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 2$^{\rm nd}$ of June 2011 to the 11$^{\rm th}$ of August 2011 (10 weeks). The aim of the visit was to carry work on both fields of electron-hole bilayers and ultracold polar fermions in a layer structure in collaboration with Dr M. Parish, an EPSRC Career Acceleration Fellow working in the Theory of Condensed Matter group. As explained in this report, most of the objectives originally proposed in the project have been successfully met and have led to one publication on this topic soon to be 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.

In addition to completing the proposed project, I have also coordinated my visit with the visit to Cambridge of Dr Jonathan Keeling (St. Andrews University), with whom I am developing several projects on the interplay between disorder and interaction and their influence on the properties of microcavity polariton systems. Moreover I have been interacting with Dr C. Creatore, also at the Cavendish, with whom I have set up new projects on pattern formation in polaritonic systems. Finally, during my stay in Cambridge, I have been able to complete a review on the occurrence of quantised vortices in polariton fluids (Ref. 2. of the submitted and projected publications), in which I have acknowledged partial foudings from this project.

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

A. Density instabilities in a two-dimensional dipolar Fermi gas

Most of my 10 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 single two-dimensional layer. Of particular interest are fermionic polar molecules confined in two-dimensional geometries, since these systems are experimentally accessible, having reduced atom losses (de Miranda *et al.*, 2011; Ni *et al.*, 2010).

We have been focusing on a dipolar Fermi gas in a *single* layer, which is the canonical Fermi system for dipole-dipole interactions in 2D. Here, the dipole moments are all aligned by an external electric field, making an angle θ with respect to the normal of the 2D plane (Fig. 1). For $\theta \neq 0$, the anisotropy of the interaction provides an exotic twist to the problem and has led to predictions of anisotropic density-wave (stripe) phases (Sun *et al.*, 2010; Yamaguchi *et al.*, 2010) and p-wave superfluidity (Bruun and Taylor, 2008).

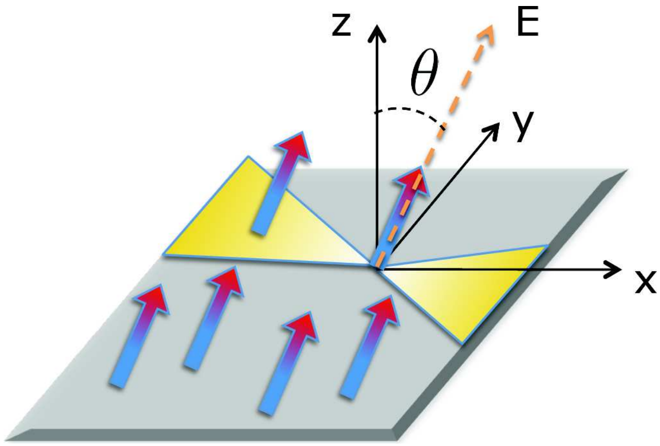

FIG. 1 Schematic representation of fermionic polar molecules confined in a single two-dimensional layer, where the molecule dipole moments are all aligned by an external electric field.

We have been showing that the Random Phase Approximation (RPA) for the density-density response function is never accurate for the 2D dipolar Fermi gas. In addition, RPA does not settle the question of whether or not the 2D dipolar Fermi gas spontaneously breaks rotational symmetry and forms a stripe phase for *isotropic* interactions ($\theta = 0$), which is of fundamental interest to other quasi-2D systems such as the cuprate superconductors (Kivelson *et al.*, 1998).

To incorporate correlations beyond RPA, we use a modified version of the Singwi-Tosi-Land-Sjölander (STLS) scheme (Singwi *et al.*, 1968), which has had much success in describing electron systems (Giuliani and Vignale, 2005). Using this formalism, the effect of correlations is evident in the pair correlation function derived from the density-density response function, where we observe a "correlation hole" forming around each fermion with increasing interaction. We map out the instabilities of the density-density response function and we see the existence of a stripe phase, similarly to RPA (see Fig. 2). However, in contrast to RPA, we also observe a collapse instability for sufficiently large θ, which is consistent with Hartree-Fock calculations (Bruun and Taylor, 2008; Ya-

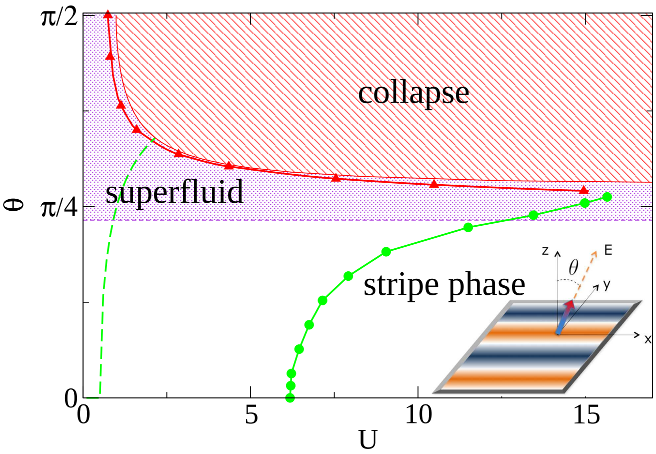

FIG. 2 Phase diagram for a 2D dipolar Fermi gas as a function of dipole orientation angle θ, as defined in the inset, and dimensionless interaction strength $U = mD^2 k_F/\hbar^2$, where D is the dipole moment and k_F is the Fermi wave vector. The green circles mark the transition to a stripe phase while the red triangles correspond to the collapse instability. For comparison, we include the RPA result for the stripe instability (dashed green line) and the region where p-wave superfluidity occurs, as predicted by Ref. (Bruun and Taylor, 2008)

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maguchi *et al.*, 2010). Last but not least, we can show that the system does indeed spontaneously break rotational symmetry to form a stripe phase when when the dipoles are oriented perpendicular to the layer ($\theta = 0$), in defiance of conventional wisdom.

III. FUTURE COLLABORATION WITH HOST INSTITUTION

The completion of this projects opens a wealth of new directions to explore.

1. The study within the same formalism of the rich phase diagram in bilayers and the multi-layers.
2. Signatures of superfluidity in bilayers by studying the pair correlation function within the formalism used in this project.
3. extend the static STLS study above to the (quantum) dynamical case.

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

IV. SUBMITTED AND PROJECTED PUBLICATIONS

We are about to submit a publication to *Phys. Rev. Lett.* as an outcome of this project:

1. M. M. Parish and F.M. Marchetti, "Density instabilities in a two-dimensional dipolar Fermi gas".

In addition, the following publication has been the result of the work carried under this very same grant

2. F.M. Marchetti and M.H. Szymanska "Vortices in polariton OPO superfluids", cond-mat/1107.4487 (http://arxiv.org/abs/1107.4487).

I have acknowledged the support received from the European Science Foundation (ESF) in all the publications mentioned above and from future ones resulting from this grant, as I will also forward reprints to the ESF Secretariat as soon as available.

References

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