Part III Student Projects 2019-20

Dynamical optical potentials for ultracold atoms

Optical dipole potentials provide a versatile tool to trap objects both at microscopic and macroscopic scales, as highlighted via the share of the 2018 Physics Noble prize awarded to Arthur Ashkin [1]. In the field of ultracold atomic gases, optical potentials created via lasers are used not only to trap the atoms, but to engineer arbitrary potentials. Variety of optical potentials have been implemented in these systems, including parabolic and uniform ones, periodic lattice potentials, and controlled disorder, allowing studies of a wide range of classical and quantum phenomena [2]. Extending these ideas to dynamical potentials, which can be tuned in real time, further enhances the capabilities of these systems to study out of equilibrium phenomena. The aim of this project will be to develop and test (some) experimental setups to generate such potentials. Some options will be:

1. **Spatial light modulation**. Spatial light modulators provide a flexible way to impose close to arbitrary light potentials on ultracold atoms. Using digital micromirror devices (DMDs) [3], we produce Bose-Einstein condensates in a box-like potential (see Fig. 1). These devices also offer the possibility of dynamically changing the potentials, which can be used to excite the ultracold gas and in principle probe its full excitation spectrum. Furthermore, they can also be used to correct the aberrations created by various optical elements. The aim of the project will be:
    a. Get familiar with the working of a DMD as a spatial light modulator
    b. Design an optical setup and develop algorithms to test and remove the optical aberrations using a DMD.
    c. Implement and test dynamical potentials created via a DMD.

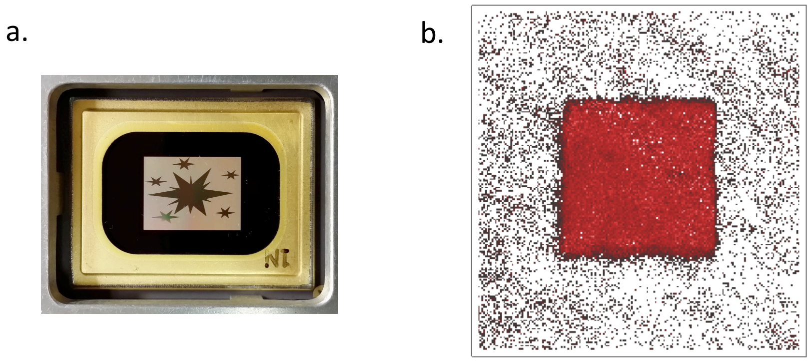

Figure 1. a. A digital micromirror device, ready to display a pattern, **b.** An absorption picture of an atomic cloud in a square box potential (size: 50 x 50 μm^2) in our lab.

2. **Optical transport with a focus-tuneable lens**. Transporting an atomic cloud over macroscopic distances is one of the most common applications of dynamical optical potentials. Such transport is often done either via magnetic traps, using a chain of overlapping coils or translation stages that move a pair of coils, or in case optical potentials using a translation stage to move a lens and hence the focus of a laser beam. While successful, all these methods also have limitations, for example because they can limit the necessary optical access to ultracold atoms or introduce detrimental vibrations. A focus-tuneable lens provides a compact

alternative that could eliminate these problems, allowing transport of atoms [4] by simply applying to it a changing voltage (see Fig. 2). The aim of the project will be to:

a. Calculate the necessary requirements of such a lens for a real experiment.
b. Build and test a setup based on such a lens.

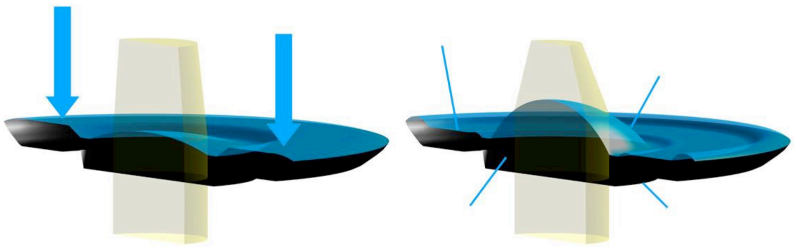

Fig 2. **Focus-tuneable lens**. An externally applied current presses the liquid towards the centre of the lens, thus changing the lens curvature and its focal length [5].

A student would focus on one particular task that would be decided on jointly and would ideally play to their strengths and interests. The proportions of experimental, computational and theoretical components of the projects thus may vary.

Engineering interatomic interactions in ultracold atomic gases

One of the main appeals of using ultracold atomic gases for fundamental many-body research is the possibility to easily manipulate various system parameters like external potentials, spin state of the atoms, or interparticle interactions. Tuning interactions, for example via a Feshbach resonance [6], provides a versatile way of going beyond single-particle quantum mechanics and studying many-body quantum phenomena. The aim of this project will be to develop experimental setups for tuning interactions in an ultracold atomic gas. Some possibilities are:

1. **Magnetic field control of interactions**. Tuning interactions via a Feshbach resonance is done using an externally applied magnetic field. Such fields are generated by electromagnets, with technical requirements including generating high fields (up to 500 Gauss), fast switching (on a microsecond scale), compactness of the coils, and proper thermal management. For example, Fig. 3a shows the set of electromagnets around our current experiment. The aim of this project will be:
    a. To explore various electromagnet designs satisfying the above requirements (Fig. 3b shows one recently proposed design).
    b. To design, build and test electromagnetic coils for a new experiment.

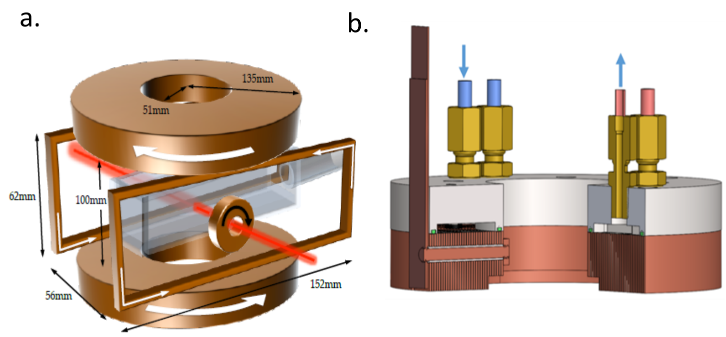

Fig 3. a. Schematic illustrating the electromagnets in our existing experiment. **b.** A recently implemented design of electromagnets in a different ultracold atoms lab [7].

2. **Optical quenching of interparticle interactions**. A different approach to (almost suddenly) change interactions is via optical fields. The basic idea is to change the spin state of the atom via an optical two-photon (Raman) transition, and exploit the fact that the interactions are spin-dependent. The aim of the project will be to:
    a. Theoretically explore the experimental requirements for such an optical process, including for example laser powers and frequencies.
    b. Develop such a spin changing protocol in a real ultracold atoms experiment.

    This project could also have various theoretical and/or experimental extensions, since similar two-photon processes can be used for creation of synthetic gauge fields and spin-orbit coupling in ultracold atomic gases.

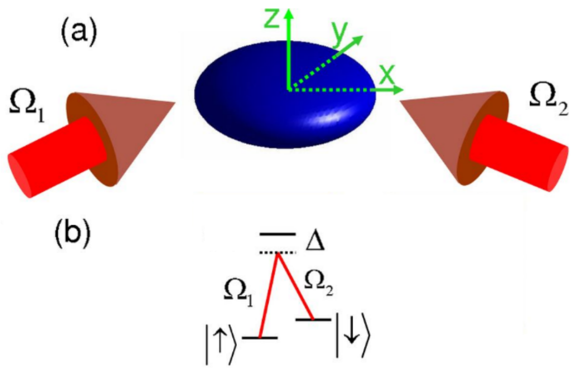

Fig 4. Basic scheme of a spin-changing Raman process implemented via two laser fields. Figure adapted from [8]. Very similar processes are used to induce synthetic gauge fields and spin-orbit coupling for neutral ultracold atoms.

References:

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6. Feshbach resonances in ultracold gases, Rev. Mod. Phys. **82**, 1225 (2010).

7. Compact bulk-machined electromagnets for quantum gas experiments, SciPost Phys. **6**, 048 (2019).

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