PhD Research Project – Giulio Biagioni (giulio.biagioni@unifi.it)

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Exploring the supersolid state of matter

Introduction The supersolid is an exotic quantum phase of matter in which the same atoms that form a crystalline structure are delocalized and are responsible for the coherent flow of mass, typical of superfluids. After 50 years from the first theoretical speculations, the supersolid phase has been observed in a quantum gas of strongly magnetic atoms, in the team directed by Prof. G. Modugno [Ta19], which I joined for my Master's thesis project. The discovery has produced great excitement in the community, since the fascinating properties of the supersolid, which should display a behavior halfway between a solid and a superfluid, are now likely to be explored in the laboratory.

Status of the field The supersolid currently produced in the lab is a cluster supersolid: each lattice site is composed of thousands of atoms, contrary to the traditional supersolid searched for in the helium community, formed by one atom per lattice site. Moreover, the low atom number typical of quantum gases experiments combined with its cluster characteristics make the dipolar supersolid, up to now, a severely finite-size system: it is composed of just 3-4 density maxima (or 'droplets'), arranged in a one-dimensional configuration. Despite this limitation, some important and general properties of the supersolid have been observed yet. Modugno's group has demonstrated the phase coherence between different supersolid droplets [Ta19] and the appearance, in the excitation spectrum, of two Goldstone modes, arising from the double symmetry breaking of the supersolid [Ta19b]. In the contest of my Master's thesis project, I have measured the moment of inertia of the supersolid, which results well below the classical value. This anomalous behavior under rotation is considered a smoking-gun proof of superfluidity for a generic system [Ta20, Bi20]. The solid part of the supersolid, however, forces the moment of inertia to be larger than that of the Bose-Einstein condensate (BEC), which is a fully superfluid system. This consideration is formalized through the definition of a superfluid fraction, that quantifies the fraction of the system that decouples from the rotation. Due to its only partial superfluidity, the supersolid is expected to show the unique property of having a superfluid fraction less than one even at zero temperature. From the experimental data, I have extracted a very high value of the superfluid fraction, which is a clear demonstration of the superfluidity of the dipolar supersolid, but our current experimental setup has prevented us from establishing if it is actually less than one, given the experimental error [Ta20, Bi20].

Research project During my PhD I plan to explore further the properties of the dipolar supersolid. This will be possible, partially, also with the existing finite-sized and one-dimensional supersolid. As a new experimental tool, I will employ an optical lattice, whose first stages of construction have been part of my Master's thesis work [Bi20]. The optical lattice offers a new way to excite the supersolid and study the peculiar interplay between its solid and superfluid nature. At first, I plan to focus on the study of the Josephson dynamics in the supersolid, which is a very general and key manifestation of quantum coherence. Josephson junctions consist of two superfluids separated by a thin barrier: a phase difference between them induces a persistent current through the barrier, powered by quantum tunneling. Originally proposed and realized with superconductors, Josephson junctions have been largely investigated also with superfluid helium and BECs in double-well optical traps. The supersolid is expected to show a new interesting kind of Josephson dynamics since the double-well structure isn't imposed externally but is auto-induced by the same atoms that participate in the Josephson current. The basic idea of the experiment is to employ the optical lattice with a period equal to two times the supersolid period to produce an imbalance in the population of two supersolid droplets. After removing the external lattice, I will study the Josephson dynamics measuring the interference pattern observed after a free expansion of the atomic system, from which one can extract the population and phase differences of the two droplets, the two key quantities whose oscillation in time reveals the Josephson dynamics. Due to the presence of the solid structure, which is compressible as in a real solid, we expect the dynamics to be highly non-linear, contrary to the Josephson junctions studied so far, so that the experiment will very likely stimulate also theoretical investigations of our system. Indeed, I plan to collaborate with the group of A. Smerzi, of the University of Florence, a leading expert of Josephson junctions.

Although the current one-dimensional supersolid available in the lab offers new and interesting phenomena to be studied, it can't, of course, enable us to explore the whole range of phenomena one can think for a supersolid. As the second step of my PhD project, therefore, I plan to tackle the problem to realize a supersolid in two dimensions, following a theoretical proposal [Lu15] suggesting to create a 2D dipolar gas with a stabilizing mechanism based on an effective three-body repulsion, obtained manipulating atomic and molecular interactions through Feshbach resonances. Such a system is expected to display a supersolid phase with smaller cluster size and hence with a higher number of droplets, arranged in a rich set of possible 2D configurations: a stripe phase and two kinds of triangular lattices. The realization of a 2D supersolid would trigger the study of numerous properties linked to superfluidity and, first of all, the ones that involve rotations. A 2D configurations, indeed, would allow measuring a superfluid fraction less than one, a task that has not been possible to fulfill during my Master's thesis work, as previously explained, or to produce a vortex, or even a lattice of vortices, in the supersolid phase, an issue that is attracting theoretical interests at the moment [Ga20].

References

[Ta19] Tanzi, Lucioni, Famà, Catani, Fioretti, Gabbanini, Bisset, Santos, and Modugno. Observation of a dipolar quantum gas with metastable supersolid properties. *Phys. Rev. Lett.*, 122, 130405 (2019).
[Ta19b] Tanzi, Roccuzzo, Lucioni, Famà, Fioretti, Gabbanini, Modugno, Recati, and Stringari. Supersolid symmetry breaking from compressional oscillations in a dipolar quantum gas. *Nature*, 574, 774 (2020).
[Ta20] Tanzi, Maloberti, Biagioni, Fioretti, Gabbanini, and Modugno. Evidence of superfluidity in a dipolar supersolid from non-classical rotational inertia. Preprint: arXiv:1912.01910. Accepted for publication in *Science* (2020).
[Bi20] Biagioni, Evidence of superfluidity in a dipolar supersolid through non-classical rotational inertia. Master's theses, University of Florence (2020).
[Lu15] Lu, Li, Petrov, and Shlyapnikov, Stable dilute supersolid of two-dimensional dipolar bosons, *Phys.Rev, Lett*. 115, 075303 (2015).
[Ga20] Gallemì, Roccuzzo, Stringari, Recati. Quantized vortices in dipolar supersolid Bose-Einstein condensed gas. Preprint: arXiv:2005.05718 (2020).