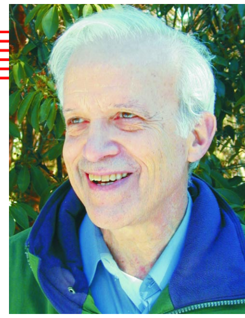

Professor Feshbach and His Resonance

Daniel Kleppner

Herman Feshbach's office at MIT was not far from mine, and so when I stumbled across the term "Feshbach resonance," it was natural to turn to him for an explanation. The phenomenon that piqued my curiosity was reported in a paper on the spectroscopy of the negative hydrogen ion. This ion had seemed an unlikely subject for spectroscopy because it has only one bound state. Nevertheless, an elegant experiment in the mid-1970s by Howard C. Bryant's group at Los Alamos revealed features in the photoionization spectrum, including a sharp line that the authors described as a Feshbach resonance. Hence my visit to Herman.

He was at his desk, happily smoking a cigar (this was quite a few years before smoking was banned). "Herman," I asked, "can you tell me what a Feshbach resonance is?" He leaned back, puffed thoughtfully on his cigar for a few moments and finally said: "Beats me!" Apparently he had never heard of the term, though possibly he was teasing—he had a waggish sense of humor. When I described the experiment, he recognized the phenomenon. Then, in a manner suggesting that atomic physicists must be pretty naive to attach someone's name—particularly his—to such a well-known effect, he volunteered that the term "Feshbach resonance" was mere atomic jargon.

A Feshbach resonance is an enhancement in the scattering amplitude of a particle incident on a target—for instance, a nucleon scattering from a nucleus or one atom scattering from another—when it has approximately the energy needed to create a quasi-bound state (more precisely, a state belonging to a closed channel) of the two-particle system. In the simplest case, the quasi-bound system decays into its original constituents and the scattering is elastic.

If a pair of ultracold atoms happens to have a bound state—otherwise known as a molecular state—close to zero energy, then during collisions they stick together for a little while as they undergo a Feshbach resonance. Few molecules actually have a bound state near zero energy, so such an event is extremely unlikely. However, if the atoms and molecules have different magnetic moments, then their relative energies can be shifted by applying a magnetic field, a technique called Zeeman tuning. If the atomic energy can be Zeeman-tuned from above the resonance to below it, the scattering length diverges, changing from positive to negative as the resonance is traversed. The scattering cross section, which is proportional to the square of the scattering length, can become enormous.

In the world of ultracold atoms, the scattering length itself is more important than the scattering cross section because the interaction between a pair of ultracold atoms is directly proportional to it. Atoms repel if the scattering length is positive and attract if it is negative. By making it possible to precisely control interactions, Feshbach resonances provide an exquisite tool for controlling the properties of atomic quantum fluids. As a result, Feshbach resonances are now at the very center of some extraordinary advances in ultracold atom research. They have provided a key for creating ultracold molecules and molecular Bose–Einstein condensates (BECs), generating solitons and atom–molecule coherences, stabilizing or destabilizing BECs, and creating novel Fermi liquids. Feshbach resonances have opened the way to a new world of quantum phenomena.

Among the treasures of this new world are molecular Bose–Einstein condensates, which have suddenly become a hot topic in many-body physics.

A little bit of history

The possibility for using a Feshbach resonance to manipulate interactions in atomic quantum fluids was pointed out in a seminal paper by Boudewijn Verhaar,[1] in 1993, several years before Bose–Einstein condensation became a reality. In 1998, in an experiment in which the scattering length in sodium was observed to vary by a factor of about 15, Wolfgang Ketterle observed a Feshbach resonance in a BEC.[2] Unfortunately, near the resonance, where the atoms could form molecules, the atoms rapidly disappeared. Such behavior was not unexpected because molecules created with a Feshbach resonance would be in a vibrationally excited state. In a collision, such a state would release enough vibrational energy to eject the collision partners from the trap that confined them. Thus, there was concern that even if a gas of ultracold molecules could be created, inelastic collisions would prevent the molecules from achieving the conditions for Bose–Einstein condensation. However, Nature is often kind to ultracold atoms, and Nature has been kind enough not only to permit molecules to undergo Bose–Einstein condensation, but to endow the condensed molecules with exceptionally attractive properties.

The possibility of creating ultracold molecules from a rubidium BEC condensate was demonstrated dramatically by Carl Wieman.[3] When he stepped the magnetic field close to a Feshbach resonance, a large fraction of the atoms disappeared, and when he stepped the field back, the atoms reappeared. In fact, it turned out that the number of atoms actually oscillated. The situation can be pictured as a two-state system: One state is atomic; the other, molecular. Near a Feshbach resonance, the states become coupled and the system oscillates, as expected in a coupled two-state system that is suddenly perturbed. The molecules in the Wieman experiment lived for about 100 μs, long enough to prove their existence, but not long enough to achieve Bose–Einstein condensation.

Subsequently, a number of groups created ultracold molecules from atomic BECs by carefully sweeping a magnetic field across a Feshbach resonance so that the system moved adiabatically from its atomic state to a molecular state. (To molecular physicists, this is known as a Landau–Zener

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transition.) However, collisions limited the molecular lifetimes to milliseconds and the atom–molecule conversion efficiency to about 5 percent. As a result, there has been no clear observation so far of the Bose–Einstein phase transition in molecules created from an atomic BEC.

A new player on the scene

The field of ultracold atoms moves rapidly and atomic Fermi fluids have now taken center stage. These are ultracold gases of alkali metal atoms such as potassium or lithium, whose nucleus has even integer spin. At low temperature, fermionic atoms in the same state do not collide: s-wave scattering is forbidden and p-wave scattering is negligible. Without collisions, however, atoms can neither thermalize nor be cooled by evaporation. Deborah S. Jin solved this problem in 1999. She cooled a system of potassium atoms in two magnetic substates to the Fermi-degenerate region.[4] Evaporative cooling worked like a charm because atoms in one substate could collide with atoms in the other substate. Last year, Jin converted the fermionic gas to the diatomic molecule by sweeping across a Feshbach resonance.[5] This experiment worked even better than one might have hoped, for about half the atoms were converted to molecules.

Then, in rapid succession, a number of groups working with both ^{6}Li and ^{40}K, found that molecules created from a two-component degenerate fermionic gas could be remarkably stable with lifetimes up to 1 second.[6] To add to the serendipity, it turned out that molecules could be created by a method even simpler than sweeping across a Feshbach resonance. Just holding the ultracold gas slightly above the molecular dissociation energy will enable the system to move to thermal equilibrium—essentially totally molecular—by converting atoms into molecules through collisions. As the number of molecules grows, those molecules abruptly undergo Bose–Einstein condensation, exhibiting the familiar pop-up in the momentum distribution that marks BEC in atoms.

Molecular condensates created from fermionic atoms are providing a new arena in which to study Fermi fluids. Although the onset of Fermi degeneracy is not signaled by a phase transition like Bose–Einstsein condensation, degenerate Fermi fluids can exhibit a phase transition that is every bit as dramatic. It is the atomic equivalent of a superconducting transition—a superfluid transition caused by the pairing of atoms whose momenta are correlated. These pairs form quasi-particles that Bose-condense, in analogy to the the formation of Cooper pairs and their condensation, as predicted by the Bardeen-Cooper-Schriefer (BCS) theory of superconductivity. The temperature of this superfluid transition is predicted to be vanishingly small for weakly interacting atoms, but if the interaction is strong—for instance, if it is increased by a Feshbach resonance—the transition temperature can move into an achievable regime (see PHYSICS TODAY, March 2004, page 21). The problem is of exceptional scientific interest: Strongly interacting Fermi fluids have never been studied in a system like an atomic quantum gas in which it is possible to precisely control every experimental parameter, including the interaction strength, and to image the systems with great clarity. Theoretical interest in the transition from BEC-like behavior to BCS-like behavior is strong, with a history[7] that originated long before the discovery of Bose–Einstein condensation.

Several groups are currently searching for a BCS-like transition that would lead to Cooper pairing.[8] The first step in exploring the crossover regime between BEC and BCS behavior is to increase manyfold the interaction in a two-component, ultracold Fermi-degenerate gas by operating near a Feshbach resonance. This system is then transformed from its initial two-component degenerate fermionic atomic state into its molecular state by sweeping across the resonance. The conversion of fermionic atoms into bosonic molecules introduces correlations in each pair of atoms because, in a diatomic molecule, momenta relative to the center of mass are exactly opposed. Momentum correlations in Cooper-paired particles extend over long distances, whereas correlations in a molecule are short range, so that the diatomic molecules do not constitute Cooper pairs. However, the molecules can be dissociated by moving the system back across the Feshbach resonance into the atomic regime. There is evidence that the momentum correlations persist above the normal atom–molecule transition threshold, although the transition threshold can be difficult to determine precisely. The search for superfluidity in atomic Fermi fluids is going full tilt, but whether Bose-condensed molecules provide the best starting point remains to be seen. In any case, fermionic atomic fluids will continue to occupy center stage for some time to come.

Unfortunately, Herman Feshbach died in 2000, before he could know that the Feshbach resonance would be the key to all these developments. He certainly would have been amused to see his name appear so widely, for he appreciated that the collisional resonance was a well-known effect. It was first analyzed by Eugene Wigner and then, in the context of photoionization, by Ugo Fano. Nevertheless, Herman would have been delighted to learn of this new inroad into many-body physics. For my part, I would have been thrilled to witness his reaction, for Herman was not only a great theorist and leader of the nuclear community, but also a great person. He was fiercely idealistic and fought for science and human rights throughout the cold war. He aided Andrei Sakharov during the dark years, helped found the Union of Concerned Scientists and the American Physical Society's panel on public affairs, and guided numerous international scientific organizations. So, when I see the term Feshbach resonance, I take pleasure in thinking of the physicist as well as the physics.

The theoretical underpinnings of Feshbach resonances in quantum fluids are described in a recent review,[9] but in a subject that is advancing as rapidly as this, one needs to consult the literature for latest results. I apologize to the many groups whose discoveries I could not discuss, and thank Chris Greene, Wolfgang Ketterle, and Vladan Vuletic for their helpful conversations with me.

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