Prospects for precision physical experiments in optics

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Until recently the sources of electromagnetic waves in the radio and γ-ray bands were much more monochromatic than optical sources. The advent of stable lasers with frequency reproducibility $\sim 10^{14}$ has uncovered new possibilities of performing experiments of interest in physics. To illustrate these possibilities, results are cited of the measurements of the quadratic Doppler effect in a gas, the magnetic hyperfine structure of a vibrational-rotational transition of methane, and the recoil effect. A number of experiments that lasers will make possible in the near future are discussed, namely, high-accuracy measurements of the Rydberg constant using two-photon absorption, measurement of the quadratic Doppler shift, measurements of the gravitational frequency shift of the earth's field, and the possibility of observing parity nonconservation in atomic transitions.

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CONTENTS

1. INTRODUCTION

Many experiments have now been performed in which a source of highly monochromatic electromagnetic radiation played a decisive part. At present the narrowest lines are produced by Mössbauer sources in the γ-ray region. These sources have made it possible most accurately to measure the gravitational shift of spectrum lines under terrestrial conditions,[1,2] the quadratic Doppler shift using a rotating source,[3] etc. (also see Ref. 4). In these experiments the relative line width was in the range 10^{-15}–10^{-16}. For the microwave frequencies, masers have been constructed which have relative line widths and frequency reproducibilities of $\sim 10^{-13}$ and are now used as frequency standards.

Until recently, the best optical sources lagged considerably behind the best microwave and γ-ray sources as regards monochromaticity. In recent years, however, the situation has changed, thanks to great progress in the frequency stabilization of lasers: from 1967 to 1974 the long-time relative stability of lasers improved from 10^{-8} to 10^{-14}. Lasers having an emission-line width of a few hertz have recently been constructed[5] and have provided the basis for the development of spectrometers with a resolving power of 10^{13}. These achievements became possible thanks to the development of narrow optical resonances in gases having widths of 10–100 kHz, which were used as reference points for frequency stabilization. The physical principles underlying the development of these resonances lie at the basis of a rapidly evolving science: nonlinear laser spectroscopy.

Highly stable lasers open up new prospects for physical experiments, which we shall discuss in this article. First, however, let us briefly examine the characteristics of a particular stable laser,[6] so that we may use its frequency reproducibility to orient ourselves in the discussion to follow.

An absorption resonance in methane, which was ≈ 40 kHz wide and nonlinear in the field, was used as a reference point to adjust the frequency of a He–Ne laser operating at $\lambda = 3.39$ μm. An important feature of this resonance is that the linear Doppler shift is eliminated, since only atoms moving almost perpendicularly to the direction of the field contribute significantly to that shift.

The amplifying tube of the He–Ne laser was ~ 2 m long and the methane absorption cell was ~ 3 m long; the diameter of the light beam in the cell was ~ 1 cm. The laser was mounted on a 50-ton base to eliminate mechanical vibrations. The long-time relative stability of this laser was $5 \cdot 10^{-15}$, and its frequency reproducibility, $3 \cdot 10^{-14}$. The figure $5 \cdot 10^{-15}$ means that the average frequency ($\omega \approx 10^{-14}$ Hz) did not drift by more than 0.5 Hz in a fairly long time (about an hour in the present case).

An important characteristic of a stable laser, which largely determines its usefulness in applications, is the reproducibility of its frequency, i.e., the accuracy with which the emission frequency of the laser can be reproduced from run to run. To determine the frequency reproducibility experimentally one observes the beats between two independently tuned stable lasers. For the particular laser under discussion, the difference $\Delta\omega$ between the average frequencies did not exceed 3 Hz; this corresponds to the frequency reproducibility $\Delta\omega/\omega =$

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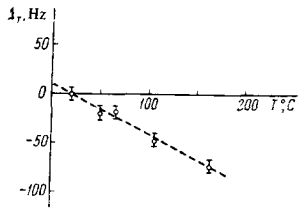

FIG. 1. Frequency shift of a laser stabilized against the power peak and operating at 3.39 μm vs the temperature of the methane absorption cell. The dashed line was calculated.

$3 \cdot 10^{-14}$ given above. If this laser were to be used as a frequency standard, we could guarantee that a second identical laser constructed elsewhere would reproduce this frequency with an accuracy of $3 \cdot 10^{-14}$, i.e., the difference between the frequencies of the two lasers would not exceed 3 Hz.

To illustrate the possible uses of stable lasers with highly reproducible frequency we describe an experiment performed at our Institute, in which the quadratic Doppler effect was measured in a gas.[7] The quadratic Doppler effect is a relativistic effect associated with time dilatation in a moving reference system. An atom moving with velocity $\mathbf{v}$ in a field of frequency ω, will see a field of frequency

$$\omega' = \frac{\omega - \mathbf{kv}}{\sqrt{1-(v^2/c^2)}} \approx \omega - \mathbf{kv} + \frac{1}{2}\frac{v^2}{c^2}\omega,$$

where $\mathbf{k}$ is the wave vector. As was noted above, the experimental method employed eliminates the linear Doppler shift ($\mathbf{k} \cdot \mathbf{v} = 0$). The quadratic Doppler shift results in a shift of the transition frequency by an amount which, after averaging over the velocities, is given by

$$\Delta\omega = -\frac{1}{2}\frac{v_0^2}{c^2}\omega,$$

where ω is the laser emission frequency and v_0 is the thermal velocity. For the $\lambda = 3.39$ μm transition in methane, the shift is

$$\Delta\omega \approx 0.5 \text{ (Hz/deg) } T \text{ (deg)}. \qquad (1)$$

In the experiment, beats were observed between two lasers whose frequencies were reproducible within $3 \cdot 10^{-14}$. When the methane cell of one of the lasers was heated the frequency of that laser was found to shift toward the red at the rate 0.5 Hz/deg (Fig. 1). The experimental results agreed with the theoretical formula (1) within 5%.

Of the other measurements that have been made with stable lasers, we should mention the resolution of the magnetic hyperfine structure of the vibration-rotation transition in methane at $\lambda = 3.39$ μm (the F_2^2 component of the $P(7)$ line of the ν_3 band).[8] An attempt directly to observe the splitting of this resonance due to the recoil effect has met with success.[5] Figure 2 shows a recording of the first frequency derivative of the intensity of the nonlinear resonance at this transition; it will be seen that there are three strong components separated by ≈11 kHz. One of the resonances is split by about 1 kHz as a result of the recoil effect. This effect is due to the fact that the absorption line is shifted with respect to the emission line by an amount equal to twice the recoil energy acquired by the atom on emitting the photon.

We shall discuss several experiments involving stable lasers which, in our opinion, could be performed now:

1) measurement of the Rydberg constant using two-photon absorption at the 1S–2S transition in atomic hydrogen;

2) measurement of the quadratic Doppler shift;

3) measurement of the gravitational frequency shift in the Earth's field; and

4) the possible observation of parity nonconservation in atomic transitions.

2. MEASUREMENT OF THE RYDBERG CONSTANT

Let us consider the possibility of improving the accuracy achieved in measurement of the quantity cR_H, which, like R_H, is called the Rydberg constant of the hydrogen atom. Available measurements of R_H and c are accurate within $9 \cdot 10^{-9}$ and $4 \cdot 10^{-9}$, respectively[9]; hence cR_H is known within $1.4 \cdot 10^{-8}$.

The constant cR_H can be expressed in terms of such fundamental constants as the electron mass m, the electron charge e, Planck's constant h, and the electron-to-proton mass ratio m/M:

$$cR_H = \left(1 + \frac{m}{M}\right)^{-1} \frac{me^4}{4\pi h^3} = 3.28805119\,(5) \cdot 10^{15} \text{ Hz}. \qquad (2)$$

An improvement in our knowledge of cR_H would lead to improvements in our knowledge of these other constants, since (2) is included among the relations used to reconcile the fundamental constants.

The proposed experiment is based on the use of stable lasers to measure the frequency of the 1S–2S transition in atomic hydrogen. Because of the hyperfine splitting of the levels there are two frequencies $\omega_{2S-1S}(F=0)$ and $\omega_{2S-1S}(F=1)$, which are separated by 1242 MHz (Fig. 3).

The energies of the hydrogen-atom levels can be calculated with great accuracy and may be written in the form

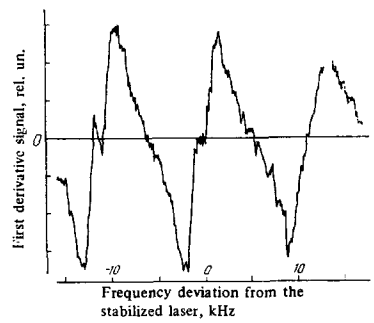

FIG. 2. First frequency derivative of the absorption intensity at the 3.39 μm transition in methane (the F_2^2 component of the $P(7)$ line of the ν_3 band). The peaks of the three resolved magnetic-hyperfine–structure resonances correspond to the zero in the derivative at −11, 0, and 11 kHz. The ≈1 kHz splitting of the resonance at −11 kHz is due to the recoil effect.

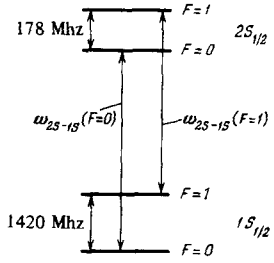

FIG. 3. Hyperfine splitting of the $1S-2S$ transition in atomic hydrogen.

$$E_n(F) = -hcR_H n^{-2} + \Delta E_n(F),$$

where n is the principal quantum number and $\Delta E_n(F)$ is a correction for the fine and hyperfine splittings and for the radiative level shift. All other corrections, e.g., for the addition to the anomalous magnetic moment of the electron, for the finite size of the nuclear charge distribution, etc. are included in $\Delta E_n(F)$.[10] Current theory and the accuracy with which the fundamental constants are known enable one to calculate these corrections with very high absolute accuracy.

The largest error in the calculation is associated with the corrections $\Delta E_1(F)$ to the $1S$ level and is due, in our opinion, to the finite size of the nucleus. The finite size of the nucleus leads to a shift of the $1S$ level of magnitude[10] $(\frac{4}{3})cR_H r_0^2/a^2$, where $r_0 \approx 1.1 \cdot 10^{-13}$ cm is the nuclear radius and a is the Bohr radius. If we assume that the size of the nucleus is known within 10%, we find that the absolute error in the position of the $1S$ level will be

$$\Delta\omega' = \frac{4}{3} cR_H \frac{2r_0 \Delta r_0}{a^2} \approx 5 \cdot 10^5 \text{ Hz}.$$

We shall assume that $\Delta\omega'$ is the accuracy with which $\Delta E_1(F)$ can be calculated.

The frequency of the $1S-2S$ transition is obviously given by

$$\omega_{2S-1S}(F) = \frac{3}{4} cR_H + \Delta\omega(F),$$

where $\Delta\omega(F) = (\Delta E_2(F) - \Delta E_1(F))/h$. If ω_{2S-1S} is measured to within $5 \cdot 10^5$ Hz, then cR_H will be measured with that same accuracy; then the relative accuracy of the measurement of cR_H will be 10^{-10}, i.e., two orders of magnitude better than the present accuracy. The accuracy of the frequency standard is now of the order of 10^{-12}, i.e., it is accurate enough to permit the suggested measurements to be made.

The choice of the $1S-2S$ transition in atomic hydrogen is dictated by two factors that make it possible to obtain a narrow optical resonance: the short radiative lifetime of the $2S$ level, which determines the limiting width of the resonance, and the possibility of using low gas pressures ($10^{-4}-10^{-5}$ Torr), since the transition takes place from the ground state. In view of the fact that the $1S-2S$ transition with absorption of a single photon is forbidden, one cannot employ the widely used methods based, for example, on using the Lamb dip.

The most suitable approach is to use the two-photon absorption resonance in a standing wave field.[11] The use of this method to measure the frequency of the $1S-2S$ transition in atomic hydrogen was proposed a few years ago[12] (see Ref. 13 for more details). The two-photon absorption resonance at this transition was recently observed experimentally in the pulsed regime,[14] and the frequencies $\omega_{2S-1S}(F=0)$ and $\omega_{2S-1S}(F=1)$ were resolved.

Let us consider a gas of hydrogen atoms in a standing wave field of frequency ω. In the case of simultaneous absorption of two photons moving in opposite directions, the absorption line has a narrow resonance at the frequency $\omega = \omega_{2S-1S}/2$ with the width γ of the two-photon transition. An important feature of such absorption is the elimination of both the Doppler shift (in a traveling-wave field the two-photon absorption line is subject to the usual Doppler broadening) and the recoil effect.

The probability for the simultaneous absorption of two photons by an atom appears in the second order of perturbation theory, and the calculations for the $1S-2S$ transition in atomic hydrogen can be carried through to the end. We can write the following formula for the number of atoms per unit volume excited per unit time to the $2S$ state:

$$\frac{dn_{2S}}{dt} \approx 10^{12} \frac{(\gamma/2)^2}{(2\omega - \omega_{2S-1S})^2 + (\gamma/2)^2} \frac{J^2 (\text{W/cm}^2)}{\gamma/P(\text{MHz/Torr})}, \quad (3)$$

where P is the hydrogen pressure and J is the energy flux density in each of the two traveling waves. If we assume that $J = 1$ W/cm^2 and $\gamma/P = 10$ MHz/Torr, we find that $dn_{2S}/dt = 10^{11}$ cm^{-3}sec^{-1} at resonance. The absorption resonance results in a corresponding resonance in the number of atoms in the $2S$ state, and the latter can be observed by various methods, such, for example, as are used to measure the Lamb shift between the $2S$ and $2P$ levels.[15]

The radiative width of the transition, which amounts to ~1 Hz, can hardly be realized in practice. For our purposes, however, such a narrow line is not required. We shall consider a resonance width of $\sim 10^5$ Hz for orientation purposes. The resonance due to the passage of atoms with thermal velocity $v_0 \sim 10^5$ cm/sec through a light beam ~0.1 cm in diameter has a width of that order.

The main factor determining the width and shift of the resonance is the quadratic Doppler shift. We have investigated the shape of the two-photon absorption line at the $1S-2S$ transition in atomic hydrogen as nonuniformly broadened by the quadratic Doppler shift.[16] The shift and broadening of the resonance are of the order of $\nu \sim \omega v_0^2/c^2$. For $v_0 = 10^5$ cm/sec we have $\nu \sim 10^4$ Hz; this is smaller than the line width that we chose for orientation purposes. Collision broadening is not significant at low gas pressures, amounting only to 10^2-10^3 Hz at $10^{-4}-10^{-5}$ mm Hg.

The experiment primarily involves the measurement of optical frequencies. In view of the considerable progress that has been made in the measurement of frequencies in the infrared region[17] we may expect this problem to be successfully solved in the very near fu-

ture. In that case we shall need a dye laser emitting at $\lambda = 4860$ Å with a stability of 10^{-10}, whose frequency will be measured by comparison with the emission of a standard whose stability is also 10^{-10}. The second harmonic of this radiation ($\lambda = 2430$ Å), obtained by methods of nonlinear optics (e.g., by using an ADP crystal), will provide the necessary resonance for two-photon absorption. We determine the resonance of the excited atoms in the $2S$ state and thereby measure the frequency of the $1S-2S$ transition. The difficulty in performing this experiment is primarily due to the low efficiency in converting the 4860 Å emission to the second harmonic. Even if the power of the dye laser operating in the single-mode regime at 4860 Å lies in the range 1–10 W, the absorption resonance will be estremely weak and it is doubtful that it could be observed.

To avoid this difficulty, it has been suggested[18] that two-photon absorption of a continuous sequence of ultrashort pulses be employed. In that case absorption resonances also arise when the sum of the frequencies of two locked modes coincides with the transition frequency. The width of these resonances is not determined by the pulse length, but by the width of the two-photon transition, while the intensity of the resonances is of the same order as in the single-mode regime.

An important advantage of the ultrashort-pulse regime is the much higher efficiency in converting the dye-laser light to the ultraviolet. The intensity of the second harmonic is higher in the ultrashort-pulse regime than in the single-frequency regime at the same power by a factor of N, where N is the number of locked modes.[19] If $N \sim 10^2$–10^3, the intensity of the resonances at the $1S-2S$ transition in atomic hydrogen will be 10^4–10^6 times higher than in the single-frequency regime. This makes it possible to perform the experiment with the necessary accuracy in the continuous regime.

3. MEASUREMENT OF THE QUADRATIC DOPPLER SHIFT

In this section we consider a method for measuring the quadratic Doppler shift in which use is made of two waves propagating in opposite directions, whose frequencies are symmetric about the transition frequency.[20]

Let there be two waves of frequencies ω_+ and ω_- propagating along the z axis in opposite directions. Let there also be an atomic beam directed along the light beam (along the z axis), the beam atoms having a transition whose frequency ω_0 is close to ω_+ and ω_-. We denote the z component of the velocity of a beam atom by v. The wave of frequency of frequency ω_+ will interact with atoms whose velocities satisfy the resonance condition $\omega_+ = \omega_0 - \mathbf{k}\cdot\mathbf{v}$; the corresponding resonance condition for the oppositely propagating wave is $\omega_- = \omega_0 + \mathbf{k}\cdot\mathbf{v}$ (we may assume that both waves have the same wave vector $\mathbf{k}$). In general, the two waves will interact with different atoms. Only when

$$\frac{\omega_+ + \omega_-}{2} = \omega_0, \tag{4}$$

i.e., when the frequencies of the two waves are symmetric about the transition frequency, will both waves interact with the same atoms—with those for which

$$v = -\frac{\omega_+ - \omega_-}{2k}. \tag{5}$$

This circumstance leads to the appearance of a resonance in the absorption coefficient for either one of the waves when $(\omega_+ + \omega_-)/2 = \omega_0$. The absorption coefficient has the form

$$\alpha \sim \left[1 - \frac{\varkappa}{2} - \frac{\varkappa}{2}\frac{(\gamma/2)^2}{\Omega^2 + (\gamma/2)^2}\right], \tag{6}$$

where $\Omega = ((\omega_+ + \omega_-)/2) - \omega_0$, γ is the homogeneous line width, and $\varkappa$ is a dimensionless saturation parameter proportional to the intensity of the field ($\varkappa \ll 1$); it is assumed that γ is much smaller than the Doppler width due to the spread of the z components of the velocities of the atoms. It is evident from (6) that on varying Ω one will observe a resonance at $\Omega = 0$ whose width is equal to the homogeneous width. The resonance fixes the frequency difference $2\Delta = \omega_+ - \omega_-$, and this, according to (5), also fixes the z component v of the velocities of the atoms interacting in resonance with the field.

The resonance frequency ω_0 of the atom is shifted as a result of the quadratic Doppler effect. If the average longitudinal velocity v_0 of the beam is much higher than the average transverse velocity u_0, one can allow for the quadratic Doppler effect with the aid of the substitution

$$\omega_0 \to \omega_0 - \frac{v^2}{2c^2}\omega_0,$$

in which v is determined by Eq. (5). This gives

$$\alpha \sim \left\{1 - \frac{\varkappa}{2} - \frac{\varkappa}{2}\frac{(\gamma/2)^2}{[\Omega + (\Delta^2/2\omega_0)]^2 + (\gamma/2)^2}\right\},$$

i.e., the resonance will now appear at the point

$$\Omega = -\frac{\Delta^2}{2\omega_0}. \tag{7}$$

Formula (7) shows that on varying Δ one will observe a quadratic dependence of the shift of the resonance on Δ.

It is convenient to observe this dependence experimentally with the aid of a stable laser in the two-frequency regime. One compares the frequency ω_+ in the $\Delta = 0$ regime with the frequency ω_r of a reference laser. Let $\delta = \omega_+ - \omega_r$. Then in the symmetric regime one measures $\Delta = (\omega_+ - \omega_-)/2$ and again compares the frequency ω_+ with the new value $\omega_r' = \omega_r + \Delta$ of the reference laser frequency. According to (7)

$$\omega_+ - \omega_2' = \delta - \frac{\Delta^2}{2\omega_0}.$$

For the case in which $\lambda = 3.39$ μm and $\Delta \approx 3 \cdot 10^8$ Hz (half the Doppler width) we have $\Delta^2/(2\omega_0) \approx 400$ Hz. If we assume that the absolute error in the frequency measurement is $\Delta\omega' = 3$ Hz, as reported in Ref. 5, we find that the accuracy in measuring the quadratic Doppler shift will be

$$\frac{\Delta\omega'}{\Delta^2/2\omega_0} \approx 10^{-2}. \tag{8}$$

We emphasize that the method under discussion for

measuring the quadratic Doppler shift automatically selects atoms having a definite longitudinal velocity in the beam, thereby eliminating the difficulties involved in producing a monochromatic beam.

The quadratic Doppler effect is the most important factor limiting the reproducibility of frequency standards in both the microwave and the optical regions.

Let us estimate the accuracy to which the effect of the quadratic Doppler shift can be eliminated when using an atomic beam in which the thermal velocity is $v_0 \sim 5 \cdot 10^4$ cm/sec. This accuracy is determined by two factors: 1) the homogeneous width of the line through which the atom interacts with the field, and 2) the angular spread of the atomic beam.

The accuracy with which the longitudinal velocity v of the atoms is selected in the two-frequency regime is $\Delta v \sim \gamma/k$. The relative magnitude of the quadratic Doppler shift for thermal velocities is, in order of magnitude, $\Delta\omega/\omega \sim v_0^2/c^2 \sim 10^{-12}$. Since the relative error in selecting the velocity is $\Delta v/v \sim \gamma/(kv_0)$, the Doppler shift will be eliminated with the relative error

$$\frac{\Delta\tilde{\omega}}{\omega} \sim \frac{\Delta\omega}{\omega}\frac{\gamma}{kv_0} \sim 10^{-12}\frac{\gamma}{kv_0}.$$

An angular spread θ_0 of the atomic beam corresponds to transverse velocities $u_0 \sim \theta_0 v_0$. The relative magnitude of the quadratic Doppler shift due to the transverse velocities is

$$\frac{\Delta\tilde{\omega}}{\omega} \sim \frac{1}{2}\frac{u_0^2}{c^2} \sim \theta_0^2\frac{\Delta\omega}{\omega} \sim 10^{-12}\theta_0^2.$$

Since we assumed a frequency reproducibility of $\sim 10^{-16}$ for orientation purposes, we should eliminate the quadratic Doppler shift to that same accuracy. In that case we should have $\gamma/(kv_0) \sim 10^{-4}$ (e.g., $\gamma \sim 10^5$ Hz and $kv_0 \sim 10^9$ Hz) and $\theta_0 \sim 10^{-2}$ ($\sim 0.5°$), and it is entirely possible to meet these conditions.

The above estimates are based on the assumption that it will be possible to construct a laser having a frequency reproducibility of $\sim 10^{-16}$; in that case we see from Eq. (8) that the error in measuring the quadratic shift should amount to $\sim 10^{-4}$.

4. THE GRAVITATIONAL SHIFT OF SPECTRUM LINES

Einstein listed three effects that could be used for an experimental test of the general theory of relativity: the gravitational shift of spectrum lines, the deflection of a light ray in the Sun's gravitational field, and the advance of Mercury's perihelion. At present an accuracy better than 1% has not been achieved in measuring these and other such effects. That the accuracy is so poor is due to the fact that within the Solar System the effects are small.

In this section we discuss the possibility of using stable lasers to measure the gravitational shift of spectrum lines in the Earth's field.

When light propagates between two points 1 and 2 at which the gravitational potential is φ_1 and φ_2, respectively, the relative shift of the frequency ω is

$$\frac{\Delta\omega}{\omega} = \frac{\varphi_1 - \varphi_2}{c^2}.$$

The best accuracy in measuring this effect was achieved in the γ-ray region using the Mössbauer effect.[2] The experiments were performed at the Earth's surface, where

$$\frac{\Delta\omega}{\omega} = \frac{gh}{c^2} \approx 10^{-16}h\ (\text{m}),$$

here g is the acceleration due to gravity and h is the altitude difference. In the experiment[2] h was 25 m and 14.4-keV γ rays were used. The relative error of the frequency measurements was $5 \cdot 10^{-17}$, corresponding to a 1% error in measuring the shift.

The gravitational frequency shift could be determined experimentally by observing the beats between two stable lasers, one of which being located, for example, on a mountain. If $h = 5$ km, then $\Delta\omega/\omega = 5 \cdot 10^{-13}$. For definiteness we shall assume that the lasers will have the same frequency reproducibility as was reported in Ref. 6, i.e., that the relative error $\Delta\omega'/\omega$ in measuring the frequency will be $3 \cdot 10^{-14}$. Then the error in measuring the gravitational frequency shift will be

$$\frac{\Delta\omega'}{\Delta\omega} = \frac{\Delta\omega'/\omega}{\Delta\omega/\omega} = 6 \cdot 10^{-2} = 6\%.$$

The main advantage of laser light is that it can be propagated to great distances. Despite the fact that frequency measurements in the optical region are still three or four orders of magnitude less accurate than in the γ-ray region, the absolute gravitational frequency shift is considerably larger.

The idea of using artificial earth satellites (AES) is intriguing. In this case $\Delta\omega/\omega \sim 10^{-10}$, and in measuring the effect, the error due to instability of the lasers is $\Delta\omega'/\Delta\omega \sim 10^{-4} = 0.01\%$.

However, the main errors in using AES are evidently those due to orbital variations. The most important is the error Δv in determining the component of the AES velocity in the propagation direction of the light beam, which leads to a Doppler frequency shift of magnitude $\Delta\omega \sim \Delta v \cdot \omega/c$. To achieve the accuracy $\Delta\omega/\omega \sim 10^{-14}$, we must keep Δv extremely small: $\Delta v \sim 10^{-3}$ cm/sec. Hence it is not yet clear that AES can be used to measure the gravitational frequency shift.

5. PARITY NONCONSERVATION IN ATOMIC TRANSITIONS

The possibility of detecting the weak interaction of electrons with protons and neutrons by observing parity nonconservation in atomic transitions is now being widely discussed.[21–25] A detailed discussion of the theory and the proposed experiments in this area, as well as a comprehensive bibliography, will be found in recent review articles.[26,27] Here we shall just briefly examine the physical manifestations of the effect.

According to theoretical models (see, e.g., Ref. 28)

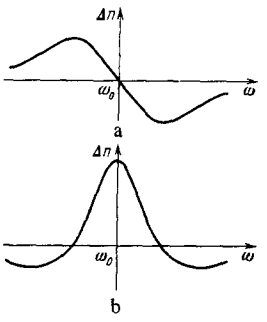

FIG. 4. Frequency dependence of the difference between the refractive indices for right- and left-hand polarizations: a) for parity nonconservation in the atomic transition due to the weak interaction; b) in a uniform magnetic field.

this interaction is P-odd, and this results in nonconservation of the parity of the atomic states (the atomic states acquire small admixtures of the opposite parity). We may therefore expect qualitatively new effects in the interaction of optical fields with atoms, and in particular, we may expect to observe rotation of the plane of polarization in a gas.[21]

Let V be the matrix element for an atomic transition of frequency ω_0. Then the additional refractive index n will be proportional to $|V|^2$ and, as usual, will have the frequency dependence indicated in Fig. 4a. If parity is not conserved, there will also appear a transition matrix element V' whose parity is opposite to that of V. In that case the refractive indices for right- and left-hand polarizations turn out to be different:

$$n_\pm = \left|\frac{V \pm \xi V'}{V}\right|^2 n,$$

where ξ is a small model-dependent parameter for which different variants of the theory yield various values in the range from 10^{-9} to 10^{-11}. Obviously,

$$\Delta n = n_+ - n_- = n\xi \operatorname{Re}\frac{V'}{V}.$$

The angle through which the polarization plane rotates on a path of length L is

$$\psi = \frac{1}{2}\frac{\omega}{c} L \Delta n.$$

We note that the frequency dependence of Δn is like that of n (see Fig. 4a).

A gas also becomes optically active when a magnetic field is applied, and this may simulate the effect being sought. In that case the dependence of Δn on the magnetic field strength has a different form: $\Delta n \sim \Omega_0 \partial n/\partial\omega$, where Ω_0 is the Zeeman splitting of the levels. The frequency dependence of Δn is also different (Fig. 4b), and use may be made of this in an experimental attempt to detect the effect of parity nonconservation when it is impossible completely to screen out the magnetic field.

By stabilizing the laser frequency at the center of the line and applying an additional magnetic field one can arrange things so that the rotation angle at the center of the line will vanish. This will mean that the external magnetic field has been cancelled out. The degree of cancellation depends on the stability of the laser frequency.

For definiteness we shall consider a specific transition—the $6P_{1/2}$–$6P_{3/2}$ transition in thallium ($\lambda = 12\,833$ Å), which has been suggested[25] for use in an attempt to observe the effect of parity nonconservation. This is a magnetic dipole transition. The admixed matrix element V' is a dipole transition matrix element. Calculations by Khriplovich[25] based on Weinberg's theory[28] showed that $\psi/L = 10^{-5}$ rad/m in thallium vapor at 100 Torr (which corresponds to a temperature of 1196 °C) when the detuning from the transition frequency is $\omega - \omega_D = 2.4\omega_D$, where ω_D is the Doppler frequency. The absorption coefficient α is 0.01 cm^{-1}. Then according to (4) the difference between the refractive indices will be

$$\Delta n = 4 \cdot 10^{-12}.$$

We suggest that stable lasers be used to detect the effect of parity nonconservation in atomic transitions. The difference between n_+ and n_- leads to shifts of the eigenfrequencies of the laser cavity, and these shifts differ for right- and left-hand polarizations by the quantity

$$\Delta\omega = \omega\Delta n \approx 1 \text{ kHz}.$$

For definiteness we shall assume that the frequency reproducibility for the right- and left-hand polarizations is the same as reported in Ref. 6, i.e., that the error in measuring these frequencies is $\Delta\omega' = 3$ Hz. Then the error in measuring the refractive index difference due to parity nonconservation effects will be

$$\frac{\Delta\omega'}{\Delta\omega} = 3 \cdot 10^{-3} = 0.3\%.$$

We suggest the ring-laser scheme diagramed in Fig. 5 for observing parity nonconservation in atomic transitions (for more details on ring lasers see, e.g., Refs. 29 and 30). An optically active element is placed in the cavity of the stable laser to eliminate frequency pulling between the right- and left-hand polarizations. In this case the right- and left-hand polarizations of the same type of oscillations will be generated at different frequencies and will not affect one another. The difference between the frequencies of the right- and left-hand polarizations is determined by the detector. After that, the cell containing thallium vapor is placed in the laser resonator, and this, also having natural optical activity, shifts the beat frequency between the right- and left-hand polarizations further by ~1 kHz.

We emphasize that in this experiment one does not

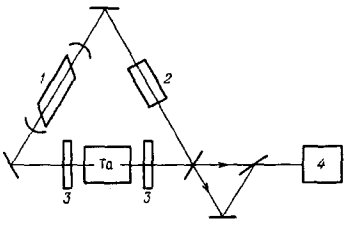

FIG. 5. Ring laser scheme for observing the effect of parity nonconservation: 1—laser, 2—antipulling element, 3—quarter wave plates, 4—detector.

measure the frequencies of the right- and left-hand polarizations, but only their difference. Accordingly, the requirements on the stability of the laser should not be too severe since mechanical fluctuations shift the frequencies of the left- and right-hand polarizations in the same way, leaving their difference unchanged.

* * *

In this article we have considered the physical possibilities of performing new precision experiments in optics.

In addition to that, lasers have a number of advantages over sources in other regions of the spectrum which make it possible to perform experiments at a qualitatively new level. These advantages include good propagation characteristics of the laser beam, the possibility of quickly readjusting the frequency, and a relatively short signal-recording time. An experiment with a relative accuracy of 10^{-15} requires a measuring time of ~1 sec, whereas the measuring time required for an experiment of the same accuracy in the microwave region would be five orders of magnitude longer.

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