Fermi-Bose quantum degenerate ^{40}K-^{87}Rb mixture with attractive interaction

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We report on the achievement of symultaneous quantum degeneracy in a mixed gas of fermionic ^{40}K and bosonic ^{87}Rb. Potassium is cooled to 0.3 times the Fermi temperature by means of an efficient thermalization with evaporatively cooled rubidium. Direct measurement of the collisional cross-section confirms a large interspecies attraction. This interaction is shown to affect the expansion of the Bose-Einstein condensate released form the magnetic trap, where it is immersed in the Fermi sea.

The recently demonstrated quantum degeneracy of Fermi-Bose (FB) mixtures of dilute atomic gases [1–3] promises to further enrich the fascinating field of physycs of degenerate matter at ultralow temperatures [4,5]. When a Bose-Einstein condensate (BEC) interacts with a Fermi gas, novel phenomena can occur. The most appealing is certainly BCS-like fermionic superfluidity, since BEC could affect interactions between fermions [6,7]. Furthermore, different FB interaction regimes could allow studies of phase-separation [8,9] or of the stability properties of the binary mixtures [10].

The mixtures so far reported have in common the use of fermionic ^{6}Li, combined with a BEC of the other isotope [1,2], or of ^{23}Na [3]. For the ^{6}Li-^{7}Li mixtures the FB interaction is repulsive, with possible consequences on the separation of the components, and eventually on the thermal contact. For the ^{6}Li-^{23}Na case, the interaction has not been measured, however the theoretical predictions are again in favour of a repulsive character [11]. A different, promising scenario would be offered by mixtures combining ^{40}K with ^{87}Rb. Indeed, precise ^{41}K-^{87}Rb interspecies collisional studies at ultralow temperatures [12], allowed to infer an attractive character for the interaction of the ^{40}K-^{87}Rb pair. In addition, the scattering length is large and, as a consequence, sympathetic cooling of ^{40}K should be as efficient as in the case of BEC of ^{41}K [13]. This would lead to a K-Rb FB degenerate mixture with ^{40}K, early brougth to quantum degeneracy with a single-species experimental configuration [14]. This new combination, with a different interaction character, would be extremely interesting, for instance because the absence of a phase separation could allow efficient cooling well below the Fermi temperature. Also, new phenomenology on the structure and stability of the system has been recently predicted as a consequence of the attractive interaction for this mixture [15].

In the present Letter, we report the production of such a novel macroscopic quantum system, in which a degenerate ^{40}K Fermi gas, composed by more than 10^4 atoms, coexists with a ^{87}Rb Bose-Einstein condensate of up to 5×10^4 atoms. In this experimental approach, evaporatively cooled bosons are used as a refrigerator for the Fermi gas. Also for these two species, sympathetic cooling demonstrates to be particularly efficient in overcoming the impossibility of a direct evaporative cooling in a single component Fermi gas [16].

We produce the degenerate mixture using the apparatus described in Ref. [13]. In brief, about 10^5 ^{40}K atoms and 5×10^8 ^{87}Rb atoms at a temperature around 100 μK are loaded in an elongated magnetostatic trap using a double magneto-optical trap apparatus. Differently from the ^{41}K case [13], magneto-optical trapping of ^{40}K with ^{87}Rb is efficient, as was also shown in Ref. [17]. Prior to magnetic trapping, both species are prepared in their doubly polarized spin state, $|F = 9/2, M_F = 9/2\rangle$ for K and $|F = 2, M_F = 2\rangle$ for Rb. They experience the same trapping potential, with axial and radial harmonic frequencies $\omega_a = 2\pi \times 24$ s^{-1} and $\omega_r = 2\pi \times 317$ s^{-1} for K, while those for Rb are a factor $(M_{Rb}/M_K)^{1/2} \approx 1.47$ smaller. Evaporative cooling is performed selectively on the Rb sample while the K sample is sympathetically cooled through elastic interspecies collisions. Differently from the scheme used for the boson-boson mixture, where microwave radiation had to be used to selectively evaporate rubidium, here the different gyromagnetic factors of the two species allow the simpler radio-frequency evaporation scheme to be implemented [18].

With an evaporation ramp lasting about 25 s we are able to cool typically 2×10^4 K atoms and 10^5 Rb atoms to below 1 μK. Sympathetic cooling of ^{40}K with Rb is very efficient, with a large ratio of "good" elastic collisions to "bad" inelastic collisions. We have measured the interspecies cross-section by performing a rethermalization measurement at a temperature around 400 nK, where both species are still thermal gases. We drive the mixture out of equilibrium

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with a short parametric heating phase, selective on Rb [12], and we observe the subsequent heating of K, which is mediated by elastic interspecies collisions. For a K sample composed by 1.2×10^4 atoms, coexisting with 5×10^4 Rb atoms we measure a short thermalization time τ=57(20) ms. At these ultralow temperatures the collisions proceed almost exclusively along the s-wave channel and, following the model discussed in [12] τ is linked to the scattering length a through

$$\frac{1}{\tau} = \frac{4\pi a^2 \xi \bar{n} v}{\alpha_s k_B T}, \tag{1}$$

where $\bar{n} = (\frac{1}{N_K} + \frac{1}{N_{Rb}}) \int n_K n_{Rb} d^3x$ is the effective density of K and Rb atoms, v is their relative velocity, $\xi \approx 0.86$ is a factor which takes into account the different mass of two colliding atoms, and $\alpha_s \approx 2.7$ is the average number of collisions needed for thermalization. Even thought K atoms cannot thermalize between themselves, since s-wave collisions are forbidden for identical fermions, the thermalization with Rb happens on a timescale longer than the mean period of oscillation in the trap which assure thermalization of the K sample. Actually we have observed that both density and momentum distribution have gaussian profiles that lead to the same temperature. From the measured τ we derive a quite large magnitude for the ^{40}K-^{87}Rb scattering length: $|a|$=300(100) a_0. Here the uncertainty is dominated by that on τ and by a 40% uncertainty on the atom number. The direct measurement with the fermionic isotope is in very good agreement with the value a=-261^{+170}_{-159} a_0 that we previously inferred by mass-scaling from collisional measurements on the bosonic ^{41}K-^{87}Rb mixture [12]. The measurement of a large value for $|a|$ also confirms the *attractive* character of the interaction, since a positive scattering length would have been compatible only with a much smaller magnitude [13].

By further cooling the mixture we have evidence of the formation of a degenerate Fermi gas coexisting with a Bose-Einstein condensate. In Fig. 1 we report a series of absorption images of the mixture for three different final energies of the evaporation ramp, which reveals the different nature of the two degenerate gases. Both samples are imaged in the same experimental run, by using two short, delayed light pulses. The images are taken after a balistic expansion appropriate to measure the momentum distribution of the samples; in particular the expansion lasts 4.5 ms for K and 17.5 ms for Rb. Sections of such images are also reported: they are taken along the vertical direction for K, and along the horizontal direction for Rb. With our experimental parameters, we have a Fermi temperature T_F=250 nK and a critical temperature for BEC T_c=110 nK for of a sample composed by 10^4 and 2×10^4 atoms, respectively.

A thermometry of the system is provided by the bosonic component, assuming thermal equilibrium between the two components. As the temperature is decreased by almost a factor of two (from top to bottom in Fig. 1), Rb undergoes the phase-transition to BEC, while the width of the fermionic component remains almost constant. A fit of the coldest K cloud with a Thomas-Fermi profile [19] gives a radius R=52 μm, which is consistent to within 10% with the minimum radius allowed by Fermi statistics: $R = R_F\sqrt{1+\omega_r^2\tau^2}$, where $R_F = \sqrt{2k_BT_F/(M\omega_r^2)}$ is the Fermi radius and τ is the expansion time. The *quasi-pure* condensates in Fig. 1 contains less than 40% of thermal fraction, indicating that the temperature of the Fermi gas is about T=80 nK, corresponding to 0.3 T_F. We note that at these temperatures the lifetime of each of the two species is not affected by the presence of the other one, indicating the absence of relevant inelastic collisional channels.

A further evidence of the achievement of quantum degeneracy is obtained by studying the gaussian $1/e$ width of the fermionic sample as a function of temperature. As shown in Fig. 2 the square of the width, normalized to R_F, scales linearly for $T > T_F$, indicating thermal equilibrium between K and Rb. Below T_F, the data deviate from the behavior expected for a classical gas, and indeed they are better reproduced by the prediction of the model for an ideal Fermi gas [19].

It is worth noting that we have also observed degenerate mixtures in which the thermal fraction of the condensate was below our detection limit of nearly 30%, hence the attainment of temperatures lower than those reported cannot be excluded. However, boson thermometry is no longer working in this regime, and different techniques would be necessary to investigate the evolution of sympathetic cooling when both species are well below their critical temperatures.

In the present experiment we have a clear evidence of thermal contact between the two degenerate species, also when no thermal cloud is detectable for Rb. This evidence is obtained by leaving the degenerate mixture in the magnetic trap for a relatively long time after the end of the evaporation. The Rb temperature is kept constant by means of a radio-frequency shield, but the background heating ($\approx$ 100 nK/s) caused by fluctuations in the magnetic field, continuously removes atoms from the BEC. This is illustrated in Fig. 3, together with the symultaneous behavior of K. The evolution of the width of the fermionic distribution indicates that K starts to heat up only when Rb is almost completely evaporated from the trap. Although, as shown in Fig. 2, the gaussian width is not a sensitive "thermometer" at low temperatures, the results reported in Fig. 3 are significant. Indeed, should K be thermally decoupled from Rb, its heating at the observed rate would manifest already after 1 s even in the extreme case of a starting temperature $T << T_F$.

It is instead difficult to state whether the thermal contact is direct or mediated by a possible, undetected thermal cloud. In our magnetic trap, the centers of mass of the two species are displaced due to the different gravitational sag for K and Rb. However, such displacement, $\Delta z = 2.9\ \mu$m, is not sufficiently large to affect the geometrical overlap of the two degenerate components, since the radial sizes of the Fermi and Bose gases are R_F=5.1 μm and R_B=2 μm, respectively. Therefore, the BEC is completely immersed in the Fermi sea, with a ratio of the two volumes of approximately 1:16, hence direct thermal exchange is possible. However, the contribution of an undetected thermal cloud cannot be excluded, also because of the large K-Rb interaction. For instance at T=0.5T_F 10^4 uncondensed bosons would thermalize with an equal number of fermions in about 50 ms.

The attractive interspecies interaction is likely to affect the density profile of both degenerate gases. Our experimental configuration is more suitable for the observation of the effect of the mutual interaction on the boson. While the Rb BEC is completely immersed in the Fermi sea, only a relatively small volume fraction of K is exposed to the attraction. Actually, we have been able to evidence a modification on the bosonic sample due to the presence of the other species. Fig. 4 shows the Rb condensate after 15.5 ms of expansion: the recording on the left refers to a Rb BEC produced in absence of K. The aspect ratio close to 1.35 is in agreement with the theoretical expectation for our trapping parameters [20]. When instead BEC coexists with the K Fermi sea, the aspect ratio is increased to 1.5, as shown on the right of Fig. 4. While this constitutes a direct evidence of the interaction, it is not straightforward to assume this observations as a quantitative indication of the tigther confinement predicted in Ref. [15]. Indeed, the theoretical model applies to an ideal situation of equal masses and of a spherical trapping potential. Furthermore, also possible effects of the interaction with K during the early phases of the expansion cannot be ruled out a priori, and would be interesting to be explored in future investigation.

In conclusion we have produced a stable degenerate mixture where a Rb BEC is fully immersed in a K Fermi sea. The attractive interaction constitutes an important novelty, since it allows to keep thermal contact between the FB components in the degenerate regime, where also loss-induced heating of the Fermi gas may play a significant role [21]. A deeper exploration of the degenerate regime would require the development of new thermometry, and a possible scheme could be based on the production of velocity-selected Rb atoms [22] for the study of their collisional relaxation in the fermionic gas [23]. We also reported first evidence of the effect of the strong FB interaction on the density profiles. The system is suitable for a deeper insight in this phenomenology, for instance through the study of the dynamics induced by the interaction, following the release of one of the two species from the trap [24].

New possibilities are also opened for the production of homo- and hetero-nuclear molecules. In particular, as recently discussed in Ref. [25], dipolar fermions would provide a new landscape for the quest of fermionic superfluidity.

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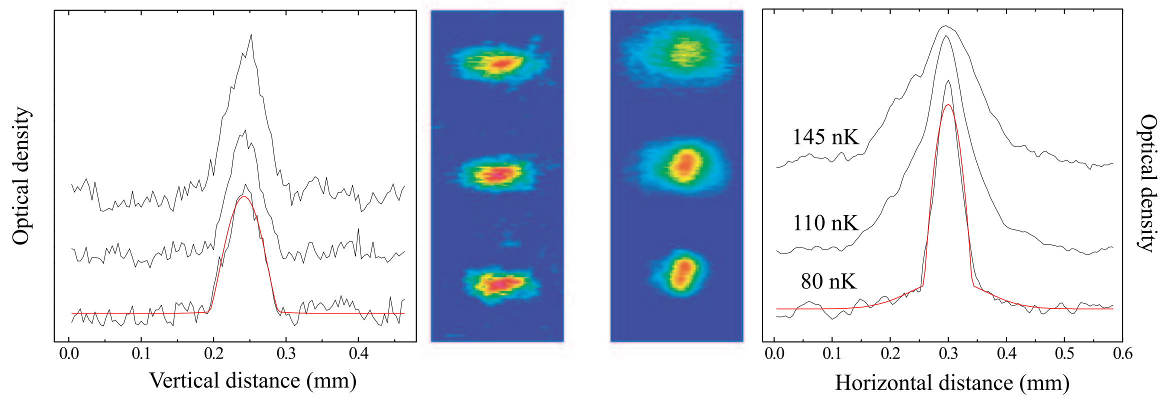

FIG. 1. Symultaneous onset of Fermi degeneracy for ^{40}K (left) and of Bose-Einstein condensation for ^{87}Rb (right). The absorption images are taken for three decreasing temperatures, after 4.5 ms of expansion for K and 17.5 ms for Rb, and the sections show the profile of the momentum distributions. The bosons provide a thermometry of the system: in the coldest sample, the Rb BEC has a 40% thermal component, and the temperature is T=0.74T_c=80 nK, which corresponds to T=0.3T_F for K. The Thomas-Fermi radius of the K profile is R=52 μm, consistent with the radius expected for a degenerate Fermi gas.

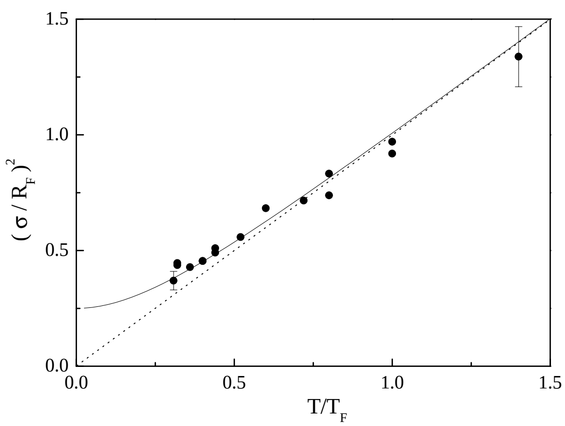

FIG. 2. Gaussian $1/e$ radius of the radial distribution of K atoms, versus the reduced Fermi temperature. The temperature is given by the Rb sample and T_F=250 nK. The solid line is the theoretical prediction for an ideal Fermi gas, while the dotted line is the classical behavior.

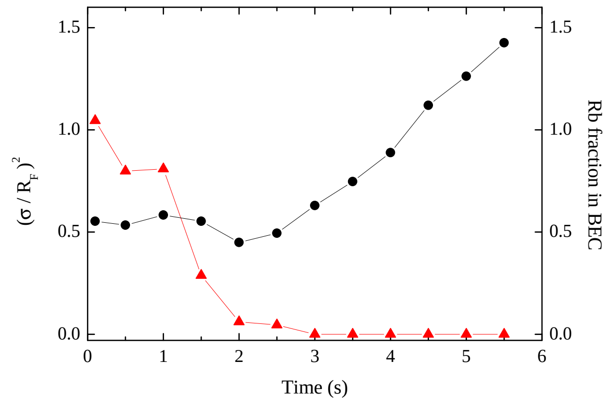

FIG. 3. Evidence of thermal exchange between the two degenerate gases. The gaussian width of ^{40}K (circles) increases only when ^{87}Rb atoms (triangles) are almost completely evaporated from the trap, as explained in the text. The solid lines are a guide to the eye.

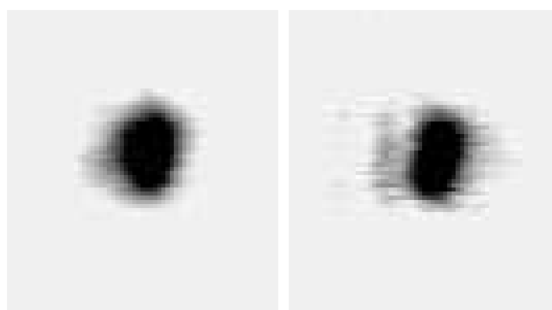

FIG. 4. Evidence of the interaction between the Rb BEC and the K Fermi gas. The aspect ratio after 15.5 ms of expansion is increased to 1.5 (rigth) in presence of K, from the normal value of 1.35 (left) in absence of K.