Hanle Effect in Coherent Backscattering

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We study the shape of the coherent-backscattering (CBS) cone obtained when resonant light illuminates a thick cloud of laser-cooled rubidium atoms in the presence of a homogenous magnetic field. We observe new magnetic field-dependent anisotropies in the CBS signal. We show that the observed behavior is due to the modification of the atomic-radiation pattern by the magnetic field (Hanle effect in the excited state).

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When a multiply scattering medium is illuminated by a laser beam, the scattered intensity results from the interference between the amplitudes associated with the various scattering paths; for a disordered medium, the interference terms are washed out when averaged over many sample configurations, *except* in a narrow angular range around exact backscattering where the average intensity is enhanced. This phenomenon, known as coherent backscattering (CBS), is due to a two-wave constructive interference (at exact backscattering) between waves following a given scattering path and the associated reverse path, where exactly the same scatterers are visited in the reversed order [1]. The maximum enhancement is obtained when the amplitudes of the interfering paths are exactly balanced. For a convenient choice of polarization, time-reversal symmetry directly implies the equality of the interfering amplitudes. More generally, the interference phenomenon is very robust and qualitatively insensitive to most characteristics of the sample and illuminating wave.

However, applying a magnetic field on the sample breaks the time-reversal invariance. It was predicted [2], then experimentally observed [3] and theoretically studied [4,5] that it results in a decrease of the CBS enhancement as well as some rather complicated behavior of the cone shape. In our current understanding of CBS, two ingredients are essential: the individual scattering event, characterized, for example, by the radiation pattern of each scatterer (this is the single scattering ingredient), and the propagation in the medium between scattering events (this is the "average effective medium" ingredient). Of course, these two ingredients are not independent since the optical theorem links the propagation in the medium to the individual scattering. In the presence of a magnetic field, both ingredients can be affected. For the propagation, this is well known under the name of Faraday effect (and the Voigt or Cotton-Mouton effect) and can be described by the modification of the complex refractive index by the magnetic field. The magnetic field-induced variation of the radiation pattern is much less studied, because it is very small in usual magneto-optically active materials; it is responsible for the "photonic Hall effect" predicted by van Tiggelen [6] and later observed experimentally [7]. In this paper, we show a novel situation where it is experimentally and theoretically possible to discriminate between the two ingredients and where the modification of the radiation pattern dominates the propagation effects.

In our experiment, we analyze coherent backscattering of resonant light by a dilute gas of laser-cooled rubidium atoms. Some features of this medium differ markedly from those used in previous CBS experiments. First, the cold atomic cloud constitutes a monodisperse sample of point scatterers, highly resonant in the vicinity of the optical transition. This implies a dramatic increase of the scattering cross section at resonance, but also a great sensitivity to any external perturbation such as a magnetic field. Typically, a few Gauss are enough to bring the atom completely off resonance, in sharp contrast with previous studies where teslas were needed to induce significant effects [3]. Concurrently, a giant Faraday effect is observed in the cold atomic cloud [8]. Another important difference with classical systems is the presence of a quantum internal structure, which has been shown to strongly reduce the coherent-backscattering interference [9]. Obviously, the addition of a magnetic field will affect the contrast of the CBS cone in various ways, and we have indeed observed new behaviors that will be described somewhere else. In the present Letter, we focus on the shape of the cone rather than its intensity.

The experiment has been described elsewhere [9]. We use the $F = 3 \rightarrow F' = 4$ transition of the D2 line of Rb^{85} (wavelength $\lambda = 780$ nm, natural width $\Gamma/2\pi = 5.9$ MHz) where F here denotes the hyperfine angular momentum. The temperature of the atoms is in the 100 μK range. We show in Fig. 1 some CBS cones obtained in the linear polarization channels, for different values of the magnetic field and laser detuning. After scaling and substraction of the incoherent background (average intensity in the wings of the peak), we plot the detected far-field intensity isolines. The horizontal and vertical coordinates correspond to the two azimuthal

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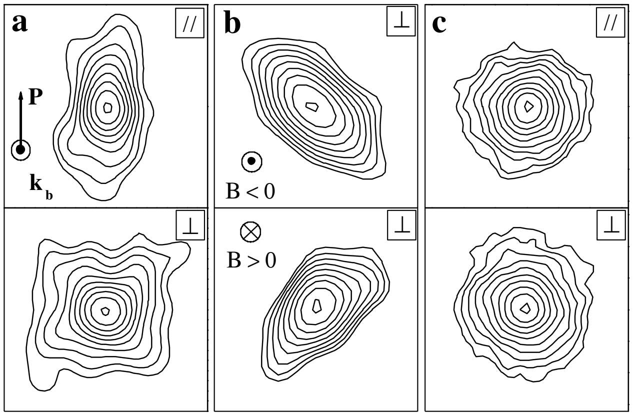

FIG. 1. Experimental CBS cones. The far-field backscattered intensity is plotted as a function of the two azimuthal scattering angles (maximum intensity at center; we use a logarithmic scale for the isolines for a better visualization of the wings where the anisotropy is more pronounced; the lowest isoline corresponds to roughly 10% of the peak value). The total angular range is 2 mrad. **P** denotes the incident polarization. (a) $B = 0$, top: lin $\parallel$ lin, bottom: lin $\perp$ lin; (b) both cones in lin $\perp$ lin, top: $B = -8$ G, bottom: $B = +8$ G; note the 90° flip when B changes sign. (c) $B = +10$ G and $\delta_L = -2.6\Gamma$, top: lin $\parallel$ lin, bottom: lin $\perp$ lin.

scattering angles. The magnetic field **B** is orthogonal to the plane of the figure, like the backscattered light wave vector $\mathbf{k}_b$ which points towards the reader. The incident light polarization is parallel to the vertical axis of the figure. Since we will care about the sign of magneto-optical rotations, we have to precise our conventions. A positive magnetic field is parallel to the incident light wave vector $\mathbf{k}_i (= -\mathbf{k}_b)$ with the same orientation. A positive angle corresponds to a counterclockwise rotation when $\mathbf{k}_i$ points towards the observer.

For resonant light (laser detuning $\delta_L = \omega_L - \omega_A = 0$ where ω_L and ω_A are the laser and atomic frequencies, respectively) and zero magnetic field $B = 0$, we obtain in the lin $\perp$ lin channel a cushion-shaped cone with a fourfold symmetry shown in Fig. 1(a) (bottom). In the parallel channel (top), the cone has an elliptical shape with its large axis parallel to the incident polarization. In the presence of a magnetic field, we observe in the lin $\perp$ lin channel (b) that the cone has now an elliptical shape with an inclination of 45° from the incident polarization, which does not depend on the magnetic field strength. It is remarkable that, when the sign of the magnetic field is reversed, the cone flips by 90°. In the lin $\parallel$ lin channel, the shape of the cone does not significantly change with the magnetic field. When the laser is detuned with respect to the zero-field atomic transition, the cones in both the lin $\parallel$ lin and lin $\perp$ lin channels become isotropic, as shown in Fig. 1(c).

To understand the features observed in Fig. 1, we need to remember that the CBS cone shape is closely linked to the distribution of distances between first and last visited scatterers in the sample. In fact, it is the Fourier transform of the transverse intensity profile of the scattered light when the sample is illuminated by a narrow light beam [3]. Thus, any scattering asymmetry inside the medium immediately results in a cone-shape asymmetry. For the discussion of the observed effect, it turns out (see below) that the internal structure (Zeeman sublevels) of the atom is not crucial. We thus first consider the simplest case where the atomic transition is $J = 0 \rightarrow J' = 1$. The Zeeman effect induces a splitting of the atomic resonance line into three components separated by μB where B is the magnetic field and $\mu/2\pi = 1.4$ MHz/G is the Zeeman shift rate. As soon as the Zeeman shift is comparable to the resonance width (magnetic field of the order of 4 G), the scattering cross section of the atom is strongly modified. For simplicity, we restrict the discussion to a resonant excitation $\delta_L = 0$. In this case, the response of the atom to a linearly polarized field is that of a dipole rotated from the incident polarization by an angle $\varphi = \arctan(2\mu B/\Gamma)$, in the plane perpendicular to B. This rotation is responsible for the well-known fluorescence dip curve observed in typical Hanle experiments in the excited state [10]. The effect of the magnetic field on the average effective medium is also well known: in the direction of the magnetic field, it induces the Faraday effect, i.e., a rotation of the electric field around the magnetic field. For a weak magnetic field $\mu B \ll \Gamma$, the Faraday angle θ_F per mean-free path is $\theta_F \simeq -\mu B/\Gamma$ [8]. It is crucial to note that it has a sign *opposite* to that of the atomic dipole rotation. As CBS involves both propagation and individual scattering, the experimental observation of the sign of the rotation makes it possible to determine the dominant effect. As will be discussed later, our experimental results indicate that the rotation of the atomic dipole dominates in this situation.

We propose a simple model which explains the observed cone-shape behavior, taking into account only the rotation of the atomic dipole. We will restrict the discussion to the case of double scattering, as it is known to be dominant in our experimental conditions and because anisotropy effects are expected to decrease for higher order scattering. Because of the exponential attenuation of light inside the sample, the first and last scatterers of most paths lie in a "skin layer" of thickness approximately one scattering mean-free path under the surface of the sample. Thus, we will assume that all propagation takes place in the transverse plane, orthogonal to the incident wave vector. In addition, we will neglect all propagation effects (i.e., Faraday and Cotton-Mouton). Note that in the described geometry, the Faraday effect *between* scatterers is indeed absent.

Let us now consider an initial polarization vector **P**. The first scatterer radiates a wave at an angle Ψ from **P** towards the second atom, which then radiates in the backscattering direction where the field is analyzed along the polarization **A** at an angle α with **P**. The angular dependence of the interference term between reverse paths is readily given by $\sin^2(\varphi - \Psi)\sin^2(\varphi + \Psi - \alpha)$. This formula (valid for resonant light) allows us to understand most of the observed behavior of the CBS interference pattern. Using a general symmetry argument, one can show that the CBS cone should remain symmetric with respect to the bisectors of the incident and detected polarizations directions. Indeed, the expression given above is invariant by the transformation $\Psi \rightarrow \alpha - \Psi$. In a polar plot, it exhibits two orthogonal pairs of lobes along the two bisectors. Each pair has two symmetric lobes, and the intensity ratio R between the two pairs is $R = \tan^4(\alpha/2 - \varphi)$. Thus, in most cases one lobe pair dominates over the other, yielding a cone with an elliptical shape along one of the bisectors. When varying the value of $\alpha/2 - \varphi$ (either by scanning the magnetic field or rotating the analyzer), the intensity of the dominant lobe decreases while the smallest lobe grows, until $\alpha/2 - \varphi = \pi/4$, where they are of equal intensity (a fourfold symmetry of the cone is there recovered). Above this threshold value, the roles of the two pairs of lobes are interchanged: one thus observes a flip of the CBS cone orientation by 90°. Moreover, in the lin $\perp$ lin channel ($\alpha = \pi/2$), $B \rightarrow -B$ flips the cone as observed in Fig. 1(b). In our model, the value α_f corresponding to the flip threshold is simply related to the magneto-optical rotation through $\alpha_f = 2\varphi + \pi/2$. So far, we have neglected all propagation effects. However, note that the Faraday rotation due to the propagation of the light through the "skin layer" separating the sample surface from the first scattering event [5] would have the same qualitative influence on the cone shape as the dipole rotation φ, but with the opposite sign as emphasized earlier. As it will be discussed later, our results indicate that the dipole rotation dominates in this experiment.

Figure 2 shows some examples of the double scattering CBS cones obtained in the linear channels with this model. (a) and (b) correspond to the same parameters as in Fig. 1. One clearly sees [(a), bottom row] the distinctive clover-leaf shape in the lin $\perp$ lin channel at $B = 0$ with four lobes along the bisectors (at 45°). At nonvanishing magnetic field one of the lobe pairs is favored depending on the sign of φ (b). The comparison between Figs. 1 and 2 confirms that the CBS cone tilt observed experimentally is consistent with the sign of the dipole rotation, and that our simple model catches the essential part of the physics. For off-resonant excitation $\delta_L \neq 0$, the picture becomes more complex since the induced dipole is elliptical. However, if the Zeeman splitting is large enough $\mu B \gg \Gamma$ and if the laser frequency is tuned to resonance with one of the circular components $\delta_L = \pm\mu B$, then the dipole is essentially circular and the cone is isotropic in agreement with the data in Fig. 1(c).

We now discuss the effect of the internal structure in the ground state, which is neglected in the previous model. Because of its internal structure, the rubidium

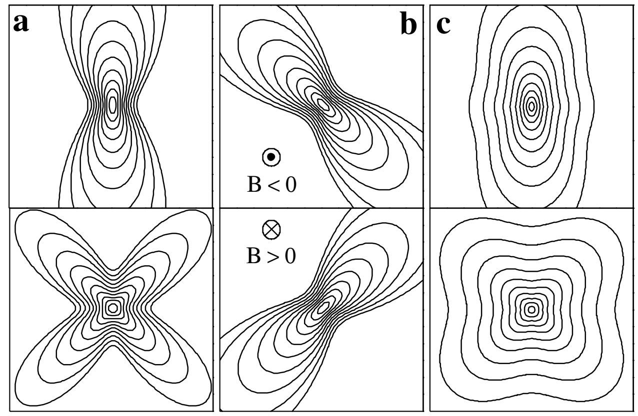

FIG. 2. Theoretical CBS cones (double scattering). (a) and (b) use the $J = 0 \rightarrow J' = 1$ transverse plane model described in text (same parameters as in Fig. 1). (c): cones in lin $\parallel$ lin (top) and lin $\perp$ lin (bottom) for a $F = 3 \rightarrow F' = 4$ transition and $B = 0$ (semi-infinite medium); the cones shapes are rounded off compared to (a), but the symmetry properties are identical.

atom does not behave like a pure dipole scatterer. More specifically, the radiation pattern depends on the ground state magnetic sublevels m_g and m'_g, respectively, before and after the scattering event. To determine the total CBS signal, one has to sum over all possible transitions ($m_{g1} \rightarrow m'_{g1}$, $m_{g2} \rightarrow m'_{g2}$) of two atoms. We have computed numerically the total CBS signal in this case and found that, for moderate B values (up to a few G), the symmetry of the CBS pattern is only weakly modified compared to the $J = 0 \rightarrow J' = 1$ case. Indeed, in this regime, the CBS signal is dominated by the "Rayleigh" transitions $m_g \rightarrow m_g$, yielding the same behavior as in the $J = 0 \rightarrow J' = 1$ situation. Thus, and this is the important point, we can still use the results of the simple $J = 0 \rightarrow J' = 1$ model with an average dipole rotation φ to describe the cone behavior for the $F = 3 \rightarrow F' = 4$ transition of rubidium. One illustration of the effect of the internal structure is given in Fig. 2(c) where we plot the double scattering CBS signal at $B = 0$ in the lin $\parallel$ lin (top) and lin $\perp$ lin (bottom) channels for the $F = 3 \rightarrow F' = 4$ transition and a semi-infinite geometry. The main effect of the internal structure in this case is a rounding-off of the cone features. The comparison with the experimental cones of Fig. 1(a) yields a nice agreement.

In order to make a quantitative test of our model, we have experimentally measured the dipole rotation φ [open squares in Fig. 3(a)] by analyzing the polarization of resonant light scattered by an optically thin atomic cloud (optical thickness 0.05). In this regime, Faraday rotation and multiple scattering are negligible. The solid line in Fig. 3(a) corresponds to the theory for a $F = 3 \rightarrow F' = 4$ transition and agrees well with our measurements. In a different experiment, we have measured the Faraday rotation *per mean-free path* θ_F [solid squares in Fig. 3(a)] by recording, as a function of B, the polarization rotation

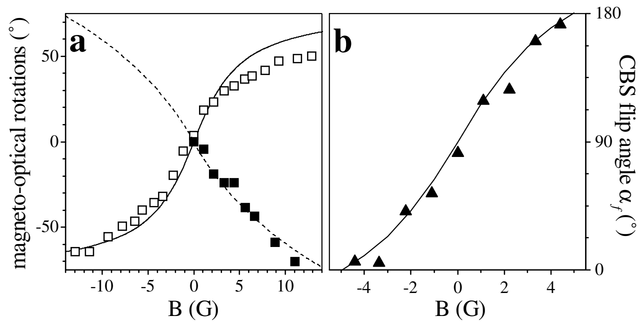

FIG. 3. Magneto-optical rotations. (a): measured dipole rotation φ (□) and Faraday rotation *per mean-free path* θ_F (■). The curves correspond to the theory for a $F = 3 \rightarrow F' = 4$ transition (see text for sign conventions). Note that the two rotations have opposite signs. (b): measured CBS flip angle α_f (▲) compared to the $F = 3 \rightarrow F' = 4$ model neglecting all propagation effects (solid line).

of light transmitted by a cloud of fixed optical thickness 1. When the magnetic field increases, the total scattering cross section decreases yielding an increasing mean-free path. Thus, in order to keep the optical thickness constant one has to increase either the density or the size of the cloud. We emphasize that the sign of the Faraday rotation is indeed opposite to that of the dipole rotation (i.e., negative). We also note that the Faraday rotation per mean-free path increases with the magnetic field due to the increasing mean-free path [11]. The dotted curve corresponds to the theory for a $3 \rightarrow 4$ transition and is again in excellent agreement. Finally, the triangles in Fig. 3(b) show the measured angle α_f for which the dominant lobe of the cone in the lin $\perp$ lin channel flips by 90°, as a function of the magnetic field, compared with our model taking into account the internal structure (line). The measurement is unpractical above $B = 4$ G due to poor cone contrast.

The excellent agreement between the experiment and our model on both the sign and magnitude of the magneto-optical rotation in the CBS signal indicates that the Faraday rotation through the "skin layer" is negligible in our configuration, and confirms the magnetic field-induced dipole rotation as the mechanism underlying the observed CBS anisotropies. Since the Hanle rotation and Faraday rotation per mean-free path are of the same order of magnitude [see Fig. 3(a)], this is probably due to an effective skin layer thinner than a mean-free path. However, a full Monte Carlo simulation would be necessary to properly address this question.

In conclusion, we report in this paper the observation of various anisotropies in the shape of the coherent-backscattering cone from cold rubidium atoms in a magnetic field. The observed behavior differs radically from previous work on magneto-optically active samples where the cone features were determined by the Faraday effect during the propagation between scatterers. In our situation, the observed anisotropy is due to the modification of the atomic-radiation pattern by the magnetic field. This observation illustrates the new regimes that are accessible through the use of cold atoms as a highly resonant scattering medium for light. Some more elaborate modeling is needed to understand in detail the roles of propagation versus individual scattering effects in our sample, in particular, to explain the behavior of the CBS enhancement factor in the presence of a magnetic field.

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