Collision integral in problems of the coherent optics of gaseous media

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Recent experiments on the nonexponential decrease in the intensity of the photon echo with increasing time interval between the exciting pulses can be explained by a model of depolarizing elastic collisions. It is not necessary to appeal to other relaxation mechanisms, involving velocity-changing collisions.

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How to write the collision integral in the equation for the optical-coherence matrix of resonant atoms is one of the most important questions in the coherent optics of gaseous media. We recall that elastic scattering of a resonant atom by a nonresonant atom of a buffer gas causes a change in the internal state of the resonant atom (a depolarization) and also a change in its velocity. The collision integral in the equation for the optical-coherence matrix can be broken up into two parts in this case.[1] The first part, determined by the total scattering cross section of the colliding atoms, describes the change in the polarization of the resonant atom in the course of the collision. The second part reflects the scattering involving a change in velocity. If the effective scattering angle is sufficiently small, and small-angle scattering is predominant, the second part of the collision integral contains a small parameter and can be discarded in several problems of the coherent optics of gaseous media. Obviously, this part of the collision integral can be ignored when it does not generate any qualitatively new effects.

Berman *et al.*[2] have suggested in this connection that one such qualitatively new effect is an effect which has been observed in some recent experiments[3,4] with atomic gases: a nonexponential intensity decay of the photon echo with increasing time interval (τ) between the exciting light pulses. We show in the present letter, however, that this nonexponential decay can be explained by a model of depolarizing elastic collisions.

In the model of depolarizing elastic collisions, the relaxation characteristic $\mathscr{T}(v)^{(1)}$, which describes the collision-induced relaxation of the polarization vector of the medium (this vector corresponds to a group of atoms moving at the velocity $\mathbf{v}$), depends on v and is determined by the amplitudes for the scattering of the resonant atom in states a and b by nonresonant atoms of the same gas or of a buffer gas.[1] To calculate the scattering amplitudes we must in turn know the interaction potentials of the colliding atoms. It is thus a complicated matter to find the function $\mathscr{T}(v)^{(1)}$ explicitly, so we will consider only some simple cases as examples.

The model of absolutely hard spheres was used by Berman *et al.*[2] to explain the nonexponential decay of the intensity of the photon echo formed in resonant levels corresponding to different electronic states. Berman *et al.*[2] incorporated in this model the effect of the change in the velocity of the resonant atoms during the collision on the intensity decay of the photon echo.

We wish to point out that, in contrast with the approach of Ref. 2, the v dependence of $\mathscr{T}(v)^{(1)}$ itself causes a nonexponential intensity decay of the photon echo. To derive $\mathscr{T}(v)^{(1)}$ we initially adopt the same impenetrable-sphere model which was used by Berman *et al.*[2] For the case in which the mass of the buffer atom is much larger than that of the resonant atom we have

$$\mathscr{T}(v)^{(1)} = \Gamma(v/u). \tag{1}$$

Here Γ is proportional to the number density of the buffer-gas atoms and does not depend on v; u is the average thermal velocity of the resonant atoms.

The electric field of the photon echo is found by a method similar to that used in Ref. 5, but in the present letter we assume that the relaxation characteristic $\mathscr{T}(v)^{(1)}$ of the optical-coherence matrix is not a constant but instead a function of the velocity of the excited atoms, v. As a result, we find that the intensity (I_e) of the photon echo formed by small-area exciting pulses in a narrow spectral line[5] can be expressed as the following function of the time interval τ:

$$I_e \propto \exp[-2(\gamma_a^{(0)} + \gamma_b^{(0)})\tau] J^2(\Gamma\tau). \tag{2}$$

Here $1/\gamma_a^{(0)}$ and $1/\gamma_b^{(0)}$ are the relaxation times of the resonant levels a and b for the relaxation due to radiative decay and inelastic gas-kinetic collisions;

$$J(y) = -\frac{2}{\sqrt{\pi}}y + (1+2y^2)\exp(y^2)[1-\Phi(y)]; \tag{3}$$

and $\Phi(y)$ is the error integral.

It can be seen from (2) that the echo intensity is the product of an exponential function and a function of the parameter $\Gamma\tau$. The deviation from an exponential behavior in (2) must therefore stem exclusively from the behavior of function (3). The magnitude of this deviation can be judged from a plot of the function

$$\sqrt{\pi}(4\Gamma\tau)^{-1}\ln[J/(\Gamma\tau)] \tag{4}$$

(curve 1 in Fig. 1). Our reason for choosing function (4) as a measure of the extent to which the photon-echo intensity deviates from an exponential behavior as a function of τ is as follows. If $J(\Gamma\tau)$ were an exponential function of the parameter $\Gamma\tau$, then the function (4) would be a constant, and this constant could be made equal to -1 through a suitable normalization. Then any deviation from a value of -1 in function (4) would imply a deviation, to some degree or other, from an exponential decay of the echo intensity with increasing τ.

To see that the effect which we have observed can also be seen in other potentials (potentials more realistic than that of absolutely hard spheres), we calculated $\mathscr{T}(v)^{(1)}$ for a van der Waals potential for the case in which the ratio of the mass of the buffer atom to the mass of the resonant atom is large. We found

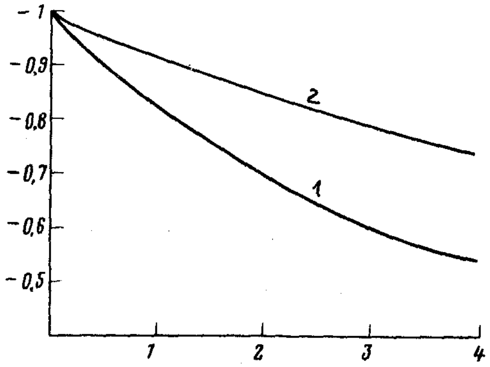

FIG. 1. 1—The function (4); 2—the function (7). For curve 1, the abscissa scale shows the values of the parameter $\Gamma\tau$; for curve 2, it shows the values of $\Gamma_B\tau$.

$$\mathscr{T}(v)^{(1)} = \Gamma_B (v/u)^{3/5}, \tag{5}$$

where Γ_B is proportional to the number density of the atoms of the buffer gas and is independent of v. If $\mathscr{T}(v)^{(1)}$ is described by (5), then we again find expression (2) for the echo intensity, but now

$$J(y) = \frac{4}{\sqrt{\pi}} \int_0^\infty x^2\, dx \, \exp(-x^2 - 2yx^{3/5}). \tag{6}$$

In this case, the function

$$\sqrt{\pi}\,[4\Gamma_B \tau \Gamma(1.8)]^{-1} \ln[J(\Gamma_B\tau)], \tag{7}$$

which is a measure of the deviation from the exponential decay, is shown by curve 2 in Fig. 1. Here $J(\Gamma_B\tau)$ is given by (6), and Γ (1.8) is the gamma function. A comparison of curves 1 and 2 shows that the deviation from an exponential decay with increasing τ depends on the particular interaction potential of the colliding atoms. The choice of a suitable model for the interaction of the atoms should thus be discussed in a comparison of theoretical and experimental data.

We note in conclusion that these results point out the need for further experiments to determine the reason for the nonexponential intensity decay of the photon echo in gaseous media.

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