Exchange Visit Grants: Scientific Report

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I. PURPOSE OF THE VISIT

I visited the Theory of Condensed Matter group in the Cavendish Laboratory, at the University of Cambridge from the 6th of June 2012 to the 24th of August 2012 (11 weeks), extending of one week my originally planned 10 week visit. The aim of the visit was to carry work on both fields ultracold polar fermions in both 2D layer and bilayer structures, as well as semiconductor exciton-polaritons. My visit to the Theory of Condensed Matter group at the Cavendish as been coordinated with the visit of three researchers from the UK, with whom I am currently collaborating on the above subjects: Dr Meera Parish (LCN, UCL) in the period 18/06/2012–24/07/2012, Dr Jonathan Keeling (St' Andrews University) in the period 30/07/2012–04/08/2012, and Dr Marzena Szymanska (Warwick University) in the period 06/08/2012–18/08/2012. As explained in this report, most of the objectives originally proposed in the project have been successfully met and have led to one publication submitted to *Phys. Rev. Lett.* (Ref. 1. of the submitted and projected publications). My visit has strongly benefit from the environment provided by the host institution, the Cavendish Laboratory, Cambridge.

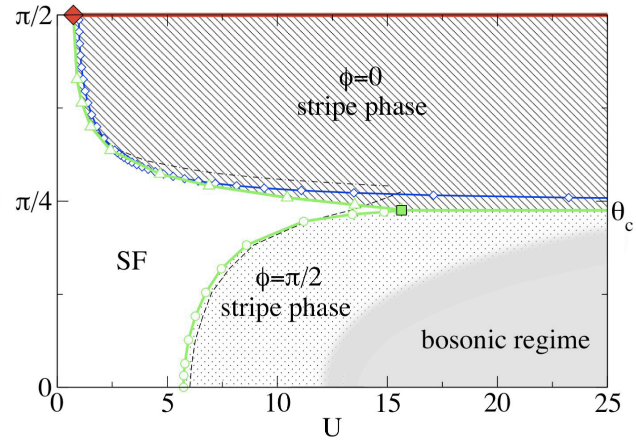

FIG. 1 (Color online) Phase diagram for a dipolar Fermi gas in a bilayer at fixed interlayer distance, $k_F d = 2$, as a function of the tilt angle θ (see Fig. 2) and interaction $U = mD^2 k_F/\hbar^2$. The liquid phase is superfluid (SF). The (green) open triangles [circles] set the boundary of the stripe phase oriented along $\phi = 0$ [$\phi = \pi/2$], derived from a self-consistent STLS calculation. The filled (green) square at $\theta_c \simeq 0.75$ and $U \simeq 15.65$ is a quantum critical point beyond which there is a phase transition between the two stripe phases. The (blue) open diamonds for the $\phi = 0$ stripe phase are instead determined including exchange correlations only (see text). These boundaries can be compared to the $\phi = \pi/2$ stripe transition (dashed line) and the collapse instability (dashed-dotted line) for the single-layer case (Parish and Marchetti, 2012). The shaded "bosonic" region is where the system can be described in terms of interlayer bosonic dimers. The (red) filled diamond and thick (red) line at $\theta = \pi/2$ indicate collapse in the bilayer.

II. DESCRIPTION OF THE WORK CARRIED OUT DURING THE VISIT AND MAIN RESULTS OBTAINED

A. Ultracold dipolar Fermi gases in the bilayer geometry

Six of my 11 week visit to the Cavendish Laboratory in Cambridge have been devoted in collaborating with M. Parish on the originally proposed project on inhomogeneous phases of fermionic polar molecules confined in a two-dimensional bilayer geometry.

Density-wave phases such as stripes are apparently ubiquitous in nature. They are typically found in quasi-two-dimensional or layered materials, where they manifest as periodic modulations of the electron density within the two-dimensional (2D) layers. However, despite their ubiquity and potential importance, their origins and behavior are still under debate. One route to gaining insight into the problem is to study cleaner, more tunable analogues of these electron systems. Quantum degenerate Fermi gases with long-range dipolar interactions (Baranov, 2008; Carr *et al.*, 2009) provide just such a system in which to investigate density-wave phases. Such dipolar Fermi gases have recently been realized experimentally with both magnetic atoms (Lu *et al.*) and polar diatomic molecules (Heo *et al.*; Ni *et al.*, 2008; Wu *et al.*). In particular, ultracold polar molecules of ^{40}K ^{87}Rb have been confined to 2D layers using an optical lattice (de Miranda *et al.*, 2011), thus paving the way for exploring long-range interactions in low dimensional systems.

For a 2D gas of polar molecules, the dipole-dipole interactions can be controlled by aligning the dipole moments with an external electric field. For small dipole tilt angles θ with respect to the plane normal, the dipolar interactions are purely repulsive, while for $\theta \gtrsim \pi/4$, the interactions acquire a significant attractive component such that the dipolar Fermi system is unstable towards collapse for sufficiently strong interactions (Bruun and Taylor, 2008; Parish and Marchetti, 2012; Sieberer and Baranov, 2011; Yamaguchi *et al.*, 2010). Away from collapse, in the repulsive regime, previous theoretical work has predicted the existence of a stripe phase (Babadi and Demler, 2011; Parish and Marchetti, 2012; Sieberer and

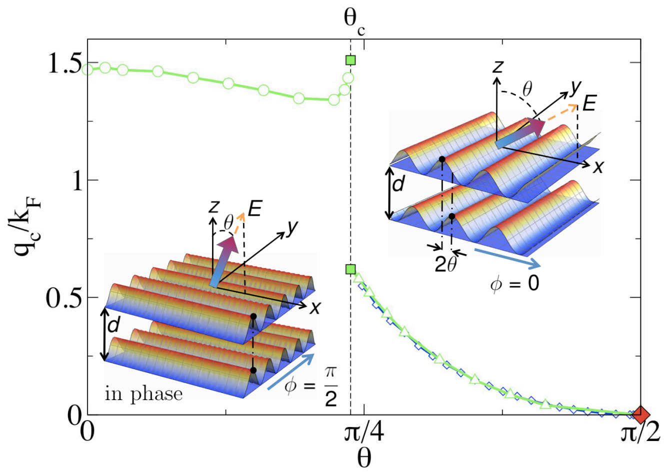

FIG. 2 (Color online) Critical wave vector q_c/k_F for the $\phi = \pi/2$ stripe phase ($\theta < \theta_c$) and the $\phi = 0$ one ($\theta > \theta_c$) — same parameters and symbol scheme as in Fig. 1. The insets depict the alignment of the dipoles with the electric field E and the features of the two different stripe phases. For the $\phi = 0$ stripe phase, the density modulations in the two layers have a phase shift $\eta \simeq 2\theta$, while the wave vector q_c decreases with increasing tilt angle θ down to $q_c = 0$ for $\theta = \pi/2$ (filled [red] diamond), where the gas collapses. For density modulations along $\phi = \pi/2$, q_c appears to be fixed by the density.

Baranov, 2011; Yamaguchi *et al.*, 2010), even for the case where the dipolar interactions are *isotropic* ($\theta = 0$) and the system must spontaneously break rotational symmetry (Parish and Marchetti, 2012).

In this project, We have determined the phase diagram of the bilayer system within linear response theory, using a version of the Singwi-Tosi-Land-Sjölander (STLS) scheme (Singwi *et al.*, 1968) recently developed in Ref. (Parish and Marchetti, 2012). Based on this analysis, we show that the bilayer geometry can actually stabilize the collapse of the 2D Fermi gas to form a new density wave (Fig. 1). However, in contrast to the stripes in the repulsive regime, this new stripe phase has density modulations along the direction of the dipole tilt (Fig. 2) and can also be well described by a simplified STLS theory that involves exchange correlations only. Our work thus reveals a new quantum phase transition between two different stripe modulations, where one phase is driven by strong repulsive correlations and the other is driven by the bilayer architecture.

Our predicted stripe phases should be accessible experimentally with cold dipolar gases. In particular, the bilayer distance $k_F d = 2$ can be achieved for a typical 2D density $n \sim 1.3 \times 10^8$ cm^{-2} and layer spacing $d = 500$ nm. Polar molecules such as LiCs (Carr *et al.*, 2009) have dipolar moments $D \sim 0.35 - 1.3$ Debye (corresponding to $U \sim 1 - 14$), which allows one to explore both $\phi = 0$ and $\phi = \pi/2$ stripe phases. Furthermore, the newly explored NaK molecules (Wu *et al.*) allows one to reach even larger values of the interaction strength ($D \sim 2.7$ Debye and $U \sim 28$).

The result of this work has been submitted for publication to *Phys. Rev. Lett.* (Ref. 1. of the submitted and projected publications).

B. Resonance polariton-bipolariton superfluidity

I am carrying on this project mostly in collaboration with Dr Jonathan Keeling (St' Andrews University), who has been visiting the Cavendish for one week during my stay.

We have been considering the case where the scattering properties of two polaritons in the left- and right-circular polarisation states can be driven through a scattering resonance because of the possibility of forming a bipolariton state. Microscopically, the scattering resonance is due to the biexciton bound state and the detuning parameter is given by the detuning of the cavity photon energy from the biexciton energy (Carusotto *et al.*, 2010; Wouters, 2007). The minimal description of this situation is a heteronuclear one-channel Hamiltonian (Keeling, 2008) for the left- and right-circular polarization polariton fields.

The scope of this project is to look at the equilibrium phase diagram and understand the expected phase transition between an "atomic" polariton superfluid phase, where both polaritons and bipolaritons displace off-diagonal long-range order (ODLRO), to a "molecular" superfluid phase, where only the bipolariton ODLRO and superfluidity are present.

Considering as a reference the case of a single-channel single-species atomic gas of bosons (Radzihovsky *et al.*, 2004; Romans *et al.*, 2004), we have been developing a variational mean-field approximation in order to derive the phase diagram. This project is still work-in-progress, and I expect to complete it during the next few months.

III. FUTURE COLLABORATION WITH HOST INSTITUTION

The completion of the first project opens a wealth of new directions to explore. Just to mention few

1. The study within the same formalism of dipolar Fermi gases in the multi-layer geometry.
2. Possibility of imbalance the densities in the different layers.
3. Consider the bosonic limit in the bilayer geometry where a Fermion in one layer tightly binds with a Fermion in a second layer.

I am planning to visit the Cavendish Laboratory again during the next academic year.

IV. SUBMITTED AND PROJECTED PUBLICATIONS

During my stay in Cambridge, I have submit a publication to *Phys. Rev. Lett.* as an outcome of this project:

1. F. M. Marchetti and M. M. Parish, "Density-wave phases of dipolar fermions in a bilayer " arXiv:1207.4068.

In addition, I expect to have a ready publication to submit about "Resonance polariton-bipolariton superfluidity" in the next few months. I have acknowledged the support received from the European Science Foundation (ESF) in the publication mentioned above and in future ones resulting from this grant, as I will also forward reprints to the ESF Secretariat as soon as available.

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