Expansion of a Fermi gas interacting with a Bose-Einstein condensate

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(Dated: March 14, 2021)

We study the expansion of an atomic Fermi gas interacting attractively with a Bose-Einstein condensate. We find that the interspecies interaction affects dramatically both the expansion of the Fermi gas and the spatial distribution of the cloud in trap. We observe indeed a slower evolution of the radial-to-axial aspect ratio which reveals the importance of the mutual attraction between the two samples during the first phase of the expansion. For large atom numbers, we also observe a bimodal momentum distribution of the Fermi gas, which reflects directly the distribution of the mixture in trap. This effect allows us to extract information on the dynamics of the system at the collapse.

PACS numbers: 03.75.Ss, 03.75.Kk, 67.60.-g

The dynamics of dilute quantum gases released from a trapping potential, has provided crucial information on the interaction properties of such systems. For instance, the anisotropic expansion of a Bose-Einstein condensate (BEC) gave the first direct evidence of the role of the boson-boson interaction and provided an important test of the validity of the hydrodynamic equations for a collisionless superfluid [1, 2]. Also two-component Fermi gases at Feshbach resonances have been recently found to exhibit a large anisotropic expansion [3, 4] which can be described by hydrodynamic equations [3, 5]. This has confirmed the achievement of a strongly interacting Fermi gas, which is one of the requisites for fermionic superfluidity. So far the experimental study of the expansion of quantum gases has been focused essentially on systems composed by one- or two-component gases of either bosonic or fermionic nature. Here we extend the study to a Fermi-Bose system in the collisionless regime. We use a two-species mixture composed by potassium and rubidium atoms which exhibits a large interspecies attraction ($a_{BF} = -410_{-80}^{+80} a_0$). We have already found a modified expansion of the condensate in the mixture [3]. We now study in detail the behavior of the Fermi gas and we observe an anisotropic expansion in the presence of a BEC. In particular, we find a slower evolution of the radial-to-axial aspect ratio, which is mainly due to a dynamical trapping potential produced by the bosons during the early stage of the expansion. We also observe an enhancement of the effect increasing the overlap of the two clouds in trap and, for a large number of condensed atoms, we find a bimodal momentum distribution of the expanded fermions which reflects directly their initial spatial distribution in trap. Finally, we perform a study of the expansion at the onset of the collapse of the Fermi gas [6], which is reached for even larger atom numbers in the mixture. This provides information on the new equilibrium state reached by the fermions after the collapse and on the timescale for the equilibration.

The procedure for creating an ultracold Fermi-Bose mixture of $^{40}$K-$^{87}$Rb atoms has been described in detail in Ref. [8]. We cool typically a few $10^4$ fermions and up to $10^5$ bosons to the quantum degenerate regime. Both species are trapped in their stretched spin states, $|F = 9/2, m_F = 9/2 \rangle$ for K and $|2, 2 \rangle$ for Rb. These states experience the same trapping potential, with axial and radial harmonic frequencies $\omega_a = 2 \pi \times 24 \text{s}^{-1}$ and $\omega_r = 2 \pi \times 317 \text{s}^{-1}$ for K, while those for Rb are a factor $(M_{Rb}/M_K)^{1/2} \approx 1.47$ smaller. For our experimental parameters, the Fermi temperature for K is of the order of $T_F = 300 \text{nK}$ and the critical temperature for BEC of Rb is $T_c = 150 \text{nK}$. The experiments described here have been performed at the lowest detectable temperature of the mixture, corresponding to $0.2 T_F$ for fermions and $0.65 T_c$ for bosons. To study the expansion of the two species we suddenly switch off the magnetic confinement and we detect the mixture at different expansion times $t_{exp}$ by means of two-color absorption imaging. From the imaging, we determine simultaneously the radial-to axial aspect ratio of both samples.

In a first experiment, we have studied the time evolution of the aspect ratio of the Fermi gas interacting with a BEC. As shown in Fig. [1] during the expansion the aspect ratio is always smaller than that measured for a Fermi gas coexisting with a dilute thermal cloud of bosons. The condensate, on the contrary, inverts its aspect ratio more rapidly in presence of the Fermi gas. As we have already discussed [8], the expansion of bosons reveals an enhancement of density of the two gases in trap due to the interspecies attraction, which results in an effective tighter confinement. Indeed, if one assumes that also the interaction is switched off at the release from the trap, this would lead to a faster evolution of the aspect ratio. On the contrary, the observed behavior of the Fermi gas gives now evidence that the mutual attraction felt by the two species after the magnetic confinement is switched off, plays a crucial role in the expansion dynamics. Indeed, during the early stage of the expansion, each of the two gases experiences a time-dependent trapping
FIG. 1: Modification of the expansion of a K Fermi gas due to the interaction with a Rb BEC. The radial-to-axial aspect ratio of a cloud of $4 \times 10^4$ fermions evolves more slowly in presence of $3.5 \times 10^4$ condensed bosons (solid circles) than in presence of a similar number of uncondensed bosons (open circles). Each data point is the average of five or six measurements. The y-axis has been rescaled to take into account a distortion of our imaging apparatus. The dashed line is the calculated expansion of a pure Fermi gas, while the solid line is the prediction for an interacting Fermi gas [12].

potential produced by the other species. In this phase the negative interaction energy is converted into kinetic energy which, in general, can be unevenly distributed between the two samples. Fig. 1 shows that, in this system, the Fermi gas is taking a large part of the interaction energy, which results in a largely reduced kinetic energy in the radial direction, and therefore in the slower evolution of the aspect ratio. This interpretation is confirmed by a comparison with the theoretical study of the expansion of a Fermi-Bose mixture presented in Ref. [10]. As shown in Fig. 1 the observed evolution of the aspect ratio of the Fermi gas is qualitatively well reproduced by the theoretical prediction (solid line) calculated in the collisionless regime. Note that this is actually the regime of our system, for which we measure a collisional rate smaller than the trap frequencies [11].

We stress that our results reveal that the two species experience differently the interspecies attraction due to their different density distributions and energy scales. Indeed, the Fermi gas is dominated by the attraction during the early phase of the expansion while the evolution of the condensate is mostly affected by the modification of the in-trap profile. This kind of phenomenology is clearly not accessible in a two-component mixture with a single density distribution. The numerical analysis of Ref. [10] and our experimental results suggest that the interspecies interaction affects not only the expansion velocity of the Fermi gas but also the asymptotic value of its aspect ratio. To understand the general behavior, we derive an analytic expression of the asymptotic value of the aspect ratio using a scaling approach [12]. Following Ref. [10] and to first order in $\epsilon = \omega_a/\omega_r$, we assume that the radii of the bosonic cloud evolve in the radial direction according to

$$R_b^r(t) = R_b^r(0)\sqrt{1 + (3\omega_r^r)^2 t^2},$$

where $\beta$ is an effective renormalization of the bosons trap frequency $\omega_r^r$, and in the axial direction like $R_b^a(t) \approx R_b^a(0)$. For our cigar shaped harmonic trap, we find that the aspect ratio approaches an asymptotic value

$$\frac{R_r}{R_a} \to \frac{\alpha}{\sqrt{1 - \frac{3}{2} \lambda}},$$

where $\omega_r^r = \alpha \omega_r$ is the effective trap frequency of the fermions in the radial direction, with $\alpha^2 = (\beta^2/3\chi_r)(1 - \sqrt{1 - (6\chi_r - 9\chi_r^2)\lambda^4/\beta^4})$ and $\lambda = \omega_r/\omega_r^r$. The coupling function $\chi_{i=(a,r)}$ characterizes the interspecies interaction:

$$\chi_i = \frac{E_{int}}{E_{ho}} + \frac{g_{bf}}{E_{ho}} \int d^3 x \frac{\partial n_f}{\partial x} x_i n_b,$$

with $E_{int} = g_{bf} \int d^3 x n_f n_b$, $E_{ho} = \int d^3 x V_{ho} n_f$, and $V_{ho}$ the harmonic confinement. Eq. 1 shows that the expansion of the fermions is directly coupled to the one of bosons via the parameter $\beta$. The aspect ratio reaches a value which depends only on the interaction with the condensate in trap and on $\beta$. Note that Eq. 1 reduces to the one found in Ref. [5] for two coupled clouds with the same density distribution ($n_b = n_f$). In this case, the coupling function takes the simpler form $E_{int}/E_{ho}$ and, for an attractive interaction, the aspect ratio of the two clouds approaches always a value smaller than one. In a Fermi-Bose mixture, this result is no longer true and the asymptotic value for the Fermi gas can be smaller or larger than one, depending on the bosons expansion and on the coupling function $\chi$. For our specific parameters, we find that $R_r/R_a \to 0.8$, which is smaller than one, in accordance with our experimental results [14]. Note that Eq. 1 indicates that in general it is not possible to extract the sign of the interspecies interaction just from the asymptotic value of the aspect ratio.

We have investigated how the expansion of the Fermi gas depends on the atom numbers in the mixture. We find that the aspect ratio decreases reducing the number of fermions at a constant number of bosons, as shown in Fig. 2(a). This behavior is not surprising because a decrease on $N_F$ corresponds on the one hand to a reduction of the overall density and therefore of the interaction energy. On the other hand it leads to a decrease of the Fermi radius ($R_F \propto (N_F)^{1/3}$), resulting in a better spatial overlap of the two samples. An alternative way to increase the extension of the overlap region is to increase $N_B$ at constant $N_F$ which also leads to a larger density in the overlap region. In this case, we observe the appearance of a double distribution in the radial profile of fermions with a narrow peak surrounded by a broader
FIG. 2: Aspect ratio of the Fermi gas at 8 ms of expansion varying the atom numbers in the mixture. The interspecies overlap region is enhanced either (a) decreasing $N_F$, for $N_B \approx 6 \times 10^4$ or (b) increasing $N_B$ with $N_F \approx 2.4 \times 10^4$. Above $N_B = 6 \times 10^4$, we observe the appearance of a bimodal radial (see Fig. 2(b)). The aspect ratio of the central component (solid triangles) is obtained fitting both the radial and axial distribution with a two-peak gaussian function. The dashed lines indicate the nominal value of the aspect ratio for a pure Fermi gas.

distribution, as illustrated in Fig. 3. This double distribution gives the first direct evidence of the enhancement of the fermions density in trap arising from the attraction with bosons. We attribute indeed the narrow distribution to the fermions trapped into the condensate while the broader distribution is occupied by the more energetic atoms outside the overlap volume. Only the central component experiences the trapping potential produced by the bosons during the first phase of the expansion and its expansion is slowed down accordingly. The other component instead expands normally. The momentum distribution therefore reflects the spatial distribution in the trap. Note that, in absence of an interspecies attraction during the expansion, the effect in trap would vanish in a characteristic time of the order of $1/\omega_r$ and one could detect the enhancement of density only studying the spatial distribution in trap, which is not experimentally accessible. We observe the bimodal distribution only in the radial direction, confirming that the interaction energy between the two clouds is exchanged mainly in the more tightly confined direction [1, 3].

In Fig. 2(b), we show a quantitative study of the aspect ratio of fermions in the regime of large boson number. For low $N_B$, where we are not able to distinguish the two distributions, the aspect ratio is only moderately affected by the Bose-Fermi interaction. For sufficiently large $N_B$, the two different distributions become visible and we can measure the aspect ratio of just the fraction of fermions interacting with the bosons. In this case, we detect a reduction of the aspect ratio down to one half of the non-interacting value.

Finally, by further increasing the atom numbers in the mixture, we study the aspect ratio of the Fermi gas at the occurrence of the collapse. We recall that an instability of the Fermi gas appears in this system when the interspecies attraction is no longer balanced by the Pauli repulsion [9]. In our system, the collapse is detected as a sudden drop of $N_F$ to typically less than half its original value. We now observe that, after the col-
Ref. [9]. As shown in Fig. 4, increasing the collapse for the measurements already reported in the evolution of the aspect ratio of the fermions across the experimental. To investigate the timescale of the strongly out of the equilibrium which we do not observe with a larger aspect ratio, or to an oscillating Fermi gas remaining fermions are mostly located in the outer region, the condensate are lost through inelastic processes while the exactly the fermions in the high density region within the expansion from the trap. Our observation is somehow surprising, since one could expect that during the collapse the system has reached a new equilibrium distribution in which most of the fermions are immersed in the condensate feeling a large interspecies interaction during the expansion from the trap. Our observation is somehow surprising, since one could expect that during the collapse the fermions in the high density region within the condensate are lost through inelastic processes while the remaining fermions are mostly located in the outer region. This would correspond either to a faster expansion with a larger aspect ratio, or to an oscillating Fermi gas strongly out of the equilibrium which we do not observe in the experiment. To investigate the timescale of the equilibrium process of the Fermi gas, we have analyzed the evolution of the aspect ratio of the fermions across the collapse for the measurements already reported in Ref. [9]. As shown in Fig. 4 increasing $N_B$ we first observe a small decrease of the aspect ratio followed by a jump to a lower value just in correspondence to the collapse. The aspect ratio then slowly tends to the unperturbed value as the BEC is completely evaporated. Since we invariably see a smaller aspect ratio just after the collapse, we can conclude that the system finds a new equilibrium distribution in a time scale smaller than 50 ms, which is our effective time resolution in the experiment.

In conclusion, we have studied the effect of the attractive interaction with a BEC on the expansion of a Fermi gas. We observe an anisotropic expansion of the cloud which consists in a slower evolution of the aspect ratio which approaches an asymptotic value smaller than the unity. The opposite behavior that we find for the BEC and, most of all, the observation of a bimodal momentum distribution of the Fermi gas confirm that the phenomenology of a system composed by two species with different spatial distribution is much richer of than that expected for a one distribution gas. Here we also show that the peculiar expansion of the Fermi gas can be used to extract information on the atoms which are overlapped with the BEC in trap. In future experiment it would be interesting to study the expansion of the mixture at the crossover from the collisionless to the hydrodynamics regime by tuning the interaction via Feshbach resonances. These study on strongly interacting Fermi-Bose mixture can be relevant also for the recently observed mixtures of fermionic atoms and condensed bosonic molecules.

We are grateful to X. J. Liu, H. Hu, M. Modugno and H. Ott for fruitful discussions and to F. Riboli for contributions to the experiment. This work was supported by MIUR, by EU under the Contract HPRICT1999-00111, and by INFM, PRA “Photonmatter”.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Fig4}
\caption{Evolution of the aspect ratio of the Fermi gas (solid triangles) and of the number of bosons (empty circles) and fermions (solid circles) at the collapse. During the final stage of the bosons evaporation, the aspect ratio decreases, and suddenly drops to a much lower value after the collapse (highlighted region). The aspect ratio is measured at 5 ms of expansion and the error bars are the standard deviation of different measurements.}
\end{figure}

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