TEMPERATURE SHIFT OF LAMB DIP IN METHANE AT $\lambda = 3.39\ \mu$

S.N. Bagaev and V.P. Chebotaev
Institute of Semiconductor Physics, Siberian Division, USSR Academy of Sciences
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We report here observation of a temperature shift of the Lamb dip in a low-pressure molecular gas. As shown in [1], a sharp decrease of the impact shift of the Lamb dip is observed at low pressures. This has made it possible to observe the temperature shift of the dip, which coincide in magnitude and sign with the shift due to the transverse Doppler effect. These experiments can therefore be regarded as the first observation of the influence of relativistic effects on the shape of the absorption line of a molecule[1)] and on the frequency reproducibility of gas lasers.

Owing to the relativistic time contraction, the emission frequency or the resonant absorption frequency of the moving atom (molecule) experiences an additional red shift that depends on the absolute velocity. The emission frequency ω received by an immobile observer is given by the known expression:

$$\omega = \omega_0 \frac{\sqrt{1-\left(\frac{v}{c}\right)^2}}{1-\frac{v_z}{c}}$$

where ω_0 is the emission frequency of the immobile atom, v is the absolute velocity of the atom, v_z is the projection of the velocity on the observation direction, and c is the speed of light.

Under the conditions of our experiment, the width of the Lamb dip is much smaller than the Doppler width. At the line center, the standing-wave field interacts with the atoms having $v_z \ll \bar{v}$, where $\bar{v} = [2kT/m]^{1/2}$ is the characteristic thermal velocity of the atom, k is Boltzmann's constant, T is the gas

1) The temperature shift of the γ-quantum frequency, connected with the transverse Doppler effect, was observed earlier in [2, 3] with the aid of the Mossbauer effect.

temperature, and m is the mass of the atom. Since the average transverse velocity $v_2 \sim \bar{v}$, the emission line center of an ensemble of atoms with a fixed transverse velocity v_r and a Maxwellian distribution of the velocity projections v_z experiences a red shift.

$$\Delta\omega = -\frac{1}{2}\left(\frac{v_r}{c}\right)^2 \omega_0 .$$

Taking into account the Maxwellian velocity distribution and averaging the contribution of atoms with different v_r, we obtain for the shift of the Lamb dip

$$\Delta_T = -\frac{1}{2}\left(\frac{\bar{v}}{c}\right)^2 \omega_0 = -\frac{kT}{mc^2}\omega_0 . \qquad (2)$$

In methane, which was used in the experiments described below, the temperature-induced red shift of the Lamb dip is 0.52 Hz/deg. Observation of such a shift requires that the relative accuracy of tuning to the dip center be 10^{-13}. This has now become possible in view of the progress in gas-laser frequency stabilization.

The experiments were performed with frequency-stabilized gas lasers using the apparatus of [1]. The frequency was stabilized with internal methane absorption cells in He-Ne lasers at $\lambda = 3.39\ \mu$. The lasers were tuned to the center of the Lamb dip in the absorption by means of the generation-power peak[2]. The statistical properties of the radiation and the reproducibility of the laser generation frequency are described in [1].

The temperature shift of the center of the Lamb dip was revealed by the shift of the generation frequency of one of the lasers when its absorption cell

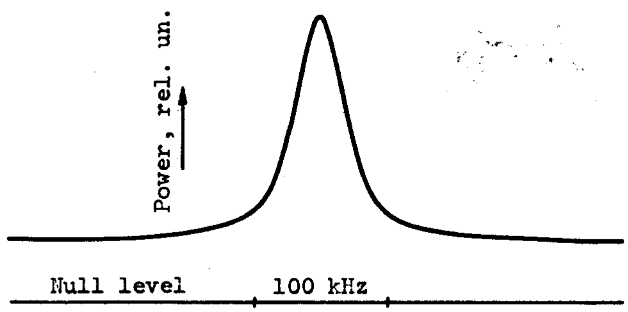

Fig. 1

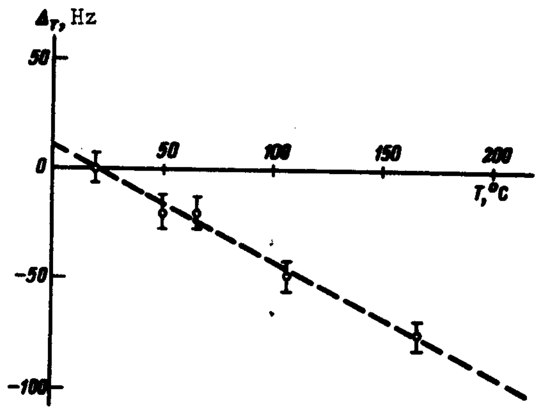

Fig. 2

Fig. 1. Generation power vs. He-Ne laser frequency near the methane absorption resonance. Methane pressure in cell $\sim 8 \times 10^{-4}$ Torr.

Fig. 2. Frequency shift of a laser stabilized against the generation power peak, when the absorption cell is heated. Dashed curve - calculated from formula (2).

[2]) References to earlier work are contained in [1].

was heated. Measures were taken to exclude the mutual influence of the lasers. The gas was fed to the cells simultaneously, so that the pressure in the cells was practically the same. The experiments were performed at different methane pressures from 4×10^{-4} to 10^{-3} Torr. When the cell was heated by 200°C the gas density in it did not change more than 10%. The parameters of the generation power peak (see Fig. 1) ensured the required tuning accuracy. The frequency difference between the two lasers was measured with electronic frequency meters with averaging times 1 and 10 sec. The results of the measurements in different series of experiments are shown in Fig. 2. The rms measurement error corresponded to the short-duration frequency stability at the indicated averaging times. The average frequency at the center of the dip was fixed, just as in [1], accurate to several Hz. Within the limits of experimental error, the observed dependence is linear with a slope 0.5 ± 0.05 Hz/deg, which agrees with the calculated 0.52 Hz/deg.

At the working pressures of the methane, the impact shift of the Lamb dip is less than 10 Hz. The influence of a change in the gas density on the shift, just like the change in the scattering cross section with increasing velocity of the colliding molecules, lies within the limits of the experimental error. This circumstance, together with the good agreement between the experimental and theoretical data, shows that the shift is caused by the transverse Doppler effect. We note that the accuracy of our experiments is comparable with the accuracy of the experiments in [2, 3].

The experiments have shown that to obtain a frequency reproducibility 10^{-14} in our experiments it is necessary to maintain the temperature with an absolute accuracy 1°C, which of course entails no great difficulty. In flow-through systems, the influence of the transverse effect may be stronger.

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