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Velocity of Gamma Rays from a Moving Source*

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Serious difficulties from extinction are shown to exist in the interpretation of past experiments on γ rays from moving sources. 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, taking account of extinction, 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] They were prompted in part by the suggestion[2] that past experiments with light may have been vitiated by extinction of the incident light wave in the sense of the extinction theorem of Ewald and Oseen. It has not been realized in connection with these new experiments that extinction exists also for γ rays. While the extinction coefficient for high-energy radiation turns out to be orders of magnitude smaller than for light, it is not a negligible factor in experiments of this sort. This is because the amounts of material which lie in the path of the radiation are comparable to the extinction lengths.

In what follows, we propose to show how the magnitude of the extinction distance can be estimated, then to indicate how extinction interfered seriously with the results of recent measurements of γ-ray speed, and finally and chiefly, to describe a new experimental determination of γ-ray speed from moving sources.

To attempt an estimate of the extinction coefficient on the basis of a macroscopic model of the medium, as has been done recently,[3] appears to be risky. The field quantities used in such a model are averages over the microscopic fields experienced by individual electrons. It would seem quite possible that at points within a wavelength or so of the surface the macroscopic average of the field of an electromagnetic wave would not be the same as that in the interior of the medium.[4] We turn instead to a consideration of the forward scattering in the medium.

It is well known that for a plane wave, $E=e^{ikx}$, incident normally on a layer dx, of a medium $dE_s/Edx = N\lambda f(0) = (n-1)/\lambda$, where dE_s is the amplitude scattered coherently forward by the layer to a point far away, N is the number of scattering centers per unit volume, $f(0)$ is the real part of the forward scattered amplitude, n is the index of refraction, and $\lambda = 1/k$[5]. This very general result, closely related to the optical theorem, is valid for almost any form of wave motion and all frequencies.

When the incident and scattered waves are indistinguishable, as for electromagnetic radiation, the superposition of the two results in a change in phase, since dE_s and E differ in phase by $\Delta\phi = \pi/2$. Thus we have $dE_s/Edx = d\phi/dx = (n-1)/\lambda$, an experimental fact which is well known in physical optics.

When the incident and scattered waves are distinguishable, we would expect the scattering to result in an exponential decrease of incident amplitude with an attenuation coefficient of $N\lambda f(0)$. A closely related phenomenon here is the primary extinction of x rays in a perfect crystal whose reflecting planes are parallel to the crystal surface. At the Bragg angle θ, the primary intensity is attenuated in the primary ray direction with an extinction coefficient which is essentially $\mu = 2N\lambda f(2\theta)$.[6] This expression differs from the one above by a factor of 2 because it refers to attenuation of wave energy rather than wave amplitude, and by the replacement of $f(0)$ by $f(2\theta)$ since in this case there is coherent scattering at an angle of 2θ instead of zero. However, the process is fundamentally the same at either angle,[7] so the phenomenon of primary extinction of x rays[8] is an additional illustration from a different

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[1] T. Alväger, 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. R. Haseltine, Am. J. Phys. **32**, 173 (1964).

[4] Even in the electrostatic case the usual process of averaging the microscopic field involves unavoidable errors which are large at many molecular diameters from the boundary of a solid or liquid medium. See, e.g., J. H. Van Vleck, *The Theory of Electric and Magnetic Susceptibilities* (Oxford University Press, London, 1932), p. 12, footnote 13.

[5] See, e.g., J. Hamilton, *The Theory of Elementary Particles* (Clarendon Press, Oxford, 1959), p. 18.

[6] The exact expression differs from this by factors of unity or less which depend on the state of polarization of the primary radiation and the crystal structure factor. These factors all approach unity as θ approaches zero. For the exact expression, see Arthur H. Compton and Samuel K. Allison, *X-Rays in Theory and Experiment* (D. Van Nostrand Company, Inc., New York, 1935). The expression (6.55) on p. 393 can be thrown into this form with the aid of expression (4.46) on p. 280. See also *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, 1947), Vol. 32, p. 194, Eq. (50.7).

[7] See Ref. 6, pp. 371, 372. Compare Eqs. (6.11) and (6.12).

[8] Perfect crystals to which the dynamical theory of x-ray diffraction applies and for which it predicts the above extinction coefficient are rarely encountered in practice. When they are, their measured reflection coefficients are in good agreement with the theoretical predictions. Moreover, the modification of the theory to take account of the mosaic structure of real crystals finds abundant confirmation in experiment. See, for example, R. W. James, *The Optical Principles of the Diffraction of X-Rays* (G. Bell and Sons, London, 1958), pp. 328–332.

frequency range of the general result quoted above.

In experiments designed to measure the velocity of radiation from a moving source, one is trying to get data which rule out the possibility that the velocity is different from c. Presumably, the hypothesis which one is trying to disprove, the only one which justifies a new experiment on this old question, is the following: The original radiation which had a velocity different from c was extinguished in the process of coherent forward scattering in stationary matter between source and detector; this scattered radiation, which was actually measured, had a velocity c. On this hypothesis, there would be a difference between the velocities of the primary and scattered radiation and this physical difference would mean, according to the preceding discussion, that the intensity traveling with the velocity of the primary wave would be expected to decrease exponentially to $1/e$ of its initial value in a distance of $1/2N\lambda f(0)$. If one calculates this extinction length he finds that for 0.5-MeV γ rays it is 19 cm of air and 0.3 mm of Lucite [at γ-ray energies, $f(0)$ is e^2/mc^2, the classical electron radius]. Thus, in Sadeh's experiment,[1] the 1-mm target used to produce the annihilation radiation, whose speed was measured, was about 3 extinction lengths in thickness and the 60-cm flight path over which the speed was timed was also about 3 extinction lengths in thickness. In the other experiment, that of Alväger, Nilsson, and Kjellman,[1] 4.4-MeV γ rays were used whose extinction lengths in air and carbon are 1.7 m and 1.4 mm, respectively. So their flight path of 5 m in air amounted to almost 3 extinction lengths, and there was additional extinction in the carbon-containing target whose composition and thickness were not specified. It is clear that the extinction in both of these experiments was severe. Only a detailed analysis of its effect on the interpretation of the results would permit a conclusion as to just what, if anything, the results proved about the constancy of the velocity of "light."

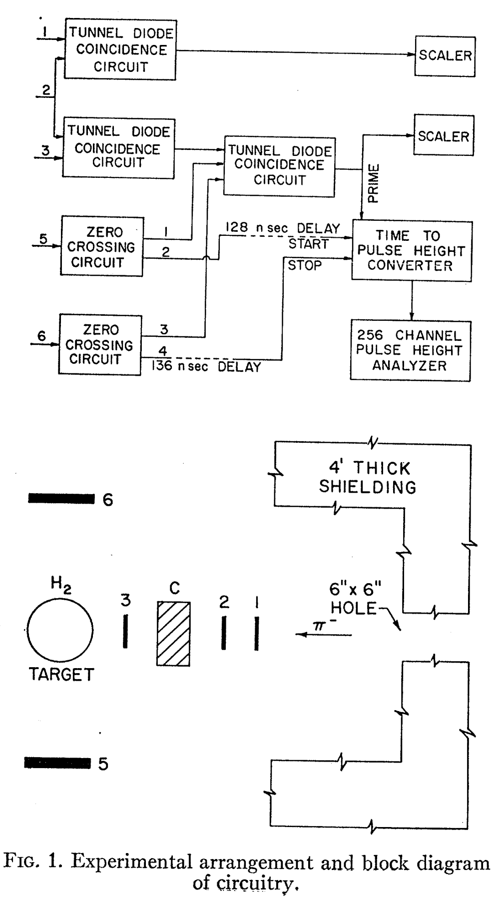

FIG. 1. Experimental arrangement and block diagram of circuitry.

Following recent suggestions,[2,9] we have measured the relative speed of the 68-MeV γ rays from the decay in flight of neutral pions. While extinction is not negligible in our experiment, it is much less than in the experiments just referred to and small enough that a definite conclusion can be drawn from the results. Two optical experiments designed to verify the constancy of the velocity of light have been reported recently.[10]

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[11,12] 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 and no extinction, two time intervals would be recorded, separated by $4k\beta d/c$. The complications introduced by considering extinction will be discussed later.

There is one feature of this experiment which is important, 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

[9] W. G. V. Rosser, Nature **190**, 249 (1961).

[10] F. B. Rotz, Phys. Letters **7**, 252 (1963); G. C. Babcock and T. G. Bergman, J. Opt. Soc. Am. **54**, 147 (1964). It is planned to discuss elsewhere difficulties which arise in the interpretation of these two experiments.

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

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

doubt about the velocity of the source of the γ rays. Past measurements of the aberration angle[11] (confirmed roughly during our experiment) and the Doppler energy shift[12] 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. ×6-in.×4-ft 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. ×4 in.×$\frac{1}{4}$ in. and the two γ-ray counters 5 and 6 were 6-in.×6-in.×$\frac{1}{2}$-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 (~1500/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 converter[13] (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.

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

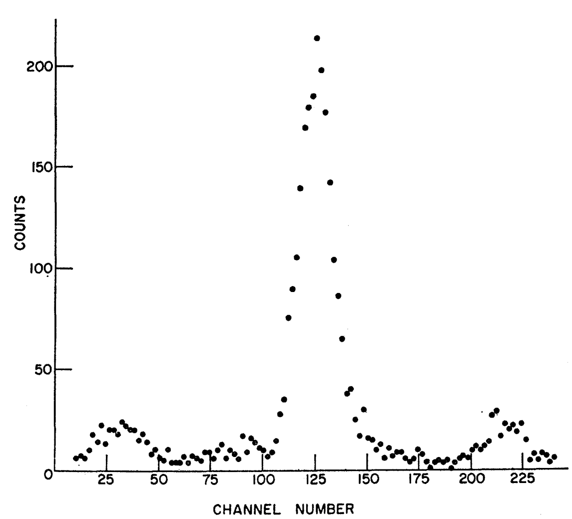

FIG. 2. Data for detector–target distance of 19 in., 2 channels per point. The main peak is due to the γ–γ pairs from π^0 decay. The side peaks at about channels 32 and 217 are from γ–n pairs as explained in the text.

[13] G. Culligan and N. H. Lipman, Rev. Sci. Instr. 31, 1209 (1960).

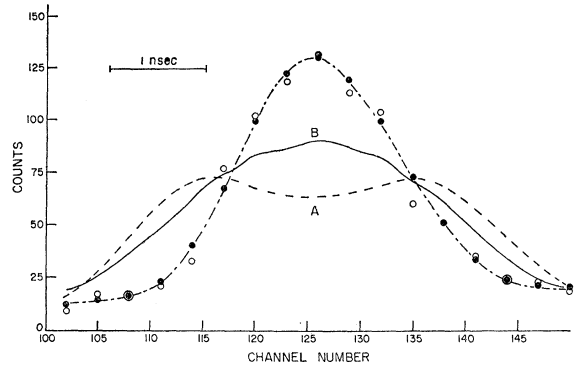

FIG. 3. Data for detector–target distances of 7 in. (black dots) and 47 in. (open circles), 3 channels per point. The results to be expected on the assumption that the photon velocities were $c \pm v$ are also shown—curve A without extinction, curve B with extinction. Curves A and B and the data at 7 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.

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, $\beta = 0.14$.[14]

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 two calculated curves. One curve, A, was calculated on the assumption of no extinction; the other curve, B, makes allowance for extinction. Both correspond to $k = 1$.

As described earlier, curve A 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.

For curve B the question is how the extinction should be handled: The hypothesis which is being investigated is in drastic conflict with physical theory at such a basic level that it is difficult to be sure what line of reasoning it is safe to employ. We have adopted the following because it seems reasonable. We assume that the fraction of intensity which was *not* extinguished was proportional to the number of photons which escaped from the target with unchanged velocity (different from c by hypothesis). Conversely we assume that the fraction of intensity which *was* extinguished was proportional to the number of photons which left the target with a velocity c. This assumption is in harmony with the usual quantum mechanical interpretation that the number of photons is proportional to the classical radiation intensity. The experimental results which would now be expected on the hypothesis of the nonconstancy of c are more complicated. Instead of the two predicted in the absence of extinction we now have five peaks spaced equally. The details of the way in which these five peaks were obtained and superposed to make curve B are given in the Appendix.

It is immediately clear from Fig. 3 that our experimental results at 47 in. are in complete disagreement with both of the calculated curves. We have compared the results especially with curve B for which extinction has been taken into account. Chi square tests yield the following limits on the value of k in the expression $c \pm kv$ for the γ-ray speed: $k \leq 0.5$ with a confidence level of 99.9%, $k \leq 0.4$ with a confidence level of 90%.

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. It seems to us that the only objection which could be raised to this conclusion is the following: Practically all photon velocities might have been reduced to c if the extinction had been greater than we estimated. This seems most unlikely to us since the expression $\mu = 2N\lambda f(0)$ for the extinction coefficient not only results from very general arguments but also receives confirmation from experiment for both light and x rays. Furthermore, the classical value of $f(\theta)$ which is concerned with (Thomson) scattering at low energies turns out to be an upper limit to the $f(\theta)$ for (Compton) scattering at higher energies. This follows not only from theory for all angles θ but, more important for our argument, it also follows from measurements of the cross sections which agree with theory at all angles for which they have been observed. Therefore, the classical low-energy value of $f(\theta)$ at $\theta = 0$ should also be an upper limit to $f(0)$ for high energies independent of theory. Granted this, we have not underestimated the amount of extinction in our experiment and our conclusion holds.

APPENDIX

On the hypothesis of the nonconstancy of c and with consideration of extinction, the various possible kinds of coincident photon pairs are found by considering all possible combinations of velocity of the photons in a pair:

[14] This value may be calculated from the data published by W. Selove and M. Gettner, Phys. Rev. 120, 593 (1960).

TABLE I. The various possible pairs of coincident photons and their arrival time differences on the hypothesis of nonconstancy of c. See the Appendix for the calculation of the numbers in columns 3, 6, and 7.

Photons detected in start counter			Photons detected in stop counter			Relative number of photon coincidences		Difference in arrival times of coincident pairs
Type	Speed	Relative number	Type	Speed	Relative number			
Forward, unextinguished	$c+kv$	0.671	Backward, unextinguished	$c-kv$	0.550	0.369		$2\ kd\beta/c$
Forward, unextinguished	$c+kv$	0.671	Backward, extinguished	c	0.450	0.302	} 0.483	$1\ kd\beta/c$
Forward, extinguished	c	0.329	Backward, unextinguished	$c-kv$	0.550	0.181		
Forward, extinguished	c	0.329	Backward, extinguished	c	0.450	0.148	} 0.296	$0\ kd\beta/c$
Backward, extinguished	c	0.450	Forward, extinguished	c	0.329	0.148		
Backward, extinguished	c	0.450	Forward, unextinguished	$c+kv$	0.671	0.302	} 0.483	$-1\ kd\beta/c$
Backward, unextinguished	$c-kv$	0.550	Forward, extinguished	c	0.329	0.181		
Backward, unextinguished	$c-kv$	0.550	Forward, unextinguished	$c+kv$	0.671	0.369		$-2\ kd\beta/c$
						2.000		

$(c+kv, c-kv)$, $(c+kv, c)$, $(c, c-kv)$, (c,c), $(c, c+kv)$, $(c-kv, c)$, $(c-kv, c+kv)$. These seven combinations give only five different time intervals for equidistant detectors: The second and third yield the same time interval, within our accuracy, as do the fifth and sixth. These intervals are shown in the last column of Table I.

The intensities of these different kinds of coincidences are found as follows. From the expression for the extinction distance, $1/2N\lambda f(0)$, it is easy to estimate the fraction of an extinction length represented by the radius of liquid H_2 and the aluminum and stainless steel walls of the target. For a mean photon energy of 68 MeV these fractions are 0.246, 0.172, and 0.058, respectively. The sum of these should be corrected by $+20\%$ and -20% for the Doppler shift of the wavelengths of the forward and backward radiation and then used to estimate the extinction. We obtain in this way fractional extinctions of 0.329 and 0.450 and correspondingly fractional transmissions of 0.671 and 0.550 for the forward and backward radiation, respectively. These figures include a small correction for the extinction in two structural copper strips $\frac{1}{2}$ in. wide, $\frac{1}{16}$ in. thick running the height of the target, which lay between the liquid hydrogen and the detectors. These numbers which represent relative numbers of photons can now be used to calculate the relative numbers of the various possible kinds of photon coincidences. This is done by multiplying together the relative numbers of photons of both types involved in a given kind of coincidence and repeating for each kind of coincidence. The results are shown in the next to last column of Table I. (These numbers add up to 2, corresponding to the 2 photons in each coincident pair.)

The next and final step is to calculate the composite curve which would be obtained by superposing five separate curves, each with the shape of our experimental curve at 7 in. and with the relative intensities and separations, given by the last two columns of Table I. The composite curve obtained in this way is labeled B in Fig. 3.