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Light localization in cold and dense atomic ensemble

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Abstract. We report on results of theoretical analysis of possibilities of light strong (Anderson) localization in a cold atomic ensemble. We predict appearance of localization in dense atomic systems in strong magnetic field. We prove that in absence of the field the light localization is impossible.

The analysis of possibilities of light strong (Anderson) localization in a cold atomic ensemble is based on the consistent quantum-posed theoretical approach developed previously in [1]. In the frame of this approach we solve nonstationary Schrodinger equation for the wave function of the joint system consisting of N motionless atoms and the weak electromagnetic field. We take into account vector nature of the field and do not introduce any model of continuous media. Restriction of the total number of states taken into account by the states with no more than one photon in the field allows us to obtain finite set of equation for Fourier component of amplitudes of states with one excited atom. This set of equation is solved numerically and amplitudes of the other states are calculated through found ones. The procedure gives us opportunity to find approximately the wave function of the system and consequently analyze both the properties of atomic system and the light. This approach was successful used in various applications [2]-[4].

To analyze the possibilities of strong localization at first we studied the fulfillment of Ioffe-Regel criterion [5]. For this purpose we calculated dispersion of dielectric susceptibility of cold atomic gases [6]. We showed that there was a spectral region where the photon mean free path was less than its wave length, i.e. where the criterion was satisfied. The fulfillment of the Ioffe-Regel criterion is likely a necessary, but not sufficient condition for strong localization. A clearer answer to the question about light localization in cold gases can be obtained by means of analysis of the incoherent radiation transfer in such gases. We studied the light transport and trapping in cold dense atomic clouds by several ways [7]-[9]. Particularly we have analyzed

(i) Afterglow dynamics of clouds excited by pulse radiation.
(ii) Spatial distribution of atomic excitation in quasi homogeneous ensemble caused by monochromatic coherent light.
(iii) Transmission coefficient of the cloud for different conditions.
(iv) Statistical properties of atomic excitation and light transmission.

This analysis showed no noticeable signs of light strong localization effects, even in those parameter regions where the Ioffe-Regel criterion of strong localization was satisfied. However, a comparative calculation performed in the framework of the often-used scalar approximation to the dipole-dipole interaction displayed explicit manifestation of strong localization for some conditions. This result was confirmed in the frame of scaling theory of localization [10]. Analysis of the Thouless number based on calculation of collective eigenstates of cold atomic ensemble, as well as analysis of their spatial localization based on calculation of inverse participation ratio showed that strong localization of light cannot be achieved in a random three-dimensional ensemble of atomic scattering [11]. Localization is reclaimed if the vector character of light is neglected. Performed calculations demonstrate the importance of the vector character of electromagnetic waves in the context of the Anderson localization problem and elucidate the role of resonant dipole-dipole interactions in multiple light scattering. At the same time they cause to anticipate that suppressing this interaction can open the way to localization. Our analysis shows that static magnetic field giving rise to Zeeman splitting changes the nature of atomic exchange of photons in the ensemble and essentially modifies resonant dipole-dipole interatomic interaction [12] (see also [13]). This effect influences strongly on light trapping. The efficiency of magnetic field depends on specific type of optically excited atomic transition, particularly on magnetic quantum numbers of quasi resonant states. We found out appearance of long lived polyatomic collective states which lifetimes essentially exceed those take place in the absence of magnetic field. Calculation of inverse participation ration shows that these states are localized. Scaling analysis of collective eigenstates distribution revealed that, in many aspects, this distribution exhibits the behavior expected for the Anderson transition driven by disorder [13]. On the basis of our approach we analyze also the possibility to observe manifestation of these long-lived localized states in experiment. We study the dynamics of fluorescence of atomic clouds initiated by pulse radiation. For an appropriate choice of frequency and polarization of the exciting pulse, the field is expected to speed up the fluorescence of a dilute atomic system. In a dense ensemble, the field does not affect the early-time superradiant signal but amplifies intensity fluctuations at intermediate times and induces a very slow, nonexponential long-time decay [14]. We analyze as well the influence of magnetic field on the steady-state transmission of plain layer of motionless atomic scatterers.

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