Clustering of the electron-hole liquid

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Abstract

Free excitons created in semi-metals and semiconductors under irradiation of light may condense into an electron-hole liquid when their density is large enough. This quantum phenomenon has been intensively studied theoretically and experimentally. The exciton gas undergoes Mott's metal insulator phase transition at much lower density. This mismatch between the critical value of the density for the instability of the free excitons and the threshold value of the density for the appearance of the electron–hole liquid stimulated a controversial dispute over a decade of what arises in the range of densities between these two critical values. We show that a new structural liquid consisting of the charged clusters can be formed where each cluster is like a molecule consisting of different numbers of electrons and holes.

Key words: clusters; electron-hole liquid; excitons; phase diagram

1. Introduction

It is well established that in semiconductors under irradiation of light the mixture of electrons and hole is created.[1] At low densities it is in the form of exciton gas, where an electron and a hole or a small number of them are bound together. When the density increases above the critical value the system undergoes a phase transition into a liquid phase.[2] In a long series of carefully analysed measurements of the luminescense spectra in Si Smith and Wolfe [3] found a third phase, which they called a condensed plasma phase (CP). It is also a liquid like phase because the density remains roughly constant with increasing temperature.

In this work we present a microscopic many-body theory based on a variational Jastrow–Feenberg wave function which is very accurate in strongly correlated but dilute mixtures. The perfect screening of the Coulomb interaction at long distances is naturally embedded into this method. The attraction between two impurities induced by the many-body effects due to the non-monotonic screening becomes at intermediate ranges stronger than the Coulomb repulsion. At the critical density it is strong enough to bind clusters of impurities. This may indicate a phase transition into a mixture of charged clusters. The condensed plasma phase observed by Wolfe and Smith[3] may be related to our finding.

2. Phases of charged mixtures

We study positively charged particles of mass m_h embedded among negatively charged particles with mass m_e. The ionic background is assumed to be structureless jellium, but its charge neutralizes the charge of the mixed particles. One positive impurity collects around a screening cloud of negative particles and their distribution is determined by the radial distribution function $g^{(he)}(r)$. Near the impurity the distrubution is strongly peaked and in the case of a positron the height of the peak is measured by the annihilation rate $\lambda = \frac{12}{r_s^3} g^{(he)}(r=0) 10^{-9} \frac{1}{s}$.

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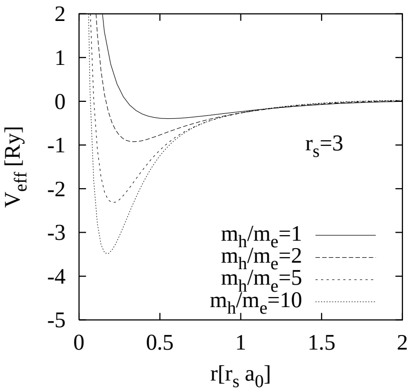

Fig. 1. The effective interaction between positive impurities in the electron gas at $r_s = 3$ for impurity masses marked in the figure.

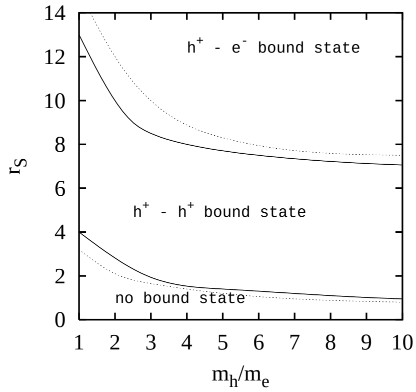

Fig. 2. The phase diagram of impurities, marked with h^+, in the charged Bose gas (dotted curves) and in the electron gas (solid curves).

The effective interaction between two positive impurities $V_{\text{eff}}^{(hh)}(r)$ can be calculated within the variational theory [4] after the impurity distribution function is known. The interaction has the $1/r$ repulsion at short distances, but the perfect screening makes it short ranged. The results at $r_s = 3$ for different impurity masses are given in Fig. 1. They clearly show that the many-body effects over-screen the Coulomb interaction and the attraction increases with increasing mass ratio. Heavy positive impurity attracts light electrons so strongly that it is effectively recharged attracting another such impurity. When the mass of the impurities $m_h > 2m_e$ at $r_s = 3$ they form a bound state. In Fig. 2 we have collected the phase diagram for impurities in both the charged Bose gas and the electron gas in the density–mass plane. At high densities and low impurity masses no bound state can be formed. With decreasing density the binding of impurities becomes possible much before the isolated impurities bind electron clusters.

The mixture of electrons and holes can be created experimentally in semiconductors and semimetals. It is unstable against annihilation, but if the annihilation rate is reduced or prevented the metastable mixture can exist long enough to form the electron-hole liquid. [2]. Here we search for the stability limits of the electron-hole mixture by varying the density and mass ratio using the microscopic variational approach [4]. Two elementary excitation modes of the charged mixture are plasmon and sound modes. The speed of sound is connected to the compressibility and for a stable system that must be positive. For the mixture of charged bosons that condition is not satified and such a system can not be stable for any mass ratios or finite concentrations. In comparison, the one-component charged boson fluid is stable due to the background jellium charge, which is not allowed to collapse. Thus the essential element for the stability of the mixture of charged particles is the fermion exchange repulsion. At high densities that short-range repulsion between electrons and holes is able to prevent the collapse of the system into clusters, but when the density is decreased also the fermionic mixture becomes unstable. At the critical density the speed of sound of the accoustic mode drops rapidly to zero and no stable solution for the homogeneous mixture can exist. The fermionic repulsion shifts the lower stability line of Fig. 2 between the homogeneous mixture and bound clusters to higher densities. For the mass ratio $m_h/m_e = 1$ the clustering occurs at $r_s = 5.2$.

In concluding, we have used variational theory to study phases of mixtures of charged particles and shown that two impurities form a molecule like pair. In the electron-hole mixture this becomes the instability between homogeneous and clustered phases. The phase observed by Smith and Wolfe[3] called the condensed plasma phase may consists of such charged clusters.

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