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Quantum Mesoscopic Physics: Coherent Backscattering of Light by Cold Atoms

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Abstract

Propagation in a random medium is often described by a random walk and a diffusion coefficient. However in the mesoscopic regime, where wave properties cannot be neglected, interferences alter the diffusion process leading in extreme situations to strong (Anderson) localisation. The recent observation of coherent backscattering of light by laser cooled atoms has opened the way to new studies in previously not accessible regimes. In this paper we present some of the questions addressed by these experiments, allowing for a more complete understanding of the physical processes involved in this quantum mesoscopic regime.

1 INTRODUCTION

The control of the propagation of light has always been a important issue, starting from the first use of mirrors to the more complex optical fibres. One particular aspect is the storage of light, as one would trap a particle in a box. In one dimension the solution to this problem is a (high finesse) Fabry-Perot cavity, where frequency dependant transmission and reflection coefficients can be associated with a large build-up factor of the electric field in the cavity and a corresponding long decay time of the energy stored inside such a cavity. Extending the idea of a Fabry-Perot cavity to three dimensions has been very difficult, because of the angular dependence of the reflection coefficient of standard mirrors. Nevertheless, in recent years, techniques have been developed to realise the three dimensional equivalent of Bragg mirrors. These photonic crystals (see fig. 1a), are now a very important subject for fundamental and applied research. The principle underlying the existence of photonic bandgaps, i.e. a frequency domain where no propagation of light is allowed, similar to the energy gaps for electron propagation in semi-conductor physics, is the phenomenon of interference between multiply scattered waves.

An alternative approach for wave localisation has been used in a different community, where a random medium is used to multiply scatter the waves [1, 2, 3]. This solution would be more like the trapping in a sponge (fig. 1b), rather than in a regularly shaped box. Despite the apparent mayor difference between a photonic crystal and a random medium, many similarities exist, not only in the resulting cancellation of the propagation of the light wave, but also in the physical origin of the processes involved. The most important common feature is the role of interferences between multiply scattered waves.

Fig. 1. (a)A photonic crystal; (b)a sponge : random equivalent to a box or photonic crystal?

In is likely that exploiting the analogy between photonic crystals and Anderson localisation might lead to useful tools to better understand the wave propagation in random media[4]. As the experimental and theoretical study of photonic crystals are more advanced than those of strongly scattering media, the transfer of knowledge it is probably more directed towards to later community, even though one should not neglect the new concepts developed in the random media community such as random lasers[5, 6]. It is also important to note, that differences that exist between these two fields of research, such as the extensive use of statistical physics for the theoretical treatment or the configuration average for the signal acquisition for random media, can have important consequences. Nevertheless describing strong localisation of waves as the random equivalent of photonic crystals might help to better understand the physics of strong localisation of waves in random media.

One first step to analyse the role of interferences in the propagation of light in random media consists in the study of coherent backscattering, a signature of interference in multiple scattering. Many detailed studies have been performed since the first experiments in the eighties[7, 8, 9]. Using cold atoms as scattering medium has been motivated by the fact that one can have a good control over many important parameters. Since the first observation of coherent backscattering of light by cold atoms[10], many surprising effects have been discovered, either related to the quantum internal structure of the atoms or to the resonance character of the scattering cross section[11]. In this paper, we will briefly describe the principle of coherent backscattering and the characteristics of the backscattering cone (section 2), then turn to the results obtained on a vapour of laser cooled atoms as the random medium and discuss various aspects which can be studied with such a system (section 3).

2 COHERENT BACKSCATTERING

2.1 Principle of coherent backscattering

Coherent backscattering has been described in many references[12, 13, 14], so let us only give a brief summary of the principles. We want to study the situation of multiple scattering of waves, and we will focus here only on electromagnetic waves (light waves) even though most of the following discussion would apply to any other kind of waves, such as matter waves, acoustic or seismic waves.

It is well known that when monochromatic light is elastically scattered from a disordered medium, the detected intensity shows strong fluctuations as a function of the detection angle. This is a result of interferences between all partial waves and is known as speckle pattern. When all these waves are independent random variables, the phases associated with different scattering paths are essentially uncorrelated. This is the case for interferences between different single scattering events and in general also when multiple scattering is involved[15]. It is thus difficult to distinguish in a speckle pattern whether only single scattering or also multiple scattering events are involved.

In the case of a speckle pattern obtained by interference between single scattering events,

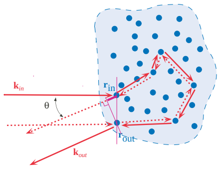

Fig. 2. reciprocal paths in multiple scattering

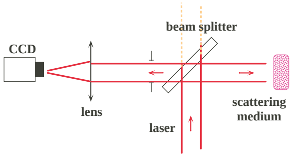

Fig. 3. experimental set-up for detection of coherent backscattering

averaging over the positions of the scatterers will wash out interferences and produces a smooth reflected intensity distribution. However, for multiple scattering, the electric fields are not always independent variables. This is illustrated in fig. 2. Consider two reciprocal paths (full and dotted line in fig. 2). The optical path inside the medium is exactly the same and the phase difference $\Delta\Phi$ corresponding to reciprocal paths can be written as

$$\Delta\Phi = (k_{in} + k_{out}).(r_{in} - r_{out}), \tag{2.1}$$

where, k_{in} (resp. k_{out}) are the incoming (resp. outgoing) wavevector and r_{in} (resp. r_{out}) is the position of the first (resp. last) scatterer involved in one scattering path. In general, this phase is randomly distributed, following the random distribution of r_{in} and r_{out}. However, in the special case when $k_{in} + k_{out} = 0$, i.e. in the backward direction ($\theta = 0$), the phase difference is zero for any spatial distribution of the scatterers! In this case ($\theta = 0$) one will have to add coherently the electric fields two by two (direct and reciprocal paths) which leads to a twicefold enhancement compared to the situation where the intensities would be added ($\theta \neq 0$). This phenomenon is known as coherent backscattering (CBS).

2.2 Observation of coherent backscattering

The experimental observation of CBS is straightforward in principle and a typical set-up is shown in fig. 3. In practise some care has to be taken to eliminate stray light and a well collimated beam is often required to obtain an enhancement factor close to the maximal value of 2.

Using a classical static sample as scattering medium (such as a piece of white paper or piece of teflon), one can observe on the CCD camera the typical speckle pattern : if the camera is placed in the focal plane of the collecting lens, each pixel of the camera corresponds to a scattering direction θ and one immediately obtains the angular intensity distribution of the far field. As mentioned previously it is difficult to extract from such a result (shown in fig. 4a), to know whether single or multiple scattering is dominant. Performing a configuration average, which can be done by rotating the scattering sample and integrating the intensity on the camera, one observes the enhanced backscattering (see fig. 4b), signature of interferences in multiple scattering.

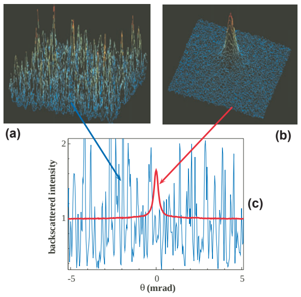

Fig. 4. (a) speckle pattern obtained from a static sample; (b) coherent backscattering cone, obtained after configuration average; (c) line cuts through the pictures (a) and (b)

2.3 Properties of the backscattering cone

Detailed descriptions of the properties of coherent backscattering can be found in many references. We will here only give some useful pictures to illustrate the basic ingredients. As mentioned above, the phase difference between reciprocal paths only depends on the first and the last scatterer. One can thus make an analogy to the interference pattern obtained with a Young double slit experiment. In the case of coherent backscattering, each configuration corresponds to a collection of randomly distributed double slits whose spacing depends on the path length, scaled by the mean free path l. The configuration average amounts to add up independent interference fringes and only the central, white fringe will remain above a flat background. This analogy allows to understand that the width of the coherent backscattering cone, which can be obtained from a more detailed analysis, is given by[16, 17] :

$$\Delta\theta_{CBS} \approx \frac{1}{kl} \tag{2.2}$$

with $k = 2\pi/\lambda$ being the wavevector of the propagating field.

An alternative view of coherent backscattering is to liken CBS to a Sagnac interferometer[18]. Indeed, the two paths followed by the reciprocal waves are identical, very much so as in a closed loop Sagnac interferometer (see fig. 5). There is obviously a difference as in the case of CBS the two loops would formally only be closed outside the scattering medium and in the most common case only in far field where the detection takes place. Such a description of CBS might lead to the proposal of new experiments, as one now has to deal with a multitude of self aligned Sagnac-like interferometers. Let us note, that the known consequence of rotation of a Sagnac interferometer would correspond in a CBS experiment to rotate no only the sample but also the source and the detector. One will hence not be surprised to discover some detailed differences to a real Sagnac interferometer. One interesting question will be the sensitivity of this new kind of Sagnac-like interferometer. In a standard ring configuration, the sensitivity to rotation e.g. is increasing as the area enclosed by the ring cavity. In a CBS type experiment, it is likely to depend on the area of the loops involved. Indeed an important factor is the time needed for a round trip of the wave in the loop (or the corresponding phase shifts for a CW experiment). This time scale can be increased by many orders of magnitude if highly resonant scatterer such as atoms are used[21]. This crude comparison shows that an alternative approach to CBS might lead to a new interpretation with new ideas of exploiting this particular interference effect.

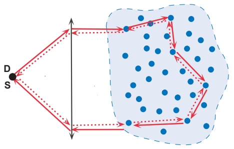

Fig. 5. CBS pictured as a Sagnac interferometer : the source (S) and the detector (D) are the two connecting points of the loop, 'folded' onto each other in practise by using a beam splitter (not shown here)

3 COHERENT BACKSCATTERING AND COLD ATOMS

3.1 Interest of cold atoms for coherent backscattering

Quantum effects in multiple scattering constitute a new challenge. In this respect, atoms are unique candidates as they exhibit quantum features in various ways. Coupling to vacuum fluctuations e.g. is responsible for unusual properties of the scattered light (elastic and inelastic spectra). In our experiments, the scattering medium is are laser-cooled atoms of Rubidium or Strontium atoms which constitute a perfect monodisperse sample of strongly resonant scatterers of light. The quality factor Q of the transition we use is $Q = \nu/\Delta\nu \approx 10^8$. The scattering cross section can thus be changed by orders of magnitude by a slight detuning of the laser frequency. This is a new situation compared to the usual coherent multiple scattering experiments where resonant effects, if any, would be washed out by the sample polydispersivity. Moreover the duration of a single resonant scattering event (delay time) $\tau_D \sim 1/\Gamma$ largely dominates over the free propagation time between two successive scattering events. This leads to an important modification of the dominant ingredients in multiple scattering.

3.2 Observation of coherent backscattering of light by cold atoms

In order to look for coherent backscattering of light by cold atoms, one has to replace the piece of teflon as scattering medium (see fig. 3) by a magneto-optical trap (MOT). Many technical problems (such as switching off the trapping fields) are important and have been described in [10]. Note that in contrary to the experiment with a piece of teflon, we are not able to register a speckle pattern with cold atoms, as the atoms continue to move even at the low temperature obtained by laser cooling techniques, and the detected signal is too small to avoid long integration times. We thus can only observe the averaged signal. This result is shown in fig. 6. The clear enhanced backscattering is the prove that interferences survive in the successive scattering by resonantly driven atoms. This is not a real surprise, as it is known that for low driving fields, the scattering process is elastic and a fixed phase relation between the incident and the scattered field exist. But this results stresses the fact that the scattering of a 'photon' by an atom, even though random in respect to the direction of scattering, does not erase all information of the incident 'photon'.

3.3 Simple classification of physical effects involved in coherent backscattering

The study of CBS with laser cooled atoms allowed us to stress several points of the theoretical discussion on CBS. Let us therefore try to separate the exact process of multiple scattering in different effects. Even though such a separation might not always be rigorous, it might help to get some physical inside in some regimes of particular interest. One attracting description

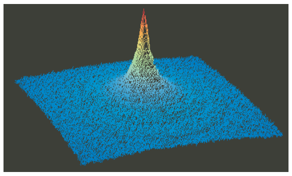

Fig. 6. Angular averaged CBS signal of light by a vapour of cold Rubidium atoms.

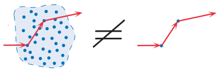

Fig. 7. The double scattering contribution in a multiple scattering medium is different from scattering by a pair of particles : in principle the effective medium has to be considered in the case of multiple scattering

of the processes involved in multiple scattering of waves in a random medium is to consider them as a succession of scattering event, separated by a propagation in an effective medium (see fig. 7). The role of the effective medium can be illustrated by the difference one expects from a situation where one considers double scattering from a pair of atoms in opposition to the contribution to double scattering in a cloud of atoms. The importance of this distinction has been illustrated by an experiment of the role of the magnetic field on CBS with cold atoms [19], where we have shown that the dominant effect is the modification of the differential cross section at the scattering process (known as Hanle effect) rather than the role of the modified effective medium (known as Faraday effect[20]). In all our past experiments on CBS, the role of the effective medium has been negligible. However, in our recent time resolved experiments we have shown that this effective medium cannot always been neglected : the frequency dependence of the transport time has an important contribution from the effective medium [21]. Let us note at this point that the breakdown of the multiple scattering into a succession of scattering followed by propagation events is not likely to be useful in the regime of strong localisation, where the scattering has to take place in the near field. This illustrates the limited range of validity of physical pictures, however efficient and important they are.

Another interesting discussion concerns the contrast (height) of the coherent backscattering cone. As this cone results from two wave interference (between reciprocal paths), the contrast is the depending on the relative amplitude (modulus) of the interfering waves and on their relative phases (in backward direction). In more general terms, the far field signal is the Fourier transform of the near field spatial correlation function. The enhanced backscattering signal is thus evidence of transverse correlation (induced by interferences) of the electric field at surface of the random medium. Again, it is important to keep in mind that a distinction into phase and amplitude effects can have a limited range of validity, as one could imagine situations where correlations between phase and amplitude of reciprocal waves would yield a reduced contrast of coherent backscattering.

3.4 Role of the internal structure of the atoms : an amplitude effect

Even though a unambiguous identification of reduced correlation might not always be straightforward, some situation allow for a clear identification of the phase and amplitude effect on

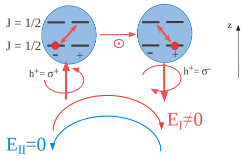

Fig. 8. Simple model to explain the role of the quantum internal structure of the atoms. The 'direct' path (E_I), where the atom in the $m_J = -1/2$ is visited before the atom in the $m_J = +1/2$ has a non zero amplitude in the helicity preserving channel; the reciprocal path (E_{II}) in contrast has zero amplitude.

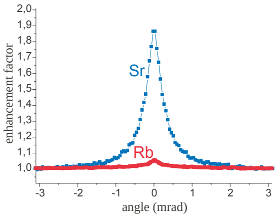

Fig. 9. CBS signal with laser cooled Rubidium and Strontium atoms. In the helicity preserving channel, a drastic reduction due to an amplitude effect based on the quantum internal structure of the atoms is observed

the contrast of coherent backscattering. One such situation is the role of the quantum internal structure of the atoms on the CBS contrast.

In the most simple case, with only one quantum internal state for the ground state of the atom, one expects the maximum contrast in a particular polarisation channel. This has indeed been observed on our experiment with Strontium atoms (see fig. 9). However when atoms can be distributed among several Zeeman levels in the ground state, as in the case of our Rubidium experiments, even in the ideal helicity preserving polarisation channel, the amplitudes of the reciprocal are not identical. Taking as a simple model a $J = 1/2 \to J' = 1/2$ transition (see fig. 8), one can see that the reciprocal amplitudes are different in general as soon as pairs of atoms in different ground states are involved[22]. In this situation, the phases of the two reciprocal waves are exactly compensated in backward direction, so only the amplitude (modulus of the waves) is involved in the resulting reduced backscattering signal. Fig. 9 shows the drastic effect of this amplitude effect.

4 CONCLUSION

We have presented in this contribution some results of coherent backscattering of light by cold atoms and proposed a classification of the various effects involved in multiple scattering. Recent experiments in our group focus on the study of time resolved detection of the multiple scattering and of the role of large driving fields[23], where large saturation parameters should lead to inelastic scattering. These experiments will contribute to a better understanding of the dominant processes involved in multiple scattering of light in laser cooled atoms and constitute important steps towards to observation of strong localisation of light. More experiments will be needed, including the study of the fluctuations of the scattered field, where one could expect to find new signatures of interferences in multiple scattering. A natural extension of these studies will be the atom optic analogue : multiple scattering of matter waves in a random potential, which could be realised by a random light pattern. Such experiments, which will exploit the wave nature of atoms, might require the use of ultra-cold samples such as Bose-Einstein condensates. In this context it will be interested to compare the similarities, but also the fundamental differences between the multiple scattering of light and matter waves.

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