VOLUME 60, NUMBER 2 PHYSICAL REVIEW LETTERS 11 JANUARY 1988

Test of the Isotropy of the Speed of Light Using Fast-Beam Laser Spectroscopy

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(Received 19 May 1987; revised manuscript received 3 November 1987)

We report on a novel experiment sensitive to the anisotropy of the one-way speed of light. The frequency of a two-photon transition in a fast atomic beam is compared to the frequency of a stationary absorber while the direction of the fast beam is rotated relative to the fixed stars. The experiment yields an improved upper limit for the anisotropy: $\Delta c/c \leq 3\times 10^{-9}$.

PACS numbers: 03.30.+p

In special relativity the speed of light c is a universal constant. It is isotropic and independent of the source velocity. However, the observed anisotropy of the 3-K cosmic radiation[1] has renewed interest in experiments designed to test the universality of c.

One class of experiments, typified by the Michelson-Morley and Kennedy-Thorndike experiments (and their modern laser versions), looks for the variation in the length of a "meter stick" as the laboratory apparatus is rotated in space.[2] These experiments measure the isotropy of space in terms of the round-trip averaged speed of light, and so cannot provide information on the one-way variation, if any, of c. Another type of experiment looks for the variation in the rate of a moving atomic[3] or nuclear[4] clock. The relativistic Doppler-shifted clock frequency is compared to a standard clock at rest with an observer to derive any variation in the clock rate, either as a function of the clock velocity, or as a function of the spatial direction in which the observer receives the clock signal. These experiments can be sensitive to the one-way speed of light, in contrast to the round-trip experiments mentioned above.

Our experiment identifies the value of the speed of light in a certain direction Θ relative to a preferred direction by measuring the Doppler shift of a beam of fast atoms resonantly excited by a collinear laser beam. The velocity of the atoms is determined by simultaneous measurement of the Doppler shift with a counterrunning laser beam at direction $\Theta-\pi$. An anisotropy in the one-way propagation speed of light of the type $c'=c(1+\epsilon\cos\Theta)$ would produce a shift in the laser frequency ν_0 of $\Delta\nu=\epsilon\cos\Theta\,\nu_0 u/c$, where u is the beam velocity. This relation can be derived from a heuristic modification of the special relativity formulation by the substitution of c' for c.[3] Rotation of the Earth imposes a sidereal modulation on the Doppler-induced frequency shift if $\epsilon\neq 0$. With a north-south beam axis at the latitude of 56°, the amplitude of the modulation will be reduced by a factor of $\cos\delta\sin 56°$. Here δ is the declination of the preferred direction in space, which may be associated with the symmetry axis of the 3-K background radiation ($\delta=-6.1°\pm 1.5°$, right ascension $=11.2\pm 0.2$ h[1]).

Clearly the mere substitution of c' for c is not an adequate way to treat an anisotropic speed of light. An alternative approach can be based on the test theory of Mansouri and Sexl.[5] In the case of a standard clock-synchronization procedure this theory does not lead to any genuine anisotropy in the one-way speed of light. However, through the variation of the atomic-beam velocity as seen from an isotropic reference frame, a laser-frequency modulation of the type $\Delta\nu=\epsilon\cos\Theta\,\nu_0 u/c$ is predicted. The "anisotropy parameter" ϵ is expressed as $(1+2\alpha)v/c$, with $\alpha=-\frac{1}{2}$ corresponding to the special theory of relativity. v is the velocity of the laboratory relative to the reference frame. By now the most precise direct test of special relativity yields $\alpha=-\frac{1}{2}\pm 2\times 10^{-5}$.[6]

Our experiment makes use of the $3s[\frac{3}{2}]_2^0-4d'[\frac{5}{2}]_3^0$ two-photon transition in a beam of fast ^{20}Ne atoms traveling collinearly with two counterpropagating beams from a single laser. The intermediate state, $3p'[\frac{3}{2}]_2$, is tuned into resonance for single-photon absorption by selection of the atomic-beam speed. The two-photon absorption (TPA) rate is strongly enhanced[7,6] by the establishment of the intermediate-state resonance which defines a unique beam velocity. Another advantage of being exactly tuned to intermediate-state resonance is that the near-resonant ac Stark shift vanishes.

The laser frequency as dictated by the fast-beam resonant TPA transition is compared to a reference transition in an I_2 cell at rest in the laboratory frame. In

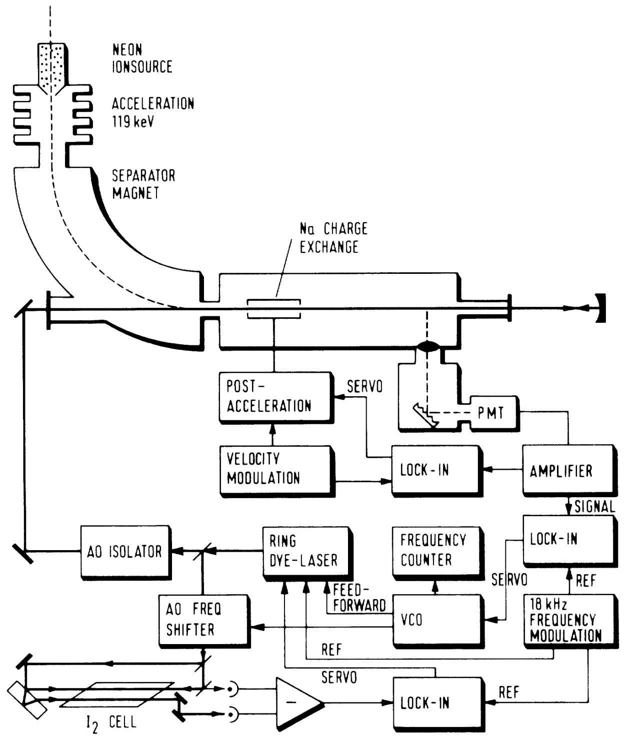

FIG. 1. Experimental apparatus used for the isotropy-of-space test, consisting of an accelerator, an actively stabilized dye laser, an acousto-optic (AO) frequency shifter, an I_2 reference cell, and a frequency counter. The dye laser is locked to a saturated I_2 absorption line. The fast-beam two-photon absorption is used for locking of the AO frequency and the fast-beam velocity.

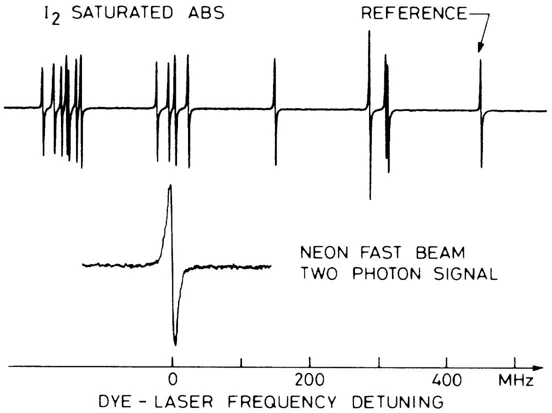

FIG. 2. Frequency of a neon fast-beam two-photon signal measured relative to a saturated I_2 absorption [No. 5239 of the iodine atlas (Ref. 8), hyperfine component *a*].

terms of an anisotropy test, we look for a variation in the difference between the two optical frequencies correlated with the Ne-beam direction in space, as modulated by the daily rotation of the Earth.

The experimental setup is shown schematically in Fig. 1. The cw dye laser was tuned to the resonant TPA transition in the fast beam. Part of the laser light was twice passed through an acousto-optic frequency shifter to give resonance with a hyperfine component of a nearby I_2 line, shown in the upper trace of Fig. 2. The main laser beam was sent into the atomic beam via a telescope and was retroreflected with a curved mirror for mode matching of the copropagating and counterpropagating laser beams. The TPA transition was monitored by the observation of fluorescence from the upper level. A "crossed" servo topology used the strong I_2 signal to lock the laser and narrow its linewidth, while the TPA signal more slowly controlled the rf source for the acousto-optic frequency shifter to ensure excellent long-term stability. Appropriate feedforward to the laser decoupled the two locks. The measured quantity, the servo-determined rf frequency, represents the difference between the resonance frequencies of the I_2 and the fast-beam quantum transitions.

In precise experiments the uncertainties are often dominated by systematic errors. In the I_2-saturated-absorption part, the major systematic effect is connected with pressure shifts. Since the vapor pressure varies strongly with temperature, the I_2 cell's cold finger was maintained at 0 °C. The stability of the I_2 lock was studied by our locking the laser to a different I_2 hyperfine component in a second cell instead of to the fast-beam resonance. The servo-determined frequency applied to the acousto-optic shifter was stable to within 2 kHz in a measuring period of 10 sec. The intensities of the saturating and probe beams were kept constant at 1.0 and 0.1 mW/mm^2, respectively, throughout the whole experiment. Increasing the laser power by a factor of 10 in one of the cells caused no measurable frequency shifts.

The main source of error on the TPA resonance in the fast beam is misalignment of the atomic and laser beams, which introduces a component of the first-order Doppler shift into the otherwise first-order Doppler-free transition frequency. To ensure that the laser beams and the atomic beam are properly aligned, a set of three apertures were placed in a straight line along the 6-m beam path. The acousto-optic modulator used as an optical isolator caused some spurious spatial modes to appear in the laser beam. These were removed by a spatial filter. The copropagating and counterpropagating laser beams were carefully mode matched and were aligned to pass straight through the three beam-line apertures by the observation of the symmetry of their ring diffraction patterns. The waists of both laser beams were centered in the interaction region, which minimizes the beam divergence and alignment errors to within 3×10^{-5} rad. The fast neon beam was aligned with the laser beams to within 10^{-4} rad by optimization of the beam current through the three beam-line apertures. The alignment errors result in a frequency shift of less than 3 kHz.

The Doppler width of the $3s[\frac{3}{2}]_2^0$-$3p'[\frac{3}{2}]_2$ one-photon transition was measured to be 25 MHz, which corresponds to a 3-V energy spread in the fast beam. At the power level used to excite the TPA in the experiment, the $3s[\frac{3}{2}]_2^0$-$3p'[\frac{3}{2}]_2$ transition is broadened to about 80 MHz with a symmetry of better than 0.3%. If the beam energy is changed slightly, the second-order Doppler effect produces a frequency shift of -27 kHz/V. Close to intermediate-state resonance this slope is modified by the ac Stark effect, having a positive slope. With the applied Rabi frequencies the resulting slope is calculated to be $+21$ kHz/V in the voltage range ± 1 V around exact resonance. Long-term velocity variations due to drifts of the acceleration and anode voltages were compensated to within 70 mV rms by a servoing of the postacceleration to the maximum of the TPA fluorescence, using the resonant dependence of the TPA transition rate with intermediate-state detuning as noted previously. With the velocity and TPA locks operating, the slight asymmetry of the velocity distribution does not work through the second-order Doppler and ac Stark effects to give a measurable shift of the TPA resonance frequency.

In the run presented in Fig. 3, data were accumulated over 36 h. The simplest way to analyze the data is to fit them by a constant and a 24-sidereal-hour cosine with variable amplitude and phase. With the use of a least-squares routine, with each datum point weighted by the variance of its 25 individual measurements, the 24-h component has an amplitude of 0.17 ± 0.38 kHz. The phase corresponds to a maximum when the fast-beam direction is at a right ascension of 10.9 ± 8.8 h. The quoted uncertainties are the formal statistical standard deviations, which are valid error limits only if the data points are uncorrelated, i.e., when there are no systematic effects. This is clearly not the case in this experiment where the standard deviation of the fit (4.9 kHz) is about 10 times larger than that of the individual data points.

A short-range correlation is apparent in the data, and is confirmed by a Fourier analysis showing low spectral power density for periods shorter than 3 h. The correlation can be taken into account by an increase of the formal statistical standard deviation by a factor of $[(\text{number of data points})/(\text{number of “independent” points})]^{1/2}$, where the number of “independent” points is the total data acquisition time divided by the correlation time: $(36\text{ h})/(3\text{ h}) = 12$. With a total of 196 data points, the statistical standard deviation will therefore be increased by a factor of 4.

One systematic effect is due to slow drifts in the emittance of the ion source which induces a dominating periodic variation with a period of about 12 h. To assess this systematic effect, the data were fitted by five parameters: A constant and two cosines, each with variable amplitude and phase. The period of one cosine was fixed at 24 sidereal hours, while the other was allowed to vary, to give a first-order modeling of the behavior of the source. The sum-squared residuals of the fit has a minimum when the period of the second cosine is at 11.8 sidereal hours. The least-squares fitting, using 24- and 11.8-h periods, results in a 24-h component of 0.81 $\pm$ 1.0 kHz, where the formal standard deviation of the 0.26 kHz has been increased to account for the short-term correlation. The phase corresponds to a maximum at a right ascension of 12.6 ± 1.3 h. The correlation-coefficient matrix shows a correlation of less than 0.15 between the 11.8- and 24-h components. The data points after the 11.8-h component is subtracted are shown in Fig. 4 as folded into a 24-h window.

If the 24-h component were due to a real effect, its phase and amplitude should remain stable when data points are removed. However, omission of the points 1 h

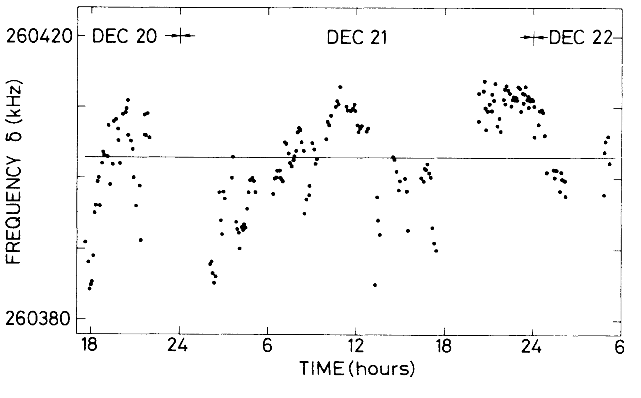

FIG. 3. The experimental data as function of time. Each datum point is the average of 25 consecutive frequency determinations each sampled in a period of 10 sec by an electronic counter. The ion-source filament was replaced at 20 h on 20 December and at 18 h on 21 December.

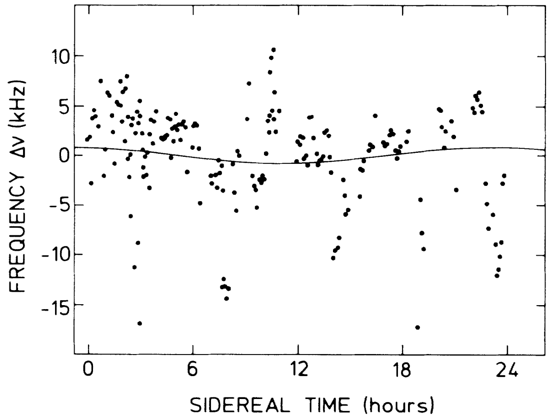

FIG. 4. Experimental data and the fitted 24-h component as a function of sidereal time. A constant of 260402 kHz and an 11.8-h period with a 7.1-kHz amplitude have been subtracted. The 24-h component has a maximum of 0.81 kHz at 23.4 h, corresponding to a right ascension of the beam direction of 12.6 h. See text.

before and after the ion-source replacements shifted the phase by 90° and changed the amplitude to 1.54 kHz with the same uncertainty as before. Therefore we conclude that the uncertainty is dominated by systematic errors, covering any potential signal smaller than 2 kHz.

Another limitation stems from the low spectral resolution associated with the duration of the run: We cannot spectrally separate a genuine sidereal signal from a spurious systematic effect at the solar period. Exact cancellation would be rather unlikely, and the masking procedure gives further assurance that we are not dealing with two canceling effects. Thus it is reasonable to conclude that *this experiment shows that the 24-h component is zero with an uncertainty of 2 kHz.* An amplitude of 2 kHz corresponds to $\epsilon = 2.8\times10^{-9}$. In the test theory of Mansouri and Sexl we find $\alpha = -\frac{1}{2} \pm 1.4 \times 10^{-6}$, using a laboratory velocity of 300 km/s.

The present experiment is similar in spirit to the previous one-way anisotropy experiments, the Mössbauer rotor[4] and the space-borne H maser.[3] Our high sensitivity represents an $\simeq 10$-fold improvement and stems from the high velocities attainable in fast beams. With the use of heavy-ion storage rings, presently under construction, cold and high-velocity particle beams will be available, and when these are combined with the recent development of ultrastable and ultranarrow-band cw dye lasers and Rydberg-atom spectroscopy, truly exciting improvements of fast-beam precision experiments are foreseen.

An equally important issue is the need of test theories of special relativity. Such theories are crucial both in defining optimum measurement strategies and in the interpretation of "null" experiments.

Discussions with and assistance from Peter Bender, Martin Kristensen, Klaus Mømer, Birger Ståhlberg, and Linda Young are gratefully acknowledged. This work was supported by the Danish Natural Science Research Council, the Carlsberg Foundation, the Nordic Accelerator Committee, the U.S. National Bureau of Standards, and the U.S. National Science Foundation, Grant No. PHY-8508594.

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