Two-body interactions play a major role in the production and in the properties of Bose-Einstein condensates (BECs) made of ultracold atoms [1]. Atomic species with naturally large repulsive interactions such as $^{87}$Rb [2] or $^{23}$Na [3] have collision properties favorable for the preparation process. However, there is growing interest in studying Bose-Einstein condensates where the interactions can be precisely tuned, magnetic Feshbach resonances [4, 5] being a key tool in this respect. One of the main motivations is the formation of an almost ideal condensate, i.e. one with vanishing interatomic interactions. Availability of such a system is essential for studying phenomena where even a weak interaction can hide the underlying physics of interest. A noticeable example is in the field of disordered systems, where experiments performed with ideal quantum gases can shed new light on the interdisciplinary phenomenon of Anderson localization [6, 7]. An ideal BEC would also be the most appropriate source for matter-wave interferometry, combining maximal brightness with the absence of collisional decoherence [8]. The possibility of dynamically tuning the interactions in a BEC could also open new directions towards Heisenberg-limited interferometry [9].

Feshbach resonances have been observed in most of the atomic species that have been condensed so far: $^{23}$Na [3], $^{85}$Rb [10], $^{133}$Cs [11, 12], $^7$Li [13], $^{87}$Rb [14], $^{52}$Cr [15]. Magnetic tuning of the interactions to small values around zero can be performed in lithium, a possibility already exploited to realize bright solitons in a weakly attractive BEC [16]. Cesium also presents an experimentally accessible region of nearly vanishing scattering lengths at which the small internal energy of a weakly interacting cesium BEC has been investigated [12].

In this Letter we report Bose-Einstein condensation of a new atomic species, $^{39}$K. Combination of broad Feshbach resonances and a small background scattering length $a_K \simeq -33 a_0$ [10] makes this system very promising for the study of weakly interacting condensates. Direct evaporative cooling of this species had been prevented by unfavorable zero-field collisional properties [17, 18]. Sympathetic cooling with $^{87}$Rb has recently proved [18] to work for $^{39}$K as efficiently as for the other potassium isotopes [13, 20], but condensation was still prevented by the negative value of $a_K$. We now bring $^{39}$K to quantum degeneracy by a combination of sympathetic cooling with $^{87}$Rb and direct evaporative cooling, exploiting the resonant tuning of both inter- and intra-species interactions at Feshbach resonances. Presence of one broad homonuclear Feshbach resonance allows us to tune $a_K$ in the condensate from large positive values to small negative values. The possibility of precisely adjusting $a_K$ around zero is demonstrated by studying the condensate expansion and its stability.

The experimental techniques we use are similar to the ones we developed for the other potassium isotopes [18, 19, 20, 21]. We start by preparing a mixture of $^{39}$K and $^{87}$Rb atoms in a magneto-optical trap. The mixture contains about $10^9$ Rb atoms at $T \simeq 100 \mu K$ and $10^7$ K atoms at $T \simeq 300 \mu K$. We simultaneously load the two species in a magnetic potential in their stretched Zeeman states $|F, m_F = 2\rangle$ and then we perform a selective evaporation of rubidium on the hyperfine transition at 6.834 GHz (the hyperfine splitting of $^{39}$K is 462 MHz). Potassium atoms are efficiently sympathetically cooled via interspecies collision [18], in spite of the small scattering length $a_{K\text{Rb}} \simeq 28 a_0$ [21]. With this technique we are able to prepare after 25 s of evaporation samples containing typically $10^6$ Rb atoms and $2 \times 10^5$ K atoms at $T=800$ nK.

Further cooling of the mixture in the magnetic potential in principle would be possible. However, condensation would be accompanied by collapse [22] because of the negative scattering length of $^{39}$K at low magnetic fields. We therefore exploit the possibility of tuning $a_K$ to positive values by performing the last part of evaporation in an optical potential in presence of a homogeneous magnetic field. We have indeed discovered several broad Feshbach resonances for this potassium isotope [24, 25].
a very favorable one being in the ground state $|1,1\rangle$ at about 400 G. We have also performed a detailed analysis of several of such resonances in order to construct a quantum collisional model able to accurately predict the magnetic-field dependence of $a_K$ [21]. We will make use of this analysis throughout this paper.

The K-Rb mixture is adiabatically transferred to an optical trap created with two focused laser beams at a wavelength $\lambda=1030$ nm, with beam waists of about 100 $\mu$m and crossing in the horizontal plane. The two species are then transferred to their absolute ground states $|1,1\rangle$ via adiabatic rapid passage, and further cooled by reducing the power in the laser beams by means of acusto-optic modulators. The optical trap is designed in such a way to evaporate mainly Rb. We find that cooling of $^{39}$K can be greatly enhanced by increasing $a_{KRb}$ at one of the interspecies Feshbach resonances that exist in this mixture [21]. At a first stage lasting 2.5 s a homogeneous magnetic field is thus tuned near a 8.5 G-wide interspecies Feshbach resonance centered at 317.9 G [22]. We find that sympathetic cooling is optimized at a field of 316 G, where $a_{KRb}\simeq 150 a_0$. At this magnetic field the homonuclear $^{39}$K cross-section is still small, $a_K \simeq 33 a_0$.

When both gases are close to quantum degeneracy ($T \simeq 150$ nK) we make $a_K$ positive and large by shifting the magnetic field in proximity of a 52 G-wide $^{39}$K resonance, centered at 402.4 G, and we continue the evaporation for 1 s. Due to the different trap depths for the two species, Rb is soon completely evaporated and further cooling of K relies just on intra-species collisions. We find for this phase an optimal scattering length $a_K \simeq 180 a_0$ obtained for $B=395.2$ G. At this field the two species are only weakly coupled, since $a_{KRb}\simeq 28 a_0$. Fig. 1 shows the phase transition of the K cloud to a Bose-Einstein condensate, detected via absorption imaging after a ballistic expansion. The critical temperature we measure is around 100 nK, and our purest condensates contain typically $3\times10^4$ atoms. The frequencies of the optical trap at the end of the evaporation are $\omega=2\pi\times (65, 74, 92)\, s^{-1}$ in the $(x, y, z)$ directions respectively. The whole evaporation procedure in the optical trap is summarized in Fig. 2.

Once the condensate is produced, $a_K$ can be further tuned. We have explored the magnetic-field region below the homonuclear Feshbach resonance in which the condensate is stable. The experiment starts with a pure BEC created at $B_0=395.2$ G. The field is then adiabatically brought to a final field $B$ in 30 ms. After 5 ms the optical trap is switched off and the cloud expands for 31.5 ms before absorption imaging is performed with a resonant beam propagating along the $y$ direction. The magnetic field is switched off just 5 ms before imaging, to ensure that $a_K$ does not change during the relevant phases of the expansion. Examples of absorption images are shown in Fig. 3. The measured atom number and the mean width $\sigma=\langle(x^2)+\langle z^2\rangle\rangle^{1/2}$ are shown Fig. 4, together with the magnetic-field dependence of $a_K$ as calculated using our quantum collision model [24].

Between 350.2 G and 350.0 G we observe a sudden drop of the atom number that can be attributed to a collapse of the BEC for too large negative $a_K$. In this regime the sample is no more in equilibrium and the presence of strong excitations is evident, see leftmost panels in Fig. 3. On the other extreme, the field can be brought in proximity of the resonance center. Here we observe that...
The lifetime of the BEC in the optical trap, including the region of large interactions or a Gaussian profile (dots) in the region of weak interactions. Atom number and width of uncondensed clouds are directly extracted from the raw images (triangles). Each data point is the average of at least three measurements.

The width of the condensate after the expansion shown in Fig. 4b features a decrease by almost a factor three as the field strength shifts from the resonance to the zero-crossing region. This is due to the variation of the interaction strength in the condensate. At the long expansion time of this experiment \( \sigma \propto \sqrt{E_{rel}} \), where \( E_{rel} \) is the release energy of the condensate. The latter quantity is expected to decrease as \( a_K^{-3/2} \) in the Thomas-Fermi limit, i.e., for large positive \( a_K \). Its value equals the kinetic energy of the harmonic oscillator ground state for \( a_K=0 \), and becomes even smaller for \( a_K < 0 \). The sharp increase of the width below 350.2 G reported in Fig. 4 reflects the presence of excitations in the collapsed system.

To gain insight into the observed phenomenology, we have compared the condensate widths with numerical calculations based on the Gross-Pitaevskii theory \(^2\). In Fig. 5 we plot \( \sigma \) as a function of \( a_K \); here the abscissa values for the experimental data have been calculated using the theoretical \( a_K(B) \). The horizontal error bar is dominated by the uncertainty in the model for \( a_K(B) \), which amounts to about 0.27 \( a_0 \) in the zero-crossing region. The decrease in \( \sigma \) with decreasing \( a_K \) is the result of two general effects: i) a reduction of the condensate width in the trap; ii) a reduction of the interaction energy released during the first phases of the expansion. Note in Fig. 5 the good agreement between theory and experiment in the broad range of values of \( a_K \) in which the condensate is stable. The slow decrease of \( \sigma \) for moderately large and positive \( a_K \) is followed by a faster decrease in the region of the zero-crossing.
ently happening at a slightly subcritical scattering length $a_K = -0.2 (3) a_0$. This might be due to a loss of adiabaticity of our magnetic-field ramp in this region of negative $a_K$. Although the ramp duration is much longer than the trap period, it might still excite the monopole collective mode of the condensate which has a vanishing frequency for $a_K$ approaching $a_c$.

In conclusion, we have produced a Bose-Einstein condensate of $^{87}$Rb atoms in which the scattering length can be precisely tuned over a large range and adjusted around zero. This atomic species is particularly advantageous in producing a weakly interacting condensate, since it combines a broad Feshbach resonance with a small background scattering length. For this resonance the theoretical model [24] predicts a sensitivity $\delta a_K/\delta B \simeq 0.55 a_0 / G$ around 350 G. Therefore, a magnetic-field stability of the order of 0.1 G will in principle allow us to tune the scattering length to zero to better than 0.1 $a_0$ in future experiments. This degree of control appears superior to that achievable in most other species which present either narrower resonances and/or larger background scattering lengths, the only exception being $^7$Li [15].

A weakly interacting $^{39}$K Bose gas may have a variety of applications, ranging from Anderson localization of matter-waves to high-sensitivity atom interferometry. We note that the in-trap size of a the weakly-interacting condensate is comparable to that of the ground state of the trapping potential, that is $\sqrt{\hbar/m_K a} = 1.84 \mu m$ in the present experiment. Such small size opens interesting perspectives for inertial measurements with high spatial resolution [31].

We expect that also a binary $^{39}$K-$^{87}$Rb BEC can be efficiently produced, thus enriching the possibilities offered by potassium-rubidium mixtures. Such binary condensate could be used for various applications and is especially appealing for the production of ultracold heteronuclear molecules.

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[1] K. Burnett, P. S. Julienne, P. D. Lett, E. Tiesinga, and C. J. Williams, Nature (London) 416, 225 (2002).
[2] M. H. Anderson, et al., Science 269, 198 (1995).
[3] K. B. Davis, et al., Phys. Rev. Lett. 75, 3969 (1995).
[4] E. Tiesinga, B. J. Verhaar, H. T. C. Stoof, Phys. Rev. A 47, 4114 (1993).
[5] S. Inouye, M. R. Andrews, J. Stenger, H.-J. Miesner, D.M. Stamper-Kurn, and W. Ketterle, Nature 392, 151 (1998).
[6] P. W. Anderson, Phys. Rev. 109, 1492 (1958).
[7] See for example J. E. Lye, L. Fallani, C. Fort, V. Guarrera, M. Modugno, D. S. Wiersma, M. Inguscio, cond-mat/0611146 and references therein.
[8] B. P. Anderson and M. A. Kasevich, Science 282, 1686 (1998); Y. Shin, M. Saba, T. A. Pasquini, W. Ketterle, D. E. Pritchard, and A. E. Leanhardt, Phys. Rev. Lett. 92, 050405 (2004); G. Roati, E. de Mirandes, F. Ferlaino, H. Ott, G. Modugno, and M. Inguscio, Phys. Rev. Lett. 92, 230402 (2004).
[9] P. Bouyer and M. A. Kasevich, Phys. Rev. A 56, R1083 (1997); L. Pezzè, L. A. Collins, A. Smerzi, G. P. Berman, and A. R. Bishop, Phys. Rev. A 72043612 (2005); G.-B. Jo, Y. Shin, S. Will, T. A. Pasquini, M. Saba, W. Ketterle, D. E. Pritchard, M. Vengalattore, and M. Prentiss, Phys. Rev. Lett. 98, 030407 (2007).
[10] J. L. Roberts, N. R. Clausen, James P. Burke, Jr., Chris H. Greene, E. A. Cornell, and C. E. Wieman, Phys. Rev. Lett. 81, 5109 (1998).
[11] C. Chin, V. Vuletic, A. J. Kerman, S. Chu, Phys. Rev. Lett. 85, 2717 (2000).
[12] T. Weber, J. Herbig, M. Mark, H.-C. Nägerl, R. Grimm, Science 299, 232 (2003).
[13] L. Khaykovich, F. Schreck, G. Ferrari, T. Bourdel, J. Cubizolles, L. D. Carr, Y. Castin, C. Salomon, Science 296, 1290 (2002); K. E. Strecker, G. B. Partridge, A. G. Truscott, R. G. Hulet, Nature 417, 150 (2002).
[14] A. Marte, T. Volz, J. Schuster, S. Dürr, G. Rempe, E. G. M. van Kempen, and B. J. Verhaar, Phys. Rev. Lett. 89, 283202 (2002).
[15] J. Werner, A. Griesmaier, S. Hensler, J. Stuhler, T. Pfau, A. Simoni, and E. Tiesinga, Phys. Rev. Lett. 94, 183201 (2005).
[16] H. Wang et al., Phys. Rev. A 62, 052704 (2000); T. Loh- tus, C. A. Regal, C. Ticknor, J. L. Bohn, and D. S. Jin, Phys. Rev. Lett. 88, 173201 (2002).
[17] M. Prevedelli, F. S. Cataliotti, E. A. Cornell, J. R. Ensher, C. Fort, L. Ricci, G. M. Tino, and M. Inguscio, Phys. Rev. A 59, 886 (1999).
[18] L. De Sarlo, P. Maioli, G. Barontini, J. Catani, F. Minardi, and M. Inguscio, Phys. Rev. A 75, 022715 (2007).
[19] G. Modugno, G. Ferrari, G. Roati, F. Riboli, R. J. Brecha, A. Simoni, M. Inguscio, Science 294, 1320 (2001).
[20] G. Roati, F. Riboli, G. Modugno, and M. Inguscio, Phys. Rev. Lett. 89, 150403 (2002).
[21] F. Ferlaino, C. D’Errico, G. Roati, M. Zaccanti, M. Inguscio, G. Modugno, A. Simoni, Phys. Rev. A 73, 040702(R) (2006).
[22] The decrease of the potassium atom number is due to spin-exchange inelastic collisions with Rb atoms in states other than $|2, 2\rangle$.
[23] J. M. Gerton, D. Strelkov, I. Prodan and R. G. Hulet, Nature (London) 408, 6813 (2000); J. L. Roberts, N. R. Clausen, S. L. Cornish, E. A. Donley, E. A. Cornell, and C. E. Wieman, Phys. Rev. Lett. 86, 4211 (2001).
[24] A. Simoni et al., in preparation.
[25] Indication of these resonances has been obtained also in an experiment at the University of Innsbruck: commu-
We find this resonance at a magnetic field very close to the value predicted in [21]. A detailed analysis of Feshbach resonances in this mixture will be the subject of a future publication.

[27] T. Weber, J. Herbig, M. Mark, H.-C. Nägerl, and R. Grimm, Phys. Rev. Lett. 91, 123201 (2003); B. D. Esry, Chris H. Greene, and James P. Burke, Jr., Phys. Rev. Lett. 83, 1751 (1999).

[28] F. Dalfovo, S. Giorgini, L. P. Pitaevskii, and S. Stringari, Rev. Mod. Phys. 71, 463 (1999).

[29] S. Stringari, Phys. Rev. Lett. 77, 2360 (1996).

[30] I. Carusotto, L. Pitaevskii, S. Stringari, G. Modugno, and M. Inguscio, Phys. Rev. Lett. 95, 093202 (2005).