Radio-frequency spectroscopy of ^{6}Li p-wave molecules: Towards photoemission spectroscopy of a p-wave superfluid

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We study rf spectroscopy of a lithium gas with the goal to explore the possibilities for photoemission spectroscopy of a strongly interacting p-wave Fermi gas. Radio-frequency spectra of quasibound p-wave molecules and of free atoms in the vicinity of the p-wave Feshbach resonance located at 159.15 G are presented. The spectra are free of detrimental final-state effects. The observed relative magnetic-field shifts of the molecular and atomic resonances confirm earlier measurements realized with direct rf association. Furthermore, evidence of molecule production by adiabatically ramping the magnetic field is observed. Finally, we propose the use of a one-dimensional optical lattice to study anisotropic superfluid gaps as most direct proof of p-wave superfluidity.

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Recently, great progress has been made in the study of strongly interacting atomic quantum gases with s-wave interaction symmetry. Prominent examples are the physics of the BEC-BCS crossover [1] or the generation of ultracold molecules [2,3]. At the same time, only relatively limited experimental data were collected near Feshbach resonances of scattering states with higher orbital angular momenta. In such scenarios, the angular anisotropy of the order parameter allows for a much richer physics than in the case of s-wave interactions. While for s-wave systems it is known that observables change smoothly when the interaction strength is varied across a Feshbach resonance [4,5], theoretical calculations predict both smooth crossover physics [6] as well as various quantum phase transitions [7,8] across a p-wave resonance. An example is the transition from a p_x-wave superfluid to a $(p_x + ip_y)$-wave superfluid that breaks time-reversal symmetry [9]. Such quantum phase transitions could be observable directly by means of rf spectroscopy [10]. Depending on the interaction strength, the superfluid phase has been found to be either stable or unstable against decay into fermionic trimers [11]. In optical lattices, even more exotic superfluid phases are expected [12]. By studying higher partial-wave superfluidity with ultracold atoms, new insight into the pairing physics of other condensed matter systems may be gained. For instance, ^{3}He [13] and the more exotic heavy-fermion superconductors such as UPt_3 [14] show p-wave symmetry, while high-T_c superconductors are known to exhibit d-wave symmetry [15].

Only few data on ultracold p-wave molecules are available. First, p-wave molecules made from ultracold ^{40}K have been studied at JILA [16]. Lifetimes on the order of 1 ms were observed for the different m_l projections. Above the threshold, that is, for positive binding energies, quasibound states are formed with lifetimes that are limited by tunneling through the centrifugal barrier. Near the Feshbach resonance, the binding energies were found to change linearly with the magnetic field. In similar experiments with ^{6}Li, the slope of this linear dependency can be measured with rf spectroscopy, and the magnetic moment of the ^{6}Li p-wave molecules has been derived [17]. Studies of the collisional stability of ^{6}Li p-wave molecules have also been performed [18].

Recently, photoemission spectroscopic methods were applied to study strongly interacting spin mixtures of ^{40}K atoms [19]. This method is based on an rf transition of the strongly coupled pair state to an atomic reference state. The momentum distribution of the atoms in the reference state is analyzed by time-of-flight imaging, and the dispersion relation in the strong coupling regime can be derived. A BCS-like dispersion with an energy offset resembling a superfluid gap was observed [19]. Detrimental final-state effects can be avoided by using a reference state that is only weakly interacting [20].

In this brief report, we apply final-state-effect-free rf spectroscopy of a strongly interacting gas of ^{6}Li atoms in state $|1\rangle$ ($|F = 1/2, m_F = 1/2\rangle$ at low fields) near the well-known p-wave Feshbach resonance at 159.15 G [21]. We detect atoms and quasibound molecules by observing rf transitions to the weakly interacting state $|2\rangle$ ($|F = 1/2, m_F = -1/2\rangle$ at low fields). By comparing the shift of the molecular resonance relative to the atomic resonance for different magnetic fields, we confirm the observations made in [17] concerning the relative magnetic moments of the molecular and atomic states.

Furthermore, we generate bound molecules with negative binding energy by means of adiabatic magnetic-field ramps similar to those used in [18]. After selectively removing the remaining atoms with a resonant light pulse, we observe a small number of bound molecules. The observed lifetime of the molecules in the presence of residual unbound atoms is compatible with a decay due to inelastic collisions [18].

The cooling procedure for generating an ultracold mixture of ^{6}Li and ^{87}Rb atoms has been detailed in a previous publication [22]. In short, we simultaneously collect both species in a magneto-optical trap, polarize their spins by optical pumping, trap them magnetically, and transfer them via an intermediate magnetic trap into a Ioffe-Pritchard-type trap. Here, they are stored in a stretched-state mixture of the Zeeman hyperfine states ^{6}Li $|F = 3/2, m_F = 3/2\rangle$ and ^{87}Rb $|F = 2, m_F = 2\rangle$. In the cylindrically symmetric Ioffe-Pritchard trap, ^{6}Li is trapped with trapping frequencies of $(\omega_r, \omega_z)/2\pi = (762, 190)$ Hz

at a magnetic-field offset of 3.5G. For ^{87}Rb, the trapping frequencies amount to $(\omega_r,\omega_z)/2\pi = (200,50)$ Hz. ^{87}Rb is selectively cooled by microwave evaporation at 6.8 GHz. The ^{6}Li sympathetically cools by interspecies thermalization. At a common temperature of 3 μK with 3×10^6 ^{87}Rb atoms and 1×10^5 ^{6}Li atoms, we stop cooling and transfer the atoms into a horizontally oriented crossed-beam optical dipole trap generated by an intensity-stabilized fiber laser running at 1075(5) nm (IPG YLR-10LP). At 2.9 W and 3.2 W of laser power in the two arms and equal beam waist radii of 58 μm, the trap depths amount to 130 μK (^{87}Rb) and 45 μK (^{6}Li) with trap frequencies of $\tilde{\omega}_{\mathrm{Rb}}/2\pi \approx (610 \times 440 \times 440)^{1/3}$ Hz (^{87}Rb) and $\tilde{\omega}_{\mathrm{Li}}/2\pi \approx (1.3 \times 0.9 \times 0.9)^{1/3}$ kHz (^{6}Li). After the transfer into the optical trap, the ^{6}Li has a temperature of about 9 μK, which under these conditions exceeds the Fermi temperature by a factor of 2.2. The trap coils are now used to generate a homogeneous magnetic bias field. We perform an rf Landau-Zener transition near 228 MHz to transfer the ^{6}Li atoms into the ground state $|1\rangle := |F = 1/2, m_F = 1/2\rangle$. The ^{87}Rb atoms are removed from the trap with a 1-ms-long optical pulse, which is resonant with the cycling transition $5^2S_{1/2}|F = 2\rangle \rightarrow 5^2P_{3/2}|F' = 3\rangle$.

In the first experiment, we ramp the magnetic field to a fixed value near the 159.15-G p-wave Feshbach resonance and record an rf spectrum by counting the atoms that are transferred into the state $|2\rangle$ at different applied rf values. Figure 1 shows a typical rf spectrum. The magnetic field is set to a value of 60 mG below the field of maximum atomic three-body losses due to the Feshbach resonance [21]. After applying a 2-ms-long rf pulse, we quickly

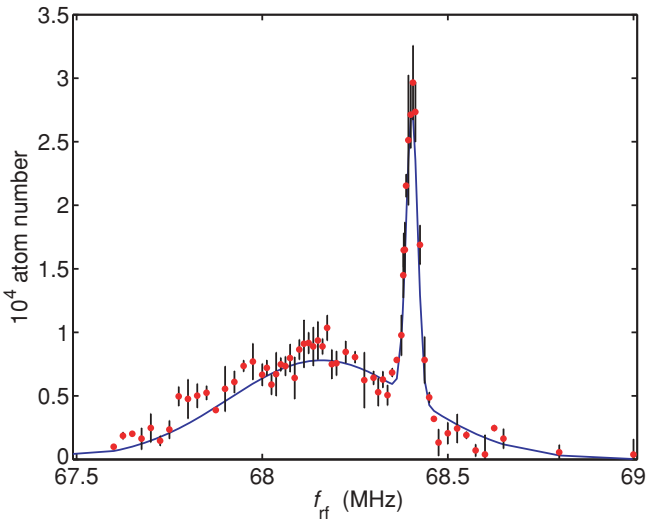

FIG. 1. (Color online) The rf spectrum taken at a magnetic detuning of −60 mG relative to the magnetic field of maximum of three-body losses. The broad molecular resonance is shifted by −270 kHz to lower frequencies relative to the narrow atomic resonance. The negative shift reflects the positive binding energy of a quasibound molecule, which is stabilized by the centrifugal barrier of the p-wave interaction. Each data point (red dot) is the average of up to seven single experimental cycles. The corresponding standard deviation is plotted as the black error bar. The blue curve is a fit with two Gaussian functions. The fit is used to determine the position of the atomic and the molecular resonances.

(<50 μs) increase the magnetic field by 150 mG and detect the atoms in state $|2\rangle$ by absorption imaging on the cycling transition $|2\rangle = 2^2S_{1/2}|J = 1/2, m_J = -1/2, I = 1, m_I = 0\rangle \rightarrow 2^2P_{3/2}|J' = 3/2, m'_J = -3/2, I' = 1, m'_I = 0\rangle$ after 50 μs time of flight. In addition to a narrow resonance which corresponds to a transition inside the unbound atoms, we also observe a broad feature which is shifted by −270 kHz relative to the atomic resonance. It is caused by rf dissociation of p-wave molecules, resulting in single atoms in the weakly interacting reference state $|2\rangle$. The frequency shift relative to the atomic resonance reflects the binding energy of the molecule, which for the observed negative shift turns out to be positive. The molecules are thus quasibound behind the centrifugal barrier of the p-wave collision channel.

The observed binding energy of 270 kHz corresponds to a magnetic field 85 mG above the value at which the energies of the molecular and the atomic states cross [17]. The spectrum in Fig. 1 was taken at a magnetic field 60 mG below the maximum of the Feshbach-resonance-induced three-body losses. Therefore, the field of maximal inelastic losses does not correspond to the magnetic field at which the atomic and the molecular states are degenerate, that is, the actual Feshbach resonance. This is due to the finite collision energy of the ^{6}Li atoms at a temperature of about 9 μK. In [23], the finite-energy shift for the resonance used here is theoretically predicted to be +0.1G for $T = 10$ μK. This is in reasonable agreement with our observation of about +145 mG. The optical trapping potential, which may lead to an additional shift due to the dynamical Stark effect of the involved states, has not been taken into account [24].

After changing the magnetic field by a small amount ΔB, the position of the molecular resonance changes by (115 ± 30) kHz, while the atomic resonance shifts only by (2.7 ± 0.3) kHz. The shift of the atomic resonance is due to the well-known hyperfine structure in the Paschen-Back regime and can be used to determine the value of ΔB. Near the Feshbach resonance, the atomic shift depends linearly on the magnetic field with a rate of 87 kHz/G, resulting in $\Delta B = (31 \pm 4)$ mG. The shift of the molecular resonance can be compared to previous experiments reported in [17]. There, the tuning of the molecular state relative to the atomic state $|1\rangle$ has been determined to be 2.354 MHz/G. Taking the Zeeman shift of state $|2\rangle$ into account, the molecular state then tunes with 2.267 MHz/G relative to our reference state $|2\rangle$. Consequently, for the ΔB given in our experiment, the molecular peak is expected to shift by (70 ± 8) kHz. The agreement with our observed value of (115 ± 30) kHz is not perfect but still reasonable and confirms the determination of the relative magnetic moments of the molecular state and the state $|1\rangle$ performed in [17].

In a second experiment, we have studied the production of p-wave molecules at the low-magnetic-field side of the Feshbach resonance, where the atoms form bound molecules with negative binding energy. As shown in Fig. 2, we employed a method similar to that used by the Tokyo group [18]. After preparation of the state $|1\rangle$ at a low magnetic field B_{prep}, we quickly ramped across the Feshbach resonance at a rate of $dB/dt = 71.7$ G/ms up to a value B_{imag}, which lies approximately 150 mG above B_{res}. We held B_{imag} for 10 ms to allow for decay of a possible overshooting of the

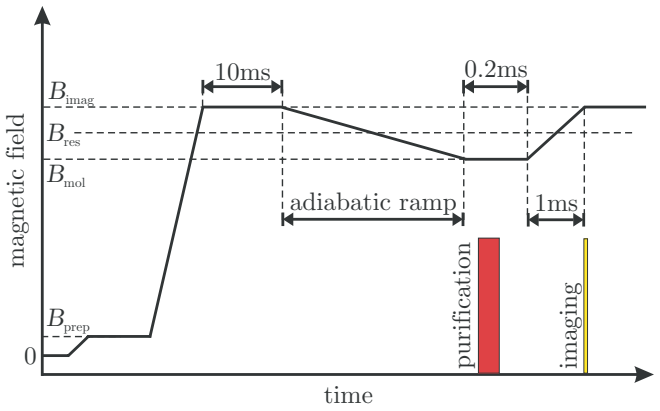

FIG. 2. (Color online) T ime sequence for the generation of p-wave molecules from a spin-polarized Fermi gas. After preparation of the state $|1\rangle$ at a field B_{prep}, we quickly (approx. 1 ms) ramped to $B_{imag} > B_{res}$, where the molecular energy is above the atomic threshold. The field was held for 10 ms to allow possible overshooting of the field to decay. Then, a slow sweep toward a lower field $B_{mol} < B_{res}$ was performed with variable ramp speed. This adiabatically transforms atoms into molecules. Next, a 25-μs purification pulse was applied in a small time window of 0.2 ms, removing all unpaired atoms. Finally, the molecules were adiabatically dissociated back into atoms within 1 ms. The atoms were imaged at the field B_{imag}. Due to the small amount of molecules produced, imaging was performed *in situ* for a higher S/N ratio.

current control circuit. We then slowly reduced the magnetic field by 305 mG to a value of $B_{mol} < B_{res}$. The duration of this step was varied and optimized for the highest molecule production. Within the next 0.2 ms, the remaining unbound atoms were removed by a 25-μs long optical pulse resonant with $|1\rangle = 2^2S_{1/2}|J = 1/2, m_J = -1/2, I = 1, m_I = 1\rangle \rightarrow 2^2P_{3/2}|J' = 3/2, m'_J = -3/2, I' = 1, m'_I = 1\rangle$ transition. The

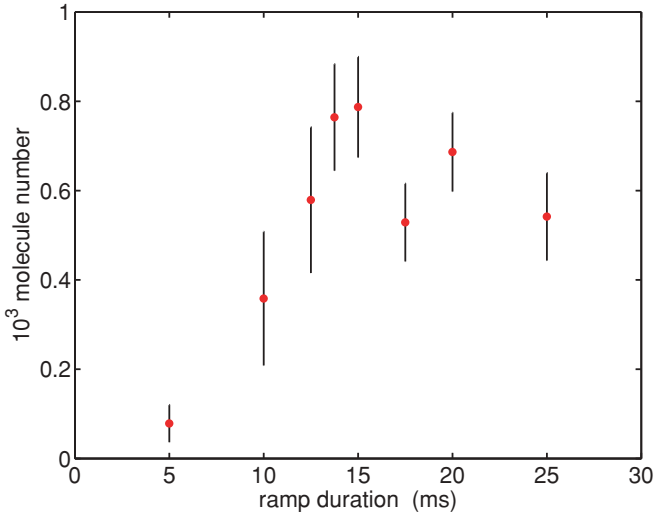

FIG. 3. (Color online) Number of bound p-wave molecules ($E_{mol} < 0$) produced through adiabatic ramping of the magnetic field across the Feshbach resonance with ramp width $\Delta B = 305$ mG. Only small amounts of bound molecules were produced, probably due to small phase-space overlap at 9 μK. The error bars correspond to one standard deviation for five to eight measurements per data point.

purified molecular sample was detected by ramping back to B_{imag} within 1 ms. This second ramp dissociated the molecules back into free atoms, which could be detected by absorption imaging. To increase the signal-to-noise (S/N) ratio, we performed the imaging *in situ*. The number of molecules generated in this way is shown in Fig. 3. Only about 3 % of all atoms are transformed into molecules in contrast to observations in [18], where up to 15 % were converted. This is probably due to the higher temperature of 9 μK here as compared to 1 μK in [18] and the corresponding reduced phase-space overlap. We have studied the lifetime of the molecular sample in the presence of the remaining unbound atoms by holding the atom-molecule mixture for a variable amount of time after the adiabatic ramp and before the purification pulse. The value for the inelastic atom-dimer coefficient $K_{dd} = 2.4^{+0.5}_{-0.3} \times 10^{-11}$ cm^3/s for $|1\rangle$–$|1\rangle$ molecules as reported in [18] is consistent with our observations.

In conclusion, we have successfully applied final-state-effect-free rf spectroscopy to an ultracold system of spin-polarized ^{6}Li atoms with strong anisotropic interaction near a p-wave Feshbach resonance. We present the spectra of molecular and atomic Zeeman transitions in the vicinity of the Feshbach resonance and confirm earlier findings concerning the binding energy of quasibound p-wave molecules. This technique can be readily extended to study p-wave superfluidity by photoemission spectroscopy similar to [19] where photoemission spectroscopy has been introduced for gases with s-wave interaction symmetry. In our current setup, the limited molecule numbers and the related poor S/N ratio of our absorption images prevent the required conversion into three-dimensional density distributions since the usually used inverse Abel transformation is very sensitive to noise [25].

After the realization of s-wave superfluidity, p-wave superfluidity will mark a further milestone in ultracold atom experiments. Several techniques for studying superfluid properties have been proposed for cold atom experiments [10,26]. Reaching the extremely low temperatures needed to achieve superfluidity remains the major obstacle [27]. Here, the Fermi-Bose mixture ^{6}Li-^{87}Rb constitutes an important candidate for reaching deep Fermi degeneracy through sympathetic cooling in specialized trap geometries [28]. Furthermore, T_c can be manipulated by applying dc electric fields [29], which reduces the required degree of Fermion quantum degeneracy.

For future experiments, we propose to use a one-dimensional optical lattice that confines the atoms into an effectively two-dimensional space ($\omega_z > \hbar k_F^2/2m$). The magnetic bias field should be perpendicular to the one-dimensional planes of the optical lattice, thereby defining the m_l projections relative to that plane. The imaging should be perpendicular to the lattice beams such that the images reveal the p-wave symmetry of the scattering process for specific m_l projections. Addressability of different m_l projections is easier in ^{40}K as it has a large magnetic dipole-dipole shift between $m_l = 0$ and $m_l = \pm 1$ states of 0.5 G [16,30]. For ^{6}Li, this shift is predicted to be quite small [23]. Dispersion curves of the gas taken by measuring rf transitions into a noninteracting final state with subsequent imaging as in [19] could be able to reveal the anisotropic superfluid gap in the dispersion curves after inverse

Abel transformation. The quantum-phase transition along the BEC-BCS crossover could also be detected using direct rf spectroscopy [10].

Future work should be devoted to increasing the number of cold ^{6}Li atoms as well as increasing the degree of quantum degeneracy. An extension of our experimental setup with an optical lattice will enable us to polarize the p-wave collisions inside a plane, thus making anisotropic effects visible in photoemission measurements under improved experimental conditions.

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