Comment on "Pairing and Phase Separation in a Polarized Fermi Gas"

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Partridge *et al*. (Reports, 27 January 2006, p. 503) reported pairing and phase separation in a polarized Fermi gas. We argue that it is not possible to distinguish the superfluid from the normal regimes in the presented data, or to discern which clouds were phase-separated. Some of the reported conclusions are inconsistent with recent experiments.

Partridge *et al*. (*1*) recently reported the observation of a quantum phase transition in a strongly interacting Fermi gas with imbalanced spin populations. Below a critical population imbalance, the study claims evidence for a homogeneous superfluid state with unequal densities. Above the critical population, it reports the observation of a core of superfluid pairs surrounded by a shell of excess spin-up atoms. We argue that the data presented in (*1*) do not unambiguously distinguish phase-separated from non–phase-separated clouds, and superfluid from normal clouds. The claims of a quantum phase transition at small polarization and of phase separation and superfluidity at large polarization are inconsistent with more detailed recent experiments.

It appears that the analysis in (*1*) was carried out without awareness that after double integration, a shell structure does not lead to a density profile with two peaks at the edges but to a flat top-hat distribution. As shown in (*2*), any spin distribution confined in a harmonic trap [with $n_\uparrow(\mathbf{r}) > n_\downarrow(\mathbf{r})$ and assuming local density approximation (LDA)] results in flat (*3*) or monotonically decreasing difference profiles. The single-peak structures found at small population imbalances in (*1*) are thus the expected outcome for any state of the gas, including phase-separated states. The results in (*1*) therefore bring into question the origin of the double-peak structures. The double peaks require a breakdown of either the LDA (sometimes called finite size effects) or the harmonic approximation. Because the LDA was generally expected to be valid for Fermi energies much greater than the energy level spacing of the trap, anharmonicities could have been a plausible explanation (*4*), given that they were not controlled or specified in the original study. However, characterization of the anharmonic trapping potential (*5*) has since ruled out this interpretation. Still, the general importance of anharmonicities in Fermi gas experiments should be noted (*4*). These experiments are usually carried out in traps with trap depths comparable to the Fermi energy. Therefore, anharmonicities have to be taken into account for any quantitative interpretation of density profiles and accurate determination of interaction energies from cloud sizes.

To demonstrate phase separation, that is, the presence of a fully paired core surrounded by a shell of excess atoms, one needs to show that the density difference of the two components abruptly changes from zero in the superfluid core to a finite value in the normal state. This requires stronger evidence than doubly integrated density profiles, such as a tomographic reconstruction of the three-dimensional (3D) density or a careful comparison with simulated profiles. In particular, it is necessary to distinguish between partial and full expulsion of the unpaired majority atoms (*6*), which was not done in (*1*, *7*). Mathematically, it is only possible to invert 1D profiles and reconstruct the 3D density if anharmonicities and deviations from the LDA are either absent or fully characterized. Given the breakdown of the LDA in the data in (*1*), it is mathematically impossible to infer whether the profiles shown represent phase-separated clouds or only distorted clouds. Therefore, our recent observation of the absence of phase separation at large population imbalances (*6*) is not inconsistent with the data in (*1*); it is inconsistent only with the interpretation in (*1*).

A breakdown of the LDA may be accentuated by phase separation but cannot be used as strong evidence for it. For example, a noninteracting Bose-Einstein condensate (BEC) strongly violates the LDA, and if it coexists with an interacting BEC, the difference profile may show double peaks without any interactions between the condensates. The cross-over from single-peak to double-peak profiles observed in (*1*) may indicate an increasing importance of LDA violation, but it does not provide evidence for a quantum phase transition. Indeed, recent more detailed experiments (*6*) have observed shell structures at small imbalances and seem to rule out the quantum phase transition claimed in (*1*).

Distorted density profiles do not imply superfluidity. Strongly interacting Fermi gases already show distorted profiles in the normal phase (*6*, *8*). It is only the observation of an abrupt change as a function of temperature that can indicate superfluidity and allows one to distinguish distortions due to superfluidity from those due to interactions present already in the normal phase. No such changes in the density profiles were reported in (*1*). We recently found that a density change at the phase transition occurs only as a small feature in the clouds' center (*6*, *8*). The phase transition from a superfluid to a normal state at a population imbalance around 0.75 was not detected in (*1*) but has now been seen using three different methods (*6*–*8*). This implies that the observation methods used in (*1*) were either not sensitive to superfluidity or that the behavior of the sample was dominated by finite size effects. Partridge *et al*. emphasized the good agreement of the cloud size with theoretical predictions as evidence for superfluidity. However, the cloud size is not expected to vary strongly as the temperature is increased above the phase transition temperature, as observed for imbalanced mixtures in (*7*).

In conclusion, Partridge *et al*. reported interesting results about interaction-induced redistributions of atoms that have been linked to the breakdown of the LDA. However, we do not believe that the claimed observations of pairing, of a quantum phase transition, and of a superfluid core surrounded by a shell of excess spin-up atoms are supported by the presented data.

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References and Notes

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