

Search for broad Feshbach resonances in the ${}^6\text{Li}$ - ${}^{40}\text{K}$ mixture

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(Dated: August 18, 2009)

We explore the widths of interspecies Feshbach resonances in a mixture of the fermionic quantum gases ${}^6\text{Li}$ and ${}^{40}\text{K}$. Experimentally, we obtain the asymmetric lineshape of the interspecies elastic cross section by measuring the distillation rate of ${}^6\text{Li}$ atoms from an optically-trapped ${}^6\text{Li}/{}^{40}\text{K}$ mixture as a function of magnetic field. This provides us with the first experimental determination of the width of a resonance in this mixture, $\Delta B = 1.5(5)$ G, being one of the broadest. We present an extended version of the Asymptotic Bound-state Model (ABM) and show that this model offers a convenient method to estimate the width and position of a large number of Feshbach resonances. Our results offer good perspectives for the observation of universal crossover physics in this mixture.

PACS numbers:

A decade of experiments with degenerate fermionic quantum gases has delivered major scientific advances as well as a whole new class of quantum many-body systems [1, 2, 3]. Feshbach resonances [4] played a central role in this development as they offer exceptional control over the interatomic interactions at low-temperatures [5]. In gases with the appropriate spin mixture the sign and magnitude of the s -wave scattering length a can be tuned to any positive or negative value by choosing the proper magnetic field in the vicinity of a resonance. In the case of fermionic atoms the role of Feshbach resonances is especially remarkable because Pauli exclusion dramatically suppresses three-body losses to deeply bound molecular states [6, 7]. The tunability has been used with great success in two-component Fermi gases of ${}^6\text{Li}$ and of ${}^{40}\text{K}$ to study and control pairing mechanisms, both of the Cooper type on the attractive side of the resonance ($a < 0$) [8] and of the molecular type on the repulsive side ($a > 0$) [9]. In particular the universal crossover from the superfluidity of a molecular Bose-Einstein condensate (BEC) towards the Bardeen, Cooper, Schrieffer (BCS) limit received a lot of attention [10].

Recently the study of heteronuclear fermionic mixtures, in particular the ${}^6\text{Li}/{}^{40}\text{K}$ mixture, has strongly gained in interest due to its additional mass imbalance. Experimentally unexplored properties of these mixtures include: superfluidity [11], phase separation [12], crystalline phases [13], exotic pairing mechanisms [14] and long-lived trimers [15]. In combination with spectroscopic measurements, precision measurements of Feshbach resonances can push the accuracy of the intermolecular potentials beyond the limitations of the Born-Oppenheimer approximation [16]. In the first experiment with the ${}^6\text{Li}/{}^{40}\text{K}$ mixture quantum degeneracy was reported by the Munich group, using a BEC of ${}^{87}\text{Rb}$ as a third species to assure thermalization of the fermions [17]. The basic interaction properties of the ${}^6\text{Li}/{}^{40}\text{K}$ system were established in experiments by the Innsbruck group

[18], in which the loss features of 13 Feshbach resonances were observed and assigned with the computationally-light Asymptotic Bound-state Model (ABM) as well as with a full coupled-channels analysis. The first ${}^6\text{Li}/{}^{40}\text{K}$ molecules were recently reported from Munich [19].

In this Letter we report the first observation of the asymmetric lineshape (Fano profile) of the inter-species elastic cross section in the K-rich ${}^6\text{Li}/{}^{40}\text{K}$ mixture near a Feshbach resonance. Very recently, also the Li-rich mixture was studied [20]. Using a variation on the evaporation method [21], we measure the rate of distillation (preferential evaporation) of ${}^6\text{Li}$ atoms from a K-rich ${}^6\text{Li}/{}^{40}\text{K}$ mixture confined in an optical dipole trap. The line shape provides for this mixture the first precision determination of a resonance position as well as the first measurement of a resonance width. Extending the ABM approach we estimate the widths of all s -wave Feshbach resonances in stable two-component ${}^6\text{Li}/{}^{40}\text{K}$ mixtures below 500 G. The experimentally characterized resonance is one of the broadest of the ${}^6\text{Li}/{}^{40}\text{K}$ system.

The ultracold mixture of ${}^6\text{Li}$ and ${}^{40}\text{K}$ is created starting from two independent two-dimensional magneto-optical traps (2D-MOTs) as beam sources for cold atoms [22]. From the cold beams we recapture about 10^9 K atoms and 10^6 Li atoms in a two-species 3D-MOT. After optical pumping we transfer up to 80% of the ${}^6\text{Li}$ and 60% of the ${}^{40}\text{K}$ into an optically plugged magnetic quadrupole trap [23]. This trap is formed by a quadrupole field with a gradient of 180 G/cm along the tight vertical axis, plugged along the horizontal axis with a 7 W blue-detuned laser beam (532 nm) focused to a waist of 16 μm . The transfer is optimized to create a spin-polarized sample of ${}^6\text{Li}$ in the $|f, m_f\rangle = |3/2, +3/2\rangle$ hyperfine state and a three-component mixture of ${}^{40}\text{K}$ in the hyperfine states $|9/2, +5/2\rangle, |9/2, +7/2\rangle$ and $|9/2, +9/2\rangle$. The three-components assure effective thermalization of the potassium by *intra*-species collisions. The lithium thermalizes sympathetically by *inter*-

species collisions with the potassium. The ${}^6\text{Li}/{}^{40}\text{K}$ mixture is cooled for 23 seconds by forced evaporation (from high field down) in the plugged trap on the microwave transitions of K ($|9/2, m_f\rangle \rightarrow |7/2, m_f - 1\rangle$) and Li ($|3/2, +3/2\rangle \rightarrow |1/2, +1/2\rangle$) simultaneously. Just before inter-species spin-exchange losses become prohibitive the evaporation is stopped to remove the non-stretched potassium states ($m_f < +9/2$) by a microwave spin-cleaning sweep (from zero field up), removing the undesired atoms in the plug-region of the trap. After cleaning, the remaining 30% of the ${}^{40}\text{K}$ is transferred together with the ${}^6\text{Li}$ into an optical dipole trap with a well depth of $U_0 = 360 \mu\text{K}$ for K ($U_0 = 160 \mu\text{K}$ for Li). The trap is created using a 5 W fiber laser ($\lambda = 1.07 \mu\text{m}$) focused to a waist of $19 \mu\text{m}$ and serving as an optical tweezer.

With an additional stage of forced evaporative cooling in the optical trap we reached - in pure ${}^{40}\text{K}$ - a quantum degenerate spin mixture at temperature $T \simeq 0.2 T_F$, where T_F is the Fermi temperature. To prepare the ${}^6\text{Li}/{}^{40}\text{K}$ mixture we apply a holding field of ~ 10 G and succeed in transferring up to 50% of the ${}^6\text{Li}$ atoms to the $|1/2, +1/2\rangle$ state by adiabatic fast passage on the microwave transition using a field sweep downwards across the resonant field chosen at ~ 9 G. The residual population of the $f = 3/2$ manifold is removed by a resonant light pulse on the ${}^2S_{1/2} \rightarrow {}^2P_{3/2}$ transition. For the Feshbach measurements the resulting clean mixture is optically transported without substantial losses by moving the optical tweezer in 3.5 s over a distance of 21.5 cm to a $12.7 \times 12.7 \times 42$ mm quartz cell extending from the main vacuum chamber. The transport is realized by moving a lens mounted on a precision linear air-bearing translation stage. In the Feshbach cell we can apply homogeneous fields (< 10 ppm/mm) of up to 500 G. At this point we have prepared a $|1/2, +1/2\rangle_{\text{Li}} - |9/2, +9/2\rangle_{\text{K}}$ mixture consisting of 4×10^3 lithium and 2×10^4 potassium atoms at temperature $T \approx 21(2) \mu\text{K}$.

In search for broad and accessible Feshbach resonances we analyzed the ${}^6\text{Li}/{}^{40}\text{K}$ two-body system with an extended version of the ABM [18]. We start from the two-body Hamiltonian for the relative motion

$$\mathcal{H} = \mathbf{p}^2/2\mu + \mathcal{V} + \mathcal{H}^{int} = \mathcal{H}^{rel} + \mathcal{H}^{int}, \quad (1)$$

containing the relative kinetic energy with μ the reduced mass, the electron spin dependent central interatomic interaction \mathcal{V} , and the internal energy \mathcal{H}^{int} of the two atoms. Here we restrict \mathcal{H}^{int} to the hyperfine and Zeeman terms and consider s -wave interactions only. Instead of solving coupled radial Schrödinger equations, the ABM approach relies on knowledge of the binding energies of the highest bound states in the two-body system, which is sufficient to determine the scattering properties, and, in particular, the position of Feshbach resonances. For ${}^6\text{Li}/{}^{40}\text{K}$ only the least bound levels of \mathcal{H}^{rel} are relevant and can be obtained using the eigenvalues E_S of the least bound states in the electron-spin singlet ($S = 0$) and

triplet ($S = 1$) potentials as free parameters; here we adapt E_0 and E_1 from Ref. [18].

The mixture is prepared in one of the two-body hyperfine eigenstates of \mathcal{H}^{int} at magnetic field B , referred to as the P -channel or open channel; for $B = 0$ denoted via the hyperfine quantum numbers as $|f_\alpha, m_{f_\alpha}; f_\beta, m_{f_\beta}\rangle$. The corresponding energy of two free atoms at rest in the mixture defines the B -dependent threshold between the scattering states ($E > 0$) and the bound states ($E < 0$) of \mathcal{H} . In the following we define \mathcal{H} relative to this threshold energy. A complete basis for the spin properties is defined via the quantum numbers S , its projection M_S , and the projection of the nuclear spins μ_α and μ_β , while demanding that the total projection $M_S + \mu_\alpha + \mu_\beta = m_{f_\alpha} + m_{f_\beta} = M_F$ is fixed. By diagonalizing \mathcal{H} starting from this ‘singlet-triplet’ basis we find the energies of the bound states, and the Feshbach resonances are localized at the magnetic fields where they intersect with the energy of the threshold.

Threshold effects cause the approximately linear magnetic field dependence of the bound-state energies to change to quadratic behavior close to the field of resonance [3, 5]. This provides information about the width of a Feshbach resonance. The ABM, as discussed thus far, does not show these threshold effects, which is not surprising because the threshold is not explicitly build into the theory; it is merely added as a reference value for comparison with the ABM eigenvalues.

However, the ABM contains all ingredients to obtain also the resonance width. Here we give a brief description [24]. The width depends on the coupling between the open channel and the various closed channels, which is determined in two steps. First we separate the open channel P , as defined above, from all other channels: the closed channels Q [25]. This is realized with a basis rotation from the singlet-triplet basis to the basis of the eigenstates of \mathcal{H}^{int} at field B . Next we diagonalize the closed-channel subspace, leaving the open-channel unaffected. We refer to the diagonal sub-spaces as \mathcal{H}_{PP} , a single matrix element that we identify with the (bare) open-channel bound-state energy $\epsilon_P = -\hbar^2 \kappa_P^2 / 2\mu$, and as \mathcal{H}_{QQ} , a matrix containing the (bare) closed-channel bound-state energies ϵ_Q . The coupling between the open and the resonant closed channel is referred to as \mathcal{H}_{PQ} .

The bare bound states (in both open and closed channel) are ‘dressed’ by \mathcal{H}_{PQ} . This is nicely treated in Feshbach’s resonance theory [26, 27]: a closed-channel bound state acquires a finite width Γ and its energy undergoes a shift Δ_{res} . If the binding energy of a certain Q -channel bound state $|\phi_Q\rangle$ is sufficiently close to the threshold the complex energy shift is given by [27]

$$\mathcal{A}(E) = \Delta_{res}(E) - \frac{i}{2}\Gamma(E) = \frac{\mu}{\hbar^2} \frac{-i\Lambda}{\kappa_P(k - i\kappa_P)}, \quad (2)$$

where $\Lambda = |\langle \phi_Q | \mathcal{H}_{QP} | \phi_P \rangle|^2$ is the coupling strength to the P -channel bound state $|\phi_P\rangle$. For $k \rightarrow 0$ the ex-

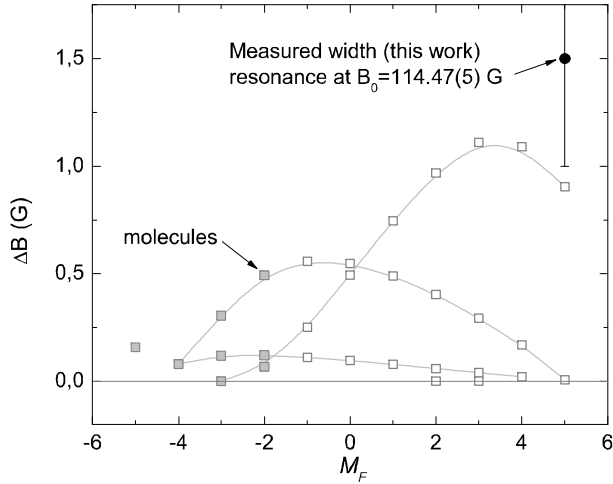


FIG. 1: ABM calculated widths of all s -wave Feshbach resonances in stable two-component ${}^6\text{Li}/{}^{40}\text{K}$ mixtures below 500 G. The lines are a guide to the eye. The point at $M_F = -5$ corresponds to the $|1/2, -1/2\rangle_{\text{Li}} - |9/2, -9/2\rangle_{\text{K}}$ mixture. All other mixtures contain the ${}^6\text{Li}$ ground state $|1/2, +1/2\rangle_{\text{Li}}$. Solid black dot: width measurement reported in this work. The mixtures with $-M_F = 5, 4, 3, 2$ (gray squares) where studied in Ref. [18]. The resonance used in Ref. [19] for molecule formation is indicated with an arrow.

pression $\Gamma \equiv \hbar^2 k / \mu R^*$ defines the characteristic length R^* [28]. The negative energy $E = \hbar^2 k^2 / 2\mu$ of the dressed bound state follows by solving the pole equation $E - \epsilon_Q - \mathcal{A}(E) = 0$. From the energy dependence of the dressed bound state we obtain an expression for the magnetic field width ΔB of the corresponding Feshbach resonance as defined by the dispersive formula for the field dependence of the scattering length,

$$a(B) = a_{bg} \left(1 - \frac{\Delta B}{B - B_0} \right). \quad (3)$$

The resonance width ΔB is given by

$$\mu_{rel} \Delta B = \frac{a^P}{a_{bg}} \frac{A}{2\epsilon_P}. \quad (4)$$

Here $\mu_{rel} = \partial \epsilon_Q / \partial B|_{B=B_0}$ is the magnetic moment of the bare Q channel relative to the open channel threshold. Note that $R^* = -\hbar^2 \epsilon_P / (\mu a^P A) = \hbar^2 / (2\mu a_{bg} \mu_{rel} \Delta B)$. The off-resonance scattering is described by the background scattering length $a_{bg} = a_{bg}^P + a^P$, where $a_{bg}^P \approx r_0$ and $a^P = \kappa_P^{-1}$. Here $r_0 \equiv (\mu C_6 / 8\hbar^2)^{1/4} \simeq 41 a_0$ is the inter-species Van der Waals range, with C_6 the Van der Waals coefficient and a_0 the Bohr radius.

The results for all s -wave resonances in stable two-component ${}^6\text{Li}/{}^{40}\text{K}$ mixtures below 500 G are shown in Fig. 1. The widest resonances for the ${}^6\text{Li}/{}^{40}\text{K}$ mixture are found to be of the order of 1 Gauss. For the experiment we selected a resonance in the fully-stretched

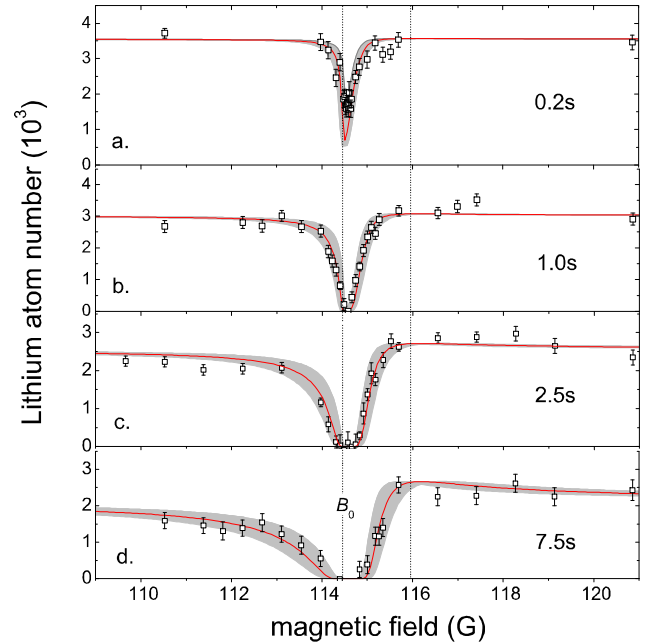


FIG. 2: (Color online) Measurement of the Feshbach resonance width. The red solid line indicates the best fit obtained for $B_0 = 114.47(5)$ G and $\Delta B = 1.5(5)$ G. The gray shaded area indicates the combined error in B_0 and ΔB .

($M_F = 5$) manifold $|1/2, +1/2\rangle_{\text{Li}} \otimes |9/2, +9/2\rangle_{\text{K}}$ with the predicted position of $B_0 = 114.7$ G as obtained with the ABM parameters $E_{0,1}$ from Ref. [18]. The predicted width is $\Delta B = 0.9$ G. This value is known to slightly underestimate the actual width [24, 29].

To observe the resonance we first ramp the field up to 107.112 G where any remaining potassium spin impurities are selectively removed by resonant light pulses. The Fano profile of the resonance is observed by measuring the distillation rate of the Li from the potassium-rich Li-K mixture in the optical trap as a function of magnetic field. To initiate this process we decrease the depth of the dipole trap in 10 ms to $U/U_0 \approx 0.15$. Aside from a small spilling loss of the ${}^6\text{Li}$ this decompresses the mixture with a factor $(U/U_0)^{3/4} \approx 0.24$ in the adiabatic limit and reduces the temperature accordingly by a factor $(U/U_0)^{1/2} \approx 0.39$. The truncation parameter for evaporation, $\eta = U/k_B T$, drops for both species by the same amount $\eta/\eta_0 \approx 0.39$. After decompression the central density of the potassium is $n_K \approx 2 \times 10^{11} \text{ cm}^{-3}$ ($n_{\text{Li}} \approx 9 \times 10^9 \text{ cm}^{-3}$ for Li) and the temperature of the mixture is $T = 9(1) \mu\text{K}$. As the truncation parameter of the lithium ($\eta_{\text{Li}} \approx 2.7$) is much smaller than that of potassium ($\eta_K \approx 6.2$) the Li preferentially evaporates at a rate proportional to the inter-species elastic cross section. As the lithium is the minority component this distillation process proceeds at an approximately constant rate. We have verified that a pure lithium cloud experiences no rethermalization by itself. The final trap depth U was

determined from the total laser power and the measured trap frequency for the potassium, $\omega_r/2\pi = 1.775(6)$ kHz. In Fig. 2 we plot the atom number after various holding times and as a function of magnetic field. We analyze our data by modeling the distillation rate. Before decompression ($\eta_{Li} \approx 7$) we observe a loss of 30% for 1s holding time on resonance. As the decompression reduces the density by a factor 4 the three-body losses can be neglected in the decompressed trap. The distillation of the lithium as a function of time t is described by $N(t) = N_0 e^{-t/\tau_{ev}} e^{-t/\tau_{bg}}$, where $N_0 \approx 3 \times 10^3$ is the initial number of lithium atoms, $\tau_{bg} = 25$ s the vacuum limited lifetime and $\tau_{ev}^{-1} \simeq n_K(\sigma(k) \hbar k/\mu) e^{-\eta_{Li}}$ the thermally-averaged evaporation rate. Here is

$$\sigma(k) = 4\pi \frac{a^2(k)}{1 + k^2 a^2(k)} \quad (5)$$

the elastic cross section with

$$a(k) = a_{bg} + \frac{a_{bg} \mu_{rel} \Delta B}{\hbar^2 k^2 / 2\mu - \mu_{rel} (B - B_0)} \quad (6)$$

the ‘Doppler shifted’ scattering length, with $a_{bg} = 56.6 a_0$ at the resonance position B_0 , and $\mu_{rel} = 1.57 \mu_B$. Note that for $kR^* \ll 1$ Eqs. (6) and (3) yield the same result for the cross section (5).

The solid lines in Fig. 2 show the best simultaneous fit of the thermally-averaged Eq. (5) to the four sub-figures, accounting for 25% variation in N_0 from one day to the next. The best fit is obtained for $B_0 = 114.47(5)$ G and $\Delta B = 1.5(5)$ G ($R^* \approx 100$ nm), where B_0 is mostly determined by the data of Fig. 2a and ΔB by those of Fig. 2d. Uncertainties in T and n_K can result in broadening of the loss features but the difference in asymmetries between Fig. 2a-d can only originate from the asymmetry of the elastic cross section around the resonance. The zero crossing of $a(k)$, prominently visible in systems with a resonantly enhanced a_{bg} like ${}^6\text{Li}$ [30] and ${}^{40}\text{K}$ [31], remains within the noise band of our distillation measurements because in the ${}^6\text{Li}/{}^{40}\text{K}$ system a_{bg} is non-resonant ($\sigma_{bg} = 1 \times 10^{-12} \text{cm}^{-2}$). Close to the expected zero crossing a narrow $M_F = +2$ Feshbach resonance occurs at 115.6 G in the $|1/2, +1/2\rangle_{\text{Li}} \otimes |9/2, +3/2\rangle_{\text{K}}$ manifold. We have observed this resonance in impure spin mixtures.

The chosen resonance offers good perspectives to meet the conditions for universal crossover physics in this mixture: $E_F, \mu_{rel} |B - B_0| \ll \Gamma/2$, where $E_F \equiv \hbar^2 k_F^2 / 2\mu$ is the characteristic relative energy of a colliding pair of atoms at their Fermi energy. The former condition corresponds to $k_F R^* \ll 1$ and is satisfied for Fermi energies $E_F \ll E^* \equiv \hbar^2 / 2\mu R^{*2} \sim 5 \mu\text{K}$; the latter condition corresponds to $k_F a \gg 1$ and is satisfied for $\mu_{rel} |B - B_0| / E^* < k_F R^* \ll 1 \Leftrightarrow |B - B_0| \ll 43$ mG.

We thank prof. E. Tiemann for stimulating discussions. This work is part of the research program on Quantum Gases of the Stichting voor Fundamenteel Onderzoek der

Materie (FOM), which is financially supported by the Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO). We acknowledge support from the German Academic Exchange Service (DAAD).

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