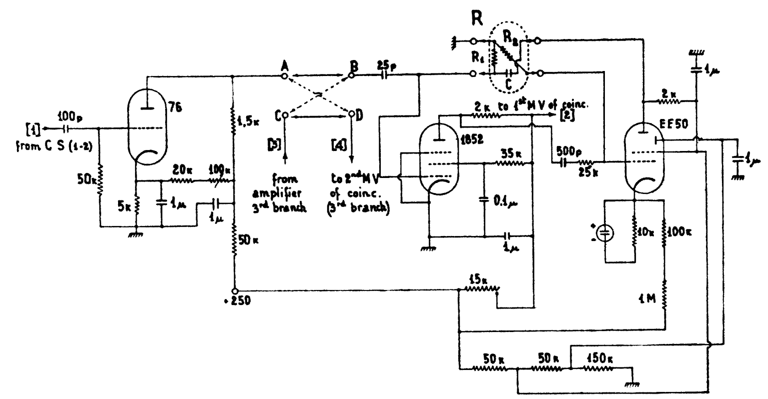

FIG. 4. Inverter and delaying multivibrator.

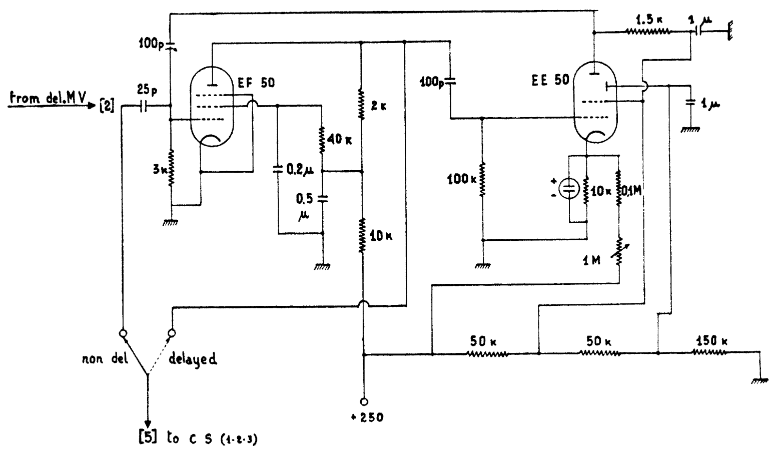

FIG. 5. First coincidence multivibrator.

counters of 4×40 cm^2 area. The absorber formed by an iron plate 5 cm thick could be inserted between the second and the third set of counters. The mesons stopped in iron decay giving electrons which, if emitted in proper direction, hit a counter of the third set.

All counters marked by A in Fig. 1(a) and (b) (29 counters 4×40 cm^2 area) belong to the fourth set, which we shall call *anti-coincidence.* Such a set, arranged to cover as completely as possible the solid angle defined by the first two sets of counters, was connected with the fourfold coincidence circuit; the intensity of the last, subtracted from the threefold coincidence intensity, allowed us to eliminate the spurious coincidences due to one or more particles of which one at least had crossed the fourth set and so reduced considerably the amount of spurious coincidences registered. Geometric reasons are mainly responsible for the anti-coincidence loss (see Section 5).

Just under the third set there is a lead plate 1 cm thick, where the decay electrons which have crossed the third set are stopped, so that they cannot reach the fourth set.

The lead plates placed on the sides of the second and the third set (Fig. 1(a), (b)) are 5 cm thick and protect these counters from the showers. For the same reason, the horizontal surface of the first lead plate 5 cm thick placed between the first and second set has been made about 45×45 cm^2 instead of 25×25 cm^2 as it was necessary to cover the solid angle formed by the first two sets of counters.

All counters are of metallic type filled with the Trost-mixture; the walls are of brass 1 mm thick. The counters of each set were connected as shown in Figs. 3, 6, and 8. This arrangement is particularly useful for sets of many counters, for it avoids in each counter all the voltage variations due to pulses in the other counters. Taking into account the time length ($\sim10^{-3}$ sec.) of each pulse and their large number, it is easy to recog-

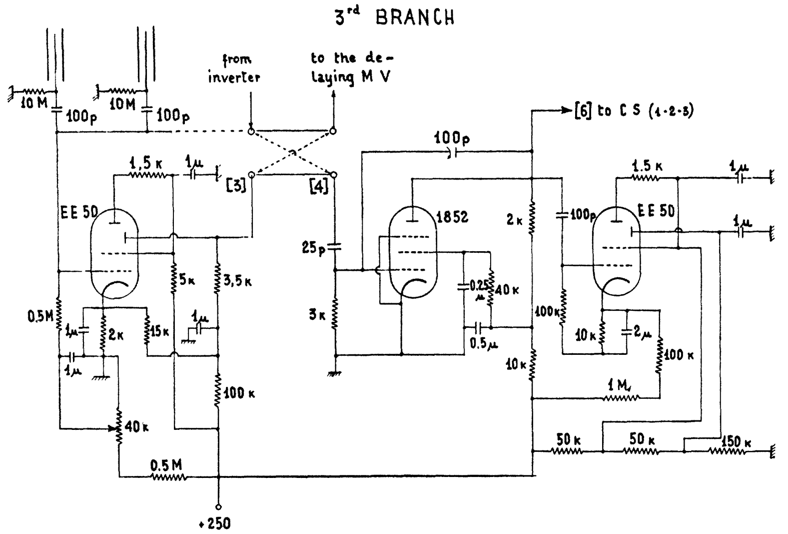

FIG. 6. Input amplifier (third branch) and second coincidence multivibrator.

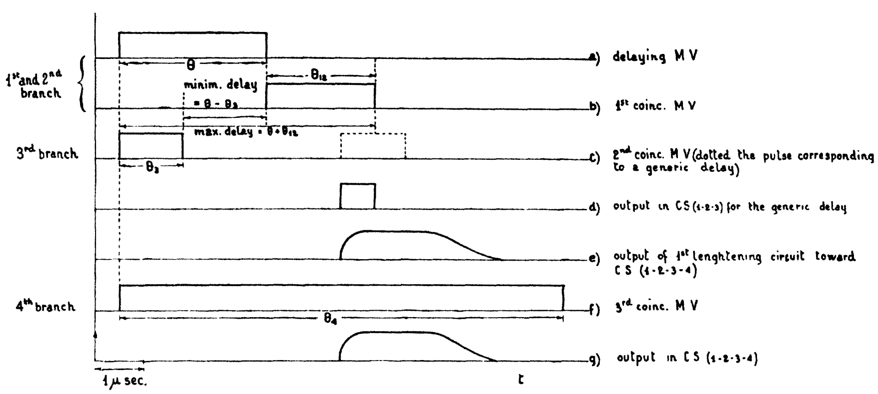

FIG. 7. Schematic diagram showing the time distribution of pulses.

nize that with a direct connection each counter would work for an appreciable fraction of time with a voltage lower than normal. The voltage on the counters was supplied by a vacuum tube stabilizer.

For the first three sets of counters a working voltage was chosen such that the sizes of the pulses was 25 volt ±10 percent. For the fourth set the size of the pulses was 35 volt ±10 percent. This has been done mainly to compensate for the reduction of the size of the pulses due to the remarkable capacity of the fourth set.

3. REGISTER SET

A block diagram of the registering set is given in Fig. 2. The more important circuit details are shown in Figs. 3–6 and 8.

The pulses of the first two branches, through an amplifying stage, enter $CS(1\text{–}2)$ which is, as $CS(1\text{–}2\text{–}3)$ and $CS(1\text{–}2\text{–}3\text{–}4)$, a twofold coincidence circuit of the type "series" (see Fig. 3).[23] At the output of CS we have a positive pulse (we get it from the secondary emission electrode)

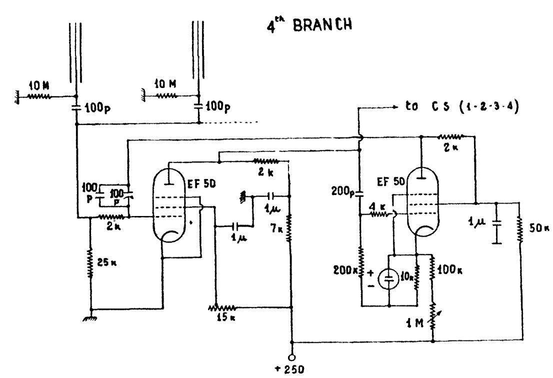

FIG. 8. Third coincidence multivibrator.

[23] Piccioni, Nuovo Cimento 1, 56 (1943).

which has to be reversed before being sent, through the AB connection, to the delaying multivibrator (MV) or to the second coincidence MV if we connect A with D.

As is known, a multivibrator is a circuit of two tubes the plates of each of which are connected by capacity to the grid of the other tube. This circuit, with proper bias, gives relaxation oscillations. However, one may adjust the bias such that the MV does not oscillate permanently, but gives only an oscillation when excited by a driving pulse. We obtain in this way a driven multivibrator; the time length and the shape of its oscillations are independent, within wide limits, of the form of the driving pulse.[24]

When a negative pulse comes in B, the delaying circuit gives a positive pulse of rectangular shape, the time length θ[25] of which depends on the values of the resistences R_1, R_2 and of the capacity C (Fig. 4); R_1, R_2 and C form an easily interchangeable element R.

The first coincidence MV (Fig. 5) as for all our MV is sensitive only to negative pulses. The pulse of the delaying MV is positive and reaches the first coincidence MV by means of a low value RC coupling. Therefore, the first MV coincidence starts immediately at the sudden decrease of the delay $-MV$ pulse, i.e., at the end of its positive pulse. The coupling condenser between the grid of EF50 and the plate of EE50 is a variable one (of the type of compensating condenser used in the normal radio sets) and allows one to adjust the time length θ_{12} of the pulse of the MV coincidence.

The behavior of all these circuits was frequently checked during the experiments by observations performed with a synchronized oscillograph (see Section 4).

One of the two $CS(1-2-3)$ tubes is connected with the output of the second coincidence MV; the other one can be connected either with the output E of the delaying MV (*non-delayed coincidences arrangement*) or with the output E of the first coincidence MV (*delayed coincidences arrangement*).

Thus at the first tube of $CS(1-2-3)$ the θ pulse or the θ_{12} pulse arrives; while at the second tube of $CS(1-2-3)$, the θ_3 pulse of the second coincidence MV arrives. This is for ***normal delay***. For *inverted delays* connections are shown in Fig. 2.

In the amplifying stage of the third branch, we used a secondary emission tube (EE50) so that the output pulse at the secondary cathode (Fig. 6) has the same sign as the input pulse. This pulse can be sent either to the second coincidence MV connecting C with D (when A is connected with B) or to the delaying MV when C is connected with B. In the first case, the *delay* is *normal;* in the second, it is *inverted*. In both cases the pulse which reaches D drives the second coincidence MV, the pulse of which has the same shape as the one of the first MV and a time length θ_3.

The coincidence pulse at the $CS(1-2-3)$ output has to be sent through a circuit (first lengthening-circuit, see Fig. 2) which may increase its time length to the counting circuit of the threefold coincidences and, at the same time, to $CS(1-2-3-4)$. At the other, input of the last circuit is supplied the pulse of the third coincidence MV (4th branch); we shall call θ_4 the time length of this pulse; θ_4 is large enough (see Fig. 7) to assure that the pulses θ_{12}, θ_3 are in coincidence with θ_4 between large limits. This MV for simplicity is driven by the counters (Fig. 8). The fourfold coincidence pulse at the $CS(1-2-3-4)$ output has to be sent to the circuit for fourfold coincidence numeration through a second lengthening circuit.

Figure 7 shows the mutual disposition, with respect to the time, of the pulses in the different circuit stage under the assumption of four contemporary pulses at the four branches input and considering the delays introduced by the branches themselves equal to zero or all equal.

In Fig. 7 it is clearly shown that the third branch-pulse must delay from a minimum of $\theta-\theta_3$ to a maximum of $\theta+\theta_{12}$ in order to give a threefold coincidence. Therefore, our set registers the portion of the decay-curve corresponding to a time interval of $\theta_{12}+\theta_3$, starting from the time $\theta-\theta_3$: we must expect that varying θ the number of the delayed coincidences due to delay electrons will follow an exponential curve.

The assumption in Fig. 7, that the delays introduced by the different branches are all equal, cannot be considered strictly true. In fact the delay introduced by one branch depends on several parameters (stray-capacity, inter-elec-

[24] Conversi and Piccioni, Nuovo Cimento **1**, 279 (1943).

[25] In general, we mean by θ_i the time length of the pulse.

trode-capacity, sensitivity of the branch, size of the counter pulse). In order to avoid considerable errors introduced by the inequality of the delays (above all on account of possible variation during the long time necessary for the experiment) we proceeded as follows: (a) We arranged the registering set so that the above-mentioned delays were as small as possible. (b) We made the delay circuit so that the delays of the branches were constant for the different interchangeable elements R (Figs. 2 and 4). Thus the difference of the branches introduces a constant delay T (positive or negative) and, therefore, only a multiplying factor $e^{-T/\tau}$ of the intensity. Of course, this does not give any source of error in the value of τ deduced from the experimental curve.

In order to insure that the pulse at the output of a branch has the smallest delay with respect to the pulse of the counter, it is necessary to introduce between the counter and the grid of the coincidence tube an amplifying stage which increases the amplitude and shortens the time length of the pulses. Now the above-mentioned delays depend mainly on plate circuits of this amplifying stage. These circuits, in fact, consist of a load resistance R in parallel with a capacity C with respect to the ground given by the various electrodes and the connecting wires. The delay given by the circuit is of the order of RC, the time constant of the circuit. For a normal tube we cannot make R lower than 50 kΩ, and on the other hand, the internal resistance of the tube, in parallel with R, is much higher. Since the value of C can be evaluated to about 20 μf, the value of RC, and, therefore, also of the delay is of the order of 10^{-6} sec. For many stages the resultant delay is, of course, the sum of the delays of each stage. Such a delay is intolerable in measurements of the present type.

As the value of C cannot be reduced appreciably, it is necessary to lower R, and therefore, in order to obtain a properly high amplification SR, it is necessary to use tubes with a high grid-plate transconductance S. For this reason in our experiment, we used tubes such as 1852, EF50, EE50, which allow one to reach amplifications of 10 to 20 with plate resistances of 2 to 3 kΩ. Under these conditions the above-mentioned delays are reduced by more than a factor 10.

Another crucial point in this experiment is that the resolving time of the set must be constant and free from any critical behavior. For such a purpose it is necessary that the size of the circuit pulses be independent, as much as possible, of the amplitude of counter pulses and constant during the experiment. Such a condition is satisfied by using an equalizing circuit as those we made on the MV principle.[24]

In the MV which we place before the coincidence circuits and in the delaying MV (Figs. 4–6, 8), high transconductance tubes were used for obtaining pulses extending over times of the order of a few microseconds and of almost rectangular shape. In addition by using these tubes the delays given by the branches were greatly reduced as above mentioned.

The use of these MV's is necessary but not sufficient to obtain a set with pulses and resolving power exactly defined, as this last condition depends also on the properties of the coincidence circuits—namely, while a Rossi coincidence circuit does not fit the above-mentioned condition on account of his high load resistance, a coincidence circuit of the "series" type[23] does not introduce any undesired delay. This circuit (Fig. 3) is more convenient than the Rossi's type also because the tubes work normally at their cut-off, saving much plate current (which is very useful for a set with many tubes) and allowing the use of capacity-resistance filters in the plate and the screen-grid supply-circuits. In addition the high slope of the tubes (EE50) we used provides that the minimum pulse necessary for the complete control of the plate current is very low ($\sim$5 volt), while on account of the normal working condition at the cut-off, it is possible to make any desired "cut" of the driving pulses.

To obtain the zero effect of a branch at the output of the coincidence circuit, a resistance of 1.5 kΩ is introduced, as shown in Fig. 3, between the plate and the secondary electrode of the other tube.

All the insulators bearing wires subject to sharp voltage variations have been made with "frequenta" in order to reduce as much as possible the ground capacity.

The different delays necessary for obtaining the decay curve were introduced by changing the R_1, R_2, C elements (arranged on a "frequenta" tube socket) forming the element R of the delaying MV (Fig. 4). The contemporary change of the values of both the resistances, and of the condenser C, allows one to keep constant the MV sensitivity and, therefore, to maintain unaltered the delays of the branches.

Low value resistances were introduced at the input of the branches in order to prevent self-oscillations which might appear as a consequence of the considerable amplification extending up to high frequencies. Low value resistances have been inserted also in the grid circuits in other parts of the set in order to reduce the corresponding currents and improve the pulse shape.

As can be seen from the diagrams, the plate feeding was unique; it was stabilized at 250 volts and could be regulated so as to compensate eventual slow variations of the stabilizer (with neon and iron-hydrogen tubes). On the other hand we have checked that variations of the plate potential of 10 percent do not affect in a noticeable way the behavior of the registering set. A small effect instead seems to take place for variations of the heating voltage of the tubes which was therefore stabilized.

In order to avoid the registration of interruptions or unexpected variations of the a.c. supply by the numerical counters, a thyratron "setting off" circuit S (Fig. 2) was introduced; this did not allow the numerator-circuits to act when the line voltage was lower than a fixed value. During the measurements taken throughout the night, a registering ammeter indicated the eventual periods of "set off" and a recording voltmeter registered the voltage variations, allowing in this way a check on the behavior of the "setting-off" circuit.

Using high transconductance amplifiers, multivibrators, and sets of "coincidences in series" we believe we have overcome all the technical difficulties inherent to the present problem.

The delays among the pulses produced by the same particle in different counters had also to be ascertained; more exactly, it was necessary to establish the frequency of these delays with respect to their value. Such delays were investigated by Montgomery and collaborators, who found that their counters (1×20 cm, filled with a mixture of argon 94 percent and oxygen 6 percent, pressure of 18 cm of Hg) had delays of about 2 μsec. with a frequency of 1.5 percent; for higher delays the frequency of the delays decreases reaching a value of about 0.5 percent for a delay of 5 μsec.

Rasetti, on the other hand, obtained full efficiency for twofold coincidences between two counters (one 2×22 cm^2 and the other 2×37 cm^2) in glass and filled with argon (5 cm Hg) and alcohol (1 cm Hg) at a resolving power of 0.5 μsec., which indicates that the above-mentioned delays are less than 0.5 μsec. For our counters (metallic type, 4×40 cm^2, filled with Trost's mixture) we found in a previous work[24] delays of 0.5 μsec. with a frequency of about 4.5 percent, and frequencies much less for delays near 1 μsec.

As it seems that such delays are mostly caused by differences in the steepness of different pulses, we have increased as much as possible the sensitivity of the registering set. The circuits we used kept a good sensitivity up to 10 MHz, so that shielding and, above all, grounding was rather difficult. The experimental conditions we finally attained were very satisfactory in this respect. We also took care to adjust each branch to the same sensitivity with respect to the counter pulses.

4. CALIBRATING SET

In order to have good accuracy in measuring the values of the delays corresponding to the different points of the decay curve, we thought that the best way was to get an oscillographic synchronized figure and to compare on the screen of the cathode-ray tube the unknown time interval with calibrating signal. The latter one was a sinusoidal signal of 1 MHz or 0.5 MHz. The distance between two consecutive crossings of the sinusoid with the zero axis gave therefore 0.5 μsec. and 1 μsec., respectively. The above-mentioned signal was obtained by means of a multiplication stage (checked on the oscillograph) and a quartz oscillator of 100 kHz (Fig. 9).

From the same oscillator, by means of a demultiplication stage, the horizontal deflecting signal was also driven, the frequency of which was 25 or 50 kHz. This signal, at first sinusoidal, was amplified through an aperiodic power stage (using a 6L6 tube) which cut on both sides the signal itself, while the central part was amplified

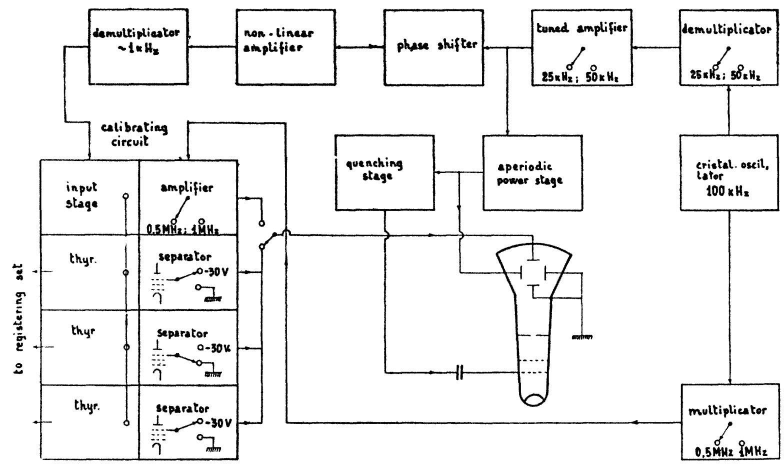

FIG. 9. Block diagram of calibrating set.

almost linearly. We could then obtain about 4 cm per μsec.

A quenching stage acted on the return. The calibration signal and the horizontal deflection, both coming from the same oscillator, were, of course, synchronized one with the other. A pulse generator which produced about 1000 pulses per second was also synchronized with the horizontal deflecting signal. Such a frequency was certainly much larger than the average number per second of the pulses, because of the zero effect of each branch, but since the registration was working with pulses of the order of 1 μsec. the overlapping of the pulses could be neglected. The only effect produced by the high frequency of the pulses was a change in the bias of those tubes which were working at cut-off with a resistance on the cathode. For the delaying MV such a variation was lower than 0.5 volt; but we have repeatedly verified the fact that a variation of 1 volt did not change at all the shape of the pulses.

In order to observe the pulses at the output of the calibrating set or at the registering stages, it is convenient to keep the pulse at the center of the oscillographic horizontal deflection. For such a purpose we used a circuit that we shall call "phase shifter," drawn from a plan given in the *Philips Technical Review*. It gave a phase-shift which could be regulated up to a maximum of about 180° with a rather constant amplitude.

The centered pulses, with a frequency of 1 MHz, were sent to a calibrating circuit consisting of three thyratrons (Fig. 10) which produced three pulses synchronized with the input pulse, but having a phase-shift among them which could be changed between 0 and 10 μsec.

The phase-shift was obtained by impressing on the grid of a 6J7 tube a pulse, driven by the above-mentioned generator, having a rising time of about 10 μsec. and by varying the thyratron bias. In this way the three pulses could be phase-shifted one with respect to the other by an amount less than 10 μsec. A minimum change of about 0.01 μsec. could be obtained.

The system has been so constructed that the ground capacity of the anode circuits of the thyratrons was as small as possible. In order to be certain that this capacity did not change during the oscillographic observations (the variation would have changed the pulse while observed) the plates of each thyratron were permanently connected through a small capacity to the grid of a 6J7 (acting then as separator tube) and the three plates of the 6J7 were connected together (Fig. 11). The passage from one to the other tube, necessary to observe one pulse or the other, was obtained by applying or not applying a high negative voltage (−30 volt) to the suppresser-grid of the 6J7's.

The calibrator allowed one to change the pulse amplitude by changing the thyratron anodic-voltage; by automatic adjustment of its cathode-bias at the same time, it was possible to maintain the pulse phase roughly constant.

The circuit proved good, especially for maintaining a constant phase of the thyratron pulses; as a matter of fact, no rippling appeared in a

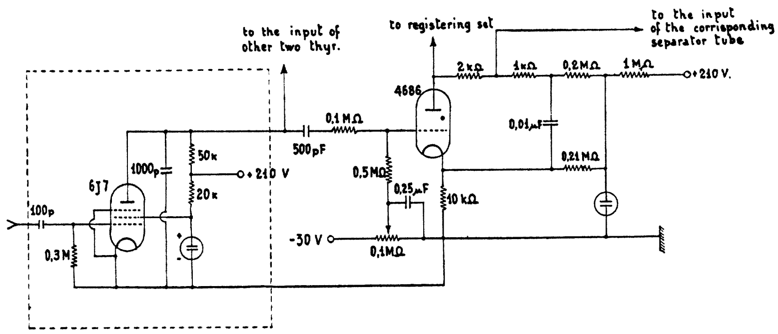

FIG. 10. Calibration circuit.

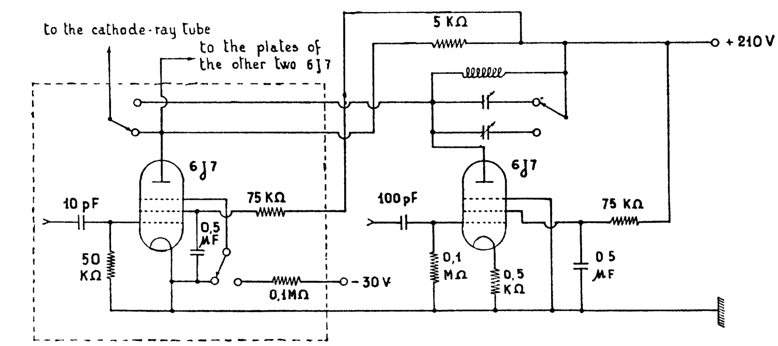

FIG. 11. Separator tube (three identical stages) and amplifier of the 0.5–1.0 MHz signal.

figure in which 1 μsec. corresponded to about 4 cm if a. c. supply did not change greatly.

The measurements of the various delays were made by marking successively over a Cellophane strip pressed against the oscillographic tube screen, the crossing points of the calibration sine wave with the zero axis and the starting point of the pulses. Normally only two branches of the calibrator were used: one connected with the first branch, the other with the third branch of the registering set, while the second and the fourth branches were short-circuited (see Section 3). Since the pulse given by a thyratron cannot be considered equal to that of a counter with respect to the steepness of the slope, the measurement did not give the absolute value of the delay but only the differences between the various delays. This is indeed what matters for the determination of the mean life.

5. CHECKS AND COMPUTATION OF RANDOM COINCIDENCES

On account of the low counting rate, it was necessary to check very frequently the proper behavior of the registering set. The more important measurements that we have repeated periodically are the following:

(a) Counting of the zero effects of the several counter sets. They were made (not very often) by means of a scale-of-16. The frequencies S^1, S^2, S^3, S^4 of the first, second, third, fourth set (pulses/min.) were as follows:

$$S^1=3300;\quad S^2=1540;\quad S^3=2350;\quad S^4=20,000.$$

For the fourth set the given value (obtained by means of two scales-of-16 in series) is approximate, because the first stage of the scale circuit missed some pulses.

(b) Check of transmission of a branch, i.e., it was ascertained that the counting rates at the input and output of each branch were equal one to the other.

(c) Measure of the twofold undelayed coincidences D_{12} between the first and the second set and of the threefold coincidences T_{123} among the first three sets. The average was:

$$D_{12}=7600/\text{hour};\quad T_{123}=5.000/\text{hour}.$$

(d) Measure of the efficiences:

$$\rho_1=Q/T_{123};\quad \rho_2=T_{124}/D_{12};\quad \rho_3=D_{34}/S_3,$$

where Q represents the intensity of the undelayed fourfold coincidences. Counting the undelayed coincidences we found the following average values:

$$\rho_1=0.948;\quad \rho_2=0.932;\quad \rho_3=0.240.$$

For these measurements we used two scale-of-8 counters, one connected to the output of the fourfold coincidences and the other connected to the output of the threefold coincidences.

(e) Oscillographic check of the amplitude of counter pulses.

(f) Measurements of the twofold delayed (with a great delay) coincidences C_d of one of the first two sets (connected with one of the first two registering branches) with the fourth set (connected with the third branch). The third branch, less sensitive than the fourth, transmitted only about the 75 percent of the pulses of the fourth set on account of the low peak value of the pulses, because of the great capacity (29 counters) of the set itself.

During these measurements we used to short-circuit the fourth branch: in this way we checked also the lengthening circuits, verifying the identity of the number of the pulses registered by the two numerator circuits.

The average was (with no great precision): $C_d=140$/hour.

(g) Determination (by means of the above-mentioned calibrator) of the times θ_{12}, θ_3, θ_4 of the three MV pulses; of the delays θ corresponding to the various elements R; and of the double of the resolving power of CS(1–2–3). We found:

$$\theta_{12}=1.2\ \mu\text{sec.};\quad \theta_3=1.3\ \mu\text{sec.};\quad \theta_4=9.0\ \mu\text{sec.}$$

The double of the resolving time of CS(1–2–3) was about 3 μsec.

(h) Check (made by taking away the voltage of the counters of one set) of the absence both of inductions among the registering branches and of external disturbances.

(i) Measurements of the intensity of the delayed coincidences with small delays. These coincidences are mainly caused by fluctuation in the steepness of the counter pulses (random delay coincidences): their intensity as a function of the delay time (that is, for the several values chosen for the elements R) is represented in Fig. 12, from which we can appreciate the variations of the absolute delay corresponding to a particular element, for instance R_{-1}, by the variation of the frequency registered with the same element R_{-1}. The variation of the absolute delay may be caused by a change in the amplitude of the pulses of the counters, as we have really verified by making measurements with different voltages on the third set of counters. The value of such variations was about 0.1 μsec. for a variation of about 30 percent in the pulse amplitude, while it became inappreciable for simultaneous voltage variation in all the counter sets. Though this shift had an equal repercussion on all the delays and did not alter the τ determination obtained by regularly alternated measurements, we checked, at least once a day, the delayed coincidence frequency with respect to the element R_{-1}.

This measurement was a critical check of the behavior of our registering set and in particular of the counters. The curve obtained with small delays is shown in Fig. 12; the small circles give counting rates corresponding to the different elements R. The curve was obtained several times during the experiment.

The threefold delayed coincidence frequency can be attributed not only to the disintegration electrons (the intensity of which we shall indicate with M) but also:

(1) To the random delay coincidences r due to the same particle which crosses the first three counter sets, giving three pulses conveniently shifted one with respect to the other. Part of them, $\rho_1 r$, are quadruple coincidences, where ρ_1 is the same efficiency Q/T_{123} which is measured for the undelayed coincidences.

(2) To the pure coincidences c due either to two particles one of which crosses the first two sets of counters and the other crosses the third with suitable disposition in time, or to three particles.

One can easily see that of the triple coincidences c, the fraction $(1-p_2p_3)c$ is caused by quadruple coincidences, where p_i are the losses corresponding to the efficiencies ρ_i, i.e.,

$$p_1=1-Q/T_{123};\quad p_2=1-T_{124}/D_{12};\quad p_3=1-D_{34}/S_3.$$

Considering that the lead plate 1 cm thick beneath the third counter set absorbs all the disintegration electrons (as can be seen from the identity of the quadruple intensity with and without absorber), we can write:

$$\text{III}=M+r+c;\quad \text{IV}=(1-p_1)r+(1-p_2p_3)c$$

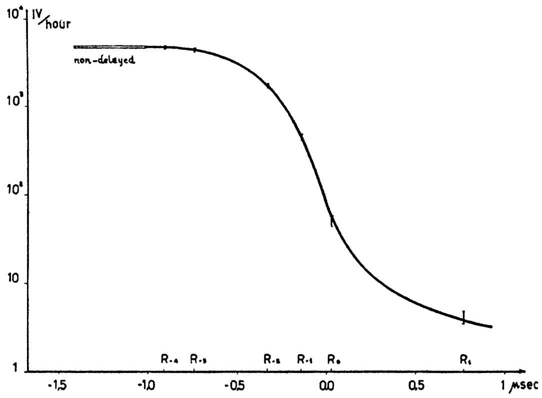

FIG. 12. Fourfold coincidence rates at small delays.

and since with our particular counter arrangement we found from the measurements: $p_1 \cong p_2 p_3 = 0.052$, we have

$$\Delta = \text{III} - \text{IV} = M + p_1(r+c) = M + \frac{p_1}{1-p_1}\text{IV}.$$

If, for convenience, we put $p = p_1/(1-p_1)$, we obtain: $M = \Delta - p\text{IV}$.

This evaluation of the random coincidences is to be preferred to that obtained from the measurements without iron, because of the smaller statistical error. In fact it should be noticed that p, which can be deduced from the measurements without delay, is known with a precision much greater than that corresponding to Δ and to IV, so that one can write

$$\pm(M)^{\frac{1}{2}} = \pm(\Delta)^{\frac{1}{2}} \pm p(\text{IV})^{\frac{1}{2}} = \pm(\Delta + p^2\text{IV})^{\frac{1}{2}},$$

but since $\Delta > p\text{IV}$ and $p = 0.055$, we can at once allow the error on M to be equal to the error on Δ.

Then

$$M = \Delta - p\text{IV} \pm (\Delta)^{\frac{1}{2}}.$$

6. DISCUSSION OF RESULTS

Figure 13 taken from the data given in the sixth columns of Tables I and III, shows the comparison between the results of the "normal" and the "inverted" measurements. The zeros of the time axis are not thought coincident for both curves, because the delays are presumed to vary from one to the other of the two groups of measurements.

However, such a variation is surely not greater than some tenths of μsec.

Figure 13 gives a rather reliable proof of the real existence of the disintegration of mesons.

The measurements for determining τ have been divided into five series corresponding to five successive periods[26] of work, during each of which the counter voltages had undergone negligible changes. The results are reproduced in Table II. Then the five series were put together, all referred to the delays of the third, i.e., introducing a correction in order to consider the small differences among the delays of the various series and those of the third. This has been evaluated by assuming an exponential decay of 2.2-μsec. mean life, as suggested by a first plot of the results.

We have considered also the small shift indicated by the intensities of the quadruple coincidences (IV) observed with R_{-1} element, which can be caused by small variations in the working conditions of the counters.

Both these intensities and the values of the losses p have been obtained as an average of the measurements made during each series.

The delay of the element R_2 has been assumed arbitrarily equal to zero, for its value—measured with the calibrating set—remained more constant than that of the other delaying-elements.

Also the R_{-1} delaying-element changed so little that we considered it as constant through all the series.

The errors in the delays have been evaluated both by considering the precision of the applied method and by repeating the measurements many times; the given values (Table II), 0.05 μsec. for the element R_1, R_2, R_3, and 0.1 μsec. for R_4, are mean square errors. They have been transformed into errors in M and combined with the statistical error always assuming an exponential slope with a mean life of 2.2 μsec. The corresponding variations of the delayed coincidence intensity is ± 2.3 percent for a change in the delay of ± 0.05 μsec.

A summary of the results of the five series of measurements is given in Table III and plotted in Fig. 14 on a semi-logarithmic scale.

The four points taken from the results of the

[26] At the end of the first series (September, 1943) we have been forced to stop our work for about two months. The consistency among the results of this and the successive series is however satisfactory. We want to thank Doctor C. Festa for the help she gave us in accomplishing the first series of measurements.

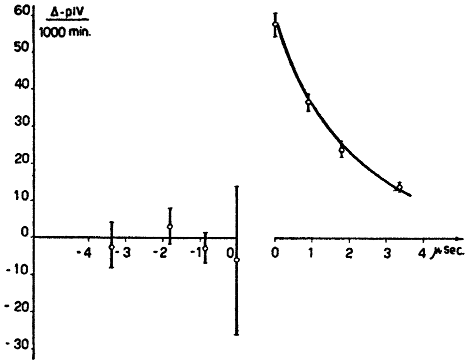

FIG. 13. Comparison between *normal* (right) and *inverted* (left) measurements (with absorber).

measurements made with the Fe absorber lie along a straight line proving in a satisfactory way the exponential shape of the decay-curve.

With the method of least squares we get for τ, using the measurements with iron absorber, a mean value 2.33 μsec. and the extreme values 2.19 and 2.50; therefore, we conclude

$$\tau = 2.33 \ \mu\text{sec.} \pm 6.5 \text{ percent.}$$

Table III gives also the results of the measurements made without iron absorber, which also are plotted in Fig. 14. It is clear that also in these conditions a small fraction of the decay electrons is present. If one takes into account the considerable errors of the points corresponding to these measurements, we find the same decay coefficient as obtained in the measurements with absorber. Also for this reason we thought it more convenient to evaluate the random coincidences by the product pIV than by the measurements without absorber.

It should be noted however that even without any correction, the results of the measurements with Fe (normal delay) would have nearly the same shape as that shown in Fig. 14, since the corrections and the random coincidences amount to but a small fraction of the effect.

The decay electrons, which appear in the measurements without Fe, are probably generated in the counter walls of the second and third set, and in the lead between the third and the fourth set.

In this last case, however, a considerable geometric limitation is imposed by the presence of the lateral anti-coincidence counters and by the long recovery-time of counters (10^{-3} sec.) which requires that the decay electron hit a counter of the third set different from the one crossed by the primary meson.

A comparison between our results and the value of the ratio $\tau/\mu c^2$ obtained from the most recent differential experiments[2–14] on anomalous absorption is of interest.

Since there are reasons to think that the value given by Nielsen, Rierson, Nordheim, and Morgan is too small we shall consider only the results of Rossi and Hall[7] and those of Bernardini, Cacciapuoti, Pancini, and Piccioni.[10] According to these measurements, as pointed out by Bernardini,[14] the most reliable value of $\tau/\mu c^2$ is $3.0 \pm 0.3 \times 10^{-8}$ sec./Mev.

Referring to this value, our determination of τ gives for the rest-energy of mesons a value be-

TABLE I. Inverted measures.

		With absorber				Without absorber			
	Delay (μsec.)	III	IV	Min.	(Δ−pIV)/1000′	III	IV	Min.	(Δ−pIV)/1000′
R_1	0.00	1002	952	318	−6.0±20	245	232	120	8.5±30
R_2	−0.91	83	80	493	−3.0±4	24	22	170	5.0±8
R_3	−1.81	35	32	370	3.0±5	39	35	413	5.0±5
R_4	−3.34	26	266	510	−2.5±/	18	17	319	0.0±2

TABLE II. Data corresponding to the five series of normal measurements with absorber (5 cm Fe).

	Series	Delay* (μsec.)	III	IV	Min.	Reduc. min.	p(%)	(Δ−pIV)/60′
R_1	1	−1.00	273	179	1430	1468	4.9	3.47±0.4
	2(a) (b)	−1.08	218	154	490 360	561 388	4.7	3.60±0.5
	3	−0.91	156	104	840	840	6.1	3.34±0.5
	4	−0.90	195	122	1116	1080	5.8	3.65±0.5
	5	−0.82	367	279	1324	1240	5.7	3.49±0.55
R_2	1	0.00	100	30	1725	1700	4.9	2.42±0.3
	2(a) (b)	0.00	44	14	715 90	755 90	4.7	2.08±0.4
	3	0.00	68	31	1179	1179	6.1	1.80±0.3
	4	0.00	122	50	1846	1798	5.8	2.30±0.3
	5	0.00	130	50	1864	1815	5.7	2.55±0.3
R_3**	3	0.97	69	21	2240	2240	6.1	1.26±0.2
	4	0.98	147	37	4072	3940	5.8	1.64±0.15
	5	0.93	121	50	3015	2988	5.7	1.37±0.2
R_4	1	2.80	39	14	1933	1703	4.9	0.86±0.17
	2(a) (b)	2.58	35 89	14	1002 550	990 550	4.7	0.79±0.18
	3	2.43		34	3921	3921	6.1	0.82±0.12
	4	2.47	133	47	6777	6500	5.8	0.77±0.085
	5	2.51	203	85	7777	7316	5.7	0.93±0.10
R_{-1}	1	−1.70			578 IV/hour			
	2(a) (b)	−1.73			1370 IV/hour 735 IV/hour			
	3	−1.70			678 IV/hour			
	4	−1.73			473 IV/hour			
	5	−1.71			478 IV/hour			

* The delays of the first series have been obtained by means of an oscillographic method, less exact than the one described in this paper.
** The delay R_3 has been introduced at the end of the second series.

tween 60 and 90 Mev; i.e., the meson mass would be about 150 electronic masses, in agreement with the mean value of the more reliable direct measurements of the meson mass, as far as we know.[27] The value of the meson mass as calculated from a weighted average of results of various authors[28–35] is, in fact, 170±20. In addition the agreement between the values of $\tau/\mu c^2$ calculated (1) from our measure of τ and from those of mass as above mentioned and (2) from the differential experiments on anomalous absorption, would suggest that the assumption on which the $\tau/\mu c^2$ calculations are based in these last experiments are reliable. In particular it would result that the hard component of cosmic rays, as observed in the lowest part of the atmosphere, is mainly formed by mesons originating more than 4000 meters above sea level, and all unstable with the same mean life.

However, our results, considered alone, cannot eliminate the assumption, recently advanced,[36] of a complex nature of the hard component, since the decay curve which we have obtained (with iron and normal delay) does not exclude the existence of mesons having, for instance, two different mean lives mixed in a suitable percentage. However this assumption does not agree with results of other experiments.[13–37]

TABLE III. Definitive results of normal measures.

		With absorber				Without absorber			
	Delay (μsec.)	III	IV	Reduc. min.	$M/60'$	III	IV	Reduc. min.	$M/60'$
R_1	−0.91	1209	838	5577	3.50±0.22	588	529	2741	0.66±0.18
R_2	0.00	464	175	7337	2.22±0.15	98	74	3133	0.38±0.09
R_3	0.97	335	106	9346	1.43±0.10	20	12	1166	0.38±0.15
R_4	2.43	499	194	20980	0.84±0.06	37	27	3322	0.15±0.06

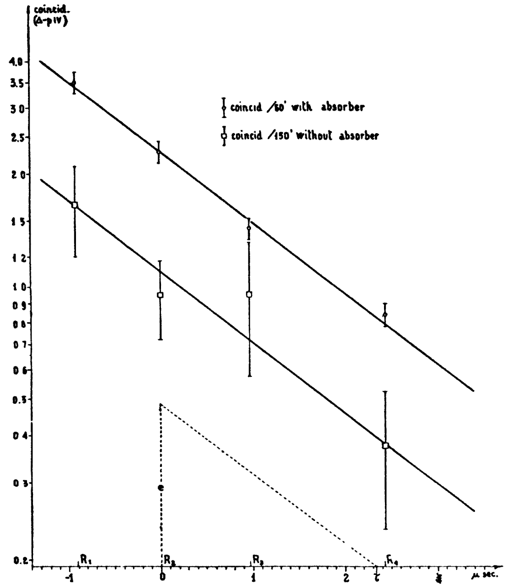

FIG. 14. Decay curve with and without absorber.

The authors take pleasure in thanking Professor G. Bernardini for many helpful discussions and Professors E. Amaldi and G. C. Wick for their advice and encouragement throughout the progress of this work. A fund for researches on nuclear physics was granted by the "Consiglio Nazionale delle Ricerche."

[27] We have not received foreign publications since 1940.
[28] Street and Stevenson, Phys. Rev. **52**, 1003 (1937).
[29] Nishina, Takeuchi, and Ichimiya, Phys. Rev. **52**, 1198 (1937).
[30] Merle A. Starr, Phys. Rev. **53**, 10 (1938).
[31] Ruhling and Crane, Phys. Rev. **53**, 266 (1938).
[32] Corson and Brode, Phys. Rev. **53**, 773 (1938).
[33] Williams and Pikup, Nature **141**, 684 (1938).
[34] J. G. Wilson, Proc. Roy. Soc. **172**, 522 (1939).
[35] Nishina, Phys. Rev. **55**, 585 (1939).
[36] Juilfs, Naturwiss. **30**, 584 (1942).
[37] Bernardini, Conversi, Pancini, Scrocco, and Wick, Phys. Rev. **68**, 109 (1945).