Rayleigh scattering in a dense spin-polarized gas

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The Rayleigh scattering spectrum of a spin-polarized alkali-metal gas near the D lines is investigated. It is shown that in a sufficiently dense gas mixture the spectral scattering intensities depend nonlinearly on the polarization of the gas. The polarization can be determined from the ratio between the scattering intensities of the right- and left-circularly polarized waves. © *1995 American Institute of Physics.*

1. INTRODUCTION

High-pressure spin-polarized ^{3}He has been obtained in several laboratories in recent years.[1–3] The helium nuclei are polarized as a result of spin-exchange collisions with optically polarized rubidium atoms with density between 0.5×10^{15} and 1×10^{15} cm^{-3}. One-hundred percent polarization of the electron spin of the rubidium atoms is achieved under those experimental conditions. In this paper we wish to focus attention on the special features of Rayleigh scattering in a similar mixture near the D resonance lines of the alkali metal.

Near resonance, the optical polarizability of the mixture and the integrated scattering intensity are determined by the small impurity of alkali-metal atoms. The presence of a buffer gas at high pressure allows hypersonic waves to propagate and causes a Brillouin triplet to be observed. If the alkali-metal atoms are polarized, the medium has strong optical anisotropy (gyrotropy). The gyrotropy of the medium is proportional to the polarization of the gas. Near each of the D lines the polarization of the atom has a large antisymmetric component, whose magnitude is of the order of the scalar polarizability. This makes it possible to observe antisymmetric scattering, whose spectrum contains direct information on the spin relaxation processes in the gas mixture.

The total and differential cross sections for light scattering on an arbitrarily polarized atom were obtained in a recent investigation by Agre and Rapoport.[4] In our work we considered the Rayleigh scattering spectrum of a partially polarized gas of alkali-metal atoms in the presence of a buffer gas at a high pressure. Gyrotropic anisotropy creates a peculiar picture in the Rayleigh scattering spectrum of the polarized gas. The structure of the spectrum varies considerably with the polarization of the gas. The case of a dense gas (gas mixture), in which the spectral scattering intensities are nonlinearly dependent on the polarization, unlike the case of a low-density gas, in which this dependence is always linear, is most interesting. The polarization of the gas is related directly to the ratio between the scattering intensities of the right- and left-circularly polarized waves and can be determined from this ratio.

2. FLUCTUATIONS OF THE DIELECTRIC CONSTANT OF A SPIN-POLARIZED GAS

As we know,[5] the Rayleigh scattering spectrum is determined by the space-time Fourier expansion of the correlation of the dielectric constant tensor

$$I(\omega,\mathbf{q})\propto\langle\delta\epsilon^*_{il}(0,0)\,\delta\epsilon_{km}(\mathbf{r},t)\rangle u_i'^{\,*}u_k'u_lu_m^*. \tag{1}$$

Here $\omega=\omega-\omega_0$ and $\mathbf{q}=\mathbf{k}'-\mathbf{k}$ are the changes in the frequency and the wave vector associated with the scattering of light, $\delta\epsilon_{ik}$ is the fluctuation of the dielectric constant tensor, and $\mathbf{u}$ and $\mathbf{u}'$ are the unit vectors of the polarization of the incident and scattered waves.

The correlation (1) can be calculated using the explicit form of the density matrix of a spin-polarized gas with spin 1/2 (Ref. 6):

$$\hat\rho(\mathbf{v})=\tfrac{1}{2}\,n(\mathbf{v})[\hat 1+P_i\hat\sigma_i], \tag{2}$$

where $n(\mathbf{v})$ is the Maxwell distribution function with respect to the velocities, $\hat 1$ and $\hat\sigma_i$ $(i=x,y,z)$ are Pauli operators, and the absolute value of the polarization vector $\mathbf{P}$ gives the polarization of the atoms.

In matrix notation the polarizability tensor near a D line has the form

$$(\alpha_{ik})_{\mu\nu}=\alpha_0(\delta_{ik}\delta_{\mu\nu}+i\beta e_{ikl}\sigma^l_{\mu\nu}), \tag{3}$$

where

$$\alpha_0=\frac{d^2}{3\hbar(\Delta\omega-i\Gamma/2)}$$

is the scalar polarizability, d is the reduced matrix element of the atomic transition, $\Delta\omega$ is the detuning from resonance, Γ is the pressure-broadened linewidth, and e_{ikl} is the unit antisymmetric tensor. For the $D1$ line $(^2S_{1/2}-{}^2P_{1/2})$ we have $\beta=1$, and for the $D2$ line we have $\beta=-1/2$. Averaging (3) with the density matrix (2), for the dielectric constant ϵ_{ik} we obtain

$$\frac{\epsilon_{ik}-\delta_{ik}}{4}=\mathrm{Tr}(\hat\rho\alpha_{ik})=n\alpha_0(\delta_{ik}+i\beta e_{ikl}P_l). \tag{4}$$

This is essentially the dielectric constant tensor of a gyrotropic medium, in which the gyration vector (to within a con-

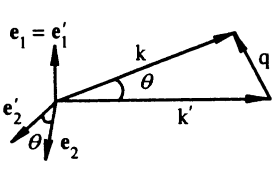

FIG. 1. Geometry of the scattering of circularly polarized waves.

stant factor) is the polarization vector $\mathbf{P}$. Circular dichroism and optical rotation appear in such a medium.

The fluctuations of the density δn and of the polarization vector $\delta\mathbf{P}$ are statistically independent, since the polarization refers to a single particle [see (2)]. Then

$$\langle \delta\epsilon_{il}^* \delta\epsilon_{km} \rangle_{\omega\mathbf{q}} \propto \langle \delta n\, \delta n \rangle_{\omega\mathbf{q}} \tilde{\alpha}_{ik}^* \tilde{\alpha}_{lm} + \bar{n}^2 \beta^2 e_{ikj} e_{lmr} \langle \delta P_j \delta P_r \rangle_{\omega\mathbf{q}}, \tag{5}$$

where $\tilde{\alpha}_{ik} = \alpha_0(\delta_{ik} + i\beta e_{ikj} P_j^{(0)})$, $\bar{n}$ is the mean atomic density, and $\mathbf{P}^{(0)}$ is the mean polarization vector of the gas. Both terms in (5) are proportional to $\bar{n}$, since in an ideal gas $\langle \delta n\, \delta n \rangle \propto \bar{n}$ and $\langle \delta P_j \delta P_r \rangle \propto \delta_{jr} (\bar{n})^{-1}$.

To calculate the correlation functions it is sufficient to know the single-moment correlators and the equations describing the dynamics of the fluctuating quantities, which are n and $\mathbf{P}$ in our case. The spin of the alkali metals is known to relax fairly slowly under the conditions described above.[1,2,7] We can therefore set $\dot{\mathbf{P}} = 0$. Density fluctuations can be described using the ordinary hydrodynamic equations without taking into account the spin degrees of freedom.

3. SCATTERING ON DENSITY FLUCTUATIONS

If the polarization unit vector of the incident wave is $\mathbf{u}$, the intensity of the scattered wave with polarization $\mathbf{u}'$, which is specified by the first term in (5), equals

$$I_{\mathbf{uu}'}^n \propto \langle \delta n\, \delta n \rangle_{\omega\mathbf{q}} |\alpha_0|^2 |B_{\mathbf{uu}'}|^2, \tag{6}$$

where

$$B_{uu'} = (u_i')^* \tilde{\alpha}_{ik} u_k.$$

Since the medium of interest to us has circular birefringence, it is convenient to work with circularly polarized waves. Figure 1 illustrates the scattering geometry. The unit vector $\mathbf{e}_3(\mathbf{e}_z)$ is parallel to the wave vector $\mathbf{k}$ of the incident wave. The wave vectors of the incident ($\mathbf{k}$) and scattered ($\mathbf{k}'$) waves form the scattering plane, and θ is the scattering angle. The unit vector $\mathbf{e}_1$ is normal to the scattering plane and parallel to the vector $\mathbf{k}'\mathbf{k}$. The unit vectors $\mathbf{e}_2$ and $\mathbf{e}_2'$ were chosen so that $(\mathbf{e}_1, \mathbf{e}_2), \mathbf{k}$ and $(\mathbf{e}_1, \mathbf{e}_2'), \mathbf{k}'$ form right-handed sets of three vectors. We define the unit vectors of the right and left circular polarization in the following manner:

$$\mathbf{u}_R = \frac{\mathbf{e}_1 - i\mathbf{e}_2}{\sqrt{2}}, \quad \mathbf{u}_R' = \frac{\mathbf{e}_1 - i\mathbf{e}_2'}{\sqrt{2}},$$

$$\mathbf{u}_L = \frac{\mathbf{e}_1 + i\mathbf{e}_2}{\sqrt{2}}, \quad \mathbf{u}_L' = \frac{\mathbf{e}_1 + i\mathbf{e}_2'}{\sqrt{2}}.$$

The expressions for the amplitudes have the form

$$\begin{aligned}
B_{RR} &= \frac{1}{2}(1 + \cos\theta) + \frac{\beta}{2}\left[\frac{(\mathbf{k}+\mathbf{k}')\mathbf{P}_0}{k} + i\mathbf{e}_1\mathbf{P}_0 \sin\theta\right], \\
B_{RL} &= \frac{1}{2}(1 - \cos\theta) + \frac{\beta}{2}\left[\frac{(\mathbf{k}-\mathbf{k}')\mathbf{P}_0}{k} - i\mathbf{e}_1\mathbf{P}_0 \sin\theta\right], \\
B_{LL} &= \frac{1}{2}(1 + \cos\theta) - \frac{\beta}{2}\left[\frac{(\mathbf{k}+\mathbf{k}')\mathbf{P}_0}{k} - i\mathbf{e}_1\mathbf{P}_0 \sin\theta\right], \\
B_{LR} &= \frac{1}{2}(1 - \cos\theta) - \frac{\beta}{2}\left[\frac{(\mathbf{k}-\mathbf{k}')\mathbf{P}_0}{k} + i\mathbf{e}_1\mathbf{P}_0 \sin\theta\right].
\end{aligned} \tag{7}$$

Let us discuss in greater detail two special cases, $\mathbf{P}_0 \parallel \mathbf{k}$ and $\mathbf{P}_0 \perp \mathbf{k}$.

In the former case

$$\begin{aligned}
B_{RR} &= \frac{(1+\beta P_0)(1+\cos\theta)}{2}, \\
B_{RL} &= \frac{(1+\beta P_0)(1-\cos\theta)}{2}, \\
B_{LL} &= \frac{(1-\beta P_0)(1+\cos\theta)}{2}, \\
B_{LR} &= \frac{(1-\beta P_0)(1-\cos\theta)}{2}.
\end{aligned} \tag{8}$$

When the spins are completely polarized along the z axis, for the $D1$ line ($\beta = 1$) we have ($P_0 = 1$) $B_{LL} = B_{LR} = 0$, and the left-polarized wave, as would be expected, does not interact with atoms and, of course, is not scattered.

As is seen from (8), at small scattering angles ($\theta \to 0$) the intensity of the depolarized part of the scattering ($R \to L, L \to R$) decreases as θ^4. The main contribution to the scattering is made in this case by its polarized part ($R \to R, L \to L$).

In the case of $\mathbf{P}_0 \perp \mathbf{k}$, it is convenient to work with linear polarization and to assume that $\mathbf{P}_0$ is parallel to $\mathbf{e}_1$. The expressions for the amplitudes B have the simple form

$$\begin{aligned}
&B_{VV} = 1, \quad B_{VH} = 0, \\
&B_{HH} = \cos\theta + i\beta P_0 \sin\theta, \quad B_{HV} = 0,
\end{aligned} \tag{9}$$

where the subscripts V and H indicate (according to the convention that has evolved) vertical and horizontal polarization of the waves relative to the scattering plane.

We note that all the scattering amplitudes B are proportional to βP_0, the incomplete limiting polarization of the gas for $|\beta| < 1$.

4. SCATTERING ON POLARIZATION FLUCTUATIONS

The intensity of a wave scattered on polarization fluctuations can be described in the form

$$I_{\mathbf{uu}'}^P \propto \langle \delta P_j \delta P_r \rangle_{\omega\mathbf{q}} \beta^2 |\alpha_0|^2 \bar{n}^2 A_j A_r^*, \tag{10}$$

where $A_j = (u_i')^* e_{ikj} u_k$, i.e., $\mathbf{A} = [\mathbf{u}'^* \mathbf{u}]$. Calculating the single-moment correlation $\langle \delta P_j \delta P_r \rangle_0$ using the density matrix (2), we obtain

$$\langle \delta P_j \delta P_r \rangle_{\omega \mathbf{q}} = f^P(\omega) \langle \delta P_j \delta P_r \rangle_0$$
$$= \frac{f^P(\omega)}{\bar{n}} (\delta_{jr} - P_j^{(0)} P_r^{(0)} + i e_{jrn} P_n^{(0)}). \qquad (11)$$

As a result, the intensity of the scattering on polarization fluctuations is written in the form

$$I^P_{\mathbf{uu}'} \propto \bar{n} f^P(\omega) \beta^2 |\alpha_0|^2 \{ |\mathbf{A}|^2 - |\mathbf{A}\mathbf{P}^{(0)}|^2 + i(\mathbf{A}[\mathbf{A}^* \mathbf{P}^{(0)}]) \}. \qquad (12)$$

The vector quantities **A** for the four cases considered in the preceding section have the form

$$\mathbf{A}_{RR} = -\frac{1}{2} \left[i \frac{\mathbf{k}+\mathbf{k}'}{k} - \mathbf{e}_1 \sin \theta \right],$$
$$\mathbf{A}_{RL} = -\frac{1}{2} \left[i \frac{\mathbf{k}-\mathbf{k}'}{k} + \mathbf{e}_1 \sin \theta \right], \qquad (13)$$
$$\mathbf{A}_{LL} = (\mathbf{A}_{RR})^*, \quad \mathbf{A}_{LR} = (\mathbf{A}_{RL})^*.$$

Next, as in Sec. 3, we consider two special cases: $\mathbf{P}_0 \parallel \mathbf{k}$ and $\mathbf{P}_0 \perp \mathbf{k}$. In the former case

$$I^P_{RR} \propto \beta^2 \left\{ \frac{1-P_0^2}{2} (1+\cos \theta) + \frac{(1+P_0)^2}{4} \sin^2 \theta \right\},$$
$$I^P_{RL} \propto \beta^2 \left\{ \frac{1-P_0^2}{2} (1-\cos \theta) + \frac{(1+P_0)^2}{4} \sin^2 \theta \right\},$$
$$I^P_{LL} \propto \beta^2 \left\{ \frac{1-P_0^2}{2} (1+\cos \theta) + \frac{(1-P_0)^2}{4} \sin^2 \theta \right\}, \qquad (14)$$
$$I^P_{LR} \propto \beta^2 \left\{ \frac{1-P_0^2}{2} (1-\cos \theta) + \frac{(1-P_0)^2}{4} \sin^2 \theta \right\}.$$

If there is 100% polarization ($P_0 = +1$), for the $D1$ line we have $I^P_{LL} = I^P_{LR} = 0$, i.e., the left-polarized wave is not scattered at all (compare the analogous formulas in Sec. 3). For $P_0 = -1$ the right-polarized wave is not scattered. For $\mathbf{P}_0 \parallel \mathbf{k}$ these assertions are perfectly obvious without calculations.

For $\mathbf{P}_0 \perp \mathbf{k}$ and $\mathbf{P}_0 \parallel \mathbf{e}_1$ we have

$$I^P_{VV} = 0, \quad I^P_{VH} = \beta^2, \quad I^P_{HV} = \beta^2,$$
$$I^P_{HH} = \beta^2 (1-P_0^2) \sin^2 \theta. \qquad (15)$$

5. SPECTRUM OF THE SCATTERED LIGHT

The spectrum of the light scattered on density fluctuations is given by the correlation $\langle \delta n \delta n \rangle_{\omega \mathbf{q}} \propto f^n(\omega)$, and the spectrum of the light scattered on polarization fluctuations is given by the correlation $\langle \delta P \delta P \rangle_{\mathbf{q}\omega} \propto f^P(\omega)$. In a low-density paramagnetic gas without a buffer gas both components have a Doppler contour, i.e., there is no way to distinguish between them spectrally.

The other limiting case of high buffer-gas pressures is of great interest. Under the condition $ql = |\mathbf{k}' - \mathbf{k}| l \ll 1$, where l is the mean free path, the hydrodynamic approach is applicable. In this case the spectrum of the scattering on the density fluctuations is the well-known triplet. The width of the central Rayleigh component γ_n is determined by the thermal conductivity of the mixture and the diffusion of the paramagnetic atoms, and the widths of the Brillouin components are determined by the damping of the sound.[8]

Polarization fluctuations are local and do not propagate in a Boltzmann gas. Therefore, the spectral function $f^P(\omega)$ in a high-pressure mixture is a Lorentzian profile at an undisplaced frequency

$$f^P(\omega) = \frac{\Gamma_P}{2\pi} \frac{1}{\Delta\omega^2 + \Gamma_P^2/4}, \qquad (16)$$

whose width is determined by the diffusion of the paramagnetic atoms and the relaxation of the spin momentum $\Gamma_P = Dq^2 + \Gamma_{SD}$.

Here D is the diffusion coefficient of the heavy paramagnetic gas in the light buffer. The depolarization (spin destruction) constant Γ_{SD} depends on the composition and pressure of the gas mixture.[2] Thus, the central component is a sum of two Lorentzian contours with different widths. Let us examine the ratio between the line intensities in the triplet for the two special cases near the $D1$ line ($\beta = 1$).

For $\mathbf{P}_0 \parallel \mathbf{k}$ the total spectral intensities can be written in the form

$$I_{RR} = \frac{(1+P_0)^2 (1+\cos\theta)^2}{4} f^n(\omega) + \left\{ \frac{(1-P_0^2)(1+\cos\theta)}{2} + \frac{(1+P_0)^2}{4} \sin^2\theta \right\} f^P(\omega), \qquad (17a)$$

$$I_{RL} = \frac{(1+P_0)^2 (1-\cos\theta)^2}{4} f^n(\omega) + \left\{ \frac{(1-P_0^2)}{2} \times (1-\cos\theta) + \frac{(1+P_0)^2}{4} \sin^2\theta \right\} f^P(\omega). \qquad (17b)$$

The values of I_{LL} and I_{LR} are obtained from (17a) and (17b) by changing the sign in front of P_0.

It is seen from (17b) that at small scattering angles, scattering on polarization fluctuations dominates the depolarized scattering.

For $\mathbf{P}_0 \perp \mathbf{k}$ and $\mathbf{P}_0 \parallel \mathbf{e}_1$ only polarization fluctuations appear in the depolarized scattering. In this case

$$I_{VV}(\omega) = f^n(\omega), \qquad (18a)$$
$$I_{VH}(\omega) = I_{HV}(\omega) = f^P(\omega), \qquad (18b)$$
$$I_{HH}(\omega) = \{\cos^2\theta + P_0^2 \sin^2\theta\} f^n(\omega) + \{\sin^2\theta - P_0^2 \sin^2\theta\} f^P(\omega). \qquad (18c)$$

6. DISCUSSION OF RESULTS

The picture of the Rayleigh scattering in a paramagnetic Boltzmann gas with optically induced polarization $\mathbf{P}_0$ is the sum of the scattering on density fluctuations $I_n(\omega)$ and the scattering on spin-polarization fluctuations $I_P(\omega)$, $I(\omega) = I_n(\omega) + I_P(\omega)$, where $I_n(\omega)$ and $I_P(\omega)$ are given by Eqs. (6) and (10). As follows from these equations, the frequency-integrated scattering intensities of the circularly polarized waves are linearly dependent on the polarization of the gas P_0, and their ratio at small scattering angles equals

$$\frac{I_{RR}}{I_{LL}}(\theta\rightarrow 0)=\frac{1-P_0}{1+P_0}. \tag{19}$$

Thus, it is convenient to determine the polarization of the gas P_0 from this ratio at small scattering angles.

Let us now examine the dependence of the spectral composition of the scattered light on the polarization of the gas P_0. When the polarization vector $\mathbf{P}_0$ is perpendicular to the scattering plane ($\mathbf{P}_0 \perp \mathbf{k}, \mathbf{k}'$), the spectrum is described by Eqs. (9) and (15). It follows from these equations that

1) at small scattering angles ($\theta\approx 0$) the scattering spectrum does not depend at all on the polarization of the gas, i.e., $I_{VV}(\omega)=f^n(\omega)$, $I_{VH}(\omega)=I_{HV}(\omega)=f^P(\omega)$, and $I_{HH}(\omega)=\cos^2\theta f^n(\omega)\rightarrow f^n(\omega)$;

2) in the case of scattering at a right angle $\theta=90°$, only $I_{HH}(\omega)\simeq P_0^2 f^n(\omega)+(1-P_0^2)f^P(\omega)$ depends on the polarization, and this dependence is nonlinear.

In the limiting case $P_0\rightarrow 1$, the polarization fluctuations "freeze," and only the density fluctuations which are isotropic in angle remain: $I_{HH}(\omega)\{P_0\rightarrow 1\}\rightarrow f^n(\omega)$.

Let us consider the second case, in which $\mathbf{P}_0 \parallel \mathbf{k}$ [see Eqs. (8) and (14)]. As is seen from these equations, the spectral scattering intensities $I_{RR}(\omega)$, $I_{RL}(\omega)$, $I_{LR}(\omega)$, and $I_{LL}(\omega)$ include both linear and quadratic functions of the polarization P_0. In the case of small scattering angles $\theta\approx 0$, the functions defining the dependence of the scattering spectrum on the polarization of the gas become very simple:

$$\begin{aligned}
&I_{RR}(\omega)=(1-P_0)^2 f^n(\omega)+(1-P_0^2)f^P(\omega),\\
&I_{LL}(\omega)=(1+P_0)^2 f^n(\omega)+(1-P_0^2)f^P(\omega), \qquad (20)\\
&I_{RL}=I_{LR}=0.
\end{aligned}$$

Equations (20) describe the redistribution of the scattered light in the spectrum as the polarization of the gas atoms varies. In an unpolarized gas ($P_0=0$) the scattering is the sum of two equal components $I_{RR}=I_{LL}=f^n(\omega)+f^P(\omega)$. In nominal units (when we set $\int f^n(\omega)d\omega=1$ and $\int f^P(\omega)d\omega=1$) the total intensity is equal to 4. In the limiting case of a completely polarized gas ($P_0=1$) $I_{RR}=0$, and $I_{LL}(\omega)=4f^n(\omega)$, i.e., the integrated scattering intensity remained unchanged (equal to 4 in scaled units); however, the polarization fluctuations vanished and the density fluctuations increased in the scattering spectrum. Thus, polarization of the gas results, on the one hand, in "freezing" of the polarization fluctuations and, on the other hand, in alteration of the effective polarizability of the left-polarized (or right-polarized) atoms $\alpha_{\mathrm{eff}}=\alpha_0(1\pm P_0)$ for the density fluctuations. We note that the quadratic dependence of the scattering spectra (20) on the polarization P_0 vanishes in the case of a low-density gas, in which the profiles of $f^n(\omega)$ and $f^P(\omega)$ coincide and are purely Doppler. This case corresponds to the condition $ql\gg 1$, where l is the mean free path of the paramagnetic gas.

Let us now evaluate the order of magnitude of the widths of $f^n(\omega)$ and $f^P(\omega)$, which reflect the relaxation processes of the density and spin-polarization fluctuations in the paramagnetic gas. In the dense-gas limit ($ql\ll 1$), the spectrum of the scattering on the density fluctuations $f^n(\omega)$ has the form of a well resolved triplet, and the scattering on the polarization fluctuations $f^P(\omega)$ produces a Lorentzian at an undisplaced frequency [see Eq. (16)].

The scalar triplet for scattering on density fluctuations is well known and consists of three Lorentzians in the case of a pure gas: a central Rayleigh component, whose width γ_n is determined by the thermal conductivity of the gas, and two Brillouin sound components [$\omega=\pm qu_s$, $u_s^2=(c_p/c_v)(T/m)$], whose widths are determined by the damping of the sound. In the case of a mixture of gases, there is a second Lorentzian at an undisplaced frequency, whose width is determined by the diffusion coefficient of the scattering particle in the gas mixture.[8]

Note that a sufficiently dense gas has a range of frequencies ($\omega>\gamma_n$) in which $f^P(\omega)=0$ and $f^n(\omega)=f^n(\pm qu_s)\neq 0$. Then Eqs. (20) give an intensity ratio which is nonlinear with respect to P_0

$$\frac{I_{RR}}{I_{LL}}(\omega=\pm qu_s)=\frac{(1-P_0)^2}{(1+P_0)^2},$$

while at an undisplaced frequency ($\omega\simeq 0$), where $f^n(\omega)\simeq f^P(\omega)$ holds, we have

$$\frac{I_{RR}}{I_{LL}}(\omega\approx 0)=\frac{1-P_0}{1+P_0}.$$

Thus, the dependence of the scattering spectrum on the polarization of the gas can differ considerably in different regions of the spectrum.

It is seen from the above equations that the polarization of the atoms and the spin relaxation constants can be determined from the intensities of the scattering and its spectrum when the observation geometry and the composition of the working mixture have been suitably selected. The working mixture which is usually used in optical-polarization experiments consists of a Rb vapor with density from 0.5×10^{15} to 1×10^{15} cm^{-3} and He at pressures from 3 to 10 atm,[1)] i.e., $N_{\mathrm{He}}\simeq 1\times 10^{20}$ to 3×10^{20} cm^{-3}. Using the data in Ref. 8 and taking the gas-kinetic radius of rubidium to be $r_{\mathrm{Rb}}\simeq 3r_{\mathrm{He}}$, for the mean free path of the rubidium atoms in a mixture with helium we obtain the estimates

$$l_{\mathrm{Rb\,He}}\approx(N_{\mathrm{He}}\cdot 10^{-14})^{-1}\ \mathrm{cm},$$

$$l_{\mathrm{Rb\,Rb}}\approx(N_{\mathrm{Rb}}\cdot 8\cdot 10^{-14})^{-1}\ \mathrm{cm}.$$

Also, $q=2k\sin\theta/2\sim k\theta\sim 10^5\theta$ cm^{-1}. As θ is varied from 90° to $\theta\simeq 0.1°$, the diffusive part of the width of the undisplaced line varies from $\sim 10^8$ s^{-1} to 10^2 s^{-1}. With consideration of the data in Refs. 1, 2, and 7, at the parameters of the gas mixture indicated above the characteristic spin destruction constant is $\Gamma_{SD}\simeq 10^3$ s^{-1}. Here the Rb+Rb and Rb+He collisions make approximately identical contributions. Other inert gases cause considerably faster destruction of spin polarization.

Thus, the observation of depolarized scattering permits determination of the spin relaxation constant. We note that polarization of the atoms is not required for this; therefore, the concentration of alkali-metal atoms can be increased significantly, and the different mechanisms of spin relaxation can be distinguished.

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[1] As well as ~100 torr nitrogen, which is of negligible importance.

[1] T. E. Chupp, M. E. Wagshul, K. P. Coulter *et al.*, Phys. Rev. C **36**, 2244 (1987).

[2] B. Larson, O. Häusser, P. P. J. Delheij *et al.*, Phys. Rev. A **44**, 3108 (1991).

[3] Yu. Bogdanov, K. V. Volodchenko, S. I. Kanorskii *et al.*, Preprint No. 129, P. N. Lebedev Physics Institute, Academy of Sciences of the USSR, Moscow, 1991.

[4] M. Ya. Agre and L. P. Rapoport, Zh. Éksp. Teor. Fiz. **104**, 2975 (1993) [JETP **77**, 382 (1993)].

[5] L. D. Landau and E. M. Lifshitz, *Electrodynamics of Continuous Media*, Pergamon, Oxford, 1984.

[6] K. Blum, *Density Matrix Theory and Applications*, Plenum Press, New York, 1981.

[7] R. J. Knize, Phys. Rev. A **40**, 6219 (1989).

[8] R. P. C. Schram, G. H. Wegdam, and A. Bot, Phys. Rev. A **44**, 8062 (1991).

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