Experimental Determination of the Disintegration Curve of Mesotrons

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The disintegration curve of mesotrons has been experimentally determined by investigating the delayed emission of disintegration electrons which takes place after the absorption of mesotrons by matter. Within the experimental errors, the disintegration curve is exponential and corresponds to a mean lifetime of 2.3 ± 0.2 microseconds.

1. INTRODUCTION

THE purpose of the experiment described in the present paper was to determine the disintegration curve of mesotrons at rest. The experiment was performed by investigating the delayed emission of the disintegration electrons, which takes place after the absorption of mesotrons by matter.

Experiments more or less closely related to the present one have been reported previously by Montgomery, Ramsey, Cowie, and Montgomery,[1] by Rasetti,[2] and by de Souza Santos.[3] The experiment by Montgomery and his collaborators failed to give any significant result. The experiment by Rasetti consists essentially of the determination of two points of the disintegration curve and gives a mean life of (1.5 ± 0.3) μsec. under the assumption of an exponential decay. De Souza Santos reports some very surprising results which seem to indicate that the disintegration processes are not distributed according to an exponential but rather according to a Gaussian law with center at 5 μsec.

The previous experiments were performed by means of special coincidence circuits designed in such a way as to record only those electrons which were emitted from the absorber within preselected time intervals after the arrival of the mesotrons. We have succeeded in increasing the selectivity and the statistical accuracy of the method considerably by recording all decay electrons and measuring the time interval between the arrival of each mesotron and the emission of the corresponding electron. The circuit used for this measurement will be referred to as the *time circuit*.

[1] C. G. Montgomery, W. E. Ramsey, D. B. Cowie, and D. D. Montgomery, Phys. Rev. **56**, 635 (1939).
[2] F. Rasetti, Phys. Rev. **60**, 198 (1941).
[3] M. D. de Souza Santos, Phys. Rev. **62**, 178 (1942).

In its simpler form, the time circuit measures the delay τ between the pulses of two Geiger-Müller counter tubes A and B. The two pulses are fed to two separate inputs a and b. At the output a signal is obtained, the amplitude of which is a function of τ. This signal can be recorded either with a cathode-ray oscilloscope and a photographic camera or with a pen-writing instrument. If only counter A is discharged, a large output pulse is recorded (corresponding to $\tau=\infty$). No pulse is recorded if only counter B is discharged. While the circuit is primarily designed for the measurement of *positive* delays (counter B discharged *after* counter A), the "zero line" can be shifted by introducing an artificial delay in the branch b so that small *negative* delays (counter B discharged *before* counter A) may be also measured.

A slight modification of the time circuit makes it possible to measure the delay between a coincidence of two counters A_1 and A_2 and the pulse of a third counter B. In the modified circuit a signal is recorded whenever A_1 and A_2 are discharged within 15 μsec. of each other and the amplitude of the signal is a function of the delay between the pulse of either counter A_1 or A_2, whichever is discharged later, and the pulse of counter B.

The time circuit was calibrated by means of artificially produced double pulses with known time separations. To generate such pulses we used two different circuits, in which the time scale was supplied by the rate of charge of a known condenser through a known resistor and by the period of a crystal-controlled quartz oscillator, respectively. The calibration curves obtained with the two circuits differ by about 10 percent. The circuit involving the quartz oscil-

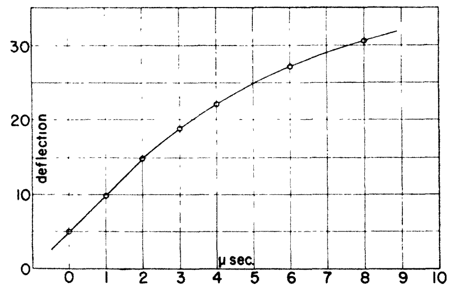

FIG. 1. Calibration curve of the time circuit.

lator appears to be more reliable and has been adopted in the final measurements. Figure 1 gives a sample of a calibration curve obtained with this circuit.

A detailed description of the construction, the operation, and the calibration of the time circuit will be given elsewhere.

2. TIME LAGS OF GEIGER-MÜLLER COUNTERS

The discharges of Geiger-Müller counters are known to be affected by variable time lags.[1,4] Since the data published so far on this phenomenon did not appear sufficiently definite and complete, a preliminary test was made to determine whether or not the natural time lags of the counters could seriously affect our main measurements.

Figure 2 represents schematically the arrangement used for this test. The Geiger-Müller counters L, A, and B are of the all-metal type, filled with a mixture of argon (10 cm Hg) and alcohol (1 cm Hg). A and B are 20 cm long, 2.5 cm in diameter, with a central wire of 7-mil tungsten. They are operated about 120 volts above starting potential. The three counters L are connected in parallel. The pulses of counters L, A, and B are fed to a threefold coincidence circuit C. Counters A and B are also connected to the inputs a and b of the time circuit T. The output pulses of the coincidence circuit are used to turn on the beam of a cathode-ray oscilloscope included in the recording apparatus R, while the output pulses of the time circuit are fed to the deflecting plates of the same oscilloscope. Whenever a particle traverses counters L, A, and B a record is obtained from which the time lag between the discharges of counters A and B can be determined.

Measurements were taken with two different pairs of counters and the distributions of the time lags recorded are represented in Fig. 3. It will be noted that the center of gravity of the delays falls at about 0.1 μsec. rather than at 0. This shift is accounted for by the difference in shape between the pulses of the counters and those of the calibrating circuit. A slight influence of the pulse shape on the output signal of the time circuit may be anticipated from an analysis of this circuit. The existence of such an effect has been experimentally verified by changing the pulse shape of the calibrating circuit with added capacities. It has been verified also that the absolute magnitude of the error involved does not change when the size of the delay is increased.

The observed delays seem to be distributed about 0.1 μsec. according to an approximately Gaussian law with a r.m.s. deviation of about 0.2 μsec. This time is short compared with the lifetime of mesotrons which is known to be of the order of several μsec. We conclude that the natural time lags of alcohol-argon counters are small enough to make their use possible in a direct measurement of the lifetime of mesotrons. This is not necessarily true for other types of counters.

3. THE DETERMINATION OF THE DISINTEGRATION CURVE

The geometrical arrangement of counters and absorbers in our main experiment (Fig. 4) was not essentially different from the arrangements used by Rasetti and by de Souza Santos. The three counters L were connected in parallel and so were the four counters B and the five counters M. Nine cm of lead was placed in P_1 to cut off the electron component of cosmic rays. A brass plate

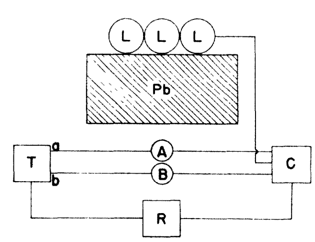

FIG. 2. Experimental arrangement for the measurement of natural time lags of Geiger-Müller counters.

[4] C. G. Montgomery and D. D. Montgomery, Phys. Rev. **59**, 1045 (1941).

of dimensions 25.5×8×2.3 cm was placed in Br and a lead plate 1.4 cm thick in P_2. The number of mesotrons traversing L, A_1, and A_2 was about 600 per hour, and of those 11 ± 2 were absorbed by the brass plate Br. The last figure was determined by recording the number of anticoincidences (L, A_1, A_2, $-M$) with and without the brass plate.

Counters L, A_1, A_2, and B were connected to the coincidence branch of an anticoincidence circuit C while counters M were connected to the anticoincidence branch of the same circuit. Since counters M completely cover the solid angle subtended by L, A_1, A_2, and B, the mesotrons traversing these counters do not produce anticoincidences except for lack of efficiency of the counter group M and for the few mesotrons stopped by the lead plate P_2. Anticoincidences may also be produced by showers coming from the side or by large-angle scattering of mesotrons in the plate Br. Finally, there will be anticoincidences caused by mesotrons which traverse L, A_1, A_2, and which are stopped in Br and then disintegrate into electrons which discharge one of the counters B. The resolving time of the anticoincidence circuit was very large compared with the lifetime of the mesotrons, so that practically no anticoincidences were lost because of the finite life of the mesotrons in the brass plate. The purpose of the lead plate P_2 was to decrease the probability of counters M being discharged by a decay electron and thus prevent the recording of an anticoincidence.

Counters A_1, A_2, and B were also connected to the inputs a_1, a_2, and b of the time circuit T. The output pulses of C and T were fed to the recording device R, which operated in such a way that a pulse from T was recorded only when it was accompanied by a pulse from C within approximately 10^{-2} second. In the first part of the measurements the recording instrument was a cathode-ray oscilloscope, as in the experiments on the time lags of counters (see Section 2). Later it was found more convenient to change to a pen-writing instrument. It may be mentioned that the results obtained in the two sets of measurements were perfectly consistent with each other.

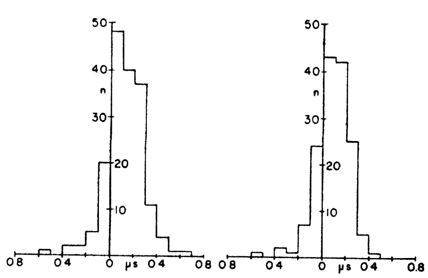

FIG. 3. Distribution of natural time lags for two different pairs of counters. The ordinates n are the numbers of delays recorded per 0.1-μsec. interval.

As we have just seen, a pulse is recorded by R

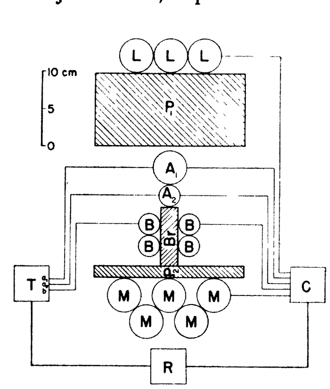

FIG. 4. Experimental arrangement for the determination of the disintegration curve of mesotrons.

whenever an anticoincidence (L, A_1, A_2, B, $-M$) occurs and the amplitude of this pulse is a measure of the time interval between the coincidence (A_1, A_2) and the pulse of B. Apart from the time lags of the counters, this time is equal to the life of the mesotron in the brass plate Br, when the anticoincidence is caused by a disintegration process. The time is practically zero when the anticoincidence is caused by spurious effects; i.e., lack of efficiency of counters M, absorption of mesotrons in P_2, showers coming from the side, or scattering.

The results obtained are summarized in Table I (Exp. A) along with the results of some control runs carried out without the brass plate Br (Exp. B). The last measurements were taken partly with and partly without the lead plate P_2. No difference exceeding the statistical fluctuations was found in the two cases. We consider the delays larger than 0.99 μsec. almost entirely caused by disintegration processes. In the interval $0.55<\tau<0.99$ μsec. most of the delays are again due to the same cause, at least in Exp. A, while most of the anticoincidences accompanied by delays smaller than 0.55 μsec. are accounted for

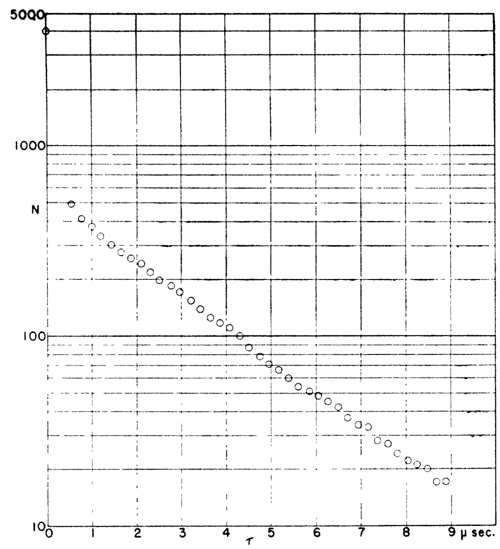

FIG. 5. Experimental disintegration curve of mesotrons. The abscissa τ is the delay recorded by the time circuit, the ordinate is the logarithm of the number N of anticoincidences accompanied by delays larger than the corresponding abscissa (Exp. A).

by spurious effects. The frequency distribution of the delays recorded in Exp. A is represented on a semi-logarithmic scale in Fig. 5. The experimental points lie on a straight line as closely as one can expect considering the statistical fluctuations, with the exception, of course, of the point at $\tau=0$ and possibly the one at 0.55 μsec. Hence the disintegration of mesotrons follows an exponential law as does any ordinary disintegration process.

The above interpretation of our experimental results is substantiated by the following analysis of possible sources of error.

(a) A delay may be recorded if a spurious anticoincidence is accompanied by a spontaneous time lag in counter B. However, direct measurements have shown (Section 2) that the natural time lags of counters hardly ever exceed 1 μsec., while in Exp. A almost 10 percent of the anticoincidences were accompanied by delays larger than this amount.

(b) When counters A_1, A_2 are discharged and none of counters B is, the time circuit T gives a large pulse. This pulse will be recorded by R if it is preceded by an anticoincidence (L, A_1, A_2, B, $-M$) within a time shorter than the recovery time of $C(\sim 10^{-2}$ sec.), or if it is followed by such an anticoincidence within a time shorter than the recovery time of $T(\sim 10^{-2}$ sec.). It can be shown that about 0.3 percent of the anticoincidences recorded should be accompanied by such spurious pulses simulating delays larger than 1 μsec., and that more than half of these delays should be larger than 10 μsec. Hence only the number of very long delays may be affected appreciably by the above chance coincidences.

(c) A delay may be recorded when an anticoincidence (L, A_1, A_2, $-M$) is followed by an independent pulse in one of counters B within a time shorter than the resolving time of the anticoincidence circuit. It may be estimated that this will happen about once every 1500 events recorded under the conditions of Exp. A. Thus the effect is negligible.

That neither natural time lags of counters nor chance coincidences are responsible for any large fraction of the observed delays is most clearly confirmed by Exp. B where the removal of the brass plate Br is seen to reduce the number of delays larger than 0.99 μsec. much more strongly than the total number of anticoincidences recorded. This result is self-evident if the delays are produced by disintegration of mesotrons in Br. It could hardly be understood if the delays were to be accounted for by time lags or by chance coincidences. It seems likely that the most of the delays between 0.99 and 8.91 μsec. in Exp. B are due to disintegration processes taking place mainly in the walls of the counters. This view is supported by the fact that the distribution of these delays seems to be more or less the same as in Exp. A as far as one can tell from the small number of events recorded. In Exp. B more delays between 0.55 and 0.99 μsec. were recorded than are explainable by decay of mesotrons. Some

TABLE I. Summary of the experimental results. t is the time of observation in hours, n the number of anticoincidences recorded for which the delay τ is within the specified interval. Experiments A and B were performed with and without the brass plate Br, respectively.

Interval (microseconds)	Experiment A n	n/t	Experiment B n	n/t
$\tau<0.55$	3506	6.51	1298	5.57
$0.55<\tau<0.99$	121	0.22	23	0.10
$0.99<\tau<4.95$	307	0.57	21	0.09
$4.95<\tau<8.91$	54	0.10	2	0.01
$\tau>8.91$	17	0.03	5	0.02
Total	4005	7.43	1349	5.79

of these delays must be attributed to time lags of the counters.

4. NUMERICAL VALUE OF THE LIFETIME

For the evaluation of the lifetime τ_0 we shall use the following equation:

$$\begin{aligned}\rho &= [N(\tau_1)-N(\tau_2)]/[N(\tau_2)-N(\tau_3)] \\ &= [\exp(-\tau_1/\tau_0)-\exp(-\tau_2/\tau_0)]/ \\ &\qquad [\exp(-\tau_2/\tau_0)-\exp(-\tau_3/\tau_0)], \quad (1)\end{aligned}$$

where $N(\tau)$ is the number of mesotrons surviving at the time τ after their absorption in the brass plate. If we take $\tau_1=0.99$ μsec., $\tau_2=4.95$ μsec., $\tau_3=8.91$ μsec., then $\tau_2-\tau_1=\tau_3-\tau_2=\Delta\tau=3.96$ μsec. Equation (1) reduces to

$$\rho=\exp(\Delta\tau/\tau_0),$$

and the experimental data set forth in Table I yield

$$\tau_0=2.3\pm0.2\ \mu\text{sec.},$$

where the error indicated is the standard statistical error.

We have selected the above method of calculation which does not involve delays larger than 8.91 μsec. because an appreciable number of these delays may have been produced by chance coincidences.

It is important to examine whether and to what extent our results may be affected by errors other than purely statistical.

(a) Delays due to chance coincidences have been neglected. An approximate correction for these delays would lower the value of the lifetime by 0.05 μsec. which is negligible compared with the statistical error.

(b) When a disintegration process is recorded, the time measured by the time circuit is not exactly equal to the time interval between the arrival of the mesotron and the emission of the decay electron. This is so because of the time lags of the counters and because of the small error caused by the difference in shape between the pulses of the counters and of the calibration circuit (see Section 2). Both sources of error may be included in an error function $f(\tau')$ such that $f(\tau')d\tau'$ gives the probability of recording a delay between $\tau+\tau'$ and $\tau+\tau'+d\tau'$ when the actual delay is τ. The function $f(\tau')$ is not symmetrical with respect to zero. It is important to note that it is independent of τ. Let $N(\tau)$ be the true disintegration curve of mesotrons. The observed disintegration curve will be, for all $\tau>\tau_1$:

$$N_{\text{obs}}(\tau)=\int_{-\tau_1}^{+\tau_1} N(\tau-\tau')f(\tau')d\tau',$$

where τ_1 is such that $f(\tau')$ is practically zero for $|\tau'|>|\tau_1|$ and we may take $\tau_1=0.99$ μsec. If $N(\tau)$ is an exponential function, $N(\tau)=A\exp(-\tau/\tau_0)$, then

$$\begin{aligned}N_{\text{obs}}(\tau) &= A\exp(-\tau/\tau_0) \\ &\qquad \times\int_{-\tau_1}^{+\tau_1} f(\tau')\exp(\tau'/\tau_0)d\tau' \\ &= \text{const.}\times\exp(-\tau/\tau_0).\end{aligned}$$

It is seen that the observed and the true disintegration curves have identical shapes for $\tau>\tau_1$. Hence no error will be made by evaluating the lifetime from the observed disintegration curve if delays smaller than τ_1 are disregarded.

(c) Apart from the statistical fluctuations, the only serious source of error may thus lie in the calibration curve of the time circuit. The accuracy of this calibration is difficult to evaluate. As already mentioned in Section 1 two separate methods gave calibration curves different by about 10 percent. It is easy to see how time intervals determined by the rate of charge of a condenser may be in error by as much as 10 percent, mainly on account of the difficulty in the evaluation of stray capacities. It seems, however, that time intervals determined by the period of a quartz oscillator should be considerably more accurate. Since the calibration curve obtained with the quartz oscillator was finally adopted, we feel safe in assuming that the error in the calibration is small compared with the statistical error.

The value of the lifetime given by the present experiment is larger than the one determined by Rasetti. We do not feel, however, that the two experiments are in serious disagreement, because of the statistical errors and also because of the possibility of some error in the calibration of Rasetti's circuit.

Our results are in complete disagreement with those of de Souza Santos with regard to the shape of the disintegration curve as well as to the average value of the lifetime.

A comparison between the present results and those obtained from the absorption anomaly in air involves knowledge of the mesotron mass μ because the latter method gives essentially the ratio τ_0/μ. According to the most reliable measurements, μ seems to be between 160 and 240 electron masses.[5] The present value of τ_0 together with the value of τ_0/μ determined by Rossi and his collaborators[6] gives $\mu=160$ electron masses which is within the above limits, while the value of τ_0/μ determined by Nielsen and his collaborators[7] would give $\mu=360$ which seems definitely too large.

[5] See T. A. Wheeler and R. Ladenburg, Phys. Rev. **60**, 754 (1941).

[6] B. Rossi and D. B. Hall, Phys. Rev. **59**, 223 (1941). B. Rossi, K. Greisen, J. C. Stearns, D. K. Froman, and P. G. Koontz, Phys. Rev. **61**, 675 (1942).

[7] W. M. Nielsen, C. M. Ryerson, L. W. Nordheim, and K. Z. Morgan, Phys. Rev. **59**, 547 (1941).

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The Near Infra-Red Spectrum of Water Vapor

Part II. The Parallel Bands ν_3, $\nu_1+\nu_3 \cdot \nu_2+\nu_3$ and the Perpendicular Band ν_1

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An analysis of the rotational structure of the three "parallel" type bands, ν_3, $\nu_1+\nu_3$, and $\nu_2+\nu_3$ and the "perpendicular" type band ν_1 has been carried out. The data lead to the following effective values of A, B, and C: ($A=h/8\pi^2I_a$, $B=h/8\pi^2I_b$, $C=h/8\pi^2I_c$); $A(\nu_1)=27.26$ cm^{-1}, $B(\nu_1)=14.28$ cm^{-1}, $C(\nu_1)=9.17$ cm^{-1}; $A(\nu_3)=26.50$ cm^{-1}, $B(\nu_3)=14.40$ cm^{-1}, $C(\nu_3)=9.10$ cm^{-1}; $A(\nu_1+\nu_3)=26.04$ cm^{-1}, $B(\nu_1+\nu_3)=14.16$ cm^{-1}, $C(\nu_1+\nu_3)=8.95$ cm^{-1}; $A(\nu_2+\nu_3)=29.32$ cm^{-1}, $B(\nu_2+\nu_3)=14.56$ cm^{-1}, $C(\nu_2+\nu_3)=9.06$ cm^{-1}. These data permit a redetermination of the vibrational constants ω_i, x_i, x_{ik}, and γ. The new values obtained for the ω_i are the following: $\omega_1=3829.4$, $\omega_2=1654.5$, and $\omega_3=3940.1$.

INTRODUCTION

In a relatively recent article[1] the author has reported new and much improved data on the vibration-rotation bands ν_2 and $2\nu_2$ which arise out of variations of the electric moment parallel to the axis of the intermediate moment of inertia. From an analysis of these data certain of the vibration-rotation constants, already evaluated by Darling and Dennison,[2] have been verified. In this communication a set of improved data is presented on the bands ν_3, $\nu_1+\nu_3$, and $\nu_2+\nu_3$ which originate with variations of the electric moment parallel to the axis of the smallest moment of inertia and the band ν_1 which is of the perpendicular type. The former oscillations are sometimes spoken of as parallel oscillations because they are parallel to the axis of the smallest moment of inertia which in a limiting case may be thought of as an approximate symmetry axis. The band ν_1 is of the type discussed in Part I. The analysis of these bands permits one to make somewhat improved determinations of a considerable number of the vibration-rotation constants of the water vapor molecule.

[1] H. H. Nielsen, Phys. Rev. **59**, 565 (1941).

[2] B. T. Darling and D. M. Dennison, Phys. Rev. **57**, 128 (1940). Cited as D and D later.

EXPERIMENTAL

The experimental procedure was here entirely the same as for the work reported in Part I, the water vapor in the optical path of the spectrometer acting as the absorbing layer. In order to obtain any resolution whatever in the region of intense absorption near 2.7μ it was necessary