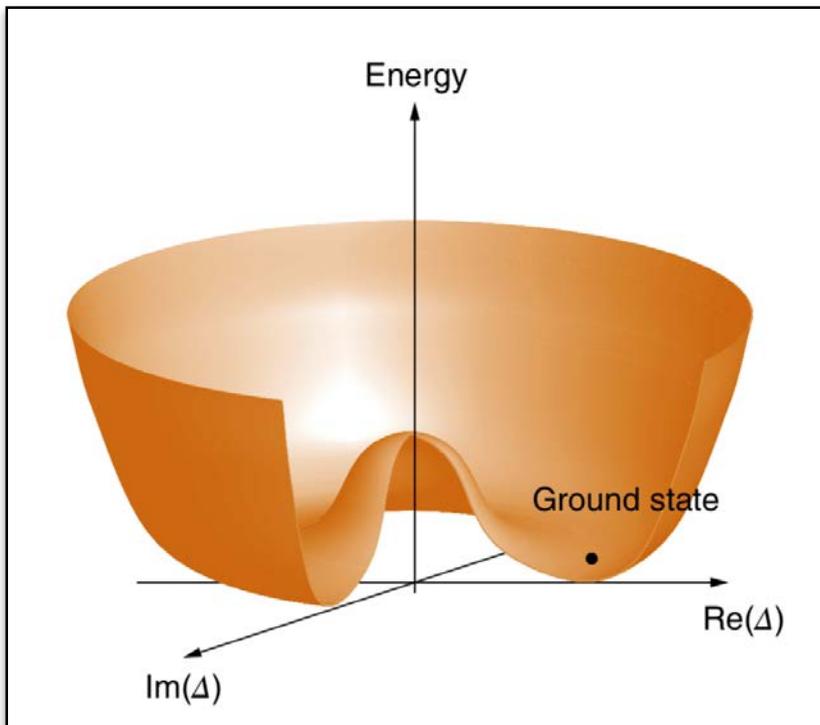


**OSCAR\* Reports—**  
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## Higgs mode in a strongly interacting fermionic superfluid

A. Behrle, T. Harris, J. Kombe, K. Bao, M. Link, J.-S. Bernier, C. Kollath, M. Köhl (OSCAR Project B4)

*Nature Physics* **14**, 781-785 (2018)

As a quantum field excitation, the Higgs boson is nothing but a radial motion in a potential like that in our cover image. The corresponding angular motions are the so-called Goldstone bosons which give mass to the W and Z gauge bosons and thereby make the weak force weak. The same “wine bottle” or “Mexican hat” shape of potential is also used to describe Bose-Einstein condensation. Observing Higgs physics in quantum gases needs more than BEC, however.

Not all Mexican hat shapes describe the same physics. The curving surface *can* describe two distinct excitation modes, *if* it represents a potential energy  $V(x,y)$  in a two-dimensional *coordinate* space. If instead it is the full Hamiltonian  $H(x,p)$  in a 2D *phase* space, however, then this is the phase space of a single degree of freedom, and so there cannot be two separate Goldstone and Higgs modes. It is this second case that applies to condensates of point bosons.

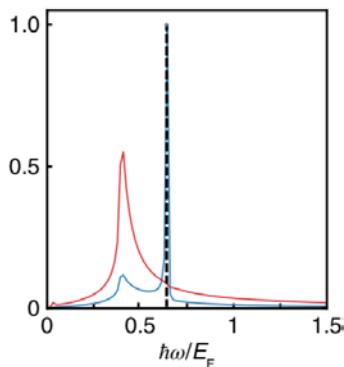
In a fermionic superfluid, however, the Cooper pairs which condense are *composite* bosons that can dissociate into unbound pairs of fermions or holes. Most dissociation channels are simply decay into a continuum of single-(quasi)particle excitations, but at least in a weakly interacting Fermi superfluid, there is one collective mode in which Cooper pairs at all momenta form and reform together, so that the BCS order parameter itself oscillates. This is the Higgs mode that a simple BEC lacks.

The Higgs mode of a Fermi superfluid is not easy to see, however. Only symmetry between particles and holes keeps it from coupling to all the continuum modes and dissolving among them. Particle-hole symmetry only holds near the Fermi surface, and since stronger interactions between

fermions bring modes farther from the Fermi surface into play, they can easily destabilize the Higgs mode.

Precisely what happens to the Higgs for strongly interacting fermions is in fact an important issue in superfluidity and superconductivity. The question has long defied not only theory but also experiment, because even where the Higgs mode is stable enough to observe, it is hard to excite it in preference to the continuum modes. What our OSCAR colleagues have now done, however, is to use an additional atomic state as a kind of reservoir into which interacting fermions can be shifted coherently. This at last allows clean excitation of the Higgs mode.

With the interaction strength of trapped fermions tuned from weak to strong, the broadening and ultimate dissolution of the Higgs mode have now been traced. OSCAR



has made a major contribution on a basic problem.

## Experimental realization of a Rydberg optical Feshbach resonance in a quantum many-body system

O. Thomas, C. Lippe, T. Eichert, H. Ott  
(OSCAR Project B2)

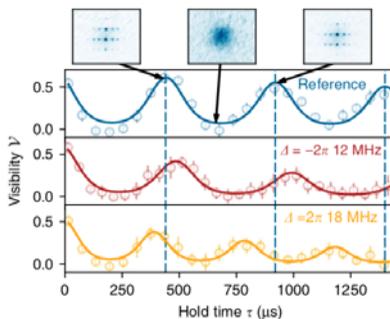
*Nature Communications* **9**, 2238 (2018)

When atoms collide elastically, without binding together into a molecule, the relative phase they acquire from the interaction depends on how closely they came, energetically, to a molecular bound state. A nearly resonant molecular state creates a large phase shift—which means a strong interaction.

Experiments can thus tune interaction strengths by shifting the energy of the molecular state, to bring it close to a scattering resonance. This can be done with magnetic fields, but only for some kinds of atoms. Other atoms can instead be made to approach a molecular state of much higher energy by absorbing a photon from a laser field. The problem here is that approaching the resonance closely tends to produce unstable molecules which break apart violently, so that the atomic gas has strong losses instead of strong interactions.

Our OSCAR colleagues have shown how to avoid this problem with optical Feshbach resonances, however, by using a special kind of molecular state: a long-range molecule in which a highly excited “Rydberg” electron from one atom wanders off to another atom several hundred Angstroms away. Although Rydberg states are highly excited, they actually decay much more slowly than less excited states, because the distant electron orbits slowly and hence radiates less. Molecular states of this tenuous kind therefore offer optical Feshbach resonances which can tune interaction strength without high loss.

The OSCAR B2 experiment has shown the method works with a beautiful proof. When interacting atoms are trapped in an optical lattice, their phases evolve at a frequency  $N\Omega$



given by their interaction strength  $\Omega$  times the number  $N$  of atoms in each lattice well. With these numbers varying across the whole gas sample, the phase disperses. The interference peaks that are seen when the gas cloud is released from the lattice therefore become fainter, the longer the atoms are held in the lattice before release, because their phases disperse more over time.

If the atoms are held longer still, though, their interference revives! The number of atoms is always an integer, and so the phases gained by atoms trapped in different-sized groups differ by integer multiples of  $2\pi$  whenever the hold time is an integer multiple of  $1/\Omega$ . Measuring interference revival time in lattice-held gas clouds thus measures the interaction strength. It directly confirms that optical Feshbach resonances with long-range Rydberg molecular states can indeed shift the atomic interaction strength substantially, allowing tunable interactions for a new range of atomic species.

## Fluorescence enhancement by dark plasmon modes

M. Peter, J.F.M. Werra, C. Friesen, D. Achnitz, K. Busch, S. Linden (OSCAR Project A3)

*Applied Physics B* **124**(5), 83 (2018).

A faintly playing music box becomes surprisingly loud when merely placed on a sounding board. The board is not just a boundary condition: its own vibrations resonate with the source, amplifying it. When this kind of environmental enhancement of small sources works well, it makes the difference between a cheap violin and a Stradivarius.

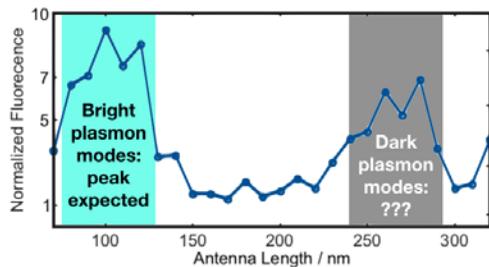
What works for sound can also work for light, just at much smaller sizes. The music box or bowed string becomes a colloidal semiconductor nanocrystal—a quantum dot—which fluoresces at sub-micron wavelengths; the sound board is now a nano-antenna. The sound board's vibrations are now the antenna's plasmon modes, coupled to the quantum dots by near-field electro-dynamics. The sound heard by the audience is now the electromagnetic far-field radiation. Building nano-antennas to amplify small electromagnetic signals is a basic capability for information technology on nano-scales.

Small sources do not all radiate efficiently. Plasmon modes which do not provide a varying electric dipole moment couple to the radiation field only through higher charge moments, lowering radiation power by a factor of order  $[(\text{antenna size})/(\text{wavelength})]^2$  or more. Dipole modes are therefore called *bright* while other modes are *dark*.

A dark plasmon mode should not only fail to amplify a nearby emitter with which it resonates: it should effectively quench the emitter. An excited plasmon mode in a nano-antenna is a current in a real conductor, and the energy which it cannot transmit as radiation is simply lost to resistance. So if a

resonant dark plasmon mode has strong near-field coupling to the fluorescent emission of a nearby quantum dot, one would expect the antenna to capture the fluorescent emission efficiently ... and convert it to heat.

So one would think, but it is not always so. Recent work by OSCAR colleagues has shown strong evidence of fluorescence *enhancement* in quantum dots, instead of the expected suppression, by a dark plasmon mode of a nearby nano-antenna. The observation is not paradoxical—dark modes are not generally perfectly dark, but only much less bright than bright modes, and the much-reduced strength of quadrupole radiation can still be enough to provide significantly enhanced quantum dot fluorescence. Nonetheless the effect shows a surprisingly clear victory of resonant amplification over electrical resistance, and



indicates that the opportunities for this kind of environmental control over small signal sources may be broader than previously hoped.