P-wave Feshbach resonances of ultracold ^{6}Li

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P-wave Feshbach resonances of ultracold ^{6}Li

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We report the observation of three *p*-wave Feshbach resonances of ^{6}Li atoms in the lowest hyperfine state $f=1/2$. The positions of the resonances are in good agreement with theory. We study the lifetime of the cloud in the vicinity of the Feshbach resonances and show that, depending on the spin states, two- or three-body mechanisms are at play. In the case of dipolar losses, we observe a nontrivial temperature dependence that is well explained by a simple model.

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In the presence of a magnetic field, it is possible to obtain a quasidegeneracy between the relative energy of two colliding atoms and that of a weakly bound molecular state. This effect, known as a Feshbach resonance, is usually associated with the divergence of the scattering length and is the key ingredient that led to the recent observation of superfluids from fermion atom pairs of ^{6}Li [1–4] and ^{40}K [5]. Up to now these pairs were formed in *s*-wave channels but it is known from condensed matter physics that fermionic superfluidity can arise through higher angular momentum pairing: *p*-wave Cooper pairs have been observed in ^{3}He [6] and *d*-wave cooper pairs in high-T_c superconductivity [7]. Although Feshbach resonances involving *p* or higher partial waves have been found in cold atom systems [8–10], *p*-wave atom pairs have never been directly observed.

In this paper we report the observation of three narrow *p*-wave Feshbach resonances of ^{6}Li in the lowest hyperfine state $f=1/2$. We measure the position of the resonance as well as the lifetime of the atomic sample for all combinations $|f=1/2,m_f\rangle+|f=1/2,m_f'\rangle$, henceforth denoted (m_f,m_f'). We show that the position of the resonances are in good agreement with theory. In the case of atoms polarized in the ground state $(1/2,1/2)$, the atom losses are due to three-body processes. We show that the temperature dependence of the losses at resonance cannot be described by the threshold law predicted by [11] on the basis of the symmetrization principle for identical particles. In the case of atoms polarized in $(-1/2,-1/2)$ or that of a mixture $(1/2,-1/2)$, the losses are mainly due to two-body dipolar losses. These losses show a nontrivial temperature dependence that can nevertheless be understood by a simple theoretical model with only one adjustable parameter. In the $(1/2,-1/2)$ channel, we take advantage of a sharp decrease of the two-body loss rate below the Feshbach resonance to present a first evidence for the generation of *p*-wave molecules.

The *p*-wave resonances described in this paper have their origin in the same singlet $(S=0)$ bound state that leads to the *s*-wave Feshbach resonances located at 543 G and ~830 G. The latter has been used to generate stable molecular Bose-Einstein condensates [1–4]. In order to discuss the origin of these resonances, it is useful to introduce the molecular basis quantum numbers S,I, and l, which correspond to the total electron spin $\boldsymbol{S}=\boldsymbol{s}_1+\boldsymbol{s}_2$, total nuclear spin $\boldsymbol{I}=\boldsymbol{i}_1+\boldsymbol{i}_2$, and orbital angular momentum $\boldsymbol{l}$. Furthermore, the quantum numbers must fulfill the selection rule

$$S+I+l=\text{even}, \tag{1}$$

which is a result of the symmetrization requirements of the two-body wave function. Since the atomic nuclear spin quantum numbers are $i_1=i_2=1$, and $S=0$, there are two possibilities for the total nuclear spin in combination with an *s*-wave $(l=0)$ collision: $I=0$ and $I=2$. These two states give rise to the two aforementioned *s*-wave Feshbach resonances. For *p*-wave $(l=1)$ collisions only $I=1$ is possible. This bound state may then give rise to the three *p*-wave Feshbach resonances of Fig. 1. This threshold state does not suffer from exchange decay, and is therefore relatively stable. Our predicted resonance field values B_F (Table I) result from an analysis which takes into account the most recent experimental data available for ^{6}Li. The calculation has been performed for all spin channels (m_f,m_f') and a typical collision energy

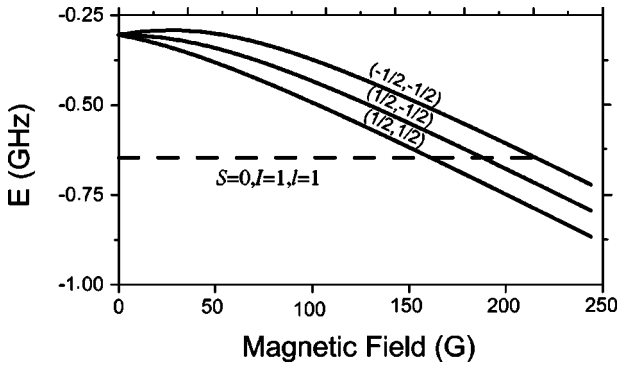

FIG. 1. Coupled channels calculation of *p*-wave binding energies, which give rise to Feshbach resonances at threshold. The two-atom states (full line) are indicated by their quantum number (m_{f_1},m_{f_2}), while the bound state (dashed line) is labeled by the molecular quantum numbers S,I, and l.

TABLE I. Theoretical and experimental values of the magnetic field B_F at the *p*-wave Feshbach resonance for ^{6}Li atoms in $|f_1=1/2,m_{f_1}\rangle$ and $|f_1=1/2,m_{f_2}\rangle$.

(m_{f_1},m_{f_2})	Theory (G)	Experiment (G)
$(1/2,1/2)$	159	160.2(6)
$(1/2,-1/2)$	185	186.2(6)
$(-1/2,-1/2)$	215	215.2(6)

of 15 μK. A more detailed analysis will be published elsewhere [12].

Experimentally, we probe these *p*-wave resonances using the setup described in previous papers [13,14]. After evaporative cooling in the magnetic trap, we transfer $\sim 5\times 10^5$ atoms of ^{6}Li in $|f=3/2, m_f=3/2\rangle$ in a far-detuned crossed optical trap at low magnetic field. The maximum power in each arm is $P_h^0=2$ W and $P_v^0=3.3$ W in the horizontal and vertical beam, respectively, and corresponds to a trap depth of ~ 80 μK. The oscillation frequencies measured by parametric excitation are, respectively, $\omega_x=2\pi\times 2.4(2)$ kHz, $\omega_y=2\pi\times 5.0(3)$ kHz, $\omega_z=2\pi\times 5.5(4)$ kHz, where the $x(y)$ direction is chosen along the horizontal (vertical) beam. A first radio-frequency (rf) sweep brings the atoms to $|f=1/2, m_f=1/2\rangle$ and, if necessary, we perform a second rf transfer to prepare the mixture $(1/2,-1/2)$ or the pure $(-1/2,-1/2)$. The variable magnetic field B is the sum of two independent fields B_0 and B_1. B_0 offers a wide range of magnetic field while B_1 can be switched off rapidly. After the radio-frequency transfer stage, we ramp the magnetic field to $B_0\sim 220$ G with $B_1\sim 8$ G in 100 ms. When needed, we reduce in 100 ms the power of the trapping beams to further cool the atoms. For the coldest samples, we obtain at the end of this evaporation sequence $N\sim 10^5$ atoms at a temperature ~ 5 μK. This corresponds to a ratio $T/T_F\sim 0.5$, where $k_BT_F=\hbar(6N\omega_x\omega_y\omega_z)^{1/3}$ is the Fermi energy of the system. To reach the Feshbach resonance, we reduce B_0 in 4 ms to its final value $B_{0,f}\sim B_F$, near the Feshbach resonance. At this stage, we abruptly switch off B_1 so that the total magnetic field is now close to resonance. After a waiting time in the trap $t_{\rm wait}=50$ ms, we switch off the trapping and the magnetic field and we measure the remaining atom number after a 0.35 ms time of flight.

We show in Fig. 2 the dependence of the atom number on the final value of $B_{0,f}$ in the case of the spin mixture $(1/2, -1/2)$ at a temperature $T\sim 14$ μK. As expected from theory, we observe a sharp drop of the atom number for values of the magnetic field close to 186 G. The other two *p*-wave Feshbach resonances have a similar loss signature and Table I shows that for all spin channels, the resonance positions are in good agreement with predictions. Note that in Table I the uncertainty is mainly due to the magnetic field calibration while the short term stability is $\lesssim 50$ mG.

To evaluate the possibility of keeping *p*-wave molecules in our trap, we have studied the lifetime of the gas sample at the three Feshbach resonances. We have measured the number N of atoms remaining in the trap after a variable time $t_{\rm wait}$. Accounting for two- and three-body processes only, N should follow the rate equation

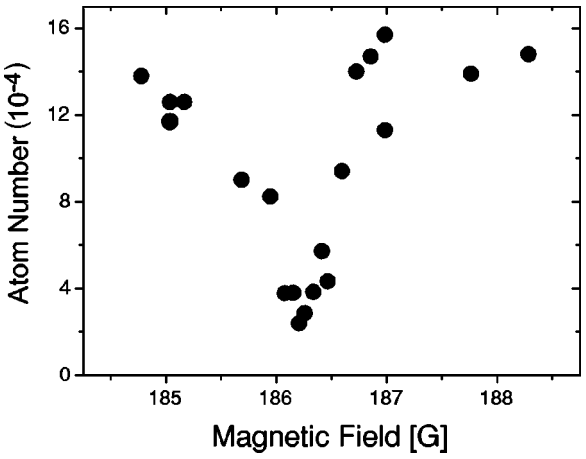

FIG. 2. Atom number vs magnetic field $B_{0,f}$ after a 50 ms wait for atoms in the spin mixture $(1/2,-1/2)$ at $T\sim 14$ μK. The sharp drop close to $B_0\sim 186$ G over a range $\simeq 0.5$ G is the signature of the *p*-wave Feshbach resonance predicted by theory.

$$\frac{\dot{N}}{N}=-G_2\langle n\rangle-L_3\langle n^2\rangle, \tag{2}$$

where n is the atom density and $\langle n^a\rangle=\int d^3r\, n^{a+1}/N$ $(a=1,2)$ is calculated from the classical Boltzman distribution. In this equation, we can safely omit one-body losses since the measured decay time is ~ 100 ms, much smaller than the one-body lifetime ~ 30 s.

In the $(1/2,1/2)$ channel, we find that three-body losses are dominant. The dependence of L_3 with temperature is very weak [Fig. 3(a)]. A theoretical calculation of the temperature dependence of three-body loss rate has been performed in [11] and it predicts that in the case of indistinguishable fermions L_3 should be proportional to T^λ, with $\lambda\geqslant 2$. Although this prediction seems in disagreement with our experimental

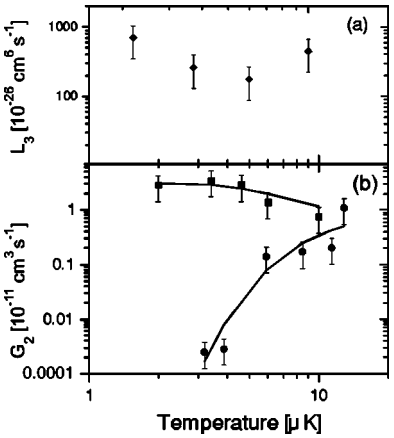

FIG. 3. Variations of (a) three-body and (b) two-body loss rates vs temperature at the Feshbach resonance. (a) ♦: atoms in the Zeeman ground state $|f=1/2,m_f=1/2\rangle$, $B_{0,f}\sim 159$ G. (b) ■: atoms polarized in $|f=1/2,m_f=-1/2\rangle$, $B_{0,f}\sim 215$ G. ●: the mixture $|f=1/2,m_f=1/2\rangle+|f=1/2,m_f=-1/2\rangle$, $B_{0,f}\sim 186$ G. In both cases, the full line is a fit to the data using the prediction of Eq. (4) with the magnetic field as the only fitting parameter.

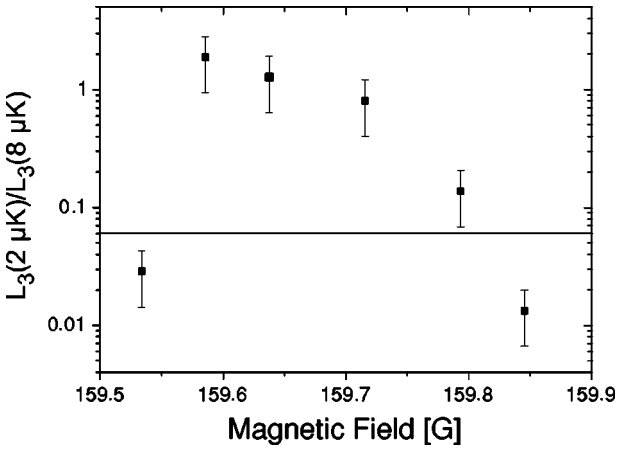

FIG. 4. Ratio $L_3(T=2\ \mu\text{K})/L_3(T=8\ \mu\text{K})$ of the three-body decay rate for two different temperatures for a gas of atoms polarized in $|f=1/2, m_f=1/2\rangle$. The full line is the threshold law $L_3 \sim T^2$.

results, the analysis of [11] relies on a Wigner threshold law, i.e., a perturbative calculation based on the Fermi golden rule. At the Feshbach resonance where the scattering cross section is expected to diverge, this simplified treatment is not sufficient. This suggests that three-body processes must be described by a more refined formalism, analogous to the unitary limited treatment of the *s*-wave elastic collisions [15]. To confirm this assumption, we have compared the loss rates at two given temperatures ($T=2\ \mu$K and $T=8\ \mu$K, respectively) for various values of the magnetic field (Fig. 4). If the threshold law is valid, then the ratio $L_3(2\ \mu\text{K})/L_3(8\ \mu\text{K})$ should always be smaller than $(2/8)^2 \sim 0.0625$ (full line of Fig. 4). As seen before, experimental data show no significant variation of L_3 with temperature near resonance. However, when the magnetic field is tuned out of resonance we recover a dependence in agreement with [11].

In contrast to *s*-wave Feshbach resonances where dipolar losses are forbidden in the $f=1/2$ manifold [16], the losses at resonance are found to be dominantly two body in the $(1/2,-1/2)$ and $(-1/2,-1/2)$ channels. The variations of the two-body loss rate with temperature are displayed in Fig. 3(b). The temperature dependence appears very different in the two cases. We show now that this is the consequence of a strong sensitivity to magnetic field detuning from resonance, rather than a specific property of the states involved. In an extension of the work presented in [17], we describe inelastic collisions by two noninteracting open channels coupled to a single *p*-wave molecular state [18]. This model leads to an algebra close to the one describing photoassociation phenomena [19] and the two-body loss rate at energy E is given by

$$g_2(E) = \frac{KE}{(E-\delta)^2 + \gamma^2/4}. \tag{3}$$

Here $\delta = \mu(B - B_F)$ is the detuning to the Feshbach resonance and K, μ, and γ are phenomenological constants, depending on the microscopic details of the potential [21]. For each channel, these parameters are estimated from our coupled-channel calculation (Table II). To compare with experimental

TABLE II. Parameters characterizing the two-body loss rates for $(1/2,-1/2)$ and $(-1/2,-1/2)$ spin channels.

(m_{f_1}, m_{f_2})	K ($\text{cm}^3\ \mu\text{K s}^{-1}$)	γ (μK)	μ ($\mu\text{K G}^{-1}$)
$(1/2,-1/2)$	1.21×10^{-13}	0.05	117
$(-1/2,-1/2)$	7.33×10^{-13}	0.08	111

data, Eq. (3) is averaged over a thermal distribution and for $\delta > 0$ and $\delta \gg \gamma$ we get

$$G_2 \sim 4\sqrt{\pi}\frac{K}{\gamma}\left(\frac{\delta}{k_B T}\right)^{3/2} e^{-\delta/k_B T}. \tag{4}$$

Equation (4) is used to fit the data of Fig. 3(b), with $B - B_F$ as the only fitting parameter. We get a fairly good agreement if we take $B - B_F = 0.04$ G (0.3 G) for the $(-1/2, -1/2)[(1/2,-1/2)]$ channel, illustrating the extreme sensitivity of G_2 to detuning and temperature. This feature was also qualitatively tested by measuring the variations of G_2 with magnetic field at constant temperature. Another interesting feature of Eq. (4) is that it predicts that the width δB of the Feshbach resonance, as measured by atom losses, should scale like $k_B T/\mu$. For a typical temperature $T \sim 15\ \mu$K, this yields $\delta B \sim 0.15$ G, in agreement with the resonance width shown in Fig. 2.

From Eq. (4) we see that G_2 nearly vanishes at $\delta = 0$. The thermal average of Eq. (4) for $\delta = 0$ yields $G_2(\delta=0) \propto K k_B T$. The ratio between the maximum two-body loss rate ($\delta = 3k_B T/2$) and that at $\delta = 0$ is then $\sim k_B T/\gamma$, $\sim 10^2$ for $\sim 10\ \mu$K. In the region $\delta < 0$ where we expect to form molecules, we benefit from a $1/\delta^2$ further reduction of the two-body losses [see Eq. (4)].

We have checked the production of molecules in $(1/2, -1/2)$ by using the scheme presented in [13,22]. We first generate molecules in $|S=0, I=1, l=1\rangle$ by ramping in 20 ms the magnetic field from 190 G $> B_F$ to $B_{\text{nuc}} = 185$ G $< B_F$. At this stage, we can follow two paths before detection (Fig. 5). Path 1 permits us to measure the number N_1 of free atoms: by ramping *down* in 2 ms the magnetic field from 185 G to 176 G, we convert the molecules into deeply bound molecu-

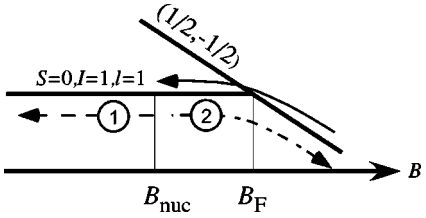

FIG. 5. Molecules are generated by ramping from a magnetic field higher than B_F to $B_{\text{nuc}} < B_F$. From there, two paths are used. In path 1 (dashed line), the magnetic field is decreased to create tightly bound molecules that will not appear on absorption images. In path 2 (dashed-dotted line), the magnetic field is ramped up across resonance to dissociate the molecules. The efficiency of the molecule production is simply given by $(1 - N_1/N_2)$, where N_i is the atom number measured after path i.

lar states that decay rapidly by two-body collisions. Path 2 gives access to the total atom number N_2 (free atoms + atoms bound in *p*-wave molecules). It consists of ramping *up* the magnetic field in 2 ms from B_{nuc} to 202 G$>B_F$ to convert the molecules back into atoms. Since the atoms involved in molecular states appear only in pictures taken in path 2, the number of molecules in the trap is $(N_2-N_1)/2$. In practice, both sequences are started immediately after reaching B_{nuc} and we average the data of 25 pictures to compensate for atom number fluctuations. We then get $N_1=7.1(5)\times10^4$ and $N_2=9.1(7)\times10^4$ which corresponds to a molecule fraction $1-N_1/N_2=0.2(1)$. Surprisingly, we failed to detect any molecule signal when applying the same method to $(1/2,1/2)$ atoms.

Since the dramatic reduction of inelastic losses close to a *s*-wave Feshbach resonance [23] was a key ingredient to the recent observation of fermionic superfluids, the formation of stable atom pairs requires a full understanding of the decay mechanisms at play close to a *p*-wave resonance. In this paper we have shown that in the particular case of two-body losses, the maximum losses take place when the detuning is positive. Since stable dimers are expected to be generated for negative detuning, dipolar losses should not present a major hindrance to further studies of *p*-wave molecules.

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