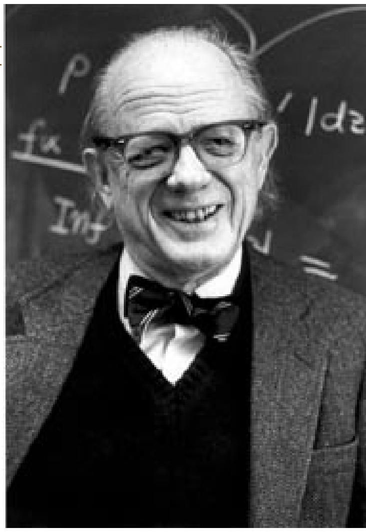
Resonating with Feshbach

Frank Wilczek

Herman Feshbach (1917–2000) is an MIT hero. He was on the faculty for more than 50 years, and chaired the physics department for 10 years. His accomplishments in scientific research and education were recognized with our nation's highest award for such work, the National Medal of Science, in 1986. You can read more about Feshbach's career highlights and the honors he gathered in his Wikipedia entry, *en.wikipedia.org/wiki/Herman_Feshbach*. Since it's encyclopedic, I won't have to be.

MY FIRST ENCOUNTER WITH FESHBACH was through his famous textbook, *Methods of Theoretical Physics*, co-authored with Philip Morse. (It has just been re-issued: *feshbachpublishing.com*.) This is an authoritative account, in two volumes of about 1,000 pages each, of the classic mathematical methods for analyzing continuum phenomena. As a student, two things in the book particularly impressed me. One was the second chapter, "Equations Governing Fields." In that chapter, the equations for vibrations of elastic media, motion of fluids, diffusion, electromagnetism, and quantum mechanics are derived and discussed, one after the other. Behold, they are basically the same equations! That demonstration, by convincing example, of the Unity of Physics made a



big impression on me at the time—and it still does. The other was the elaborate 3-D illustrations that pepper the book. Long before the best-selling *Magic Eye* series, Morse and Feshbach invited you to relax, cross your eyes, and see strange shimmering stereoscopic objects leap off the page. The equipotentials in oblate spheroidal coordinates came to life. Really.

Nowadays, probably Feshbach's most widely known contribution to physics is the concept known as "Feshbach resonance." This, too, has a Wikipedia entry, *en.wikipedia.org/wiki/Feshbach_resonance*. It is a subtle, beautiful phenomenon in quantum mechanics. (In principle, there is also a classical version, but it is not so important.) The underlying idea, familiar to all students of quantum mechanics, is that the existence of nearly stable bound states (that is, resonances) of two objects dramatically influences how those two objects interact when their total energy is near that of the bound state. Specifically, when the total energy of the objects is close to the energy of the resonance, they interact strongly, and their scattering cross-section becomes very large. Feshbach's novel observation was that if you could trade kinetic energy of the objects for excitation energy, *e.g.*, internal vibrations, you could bring them to a halt. Then, with the motion of the objects minimized, they'd be bound together even by weak attractive forces. By that strategy, you make a Feshbach resonance. [I said "you could" and "you make" just now, but of course I don't mean that literally. The point is, that the equations of quantum mechanics automatically explore the Feshbach resonance, as a so-called virtual state, without anyone having to intervene actively.] Thus the internal structure of the objects, which governs their possible excitation energies, is reflected in their interactions. Turning it around, by altering the internal structure, we can engineer their interactions and scattering properties. For example, we can use magnetic fields to tune atoms to interact in convenient or interesting ways.

"Feshbach resonance... is a subtle, beautiful phenomenon in quantum mechanics."

Feshbach resonance engineering is a central tool for producing Bose-Einstein condensates. It is now also used in many other creative ways to make atomic systems with interactions to order. At this frontier of physics, basic questions about the nature of superfluidity, the transition between insulating and conducting states, and many other classic issues of condensed matter physics can be addressed using experimental systems that are ideally clean and well characterized. Roughly speaking, and ignoring many practical challenges

Feshbach Resonance In Action

by Martin Zwierlein (PhD '06)

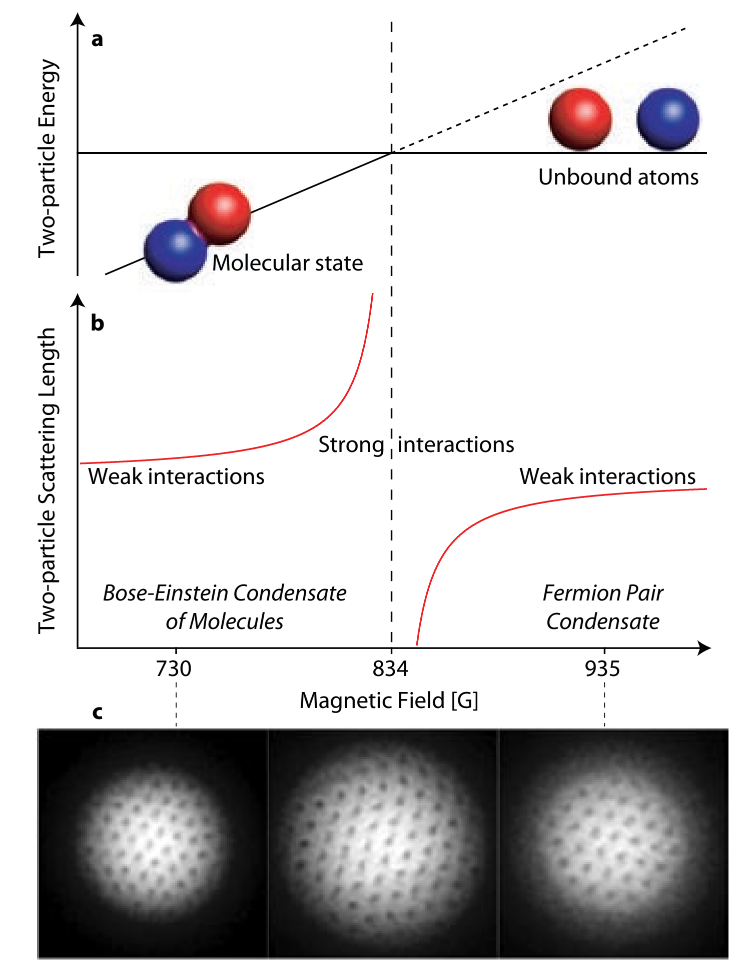
Feshbach resonances are a unique tool for the study of ultracold atoms. By the simple change of a magnetic field, the interactions between atoms can be controlled over an enormous range. This tunability arises from the coupling of free unbound atoms to a molecular state in which the atoms are tightly bound (*Figure a*). The closer this molecular level lays with respect to the energy of two free atoms, the stronger the interaction between them. Indeed, right on resonance the scattering length describing this interaction diverges (*Figure b*).

In gases of **FERMIONIC ATOMS** (those which are made out of an uneven number of protons, neutrons and electrons), such as Lithium-6, Feshbach resonances can be used to create fermionic superfluids. On the molecular side of the resonance, pairs of fermions can form stable molecules that are **BOSONS** (that is, they contain an even number of elementary particles). At low enough temperatures, these molecules will condense into one macroscopic matter wave, a Bose-Einstein condensate. As we cross the Feshbach resonance, the molecular state disappears and isolated atom pairs would not bind. Nevertheless, when embedded in the cloud of all the other atoms, two fermions can still form a loosely bound pair, whose size can become comparable to, or even larger than, the average distance between particles. A Bose-Einstein condensate of these fragile pairs is called a **BCS-STATE**, after Bardeen, Cooper and Schrieffer. This is what occurs in superconductors, in which current flows without resistance due to a condensate of electron pairs, *i.e.*, "Cooper pairs."

Figure c shows images of fermionic superfluids of Lithium-6 atom pairs at various interaction strengths near a Feshbach resonance. The gases have been set in rotation to reveal their superfluid character: they are pierced by a regular array of vortices—tiny quantum whirlpools—which is the way superfluids can carry angular momentum.

and complications, the Feshbach resonance idea gives us a way to make analog computers to simulate the effect of whatever interactions we're interested in, simply by setting up atoms to have those interactions. It may even be possible to make the atoms mimic nuclei, or quarks, and exploit them to solve the equations that govern neutron star interiors!

Looking even further ahead, there are visionary proposals to exploit our newfound control of the quantum world to build general purpose quantum computers that would accept "programs" to solve a wide variety of problems. Quantum computers would be very good, of course, at solving problems in quantum mechanics, such as the design of molecules with desired properties,



e.g., catalysts or even drugs. More surprisingly, they could be used to crack cryptographic codes.

How Herman Feshbach, with his appreciation for the unity of physics and the power of mathematics to understand and control Nature, would have loved all this! Adding further spice is the fact that Herman's primary inspiration for the Feshbach resonance came from an entirely different domain. Indeed, his specialty was not atomic physics, but nuclear physics. His quest was to understand the rich phenomenology of nuclear reactions. The wide-ranging consequences of his fundamental studies provide a wonderful case study in the value of curiosity-driven research.

Herman Feshbach's feeling for unity and harmony extended beyond the boundaries of physics, conventionally understood. He was among the founders of the Union of Concerned Scientists and its first chair. As president of the American Physical Society, he established a human rights committee, which intervened on behalf of oppressed physicists on both sides of the Iron Curtain. In these endeavors, he embodied the ideas that physicists are and ought to be responsible members of the civil society that surrounds them, and of humanity as a whole.

Professor FRANK WILCZEK *is considered one of the world's most eminent theoretical physicists. He is known, among other things, for the discovery of asymptotic freedom, the development of quantum chromodynamics, the invention of axions, and the discovery and exploitation of new forms of quantum statistics (anyons). When only 21 years old and a graduate student at Princeton University, in work with David Gross he defined the properties of color gluons, which hold atomic nuclei together.*

Professor Wilczek received his B.S. degree from the University of Chicago and his Ph.D. from Princeton University. He taught at Princeton from 1974–81. During the period 1981–88, he was the Chancellor Robert Huttenback Professor of Physics at the University of California at Santa Barbara, and the first permanent member of the National Science Foundation's Institute for Theoretical Physics. In the fall of 2000, he moved from the Institute for Advanced Study, where he was the J.R. Oppenheimer Professor, to the Massachusetts Institute of Technology, where he is the Herman Feshbach Professor of Physics. Since 2002, he has been an Adjunct Professor in the Centro de Estudios Científicos of Valdivia, Chile.

Professor Wilczek has been a Sloan Foundation Fellow (1975-77) and a MacArthur Foundation Fellow (1982-87). He has received UNESCO's Dirac Medal, the American Physical Society's Sakurai Prize, the Michelson Prize from Case Western University, and the Lorentz Medal of the Netherlands Academy for his contributions to the development of theoretical physics. In 2004 he received the Nobel Prize in Physics, and in 2005 the King Faisal Prize. He is a member of the National Academy of Sciences, the Netherlands Academy of Sciences, the American Philosophical Society, and the American Academy of Arts and Sciences, and has been a Trustee of the University of Chicago. He contributes regularly to Physics Today *and to* Nature, *explaining topics at the frontiers of physics to wider scientific audiences. He received the Lilienfeld Prize of the American Physical Society for these activities. Two of his pieces have been anthologized in* Best American Science Writing *(2003, 2005). Together with his wife Betsy Devine, he wrote a beautiful book,* Longing for the Harmonies *(W.W. Norton). His new book,* Fantastic Realities: 49 Mind Journeys and a Trip to Stockholm *(World Scientific) is currently rolling off the presses.*