Cold Atoms and Polaritons: the Crossroads

ESF Short-Visit Grant Report - POLATOM Network

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1 Aims and Purposes of the Visit

The present *report* follows a short visit granted by the POLATOM network of the European Science Foundation. The grant supported my participation in the school *"Quantum Matter at Ultralow Temperatures"*, held in Varenna (Italy) on July 2014.

During a pre-doc training at Los Alamos National Laboratory (New Mexico, USA) I first came into contact with plasmonic systems. I am currently involved in a joint PhD program on cold-atom physics between the universities of Trento (IT) and Montpellier (FR, current location). During my research on the propagation of 2D matter waves in periodic and non-periodic structures of scatterers [1], I became aware of recent theoretical and experimental studies on polaritons in honeycomb structures [2]. This renewed my interest in the physics of polaritons and this summer school, organized by the Società Italiana di Fisica, represented a unique occasion to attend courses and face renowned experts in the domain of cold gases and polaritons physics.

My participation in this school gave me the chance to deepen my knowledge in the fascinating and expanding fields of cold-atoms and polaritons, with particular interest in the crossroads between these two domains. In this *report* I will overview the competences I acquired in these two fascinating fields. In particular I found intriguing the investigations on what can be considered a "cold-gases analog" of polaritons, i.e. the polarons, introduced by Prof. E. Demler and Prof. T. Giamarchi.

2 Cold-Gases

When one or several atoms are cooled down below few micro-kelvins their quantum nature takes over their "billiard-ball" behavior, usually adopted to describe the physics of a gas at room temperature. We thus talk of *cold* or even *ultracold* atoms and gases. The transition from the classical to the quantum regime takes place when, at ultra-low temperatures, the *de Broglie* wavelength associated to the cold atom gets larger than the average inter-particle distance. In such a situation the behavior critically depends on the bosonic or fermionic nature of the atoms and on the way they interact with each other. The attainment of Bose-Einstein condensation (BEC) in diluite ultracold gases is considered a milestone of modern physics [3], together with, a few years later, the realization of degenerate atomic Fermi gases [4].

For what concerns the interaction, the low-energy nature of the scattering makes it suitable to describe the process via a s-wave contact-interaction. For two atoms of mass m and relative distance r it takes the form

$$U_{\text{con}} = \frac{4\pi\hbar^2}{m}\, a\, \delta(r). \tag{1}$$

Remarkably in cold gases the inter-atomic scattering length a can be experimentally tuned in a number of ways. The most common technique employs the so-called Fesbach resonances [5], in which the coupling between a free and a bound scattering state can be resonantly enhanced via a static magnetic field B, leading to a resonant behavior in $a(B)$.

Thanks to the fundamental role played by the scattering length a, the behavior of an ultracold system can be experimentally tuned. For example, 3D bosonic systems with $a > 0$ are stable and the BEC phase can be reached [3], while for $a < 0$ bosons attract each other and the system can eventually collapse [6]. Other interesting phenomena can be investigated considering a two-component Fermi gas near a resonance of the s-wave scattering length. The ability to tune the interaction allows to explore the *crossover* from a weak attraction, when fermions form pairs in momentum space according to the Bardeen-Cooper-Schrieffer theory (BCS) resulting in a superfluid behavior, to a strong attraction, case in which fermions forms tightly bound pairs in real-space leading to a BEC of composite bosons. This phenomenon is referred to as BEC-BCS crossover [7].

Beside the contact interaction other long-range interactions are raising the interest of the cold-gases community. An intensively studied one is the dipolar interaction [8], boosted by the recent experimental developments in the field of ultracold dipolar gases. Bose-Einstein Condensates of magnetic atoms have been realized using chromium, erbium, and dysprosium. However, atomic magnetic moments are pretty small and the recent realization of ultracold heteronuclear molecules (RbK and NaK), which carry large electric dipole moments, offers a promising route towards stronger dipolar effects. Rydberg atoms boast much larger dipole moments but yield challenging experimental problems associated with time and length scales.

3 Polaritons

Polaritons are quasiparticles resulting from strong coupling of electromagnetic waves with an electric or magnetic dipole-carrying excitation. Two typical systems in which such quasiparticles arise are Quantum Wells (QW) in microcavities and the surface of metallic plates.

3.1 Exciton Polaritons in Quantum Wells

A quantum well consists of a thin semiconductor layer embedded in a different semiconductor compound acting as “barrier” material. The chemical composition of the well is chosen to have the bottom of the conduction band at a lower energy than the surrounding material, thus producing quantum confinement of both electrons and holes [9]. The first excited state, of energy $\hbar\omega_{\text{exc}}$, corresponds to the excitation of a two-dimensional electron-hole pair which results confined in the QW layer, this is the so-called exciton.

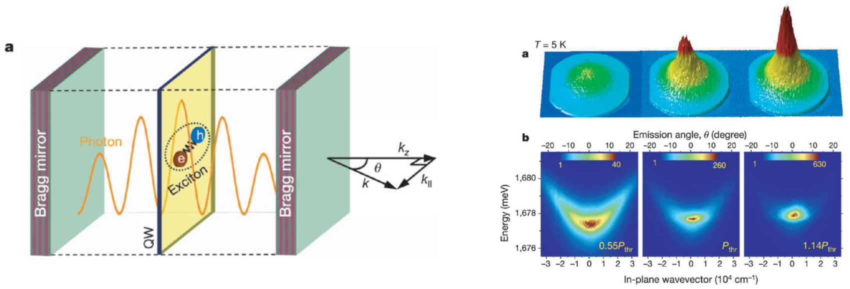

Figure 1: Left Panel: Sketch of a planar semiconductor microcavity with and embedded quantum well. The cavity photon mode is strongly coupled to the excitonic transitions in the QW. Right panel: Experimental observation of exciton polariton BEC obtained by pumping excitations in the system via an external laser beam. Due to EP-EP interactions, the gas of quasiparticles can thermalize to the BEC state. Figures from [10].

By construction the QW results placed inside an optical cavity (cf. Fig. 1), which would have a resonant frequency ω_{cav}. A strong coupling of exciton and cavity mode can be reached by placing the QW at the antinodes of the cavity field and tuning ω_{cav} in the vicinity of ω_{exc}. The quasiparticle arising from this resonant coupling is indeed the Exciton Polariton (EP). Since electron and hole are fermions, the composite exciton is a bosonic particle, such as the photon. Condensation of the EP quasiparticle is thus possible and researchers have successfully explored the physics of BEC in gases of EP (cf. Fig. 1) [10].

When a pattern is etched on the metallic plate on which excitons live, an effective periodic potential is then felt by the EPs. This can be used to build-up quantum simulators of condensed matter systems using semiconductor microcavities. On a recent paper [2] the band structure of polariotns have been studied both theoretically and experimentally in the presence of a honeycomb lattice, made of hundreds of coupled micropillars etched in a planar semiconductor microcavity (cf. left panel of Fig. 2). The authors show how in this system Dirc cones in the energy-momentum dispersion relation can be naturally observed, demonstrating the potential of EP systems for quantum simulation. Position, shape and size of each lattice site can be controlled at will during fabrication, paving the way to study a wide range of intriguing effects, like disorder-induced ones.

3.2 Surface Plasmon Polaritons

At the interface between any two materials (such as metal-dielectric or metal-vacuum interfaces) a mode of coherent oscillation of surface electrons

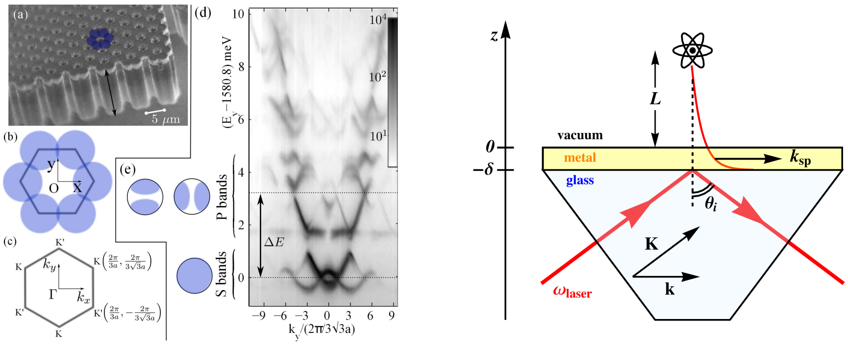

Figure 2: Left Panel: (a) Microscope image of the microstructure considered in [2]. (b) Overlap between pillars. (c) First Brillouin zone of the hexagonal lattice. (d) Measured momentum space energy along the $k_x = 2\pi/3a$ line. (e) Sketch of the real space distribution of s and p modes in a single pillar. Figure from [2]. Right panel: Kretschmann excitation scheme of surface plasmons via an external laser beam. The resulting evanescent field outside the metallic plate can be used to tailor the atom-surface interaction forces to create barriers or trapping wells. Figure from [11].

exists. Such a mode is called Surface Plasmon (SP). If for instance we consider a metal-vacuum interface, the charge motion on the surface creates a strong electromagnetic field outside (but also inside) the metal and this allows to say that we are actually facing a quasiparticle of mixed matter- and electromagnetic-wave nature: a Surface Plasmon Polariton (SPP). They are a type of surface wave, guided along the interface in much the same way that light can be guided by an optical fiber.

Different experimental configurations of prisms, laser beams and metallic plate exists in order to excite a SP. One of these is the so-called Kretschmann configuration (cf. right panel of Fig. 2), in which a laser shines with an angle θ_i on the back of a metallic plate glued on a prism. If the laser frequency and angle of incidence match a resonance condition, SPs are excited on the metallic plate. The presence of SPPs have been proved to significantly modify the surface-force felt by an atom close to the metallic plate. In particular the emergence of a potential barrier have been experimentally investigated in [12]. More sophisticated configurations, recurring for instance to the use of two laser beams, may be useful to realize tailored nano-traps or space-modulated potentials [11].

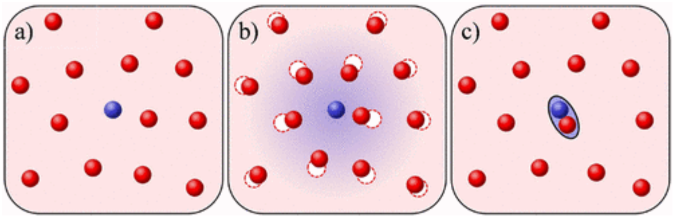

Figure 3: Schematic representation of an impurity moving in a degenerate Fermi gas. (a) For weak attraction, an impurity (blue) experiences the mean field of the medium (red). (b) For stronger attraction, the impurity surrounds itself with a localized cloud of environment atoms, forming a polaron. (c) For strong attraction, the impurity can form a molecule with a particle from the medium. Figure from [13].

4 Polarons

In the previous section we introduced the polariton: an electromagnetic excitation dressed-up by the photonic field. Another similar quasiparticle is of relevant interest in condensed matter, it is the polaron: an electromagnetic excitation dressed-up by the phononic field. Such kind of quasiparticles can be observed in cold-atoms system, as presented by Prof. E. Demler and Prof. T. Giamarchi during the courses of the Varenna Summer School.

4.1 Polarons in Condensed Matter

The polaron concept was first proposed by Lev Landau in 1933 to describe an electron moving in a dielectric crystal where the atoms move from their equilibrium positions to effectively screen the charge of an electron, which results dressed in a phonon cloud. Dielectric theory describes the phenomenon by the induction of a polarization around the moving charge. The induced polarization will follow the electron in his motion so that the carrier, together with the induced polarization, can be considered as one entity, called a polaron. Both electric and magnetic polarons exist, corresponding to a carried electric or magnetic polarization.

4.2 Polarons in Cold-Atoms Ensembles

Performing *ab-initio* calculations of the properties of polaronic quasiparticles is a quite challenging task. This is why a huge theoretical and experimental effort has been done in the quest for systems showing similar physical properties but in a more controllable scenario. Once again cold-atoms gases jumped in front of the line due to the possibility to tune the interactions, to control the trapping potentials and to perform high-quality measurements.

In this direction an interesting experimental realization, cited by Prof. E. Demler in Varenna, has been reported in [13], where a fermionic version of the solid-state polaron has been observed. Indeed, using spin-1/2 lithium atoms, a spin-down "impurity" atom is immersed into a Fermi sea of spin-up atoms, forming a quasiparticle known as a Fermi polaron. Depending on strength of the contact interaction between the impurity and the atoms of the Fermi sea, several regime can be investigated. As depicted in Fig. 3, when the interaction is weak the impurity sees the mean field generated bu the majority component, but the latter is not affected by the presence of the impurity, thus no polarons are excited in the system. When the interaction strength grows, finally the impurity modifies the densities on its neighborhood and the polaron appears. However if the interaction is too strong the impurity would form a molecular bound-state with a single atom of the sea and the polaron is lost again. Other experiments using bosonic species have also been realized and the effects due to the presence of Bose polaritons have been detected [14]. Such experiments have also been presented in the talks by Prof. T. Giamarchi in Varenna.

5 Conclusions and Perspectives

My participation in the courses of the *"Enrico Fermi"* Summer School on *"Quantum Matter at Ultralow Temperatures"* has been undoubtedly an enriching experience. During the ten days spent in Varenna I met renowned experts of cold gases, getting aware of the cutting-edge themes of research and of the open questions in the field. I had the chance to interact and exchange ideas with other PhD students, several of which are working on themes related to my current project. Interesting perspectives for future theoretical and experimental collaborations have been established. Furthermore I met previous collaborators and co-authors from the University of Trento, with which we planned new teamwork. This school boosted my interest toward polaritonic and polaronic systems. The connection between these quasiparticles and cold gases is now more clear and the perspective of working on these subjects fascinates me. The school renewed my interest in the possibility of tailoring atom-surface forces with SPPs and I got several new ideas to develop and improve my work [11].

To conclude I sincerely thank the POLATOM Network of the European Science Foundation for its financial support of this stimulating experience.

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