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Experiments on the ferromagnetic behavior of atomic repulsive Fermi gases

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Summary. — Ferromagnetism is a pure quantum correlation phenomenon, and yet it is responsible for most magnetic phenomena that we encounter in everyday life. Metallic magnets, such as iron and nickel, owe their magnetic behavior to mobile conduction electrons, whose spins can align with one another giving rise to non-zero magnetization. In the 1930s, Edmund C. Stoner first devised a simple and minimal model, where a ferromagnetic instability of the homogeneous Fermi gas is afforded only through short-range repulsive interactions. While his model captures the fundamental physics behind itinerant ferromagnetism, various additional effects in solid materials, such as orbital couplings and peculiar band dispersions, make it difficult to isolate the Stoner mechanism. Here we present our experimental investigation performed on an ultracold Fermi mixture of ^{6}Li atoms where only genuine short-range repulsive interactions are present. Studying the stability of an artificially created ferromagnetic state, we provide a signature of a Stoner-like instability in a metastable system.

1. – Introduction

Can short-range repulsive interactions in a homogeneous Fermi gas drive a paramagnetic-to-ferromagnetic phase transition? The physics of itinerant ferromagnetism in solids can be intuitively described by the so-called mean-field Stoner model of a repulsively interacting two-component Fermi gas: [1]: once the repulsive interaction energy between electrons overcomes the kinetic energy, a ferromagnetic phase is energetically favored over a paramagnetic phase. This model is crucial to understand the magnetic properties of everyday life magnets, made of common metals like iron, nickel or cobalt [2,3]. In those materials the carriers of magnetism are the unsaturated d-band electrons, which are extremely mobile and can be thought of as a free gas with short-range repulsive interactions resulting from the screened Coulomb potential. The possibility that

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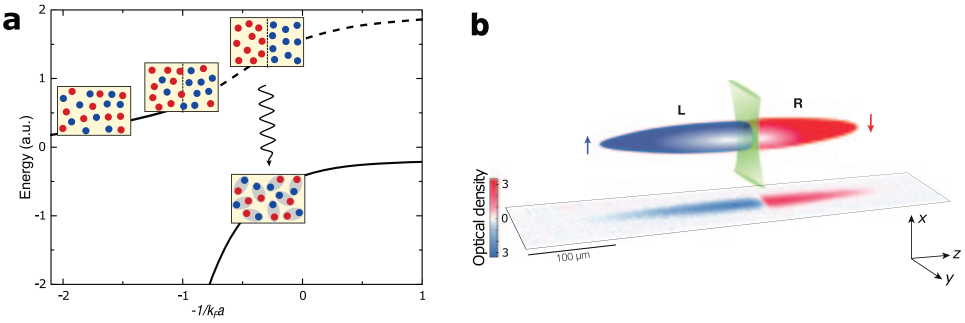

Fig. 1. – (a) Sketch of the lower (ground) and upper (excited) energy branches of a Fermi gas with short-range interactions in the vicinity of a Fano-Feshbach resonance. We prepare the system in the upper branch and we study the dynamics at different interaction strengths. As interactions increase, the system becomes unstable to the decay in the lower paired state. (b) Illustration of the system in the artificially created ferromagnetic configuration: the two spin components of the gas are kept spatially separated by a thin potential barrier. Below is shown an experimental density profile obtained via spin-resolved *in situ* absorption imaging. The figure is adapted from ref. [4].

repulsive interactions suffice to sustain ferromagnetism even in the absence of any additional ingredient, such as flat dispersion bands or multi-orbital exchange in solids is still nowadays debated. However, even with the unparalleled control and purity of ultracold atom experiments, evidences confirming Stoners mechanism for ferromagnetism have remained elusive [5, 6]. The main issue is that genuine short-range repulsive interactions, close to a Fano-Feshbach resonance, arise from the underlying attractive Van Der Waals potential, which supports a weakly bound molecular state [7]. As depicted in fig. 1(a), the energy diagram of the many-body system across the Fano-Feshbach resonance includes two energy branches: the repulsive (upper) branch and the attractive (lower) branch. For positive scattering length (repulsive interaction) the upper branch is unstable to the decay onto the lower paired branch via three-body recombination processes [8-11]. The Stoner model predicts with textbook calculation a ferromagnetic phase transition at an interaction strength of $k_F a \simeq \pi/2$, where k_F is the Fermi wave number and a is the scattering length. At this interaction level, the recombination rate to molecules is of the order of $E_F/\hbar$, with E_F being the Fermi energy. This timescale is so short that the gas has no time to stabilize magnetic correlations before decaying in the lower branch.

We tackle this problem following a new experimental approach. We initialise the gas in a state that closely resembles the fully ferromagnetic phase, two macroscopic domains containing only spin $\uparrow$ and spin $\downarrow$ particles respectively separated by few mean interparticle spacing. This strategy is very effective to reduce the adverse effects of inelastic processes, that can take place only at the domains interface. As a consequence, we are able to characterize the onset and the decay of this magnetic phase in such strongly repulsive Fermi systems.

2. – Experimental setup

Our system consists in an ultracold balanced mixture of ^{6}Li atoms, in its two lowest Zeeman states that we denote as $|\uparrow\rangle$ and $|\downarrow\rangle$. The temperature of the gas is controlled via an all-optical cooling procedure [12] and its final value ranges between $\sim 0.1\,T_F$

and $\sim 1\,T_F$, where $T_F = E_F/k_B$ is the Fermi temperature. At those temperatures only s-wave scattering processes are allowed, therefore the interactions can be effectively described by the single dimensionless parameter, $k_F a$, which can be experimentally tuned via a broad Fano-Feshbach resonance located around 832 G [13]. The gas is trapped in a cigar-shaped optical dipole potential consisting of two crossed red detuned laser beams, characterized by a harmonic confinement of $\nu_z \simeq 2\pi \times 21\,\mathrm{Hz}$ along the axial direction and $\nu_\perp \simeq 2\pi \times 260\,\mathrm{Hz}$ along the radial direction.

As sketched in fig. 1(a), we spatially separate the spin $|\uparrow\rangle$ and spin $|\downarrow\rangle$ components along the axial direction of the trap with a magnetic gradient and we superimpose at the interface between the two domains a thin repulsive barrier [14], created by shining a sheet of blue detuned light. Its thickness is of the order of $2\,\mu$m, corresponding to a few mean inter-particle spacing. The intensity of the repulsive barrier is high enough to make the spatial overlap between $|\uparrow\rangle$ and $|\downarrow\rangle$ wave function negligible, thus preventing the upper branch to undergo rapid relaxation processes. Before initiating the dynamics we change the Feshbach magnetic field to reach the target interaction strength $k_F a$.

3. – Observation of persistent magnetization

We start the dynamics by adiabatically removing the repulsive barrier, letting the two clouds slowly approach each other. We monitor the evolution in time of the magnetization ΔM, defined as

$$\Delta M = \frac{M_\uparrow - M_\downarrow}{2}, \tag{1a}$$

where $M_{\uparrow(\downarrow)} = (N_{\uparrow(\downarrow),L} - N_{\uparrow(\downarrow),R})/(N_{\uparrow(\downarrow),L} + N_{\uparrow(\downarrow),R})$, and $N_{\uparrow,L(R)}$ and $N_{\downarrow,L(R)}$ are the spin $|\uparrow\rangle$ and $|\downarrow\rangle$ populations in the left (right) reservoir. As plotted in fig. 2(a), the magnetization initially decreases from 1 to a value of ~ 0.92, then its decay stops and the system remains frozen in a ferromagnetic spatial configuration for a finite amount of time. After the initial diffusion, attributed to the atoms in the outer shell of the cloud where the local $k_F a$ is smaller, the repulsive interaction among the atoms at the interface between the two polarized regions provides a sufficient energy for the spin domain wall to be stable. In the absence of the molecular branch this configuration would be indefinitely stable [15]. Instead, a particle in the vicinity of the domain wall can tunnel on the other side forming a so-called repulsive polaron [16], that can tipically decay into a molecule. The higher is the interaction parameter $k_F a$, the slower is this process, since the energy cost associated with the creation of the repulsive polaron becomes higher. On the other hand, the spatial size of a dimer in the lower branch becomes bigger, making the molecular formation faster. The overall timescale depends on the competition between those two processes and affects the duration of the plateau τ_P in the magnetization [4].

In order to quantify the smallest interaction strength required to temporarily stabilize the domain wall, we measure the behavior of ΔM for different $k_F a$ and we define the critical interaction parameter $(k_F a)_c$ as the minimum value for which it is possible to observe a flat plateau in the magnetization. A further increase of the interaction strength leads to larger τ_P, until it reaches its maximum at unitarity, *i.e.* $1/(k_F a) = 0$. The duration of the plateau also depends on the temperature of the system: as the gas gets hotter, τ_P decreases. For temperatures higher than $\sim 0.7\,T_F$ we do not observe any plateau regardless of the value of $k_F a$. In fig. 2(b) we plot the measured critical interaction for different initial temperatures, dividing the temperature-interaction plane

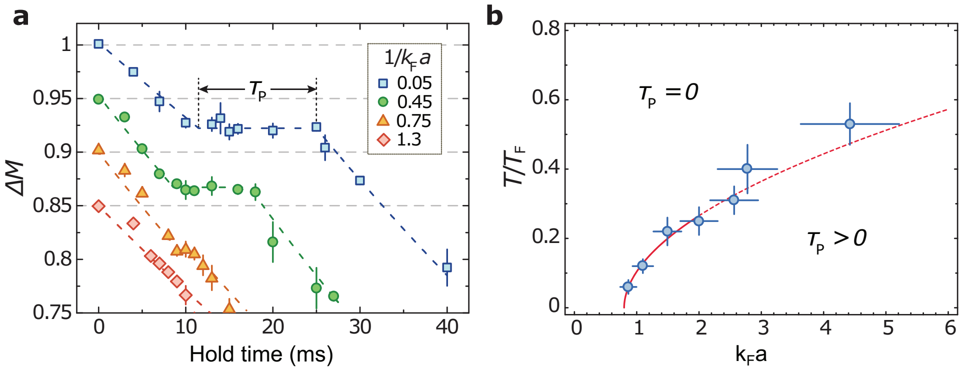

Fig. 2. – (a) Magnetization ΔM as a function of time after the barrier removal at $T/T_F = 0.12(2)$. The origin of time axis correspond to the removal of the optical barrier. The different colors, corresponding to different interaction strength, are artificially shifted on the vertical axis of 0.05 to improve the readability: the zero time point always corresponds to a full magnetized system $\Delta M = 1$. The error bars indicate the s.e.m of typically 5 independent measurements. (b) For each temperature, the data points indicate the minimum interaction $(k_F a)_c$ at which we observe a finite plateau in the magnetization. The shaded region indicates the parameter region where $\tau_P > 0$. The solid line shows the fit of the low temperature data points ($T/T_F < 0.3$) with the power law function of eq. (2), determined by the low temperature expansion of the critical interaction within Fermi liquid theory. This figure is adapted from ref. [4].

into two regions: the one where the magnetization exhibits a plateau ($\tau_P > 0$), and the other where the magnetization is strictly decreasing ($\tau_P = 0$). We fit the lowest-temperature points ($T/T_F < 0.3$) with the following power-law function:

$$\frac{T}{T_F} \propto \left[(k_F a)_c(\frac{T}{T_F}) - (k_F a)_c(0)\right]^{\alpha}, \tag{2a}$$

obtaining as result $\alpha_{fit} = 0.52(5)$ and $(k_F a)_c(0)_{fit} = 0.80(9)$. The fitted exponent matches the $\alpha_{FL} = 1/2$ value predicted by a Fermi liquid low-temperature expansion [4]. The fitted zero-temperature critical interaction is in agreement with the value obtained from Quantum Monte Carlo simulations [17, 18], while it is lower than Stoner's pure mean-field result.

4. – Conclusions

In this work we investigate itinerant ferromagnetism of a Fermi gas in the clean framework offered by ultracold atoms, exploiting a broad Fano-Feshbach resonance to realize and tune genuine short-range repulsive interactions. Our experimental strategy allows us to circumvent the influence of pairing processes and it provides a signature of a metastable Stoner-like ferromagnetic state, characterized by a time window during which the two polarized spin domains remain immiscible.

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