Optically Trapped Fermi Gases Model Strong Interactions in Nature

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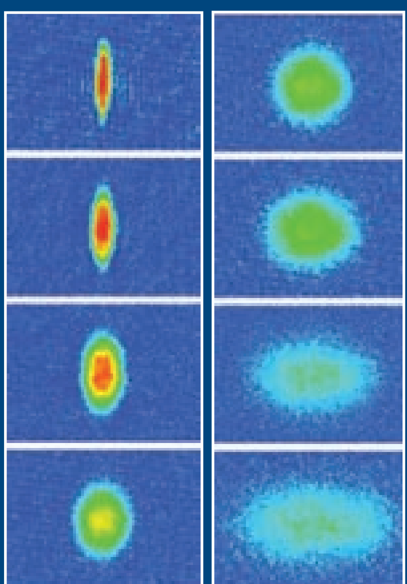
Ever since scientists first observed a degenerate, strongly interacting Fermi gas in 2002,[1] the field of interacting Fermi gases has made spectacular progress. Strongly interacting Fermi gases are produced in an optical trap, by using a magnetic field to tune them to a collisional (Feshbach) resonance.[1,2] In this regime, the gas exhibits remarkable properties, such as highly anisotropic expansion,[1] universal thermodynamics[1,3] and high-temperature superfluidity.[4,5]



Elliptic flow in an ultracold, strongly interacting Fermi gas, after release from an optical trap. (Top, left to bottom, right) Increasing time after release, 100-2000 μs. During free expansion into an ultrahigh vacuum, the gas remains nearly stationary in the vertical direction, while rapidly expanding in the horizontal directions. [From Ref. 1.]

Strongly interacting Fermi gases may even provide a model of the hydrodynamics in a quark-gluon plasma (QGP), a state of matter that existed microseconds after the Big Bang, when, it is believed, the universe comprised a superhot gas of quarks and gluons, which are fundamental constituents of all matter. Recently, physicists at the Relativistic Heavy Ion Collider (RHIC) in Brookhaven, N.Y., have reproduced the conditions for a QGP, producing temperatures of two trillion degrees Kelvin in a cigar-shaped plasma.

A signature of a QGP, and of minimum viscosity hydrodynamics, is the observation of "elliptic flow," a remarkable phenomenon in which the plasma expands much more rapidly in one direction than another. This type of flow is very different from that of an ordinary gas, which expands evenly in all directions. Elliptic flow arises when an initially cigar-shaped gas expands: The pressure gradient in the narrow direction is much larger than that in the long direction, producing the largest acceleration in the narrow direction. The result is that the cigar-shape is inverted after the gas expands, yielding an ellipse.

QGP physicists Ed Shuryak, Uli Heinz and Miklos Gyulassy noticed an amazing similarity between the elliptic flow observed in experiments at RHIC and the anisotropic expansion of an ultracold, strongly interacting Fermi gas of ^{6}Li atoms at temperatures 20 orders of magnitude colder. When released from a cigar-shaped optical trap,[2] the cloud expands rapidly in the narrow direction, while remaining nearly stationary in the long direction,[1] as shown in the figure. These Fermi gases permit studies of hydrodynamic flow over a wide range of temperatures, including both superfluid and strongly collisional regimes.[1]

In the past two years, groundbreaking studies by several groups have provided substantial evidence for high temperature superfluidity in strongly interacting Fermi gases,[4] including the observation of quantized vortices.[5] In these high-temperature superfluids, the transition temperature is a large fraction of the Fermi temperature, which sets the temperature scale at which degeneracy first occurs. Superfluidity arises from strong pairing between spin-up and spin-down atoms, analogous to the mechanism that is responsible for superconductivity in solids.

Measurements of the heat capacity and the damping of collective modes reveal transitions in behavior, close to the predicted superfluid transition temperature,[4] which is near 30 percent of the Fermi temperature. While the superfluid transition in the atomic gases occurs at a fraction of microKelvin, it corresponds to a transition temperature of several thousand degrees in a condensed matter system, where the Fermi temperature is much higher. Hence, these strongly interacting Fermi gases may provide new insights into mechanisms for high temperature superconductors.

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Spontaneous Ordering in a Cold Atomic Cloud

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Collective phenomena are frequently encountered in optics. Lasing and optical bistability are prominent examples. Ensembles of cold atoms subject to coherent unidirectional pumping represent further examples of spontaneously emerging macroscopic order.

Here, the collective behavior is triggered by atomic recoil; this contributes to a modulation in the atomic density, which gives rise to a coherent backward field. We show that this problem can be mapped onto that of synchronization of globally coupled oscillators—a very general phenomenon occurring in biological systems (e.g., fireflies), plasma and laser physics. In the problem we studied, the atomic position in the standing wave and the backward-field amplitude play the roles of the oscillator's phase and of the "mean field" coupling, respectively.

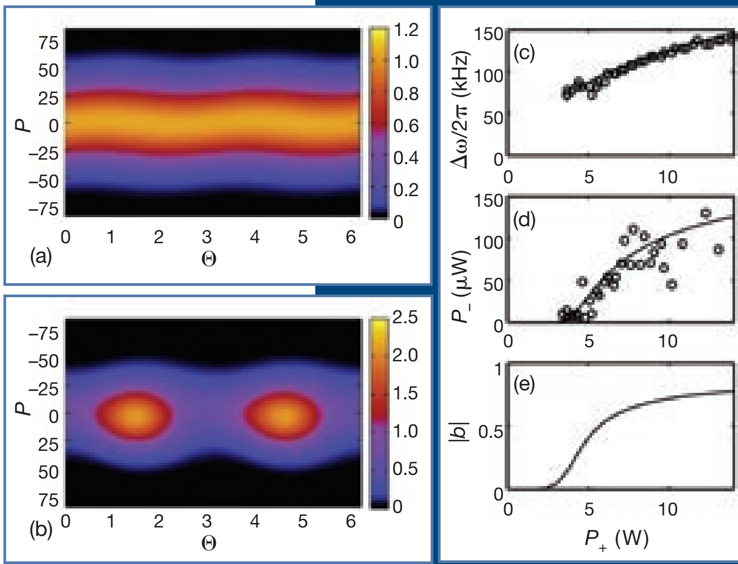
This effect was predicted several years ago and is known as Collective Atomic Recoil Lasing (CARL).[1] A clear physical understanding of it was gained by properly modeling the thermalization mechanisms.[2] As a result, it was possible to identify a genuine nonequilibrium phase-transition either below a critical temperature or above a critical injected field. These results motivated the first experiment that convincingly demonstrated the CARL transition.[3]

The setup consists of an 8.5-cm-long high-Q-ring cavity (finesse 80000). One of its two counterpropagating modes is resonantly pumped by a Ti-sapphire laser. We load ^{85}Rb atoms from a magneto-optical trap into the cavity mode. With typically 10^6 atoms, we achieve peak densities of 2×10^{11} cm^{-3} at a temperature of around 100 μK. With the additional influence of an optical molasses, when the injected field exceeds a critical power (see figure), red-shifted backward emission occurs. This relative shift increases with the distance from threshold.

The physical interpretation is the following: If the forward field is large enough, a spontaneously generated density grating is self-strengthened by giving rise to a larger backward-field through back scattering of the impinging light. Below threshold, instead, atomic diffusion unavoidably connected with optical molasses washes out the grating.

Expanding on previous work,[2] we developed a model to obtain a quantitative description of the experimental results.[4] By exploiting the large laser detuning at which the experiments were conducted and the global nature of the coupling, we developed a description in terms of a Fokker-Planck equation (FPe) for the single-atom probability distribution, thus allowing for the investigation of the combined action of the cavity fields, momentum cooling and spatial diffusion. This FPe is coupled to the cavity modes via the Maxwell equations.

This description allowed us to reproduce all the experimental features observed so far: threshold, red-shifted emission, and the dependences with respect to the atom's number, interaction strength and distance from threshold.



Phase space probability distribution slightly above (a), and far from threshold (b), derived from the FPe model. The atomic position and momentum are normalized to the photon wave vector and momentum, respectively. Dependence of the backward field frequency (c) and power (d), and of the spatial grating amplitude (e), on the pump power. Circles mark experimental results; the solid curves represent the best fit from the FPe model.

The structure of the resulting equations closely resembles that of the Kuramoto model,[5] a well-known and general dynamical system introduced to describe phase-synchronization in globally coupled rotators. This analogy opens the door to new and exciting perspectives and potential applications in samples of coherently pumped cold atoms.

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