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Weak Localization of Light in Ultracold Atomic Gases

Mark D. Havey[1,*] and Dmitriy V. Kupriyanov[2,†]

[1]Department of Physics, Old Dominion University, Norfolk, VA, USA 23529
[2]Department of Theoretical Physics, State Polytechnic University, 195251, St.-Petersburg, Russia

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Abstract

We summarize recent experimental and theoretical advances in the physics of coherent multiple light scattering in ultracold atomic gases. Current outstanding problems are reviewed, along with prospects for significant new insights into mesoscopic physics in ultracold atomic samples. The possibility of experimental demonstration of strong localization of light in atomic gases is discussed.

1. Introduction

In various discussions of light localization in the literature, authors have customarily classified physical conditions as being in a weak or a strong localization limit. However, in spite of the terminology, there is considerable physical difference between the two and, as pointed out by Lagendijk *et al.* [1], there is no localization in weak localization of light. Nevertheless, it is the purpose of this comment to provide an overview of the fascinating range of mesoscopic atomic physics that is associated with weak localization. These include the role, in ultracold atomic gas samples, of wave interference in light transport, in static magnetic properties, in the interplay between multiple scattering and nonlinear optics, and on coherent manipulation of multiple scattering in mesoscopic systems. We also discuss one of the most important scientific aims of research in this area: to demonstrate and understand localization, by disorder, of electromagnetic excitations in ultracold atomic gases. To these ends, we provide here a brief summary of the basic interference phenomena that give rise to wave localization. This is followed by a description of recent scientific developments that have measured the impact of wave interference on light propagation in ultracold atomic gases. We conclude by laying out some of the areas that promise significant advances in the next few years.

2. Coherent backscattering and atomic physics

Coherent backscattering of light from disordered samples was first reported by Ishimaru *et al.* [2] in 1984. This paper was quickly followed by other experimental and theoretical work by Wolf *et al.* [3] and Albada *et al.* [4], including explanation of the effect based on consideration of classical electromagnetic wave scattering in a disordered medium. The essential mechanism offered was that electromagnetic wave scattering along reciprocal, or time-reversed, multiple scattering paths preserves the relative phase. The result of phase preservation is that an unusual type of configuration-averaged interference effect, the coherent backscattering cone, leads to an enhancement by as much as a factor of two in the intensity of light backscattered from liquid or condensed samples. This cone has an angular width, for a semi infinite sample, on the order of $\Delta\theta \sim 1/kl$, where k is the wave vector of the light in the medium, and l is the scattering mean-free-path. This width is normally of the order of a few milliradians, possibly explaining why such a robust effect had not previously been reported. These studies were done in the weak localization regime, characterized by the condition $kl \gg 1$; *viz.*, the scattering process may be viewed as a sequence of individual scattering and propagation elements. Under weak localization conditions, recurrent scattering, in which light scattered from a scattering center within the medium returns to one of the scatterers in a chain, is expected to be of limited importance. The main observable in this case is the coherent backscattering cone, in which individual scattering chains are closed by external optical means. Since the initial observations, detailed studies and broad applications have led to a deep understanding of much of the physics, in the weak localization regime, associated with scattering from classical samples [5, 6].

Ultracold atomic gases have unique characteristics which make them attractive systems for study of coherent multiple light scattering, particularly in comparison with studies of solid samples or hot atomic vapors. For example, atomic dipole resonances have large cross-sections and exceptionally high Q values. Atomic vapor samples are essentially monodisperse, and interactions with external static and dynamic fields are well understood. Although the study of multiple light scattering in hot atomic vapors has a long history, the near-absence of inhomogeneous broadening by atomic motion creates new opportunities for study of coherence effects in ultracold atomic gases. Here we briefly sketch the formalism used to describe multiple light scattering in such a situation. We refer readers to the references for further details.

In theoretical applications, weak field scattering, described under the assumptions of a perturbation theory approach, is normally considered. Then the microscopic transverse electric field, expressed by its "dressed" Heisenberg operator at the spatial point $\mathbf{r}$ and at time t, is modified in the multiple scattering process as follows

$$\hat{\boldsymbol{E}}^{(+)}(\boldsymbol{r},t) = \hat{\boldsymbol{E}}_0^{(+)}(\boldsymbol{r},t) + \sum_a \hat{\boldsymbol{E}}_a^{(+)}(\boldsymbol{r},t) + {\sum_{ab}}' \hat{\boldsymbol{E}}_{ab}^{(+)}(\boldsymbol{r},t) + {\sum_{abc}}' \hat{\boldsymbol{E}}_{abc}^{(+)}(\boldsymbol{r},t) + \cdots \qquad (1)$$

This expansion, written for the positive frequency component of the electric field, shows how different scattering orders, starting from the single, then double and triple scattering up to higher orders, subsequently contribute to the outgoing Heisenberg operator. The indices a, b, c, *etc.* enumerate the atoms participating in the scattering process. In double scattering $a \neq b$, but in higher scattering orders *recurrent* scattering is possible, and some of the indices can coincide.

The main macroscopic observables responsible for the coherent backscattering cone profile and for its spectral characteristics are found within the first order interference or

*Electronic address: mhavey@odu.edu
†Electronic address: Kupr@DK11578.spb.edu

correlation properties of light, which are completely described by the following correlation function for the polarization components of the outgoing electric field

$$D_{\mu\nu}^{(E)}(\boldsymbol{r}, t; \boldsymbol{r}', t') = \langle \hat{E}_{\nu}^{(-)}(\boldsymbol{r}', t')\hat{E}_{\mu}^{(+)}(\boldsymbol{r}, t)\rangle. \tag{2}$$

Here the angle brackets denote the statistical averaging over the initial state of atoms and light. In the case of an ultracold atomic gas which is not in a quantum degenerate phase, the locations of the atoms can be approximately identified with those of classical objects distributed in a macroscopic volume. In practical calculations the microscopic expansion of the field operators, contributed to the correlation function of light, can be mesoscopically averaged, keeping only the leading and non-vanishing "ladder"- and "crossed"-type terms. The crucial point in such an averaging procedure is that the propagation of the light spectral mode within the sample volume is described by the Fourier transform of the retarded Green's function, which is responsible for the dispersion and attenuation characteristics of the ultracold atomic sample. Thus the original Green's function for vacuum propagation (appearing after direct substitution of (1) into (2)) is modified by the replacement:

$$\delta_{ij}^{\perp}\frac{1}{r_{12}}\exp\left[\mathrm{i}k_{12}r_{12}\right] \rightarrow -\frac{1}{\hbar}D_{ij}^{(R)}(\boldsymbol{r}_1, \boldsymbol{r}_2, \omega_{12}) \tag{3}$$

where ω_{12} is given by the Doppler-shifted frequency of light propagating between any pair of the scatterers 1 and 2 in the direction linking their locations from point $\boldsymbol{r}_1$ to point $\boldsymbol{r}_2$. In the left-hand side the $\delta_{ij}^{\perp}$ symbol is the Kronecker symbol for the respective transverse modes, $k_{12} = \omega_{12}/c$ and $r_{12} = |\boldsymbol{r}_2 - \boldsymbol{r}_1|$.

For further spectroscopic analysis it is convenient to express the time-correlation function of light at a point detector as

$$\frac{c}{2\pi}D_{\mu\nu}^{(E)}(\boldsymbol{r}, t; \boldsymbol{r}, t') = \mathrm{e}^{-\mathrm{i}\omega_R\tau}I_{\mu\nu}(\tau) \tag{4}$$

where ω_R denotes the carrier frequency of the scattered light, which in general can be shifted from the input frequency ω because of inelastic Raman scattering. The outgoing intensity is described by the Poynting vector at point $\boldsymbol{r}$ and is given by the correlation function considered at coincident times $t = t'$. By calculating the Poynting vector one recovers the coherent backscattering cone profile. The dependence of the correlation function on $\tau = t' - t$ comes from the spectral distribution of the scattered modes. The Fourier transform

$$I(\omega) = \sum_{\mu=1,2}\int_{-\infty}^{\infty}\mathrm{d}\tau\,\mathrm{e}^{\mathrm{i}(\omega-\omega_R)\tau}I_{\mu\mu}(\tau) \tag{5}$$

gives the spectral distribution of the scattered intensity in the vicinity of the Raman frequency. Knowledge of the spectral distribution (5) provides information about the velocity distribution and possible correlations existing in an ultracold atomic sample. In the general case, the correlation function can be calculated with a Monte-Carlo technique for realistically modelled atomic samples and then compared with experimental data.

Experimental study of coherent backscattering (CBS) entered the atomic physics community in 1999 with reports by Labeyrie *et al.* [7, 8] on measurement of CBS of resonance radiation from an ultracold sample of ^{85}Rb atoms confined in a magneto optical trap (MOT). In these pioneering experiments, linearly or circularly polarized light tuned to the $F = 3 \rightarrow F' = 4$ hyperfine transition was resonantly scattered from the ultracold atoms. The angular distribution of backward scattered light was then measured in different polarization channels. The CBS effect was observed in all polarization channels studied, with an observed cone of the order of a few milliradians in width. A surprising result was that the enhancement was much less than the factor of two approximately observed in CBS from classical scatterers; in the rubidium experiments, the enhancement was on the order of 1.15, depending on the polarization of the detected light. It was soon realized that reduction of the enhancement was due to the Zeeman degeneracy in ^{85}Rb; elastic Raman transitions induced by the multiply scattered light necessitated generalizing the reciprocity condition to account for the number of non reciprocal scattering channels now available, even for elastic scattering, see Jonckheere *et al.* [9] and Müller *et al.* [10]. Inelastic Raman transitions to the energetically lower $F = 2$ level played a much smaller role in the reduction. Subsequent measurements by Kulatunga *et al.* [11] and detailed Monte Carlo simulations by Kupriyanov *et al.* [12] and Labeyrie *et al.* [13, 14] were in accordance with the initial and subsequent atomic rubidium experiments. The influence of the degeneracy of the atomic transitions has also been considered by Wilkowski *et al.* [15], and found to be in general agreement with simulations of the process. Finally, variation of the CBS enhancement with frequency offset from atomic resonance has been experimentally and theoretically explored by Labeyrie, *et al.* [16] and by Kupriyanov *et al.* [17]; for detuning values near resonance, and of the order of several natural widths, the main effects appear to be due to variation in the number of scattering orders contributing to the process. Later important measurements by Bidel *et al.* [18] on the $^1S_0 \rightarrow {}^1P_1$ resonance transition in strontium showed an enhancement of nearly two, in correspondence with the classical expectation for this transition, in the helicity preserving polarization channel.

3. Further studies of atomic coherent backscattering

Since 2000, experimental and theoretical efforts have been directed toward exploring a number of effects beyond the fundamental atomic CBS process. Among these are measurements and simulations by Labeyrie *et al.* [19, 20] of the Faraday and Hanle effects and the interplay between the CBS multiple scattering process and the well understood magnetic interactions responsible for these effects. Significant magnetic-field sensitivity of the CBS enhancement has been observed, as well as modification of the symmetry of the angular profile of the backwards scattered light intensity. The CBS enhancement may also be modified by breaking the Zeeman degeneracy in the lower level, and by selecting a polarization channel with a reduced number of contributing Raman channels. This was accomplished experimentally by Sigwarth *et al.* [21] in 2004. A similar effect results from magnetization of the medium by optical pumping, as recently predicted by Kupriyanov *et al.* [17].

Another fascinating and little explored area is the influence of saturating incident fields in an ultracold multiple scattering atomic environment. Initial measurements in this regime by Chanèliere *et al.* [22] in strontium showed a distinctive signature of coherence loss for relatively small saturation parameters $s \leq 1$; for resonance excitation, the CBS enhancement monotonically decreased with increasing incident field intensity. A similar effect has been observed by Balik *et al.* [23] in measurements of CBS with linearly polarized light on the $F = 3 \rightarrow F' = 4$ transition in atomic ^{85}Rb. Measurements with circularly polarized light, on the other hand, showed little variation in enhancement with increasing saturation parameter for $s \leq 1$. No quantitative comparisons between the experimental results and simulations or theoretical models have yet been made. On the other hand, there is significant more general theoretical research by a number of groups in this challenging area [24–26].

4. Areas of current and potential future research

One of the principal scientific aims of research discussed in this comment is demonstration and theoretical description of strong localization of light in an ultracold atomic gas. Strong localization is the electromagnetic analog of Anderson [27] localization of electrons. We point out that reports by Wiersma *et al.* [28] and Chabanov *et al.* [29] of strong light localization in condensed samples have appeared in the literature; we are concerned here with such a phase transition in an ultracold atomic gas.

Effects due to strong localization are expected to occur for atomic densities on the order of that given by the Ioffe-Regel condition; $kl \leq 1$, where k and l have been defined earlier in this comment. This condition implies an ultracold atomic density greater than 10^{13} atoms/cm^3; densities on this order can be obtained with current laser cooling techniques. Even increasing the density into this general range can have observable effects. For example, as recurrent scattering [1, 6] becomes more important, the diffusion coefficient for light transport becomes reduced; at the Ioffe-Regel boundary, the classical diffusion coefficient is supposed to vanish, signalling the localized state. Beyond this more specific scenario, however, atom concentrations in this range alone suggests that the general physical conditions under which strong localization might be expected are quite unusual. First, the density is sufficiently high that light scattering should be collective, for on the average each atom can be in the near field of another. Second, because of the relative proximity of the atoms, interatomic interactions via the longitudinal electric field will likely play an important role. It is expected that the electrodynamic effects of dressing and self-consistency via the transverse and longitudinal electric fields will be significant. One important outstanding question associated with this is: will it be possible to use external magnetic fields (*viz.* Feshbach resonances) to manage the interatomic interactions? Another open question is the extent to which strong field effects will be important. This point, which serves as the impetus of the strong field research mentioned earlier, is potentially important in that one photon is sufficient to saturate an isolated atomic transition. Finally, in the high density conditions associated with the Ioffe-Regel condition, the Lorentz-Lorenz correction is large, and it is expected that nonlinear optical effects can be very significant. The study of nonlinear optics alone in this regime promises to be a rich area for future scientific exploration.

In addition to the potential impact of strong localization, recent theoretical work in the weak localization regime suggests a number of additional new areas for research. For example, in detailed numerical simulations of CBS on the resonance transitions in rubidium, Kupriyanov *et al.* [30] have predicted an enhancement factor of less than unity, below the classically expected minimum of unity. This entirely nonclassical effect is due to interference between the transition amplitudes for off-resonance excitation of the D_2 hyperfine manifold with monochromatic radiation. In another arena, Wellens *et al.* [26] have calculated enhancement factors larger than the classically expected maximum of two. This effect is predicted to occur in inelastic two-photon coherent backscattering of light, and to be detectable in the spectrally resolved coherently backscattered intensity. Experimental research in some of these areas will require either large physical samples of cold atoms (or equivalently, large optical depths), or higher atomic density than a magneto optical trap normally provides.

5. Summary

We have reviewed scientific progress in exploration of coherence preservation in multiple light scattering in ultracold atomic gases. In the so called weak localization regime, a wide range of complex and fascinating phenomena have been observed or predicted. At the higher densities associated with strong localization of light, combined long-lived atomic-electromagnetic excitations may occur in ultracold atomic gases. There remain challenging experimental and theoretical problems associated with atomic gases in the strong localization density range; these include the effects of interatomic interactions, nonlinear optical processes, and the collective nature of the atomic-electromagnetic processes.

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