SATURATION EFFECTS IN MULTIPLE SCATTERING OF LIGHT BY COLD ATOMIC GASES

Brainstorming Workshop to be held at Institut Non Linéaire de Nice, Sophia Antipolis (France) from 08 to 10 October 2003. This workshop is organized through GDR 2253 IMCODE of CNRS (directors B. van Tiggelen & A. Derode) by D. Delande (delande@spectro.jussieu.fr) & Ch. Miniatura (christian.miniatura@inln.cnrs.fr).

During the last few years, large experimental and theoretical interest has been devoted to multiple scattering in gain media, be it in the localized or diffusive regime ("random lasing"). Atomic media such as cold gases offer interesting potentialities in this growing field and constitute model systems since it is relatively easy to induce $\chi^{(3)}$ non-linearities and gain by saturating the optical atomic transition. However there is an important difference with the systems studied so far : atoms both constitute the gain and the scattering medium. Light scattering becomes an intrinsic non-linear process where many photons are involved. Apart from usual phenomena like non-linear reduction of the scattering cross-section (bleaching) or non-linear optical index effects (Kerr effect), it appears that light scattering is no longer perfectly elastic. The radiated spectrum contains an inelastic broad component (Mollow triplet) which may dominates over the elastic component and which may alter the interference processes at work in multiple scattering. The role of this inelastic component is neglected in most theoretical models of random lasing. Understanding the role of these different mechanisms, directly connected to the peculiarities of the atom-light interaction, is particularly important, especially in the strongly localized regime where the localized light could saturate the atomic transition.

The aim of this brainstorming workshop is thus to gather specialists of multiple scattering to discuss the potentialities and the relevant physical processes at work in these systems and to build the best theoretical and experimental tools.

PROGRAMME

WEDNESDAY 08/10/03

9h30-10h30 : Coffee break
10h30-11h15 : Benoît Gremaud
11h30-12h15 : David Wilkowski
12h30-14h : Lunch
14h-14h45 : Guillaume Labeyrie
15h-15h30 : Coffee break
15h30- (...) : FAQ, forum, discussions ...

THURSDAY 09/10

9h30-10h : Coffee break
10h-10h45 : Thomas Wellens
11h-11h45 : Slava Shatokhin
12h-14h : Lunch
14h-14h45 : Ad Lagendijk
15h-15h30 : Coffee break
15h30- (...) : FAQ, forum, discussions ...

FRIDAY 10/10

9h30-10h : Coffee break
10h-10h45 : Christian Vanneste
11h-11h45 : Sergey Skipetrov
12h-14h : Lunch
14h-14h45 : Igor Sokolov
15h-15h30 : Coffee break
15h30- 16h30 : Concluding remarks

Coherent backscattering in nonlinear atomic media
Benoît Grémaud, LKB (Paris).

Recent works (from both theoretical and experimental points of view) on the weak localization of light by cold atoms have been achieved in the low field limit and have emphasized the impact of the quantum internal structure (Zeeman sub-levels). For higher laser intensity (saturation parameter of the order of unity), nonlinear response of the atoms occurs, giving rise to inelastic scattering. Starting from the coupled Maxwell-Bloch equations and outlining the difficulties arising from the nonlinearity, I will discuss the possible approaches to describe the properties of light propagation. Especially, in the case of two-level atoms and a scalar field, I will show (partial) results, emphasizing the reduction of the enhancement factor with increasing laser intensity. Also, different configurations are discussed, such as pump-probe experiments.

CBS on the J=0 - J=1 saturated strontium transition
David Wilkowski, LOD (Valbonne).

I will present our recent CBS experiments with a cold sample of strontium atoms, done by saturating the optical transition at $461nm$. The most surprising result is a strong reduction of the CBS enhancement factor when the saturation is increased. I will explain in details how we perform the experiment in order to remove the trivial reduction due to single scattering. I will conclude by giving physical mechanisms that could be at the origin of this reduction.

Coherent backscattering and saturation in a laser-cooled Rubidium vapor
Guillaume Labeyrie, LOD (Valbonne).

I will summarize our experimental observations on the effect of saturation on coherent backscattering (CBS) of light by a cloud of ultra-cold Rubidium atoms. The differences, both fundamental and experimental, with the case of Strontium will be discussed.

Multiple scattering of two photons
Thomas Wellens, LOD (Valbonne) & LKB (Paris).

Whereas the scattering of a very weak laser field by a gas of cold atoms can be successfully described by a single photon, those processes where two photons are scattered by the same atom contribute to the next highest order in the incoming intensity. In general, such processes change the photon frequencies, giving risen to an inelastic component of the power spectrum. As a simple toy model, we first calculate coherent backscattering of two photons by two atoms in free space. A reduction of the backscattering enhancement factor is found, due to inelastically scattered photons. Furthermore, we consider the propagation of the average field amplitude in a disordered medium of atoms, whose nonlinear susceptibility is shown to result from two-photon scattering processes.

Master equation approach to coherent backscattering of light by cold atoms
Slava Shatokhin, MPIPKS (Dresden).

Cold atomic gases are known to provide experimentally perfectly controlled conditions for the study of coherent backscattering (CBS) of light from quantum scatterers. Since CBS is a fragile interference

phenomenon, it can be amended by different mechanisms. Here, we investigate the impact of the laser-induced saturation on the CBS enhancement factor alpha. Our approach is built on a perturbative expansion of the interatomic coupling via a common bath, in the general formulation of the master equation, and allows to fully incorporate the vectorial character of the scattered field modes. In the first step, we solve the simpler problem of nondegenerate internal level structure of the atoms (equivalent to a scalar radiation field) and derive explicit expressions for the dependence of alpha on the saturation parameter s. Furthermore, we shall outline our approach for solving the vectorial problem.

Point dipoles as model for objects varying from Mie spheres to atoms in media with gain

Ad Lagendijk, Twente (The Netherlands).

We will outline envisaged experiments on a collection of a finite number of Mie spheres that will show lasing (random lasers). Point dipole models turn out to be very useful to describe these optical experiments. Gain and saturation can also be incorporated. After reviewing these models we will indicate their shortcomings. In addition we will present a wishlist for possible extensions of these models.

Random laser in the strong scattering regime

Christian Vanneste, LPMC (Nice).

Laser action in the strong scattering regime is studied numerically in a 2D random system of circular particles by coupling the Maxwell's equations with the rate equations of a four level atomic system. When pumping the active medium above threshold, the lasing modes are found to be identical to the localized modes of the system without gain. In many aspects, the spatial, spectral and time properties of the random laser are identical to those observed in a conventional laser.

Instability of optical speckle patterns in cold atomic gases ?

Sergey Skipetrov, LPM2C (Grenoble).

For a sufficiently intense optical wave propagating in a material medium, the relation between polarization of the medium P(r,t) and electric field of the wave E(r,t) is nonlinear, namely P = chi(E)E, where the susceptibility chi depends on E. If the medium is heterogeneous (disordered), the wave is scattered, giving rise to "speckles" - random distribution of wave field E(r,t) and intensity I(r,t) in space. Because chi is a function of E, speckles are induced in chi as well. This leads to a kind of distributed feedback mechanism for E(r,t). As any radio-physical system with a feedback mechanism, the system "optical wave - nonlinear disordered medium" can become unstable for nonlinearity exceeding a certain threshold. The instability may manifest itself by producing spontaneous variations of the speckle pattern I(r,t) with time despite stationary (i.e. monochromatic) incident wave and unchanging experimental conditions. Instead of being time-independent "fingerprint" of disorder, as in the linear case, I(r,t) may exhibit spontaneous and (very likely) chaotic dynamics. The physics of instability development is substantially different in diffuse (mean free path >> wavelength) and localized (mean free path < wavelength) regimes. We concentrate on the diffuse regime which is more frequently realized in experiments, but also mention the basic features of the instability phenomenon that should be expected for localized waves. Instability of optical speckle patterns in nonlinear disordered media has never been observed up to now. A medium required for its observation should have important scattering coefficient, strong third-order nonlinear susceptibility, and low absorption at a time. We discuss the possibility of fulfilling all these three conditions in a gas of cooled atoms for a near-resonant incident wave. The basic physics of light scattering in such a gas can be captured in the two-level approximation that allows us to express the phenomenological parameters of our instability theory (mean free path, nonlinear susceptibility, absorption coefficient) to microscopic parameters of the atomic gas (Rabi frequency, detuning factor, relaxation times, etc.). Finally, we comment on a more general self-consistent approach to description of interaction of light with a gas of atoms that accounts not only for scattering of light by atoms but also for "scattering" of atoms by light. Curiously, the latter "scattering" of particles (usually treated as "scatterers") by electromagnetic potential (light, usually treated as a "non-invasive" wave) can be observed even in the case of macroscopic (colloidal) particles and should certainly play an important role in light-scattering experiments in atomic gases.

Coherent backscattering of non-monochromatic light in an ensemble of ultracold polarized atoms

Igor Sokolov, Polytechnic University (St-Petersburg).

Long term interaction of intense but non-saturated polarized radiation with an ensemble of cold atoms confined to a magneto-optic trap leads to some inevitable consequences such as heating, optical pumping and accumulation of a number of non-resonant photons, coming originally from the radiation spectral wings. The consistent analysis of all these supplementary, but not negligible, processes under real experimental conditions is a rather sophisticated theoretical task. As a first approximation, we consider the probe radiation as a weak light source scattered by an atomic sample, which has been previously heated and polarized by an auxiliary light source. We discuss coherent backscattering of light and, in the weak localization regime, consider several effects associated with the finite bandwidth of the probe light spectrum and with the angular momentum atomic polarization. In our calculations, we follow the Keldysh diagram method, which is normally successfully used in studying non-equilibrium systems by means of a second quantized formalism in quantum electrodynamics approach. It let us express the final results in terms of such well defined objects of the theory as the photon correlation function associated with scattered light, single-particle atomic density matrix and the Green propagation functions of the light. The retarded- or advanced-type Green functions, responsible for light propagation between the scatterers, were derived under rather general assumptions, which basically describe the forward coherent scattering in an effective non-homogeneous medium consisting of moving atoms, non-equally populated their Zeeman sublevels. In our calculations we maintained the theoretical approach originally developed by Cohen-Tannoudji et al [J. de Phys. 1967. V. 28 P. 505; ibid P. 722] for an optically thin sample, which was modified and extended for conditions of optically dense medium. According to a general quasi-particle conception, the Green function was found as a solution of definite type Dyson equation. In some practically important cases this equation can be solved *analytically*. Based on this analytical solution, there were analyzed the angular dependencies of the cross section responsible for multiple scattering as well as the correlation and spectral properties of the scattered light. It also made it possible to look at the dynamical evolution of the scattering pulse, particularly at the time dependence of the afterglow of atomic clouds after the external radiation was switch off.