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Determination of the Constancy of the Speed of Light

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Kantor's relativity experiment has been repeated with approximately four times the sensitivity. The experiment measures the speed of light which has passed through moving glass plates by the observation of the shift of interference fringes. It was performed with the interferometric path in vacuum, and with the fringes observed at infinity. The shift predicted by the emission theory used by Kantor was 2.9 fringes. The shift found was less than 0.02 fringe.

RESULTS reported by Kantor[1] indicate that the speed of light after passing through a moving piece of glass is a function of the velocity of the glass. Because of the far-reaching effects such a conclusion would have if accepted, it was considered desirable to repeat the experiment with increased sensitivity.[2]

The experiment was performed using an interferometer like Kantor's. There were three principal differences in the equipment: (1) The optical path in the interferometer was longer; (2) a reversible motor was used; (3) the interferometer was enclosed in a vacuum chamber.

Figure 1 is a schematic diagram of the apparatus. A beam of light from the stroboscope was separated by the beam splitter into two parts, which traversed a pentagonal path in opposite directions back to the beam splitter and then followed a common path to the telescope. Under appropriate conditions an interference pattern was seen in the telescope.[3] Two similar glass windows, mounted on a rotatable arm, were placed in the beams as shown. If the velocity of light were $\mathbf{c}$ before and $\mathbf{c}+\rho\mathbf{v}$, $\rho\neq 0$, after passing through a window moving with velocity $\mathbf{v}$, and if its speed were restored to c after reflection at a stationary mirror, the fringe pattern seen when the arm was rotating would have been shifted with respect to that seen when the arm was stationary by Δf fringes,[4]

$$\Delta f = 2\rho\beta L/\lambda. \tag{1}$$

Here L is the distance M_2M_3 in Fig. 1 (the distance between the fixed mirrors either side of a window) less the thickness of the window, β is v/c, with v the common speed of the windows and c the speed of light in a vacuum, and λ is the vacuum wavelength of the light used. In this experiment observations were taken with the arm first rotating one way, then the other, so that the total shift would have been twice that given by Eq. (1). The average rotation rate was 45 rps and the distance from pivot to window center was 13.3 cm, so β was 1.25×10^{-7}. L was 276 cm, and λ was 4.74×10^{-5} cm. Hence, on the assumption that $\rho=1$, the doubled shift would have been 2.9 fringes. The shift expected in Kantor's experiment, on the same assumption, was 0.74 fringe. The Fresnel dragging coefficient, based on the theory of relativity, predicts a shift[5] (one direction of rotation)

$$\Delta f = 4\beta l(n-1)/\lambda, \tag{2}$$

when there are two windows each of thickness l and index of refraction n. The thickness l was 0.34 cm, and n was about 1.5, so that the (doubled) shift predicted relativistically was 0.0036 fringe.

Although other laboratory experiments have been done in the past to test the constancy of the speed of

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[1] W. Kantor, J. Opt. Soc. Am. **52**, 978 (1962).

[2] Three other experiments have been done recently in this area. However, none of them has been a repetition of Kantor's experiment. The results of these experiments favor relativity. T. Alväger, A. Nilsson, and J. Kjellman, Nature **197**, 1191 (1963); J. F. James and R. S. Sternberg, *ibid.*, p. 1192; D. Sadeh, Phys. Rev. Letters **10**, 271 (1963).

[3] This kind of interferometer has a long history. A. A. Michelson and E. W. Morley, Am. J. Sci. **31**, 377 (1886); G. Sagnac, Compt. Rend. **150**, 1302 (1910); A. A. Michelson and H. G. Gale, Astrophys. J. **61**, 140 (1925).

[4] These assumptions underlie Kantor's derivation of our Eq. (1); see Ref. 1, Eq. (4b).

[5] P. Zeeman, W. de Groot, A. Snethlage, and G. C. Dibbetz, Proc. Roy. Acad. Amsterdam **23**, 1402 (1922).

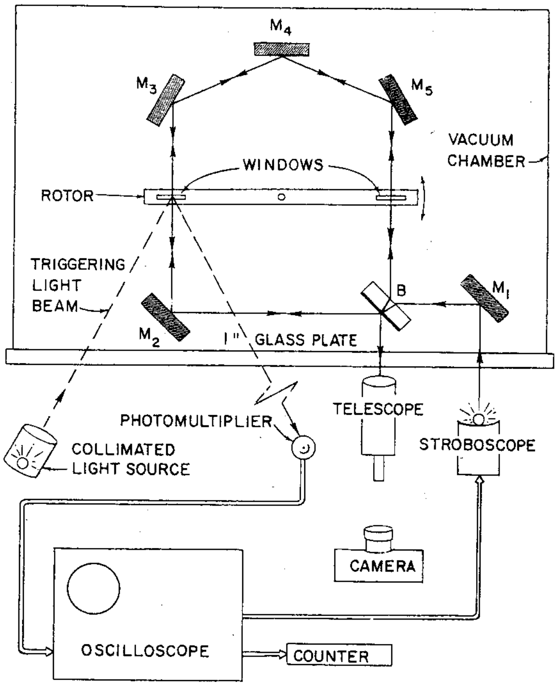

FIG. 1. General arrangement of the apparatus. The rotating arm carrying the windows is shown in the position where the stroboscope would be triggered. The stroboscope is the light source for the interferometer, M_1, M_2, M_3, and M_4 are mirrors, and B is the beam splitter.

light, an objection has been raised[6] that the presence of air might have invalidated the conclusions, and Kantor's experiment falls in the class objected to. In order to reduce the cogency of the objection, as well as to make sure that turbulent air did not disturb the fringe pattern, the present experiment was done with the entire interferometer (except light source and telescope) in a vacuum.

APPARATUS

Refer to Fig. 1. When the light source was an illuminated slit, an observer looking in the telescope saw two virtual images of the slit. The image which was reflected twice from the beam splitter was not affected by movement of the beam splitter. The two images of the slit were coherent point for point, and the situation was just that of Young's double-slit interference experiment. Straight parallel fringes were seen over a wide focusing range of the telescope. When the telescope axis was perpendicular to the line between the two virtual sources and bisected this line, the zeroth-order fringe would have appeared on the axis if there had been no dispersion in the optical system. Hence a few fringes would have been seen in white light. There was, in fact, a small amount of dispersion arising from the properties of the thin film on the beam splitter. This, however, was not large enough to destroy the visibility of the white-light fringes. When the telescope was focused on infinity, the slit could be moved perpendicularly to the optical axis without changing the fringes. Since the fringe pattern did not change with slit position, the slit could be replaced with a diffusing screen, such as frosted glass, without disturbing the fringe pattern. However, under this condition the fringes appeared only when the observing telescope was focused at or near infinity. It was found that using the stroboscope as the light source without the slit or diffusing screen did not change the fringe pattern, and the experiment was so conducted.

In order to look at the interference fringes only when the windows were normal to the interferometer light paths, the interferometer light source was a stroboscope providing flashes of essentially white light which was triggered only when the windows were in the proper position. To trigger the stroboscope, a light beam was reflected from the surface of one of the windows to a photomultiplier 15.2 m away. Since the windows were not exactly parallel to each other, the triggering light beam reached the photomultiplier only once every revolution of the windows. The pulse from the photomultiplier was amplified and shaped by an oscilloscope, which provided pulses to trigger the stroboscope and an electronic counter. The counter was used to measure the rotation rate of the windows and to count the number of flashes during photographic exposures. It must not be supposed that the slight nonparallelism of the windows spoils the experiment, for the adjustment of the instrument so that satisfactory fringes were obtained was made with the arm in the same position (within 5 min of arc) as it was when the light flashed while data were taken. Even the compensation features are very nearly preserved.

A Polaroid filter, set so that light with the electric vector vertical passed through, was placed just in front of the telescope to improve the contrast of the fringes,[7] and an interference filter was sometimes situated between the telescope eyepiece and the observer or camera. The filter had its transmission peak at 4740 Å and a half-width of 200 Å.

The windows, which were cemented to the rotating arm, were plate glass 0.34 cm thick and 3.4 cm square. The smallest mirror in the interferometer was 4.5×8 cm and was flat to 1/20 of a wavelength of light. The other three mirrors in the interferometer and the beam splitter were from a Hilger and Watts, Twyman–Green interferometer and were either 5×5 in. or 5×7 in. The telescope was a Keuffel and Esser autocollimating jig alignment telescope with crosshairs, and with a magnification of 46 when focused at infinity. To measure the vacuum, a McLeod gauge and an Alphatron gauge were used.

The adjustable mirror mounts and the base of the beam splitter were bolted to a 0.5-in. aluminum plate which was in turn bolted to the vacuum tank. The tank was connected to the vacuum pump by a piece of flexible

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[6] J. G. Fox, Am. J. Phys. **30**, 297 (1962).

[7] R. J. Kennedy, Proc. Natl. Acad. Sci. (U. S.) **12**, 621 (1926).

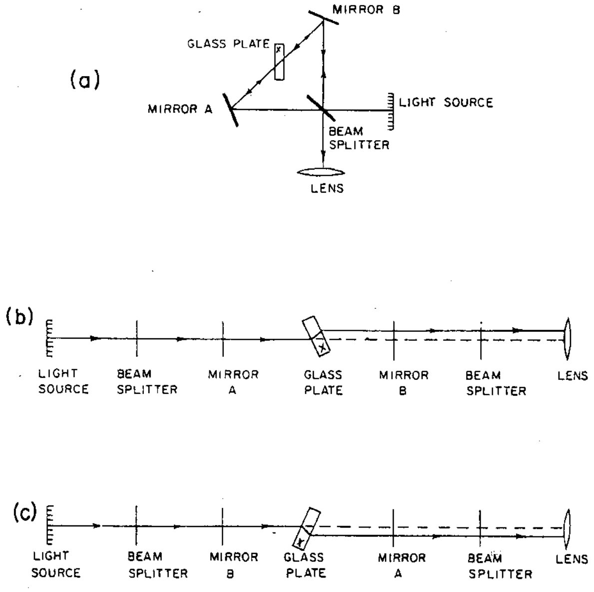

FIG. 2. Influence of a single glass plate on the interference fringes of an interferometer similar to the one used in this experiment. (a) The interferometer with the glass plate. (b) The relation of the interferometer and the glass plate to the beam transmitted by the beam splitter. (c) The interferometer with reference to the beam reflected by the beam splitter. Both (b) and (c) are with respect to an observer situated at the lens.

rubber tubing to minimize vibration. The motor for the window rotor was bolted to a piece of copper plate, which served as a heat sink for the motor. The copper plate and motor rested on a 1-in.-thick piece of plastic foam. The reversible two-phase motor had a maximum speed of about 45 rps.

A collimated white light source was used to align the interferometer initially. The mirrors and beam splitter were adjusted until the light beam from the collimator made both circuits of the interferometer at the same spots on the mirrors and windows. Then the collimator was replaced with an extended white light source with a pin in front of it, and the interferometer was adjusted until the two images of the pin coincided as nearly as possible. The autocollimation feature of the observing telescope was also used for this step. At this point in the procedure the two images were usually rotated about the telescope axis with respect to each other, so that when the telescope was focused on infinity, the fringes would not cover the whole field of view. Next, the interferometer was adjusted by rotating the beam splitter and one other mirror alternately about the horizontal axis until the fringes covered the whole field of view. If after this adjustment the fringes were not vertical, they were made so by a small rotation of the beam splitter about the horizontal axis. This did not disturb fringe clarity. Fringe spacing was adjusted by rotating the beam splitter about a vertical axis.

All observations were made with all light coming through the windows and the telescope focused on infinity. An aperture of black cardboard was placed in the interferometer to mask any light not coming through the windows. To make sure that no light was coming over or around the windows, a check was made with the telescope focused on each of the images of the windows in turn.

This interferometer has several self-compensating features. The two interfering beams travel nearly the same path in opposite directions so that an optical inhomogeneity in the interferometer path will affect both beams in almost the same way. An indication of the extent of compensation is the fact that good interference fringes were obtained with the windows in the beams and using an extended source. Figure 2 illustrates the effect of placing a window or glass plate in an interferometer similar to the one used in this experiment. Figure 2(a) shows the location and orientation of a glass plate with respect to the rest of the interferometer. Figures 2(b) and (c) show the interferometer with respect to the unfolded light beams as viewed from the lens. These figures illustrate the effect of the plate on each beam separately. The result of tilting the glass plate is to change the separation of the virtual sources, and thus to change the fringe spacing. Even the change in fringe spacing is largely compensated in the interferometer used in the experiment because there are two windows in the interferometer path placed so that the effect of one window cancels the effect of the other when both are turned through the same angle. If the glass plate in Fig. 2 is replaced by a wedge, both virtual sources shift in the same direction. But since the fringe pattern is observed at infinity, shifting both virtual sources in the same direction does not change the observed fringe pattern. First order effects, not self-compensated, would be possible differential rotation of the two windows or bowing of the windows under stresses due to high-speed rotation.

OBSERVATIONS

Visual observations and Polaroid photographs of fringes in white light using a flash duration of less than 3 μsec showed no visible fringe shift with respect to the telescope crosshair. It is estimated that a shift of 0.1 fringe would have been noticed. Observations were made continuously as the rotor came up to maximum speed. Then the rotor was reversed so that the speed was effectively doubled, and observations were made again. These observations insure that the careful measurements made later on photographs of monochromatic fringes are not in error by a whole number; that the shifts are smaller than 1 fringe in absolute value.

The appearance of the fringes was the same whether the windows were rotating or not, but taking the windows out of the path of the interfering beams changed the appearance of the fringes by rotating and narrowing them. Turbulence in the air also disturbed the fringes, so that while the chamber was being evacuated the fringes were extremely unstable. The instability lasted until the pressure was less than 10 Torr. All observations were made with the chamber evacuated to 0.02 Torr.

The photomultiplier saw both the triggering light beam and the stroboscope flash, so that the oscilloscope display indicated the delay between reception of the triggering light beam and the flash of the stroboscope. The delay from the peak of the triggering pulse to the peak of the flash was about 5 μsec (about 5 min of arc motion of the arm).

Since visual observations and Polaroid photographs in white light showed no discernible fringe shift, more sensitive determinations were made by measuring 35-mm Kodak Microfile or High-Contrast Copy film negatives on a scanning comparator.[8] The narrow-band filter was used to take these photographs.

For each data run that was to be measured on the scanning comparator, four photographs were taken (Fig. 3). The first photograph was taken with the windows stationary and normal to the interfering beams. The point where the triggering light beam fell on the photomultiplier was used to reference this position of the windows. The position of the windows could be set to about 2 min of arc, since a movement of 2 cm of the spot of light at the photomultiplier could be easily detected, and since the photomultiplier was 15.2 m from the windows. The second photograph was taken with the windows rotating at maximum speed clockwise, the third was taken with the windows rotating at maximum speed counterclockwise, and the fourth with the windows stationary in the same position as they were in the first photograph. The two photographs with the windows stationary were taken to make sure that the fringe pattern had not changed during the run.

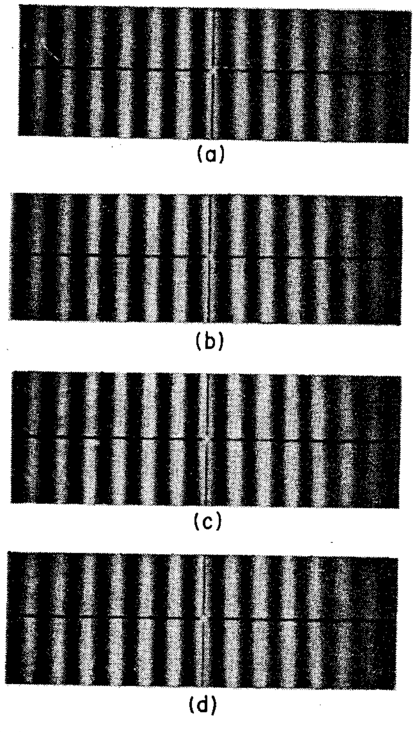
(a)
(b)
(c)
(d)

FIG. 3. Enlargements of the 35-mm photographs of Photograph Set C. (a) was taken with the windows stationary, (b) with the windows rotating clockwise at 47 rps, (c) with the windows rotating counterclockwise at 43 rps, and (d) with the windows again stationary.

On each photograph taken for reduction on the scanning comparator, between three and ten fringes were measured. The same fringes were measured on each photograph of a set of four. Both the fringe maxima and the fringe minima were measured four times each, so there were between 24 and 80 readings made on one fringe pattern. The vertical portion of the crosshair was read between 8 and 20 times on each photograph. It was not necessary to take as many readings on the crosshair as on the fringes, because the crosshair was sharper and could be located more accurately. All the readings made on the fringe pattern of one photograph were added together and divided by the number of readings to give a number which was called F_x, where x refers to the particular photograph. The average crosshair position on photograph x was called H_x, so that the shift between the photographs x and y was $D=(F_x-H_x)-(F_y-H_y)$. F_x, H_x, and D were recorded in millimeters. The average fringe spacing d was found from the differences in position of the first and last fringe minima or the first and last fringe maxima measured divided by the number of fringes in the interval. Then $\Delta f=D/d$ is the shift expressed in terms of fringes between photographs x and y.

In order to test the sensitivity of the system to the position of the arm carrying the windows, photographs were made of the fringe pattern obtained with the arm stationary at different known angles.

RESULTS AND CONCLUSIONS

The experiment was performed four times on different days. The four sets of photographs are referred to as Sets A, B, C, and D. Set A was measured by three different persons, Sets B, C, and D by one person. The adjustment of the interferometer was changed from set to set, and the spacing between fringes on the photographs varied accordingly from about 0.63 to 1.1 mm.

The standard deviation of a single setting on a fringe was approximately $0.8\,\mu$, and that of a setting on a crosshair $0.5\,\mu$. If this scatter set the limit on precision, one would expect the standard deviation of F_x-H_x to be less than $0.3\,\mu$ in all cases. It was found, however, that with Set A, the standard deviation among the three observers of F_x-H_x was $2.4\,\mu$. This corresponds to 0.0039 fringe. It is considered therefore that a fair estimate of the standard deviation in Δf is 0.0055 fringe. The range of values obtained by three observers of the fringe spacing d in a single photograph amounted to only about 0.3%, so in the conversion $\Delta f=D/d$, an average value of d was used.

When the arm holding the windows was moved 6°, a

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[8] J. M. Bennett and W. F. Koehler, J. Opt. Soc. Am. **49**, 466 (1959).

TABLE I. Results of the measurement of four sets of interference fringe photographs. The relativistic prediction for the fringe shift between clockwise and counterclockwise rotating conditions is about 0.0036 fringe, and the fringe shift between initial and final stationary conditions should ideally be zero. All fringe shifts are in fractions of a fringe. The estimated standard deviation of each shift was 0.0055 fringe.

		Fringe shift between:		
Photograph set	Observer	Initial and final stationary conditions	Clockwise and counterclockwise rotating conditions	Effective speed (rps)
A	1	−0.0141	+0.0041	88
A	2	−0.0141	+0.0020	88
A	3	−0.0162	+0.0035	88
B	1	+0.0091	+0.0052	88
C	1	−0.0032	+0.0054	90
D	1	−0.0020	+0.0036	93

shift of 0.0120±0.0065 fringe was found. As is seen below, one probably cannot regard all of this shift as a systematic effect, but its smallness shows that the ideal self-compensating features of the system were nearly realized. Shifts found when the arm was moved by 1°0′ and 0°6′ were 0.0029 and 0.0016 fringe, respectively, both less than the estimated standard deviation of the shift.

The values of the fringe shifts Δf are given in Table I for Sets A, B, C, and D. A positive value in the column for rotating conditions indicates a shift in the direction predicted by both the theory of relativity and that of simple addition of velocities. It is seen that the shifts found between the two rotating conditions scatter very little, and have a mean of about +0.004 fringe. On the other hand, the shifts between the first and last (stationary arm) photographs of a set are generally larger, and scatter much more. The reasons for this are not fully understood. In view of this uncertainty it is only claimed here that the shift between rotating conditions was less than 0.02 fringe, a value to be compared with the shift of 2.9 fringes predicted on the assumption of addition of velocities. It is also concluded that the results are, to within their own precision, in agreement with the predictions of the theory of relativity.

ACKNOWLEDGMENTS

Dr. W. R. Haseltine made many useful suggestions. We are grateful to Dr. J. M. Bennett for the use of the scanning comparator. We would like to thank Dr. T. E. Phipps and Mr. F. A. Kinder for their encouragement. Most of the data were reduced by Mrs. J. S. Brune, and Mr. P. G. Bauer constructed much of the apparatus.

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Interferometers without Collimation for Fourier Spectroscopy

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The theory is given for Fourier spectroscopy when the interferometer is not used in collimated light. The performance to be expected is compared with that given by the conventional method of an interferometer with collimation.

1. INTRODUCTION

IT is customary to use for Fourier spectroscopy an interferometer before which the light is collimated so that one limiting aperture is at infinity. The instrument is then the Twyman–Green form of the Michelson interferometer, introduced for testing optical components. Oblique rays are distributed symmetrically about the axis and the integrated effects of the variations of optical path are a minimum. However, this collimation is not essential: the equipment can be simplified by omitting the additional focusing system, when it becomes a Michelson interferometer with the two limiting apertures at a finite separation. Such a simplification is attractive in principle, but it is obtained at the cost of higher obliquity effects. In this paper the obliquity effects are derived for an interferometer limited by two circular apertures of the same size and the resultant performance is compared with that of the Twyman–Green system. The most serious sacrifice in performance occurs when a large spectral range is to be covered.

2. THEORY OF FOURIER SPECTROSCOPY

The method of Fourier spectroscopy is described by Jacquinot[1] and J. Connes.[2] Let $B(\nu)$ be the product of the spectral distribution of the light-source luminance, the transmittance of the interferometer, and the receiver sensitivity for a frequency ν. When this light is passed through an ideal two-beam interferometer in which all rays are parallel to the optical axis and the time difference for passage through the two arms is t, the flux detected is

$$F(t)=2U\int_0^\infty B(\nu)d\nu+2U\int_0^\infty B(\nu)\cos 2\pi\nu t d\nu, \quad (2.1)$$

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[1] P. Jacquinot, Rept. Progr. Phys. 23, 267 (1960).

[2] J. Connes, Rev. Opt. 40, 45, 116, 171, 231 (1961).