The Velocity of Gamma-Rays in Air*

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The velocity of 0.5-Mev gamma-rays resulting from positron annihilation has been measured by means of scintillation counters and delayed-coincidence techniques. The value obtained is $(2.983 \pm 0.015) \times 10^{10}$ centimeters per second.

INTRODUCTION

DEVELOPMENT of a coincidence-counting system capable of resolving events separated by 10^{-9} second suggested the possibility of making a direct measurement of the velocity of gamma-rays. The availability of annihilation radiation, in which two gamma-rays are emitted simultaneously in opposite directions, was essential to the success of the experiment, since reflection techniques could not be used. A suitable source of such radiation consists of a positron emitter such as Cu^{64} or Na^{22} placed in a metal container in which the positrons are stopped and annihilated.

It was not anticipated that the velocity would turn out significantly different from the values found at radar and optical frequencies; however, the experiment does provide certain features of interest: First, the range of frequencies over which the velocity of electromagnetic radiation has been accurately determined is considerably increased, from the order of 10^{10} cps and below (radar) and 10^{14} cps (visible light) to 10^{20} cps for the 0.5-Mev annihilation radiation. Second, a single traversal of path is involved, so that no questions enter about possible effects (however improbable) due to reflections or retracing of path. Third, the frequency is so remote from any resonance in the medium that within present feasible limits of accuracy the medium can be considered equivalent to vacuum. These considerations should not be confused with the reason for undertaking the experiment, which was that high resolution coincidence-counting equipment had been developed and required testing.

PROCEDURE

Scintillation counters employing a solution of terphenyl in phenylcyclohexane and EMI Type 5311 photomultiplier tubes were placed on opposite sides of a radiator containing initially about 1 curie of Cu^{64}. The source and one of the counters were attached to a suitable frame, and the transit-time difference of the two annihilation quanta was determined for five different path differences. The velocity was obtained from the slope of the best straight line, as determined by the usual least-squares method, through the experimental points representing distance *versus* delay. The general arrangement of the apparatus is shown diagrammatically in Fig. 1.

The coincidence circuit, which will be described in detail elsewhere, has a minimum useful resolving time of 1×10^{-9} second. For the present work the resolution was fixed at 5×10^{-9} second, which gave the optimum compromise between resolution and over-all counting efficiency. The delay required to cancel the gamma-ray transit time was introduced by appropriate lengths of coaxial cable (RG/7U). For a given length of cable, the counter was moved until a position giving coincidences was found. Small additional lengths of cable were then inserted or removed to obtain a detailed coincidence-delay peak (an example is shown in Fig. 2) from which the mean delay value could be accurately determined. This value was then added to the delay introduced by the "long" cable to give the total time delay. This procedure was repeated for five different cable lengths and corresponding counter positions. The probable error in the mean delay computed from the data presented graphically in Fig. 2 are 0.1×10^{-9} second.

The time delay introduced by the cables was determined by measuring the frequencies of the resonant modes under shorted termination (Fig. 3). Each mode corresponds to a voltage minimum at the input end, and the resonant frequency can be readily determined by use of commercially available instruments to four significant figures. The transmission time is given by

$$T = n/2f_n,$$

where f_n is the frequency of the nth resonant mode. The cables were checked at all resonances between 2 Mc and 400 Mc; no evidence of dispersion was found. A plot of the first four resonances of one of the cables used is shown in Fig. 4. The abscissa numbers are approximate; after the position of the minimum was found, the

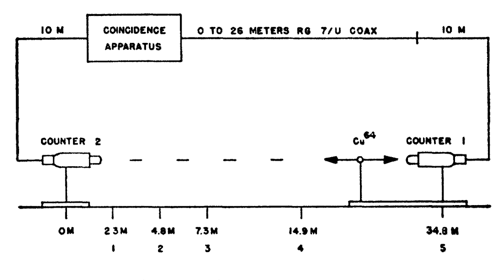

FIG. 1. Arrangement of counters, source, and coincidence apparatus.

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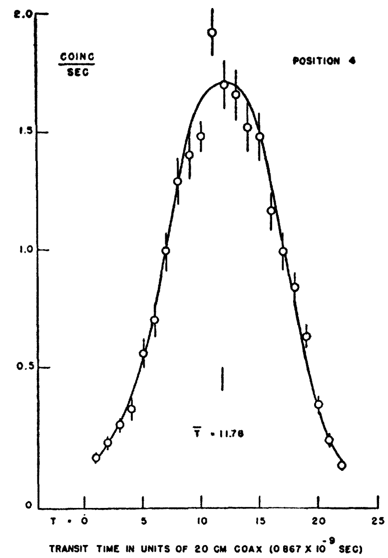

FIG. 2. Typical coincidence-delay peak.

stated frequency was determined by means of a more accurate frequency meter. The calibrations were carried out at the time the experiment was done, a necessary precaution, since cables of the type used shrink appreciably with handling.

The distances were measured with conventional two-meter sticks placed end-to-end. Comparisons with more trustworthy standards and end corrections were duly made. As indicated in Fig. 5, the distance measurements are reliable to three decimal places.

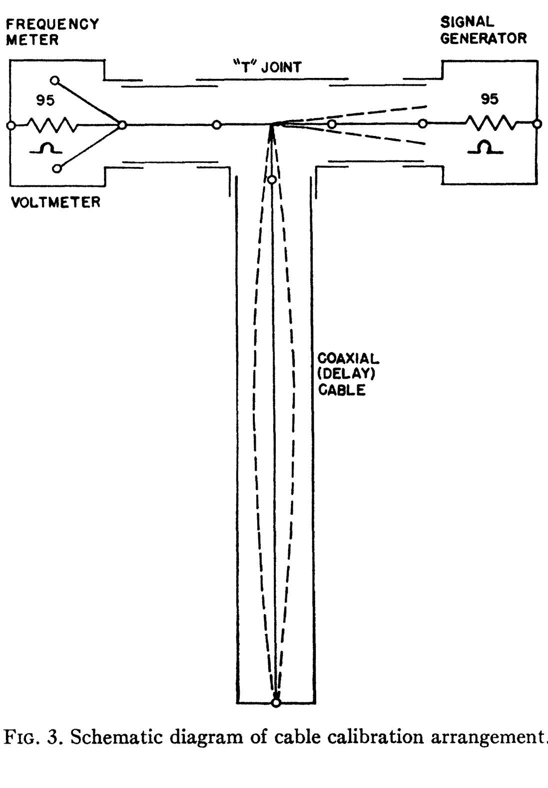

FIG. 3. Schematic diagram of cable calibration arrangement.

RESULT

The measured transit times are plotted against distance in Fig. 5; the experimental points are indicated by the intersections of the crossed lines. The length of these lines is not related to the statistical errors, which are too small to exhibit.

The velocity is determined by fitting the best straight line to the experimental points, under the assumptions that only the abscissa values are subject to appreciable error, and that the error is the same for all measurements, including those repeated at positions 2 and 5. The velocity that gives the best least-squares fit is given by[1]

$$c = [n\Sigma x_k^2 - (\Sigma x_k)^2]/[n\Sigma x_k t_k - \Sigma x_k \Sigma t_k],$$

where x_k and t_k are the measured values of the coordinates, and n is the number of points. The result is 2.983×10^{10} centimeters per second, with an estimated error of 0.5 percent. The accuracy is limited, not by statistical fluctuations in counting but by gradual changes in operating conditions that occurred over the period of a few days during which the measurements were made.

Repetition of the delay determinations at positions 2 and 5 yielded the two distinct values shown; the disparity, considerably greater than the computed probable error, is apparently due to slow variations in electron transit time in the photomultiplier tubes resulting from supply-voltage drift. Measurements of dependence of transit time on supply voltage in the EMI 5311 tubes show that at 2 kilovolts a variation of 20 volts alters the electron transit time by 4×10^{-10} second, which is of the same order as the deviations of the points from the straight line in Fig. 5. Fluctuations of 20 volts were observed while the velocity measurements were in progress, but were not followed in sufficient detail to afford corrections in the data. The fluctuations were subsequently traced to variations of

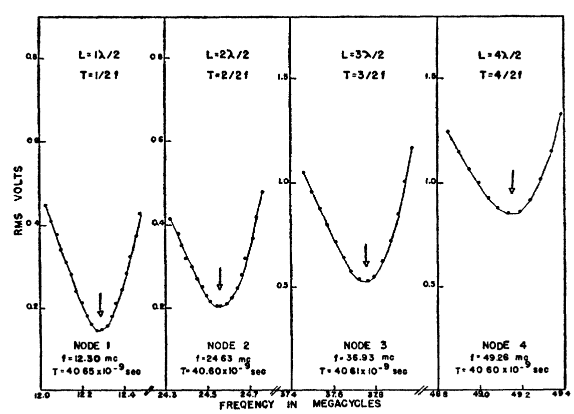

FIG. 4. Plot of typical cable resonances.

[1] A. G. Worthing and J. Geffner, *Treatment of Experimental Data* (John Wiley and Sons, Inc., New York, 1943).

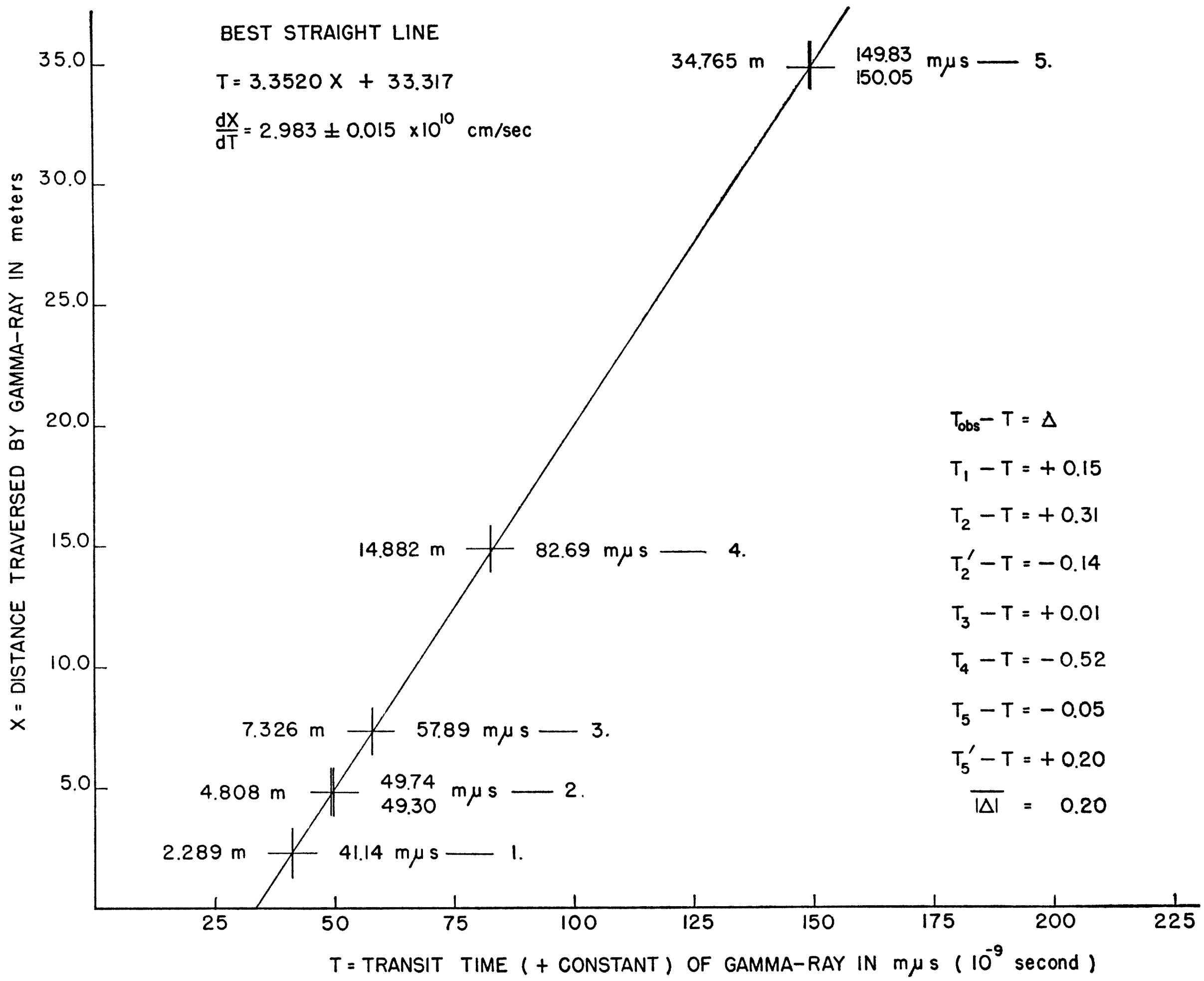

FIG. 5. Distance *versus* time of flight for annihilation radiation.

carbon resistance elements with temperature in the voltage-stabilizing circuit.

The measured velocity of annihilation quanta agrees within the estimated error with the present most probable value of c, computed by DuMond and Cohen[2] to be 2.998×10^{10} centimeters per second.

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[2] J. W. M. DuMond and E. R. Cohen, Phys. Rev. **82**, 555 (1951).