(15) for the occurrence of the modulational instability is satisfied. Hence, the scattering of the waves guarantees that they are trapped sufficiently fast in the compression region, and the compression of the plasma must continue until the condition for the applicability of Eq. (7) is violated, i.e., until the density of the kinetic energy of the plasma or of the energy becomes comparable to $H_0^2/8\pi$.

CONCLUSION

Two distinctive characteristics of MHD waves give particular importance to modulational processes in them.

1. MHD waves are oscillations with very long wavelengths which propagate in a plasma with relatively weak dissipation. The modulational instability of MHD waves can therefore proceed as a large-scale process.

2. Magneto-hydrodynamic turbulence often contains in it an appreciable amount of energy with a transfer velocity c_A which for small β is much larger than the thermal velocity. This guarantees a fast supply of energy to the compression region so that a large amount of energy can be released when the modulational instability develops.

These characteristics give us a basis for expecting that the modulational instability of MHD waves can be observed directly in natural conditions. One of the most appropriate objects where the effects considered might take place is the solar plasma, especially in the chromospheric region. If we take the following values for the parameters for the chromospheric plasma: magnetic field $H_0 \sim 10$ to 100 gauss, density $\rho \sim 10^{12}$ cm^{-3}, temperature $T \sim 10^4$ K, turbulent velocity of the order of 10 to 30 km/s, which are, probably, rather typical[5] we get $\beta \sim 10^{-3}$, $w/\rho T \gtrsim 1$. In that case all conditions for the occurrence of the modulational instability are satisfied in the chromosphere. In this connection it is fully realistic that one can identify some of the chromospheric phenomena with the modulational instability of MHD waves.

In conclusion the author expresses his gratitude for discussions of the problems raised in this paper to A.A. Galeev. D.D. Ryutov, V.D. Shapiro, And V.I. Shevchenko. The author is also grateful to G. L. Kotkin for reading the proofs of the paper and for making a number of important observations.

[1] In (2) we have dropped non-linear terms of the order $(H/H_0)^2$. This does, however, not contradict the fact that we shall in what follows when we consider the low-frequency longitudinal motion of the plasma take into account non-linearities caused by the pressure of the waves which are, as will be clear, determined by the parameter $H^2/\rho T$.

[2] We note that the above-mentioned degeneracy of Eq. (28) is connected with the fact that the space orthogonal to the z-axis is two-dimensional.

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Translated by D. ter Haar.

Kinetic cooling of a CO_2–N_2 gas mixture by CO_2-laser radiation

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(Submitted February 2, 1977)
Zh. Eksp. Teor. Fiz. **73**, 874–883 (September 1977)

We report a theoretical analysis and an experimental investigation of the cooling of a molecular gas by resonant intermode absorption of laser radiation. The actual results pertain to cooling of a CO_2–N_2 gas mixture by CO_2-laser radiation. The rate and depth of the cooling are investigated as functions of the partial composition of the mixture (including pure CO_2 gas) at different intensities and waveforms of the laser pulse. Good agreement is obtained between the theoretical and experimental results.

PACS numbers: 51.70.+f, 42.60.He

It was shown theoretically by a number of workers[1–4] that when CO_2-laser radiation is absorbed in air, the gaseous medium may be cooled rather than heated during the initial instants of time. The appearance of the kinetic-cooling effect is due to intermode resonant absorption of the CO_2-laser radiation by the molecules of the carbon dioxide. The initial interest in this effect was due to the possibility of resonant thermal self-focusing in the absorbing gas. However, this is not the only reason why the investigation of the effect of kinetic cooling is important. It suffices to state that measurement of the kinetic-cooling parameters can serve as an independent method of determining the times of vibrational relaxation in gases, since the cooling parameters are uniquely connected with the relaxation time. This effect must also be taken into consideration in the analysis of the operation of molecular gas lasers whose lower working level is not the ground level (for example, CO_2 and N_2O). In this case the effect can result from partial absorption of the intrinsic radiation by the laser medium.

The theoretical and experimental results obtained so far are not coordinated with one another. Certain theoretical results[1-4] are practically impossible to confirm under laboratory conditions. Conversely, experiments performed by the groups of Smith[5] and Katayama[6,7] cannot be fitted within the framework of the existing theories. Furthermore, the experimental data are sometimes contradictory. Thus, in a number of studies[5,6] no cooling was observed in pure CO_2 gas at atmospheric pressure. Gebhardt and Smith[5] conclude in this connection that the effect cannot take place in principle under these conditions, since the time of the vibrational-vibrational relaxation of the upper of the pair of resonant levels is shorter than the time of the vibrational-translational relaxation of the lower level. As will be shown later on, this statement is incorrect because the presence of the effect is determined not by the ratio of the indicated relaxation times, but the ratio of the fluxes of the energy transported per unit time in the relaxation processes. Subsequently, Katayama[7] and the present authors[8-10] reported observation of the effect in pure CO_2 gas at atmospheric pressure.

The present paper is devoted to a detailed theoretical and experimental investigation of the effect of kinetic cooling of a CO_2-N_2 gas mixture by absorption of CO_2-laser radiation. The theoretical results were obtained by numerically solving the system of gas kinetic equations for the reserve of vibrational quanta and the equation for the change in the gas temperature. The system of gas kinetic equations was written in the "thermodynamic" approximation,[11] which is valid up to a CO_2 pressure $p_{CO_2} \sim 0.5$ Torr (at a gas temperature $T = 300$ K and a total gas mixture $p_\Sigma = 1$ atm.)

In the experiments, we registered by an interferometry method the cooling of a CO_2-N_2 molecular-gas mixture by CO_2-laser radiation of intensity higher than 10^3 W/cm^2 in the region of relative partial pressures $X_{CO_2} \approx 0.01-1$ at $p_\Sigma = 1$ atm and $T = 300$ K. The measured depth of the cooling ranged from 0.02 to 0.2 °C. The time during which cooling was obtained ranged from a value on the order of 10 μsec in pure CO_2 gas at atmospheric pressure to 10^3 μsec at a partial pressure $X_{CO_2} = 0.01$. These data are in good agreement with the presented calculations.

We demonstrate the possibility of controlling the lifetime of the nonstationary cooling of the molecular gas by varying the rise time of the optical pulse.

1. FUNDAMENTAL EQUATIONS

We consider a CO_2-N_2 molecular-gas mixture resonantly absorbing the radiation of a CO_2 laser on the transitions

$$CO_2(02^00) \rightleftharpoons CO_2(00^01)$$

(wavelength $\lambda = 9.4$ μm) and

$$CO_2(10^00) \rightleftharpoons CO_2(00^01)$$

($\lambda = 10.6$ μm). As a result of the absorption of the radiation, the population of the vibrational level 10^00 (or 02^00) of the CO_2 molecule becomes lower at the initial equilibrium population, while the population of CO_2 (00^01) becomes higher. Accordingly, the vibrational-vibrational relaxation collision processes lower also the CO_2 (01^10) level. The nonresonant relaxation processes (i.e., the $V-T$ and $V-V'$ relaxation processes) tend to compensate for these changes in the populations of the levels CO_2 (00^01) and CO_2 (01^10) via redistribution of the energy among the vibrational and translational degrees of freedom of the gas, as a result of which the gas temperature can change.

The change of the gas temperature as a result of resonant absorption of the radiation, after establishment of the Maxwellian distribution (at $t > \tau_M \approx 10^{-10}-10^{-11}$ sec at a pressure 1 atm) is described by the heat-conduction equation

$$\frac{\partial T}{\partial t} + v\nabla T = \chi\Delta T + \Phi(t), \tag{1}$$

where v is the velocity of the convective motion of the gas; χ is the thermal diffusivity coefficient and $\Phi(t)$ is the flux of the vibrational energies into the translational degrees of freedom and is caused by the resonant excitation of the molecular vibrations.

Since the CO_2-laser radiation is absorbed by the molecules of the carbon dioxide from a state other than the ground vibrational state, the absorption coefficient α is small and its value in pure CO_2 gas at atmospheric pressure is of the order of $\alpha \approx 10^{-3}$ cm^{-1}.[5] This circumstance allows us to regard the radiation intensity as constant along path l of the ray (i.e., $\alpha l \ll 1$).

We estimate next the order of magnitude of the characteristic times τ_c and τ_T of the convection and heat-conduction processes. The characteristic time of establishment of an advanced convection is given by[12]

$$\tau_c \approx r\left(\frac{\alpha I_0 r^2 \beta g}{\rho c_p}\right)^{-1/3}, \tag{2}$$

where r is the radius of the laser beam, α is the absorption coefficient of the carbon dioxide, I_0 is the radiation intensity, β is the thermal expansion coefficient, g is the acceleration due to gravity, ρ is the gas density, and c_p is the specific heat of the gas at constant pressure.

At $r \gtrsim 0.5$ cm, $\alpha = 10^{-3}$ cm^{-1}, $I_0 = 10^6$ W/cm^2, $\rho c_p = 10^{-3}$ J/deg-cm, and $\beta g = 3.3$ cm^2/sec^2 deg, formula (2) yields

$\tau_c \gtrsim 10^{-2}$ sec. The heat-conduction time $\tau_T = r^2/\chi$ at $r \gtrsim 0.5$ cm and $\chi \approx 0.1$ cm^2/sec is of the order of 1 sec. On the other hand, the characteristic relaxation times in the CO_2–N_2 gas mixture at atmospheric pressure (at CO_2 concentrations higher than 0.1%) do not exceed 10^{-3} sec. In the time interval $\tau_M \ll t \ll \tau_c$, τ_T we can therefore neglect in (1) the terms describing the heat and mass transport.

The vibrational-energy flux $\Phi(t)$ in the right-hand side of (1) can be determined from the kinetic equations for the number of the vibrational quanta ε_i, which are defined[13] as the first moment of the vibrational distribution function within each vibrational mode. Equations of this type were obtained earlier[11] for the case of an arbitrary multicomponent mixture of harmonic oscillators. It was assumed there that a Boltzmann distribution with an individual vibrational temperature, was established over the vibrational levels for each type of oscillator; this assumption is valid if the $V-V$ relaxation processes within each vibrational mode are the fastest ones. This holds true for relative CO_2 partial pressures $X_{CO_2} \approx 0.001$ and higher at a pressure $p_\Sigma = 1$ atm and at $T = 300$ K. For these relative partial pressures of the carbon dioxide in the CO_2-N_2 gas mixture, the equations for ε_i with allowance for the absorption of the radiation by the CO_2 molecules can be written in the form

$$\frac{d\varepsilon_1}{dt} = (\mathscr{P}+W)X_{CO_2}, \tag{3}$$

$$\frac{d\varepsilon_2}{dt} = -3\mathscr{P} - P_{20}(\varepsilon_2 - \varepsilon_2^0) - 2W. \tag{4}$$

Here

$$\begin{aligned} \mathscr{P} &= \frac{1}{8}\frac{P_{3\Sigma}}{X_{CO_2}}[e^{-500/kT}\varepsilon_2^3(1+\varepsilon_1) - \varepsilon_1(2+\varepsilon_2)^3], \\ W &= \frac{\sigma I}{\hbar\omega}\left[\frac{4\varepsilon_2^2(1+\varepsilon_2)}{(2+\varepsilon_2)^4} - \frac{\varepsilon_1}{(1+\varepsilon_1)^2}\right] \end{aligned} \tag{5}$$

where ε_1 is the number of vibrational quanta per molecule of the asymmetrical CO_2-molecule vibrations type combined with the vibrations of the N_2 molecule; ε_2 is the number of vibrational quanta per molecule, of the combined symmetrical and deformation vibrational modes of the CO_2 molecule; ε_2^0 is the equilibrium value of ε_2 in the absence of radiation, σ is the absorption cross section, I is the radiation intensity, $\hbar\omega = E_{00^01} - E_{10^01}$ and E_{10^00}, E_{00^01} are respectively the energies of the vibrational levels 00^01 and 10^00 of the CO_2 molecule.

It must be noted that as a result of the combination of the symmetrical and deformation vibration modes of the CO_2 molecule, the quantity $d\varepsilon_2/dt$ acquires a factor

$$\frac{2+\varepsilon_2+3\varepsilon_2^2}{2(1+\varepsilon_2)^2}$$

which in our problem can be set approximately equal to unity with a good degree of accuracy.

The probabilities P_{20} and $P_{3\Sigma}$ of the $V-T$ process and the nonresonant $V-V'$ process, which enter in Eqs. (3) and (4), are defined by the relations

$$P_{20} = K_1 p_{CO_2} + K_2 p_{N_2}, \tag{6}$$

$$P_{3\Sigma} = (K_3 X_{CO_2}^2 + K_4 X_{CO_2} X_{N_2}) p_\Sigma, \tag{7}$$

where

$$p_\Sigma = p_{CO_2} + p_{N_2}, \quad X_{CO_2} = p_{CO_2}/p_\Sigma,$$

$X_{N_2} = p_{N_2}/p_\Sigma$, where p_{CO_2} and p_{N_2} are the pressures of the gases (in torrs). The quantities K_1 and K_2 are the rate constants (with dimension Torr^{-1} sec^{-1}) of the following respective $V-T$ relaxation process:1)

$$CO_2(01^10) + CO_2 \rightleftharpoons CO_2 + CO_2 + 667\ \text{cm}^{-1} \tag{8a}$$

$$CO_2(01^10) + N_2 \rightleftharpoons CO_2 + N_2 + 667\ \text{cm}^{-1} \tag{8b}$$

The probability $P_{3\Sigma}$ characterizes the rate of the collisionless deactivation of the $CO_2(00^01)$ state; at a gas temperature 300 °K the deactivation proceeds via the principal channels[14]:

$$CO_2(00^01) + M \rightleftharpoons \begin{cases} CO_2(11^10) + M + 273\ \text{cm}^{-1}, \\ CO_2(03^10) + M + 417\ \text{cm}^{-1}, \\ CO_2(04^00) + M - 204\ \text{cm}^{-1}. \end{cases} \tag{9}$$

The rate constant K_3 in (7) characterizes the effective rate of the processes (9) for the case $M = CO_2$; the rate constant K_4 corresponds to the case $M = N_2$.

From Eqs. (1), (3), and (4), we see that $\tau_M \ll t \ll \tau_c$, τ_T the change of the gas temperature by resonant absorption of laser radiation is described by the equation

$$\rho c_p^{RT}\frac{\partial T}{\partial t} = \Phi(t), \tag{10}$$

where

$$\Phi(t) = N_{CO_2}[E_{010}P_{20}(\varepsilon_2 - \varepsilon_2^0) - \mathscr{P}\Delta E].$$

Here N_{CO_2} is the concentration of the carbon-dioxide molecule; ΔE is the energy defect and characterizes effectively the change of the gas temperature following deactivation of the vibrational state $CO_2(00^01)$ on account of nonresonant $V-V'$ processes (see the reactions (9)); c_p^{RT} is the specific heat of the translational-rotational degrees of freedom of the gas at constant pressure.

It is seen from (10) that the condition for the existence of the effect of kinetic cooling is determined by the following relation:

$$\frac{8E_{010}P_{20}}{\Delta E \cdot P_{3\Sigma}}(\varepsilon_2 - \varepsilon_2^0) \leqslant e^{-500/kT}\varepsilon_2^3(1+\varepsilon_1) - \varepsilon_1(2+\varepsilon_2)^3. \tag{11}$$

Assuming in the saturation regime $\varepsilon_2 \approx \varepsilon_2^0/2$ and $\varepsilon_2^3/4 \approx \varepsilon_1$, we can rewrite the condition (11) in the form

$$E_{010}P_{20}/P_{3\Sigma}\Delta E \geqslant 10^{-2}. \tag{12}$$

For pure CO_2 gas at atmospheric pressure we have $E_1/\Delta E \approx 4$ and $P_{20}/P_{3\Sigma} \approx 0.6$. It follows therefore from (12) that kinetic cooling in pure CO_2 is possible. We note that the validity of using our model in the saturation regime is connected with the fact that the "bottle-

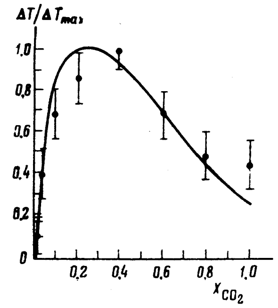

FIG. 1. Dependence of the normalized depth of cooling of the gas mixture CO_2–N_2 on the relative partial pressure of $p_\Sigma = 1$ atm (●—experiment, solid curve—theory).

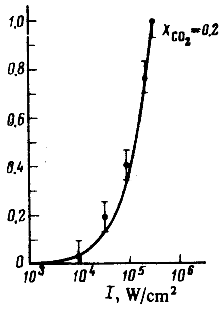

FIG. 3. Dependence of the normalized depth of cooling of the gas mixture CO_2–N_2 on the laser-radiation intensity (●—experiment, solid curve—theory).

neck" that restricts the energy influx into the considered vibrational system is due to the $V-T$ and $V-V'$ relaxation processes. The saturation regime is therefore realized at an optical-pumping probability $W = \sigma I/\hbar\omega$ of the order of $\min[P_{20}, P_{3\Sigma}]$.

2. RESULTS OF NUMERICAL CALCULATIONS

The system (3), (4), and (10) was numerically solved with a computer by a standard Kutta-Merson procedure with a solution accuracy $\varepsilon \approx 10^{-8}$. We used the experimentally obtained values of the constants K_1 to K_4, equal respectively to 200, 400, 350, and 110 sec^{-1} Torr^{-1}.[15] The following were varied in the calculations: 1) the peak intensity; 2) the pulse waveform: a rectangular pulse ($I = I_0$ at $t > 0$) and a pulse with variable rise time $I = I_0(1 - e^{-\gamma t})$ and trailing edge $I = I_0 e^{-\gamma t}$; 3) the relative partial pressure of the carbon dioxide in the range $X_{CO_2} = 0.01$–1 at a total mixture pressure $p_\Sigma = 1$ atm. The results of the numerical calculation are shown in Figs. 1–4.

The calculation was performed for two cases of resonance absorption, corresponding to the transitions $CO_2(10^00) \rightleftarrows CO_2(00^01)$ and $CO_2(02^00) \rightleftarrows CO_2(00^01)$. In the case when the absorbed radiation had a wavelength $\lambda = 9.4$ μm (the $CO_2(02^00) \rightleftarrows CO_2(00^01)$ transition) we took into consideration the deformation-type degeneracy of the vibrations of the CO_2 molecules. In this case the depth of cooling turned out to be approximately one-third the value obtained for the $CO_2(10^00) \rightleftarrows CO_2(00^01)$ transition.

Figure 1 shows the dependence of the normalized depth of cooling $\Delta T/\Delta T_{max} = f(X_{CO_2})$ on the relative partial pressure of CO_2 at a fixed pump intensity. The presence of a maximum in this dependence is due to competition of two factors. On the one hand, an increase of the concentration of the carbon dioxide (X_{CO_2}) is accompanied by an increase of the absorption of the radiation, so that the cooling depth ΔT is increased. On the other hand the total relaxation time $P_{3\Sigma}^{-1} + P_{20}^{-1} = \tau_p$ of the $CO_2(00^01)$ state is decreased, and this decreases effectively the cooling depth ΔT. The form of the obtained curve and the position of the extremum depend on the values of the constants K. Thus, for example, when the values cited above for the constants K_1, K_2, and K_3 are changed to 220, 100, and 270 sec^{-1} Torr^{-1} respectively (see, e.g., [16]), the extremum shifts towards lower values of X_{CO_2}, and the absolute value of the cooling depth decreases by a factor 1.5–2. This circumstance can be used to estimate the efficiencies of the various collision processes. Figure 1 demonstrates also the feasibility of the cooling effect in pure CO_2 at atmospheric pressure, thus confirming the estimate made above.

The dependence of the duration τ_c of the kinetic-cooling effect on X_{CO_2} is shown in Fig. 2. It turns out that the duration of the effect is determined essentially by the time $\tau_{3\Sigma} = P_{3\Sigma}^{-1}$ (P_{20} remains practically constant when X_{CO_2} is varied).

From the calculated dependence of the cooling temperature ΔT on the intensity I_0 of the optical pumping (see Fig. 3) it follows that the kinetic-cooling effect does not take place at low intensities $I_0 \lesssim 10^3$ W/cm².

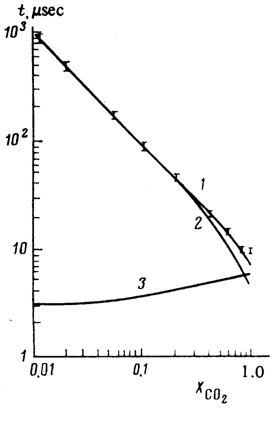

FIG. 2. Dependence of the duration of the cooling (curve 1) and of the characteristic relaxation times $P_{3\Sigma}^{-1}$ (curve 2) and P_{20}^{-1} (curve 3) on the relative partial pressure of CO_2 at $p_\Sigma = 1$ atm (●—experiment, solid curve—theory).

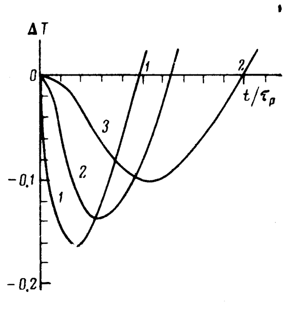

FIG. 4. Increase of the duration of the cooling by changing the rise time of the laser pulse (theory). The wave form of the pulse is specified in the form $I = I_0(1 - e^{-\gamma t})$, where t is in microseconds; $\gamma = 1$, 10^{-1}, 10^{-2} μsec^{-1} respectively for the curves 1, 2, 3; $X_{CO_2} = 0.4$; $p_\Sigma = 1$ atm.

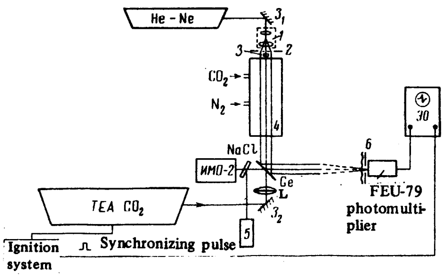

FIG. 5. Diagram of experimental setup: 1—telescope, 2—matrix, 3—phase-shifting plate, 4—cell, 5—Ge–Au receiver, 6—diaphragm.

As verified in test programs, at these values of the pump the accuracy with which Eqs. (3), (4), and (10) are solved comes into play. At medium pumps $I_0 \sim 10^4$–10^6 W/cm^2, the depth of cooling ΔT increases with increasing intensity. At $I_0 \gtrsim 10^6$ W/cm^2 saturation of the effect sets in, a fact explained by the transparentization of the transition $00^01 \rightleftarrows 10^00$ (or $02^00 \rightleftarrows 00^01$) of the CO_2 molecule.

An investigation of the cooling effect of the function of the waveform of the pulse has shown that in the case of a long pulse ($I = I_0$) the cooling depth ΔT_{max} and the cooling time τ_c turn out to be larger than in the case of a short pulse ($I = I_0 e^{-\gamma t}$). The reason is that the values of ΔT_{max} and τ_c are proportional to the time of action of the laser radiation in the time interval $t \lesssim P_{3\Sigma}^{-1} + P_{20}^{-1}$. Figure 4 illustrates the possibility of controlling the duration of the cooling effect as the result of the change in the rise time of the laser pulse. It turns out that the duration of the cooling increases and the depth of the cooling decreases with decreasing rise time.

3. EXPERIMENTAL SETUP

The depth and time of cooling of the gas was investigated with a setup illustrated in Fig. 5. The CO_2 laser radiation was directed with the aid of a beam-splitting germanium plate and a lens of focal length $F = 1$ m into a cell filled with the $CO_2 - N_2$ gas mixture. A sounding beam from a three-beam interferometer passed through the cell coaxially with the main beam. The pulse duration τ_{pulse} and the radiation energy E_{rad} were measured with a Ge-Au receiver and a calorimeter of the IMO-2 type. The infrared source was a helicoidal TEA CO_2 laser ($\lambda = 10.6$ μm) with radiation energy 0.3 J in a pulse of 3 μsec duration at half-width. The gas cell used in the experiments was a glass cylinder of length $L_{cell} = 70$ cm and diameter $d_{cell} = 8$ cm, and could be precision-filled with CO_2 and N_2 gases through leak valves. The cell windows were made of NaCl salt.

The principal operation in the experiment was the registration of the change of the refractive index of the gas in the field of the IR radiation from the CO_2 laser. To measure the refractive index we used a three-beam interferometer. Such an interferometer does not limit structurally the dimensions of the gas cell, and has therefore a higher resolution. It also has a high sensitivity and operating stability. This is due primarily to the fact that a change in the phase of the sounding beam leads not to a shift of the fringes (as in the Young interferometer) but to a change of the intensity at a given point. Structurally the three-beam interferometer is a three-hole metallic matrix with distances $a = 5$ mm between the centers of the holes and with hole radii $r_a = 0.5$ mm. The choice of the initial phase required to ensure optimal sensitivity is effected by rotating a phase-shifting glass plate mounted on a precision rotary stage. The matrix was illuminated with a beam, broadened with a telescope, from a single-mode He-Ne laser ($\lambda = 0.63$ μm). The interference pattern was registered at a distance $Z_0 = 12.5$ m, which ensured at $R_g = 1.25$ m the Fraunhofer-diffraction condition $Z_0 \gg R_g$. The intensity of the light field was measured with a photomultiplier provided with a slit $2l = 2$mm and an oscilloscope.

The oscillogram that shows by the change of the phase in the interferometer trial beam yields the time of vibrational-translational relaxation and the lifetime of the kinetic-cooling effect (see Fig. 2). The obtained vibrational-translational relaxation constant $p_{CO_2}\tau_p = 10 \pm 1.5$ μsec-atm for the gas mixture CO_2–N_2 agrees with the value ($p_{CO_2}\tau_p = 9$–13 μsec-atm) previously measured by other methods.[14] In the comparison of the results of the calculations of the time τ_c with the experimental data, the intensity of the laser beam was specified in the form $I = I_0 e^{-\gamma t}$. In the experiment, to exclude the possible influence of the waver vapor, the mixture was first dehydrated with phosphorus pentoxide P_2O_5. As seen from Figs. 1–4, the calculations and the experimental results are in quite good agreement both qualitatively and quantitatively. The somewhat higher (by 1.3 times) experimental results in comparison with the theoretical for the lifetime of the cooling in the region $X_{CO_2} \sim 1$ can be attributed to a certain influence of the inertia of establishment of the pressure waves in the laser beams. According to the estimates, the time of travel of the sounc across the beam is ~7 μsec.

The absolute values of the cooling depth determined from the experimental data turned out to be double the calculated value. The estimate of the absolute value of the cooling depth ΔT was based on a phase measurement with a three-beam interferometer. At carbon-dioxide partial concentrations $X_{CO_2} \approx 0.5$, the measured phase was $\Delta\varphi = 0.5\pi \pm 0.1\pi$. For a cell length $L = 70$ cm the temperature drop was in this case of the order of

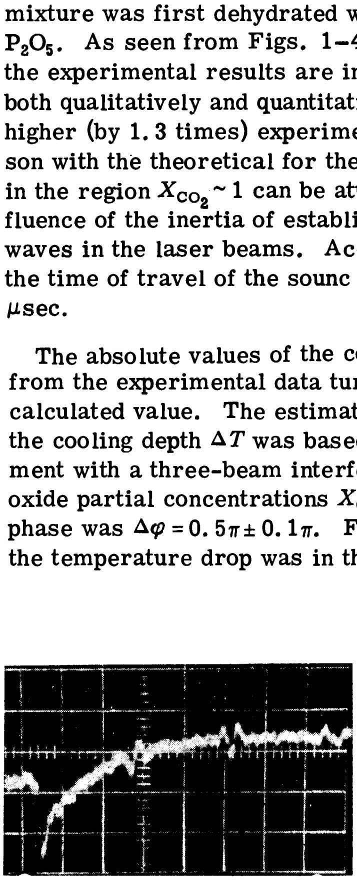

FIG. 6. Oscillogram showing the variation of the refractive index of the gas in the laser-beam channel ($X_{CO_2} = 0.1$, sweep 100 100 μsec/div).

$$\Delta T \approx \frac{\Delta\varphi\lambda_{\text{He-Ne}}}{2\pi|dn/dT|L} \approx 0.2^\circ.$$

The change of the refractive index with temperature in gases in $|dn/dT| \approx 10^{-6}$ deg^{-1}. The maximum phase change registered in our experiment was $\Delta\varphi = 0.02\pi \pm 0.01\pi$ at $X_{CO_2} \approx 0.01$. This corresponds to a change $\Delta n \approx 10^{-8}$ in the refractive index.

Notice must also be taken of some consequences of the interferometric procedure of measuring the kinetic-cooling effect. From the oscillograms of the dynamics of the variation of the refractive index of the gas (see Fig. 6) we can determine the velocity of propagation of the sound in the medium and the heat-conduction time. The oscillograms show clearly the density perturbations reflected from the cell walls. In our experiment their repetition period as a function of the CO_2 concentration was $\tau_s = 240 - 290$ μsec and was determined by the time of flight of the sound across the cell:

$$\tau_s = 2R_c/V_s\ .$$

At a cell radius $R_c = 4$ cm, the speed of sound in pure CO_2 turned out to be V_s 280 m/sec, and in the gas mixture $CO_2 - N_2$ at $X_{CO_2} \lesssim 0.1$ its value was $V_s = 330$ m/sec and agreed with the tabulated data.[17] Measurement of the heat-conduction time, which was determined from the time of restoration of the refractive index, permits either an estimate of the laser-beam radius (from the known thermal diffusivity χ) or a determination of χ if the laser-beam radius r is known. For pure CO_2 gas at atmospheric pressure, τ_T turned out to be 200 msec, yielding a coefficient $\chi = 0.1$ cm^2/sec at a laser-beam radius $r \approx 0.2$ cm in the cell.

We note in conclusion that the kinetic cooling in resonant intermode absorption of laser radiation, which was investigated in the present paper, can take place also in other molecular gases. Thus, we have recently reported[10] cooling of the molecular gas N_2O by CO_2 laser radiation. It must also be emphasized that an investigation of the mechanism and dynamics of the cooling is of interest also for problems in acoustics.[10]

It is our pleasure to thank S. A. Akhmanov and V. T. Platonenko for a useful discussion and for interest in the work.

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1) The quantities in the parentheses next to the chemical symbol of the molecule represent the excited vibrational states. The absence of parentheses means that there is no vibrational excitation.

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Translated by J. G. Adashko