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NON-CONSERVATION OF POLARITONS AS A MECHANISM OF LIGHT-ENERGY CAPTURING

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In the systems which do not conserve the total number of quasiparticles (or particles) there exist many interesting processes. One of these is the capability of such systems to capture and conserve light-energy. In this paper the system of polaritons is analysed, and the calculations show that the effect of absorption and conservation of light-energy is more pronounced than in the case of exciton system.

1. Introduction

In the previous paper[1] we examined some consequences related to nonconservation of the total number of excitons. Among other interesting phenomena, which occur in such systems, there is the capability of capturing and conserving light-energy.

In this paper we choose the system of polaritons which is, as we know, much more realistic, to investigate the phenomenon of light-energy capturing.

2. Time dependence of quasiparticle numbers

Using the unitary transformations:

$$B(\vec{k}, t) = \sum_{\varrho=1}^{2} [u_\varrho^e(\vec{k})\, \xi_\varrho(\vec{k}, 0)\, e^{-i\Omega_\varrho(\vec{k})t} + v_\varrho^{e*}(-\vec{k})\, \xi_\varrho^+(-\vec{k}, 0)\, e^{i\Omega_\varrho(\vec{k})t}]$$

$$a(\vec{k}, t) = \sum_{\varrho=1}^{2} [u_\varrho^f(\vec{k})\, \xi_\varrho(\vec{k}, 0)\, e^{-i\Omega_\varrho(\vec{k})t} + v_\varrho^{f*}(-\vec{k})\, \xi_\varrho^+(-\vec{k}, 0)\, e^{i\Omega_\varrho(\vec{k})t}]$$

$$\Omega_\varrho = \frac{E_\varrho}{\hbar}, \tag{1}$$

we can pass to the polariton operators. Index ε here means exciton's part, and f photon's part. B and a are exciton and photon operators, respectively.

Inverse transformation is:

$$\xi_\varrho(\vec{k}, 0) = u_\varrho^{\varepsilon*}(\vec{k})\, B(\vec{k}, 0) - v_\varrho^\varepsilon(-\vec{k})\, B^+(-\vec{k}, 0) + u_\varrho^{f*}(\vec{k})\, a(\vec{k}, 0) -$$

$$- v_\varrho^f(-\vec{k})\, a^+(-\vec{k}, 0). \tag{2}$$

In this way, time-dependent numbers of excitons and photons can be expressed by the operators in the moment $t = 0$.

The expressions obtained are too cumbersome to quote, so we will write down only the parts without the operators, i. e., nonhomogeneous parts. These terms give the contributions even if we take vacuum state.

$$[B^+(\vec{k}, t)\, B(\vec{k}, t)]_{nh} = \sum_{\varrho\varrho'} [v_\varrho^\varepsilon(-\vec{k})\, v_{\varrho'}^{\varepsilon*}(-\vec{k})\, \delta_{\varrho\varrho'}\, e^{-i\Omega_\varrho(\vec{k})t + i\Omega_\varrho(\vec{k})t} + (u_\varrho^{\varepsilon*}(\vec{k})\, u_{\varrho'}^\varepsilon(\vec{k}) +$$

$$+ v_{\varrho'}^\varepsilon(k)\, v_\varrho^{\varepsilon*}(k))\, (v_\varrho^{\varepsilon*}(-\vec{k})\, v_{\varrho'}^\varepsilon(-\vec{k}) + v_\varrho^{f*}(-\vec{k})\, v_{\varrho'}^f(-\vec{k})) \cdot e^{i\Omega_\varrho(\vec{k})t - i\Omega_{\varrho'}(\vec{k})t} -$$

$$- v_\varrho^\varepsilon(-\vec{k})\, u_{\varrho'}^\varepsilon(\vec{k})\, u_\varrho^{\varepsilon*}(-\vec{k})\, v_{\varrho'}^\varepsilon(-\vec{k})\, e^{-i\Omega_\varrho(\vec{k}) - i\Omega_{\varrho'}(\vec{k})t} - v_\varrho^\varepsilon(-\vec{k})\, u_{\varrho'}^\varepsilon(\vec{k})\, u_\varrho^{f*}(\vec{k})\, v_{\varrho'}^f(-\vec{k}) \cdot$$

$$\cdot e^{-i\Omega_\varrho(\vec{k})t - i\Omega_{\varrho'}(\vec{k})t} - u_\varrho^{\varepsilon*}(\vec{k})\, v_{\varrho'}^{\varepsilon*}(-\vec{k})\, v_\varrho^{\varepsilon*}(-\vec{k})\, u_{\varrho'}^\varepsilon(-\vec{k})\, e^{i\Omega_\varrho(\vec{k})t + i\Omega_{\varrho'}(\vec{k})t} -$$

$$- u_\varrho^{\varepsilon*}(\vec{k})\, v_{\varrho'}^{\varepsilon*}(-\vec{k})\, v_\varrho^{f*}(-\vec{k})\, u_{\varrho'}^f(\vec{k})\, e^{i\Omega_\varrho(\vec{k}) + i\Omega_{\varrho'}(\vec{k})t}]$$

$$[a^+(\vec{k}, t)\, a(\vec{k}, t)]_{nh} = \sum_{\varrho\varrho'} [v_\varrho^f(\vec{k})\, v_{\varrho'}^{f*}(\vec{k})\, \delta_{\varrho\varrho'}\, e^{-\Omega_\varrho)\vec{k})t + i\Omega_{\varrho'}(\vec{k})t} + (v_\varrho^{\varepsilon*}(-\vec{k})\, v_{\varrho'}^\varepsilon(-\vec{k}) +$$

$$+ v_\varrho^{f*}(-\vec{k})\, v_{\varrho'}^{f*}(-\vec{k}))\, (u_\varrho^{f*}(\vec{k})\, u_{\varrho'}^f(\vec{k}) + v_\varrho^f(\vec{k})\, v_{\varrho'}^{f*}(\vec{k}))\, e^{-i\Omega_\varrho(\vec{k})t + i\Omega_{\varrho'}(\vec{k})t} -$$

$$- (u_\varrho^{\varepsilon*}(-\vec{k})\, v_{\varrho'}^\varepsilon(-\vec{k}) + u_\varrho^{f*}(-\vec{k}))\, v_{\varrho'}^f(-\vec{k})\, v_\varrho^f(-\vec{k})\, u_\varrho^f(\vec{k})\, e^{-i\Omega_\varrho(\vec{k})t - i\Omega_{\varrho'}(\vec{k})t} -$$

$$- u_\varrho^{f*}(\vec{k})\, v_{\varrho'}^{f*}(-\vec{k})\, (v_\varrho^{\varepsilon*}(\vec{k})\, u_{\varrho'}^\varepsilon(\vec{k}) + v_\varrho^{f*}(\vec{k})\, u_{\varrho'}^f(\vec{k}))\, e^{i\Omega_\varrho(\vec{k})t + i\Omega_{\varrho'}(\vec{k})t}]. \tag{3}$$

For the functions u and v we will assume that they are real and even. They can be determined from the system of equations (see Ref. 2):

$$[E^e(\vec{k}) - \varepsilon_\varrho(\vec{k})]\, u_\varrho^e(\vec{k}) + |T|\, [u_\varrho^f(\vec{k}) + v_\varrho^f(-\vec{k}) = 0$$

$$[E^e(\vec{k}) + \varepsilon_\varrho(\vec{k})]\, v_\varrho^e(\vec{k}) - |T|\, [u_\varrho^f(\vec{k}) + v_\varrho^f(-\vec{k})] = 0$$

$$[E^f(\vec{k}) - \varepsilon_\varrho(\vec{k})]\, u_\varrho^f(\vec{k}) - |T|\, [u_\varrho^e(\vec{k}) - v_\varrho^e(-\vec{k})] + \frac{\hbar\,\omega_0^2}{2kc}\, [u_\sigma^f(\vec{k}) + v_\varrho^f(-\vec{k})] = 0 \tag{4}$$

$$[E^f(\vec{k}) + \varepsilon_\varrho(\vec{k})]\, v_\varrho^f(\vec{k}) - |T|\, [u_\varrho^e(\vec{k}) - v_\varrho^e(-\vec{k})] + \frac{\hbar\,\omega_0^2}{2kc}\, [u_\delta^f(\vec{k}) + v_\varrho^f(-\vec{k}) = 0$$

$$[u_\varrho^e(\vec{k})]^2 - [v_\varrho^e(\vec{k})]^2 + [u_\varrho^f(\vec{k})]^2 - [v_\varrho^f(\vec{k})]^2 = 1$$

$$|T| = \sqrt{\frac{2\pi N}{V\hbar c k}}\, E_a(\vec{d}^a\, \vec{e}_{kj}).$$

N is the number of elementary cels in a volume V, d is the electric dipole moment of the transition from the ground state to the a excited state, and ε_ϱ are polariton energies.

The solution of this system is:

$$v_\varrho^e(\vec{k}) = \frac{\varepsilon_\varrho(\vec{k}) - E^e(\vec{k})}{\varepsilon_\varrho(\vec{k}) + E(\vec{k})}\, u_\varrho^e(\vec{k}), \qquad \mathscr{F} = \frac{\hbar\,\omega_0^2}{2kc}$$

$$v_\varrho^f(\vec{k}) = \frac{(\varepsilon_\varrho^2(\vec{k}) - E^{e2}(\vec{k}))\,(E^f(\vec{k}) - \varepsilon_\varrho(\vec{k}) + \mathscr{F}) - 2|T|^2 E^e}{|T|\,(E^f(\vec{k}) - \varepsilon_\varrho(\vec{k}) + 2\mathscr{F})\,(\varepsilon_\varrho(\vec{k}) + E^e(\vec{k}))}\, u_\varrho^e(\vec{k})$$

$$u^f(k) = \frac{2\,|T|^2\, E^e(\vec{k})\,(E^f(\vec{k}) - \varepsilon_\varrho(\vec{k}) + 2\mathscr{F}) + (\varepsilon_\varrho^2(\vec{k}) - E^{e2}(\vec{k}))}{|T|\,(E^f(\vec{k}) - \varepsilon_\varrho(\vec{k}) + \mathscr{F})\,(\varepsilon_\varrho(\vec{k}) + E^e(\vec{k}))\,(E^f(\vec{k}) - \varepsilon_\varrho(\vec{k}) + 2\mathscr{F}}\,\cdot$$

$$\cdot\, ((E^f(\vec{k}) - \varepsilon_\varrho(\vec{k}) + \mathscr{F}) - 2\,|T|^2\, E^e(\vec{k})\mathscr{F})\, u_\varrho^e(\vec{k}). \tag{5}$$

In the following we will use the approximations:

$$E^e \approx E^f \approx \Delta, \quad \varepsilon_1 = \Delta + |T|, \quad \varepsilon_2 = \Delta - |T| \tag{6}$$

$$|T| \ll \Delta, \qquad |T| \ll \mathscr{F},$$

where Δ is the excitation energy of an isolated molecule ($\Delta \sim 5$ eV).

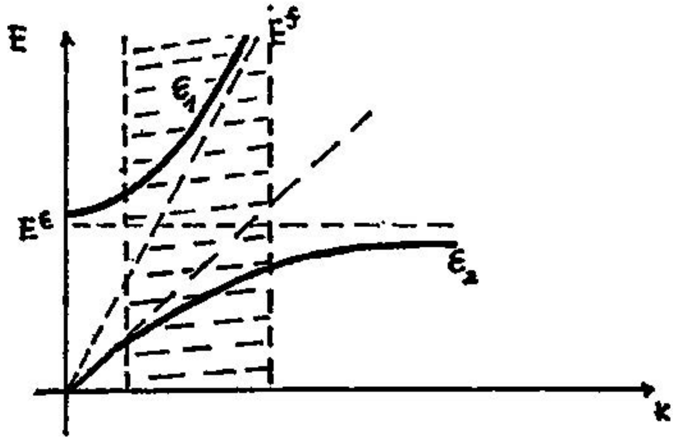

Fig. 1. The dispersion laws for the excitons (E^ε), photons (E^f) and polaritons (ε). The shaded area is the area of resonance, for which the employed approximations are valid.

For the functions u and v we have:

$$v_1^\varepsilon(\vec{k}) = \frac{|T|}{2\Delta}, \quad v_2^\varepsilon(k) = -\frac{|T|}{2\Delta}, \quad v_1^f = \frac{1}{2}, \quad v_2 = \frac{1}{2}. \tag{7}$$

With these approximations, for the absorbed energy we have:

$$A(E^\varepsilon) = N\Delta \left\{ \frac{|T|^2}{\Delta^2} \left[1 - \cos \Omega_1 t - \cos 2\Omega_2 t - \frac{1}{2} \cos(\Omega_1 - \Omega_2) t + \right.\right.$$

$$\left.\left. + 2\cos(\Omega_1 + \Omega_2) t - \frac{|T|}{2\Delta} [\cos 2\Omega_1 t + \cos 2\Omega_2 t - 2\cos(\Omega_1 + \Omega_2) t] \right\}\right. . \tag{8}$$

$$A(E^f) = N\Delta \left\{ 1 - \frac{1}{2} [\cos \Omega_1 t + \cos \Omega_2 t - 2\cos(\Omega_1 + \Omega_2) t + \right.$$

$$\left. + \frac{|T|^2}{2\Delta^2} [1 - \cos 2\Omega_1 t - \cos 2\Omega_2 t - \cos(\Omega_1 - \Omega_2) t + 2\cos(\Omega_1 + \Omega_2) t] \right\}.$$

If we take

$$\Omega_1 = \Delta_\Delta + \Omega_T, \quad \Omega_2 = \Omega_\Delta - \Omega_T, \quad \Omega_\Delta = \frac{\Delta}{\hbar}, \quad \Omega_T = \frac{|T|}{\hbar}, \quad \Omega_\Delta \gg \Omega_T, \tag{9}$$

these expressions become:

$$A(E^s) = N\Delta \left\{ \frac{|T|^2}{\Delta^2} \left[1 - 2\cos 2\Omega t \cos 2\Omega_T t - \frac{1}{2}\cos 2\Omega_T t + 2\cos 2\Omega t \right] - \right.$$

$$\left. - \frac{|T|}{\Delta} \cos 2\Omega t \cos 2\Omega_T t - \cos 2\Omega t \right]\Big\}. \qquad (10)$$

$$A(E^f) = N\Delta \left\{ 1 - \frac{1}{2} [2\cos \Omega t \cos \Omega_T t - \cos 2\Omega t] + \right.$$

$$\left. + \frac{|T|^2}{2\Delta^2} [1 - 2\cos \Omega t \cos \Omega_T t + 2\cos \Omega t - \cos 2\Omega_T t] \right\}.$$

For $t = 0$ we have:

$$A^{t=0}(E^f) = \frac{1}{2} N\Delta, \quad A^{t=0}(E^e) = \frac{1}{2} \frac{|T|^2}{\Delta^2} N\Delta, \qquad (11)$$

that is, the absorbed energy by the system is:

$$A^{t=0} = \left[\frac{1}{2} N + \frac{1}{2} \frac{|T|^2}{\Delta^2} N \right] \Delta. \qquad (12)$$

From these relations it can be concluded that the absorbed energy, by the polariton system, is greater than in the case of exciton system.

In the moment $t = 0$, more than half of the atoms of the lattice has absorbed light-energy (in exciton system every tenthousandth atom absorbed the energy). We see also that transversal vacuum photons are mainly absorbed, whereas the percentage of excitons being absorbed is approximately the same as in the case without retarded interaction.

The main mechanism of nonconservation of photons comes out from the square of vector-potential (ω_0 is plasmonic frequency). Taking into account the approximations in these calculations, it is not quite probably sure that every second atom absorbs the energy, and there exists reason to believe that relatively high percent of atoms do so. The approximations used are good in the domain which is about a hundreth part of the Brillouin zone, and the results obtained would need a factor $\sim 10^{-2}$.

3. *Conclusion*

This analysis shows that in the case of a more realistic system such as polaritons, the effect of absorption and conservation of light energy is more pronounced than is the case of exciton systems. Part of this energy is probably[3)] used for various processes in living matter, such as selforganisation, growth, etc.

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NEODRŽANJE POLARITONA I ZAHVAT SVJETLOSNE ENERGIJE

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Jedan od interesantnih procesa koji se događaju u sistemima koji ne održavaju ukupan broj kvazičestica (ili čestica), je zahvat svjetlosne energije. Jedan dio te energije ostaje u sistemu, i pretpostavlja se da ima važnu ulogu u procesima u živoj materiji. Do sada se koristio sistem eksitona kao pogodan model sistema čiji operator ukupnog broja kvazičestica ne komutira sa hamiltonijanom. Zahvaćena energija je od 50 KeV do 5 MeV. U ovom radu je ista ideja primijenjena na realniji sistem polaritona, za koji se pokazuje da je zahvaćena energija veća.