

Velocity of Gamma Rays from a Moving Source*

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We have measured the relative speed of the two γ rays emitted forward and backward by a π^0 meson decaying in flight. The velocity of the neutral pions, which were produced in the reaction $\pi^- + p \rightarrow \pi^0 + n$, was $v = 0.2c$. We have compared our results with what would have been expected on the assumption that the initial photon velocities were $c + v$ and $c - v$. The results were in complete disagreement with this assumption.

I. INTRODUCTION

There have been two measurements recently of the speed of γ radiation from moving sources.¹

In what follows, we propose to describe a new experimental determination of γ -ray speed from moving sources.

Following recent suggestions, we have measured the relative speed of the 68-MeV γ rays from the decay of neutral pions.^{2,3}

The principle of our experiment is as follows: Neutral pions were produced through the reaction $\pi^- + p \rightarrow \pi^0 + n$ by stopping a beam of negative pions from the Carnegie Tech synchrocyclotron in liquid hydrogen. Past experiments^{4,5} have shown that these neutral pions have a unique velocity given by $\beta = v/c = 0.20$. Because of the aberration of the decay γ rays, it was possible to observe only photons emitted forward and backward along the direction of the moving π^0 . We have considered the fact that the nonzero widths of our target and detectors permitted the counting of photon pairs which traveled at angles different from 180° with one another. The effect in our experiment was small (about 3%) and was taken into account. With detectors symmetrically located on opposite sides of the H_2 target (Fig. 1), we measured the difference of the arrival times Δt of the photon pairs for different detector distances. If the speed of the two photons were $c \pm kv$ (k is a constant to be determined by the experiment), then for a detector target distance d we would have $\Delta t = \pm 2k\beta d/c$ to good approximation. Thus, with good resolution, two time intervals would be recorded, separated by $4k\beta d/c$.

There is one feature of this experiment which is impor-

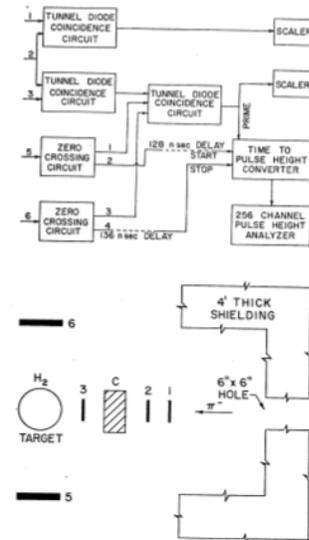


FIG. 1. Experimental arrangement and block diagram of circuitry.

tant, in view of the fact that its purpose is to test special relativity. Independently of relativity, and indeed of nuclear theory, there can be no reasonable doubt about the velocity of the source of the γ rays. Past measurements of the aberration angle⁴ (confirmed roughly during our experiment) and the Doppler energy shift⁵ of the two photons yield essentially the same value of β , namely, $\beta = 0.20$, when interpreted with the kinematics of special relativity. Even if interpreted on a theory in which the velocities of the source and the radiation are assumed additive by the rules of Galilean kinematics, the values of β calculated from the observed Doppler shift and aberration angle differ by only 2% from the value calculated with special relativity.

II. EXPERIMENTAL TECHNIQUE

The experimental arrangement and a block diagram of the circuitry are shown in Fig. 1. A beam of 80-MeV negative pions from the Carnegie Tech synchrocyclotron entered the target area through a 6-in. \times 6-in. \times 4-ft

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¹ Alvager, A. Nilsson, and J. Kjellman, *Nature* **197**, 1191 (1963); D. Sadeh, *Phys. Rev. Letters* **10**, 271 (1963).

² J. G. Fox, *Am. J. Phys.* **30**, 297 (1962).

³ W. G. V. Rosser, *Nature* **190**, 249 (1961).

⁴ J. M. Cassels, D. P. Jones, P. G. Murphy, and P. L. O' Neill, *Proc. Phys. Soc. (London)* **74**, 92 (1959).

⁵ W. H. K. Panofsky, R. L. Aamodt, and James Hadley, *Phys. Rev.* **81**, 565 (1951).

collimating hole. A differential range curve showed that the beam consisted of 45% pions, 25% muons, and 30% electrons.

The beam monitor counters 1, 2, and 3 were 4 in. \times 4 in. \times $\frac{1}{4}$ -in. and the two γ -ray counters 5 and 6 were 6-in. \times 6-in. \times $\frac{1}{2}$ -in. commercial plastic scintillators coupled to RCA-6810A photomultiplier tubes through Lucite light pipes. Counters 5 and 6 were each covered with lead plates $\frac{1}{4}$ in. thick to convert the γ rays. The thickness of carbon absorber in the beam was such as to ensure the maximum number of pions stopping in the target ($\sim 1500/\text{sec}$).

The hydrogen container was a cylinder $5\frac{1}{2}$ in. diam and 6 in. high with stainless steel walls 0.010 in. thick. It was surrounded by a thin heat shield and a vacuum wall totalling 0.083 in. of aluminum.

The difference between the arrival times of the γ rays in counters 5 and 6 was measured by a time-to-pulse height converter⁶ (THC). A coincidence of the pion telescope (123) with the pulses from counters 5 and 6 constituted the prime pulse to the THC. With this arrangement the number of uncorrelated counts, and therefore the background, was greatly reduced. Since counter 5 always provided the start pulse, a fixed delay of about 10 nsec was added to the stop pulse so that both positive and negative relative times could be detected. Finally, the output of the THC, with an amplitude proportional to the difference between the arrival times of the two γ rays from the π^0 decay, at counters 5 and 6, was fed to an RCL 256-channel pulse-height analyzer. Calibrations to be described below showed that time zero corresponded to channel 125 with a resolution of 17 channels.

The following tests on the performance of the equipment were made before and during the run:

- (1) Calibration of the time scale.
 - (a) Pulses from a pulse generator were fed to the zero-crossing circuits with fixed delays determined by the lengths of the connecting cables. For each delay the channel number of the peak of the pulse-height distribution was recorded and then plotted against the relative delay between the start and stop pulse.
 - (b) Light pulsers mounted on the light pipes of counters 5 and 6 were used to simulate the start and stop pulses. Then the same procedure as in (a) above was repeated.
 - (c) A more accurate calibration was made by putting the two γ -ray detectors, without the lead absorbers, directly in the beam and measuring the relative arrival times of the 165 MeV/c electrons present in the beam. "Negative times" were measured by putting counter 6 ahead of 5. The velocity of the electrons was assumed to be c .

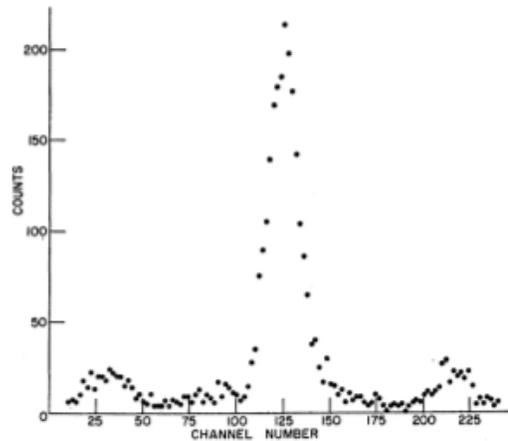


FIG. 2. Data for detector-target distance of 19 in., 2 channels per point. The main peak is due to the $\gamma - \gamma$ pairs from π^0 decay. The side peaks at about channels 32 and 217 are from $\gamma - n$ pairs as explained in the text.

The result of these measurements was that our time scale was linear throughout our useful range of measurement and corresponded to 9.2 ± 0.2 channels/nsec.

- (2) Proof that the photons from the π^0 decay were detected.
 - (a) With liquid hydrogen in the target the coincidence γ -ray counting rate was a maximum at the right absorber thickness.
 - (b) The rate decreased by a factor of about 15 when the $\frac{1}{4}$ -in.-thick lead converters were removed from the detectors.
 - (c) The rate with the lead converters in place dropped by a factor of 50 when the hydrogen was removed from the target. (d) The rate with both hydrogen and lead converters in place decreased to zero as the angle subtended by the detectors at the target was changed from 170° to less than 157° (on account of the aberration).

As an illustration of the performance of the equipment, we show in Fig. 2 the data taken at a distance of 19 in. from each detector to the target center. Clearly visible on either side of the main γ -ray peak are two side peaks which are due to the time delay between the photons and the 8.8-MeV neutrons from the competing reaction $\pi^- + p \rightarrow n + \gamma$. The value of $\beta = 0.13$ calculated from these data is in good agreement with the accepted value, $\beta = 0.14$.⁷

⁷ This value may be calculated from the data published by Selove and M. Gettner, Phys. Rev. **120**, 393 (1960).

⁶ G. Culligan and H. H. Lipman, Rev. Sci. Instr. **31**, 1209 (1960).

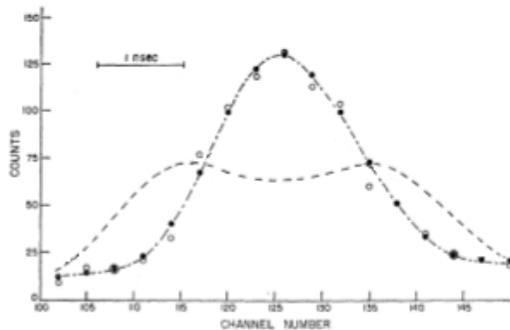


FIG. 3. Data for detector-target distances of 7 in. (black dots) and 47 in. (open circles), 3 channels per point. The result to be expected on the assumption that the photon velocities were $c \pm v$ [is] also shown. [The assumed curve] and the data at 7 in. have been normalized to the same total number of counts as the data at 47 in. The true counting rates at 7 in. were about 40 times those shown.

III. RESULTS AND DISCUSSION

We show in Fig. 3 the data which were obtained when counters 5 and 6 were first 7 in. and then 47 in. from the target center. Counting times were 4.5 and 99 h,

respectively. The point of interest is the difference, if any, between these two peaks for which the flight path of the photons differed by $d = 40$ in. First, it is to be noted that there is no significant difference in their widths; both peaks have the same width as the calibration peaks 17 channels. In order to show how much difference would be expected on the hypothesis of nonconstancy of c we also show in Fig. 3 [a] curve [that] correspond[s] to $k=1$, which] should have two peaks corresponding to the two different time intervals between pairs of γ rays arriving in the detectors. It was obtained by superposing, with the appropriate separation, two identical curves whose shape was that of our experimental curve at a source-detector distance of 7 in.

It is immediately clear from Fig. 3 that our experimental results at 47 in. are in complete disagreement with the calculated curve.

We conclude that our results provide strong evidence that the velocity of radiation from a moving source is not the classical vector sum of c and the velocity of the source. Within our accuracy, the resultant sum is c as required by special relativity.

(ADAPTED)