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Collisional cooling of a Fermi gas with three-body recombination

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Evaporative cooling stands as the prevailing method for achieving ultracold temperatures in atomic systems. Current schemes of evaporation selectively remove the hotter atoms near the edge of the trap, as the hotter and colder atoms are distributed in different spatial regions of the trapping potential. However, a long-standing goal is to directly remove the higher momentum atoms, irrespective of their spatial distribution. For this purpose, we demonstrate collisional cooling for a ^{6}Li Fermi gas through inelastic three-body recombination near a narrow Feshbach resonance. Such three-body recombination can induce either heating or cooling effects, and the decay of the quasi-bound Feshbach molecule stirs the hotter atoms away from the trapping potential. When the threshold energy of the Feshbach molecule exceeds the atom's average kinetic energy of $3/2k_BT$, the cooling effect becomes more pronounced. Finally, we observe strong temperature dependence in this collisional cooling process, with greater efficiency achieved at lower temperatures.

Methods of cooling atoms and molecules play a crucial role in building quantum simulators for studying many-body physics, and help to explore the fundamental principles of chemical reactions in the lowest temperature regime. Historically, the advances of the principles and techniques of cooling have benefited the developments of cold atomic physics. For example, magneto-optical trapping relies on the Doppler cooling mechanism[1,2], Bose-Einstein condensations are produced by evaporative cooling[3,4], and degenerate Fermi gases are generated by unitary-limited elastic collisions near the Feshbach resonance[5–8]. Most of these cooling methods fall into two categories: one utilizes laser-atom interactions to reduce the kinetic energy of the atomic system. The other one removes the atoms with higher kinetic energy from the trapping potential, lowering the temperature through the thermal equilibrium process. For the latter, the most popular technique is evaporative cooling by lowering the trapping potential as well as other variants[9–12]. One of the common feature for these evaporative processes is that they all take advantage of the different spatial positioning of hotter and colder atoms in a trapping potential.

Is there a method to direct remove the atoms in the higher momentum states regardless of the spatial difference between hotter and colder atoms? Recently, collisional cooling has been proposed for this purpose, which uses inelastic scattering processes near a narrow magnetic Feshbach resonance to enhance the kinetic energy-dependent loss[13,14]. Near the Feshbach resonance, the atoms with higher kinetic energy are closer to the threshold energy, and therefore have a higher probability of colliding. The collisions could change the internal states of the atoms, and the energy stored in the electronic state is converted into the kinetic energy of the colliding atoms, resulting the evaporation when the kinetic energy gained is much larger than the trapping potential. Since the lost atoms usually have higher kinetic energy than the thermal average value, the temperature of the atoms will be reduced. Experimentally, this method does not need to vary the trapping potential, but requires exquisite tuning of the magnetic field for precisely controlling the atomic interaction[15].

In this paper, we present the observation of collisional cooling with ultracold ^{6}Li fermionic atoms near a narrow Feshbach resonance. Our scheme is based on the framework proposed in the previous theoretical work[13,14], where the significant difference between our scheme and these proposals is that we utilize three-body recombination[16] instead of inelastic two-body collision to selectively remove hotter atoms. Compared with the two-body collision scheme, three-body recombination requires only one open channel for generating collisional cooling without the need for a second one, which makes it more feasible in experiments. In a one-dimensional Bose gas, the cooling has recently been observed with three-body recombination[17]. However, the cooling is not based on removing hot atoms through energy-dependent loss, but is because of the loss of phonon modes, which is quite different with the physics presented in this paper.

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Results

Schematic of collisional cooling

The scheme of the collisional cooling near the narrow Feshbach resonance of ^{6}Li is shown in Fig. 1. From the Bardeen-Cooper-Schrieffer side of the Feshbach resonance, when the molecular bound state in a closed scattering channel approaches the scattering state in an open channel, the threshold energy of the molecule E_t is positive and a quasi-bound molecule is temporarily formed, where the relative kinetic energy of the two colliding atoms matches the threshold energy[18,19]. Once the molecule collides with the third incoming atom, three-body recombination produces a deeper-bound molecule[20,21]. The gap energy between the quasi-bounded and the deeply-bounded molecular states is converted into the kinetic energy of the atoms. The gained kinetic energy will be higher than the trapping potential, leading to the loss of all three atoms. The three-body recombination involves the total loss of kinetic energy of all three atoms. Particularly, when the loss of kinetic energy per particle is greater than the average kinetic energy of the cloud $3/2k_BT$, the process leads to cooling, where k_B is the Boltzmann constant and T is the gas temperature. The threshold energy of E_t for the formation of quasi-molecules thus acts like a knife to selectively remove the hotter atoms.

It should be emphasized that quasi-bound molecules also decay back into the original open channel, which can be considered as an elastic collision for cloud thermalization[13]. In the Feshbach resonance, the thermalization is usually guaranteed because the three-body recombination rate $\Gamma_0 \propto K_{ad}^m$ is much smaller than the formation rate of the quasi-bound molecule $\Gamma(E)$, where K_{ad}^m is the rate coefficient of the atom-dimer interaction leading to the formation of a deeper molecule[20].

Although the principle of the three-body cooling is well understood, the observation of the signatures of cooling is rather difficult in experiments, since E_t should be controlled strictly precisely near a narrow Feshbach resonance. For ^{6}Li atoms, it needs at least part-per-million (ppm) stability of the bias magnetic field around 543.3 G. Such a cooling effect has been noticed previously[22,23], but the convincing evidence is still lacking. In this paper, we verify that the inelastic collisional cooling is actually from three-body recombination, and systematically study the magnetic field and temperature dependence of this collisional cooling. Our investigation shows the cooling efficiency becomes higher with the decrease of the atom temperature, which could support a runaway evaporative cooling down to extremely low temperature.

Heuristic explanation of this cooling

We use a noninteracting Fermi gas in a harmonic trap to explain the collisional cooling. According to the virial theorem for a harmonically trapped gas (The cooling regime of the three-body recombination is away from the resonance point, so the *s*-wave scattering length is small and the gas is a weakly interacting Fermi gas. The virial theory works reasonably under this case)[24], the average kinetic energy per particle $\langle E_k\rangle = 3/2\, k_BT$ is equal to the average potential energy $\langle E_p\rangle = U(\sigma_x, \sigma_y, \sigma_z)$, where $\sigma_{x,y,z}$ is the Gaussian width of $n(x, y, z)$. The lost potential energy per lost atom is $\dot{E_{3p}}/\dot{N}_3 = U(\sigma_x, \sigma_y, \sigma_z)$. Then, $\dot{E_{3p}}/\dot{N}_3 = \langle E_p\rangle = 3k_BT/2$. Therefore, the Boltzmann equation can be applied to a harmonically trapped gas as those done in the 3D homogeneous gases[13,25]. The collisional process in terms of density and temperature is given by (Details in Supplementary Note 3)

$$\frac{\partial n}{\partial t} = -L_3 n^3, \qquad \frac{\partial T}{\partial t} = -L_3 n^2\left(\frac{E_t}{3k_B} - \frac{T}{2}\right), \tag{1}$$

with three-body loss rate[15,20,22]

$$L_3(E_t, T) = 3K_{ad}^m\left(\sqrt{2}\lambda_T\right)^3 e^{-E_t/k_BT}. \tag{2}$$

The thermal wavelength $\lambda_T = (2\pi\hbar^2/mk_BT)^{1/2}$ and the threshold energy $E_t = 2\mu_B(B - B_0)$ for the binding energy of the Feshbach molecule with μ_B as the Bohr magneton. Eq. (1) can be solved analytically,

$$\frac{1}{n^2(t)} = 2L_3(B)t + \frac{1}{n^2(0)}, \qquad T(t) = 2\left\{\frac{E_t}{3k_B} - \left[\frac{E_t}{3k_B} - \frac{T(0)}{2}\right]\left[\frac{n(0)}{n(t)}\right]^{1/2}\right\}. \tag{3}$$

For convenience, we define $\eta_0 = E_t/k_BT(0)$. When $E_t = 3k_BT(0)/2$, the temperature will remain constant, where the leaving atom carries away the average energy of $3k_BT$ from the gas, the sum of average kinetic energy and potential energy. This is the turning point from heating to cooling. In the cooling regime, the lower temperature could result in better cooling efficiency. As shown in S.12, when T is lower, L_3 becomes larger and $n(t)/n(0)$ becomes lower, then the phase-space density ratio $F_\rho = \rho(t)/\rho(0)$ gets higher since it is monotonically decreased when $\eta_0 > 3.5$, where the phase-space density is $\rho(t) = (2\pi\hbar)^3 n(t)/(2\pi mk_BT(t))^{3/2}$.

Collisional cooling of a thermal gas

We present the magnetic field dependence of the atom number $N/N(0)$ and its density n, temperature T, phase-space density ρ, and the three-body loss coefficient L_3 in Fig. 2a–e. The simulation explains the experimental result very well. When η_0 approaches zero, the lower energy atoms are expelled from the trap due to three-body recombination, which increases the average energy of the rest gas and results in heating. Once E_t exceeds $3k_BT/2$, the leaving atoms carry more energy ($>3k_BT$) away from the gas, resulting in cooling. As shown in Fig. 2c, the best cooling rate is achieved around $\eta_0 \sim 3$, and the temperature decreases from 5.1 μK to 4 μK in 450 ms. However, ρ keeps roughly constant around $\eta_0 = 3$. Above this point, ρ slightly increases with time showing a weak cooling signature. ρ reaches a maximum when $\eta_0 \sim 9/2$. This finding agrees with our numerical simulation. In our simulation, the energy difference ΔE between the two molecular states is much larger than the trap depth, so we assume that three scattering atoms leave the trap quickly without energy exchanging collisions with other atoms.

Collisional cooling of a degenerate gas

We measure the collisional cooling of the gas when the temperature is close to the degenerate regime, as shown in Fig. 3a–e. Since the three-body loss rate $L_3 \propto 1/T^{3/2}\exp(-E_t/k_BT)$, it is expected that a higher cooling rate could be obtained in the degenerate regime compared to the thermal one. This feature is rather attractive for its role in a potential runaway cooling. In Fig. 3a–e, the initial temperature $T(0) = 0.60 \pm 0.01$ μK, and $T/T_F(t = 0)$ is 1.00 ± 0.02, where $T_F = (6N)^{1/3}\hbar\bar{\omega}/k_B$ is the Fermi temperature. During a cooling process at $\eta_0 = 4.5$, ρ increases from 0.25–0.5 and the lowest T/T_F reaches 0.79. The maximum increase of F_ρ is about 2 around $\eta_0 = 9/2$, which is larger than the maximum value of the thermal one. At this point, the corresponding cooling efficiency $\chi \equiv -\ln[\rho(t)/\rho(0)]/\ln[N(t)/N(0)]$ is about 1.3. When η_0 gets larger, χ can be significantly increased, which should enhance the cooling. But, L_3 also decreases with larger η_0, resulting in the degraded of the overall cooling effect. It is noted that our experiments have not optimized the cooling process which requires a dynamic magnetic sweep that we discuss later.

Our simulation shows that F_ρ increases when $\eta_0 > 3.5$ (in Supplementary Note 3), which agrees with the behavior of ρ in Fig. 3d. For the maximum increase of F_ρ, the simulation indicates that η must be time-dependent. As η_0 approaches the resonance, the measured L_3 deviates from the perdition of Eq. (2), which is related to the unitary-limited behavior[26,27]. Such derivation is not predicted by our heuristic model, because many-body calculation is required to predict the three-body cooling behavior in the unitary regime.

Discussion

We first discuss a scheme with a time-dependent magnetic sweep to enhance the cooling efficiency. Following the optimization approach in

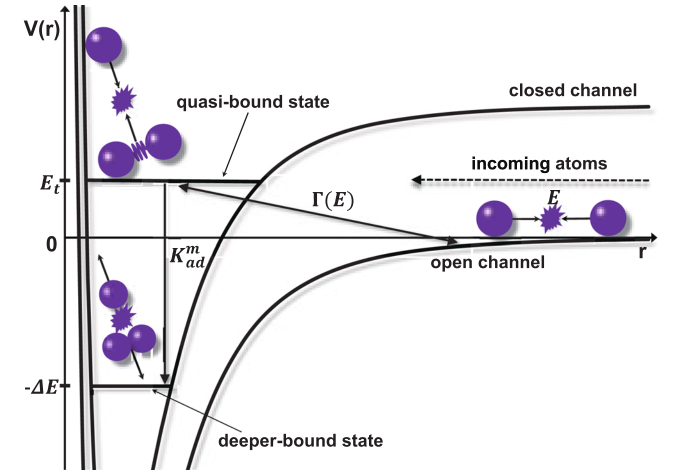

Fig. 1 | Schematic of three-body recombination near an *s*-wave narrow Feshbach resonance of a ^{6}Li Fermi gas. The black curves are the potentials of the open and closed scattering channels, respectively. A quasi-bound molecular state with a threshold energy of E_t is shown in the closed channel. A deeper-bound molecule is generated from the upper state with a rate of K^m_{ad} through the three-body process. The quasi-bound molecule decays back to the open channel with a rate of $\Gamma(E)$.

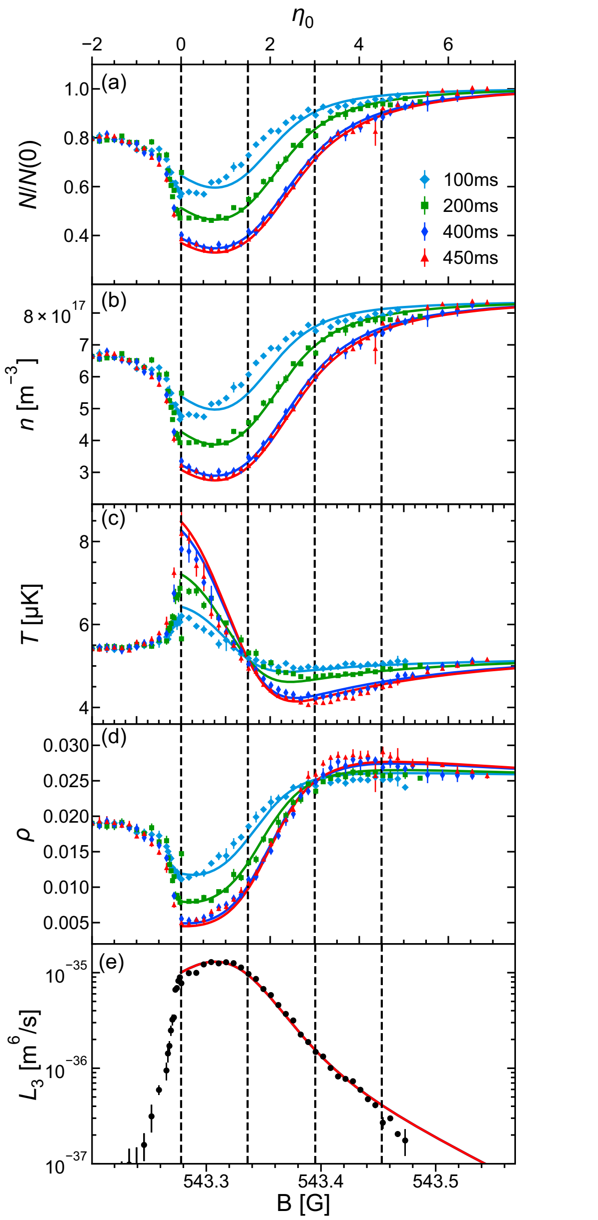

Fig. 2 | Collisional cooling of a thermal Fermi gas of $T(0) = 5.10 \pm 0.04\mu$K and $T/T_F(0) = 1.50 \pm 0.01$. a–e show the dependence of $N/N(0)$, n, T, ρ, and L_3 on magnetic field B, respectively. The black dashed lines are guiding for the η_0 = 0, 3/2, 3, 9/2. Solid curves in (**a–d**) are the simulation by Eq. (3). The red solid curve in (**e**) is the fitting result of Eq. (2) with $K^m_{ad} = 1.69 \pm 0.01 \times 10^{-16} m^3/s$. The raw data of the L_3 and the fitting procedure are included in Supplementary Note 2. The vertical error bars are the standard derivation for 2-3 measurements, and the horizontal error bars stand for the uncertainty of the magnetic field.

ref. 14 and using Eq. (1), we obtain the time-dependent of $\eta(\tau)$ as

$$\frac{d\eta}{d\tau} = \frac{1}{2}\left(\eta - \frac{13}{2}\right)\frac{n'^2}{T'^{3/2}}e^{-\eta+\frac{13}{2}}, \quad (4)$$

with dimensionless parameters $\tau = 6\sqrt{2}e^{-13/2}K^m_{ad}n(0)\rho(0)t$, $n' = n/n(0)$, and $T' = T/T(0)$. From this equation, the optimal η_0 for the different cooling time τ are shown in Fig. 4a, b, which are different from the two-body collisional cooling[14], where the optimal η_0 is constant with a value of 9/2. For a specific example $\eta_0 = 6.0$, we present the time-evolution of the atom density n_0 and the phase space density ρ_0 in the center of the trap, the atom number N, and the temperature T in the inset figure of Fig. 4b. It shows that three-body cooling has the potential to directly cool a thermal gas to a deeply degenerate regime. Moreover, the collision rate $\gamma \propto n_0^2 \exp(-\eta)/T^{3/2}$ (black line) is increased during the cooling, indicating a typical runaway scheme based on our model.

Note that the densities in Figs. 2b and 3b are defined as $n(t) = N(t)/V(0)$, where $V(0)$ is approximately the initial cloud size (see Supplementary Note 2 for details). By using $V(0)$ instead of $V(t)$ in these figures, we obtain a relatively simpler theoretical model to derive the optimal cooling curve for collisional cooling (details in the Supplementary Note 3). On the other hand, the peak density $n_0(t)$ can be obtained by $n_0(t) = N(t)/V(t)$, where $V(t)$ refers to the time-dependent cloud size $\sigma_{x,y,z}(t)$. As $V(t)$ decreases during the cooling, $n_0(t)$ will be significantly larger than $n(t)$, which indicates a better cooling capacity of three-body collisional cooling.

Second, we discuss the experimental limitations for three-body cooling. In our experiment, the range of cooling regime is only about $k_BT/2\mu_B \sim 50$ mG. To implement the cooling in this regime, it requires the stability of the magnetic field better than 10 mG. As shown in Supplementary Note 1, the fluctuation of our magnetic field is about $\sigma_B = 1.6$ mG at 543.3 G, giving the fluctuation of the threshold energy. This fluctuation limits the lowest temperature that we could achieve $2\mu_B\sigma_B/(3k_B/2) = 0.14\,\mu$K. Third, we could improve the theoretical model for three-body cooling. The current model is based on the classical kinetic theory, which agrees with our observation in the weakly interacting regime qualitatively, but deviates from the data near the resonance. We suggest to consider the entropy exchange and use a quantum kinetic model to improve the discrepancies of the whole cooling process[25,27,28].

In conclusion, we have verified that a ^{6}Li Fermi gas can be cooled to a higher phase-space density through three-body recombination near a narrow Feshbach resonance. Different from the standard evaporative cooling, our collisional cooling could use Feshbach resonance to selectively expel the atoms with certain kinetic energy. The cooling efficiency of collisional cooling increases as temperature decreases, which enables it as a useful tool for cooling novel systems, such as dipole molecules[29] or mixed atomic species[30–33].

Methods

Gas preparation

We prepare a two-component (two lowest hyperfine states of $F = 1/2, m_F = \pm 1/2$) ^{6}Li Fermi gas in a crossed-beam optical dipole trap made by a 100 W 1064 nm fiber laser. The trapping potential of the dipole trap we can generate at the highest power is about 5.6 mK. A bias magnetic

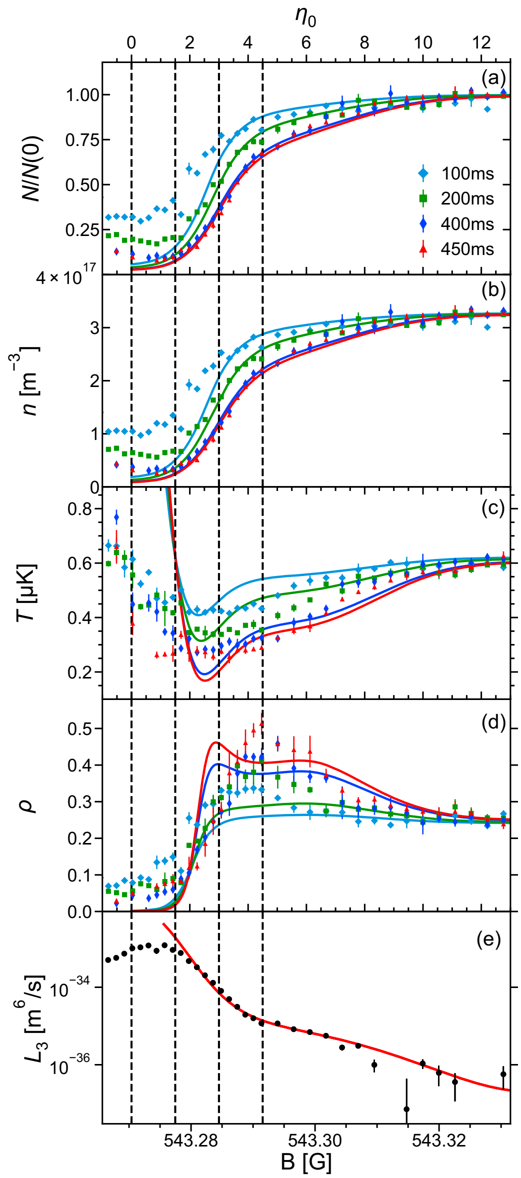

Fig. 3 | Collisional cooling of a near-degenerate Fermi gas of $T(0) = 0.60 \pm 0.01\mu$K and $T/T_F(0) = 1.00 \pm 0.02$. a–e, the black dashed lines, and solid curves are defined the same as those in Fig. 2. The red solid curve in (**e**) is the fitting results of Eq. (2) with $K^m_{ad} = 2.02 \pm 0.02 \times 10^{-15} m^3/s$. The vertical error bars and the horizontal error bars are the same as those in Fig. 2.

field of 300 G is added to generate a weakly interacting Fermi gas after the atoms are loaded from the magneto-optical trap. Before starting the evaporative cooling, a radio-frequency pulse is implemented to balance the spin mixture to 50:50. We force evaporatively cool the gas by lowering the trap to a different trap potential to generate different temperatures[20]. Then, the magnetic field is fast swept over the narrow Feshbach resonance to 570 G to calibrate the initial temperature $T(0)$ and the initial atom number $N(0)$. Notice that the two-component gas is tested to be stable at 570 G and its $s-$wave scattering length is finite. In our experiments, a 5.10 μK gas is prepared with a trap depth of 33.6 μK, and a 0.60 μK gas is generated with a trap depth of 2.8 μK.

Timing sequence of the magnetic field

The two lowest-energy hyperfine ground-state mixtures of ultracold ^{6}Li Fermi gases have an s-wave narrow Feshbach resonance around 543.3 G with a resonance width of 0.1 G. We adopted the same timing sequence as Fig. 1 of our previous experiment[15] to measure the three-body loss rate.

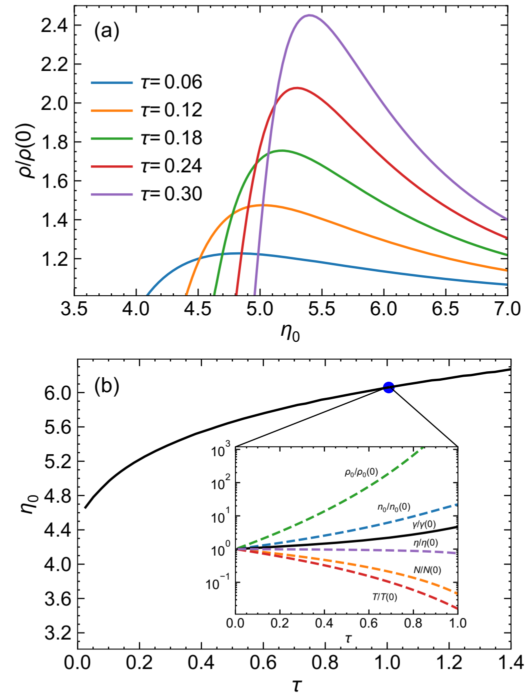

Fig. 4 | Optimization the path of the three-body collisional cooling. a The phase-space density $\rho/\rho(0)$ versus η_0 for different cooling duration τ. **b** The optimized η_0 for the maximum $\rho/\rho(0)$, which is a time-dependent value. The inset figure is the time evolution of ρ_0 and n_0 in the center of the trap, γ, η, N, and T with $\eta_0 = 6$. All the curves in the inset figure are normalized by their initial condition.

The magnetic field is swept from 570 G to a target field B_f near the narrow Feshbach resonance in about 50 ms due to the eddy effect of our setup[15]. Then, the atoms are held at B_f for a time duration of t. After the three-body recombination, the left atoms are swept back to the initial magnetic field 570 G and wait several hundred milliseconds for a gas re-thermalization. Then, we acquire the time-of-flight absorption images to avoid the high column density induced by the error of the atom number. The fluctuation of our magnetic field is controlled within a ppm-level. More details about the stability of our magnetic field are presented in Supplementary Note 1.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Code availability

Relevant code for data analysis are available in the text. Additional software used in this study is available from the corresponding authors upon reasonable request.

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References

1. Chu, S., Hollberg, L., Bjorkholm, J. E., Cable, A. & Askin, A. Three-dimensional viscous confinement and cooling of atoms by resonance radiation pressure. *Phys. Rev. Lett.* **55**, 48 (1985).
2. Lett, P. D. et al. Observation of atom laser cooled below the Doppler limit. *Phys. Rev. Lett.* **61**, 169 (1988).
3. Anderson, M. H., Ensher, J. R., Matthews, M. R., Wieman, C. E. & Cornell, E. A. Observation of Bose-Einstein condensation in a dilute atomic vapor. *Science* **269**, 198 (1995).
4. Davis, K. B. et al. Bose-Einstein condensation in a gas of sodium atoms. *Phys. Rev. Lett.* **75**, 3969 (1995).

5. DeMarco, B. & Jin, D. S. Onset of Fermi degeneracy in a trapped atomic gas. *Science* **285**, 1703 (1999).
6. Truscott, A. G., Strecker, K. E., McAlexander, W. I., Partridge, G. B. & Hulet, R. G. Observation of Fermi pressure in a gas of trapped atoms. *Science* **291**, 2570 (2001).
7. O'Hara, K. M., Hemmer, S. L., Gehm, M. E., Granade, S. R. & Thomas, J. E. Observation of a strongly interacting degenerate Fermi gas of atoms. *Science* **298**, 2179 (2002).
8. Luo, L. et al. Evaporative cooling of unitary Fermi gas mixtures in optical traps. *N. J. Phys.* **8**, 213 (2006).
9. Kinoshita, T., Wenger, T. & Weiss, D. S. All-optical Bose-Einstein condensation using a compressible crossed dipole trap. *Phys. Rev. A* **71**, 011602 (2005).
10. Hung, C.-L., Zhang, X., Gemelke, N. & Chin, C. Accelerating evaporative cooling of atoms into Bose-Einstein condensation in optical traps. *Phys. Rev. A* **78**, 011604 (2008).
11. Arnold, K. J. & Barrett, M. D. All-optical Bose-Einstein condensation in a 1.06μm dipole trap. *Opt. Commun.* **284**, 3288–3291 (2011).
12. Li, J., Liu, J., Xun, W., De Melo, L. & Luo, L. Parametric cooling of a degenerate Fermi gas in an optical trap. *Phys. Rev. A* **93**, 041401(R) (2016).
13. Mathey, L., Tiesinga, E., Julienne, P. S. & Clark, C. W. Collisional cooling of ultracold-atom ensembles using Feshbach resonances. *Phys. Rev. A* **80**, 030702 (2009).
14. Nuske, M., Tiesinga, E. & Mathey, L. Optimization of collisional Feshbach cooling of an ultracold nondegenerate gas. *Phys. Rev. A* **91**, 043626 (2015).
15. Chen, Y. et al. Characterization of the magnetic field through the three-body loss near a narrow Feshbach resonance. *Phys. Rev. A* **103**, 063311 (2021).
16. Dogra, L. H. et al. Can three-Body recombination purify a quantum gas *Phys. Rev. Lett.* **123**, 020405 (2019).
17. Schemmer, M. & Bouchoule, I. Cooling a bose gas by three-body losses. *Phys. Rev. Lett.* **121**, 200401 (2018).
18. Köhler, T., Góral, K. & Julienne, P. S. Production of cold molecules via magnetically tunable Feshbach resonances. *Rev. Mod. Phys.* **78**, 1311 (2006).
19. Chin, C., Grimm, R., Julienne, P. & Tiesinga, E. Feshbach resonances in ultracold gases. *Rev. Mod. Phys.* **82**, 1225 (2010).
20. Li, J., Liu, J., Luo, L. & Gao, B. Three-body recombination near a narrow Feshbach resonance in ^{6}Li. *Phys. Rev. Lett.* **120**, 193402 (2018).
21. Waseem, M., Yoshida, J., Saito, T. & Mukaiyama, T. Quantitative analysis of *p*-wave three-body losses via a cascade process. *Phys. Rev. A* **99**, 052704 (2019).
22. Hazlett, E. L., Zhang, Y., Stites, R. W. & O'Hara, K. M. Realization of a resonant Fermi gas with a large effective range. *Phys. Rev. Lett.* **108**, 045304 (2012).
23. E. L., Hazlett, Ph.D. thesis, *Interactions in a Dilute Fermi Gas*. https://etda.libraries.psu.edu/catalog/16275 (2012).
24. Luo, L. *Entropy and Superfluid Critical Parameters of a Strongly Interacting Fermi Gas*. https://jet.physics.ncsu.edu/theses/pdf/Luo.pdf (2008).
25. Luiten, O. J., Reynolds, M. W. & Walraven, J. T. M. Kinetic theory of the evaporative cooling of a trapped gas. *Phys. Rev. A* **53**, 1 (1996).
26. Waseem, M. et al. Unitarity-limited behavior of three-body collisions in a p-wave interacting Fermi gas. *Phys. Rev. A* **98**, 020702(R) (2018).
27. Rem, B. S. et al. Lifetime of the Bose gas with resonant interactions. *Phys. Rev. Lett*. **110**, 163202 (2013).
28. Idziaszek, Z., Santos, L. & Lewenstein, M. Sympathetic cooling of trapped fermions by bosons in the presence of particle losses. *Europhys. Lett.* **70**, 572 (2005).
29. Carr, L. D., Bourdel, T. & Castin, Y. Limits of sympathetic cooling of fermions by zero-temperature bosons due to particle losses. *Phys. Rev. A* **69**, 033603 (2004).
30. De Marco, L. et al. A degenerate Fermi gas of polar molecules. *Science* **363**, 853–856 (2019).
31. Pilch, K. et al. Observation of interspecies Feshbach resonances in an ultracold Rb-Cs mixture. *Phys. Rev. A* **79**, 042718 (2009).
32. Wang, Y., D'Incao, J. P. & Esry, B. D. Ultracold three-body collisions near narrow Feshbach resonances. *Phys. Rev. A* **83**, 042710 (2011).
33. Li, X. et al. Second sound attenuation near quantum criticality. *Science* **375**, 528–533 (2022).

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Author contributions

J.L. and L.L. conceived the idea. L.L. and J.L. designed and supervised the experiments. S.P. and H.T.L. set up experiments and performed measurements. J.L. and S.P. carried out theoretical modeling and analyzed the data. J.L., L.L., S.P., and H.T.L. contributed to writing the manuscript and preparing the figures.

Competing interests

The authors declare no competing interests.

Additional information

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