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PERSPECTIVE

Smashing magnets

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Abstract

Understanding or designing phases of matter relies in the first place on the knowledge at the microscopic level of the interactions taking place between the constituents. In quantum gases, a renewed interest is rising about the interaction between two dipoles, owing to its anisotropic and long-range character. In a new paper, Burdick *et al* (2016 *New J. Phys.* **18** 113004) demonstrate experimentally the angular-dependence of collisions between two dysprosium atoms, an atomic species that carries a magnetic dipole moment among the largest in the periodic table. This is realized by colliding two ^{164}Dy Bose–Einstein condensates, and the experiments are backed by a theoretical analysis to connect these results with the two-body scattering cross-section. This represents a further step on the way to the full control of dipole-interacting many-body systems.

Quantum gas experiments have flourished in the past twenty years. They benefit from a precise *ab-initio* understanding of the microscopic physics that governs the motion of ultracold atoms or molecules. This facilitates the modeling of many-body systems, and thus the understanding of how correlations get established [2]. This is, in principle at least, the main motivation for the study of many-body systems with quantum gases. Then, the difficulty lies in the implementation of non-trivial laws of motion, such as the ones leading to topological properties [3], or non-trivial two-body interactions between the constituents.

Historically, two-body interactions in quantum gases are of the short-range isotropic type, which can be controlled via Feshbach resonances [4]. Obviously, this limits the class of available many-body systems, and in particular makes it challenging to study magnetism. This has motivated novel experiments cooling and trapping atoms bearing a strong permanent magnetic dipole moment, and polar molecules or also Rydberg atoms, both carrying a strong electric dipole moment. While quantum degenerate samples of molecules and Rydberg atoms are at their birth, quantum gases of magnetic atoms have now been around for more than 10 years. It all started with the Bose–Einstein condensation (BEC) of chromium [5, 6], and took a new kick with quantum degenerate gases of the lanthanide species dysprosium and erbium [7, 8]. The first team to condense Dy, lead by Benjamin Lev in Stanford, is now reporting on recent experiments in a new paper by Burdick *et al* [1]. These experiments mainly consist in smashing two parts of a ^{164}Dy BEC on one another.

This method has been first implemented with short-range-interacting gases [9]. It allows to observe the differential cross-section, which governs cold collisions, and can be tracked back to the so-called scattering amplitude and the interaction potential [10]. It requires accelerating two very cold clouds (with a very narrow velocity spread) in opposite directions along a well-defined axis to induce a head-on collision. One then observes the halo of scattered atoms (with a final velocity different from the initial one), the distribution of which is given by the differential cross section. It has thus allowed to identify contributions from different partial waves (l), s- and d-wave for identical bosons [11, 12] or p-waves for identical fermions [13].

For short-range interacting atoms at ultracold temperatures, a centrifugal barrier limits the l involved in collisions to s-waves. When interactions are long-ranged (in the sense that the interaction potential varies with the inter-atomic distance r like $1/r^k$ with $k \leqslant 3$), this does not hold. The appearance of higher l channels as the range is increased was demonstrated using light-dressed interactions, and again the same collision method [14]. The interaction which takes place between two dipoles (figure 1) with $k = 3$, falls in the long-range category. This was revealed by the efficient evaporation of identical dipolar fermions (for which s-waves are forbidden)

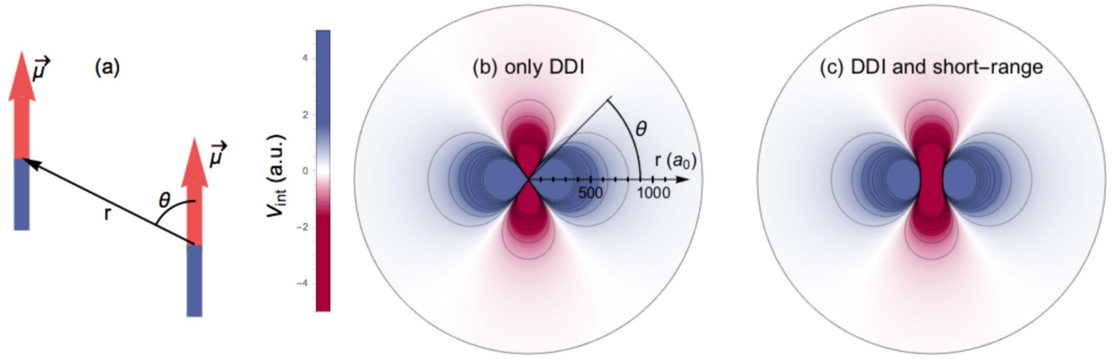

Figure 1. Dysprosium atoms possess a strong dipole moment, schematically represented in (a). (b) Shows the interaction potential $V_{\rm int}$ landscape resulting from the dipole–dipole interaction, which is anisotropic and long-range. In addition, an interaction of the van der Waals type modifies the potential at short distances, as can be seen in (c). The anisotropy of the scattering cross-section due to the DDI, as well as the short-range contribution have been observed in Burdick *et al* [1].

[15, 16]. In addition the dipole–dipole interaction (DDI) is anisotropic, it depends on the relative orientation of the dipoles, and it can couple different l channels together.

In their experiments, Burdick *et al* [1] have polarized the atomic dipole with a magnetic field and they measure the distribution of the halo of scattered atoms after collision (integrated along an imaging axis). They are able to vary the magnetic field direction and thus the angle θ between the dipoles orientation and the collision axis. They observe a very clear dependence of the scattering halo on θ, which demonstrates the anisotropy of the DDI, as well as the participation of several partial waves in the collision. In this experiment, the acceleration is created by Bragg beams applied on a single BEC. The initial velocity spread is not rigourously zero, in addition, the high density in the clouds induce multiple-collision events. To account for these effects, the experimentalists teamed up with a theoretician. The theory that is developed is based on the Boltzmann equation which describes the time evolution in phase space of a given distribution, under the effect of collisions. The use of this classical equation makes the assumption that quantum degeneracy effects can be neglected, these effects have been observed for instance in [17] and are expected to be weak in the experimental conditions.

With this, the authors can quantitatively compare experimental results and the output of simulations. This demonstrates that within the experimental uncertainties, the collisions do obey the expected differential cross-section [18]. In addition, they can extract the number of collisions involved and show that in most cases the majority of atoms from the halo collided only once. A very interesting aspect of their results stems from the fact that the atoms not only interact through the DDI, but also through the usual short-range potential (figure 1). Thus the scattering halo is the sum of two parts. Using the experiment-simulation comparison, the authors show that indeed both contribute, and they are able to extract the strength of the short-range potential (the scattering length) which fits best. Within error bars, the extracted value agrees with previous results.

These results exemplify the peculiar character of the DDI in its most simple form, a single collision event. Such efforts are needed and should be continued, quantum many-body effects have been observed with quantum gases of magnetic atoms [19–21], the full quantitative understanding of these effects requires a precise knowledge of the two-body interactions. As the dipole strength is increased from chromium to lanthanides and then to molecules, the interplay between the short- and long-range potentials is far from trivial [18, 22], and experimental checks must be performed to precisely characterize the two-body physics before considering the many-body effects.

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