Coherent light scattering from a disordered ensemble of cold atoms

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Improvements in techniques for cooling atoms in atomic traps [1] make their use very promising for practical applications in various areas of fundamental science and technology such as metrology, the development of frequency standards, and quantum information problems [2–3]. The vast majority of these applications presuppose usage of optical detection methods which are based on analysis of radiation scattered from an atomic ensemble. Among these methods ones based on measurements of coherent reflection have a range of advantages.

Coherent light reflection from an ensemble of cold atoms is possible only if the atomic density is sufficiently big so that $n\lambda^3 \sim 1$ (n is the atomic density and λ is the resonant wavelength). In this case atoms can not be considered as independent scatters of electromagnetic waves. Interatomic dipole-dipole interaction significantly influences on the optical characteristics of a medium.

For theoretical description of light scattering from dense and cold atomic ensemble we use the consequent quantum microscopic approach [4] in which the amplitude of scattered light is calculated as sum of individual contributions from all the atoms. This approach is based on solution of nonstationary Schrodinger equation for the wave function ψ of the joint system consisting of atoms and electromagnetic field. The Hamiltonian of the system H can be presented as the sum of the Hamiltonians H_0 of the free atoms and the free field, and the operator V of their interaction. We use dipole approximation and seek the wave function ψ as an expansion in a set of eigenstates of H_0.

Probe radiation is assumed to be weak coherent plane wave so that we can approximate its state as a superposition of vacuum and a small admixture of one-photon state. It allows us to restrict the total number of states of the joint system taken into account by the set of states with no more than one photon, see [4] for detail. This set consists of a infinite number of states but we can pick out the finite system of equations for the one-fold atomic excited states. Other states can be calculated via one-fold atomic excited states. Thus, we obtain the wave function ψ which allows us to calculate any characteristics of the scattered light and atomic ensemble.

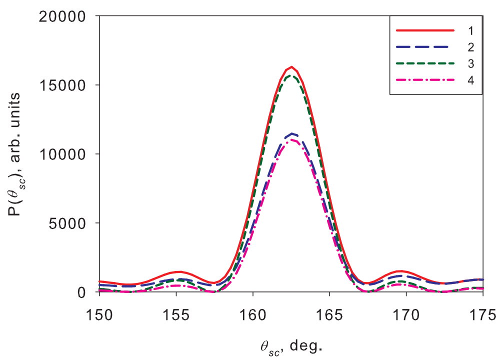

Figure 1: *Angle distribution of the scattered light power $P(\theta_{sc})$. 1, 3 s-polarization; 2, 4 p- polarization; 1, 2 total; 3, 4 coherent component*

The approach employed here allows us to consider atomic ensembles with different shapes and with arbitrary atomic spatial distributions. In the present work we focus our attention on the coherent reflection. For this purpose we consider model plane layer with uniform distribution of atomic density. We analyze main regularities of the reflection, particularly angular distribution of reflected light, the ratio between coherent and incoherent components of scattered light, the depth of subsurface layer responsible for the coherent reflection, and the reflectivity for different angles of incidence and polarizations. Our analysis reveals a discrepancy between microscopic calculations and the Fresnel equations. In our opinion, it can be explained by the fact that for resonant light the mean free path of photon is comparable with the average interatomic distance. As example of our calculation in Fig. 1 we show angular distribution of light reflected from a plane surface of ensemble. Probe light is exactly resonant to the transition of a free atom, the angle of incidence $\theta_0 = 17.5°$. The maximum of all the curves in Fig. 1 corresponds to the classical reflection angle as predicted by classical theory.

References

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