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P-wave Feshbach resonances of ultra-cold \(^6\)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 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, 2- or 3-body mechanisms are at play. In the case of dipolar losses, we observe a non-trivial 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 quasi-degeneracy 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 and \(^40\)K. 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 and d-wave in high-\(T_c\) superconductivity. Although Feshbach resonances involving p or higher partial waves have been found in cold atom systems and 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 3-body processes. We show that the temperature dependence of the losses at resonance cannot be described by the threshold law predicted by 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 2-body dipolar losses. These losses show a non trivial 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 2-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 \(\sim 830\) G. The latter has been used to generate stable molecular Bose-Einstein condensates. In order to discuss the origin of these resonances, it is useful to introduce the molecular basis quantum numbers \(S, I, \text{ and } l\). Furthermore, the quantum numbers must fulfill the selection rule

\[
S + I + l = \text{even},
\]

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

![Graph showing coupled channels calculation of p-wave binding energies](image-url)
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 $B_F$ (Tab. 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 of 15 $\mu$K. A more detailed analysis will be published elsewhere [12].

Experimentally, we probe these p-wave resonances using the setup described in previous papers [3,4]. 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 $\sim 80 \mu$K. 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 $x$ (resp. $y$) direction is chosen along the horizontal (resp. vertical) beam. A first radiofrequency (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 $\sim 5$ $\mu$K. This corresponds to a ratio $T/T_F \sim 0.5$, where $k_B T_F = \hbar(6N\omega_x\omega_y\omega_z)^{1/3}$ 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 $t_{\text{wait}} = 50$ 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 $B_{0,f}$ in the case of the spin mixture $(1/2,-1/2)$ at a temperature $T \sim 14$ $\mu$K. 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 Tab. 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 $t_{\text{wait}}$. Accounting for 2 and 3-body processes only, $N$ should follow the rate equation

$$\frac{\dot{N}}{N} = -G_2(n) - L_3(n^2),$$

(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 Boltzmann distribution. In this equation, we can safely omit one-body losses since the measured decay time is $\sim 100$ ms, much smaller than the one body lifetime $\sim 30$ s.

In the $(1/2,1/2)$ channel, we find that 3-body losses are dominant. The dependence of $L_3$ with temperature is very weak (Fig. 3a). A theoretical calculation of the temperature dependence of 3-body loss rate has been performed in [11] and it predicts that in the case of indistinguishable fermions $L_3$ should be proportional to $T^\lambda$, with $\lambda \geq 2$. Although this prediction seems in disagreement with our experimental results, the analysis of [11] relies on a Wigner threshold law, i.e., a perturbative calculation based on the Fermi golden rule. At the

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 $|f_1 = 1/2,m_{f_2}\rangle$.

<table>
<thead>
<tr>
<th>$(m_{f_1},m_{f_2})$</th>
<th>Theory (G)</th>
<th>Experiment (G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(1/2,1/2)$</td>
<td>159</td>
<td>160.2(6)</td>
</tr>
<tr>
<td>$(1/2,-1/2)$</td>
<td>185</td>
<td>186.2(6)</td>
</tr>
<tr>
<td>$(-1/2,-1/2)$</td>
<td>215</td>
<td>215.2(6)</td>
</tr>
</tbody>
</table>

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 $T \sim 14\mu$K. The sharp drop close to $B_0 \sim 186$ G over a range $\sim 0.5$ G is the signature of the p-wave Feshbach resonance predicted by theory.
Feshbach resonance where the scattering cross-section is expected to diverge, this simplified treatment is not sufficient. This suggests that 3-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 unitary limited treatment of the s-wave elastic collisions prescribed by a more refined formalism, analogous to the one describing photoassociation phenomena [19] and the 2-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 $K$, $\mu$ and $\gamma$ are phenomenological constants depending on the microscopic details of the potential [21]. For each channel, these parameters are estimated from our coupled-channel calculation (Tab. I). To compare with experimental data, Eq. (3) is averaged over a thermal distribution and for $\delta > 0$ and $\delta \gg \gamma$ we get:

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

Eqn. (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 (resp. 0.3 G) for the $(-1/2,-1/2)$ (resp. $(1/2,-1/2)$) 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 Eqn. (4) is that it predicts that the width $\delta B$ 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 (4) for $\delta = 0$ yields $G_2(\delta = 0) \propto Kk_B T$. 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 2-body losses (see Eqn. (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 $|S = 0, I = 1, I = 1\rangle$ by ramping in 20 ms the magnetic field from 190 G $> B_F$ to $B_{nuc} = 185 G < B_F$. At this stage, we can follow two paths...

<table>
<thead>
<tr>
<th>$(m_f, m_{f\prime})$</th>
<th>$K$ cm$^3$ µK$^{-1}$s$^{-1}$</th>
<th>$\gamma$ µK</th>
<th>$\mu$ µK·G$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(1/2,-1/2)$</td>
<td>$1.21 \times 10^{-13}$</td>
<td>0.05</td>
<td>117</td>
</tr>
<tr>
<td>$(-1/2,-1/2)$</td>
<td>$7.33 \times 10^{-13}$</td>
<td>0.08</td>
<td>111</td>
</tr>
</tbody>
</table>

**TABLE II:** parameters characterizing the 2-body loss rates for $(1/2,-1/2)$ and $(-1/2,-1/2)$ spin channels.
FIG. 4: Ratio $L_3(T=2\mu K)/L_3(T=8 \mu K)$ of the three body decay rate for two different temperatures for a gas of atoms polarized in $|f = 1/2, m_f = 1/2\rangle$. Full line: threshold law $L_3 \sim T^2$.

before detection (Fig. 3). Path 1 permits 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 molecular states that decay rapidly by 2-body collisions. Path 2 gives access to the total atom number $N_2$ (free atoms + atoms bound in p-wave molecules). It consists in ramping up the magnetic field in 2 ms from $B_{\text{nuc}}$ 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 $B_{\text{nuc}}$ and we average the data of 25 pictures to compensate for atom number fluctuations. We then get $N_1 = 7.1(5) \times 10^4$ and $N_2 = 9.1(7) \times 10^4$ 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 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 2-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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[18] We also neglect the splitting between the different $m_l$ predicted by [24].
[21] Note that in our case $\mu$ is positive. This corresponds to molecular states stable at low field.

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 (dash dotted), 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 $i$. 