High sensitive detection of high-order partial wave scattering in photoassociation of ultralcold atoms*

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We report on the observation of enhanced high-order partial wave scattering from atom–atom interaction via changing the temperature of a magneto–optical trap in the process of photoassociation. The high-order scattering partial wave is directly manifested through the large signal amplitude of the rovibrational resonance levels of trap-loss spectroscopy from photoassociation.

Keywords: high-order partial wave, trap-loss, photoassociation

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1. Introduction

The ability to control particle–particle interaction is crucial for exploring the quantum physics in various interaction regimes.[1] Arguably the most important example of such a control is the magnetic Feshbach resonance, which has facilitated the demonstration of fermionic superfluidity[2] in strongly interacting atomic gases and the investigations on effects from a large s-wave scattering length for atomic Fermi gases[3,4] and for Bose–Einstein condensates.[5,6] An alternative method to modify cold atomic interaction is the optical Feshbach resonance which had been implemented in Refs. [7] and [8]. The conventional low temperature superconductivity can be explained by the Bardeen–Cooper–Schrieffer theory which is based on s-wave Cooper pairing. Recently, unconventional and high temperature superconductivity, which is assumed to result from higher order partial wave interaction, is drawing increasing interest for further research. To characterize the collisional properties in the quantum regime beyond the s-wave scattering, it is essential to devise other methods to control p-, d-, and other higher order partial wave interactions.

Up to now, the atomic pairs are often formed in s-wave scattering channel but it is also known from the condensed matter physics that fermionic superfluidity can arise from higher angular momentum pairs: p-wave Cooper pairs have been observed in ^{3}He[9] and d-wave Cooper pairs in high-T_c superconductivity.[10] Although Feshbach resonances involving p or higher order partial waves have been found in cold atomic system,[11–14] the high resolution photoassociation (PA) spectroscopy of cold atoms is a robust technique for exploration and observation of high-order partial waves scattering from collisional interaction between two cold atoms.

In this paper, we report on the observation of the remarkable p- and d-partial waves besides the large signal of s-wave scattering by controlling the temperature of the MOT during PA process. The high resolution trap-loss spectroscopy from PA has been obtained, and higher rovibrational levels are observed. The signals for the rotational quantum numbers with $J = 3$ and $J = 4$ resulting from p- and d-wave scattering are enhanced compared with the amplitude of $J = 2$ which only involves s-wave scattering. Thus, the rotational number J becomes a direct signature

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for the partial waves in the collision interaction from two cold ground atoms.

2. Rotation coupling of molecule

The molecular Hamiltonian $H_{\rm Mol}$ can be expressed as

$$H_{\rm Mol} = H_{\rm CM}(X) + H_0(r_{\rm e}, R), \tag{1}$$

where X is the position of the center of molecular mass in a space-fixed coordinate, $r_{\rm e}$ is the position of the electrons relative to the center of mass in the body-fixed coordinate system and R is the internuclear separation in the body-fixed coordinates as in Ref. [15]. Thus the Hamiltonian describes the motion relative to the center of mass and can be written as

$$H_0(r_{\rm e}, R) = H_{\rm E}(r_{\rm e}, R) + H_{\rm N}(R). \tag{2}$$

Using Born–Oppenheimer approximation, we can obtain the nuclear part of the molecular wavefunction $\psi_{\rm N}(R)$ by solving the nuclear Schrödinger equation,

$$\begin{aligned} H_{\rm N}\psi_{\rm N}(R) &= \left(-\frac{\hbar^2}{2}\sum_k \frac{1}{M_k}\nabla_k^2 + U(R)\right)\psi_{\rm N}(R) \\ &= E\psi_{\rm N}(R), \end{aligned} \tag{3}$$

where $\psi_{\rm N}$ is the nuclear part of the molecular wavefunction, M_k is the reduced molecular mass, $U(R)$ is an effective potential for motion from nuclei and E is the eigen-energy of molecule. Thus, equation (2) is a central-force problem and hence the radial (R) and angular (θ, ϕ) degrees of freedom are de-coupled. The motion of two nuclei in radial direction along the internuclear axis corresponds to the vibration quantum behavior, while the angular motion of two nuclei corresponds to the molecular rotation around an axis perpendicular to the internuclear axis. Therefore the Hamiltonian of the nuclear motion can be written as,

$$H_{\rm N} = -\frac{\hbar^2}{2M_{\rm r}}\left(\frac{\partial^2}{\partial R^2} + \frac{2}{R}\frac{\partial}{\partial R}\right) + U(R) + \frac{l(l+1)}{2M_{\rm r}R^2}, \tag{4}$$

where l is the relative angular momentum of two nuclei, also it denotes the scattering partial wave from collision of two cold atoms in the ground states, and $M_{\rm r}$ is the reduced mass of the molecule.

For PA of the cesium atom, we consider that the incoming scattering state from two colliding atoms, which is described by its collisional energy E and partial wave l, is coupled to an excited molecular state characterized by vibrational quantum number v and rotational quantum number J. In this collisional process, the interatomic potential is modified by an energy term as a centrifugal term of the form $\hbar^2 l(l+1)/2M_{\rm r}R^2$, which is high enough to create effective centrifugal barriers. Thus only those partial waves occur when the collisional energy is sufficient to tunnel through this effective centrifugal barrier.

Considering the long-range molecular excited $0_{\rm g}^-$ state of Cs_2, the observed rotational quantum number J is given by $J = L + S + l$, where $L = 1$ is the total electron orbital angular momentum and $S = 1$ is the total electron spin as in Ref. [16]. Here l is the magnitude of the orbital angular momentum l of the collisional atom pair, and L and S of the excited molecule are coupled to the diatomic axis according to Hund's case (c) as shown in Fig. 1. The observation of rovibrational lines is thus a direct measurement of the number of partial waves participating in the PA process.

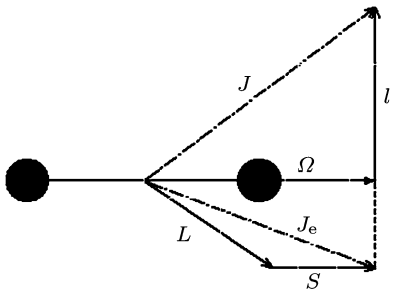


Fig. 1. Hund's case (c): L and S are the total electron orbit and spin angular momentum, $J_{\rm e} = L + S$, is the total electron angular momentum, l is the rotation angular momentum, and Ω is a projection of $J_{\rm e}$ on the internulear axis. Then J is the coupling of $J_{\rm e}$ and l, and $J = \Omega + l$.

Furthermore, the quantum numbers must fulfill the selection rule

$J + l =$ even numbers,

which is a result of the symmetrization requirement for the two-body wave function. Hence, the scattering state can only be excited to rovibrational levels J satisfying

$$|l - |L + S|| \le J \le |l + |L + S|| \,. \tag{5}$$

Let L and S both be 1 as in Eq. (5), the partial wave contributions for each rotational level J. The partial wave components for $J = 1, 2, \ldots, 6$ are mainly s, s, p, d, f, and g respectively as those in Ref. [17]. At low collisional energies, the largest contribution to the transition comes from the lowest partial wave scattering, namely s-wave.

3. Experiment

The experiment was carried out in a conventional vapor cell magneto–optical trap (MOT) where an ensemble of cesium atoms is prepared. As described in detail in Refs. [18] and [19], the background pressure is set to about 10^{-7} Pa, and a number of cold atoms $\sim 10^7$ is accumulated in the quartz vacuum chamber. The initial temperature of the cold atomic sample is measured to be $\sim$ 120 μK by using a time-of-flight method.

In this experiment, this trap consists of three pairs of mutually orthogonal laser beams with opposite $\sigma^{+/-}$ polarizations of intensity of nearly 3 mW/cm^2. A qradrupole magnetic field for the MOT was generated by a pair of anti-Helmholtz coils with a typical gradient $\sim$ 15 Gs/cm (1 Gs = 10^{-4} T) along the axis of the coils as shown in Fig. 2. The trapping and repumping lasers (DL100) were stabilized by using a standard saturated absorption technology. Finally cold cesium atoms were populated in the ground state $6S_{1/2}(F = 4)$. For high sensitive trap-loss spectroscopy, we modulated the cold atomic sample by modulating the trapping laser with amplitude and frequency.[19,20]

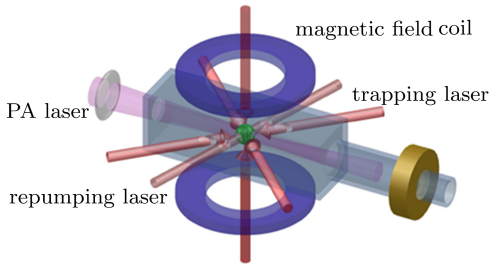


Fig. 2. (colour online) Experimental setup for photoassociation of cold atom in MOT.

The process of PA was performed by illuminating the cold atomic sample given above by a widely tunable Ti:sapphire laser. The PA laser frequency was measured by a wavelength meter with an accuracy of 0.002 cm^{-1}. Its linewidth is less than 100 kHz. The frequency was set at around $\sim$ 11681.32 cm^{-1} corresponding to the vibritional quantum number of $v \sim 17$ and scanned over a 3-GHz range in 250 s. The available output power was 600 mW and focused to a diameter of 500 μm, resulting in an intensity up to $\sim$ 300 W/cm^2.

Here the trap-loss spectroscopy was employed to detect the product of the cesium molecular dimmer instead of the molecular ionization spectroscopy.[21] The fluorescence yielded from the trapped atoms was collected by a convex lens and detected by an avalanche photodiode. A lock-in amplifier was employed to demodulate the fluorescence of the modulated cold atoms, and thus a high resolution trap-loss spectroscopy was obtained.[22] An enhanced signal-to-noise ratio can be reached compared with the direct measurement method which submerges the fluorescence signal by the stray noise. The gradient of the qradrupole magnetic field and background pressure were altered to change the temperature of the MOT, thus the larger signal of p- and d-wave scattering can be observed with high sensitivity and high resolution rather than in conventional low temperature conditions contributing mainly to s-wave scattering. However, there is no quantitative model to determine the temperature of cold atoms because the MOT can be operated in very different mechanisms by varying different parameters as mentioned in Refs. [23] and [24].

4. Trap-loss spectroscopy and enhanced high partial signal

Research on long-range 0_g^- state of cesium molecules is crucial due to its shallow potential well located at large internuclear distance and therefore has high probability in forming a cold ground state molecule.[25] In the experiment, we concentrate on the vibrational level $v = 17$ in the long-range 0_g^- state, which is induced from two free ground state atoms trapped in the MOT through the PA process by using a strong Ti:sapphire laser just as shown in Fig. 2. The number of cold atoms decreases as the PA laser tuned to a resonance frequency relative to a rovibrational state, thus leading to a strong loss spectroscopic character. For the long-range 0_g^- state, trap-loss spectroscopy with ultrahigh resolution is shown in Fig. 3, the narrow and strong resonance lines have been observed, and rotational quantum numbers are assigned in the spectrum based on the accurate spectroscopic investigation according to Ref. [25]. The s-wave scattering induced from the low temperature environment facilitates to form an excited molecule at rotational quantum level $J = 2$, where the temperature of the MOT is $\sim$ 120 μK as the initial temperature.

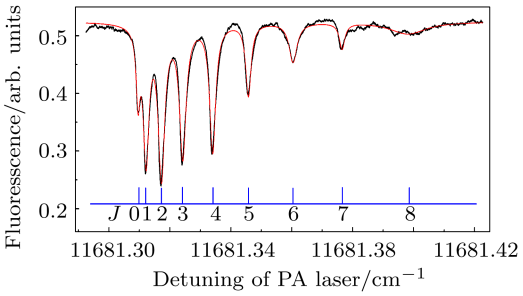


Fig. 3. (colour online) The high resolution PA spectrum for the $v = 17$ rovibrational state of the long-range molecular states 0_g^- produced in the MOT with a temperature of about ~ 120 μK. The red lines are fitting lines for experimental data.

It is interesting to note that we have observed rigid rotational states of the cesium molecule from $J = 0$ to $J = 8$. For pure s-wave scattering, the centrifugal term $\hbar^2 l(l+1)/2M_r R^2$ forms molecules mainly populated at the energy level with $J = 2$, which is the strongest rotational line in the PA spectrum as shown in Fig. 3. Signals from other high partial waves scattering are small relative to the result of s-wave scattering and this stems from low temperature in the MOT, but those from high partial wave scattering will occur due to quantum tunneling through the centrifugal barrier. Current results show the different rotational energy levels, which indicate various partial wave scattering collisions, whose signals from different rotation levels have been observed due to kinds of partial waves joined in the atom–atom collision. If the energy of collision is sufficient to tunnel through the effective centrifugal barrier, which is derived from the term $\hbar^2 l(l+1)/2M_r R^2$, the appropriate partial waves collision would occur. Thus the resonance line of $J = 2$ is the strongest due to the main contribution from low energy s-wave scattering at a low temperature 120 μK.

In order to produce more high partial waves scattering, the temperature of the MOT was altered by varying the gradient of the quradrupole magnetic field and the background pressure of vacuum chamber. As the temperature of the MOT increased from 120 μK to 200 μK, the signals from p- and d-wave scattering enhanced greatly than that from s-wave scattering and showed the same amplitude as s-wave scattering just like that in Ref. [26]. In Fig. 4(a), the enhanced resonance signal was obtained by creating a photoassociated atomic dimmer with the rotational quantum number $J = 3$ and $J = 4$, where the amplitude of the resonance line $J = 3$ was larger than that from $J = 2$, and the amplitude of $J = 4$ was the same as $J = 2$. And the result of Fig. 4(b) shows that the signal amplitudes for $J = 3$ and $J = 4$ are significantly enlarged than that for $J = 2$. This appearance revealed two other high-order partial waves (p- and d-waves) scattering occur with a larger probability than the s-wave in the MOT at a high temperature.

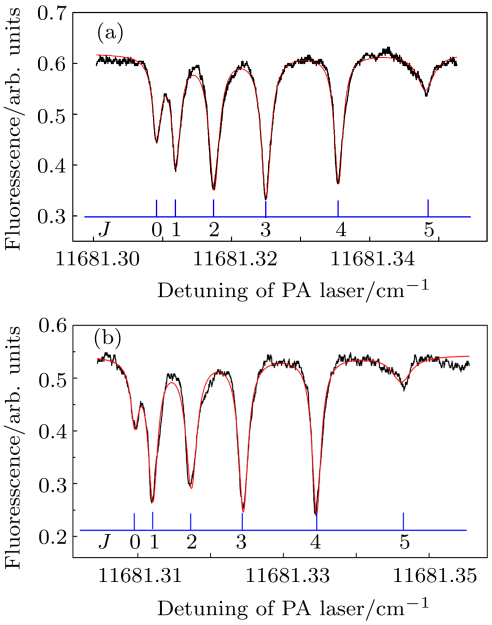


Fig. 4. (colour online) (a) The enhanced resonance signal of the rotational quantum levels $J = 3$ and $J = 4$ in photoassociation spectroscopy (PAS) with temperature 200 μK in the MOT. (b) The enhanced p- and d-wave scattering corresponding to the rotational quantum levels $J = 3$ and $J = 4$ with temperature 200 μK in the MOT.

Through enhancing the signals from high partial waves scattering by increasing the MOT's temperature, we can modify atomic high-order partial waves scattering collisions in the PA process. The scattering wave function which describes the collision of two cold atoms at a particular energy and angular momentum can be viewed as a standing wave set up between an incoming wave and the wave reflected by the short-range interatomic potential, and hence has a fixed pattern of nodes. Here the length of two consistent nodes is usually regarded as the scattering length. If the molecules formed in the PA process are stimulated emission back to the initial atomic collisional channel by the high intensity PA laser, the amplitude of the original reflected wave will reduce and the standing-wave function and nodes will also be modified. As a result, this can change the scattering length and introduce variation of cold atomic collision just like the case in Ref. [27].

5. Conclusion

We have experimentally presented that the large signals from the p- and d-partial wave scattering in atom–atom interaction are obtained in the PA process, and this is attributed to the increasing of the MOT temperature. The strong resonance lines for $J = 3$ and $J = 4$ in the trap-loss spectroscopy with high resolution present partial wave scattering collisional interaction from two cold ground atoms, corresponding to p- and d-wave scattering respectively. Based on this enhanced signal, the cold atomic collision and scattering length are estimated to be modified by using a PA laser with a high intensity. Consequently, the excited state molecules are stimulated and emitted back to initial entrance channel, because the reflected scattering wave from the short-range potential has been modified by PA process.

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