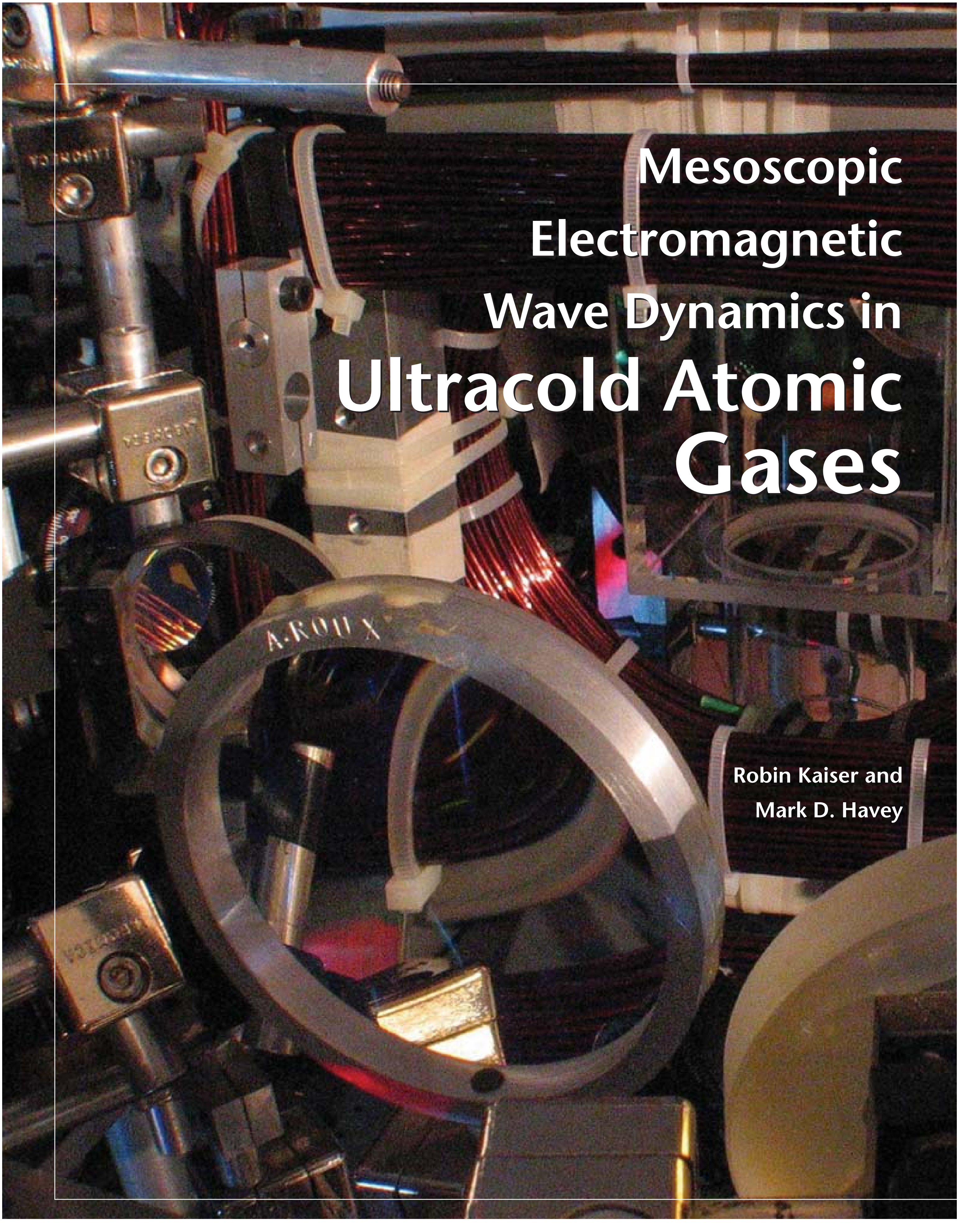

Mesoscopic Electromagnetic Wave Dynamics in Ultracold Atomic Gases

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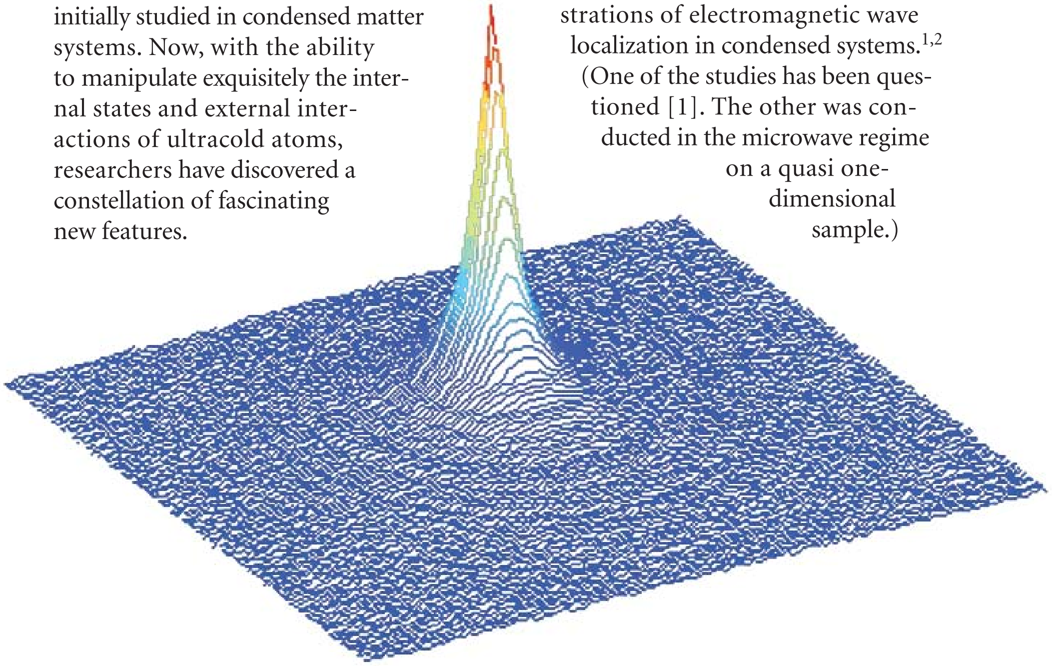
Ultracold atomic gases present a unique medium for studies of classical and quantum optical phenomena. Recent research on coherent multiple light scattering in such media shows a range of surprising effects, and suggests possibilities for strong localization of electromagnetic radiation in a dense and ultracold atomic gas sample.

Experimental developments permitting manipulation of dynamic and kinetic properties of ultracold gas-phase matter have revolutionized fundamental quantum statistical studies of atomic gases. Research demonstrating Bose-Einstein condensation (BEC) in an atomic system has spurred a vast range of experimental and theoretical work associated with this remarkable state of matter.

Subsequent studies have examined, for example, the quantum-fluctuation driven superfluid-Mott insulator transition, the potential for phase transitions in ultracold atomic plasmas, and, more recently, quantum degeneracy in trapped Fermionic atoms. Many aspects of these phenomena were initially studied in condensed matter systems. Now, with the ability to manipulate exquisitely the internal states and external interactions of ultracold atoms, researchers have discovered a constellation of fascinating new features.

An area of developing interest is the influence of disorder on atomic or mesoscopic dynamics. Recent results indicate that disorder-induced transitions from a BEC to Bose and Anderson glass phases are within current experimental capability. In addition, there has been considerable activity in the localization of light in condensed matter physics—which is a disorder-induced phase transition in the transport properties of electromagnetic radiation in strongly scattering random media. Even in weakly scattering media, there can be dynamical reduction in the diffusion coefficient.

Investigations in this area, stimulated originally by Anderson localization of electrons, have resulted in two demonstrations of electromagnetic wave localization in condensed systems.[1,2] (One of the studies has been questioned [1]. The other was conducted in the microwave regime on a quasi one-dimensional sample.)



(*Facing page*) Coherent backscattering apparatus for ultracold atomic rubidium. [Photo by Gian Luca Gattobigio and Guillaume Labeyrie.] (*Above*) Angular distribution of backscattered light intensity from an ultracold atomic rubidium gas sample, showing the coherent backscattering cone. The angular width of the cone is about a milliradian.

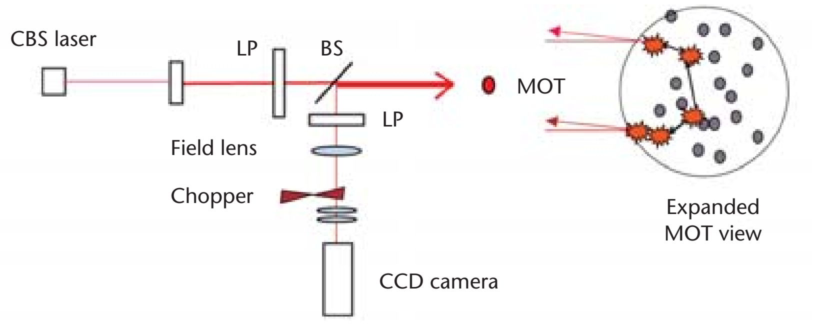


Figure 1. Schematic diagram of a typical coherent backscattering arrangement used in ultracold atom experiments.

A previous OPN feature discussed localization in the context of electrical excitation of condensed samples.[3]

Ongoing experimental and theoretical research directed toward the localization of light in ultracold samples of gas-phase Rb atoms has, until now, been focused on light scattering phenomena limited to the so-called "weak-localization" regime, which is defined by the condition $kl \gg 1$, where k is the magnitude of the local wave vector and l is the mean free path for light scattering in the medium.

Even in this restricted regime, where light scattering may be considered a sequence of separate—but coherently related—scattering events, investigators have observed or predicted a wide range of phenomena, and explored effects of atomic and light polarization, external magnetic fields, the strength of the exciting electromagnetic fields and remarkable interferences due to coherent multiple scattering.

Coherent backscattering of light

Coherent backscattering (CBS) of light from disordered media was first reported in complex random materials in 1985. As illustrated in Fig. 1, light from a well-collimated optical beam is directed toward a sample, and light scattered in the nearly backward direction (about 1 mrad) is measured as a function of angle, frequency and light polarization. When the phase accumulation in reciprocal paths is equal, constructive interference occurs among the backscattered amplitudes.

Then, a robust interferometric enhancement of up to a factor of two above the diffuse background intensity can be observed in a wide range of materials and experimental conditions. This effect, which is sometimes referred to as weak localization, represents a signature departure from descriptions of radiative transport, as obtained by averaging over phase information. Weak localization is more closely related to recurrent scattering inside the medium and its intimate effect on transport properties. By contrast, coherent backscattering is a manifestation of multiple scattering through an open loop. Such loops are typically closed by optical means external to the sample.

The interferences in CBS are often characterized by the width of the backscattering cone and the degree of enhancement above the incoherent background. For semi-infinite samples, the cone width is inversely proportional to the mean free path for light scattering in the medium. The enhancement depends, among other things, on the light polarization and the amount of single scattering that contributes to it. Ideally, for the helicity-preserving polarization channel—for which single scattering can be rejected—complete reciprocity can be obtained, accompanied by an enhancement factor of two.

CBS from ultracold atomic samples

In backscattering from an atomic gaseous sample, the same essential geometries and polarization channels are used as for condensed samples.[4,5,6,7] However, the fundamental properties of atomic scatterers are unique; these include exceptionally high Q optical scattering resonances, well-characterized level structure and spacing and well-understood responses to static and dynamic electromagnetic fields.

Atomic gases are ideal for studying the complexities of mesoscopic coherence in multiply scattering systems because of these features—along with the fact that the single-atom optical scattering matrix is known in any given case to a high degree of accuracy.

In addition, due to the well-developed experimental techniques for studying ultracold atomic physics, it is possible to reach a wide range of experimental parameters with good control, as well as to observe novel effects such as those associated with atomic recoil or quantum statistics of light.

CBS is not expected to occur at room temperature because the dephasing effects of atomic motion generate random phase shifts in otherwise reciprocal paths, suppressing the interference effect. To address this challenge, researchers conduct experiments at low temperatures that are characteristic of laser-cooled gases. Standard vapor-loaded magneto-optical trap (MOT) technology is often used for both cooling and confining the atomic gas samples.

These instruments produce approximately Gaussian spatial atom distributions on the order of one to several millimeters in diameter and with densities that are typically less than about 5×10^{10} atoms cm^{-3}. The temperature of the atoms is often on the order of 100 μK, ensuring that any decoherence due to Doppler-induced dephasing can be neglected. In addition, the Zeeman degeneracy of most atomic ground states means that there are Rayleigh, elastic Raman and inelastic Raman light scattering channels. These additional degrees of freedom in the combined light-atom system significantly reduce the enhancement.

Nevertheless, as shown in Fig. 2, there is a clear enhancement in all four standard linear and circular polarization channels. In addition, the angular size of the enhanced backscattering signal depends on both sample size and optical thickness. Finally, in spite of the complexity of these mesoscopic atomic systems, researchers have been able to create realistic Monte Carlo simulations, using measured atomic parameters and no adjustable quantities, which have shown satisfactory quantitative agreement with experimental results.

Experiments in ultracold Rb and Sr: Reciprocity lost and gained

The first experiment on CBS from ultracold atoms was conducted in Nice, France (see Ref. 5). It yielded a remarkable and robust result: Even in the polarization channel for maximum enhancement, the CBS enhancement was found to be small—typically less than 1.2. This was followed by theoretical and experimental research by that group and others that confirmed the result and provided a physical explanation for the effect (Refs. 4-7).

The effect was due to the Zeeman degeneracy of the atomic ground of ^{85}Rb, the atom that was studied in the first experiments. When these atoms are distributed in Zeeman sublevels that are initially different, a multiplicity of Raman and Rayleigh transitions occurs with various amplitudes in any given multiple scattering chain. In other words, the direct and reversed paths responsible for CBS enhancement are not generally identical in the otherwise reciprocal paths—thus leading to the observed reduced enhancement.

This result suggested that CBS using atoms with nondegenerate ground levels should lead to much larger enhancements and to a regaining of reciprocity—a hypothesis that was subsequently confirmed by Wilkowski et al. in experiments of ultracold Sr atoms, for which the $^1S_0 \rightarrow {}^1P_1$ resonance transition has a direct correspondence with a classical oscillator. In this experiment, interferometric enhancement of close to twice the incoherent background was measured in the helicity preserving channel. Figure 3 shows the much increased enhancement in Sr compared with the same polarization channel in Rb.

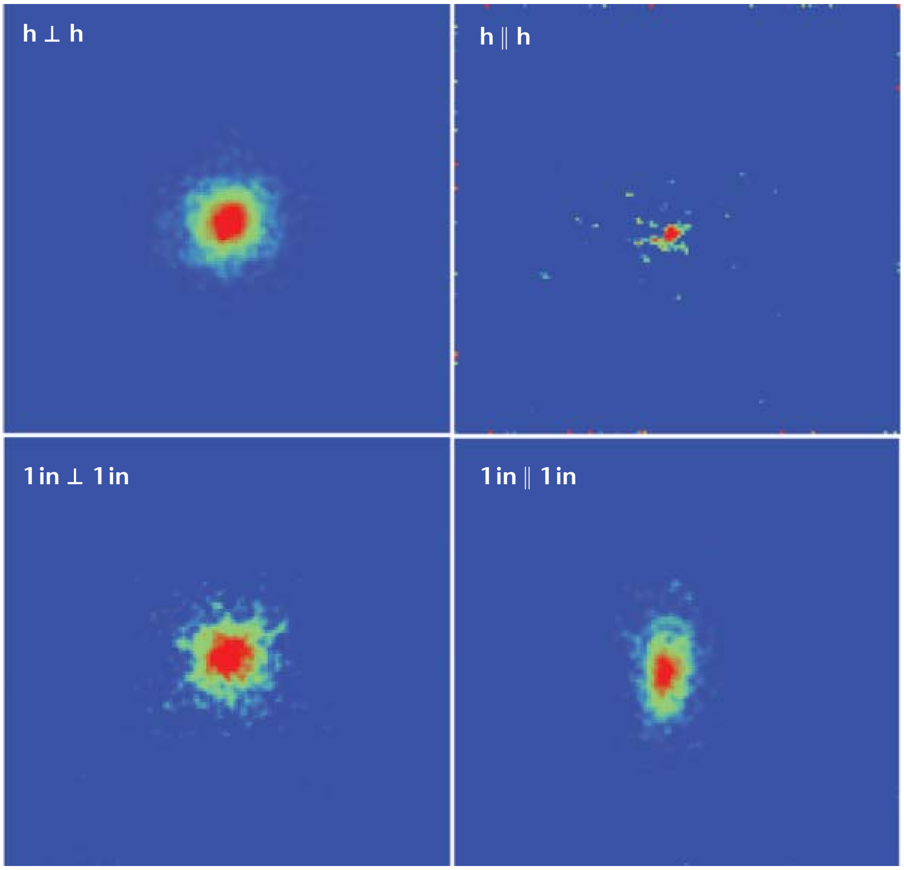


Figure 2. Images of coherent backscattering cones for four standard polarization channels, as indicated on the images.

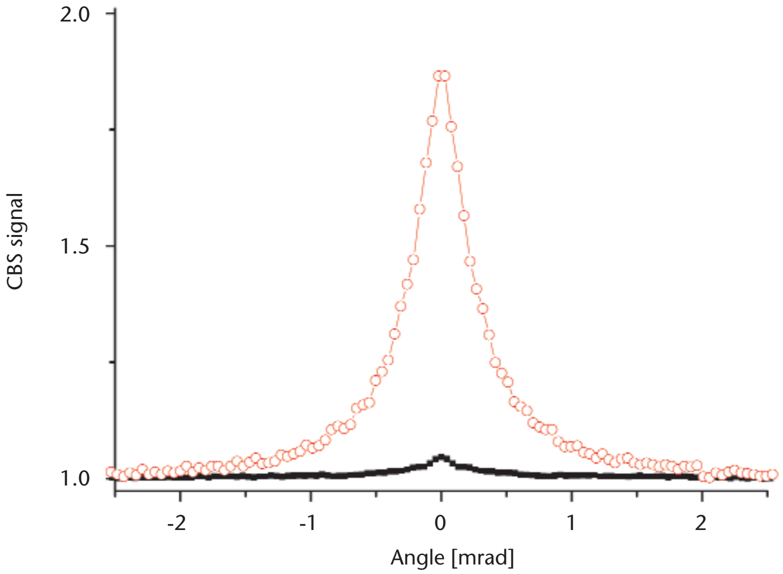


Figure 3. Comparison of coherent backscattering cones for the resonance lines in atomic Sr (red) and Rb (black), illustrating the recovery of the maximal enhancement of the CBS cone.

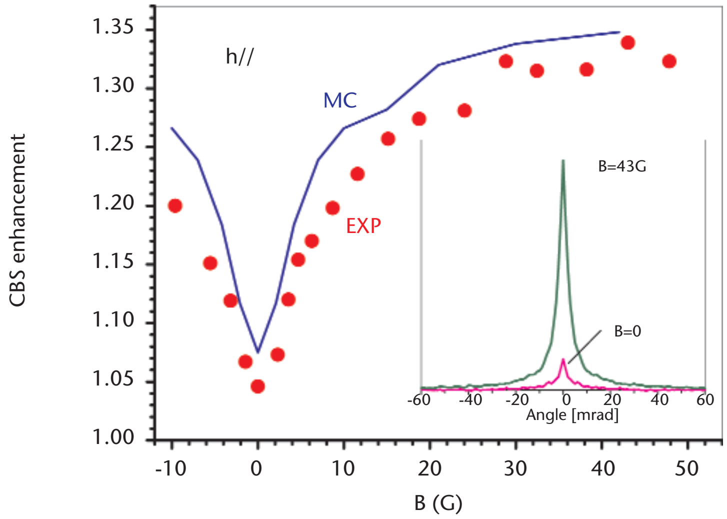


Figure 4. Magnetic-field-generated partial recovery of the coherent backscattering enhancement in ultracold atomic Rb (Ref. 10).

Magnetic interactions and coherent backscattering

It is possible to modify weak localization and CBS effects using magnetic fields, given that CBS is based on reciprocity and, to some extent, on time reversal symmetry. In condensed matter physics, weak localization is manifested via a lower diffusion coefficient of electrons, which yields a reduced conductance. Applying a magnetic field, which acts on the spins of electrons through the Aharonov-Bohm effect, results in a reduction of the interference effects between reciprocal paths.

This mechanism is key to the negative magneto-resistance observed in condensed matter physics. Experiments performed on light scattering in a medium presenting a Faraday effect have shown that a magnetic field also reduces the coherent backscattering cone due to a reduced time reversal symmetry. This reduction has been explained by the Faraday effect associated with propagation between successive scattering events.

Cold atoms are interesting to use in this context, as they are very sensitive to small magnetic fields through the Zeeman shift of the atomic states. Researchers have measured a very strong Faraday effect, showing the high sensitivity to magnetic fields on the order of a few tens of Gauss.[8]

However, in contrast to experiments in condensed samples, in the case of cold atoms, the magnetic fields not only act on the refraction index of the effective medium but also on the scattering properties via the so-called Hanle effect (modification of the differential cross-section).

By analyzing the symmetry of the coherent backscattering cone, researchers have shown that the Hanle effect dominates over the Faraday effect. Thus, it is possible to engineer the differential cross-section with a magnetic field, leading to different symmetries in coherent backscattering cones.[9]

Surprisingly, the sensitivity to the magnetic field has also allowed recovery of the full contrast between reciprocal paths, even in the presence of a degenerate ground state structure. Indeed, the existence of the electronic degeneracy of Rb atoms can be made analogous to magnetic impurities in condensed matter systems. A decoherence mechanism is based on spin flip processes, making the weak localization correction smaller than without magnetic impurities.

Spin processes can be prevented by applying a magnetic field such that the spins are aligned in the sample (i.e., with energy shifts larger than the kinetic energy), and the weak localization correction becomes more important than at zero magnetic field. Increasing the field even further yields the reduced correction due to the Aharonov-Bohm effect.

The situation is similar in cold atoms. Applying a magnetic field large enough to split the different Zeeman transitions sufficiently to overcome the natural width of the transition and tuning the laser frequency to a Zeeman-shifted transition, atoms can be selected in the same atomic ground state. It is thus possible to select an effective two-level system and to recover the full contrast of coherent backscattering[10] (Fig. 4).

An alternative method of selecting a two-level system has been proposed by Kupriyanov et al. They predicted that the CBS enhancement should also be significantly increased in a magnetized Rb vapor, prepared by optical pumping of the sample, for example.

Optical saturation and coherence loss

Stronger electromagnetic fields affect light localization in several ways, as evidenced through measurements of the coherent backscattering cone. Studies in this area are partly motivated by the possibility that the effects of stronger fields may critically influence strong light localization in atomic vapor.

One physical reason for this is that individual atoms have discrete and very high Q optical resonances, so a single photon can be sufficient to saturate an atomic transition. This would occur when the localization length is on the order of the optical wavelength.

A second is that at higher fields the atomic scattered light spectrum evolves into the well-known Mollow triplet, and so includes both elastic and inelastic components. The effective medium also develops nonlinear responses to the local fields, and these fields are distributed inhomogeneously within a given medium.

Experiments of CBS on ultracold Sr gas have indicated significant coherence loss with increasing incident fields[11] (Fig. 5). The coherence loss is reflected in the significantly reduced size of the CBS enhancement. This is, in turn, related to the Fourier transform of the mutual coherence function for the scattered light.

In the near-backscattering direction, the resultant configuration average of the two-field correlation (mainly over atom positions) reflects the overall coherence in reciprocal multiple scattering paths. Thus, the decrease in enhancement is a sharp measure of the reduction in coherence among reciprocal scattering chains. Similar effects have been observed in experiments in ultracold atomic Rb.

The field of nonlinear and saturation effects in multiple scattering is still in its infancy. Many further studies will be needed to examine the full phase space associated with stronger electromagnetic fields.

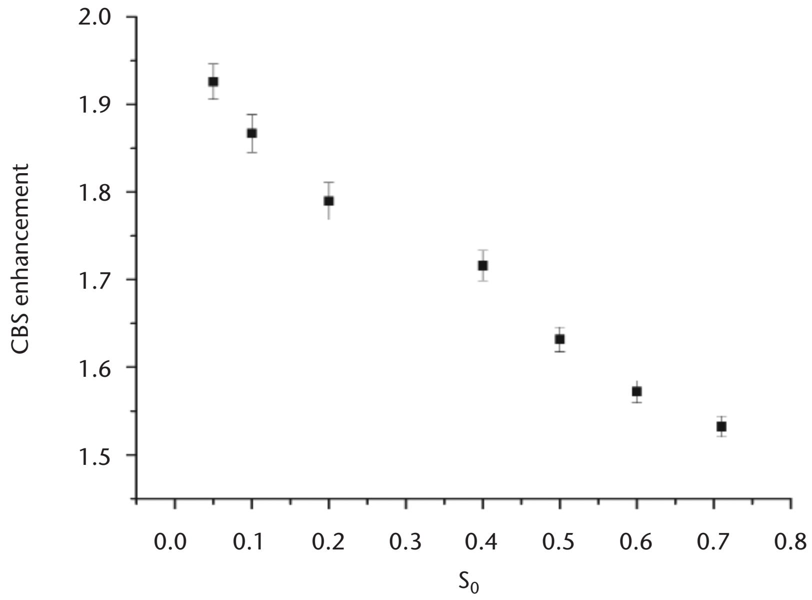


Figure 5. Reduction of the coherent backscattering enhancement for stronger incident electromagnetic fields in atomic Sr (Ref. 11).

Perspectives

Although a wide range of experiments have been conducted in condensed systems, including photonic materials, we have focused our attention on ultracold atomic vapors. To date, atomic physics studies have been in relatively dilute vapors, where multiple scattering is important but effects due to recurrent scattering are small.

These systems are ripe for further study and potential applications. For example, researchers may investigate the effect of gain in the effective medium and multiple scattering studies with nonclassical light.

In addition, research into coherence effects in radiative transport properties has predicted the possibility of destructive interference and the appearance of an anticone[12]; such effects offer unique opportunities to examine the breakdown of traditional treatments of radiative transport in atomic gases.

Another fascinating but largely unexplored area of study is the influence of nonlinear coherent optical effects in multiple scattering.

The potential attainment of strong localization of light in an ultracold atomic gas raises intriguing possibilities. Reaching proper conditions will require increasing the atomic density by several orders of magnitude beyond that attained in experiments to date.

However, such density increases have already been demonstrated for other purposes—by both magnetic and optical methods. Thus, they are well within the range of techniques of ultracold atomic physics.

At these higher densities, the influence of recurrent scattering, including local field effects, atomic recoil and other effects due to atomic internal structure and interatomic interactions, should be observable. Strongly localized subradiant excitations in such an ultracold atomic vapor would represent a unique, and as yet unobserved, complex phase of matter and radiation.

Acknowledgments

The authors wish to acknowledge the essential contributions of our many experimental and theoretical colleagues to the research reported in this article.

Financial support for this research was provided by the National Science Foundation (NSF-PHY-0355024, NSF-INT-0233292), CNRS, BNM and by the PACA region. In particular, we acknowledge the support of the joint NSF/CNRS exchange program.

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