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# Observation of momentum-induced broadening of width in narrow Feshbach resonances of ultracold $^{133}$Cs atoms

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Interactions between atoms in ultracold quantum gases play an important role in the study of the quantum simulation of many-body physics. Feshbach resonance is a versatile tool to control atomic interactions, where the atom-loss spectra are widely used to characterize Feshbach resonances of various atomic species. Here, we report the experimental observation of momentum-induced broadening of widths in atom-loss spectra of narrow $^{133}$Cs Feshbach resonances. We drive Bragg excitation to kick the Bose–Einstein condensate of Cs atoms in a cigar-shaped optical trap, and measure the atom-loss spectra of narrow Feshbach resonances of moving ultracold atoms near the magnetic fields 19.84 G and 47.97 G. We show that the widths of the atom-loss spectra are broadened for the atoms with the momenta of $2\hbar k$ and $4\hbar k$, and even observe splitting in the Feshbach resonance of the atoms with momentum $4\hbar k$. Our work may open the way for exploring the interesting physical phenomena arising from the collective velocity of colliding atoms that have been ignored in general.

**Keywords:** Bose–Einstein condensate, Feshbach resonances, atom-loss spectra

**PACS:** 37.10.De, 67.85.Hj

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## 1. Introduction

Ultracold atomic gas is one of the most fundamental paradigms of quantum many-body physical systems, in which interatomic interactions are the key to understanding many intriguing physical phenomena. Feshbach resonance (FR) provides a versatile tool to control interactions of ultracold atoms,[1] and has found numerous important applications in the study of ultracold quantum gases. Prominent examples are the attainment of atomic Bose–Einstein condensate (BEC),[2–4] the creation of ultracold ground-state molecules,[5–7] the observation of Efimov resonances,[8–12] the formation of matter wave solitons,[13,14] the exploration of universal relations in unitarity Bose gases,[15] and the study of the BEC–BCS crossover in Fermi gases.[16–18] FRs have also been widely used to study the exotic physical phenomena dominated by the atomic interactions in optical lattices and synthetic dimensions, including the strongly correlated Tonks–Girardeau gases,[19,20] the many-body localization,[21,22] the long-range tunneling dynamics,[23] the mobility edge,[24] and the frustrated chiral dynamics.[25]

An FR occurs when an external magnetic field is used for tuning the energy of two scattering atoms to approach the energy of bound molecular state, where one takes advantage of the different magnetic dipole moments between the atomic and molecular states. Due to the resonant atom–molecule coupling, the rotational angular momentum of the bound molecular state (with rotational quantum number $\ell$) determines the special partial wave of an FR, where the type of Feshbach molecules ranges from s-wave ($\ell = 0$) to g-wave ($\ell = 4$) states. In particular for ultracold $^{133}$Cs atoms, there are rich FRs with different partial waves.[26–29] Experimentally, an FR can be directly probed by measuring the atom loss as a function of magnetic field, and the resonance position is identified with a great enhancement of the loss near the FR at the low temperatures ($< 1$ μK).[1,30] However, the feature of atom-loss spectroscopy near an FR is affected by varying temperature, which induces the change of the loss amplitude, resonance position and width.[31–35] These studies are important not only for understanding the property of an FR but also for controlling the atomic interactions.

In this work, we study the effect of atomic momentum on the atom-loss spectra of narrow g-wave and d-wave FRs for $^{133}$Cs atoms near the magnetic fields 19.84 G and 47.97 G, respectively. The Bragg excitations involved with two- and four-photon processes are driven for kicking the atomic BEC

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along the direction of the weakly axial confinement of a cigar-shaped optical trap, and the atoms achieve the momenta of $2\hbar k$ and $4\hbar k$. We measure the atom-loss spectra near the narrow FRs for two different momenta, and observe the momentum-broadened widths of the FRs. For a moving BEC with the large momentum $4\hbar k$, we find the splitting of loss peak in the FRs. Our work might be useful for the exploration of center-of-mass-momentum-dependent interaction in ultracold atomic gases.[37]

## 2. Experimental procedures

Our experiment starts with a BEC of $^{133}$Cs atoms in the hyperfine state $F = 3$, $m_F = 3$ at the magnetic field of $B = 21.5$ G, which corresponds to the scattering length of $a = 238a_0$ (with $a_0$ is Bohr's radius). This initial scattering length minimizes the three-body loss of Cs atoms. We adiabatically load the condensed atoms into a cigar-shaped optical trap, which consists of two crossed 1064 nm laser beams at angle $\sim 90°$, one with waist of $\sim 300$ μm and the other with waist of $\sim 58$ μm. The resulting trapping frequencies are $(\omega_x, \omega_y, \omega_z) = 2\pi \times (126, 96, 13)$ Hz,[38,39] where $z$ is the axial direction along the propagation direction of the laser beam that provides the weak radial confinement. The BEC can almost freely propagate with non-zero momentum when it is kicked along the axial direction.

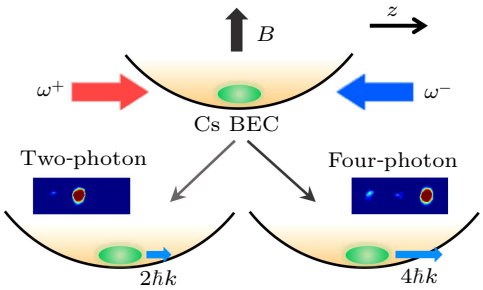



**Fig. 1.** Experimental schematic for achieving a moving BEC through multi-photon Bragg excitation. A $^{133}$Cs BEC, confined in a cigar-shaped optical trap, is illuminated by a pair of counter-propagating lasers, whose frequency detuning is precisely controlled for driving the two- and four-photon Bragg excitations. The zero-momentum atoms are coupled to the other momentum states $p = 2\hbar k$ and $4\hbar k$. After the $\pi/2$ two- and four-photon Bragg pulses, the condensed atoms get the momenta $2\hbar k$ and $4\hbar k$, respectively, and propagate along the axial direction of the optical trap. A uniform magnetic field $B$ is tuned to measure the Feshbach resonances of the ultracold Cs atoms.

For preparing a moving BEC, we use a pair of counter-propagating far-detuned laser beams to drive Bragg excitations involved with two- and four-photon processes in Fig. 1, and the zero-momentum atoms are coupled to the momentum states $p = 2\hbar k$ and $4\hbar k$, respectively, where $\hbar$ is the reduced Planck constant and $k = 2\pi/\lambda$ is the wavevector. According to the quadratic momentum–energy dispersion, we implement the resonant two- and four-photon Bragg excitations by precisely controlling the frequency difference of the counter-propagating laser beams $\Delta\omega = \omega^+ - \omega^- = 4E_R/\hbar$ and $8E_R/\hbar$, respectively, where $E_R$ is the recoil energy of Cs atoms.[40] By applying the excitation with a $\pi/2$ Bragg pulse, we obtain the moving BEC with the momenta $2\hbar k$ and $4\hbar k$ (see Fig. 1) and the corresponding transition efficiencies are about 99% and 96%, respectively. Before kicking the Cs BEC, we measure the atomic temperature through the time-of-flight method. The widths of optical density in the axial and radial directions $\sigma_z$ and $\sigma_x$ are plotted as a function of flight time in Fig. 2. The large radial trapping frequency leads to the temperature of $T_x = 20(1)$ nK, while the almost unchanged width indicates the temperature in the axial direction approaches zero. The measured large difference between the atomic temperatures in the radial and axial directions results from the larger radial trapping frequency than the axial frequency. The obtained atomic sample with ultralow temperature provides a good starting point for studying the effect of momentum on the FR.

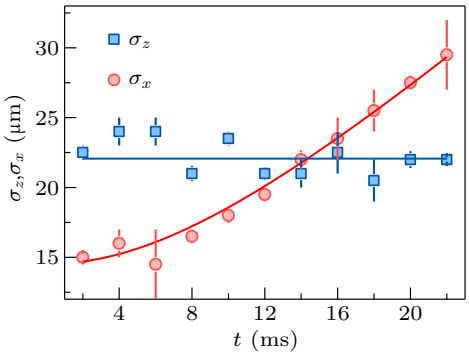



**Fig. 2.** The measured $1/e$ width of optical density, which is obtained by taking the absorption image for the atoms released from the optical trap, as a function of flight time $t$. $\sigma_x$ and $\sigma_z$ represent the widths of atomic column density distribution along the radial and axial directions, respectively. The atomic temperature along these two directions can given by using the equation[36] describing the expansion of atomic cloud during time-of-flight to fit the data, and the solid lines are the corresponding fitting lines.

## 3. Observing the momentum-broadened width of atoms-loss spectra in the narrow FRs

In the experiments of FRs, ultracold $^{133}$Cs atoms have rich FRs at low magnetic fields.[27] We measure the narrow g- and d-wave FRs of Cs atoms with different momenta near the magnetic fields of $B = 19.84$ G and 47.97 G, respectively, and study the effect of momentum on the resonance width. After imposing the different momenta on the condensed atoms, the magnetic field is rapidly ramped to a target value near an FR within 5 ms from $B = 21.5$ G, and then is kept for 500 ms. When the magnetic field is tuned to the resonance localization, the number of atoms exhibits a large three-body loss, and the atomic scattering length diverges ($a \to \pm\infty$). The accuracy of magnetic field is 2 mG, which is calibrated by the atomic transition $6S_{1/2}$, $F = 3$, $m_F = 3 \to 6S_{3/2}$, $F = 4$, $m_F = 3$ pumped by the microwave.[41] At the end of holding the magnetic field near the FR, all laser fields are switched off, and the magnetic field is quenched to $B = 17$ G with zero-crossing scattering

length.[42,43] The number of atoms in the optical trap is measured by using the standard absorption image.

We measure the FRs of Cs atoms with three different momenta near 19.84 G, and the variations of atom number remaining in the optical trap with the magnetic field are shown in Fig. 3. For the zero-momentum BEC, we use a Gaussian function to fit the typical atom-loss spectroscopy in Fig. 3(a), and the resonance location is determined as $B = 19.84$ G, which is consistent with the previously theoretical and experimental results.[26] The atom number decreases to 24% at the resonance location. The fitted full width at half maximum (FWHM) is given as $\gamma_0 = 88(3)$ mG, which describes the resonance width. When the atomic BEC is kicked to achieve the momentum $p = 2\hbar k$, the FWHM of atom-loss spectroscopy is broadened by 26% with $\gamma_1 = 116(6)$ mG. In particular, for the large momentum $p = 4\hbar k$, the broaden FWHM becomes twice as the zero-momentum case, and the fitted width is $\gamma_2 = 150(7)$ mG as shown in Fig. 3(c). More interestingly, we observe that the splitting occurs in the atom-loss spectroscopy for $p = 4\hbar k$.

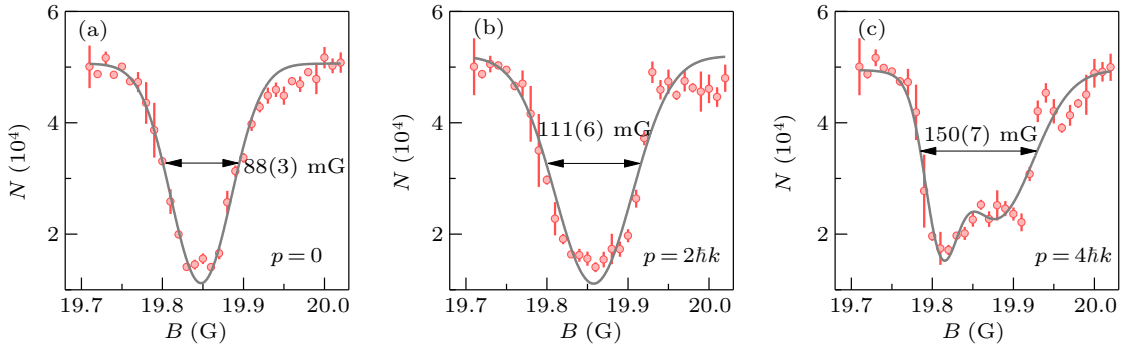



**Fig. 3.** The trap-loss spectra of the g-wave Feshbach resonance near the magnetic field 19.8 G for ultracold Cs atoms with three different momenta. The number of atoms $N$ in the optical trap after the 500 ms holding as a function of magnetic field $B$ for the momenta $p = 0$ in (a), $2\hbar k$ in (b) and $4\hbar k$ in (c). The full width at half maximum (marked by black arrows) of the atom-loss spectroscopy is derived by using a Gaussian function to fit the data, and the solid lines are the corresponding fitting curves. All error bars denote the standard deviations.

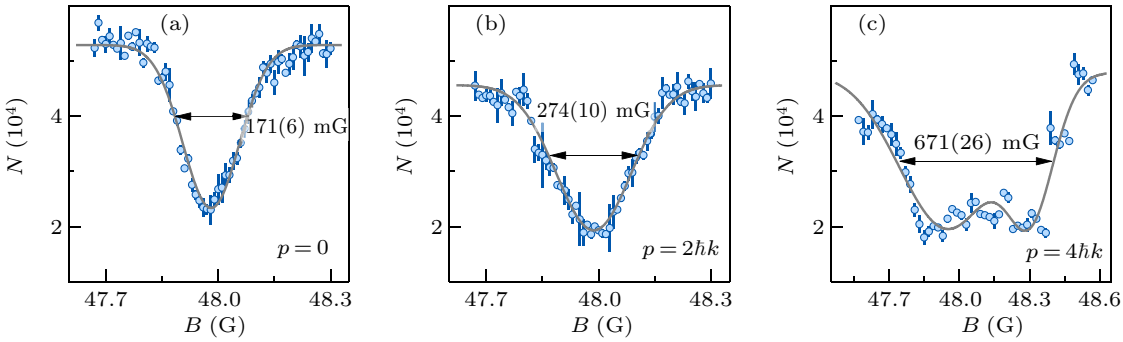



**Fig. 4.** The trap-loss spectra of the d-wave Feshbach resonance near the magnetic field 47.9 G for ultracold Cs atoms with three different momenta. The number of atoms $N$ in the optical trap after the 500-ms holding as a function of magnetic field $B$ for the momenta $p = 0$ in (a), $2\hbar k$ in (b) and $4\hbar k$ in (c). The full width at half maximum (marked by black arrows) of the atom-loss spectroscopy is derived by using a Gaussian function to fit the data, and the solid lines are the corresponding fitting curves. All error bars denote the standard deviations.

In Fig. 4(a), we show the atom-loss spectroscopy of the FR near 47.97 G for the zero-momentum BEC, and the number of atoms decreases to $\sim$ 40% at the resonance location. The fitted resonance location is $B = 47.98$ G, which agrees well with the previous experimental measurement.[44] The FWHM derived from the Gaussian fitting of the data is $\gamma_0 = 171(6)$ mG, which is larger than the width of the FR near 19.8 G as shown in Fig. 3(a). We observe the large broadening of the FWHM with $\gamma_1 = 274(10)$ mG in Fig. 4(b), when the atoms achieve the momentum $p = 2\hbar k$. In compared to the FR near 19.8 G, the momentum has a strong effect on the FWHM in the atom-loss spectroscopy of the FR near 47.9 G, as shown in Fig. 4(c). Intriguingly, for the atoms with the large momentum $p = 4\hbar k$, the fitted FWHM is given as $\gamma_2 = 671(26)$ mG, which is almost four times larger than the zero-momentum case. Besides, we show the splitting of the loss peak for $p = 4\hbar k$. The momentum-induced broadening of FR may be attributed to the Doppler effect of moving atoms at the non-zero momentum states, where the collective velocity of condensed atoms leads to the energy shift of scattering atomic states in the collision process. The momentum-broaden width in atoms-loss spectra of the FR may help to understand the dependence of interactions on the momentum of the center of mass in colliding ultracold atoms.[37]

## 4. Conclusion

In conclusion, we measure the narrow FRs of a moving Cs BEC near the magnetic fields of 19.8 G and 47.9 G,

and observe the momentum-induced broadening of widths in atom-loss spectra. We also find that the splitting occurs in the FR spectra of atoms with a large momentum $4\hbar k$. Furthermore, the angle between two Bragg laser beams is tuned for varying the transferred momentum, and the atoms can achieve different momenta. By measuring the FR spectra of atoms with varying momentum, the dependence of the broadened width on the atomic momentum will be revealed, and this may help to explain the underlying mechanism of momentum-broadened width of FR. In addition, our experiment provides a method to obtain the non-zero momentum BEC, and has potential applications in the study of the effect of kinetic term included in the nonlinear Schrödinger equation on the collective behavior of ultracold quantum gases.

## Acknowledgements

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