Physics

Physics **8**, 95 (2015)

Viewpoint

Casting New Light on Atomic Interactions

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Published October 05, 2015

Optical pulses—tuned to a magic wavelength—provide both spatial and temporal control over the interactions between atoms in an ultracold gas.

Subject Areas: **Atomic and Molecular Physics**

A Viewpoint on:
Quantum Dynamics with Spatiotemporal Control of Interactions in a Stable Bose-Einstein Condensate
Logan W. Clark, Li-Chung Ha, Chen-Yu Xu, and Cheng Chin
Physical Review Letters ***115****, 155301 2015* – Published October 5, 2015

At first glance, gases of neutral atoms cooled to nanokelvin temperatures seem like one of the more innocuous physical systems you could imagine. They consist of dilute collections of weakly interacting particles that follow the well-expounded laws of quantum mechanics. Over the last 15 years, however, this notion has been turned on its head with ultracold gases revealing previously unseen and often surprising behaviors. A key ingredient in these developments has been the ability to control atomic interactions using a so-called Feshbach resonance. In most cases, researchers use magnetic fields to access these resonances, but optical fields can also do the trick. Cheng Chin and colleagues from the University of Chicago, Illinois, have developed an optical Feshbach resonance (OFR) technique that allows both localized and time-resolved control of the interactions in the ultracold gas without disturbing the system in any other way [1]. The team used a laser operating at a "magic wavelength" that was far from any atomic transitions. This setup overcame previous OFR problems with trap distortions and heating of the gas. The new work opens the door to studies of interaction driven dynamics in quantum matter.

A Feshbach resonance occurs when the energy of two colliding atoms is tuned to coincide with a bound molecular state (see Fig. 1, top). The bound molecular state exists in a different scattering channel that is normally inaccessible (or closed) as it lies at higher energy than the atoms in the incoming (or open) channel. At short range, however, atoms may couple to a bound state within the closed channel via the hyperfine interaction. If the two channels have different magnetic moments, their relative energies can be tuned using an external magnetic field [2]. Through this tuning, the normally weakly interacting atoms can become strongly attractive or repulsive, depending on the energy difference between the incoming atoms and the closed channel bound state. In 1998,

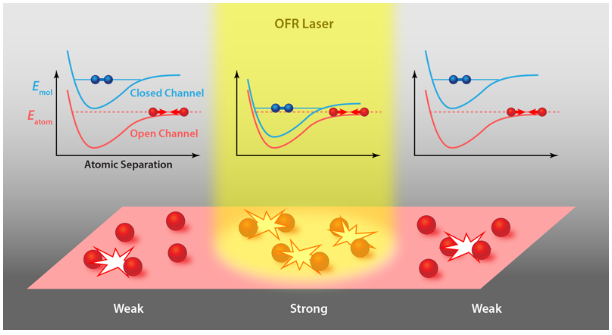

FIG. 1: Atoms in an ultracold gas typically have weak interactions. But an OFR laser can induce strong interactions in a localized region. The laser light causes a shift in the energy of a molecular bound state (E_{mol}), bringing it into resonance with the incoming energy of two colliding atoms (E_{atom}). This leads to enhanced atomic collisions without disturbing the atom trap. (APS/Alan Stonebraker and Chris Vale)

researchers demonstrated, for the first time, magnetically tunable Feshbach resonances as a means to control the interactions between atoms in a sodium Bose-Einstein condensate [3].

Magnetic Feshbach resonances have found widespread application in quantum gas experiments, where the ability to ramp up the strength of the interactions has underpinned several significant breakthroughs. In bosonic gases these resonances have made it possible to create nondispersing matter-wave solitons [4] and strongly interacting Bose gases [5]. In fermionic gases they have led to the production of resonant Fermi superfluids with high critical temperatures [6] and have enabled quantitative studies of thermodynamics that may also be found in neutron stars [7].

Despite this progress, magnetic Feshbach resonances are not without limitations. Large fields are often re-

DOI: 10.1103/Physics.8.95
URL: http://link.aps.org/doi/10.1103/Physics.8.95

quired, which are difficult to switch over short time scales. Spatial control is also problematic and, generally, only uniform magnetic fields that produce uniform changes in the interaction strength have been used. In 1996, researchers proposed a way to overcome these limitations by using an optical field to couple an open-channel atomic state to an excited molecular state [8]. This concept of optical Feshbach resonances has since grown to include any scenario where laser light is used to modify the interactions between atoms based on optical coupling to atomic or molecular states.

Optical fields offer potential advantages in that they can be switched rapidly and focused into novel patterns with high spatial resolution, allowing access to new classes of experiments with tunable interactions. To date, however, such OFR schemes have suffered from unwanted heating from off-resonant light scattering. Furthermore, applying a nonuniform optical field usually shifts the energy levels of the ground-state atoms, providing a dipole force that can strongly perturb the system.

Here, Chin and colleagues demonstrate an optical technique that overcomes these hurdles. Using cesium atoms illuminated by light at a "magic wavelength" they are able to energetically shift a molecular state, in the vicinity of the atomic scattering state, using light that is far detuned from any atomic transitions (see Fig. 1). The magic wavelength corresponds to a point where the atomic state experiences no net light shift, but an appreciable shift of the relevant molecular state still occurs. This allows the properties of the atomic scattering to be modified by the nearby molecular state in a spatially selective way, without distorting the shape of the trapping potential. Additionally, low photon-scattering rates are possible because of the large laser detuning from atomic transitions, meaning that, for the first time, one can access the equilibrium properties of gases illuminated with an OFR beam, without unwanted heating. Furthermore, as discussed in Ref. [1], the OFR technique opens the way for studies of nonequilibrium dynamics such as localized condensate collapse and soliton formation that have been inaccessible with magnetic Feshbach resonances.

In principle, this OFR technique could also be applied to other atomic species. Cesium atoms have a large energy splitting between the two dominant optical transitions, so heating due to scattering of the OFR light is not a problem. This splitting becomes smaller in lighter alkalis but should not prohibit finding an acceptable magic wavelength. Other elements such as erbium or dysprosium offer a wide selection of transitions that should also be amenable to this OFR technique. In terms of applications, OFRs offer exciting new possibilities in quantum gas research. For example, it may be possible to probe transport across interfaces between distinct many-body phases in a single gas [9] or to directly excite oscillations in strongly interacting Fermi superfluids that are analogous to the Higgs mode from particle physics [10]. These findings provide the clearest indication yet that the future for optical Feshbach resonances looks bright!

This research is published in Physical Review Letters

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DOI: 10.1103/Physics.8.95
URL: `http://link.aps.org/doi/10.1103/Physics.8.95`

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URL: http://link.aps.org/doi/10.1103/Physics.8.95