Optical Control of Magnetic Feshbach Resonances by Closed-Channel Electromagnetically Induced Transparency

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Optical control of magnetic Feshbach resonances by closed-channel EIT

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We control magnetic Feshbach resonances in an optically-trapped mixture of the two lowest hyperfine states of a ^{6}Li Fermi gas, using two optical fields to create a dark state in the closed molecular channel. In the experiments, the narrow Feshbach resonance is tuned by up to 3 G. For the broad resonance, the spontaneous lifetime is increased to 0.4 s at the dark state resonance, compared to 0.5 ms for single field tuning. We present a new model of light-induced loss spectra, employing continuum-dressed basis states, which agrees in shape and magnitude with loss measurements for both broad and narrow resonances. Using this model, we predict the trade-off between tunability and loss for the broad resonance in ^{6}Li, showing that our two-field method substantially reduces the two-body loss rate compared to single field methods for same tuning range.

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Optical control methods offer tantalizing possibilities for creating "designer" two-body interactions in ultracold atomic gases, with both high spatial resolution and high temporal resolution. By controlling the elastic scattering length, the inelastic scattering length, and the effective range, optical methods enable control of few-body and many-body systems, opening new fields of research.

Single optical field methods have been used to control Feshbach resonances, with large detunings to suppress spontaneous scattering, leading to limited tunability [1–9]. The first experiments, by Lett and collaborators in a Na Bose gas, created optical Feshbach resonances, by coupling the ground and excited molecular states in the input channel [3]. Recently, Chin and coworkers observed suppression of both spontaneous scattering and the polarizability of Cs atoms, by tuning between the D1 and D2 lines [9]. This method suppresses unwanted optical forces and achieves a lifetime up to 100 ms with rapid tuning up to tens of mG, by modulating the intensity of the control beam. Cetina and coworkers [10] vary the intensity of a far-detuned optical trapping potential to achieve a 40 mG tuning, arising from the unequal light-shifts of atomic and and molecular states.

Building on ideas suggested by Bauer et al., [7] and by Thalhammer et al., [11], we are developing two-field optical control methods [12, 13] that create a molecular dark state in the closed channel of a magnetic Feshbach resonance, as studied recently in dark state spectroscopy [14]. This approach is closely related to electromagnetically induced transparency (EIT) [15], where quantum interference suppresses unwanted optical scattering. Our two-field methods are particularly important for broad Feshbach resonances with large background scattering lengths, where they enable symmetrical tuning of the scattering length about the minimum loss point, with much smaller loss than single field methods for the same tuning [16]. The two-field methods also produce narrow energy-dependent features in the scattering phase shift, enabling large changes in the scattering length with small changes in the optical frequencies, compared to single field methods [16]. By using the optical frequency rather than the intensity as the control parameter, unwanted changes in the total trapping potential are suppressed. Further, these narrow features enable control of the effective range [13]. Analogous to the EIT method of enhancing optical dispersion in gases with suppressed absorption [15], the effective range can be modified in regions of highly suppressed optical scattering [16].

Implementation of optical control methods requires an understanding of the optically-induced level structure and energy shifts, which depend on the relative momentum of a colliding atom pair. Our original theoretical approach [12, 13] and that of other groups [7] employed adiabatic elimination of an excited molecular state amplitude, which fails for very broad resonances where the hyperfine coupling constant is large compared to the radiative decay rate. This unresolved issue has been noted previously [17].

In this Letter, we demonstrate large shifts of magnetic Feshbach resonances and strong suppression of spontaneous scattering in measurements of two-field light-induced loss spectra. Further, we present a new theoretical approach to describe control of broad and narrow Feshbach resonances in a unified manner, replacing a "bare" state description by a more natural description in terms of "continuum-dressed" states that incorporate the hyperfine coupling into the basis states. Using the measured Rabi frequencies, the predicted relative-momentum averaged loss spectra agree in shape and magnitude with data for both broad and narrow resonances.

The level scheme for the two-field dark-state technique is shown in Fig. 1. An optical field with Rabi frequency Ω_1 and frequency ω_1 couples a ground vibrational state $|g_1\rangle$ of the $^1\Sigma_g^+$ potential to an excited vibrational state $|e\rangle$ of the $^1\Sigma_u^+$ potential. A second optical field with Rabi frequency Ω_2 and frequency ω_2 couples a lower lying

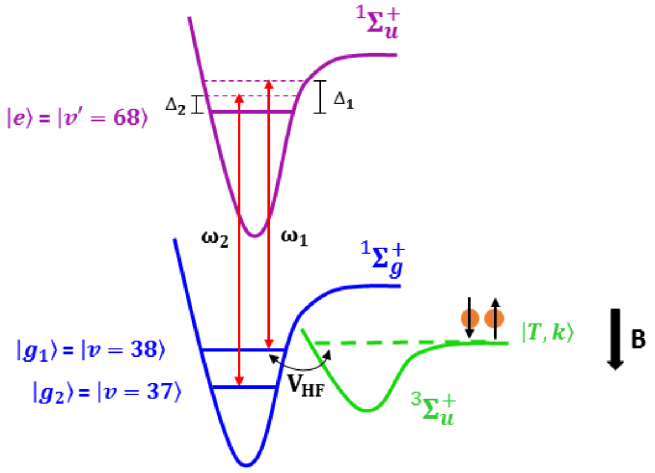

FIG. 1: Level scheme for the two-field optical technique. Optical fields of frequencies ω_1 (detuning Δ_1) and ω_2 (detuning Δ_2) , respectively, couple two singlet ground molecular states $|g_1\rangle$ and $|g_2\rangle$ to the singlet excited molecular state $|e\rangle$; V_{HF} is the hyperfine coupling between the incoming atomic pair state in the open triplet channel $|T, k\rangle$ and $|g_1\rangle$, and is responsible for a magnetically controlled Feshbach resonance.

ground vibrational state $|g_2\rangle$ to the excited vibrational state $|e\rangle$. The ω_1 beam results in a light shift of state $|g_1\rangle$ as well as atom loss due to photoassociation from the triplet continuum $|T, k\rangle$, which is hyperfine coupled to $|g_1\rangle$ and hence optically coupled to the excited state $|e\rangle$. The ω_2 beam suppresses atom loss through destructive quantum interference. In a magnetic field B, the triplet continuum $|T, k\rangle$ tunes downward $\propto 2\mu_B B$, where μ_B is the Bohr magneton, $\mu_B/h \simeq h \times 1.4$ MHz/G. The hyperfine coupling V_{HF} between $|T, k\rangle$ and $|g_1\rangle$ produces a Feshbach resonance. For our experiments with ^{6}Li, $|g_1\rangle$ and $|g_2\rangle$ are the $v = 38$ and $v = 37$ ground vibrational states and $|e\rangle$ is the $v' = 68$ excited vibrational state, which decays at a rate $\gamma_e = 2\pi \times 11.8$ MHz.

The detunings of the optical fields that couple state $|g_1\rangle$ and $|g_2\rangle$ to $|e\rangle$ are Δ_1 and Δ_2, respectively. The single photon detuning of the ω_1 beam for the $|T\rangle \rightarrow |e\rangle$ transition is a function of magnetic field and can be defined at a reference magnetic field B_{ref} as $\Delta_e = \Delta_L - 2\mu_B(B-B_{ref})/\hbar$, where Δ_L is the detuning of the optical field when $B = B_{ref}$. The two-photon detuning for the $|T\rangle - |e\rangle - |g_2\rangle$ system is $\delta = \Delta_e - \Delta_2$.

We prepare a 50:50 mixture of ^{6}Li atoms in the two lowest hyperfine levels, $|1\rangle$ and $|2\rangle$ in a CO_2 laser trap with trap frequencies $(\omega_x, \omega_y, \omega_z) = 2\pi\times(3100, 3350, 120)$ Hz. The $|1\rangle$-$|2\rangle$ mixture of ^{6}Li has a broad Feshbach resonance at $B_\infty = 832.2$ G [18, 19] of width $\Delta B_B = 300$ G due to strong hyperfine coupling of the triplet continuum to the "broad" singlet state $|g_1\rangle_B$ [13]. In addition, there is a narrow Feshbach resonance at 543.2 G of width $\Delta B_N = 0.1$ G [20] due to weak second order hyperfine

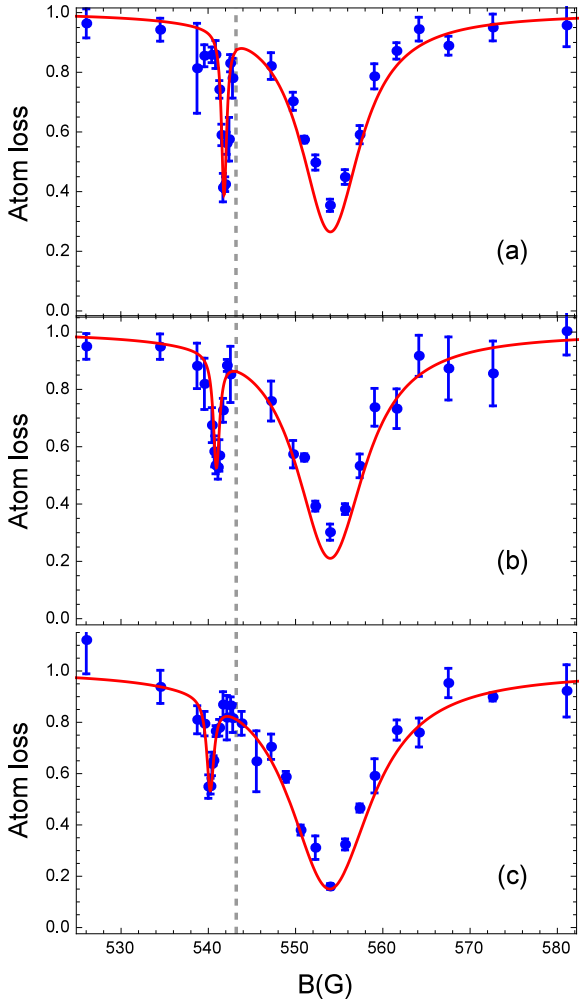

FIG. 2: Single-field-induced shift of the narrow Feshbach resonance at 543.2 G. The large loss peak on the right arises from the broad resonance; The left loss peak arises from the shifted narrow resonance. Vertical dashed line: Position of the unshifted narrow resonance. The background (non-optical) three-body loss near 543.2 G has been suppressed for clarity. Pulse duration $\tau = 5.0$ ms; $T = 5.4\,\mu$K; $\Delta_L = \Delta_1 = 30.2$ MHz; (a) $\Omega_1 = 2.00\,\gamma_e$; $B'_{res} = 541.9$ G (b) $\Omega_1 = 2.65\,\gamma_e$; $B'_{res} = 541.0$ G (c) $\Omega_1 = 3.10\,\gamma_e$; $B'_{res} = 540.2$ G; $\gamma_e = 2\pi \times 11.8$ MHz. Blue dots: Experiment; Solid red curves: Continuum-dressed state model [16].

coupling of the triplet continuum $|T\rangle$ to the "narrow" singlet state $|g_1\rangle_N$ [13]. After forced evaporation, and re-raising the trap to full trap depth, we have approximately 10^5 atoms per spin state for our experiments. We generate both the ω_1 and ω_2 beams from diode lasers, locked to a stabilized cavity near 673.2 nm. The relative frequency is $\simeq 57$ GHz [14] with a jitter < 100 kHz. The absolute frequency stability is $<$100 kHz. Both laser beams are polarized along the bias magnetic field z-axis [16].

Initially, we use a single field (ω_1) to observe the shift of

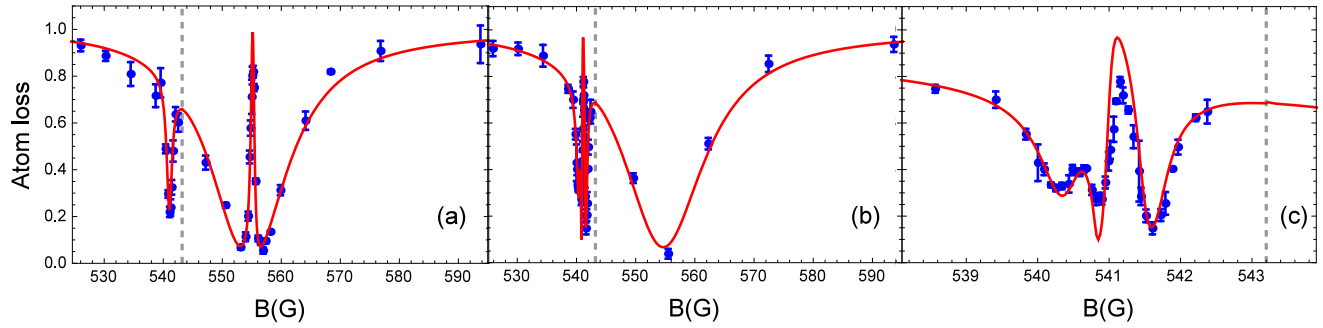

FIG. 3: Loss suppression using the two-field optical technique. The ω_1 beam shifts the narrow Feshbach resonance. The frequency of the ω_2 beam is chosen to suppress loss from (a) the broad resonance (b) the shifted narrow Feshbach resonance; (c) Expanded view of (b) near the loss suppression region. Pulse duration $\tau = 5.0$ ms; $T = 4.5\,\mu$K; $\Omega_1 = 2.6\,\gamma_e$; $\Omega_2 = 0.8\,\gamma_e$; $\Delta_L = \Delta_1 = 30.2$ MHz; $B'_{res} = 541.1$ G. Vertical dashed line: Position of the unshifted narrow resonance. Solid red curves: Continuum-dressed state model [16].

the narrow Feshbach resonance in the atom loss spectra. After forced evaporation at 300 G, the magnetic field is swept to the field of interest and allowed to stabilize for $\simeq 1$ sec, which produces a background three-body loss at 543.2 G. Then the ω_1 field illuminates the atoms for 5 ms, with a detuning $\Delta_L = 30.2$ MHz (with $\Delta_L \equiv 0$ for $B = B_{ref} = 543.2$ G), after which the atoms are imaged at the field of interest to determine the density profile and the atom number.

Single field atom loss spectra versus magnetic field, Fig. 2, exhibit two loss peaks: i) A broad peak arises at 554 G, where the ω_1 optical field is resonant ($\Delta_e = 0$) with the $|T\rangle \rightarrow |e\rangle$ transition. Here, the transition arises from the hyperfine coupling of $|T\rangle$ to $|g_1\rangle_B$, far from the resonance at 832.2 G. ii) A narrow peak below 543.2 G occurs as the magnetic field tunes the triplet continuum near $|g_1\rangle_N$, which is light-shifted in energy, and hence in magnetic field, to B'_{res}, due to the ω_1 optical field, detuned from the $|g_1\rangle_N \rightarrow |e\rangle$ transition by $\Delta_1 = \Delta_L = 30.2$ MHz (see Fig. 1). At this field, the transition strength is maximized, while the ω_1 optical field is off-resonant with the $|T\rangle \rightarrow |e\rangle$ transition by $\Delta_L = 30.2$ MHz. For a $\Omega_1 = 3.1\gamma_e$, the narrow resonance is shifted downward by 3.0 G, approximately 30 times the width ΔB_N. The continuum-dressed state model (solid red line) reproduces the shift of the narrow resonances and the amplitudes of both the narrow and broad resonances, using the measured Ω_1 [16].

We suppress loss by applying a second field ω_2, Fig. 3. At the magnetic field of interest, the ω_2 beam is adiabatically turned on over 30 ms. Then the ω_1 beam is applied for 5 ms, after which both beams are turned off abruptly. The ω_2 beam creates an optical dipole trap and provides additional confinement in the z-direction, due to its high intensity, changing the axial trap frequency from 120 Hz to 218 Hz [16]. With $\Delta_2 = \Delta_e = 0$, loss is suppressed at the center of the broad peak Fig. 3a. For $\Delta_2 = \Delta_1 + 2\mu_B\,(543.2 - B'_{res})$, the loss is suppressed at the center of the shifted narrow peak, Fig. 3b and 3c. The continuum-dressed state model (red solid curves) predicts the features for all three data sets using the same Rabi frequencies Ω_1 and Ω_2, which are close to the predicted values [16]. We note that the predicted central peaks in Fig. 3c are somewhat larger than the measured values, which may arise from jitter in the two-photon detuning and intensity variation of the Ω_2 beam across the atom cloud.

We have also measured light-induced loss and loss suppression as a function of the ω_1 laser frequency near the broad resonance. Data for $B = 840$ G is shown in Fig. 4, where $\Delta_2 = 10$ MHz. Since the maximum suppression occurs for $\Delta_e = \Delta_2$, we observe an asymmetric loss suppression window. By measuring the number of atoms as a function of time with the magnetic field tuned to the suppression point, Fig. 5, we observe an increase of the inelastic lifetime near the broad resonance of ^{6}Li from 0.5 ms with a single laser field to 400 ms with the two-field method, despite the large background scattering length of $-1405\,a_0$ [18, 19] limited by jitter in the two-photon detuning.

Measured light-induced loss spectra are compared to predictions by calculating the atom loss rate [16]. For a 50-50 mixture of two hyperfine states, the total density decays according to $\dot{n}(\mathbf{r},t) = -\frac{1}{2}\langle K_2(k,\mathbf{r})\rangle\,[n(\mathbf{r},t)]^2$. Here, the angle brackets in $\langle K_2(k,\mathbf{r})\rangle$ denote an average over the relative momentum $\hbar k$ distribution. As the Rabi frequencies that determine K_2 generally vary in space, we include an additional position dependence in $\langle K_2\rangle$. For simplicity, we assume in this paper a classical Boltzmann distribution, which is applicable in the high temperature regime employed in the measurements and defer treat-

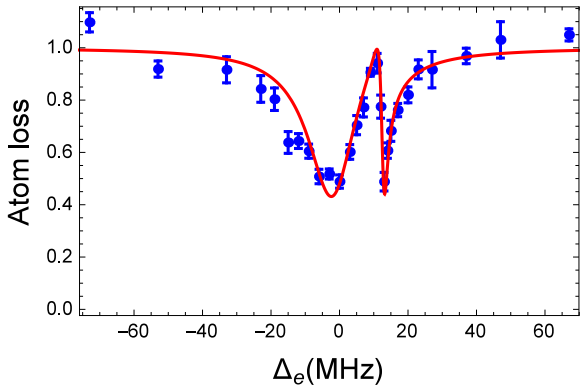

FIG. 4: Loss suppression near the broad resonance at 832.2 G, for $B = 840$ G, as a function of single photon detuning by sweeping the ω_1 laser frequency. Pulse duration $\tau = 5.0$ ms; $T = 14.8\,\mu$K $\Omega_1 = 1.36\,\gamma_e$; $\Omega_2 = 0.9\,\gamma_e$; $\Delta_2 = 10.0$ MHz. Maximum suppression occurs for $\Delta_e = \Delta_2 = 10.0$ MHz, where $\delta_e = 0$. Solid red curve: Continuum-dressed state model [16].

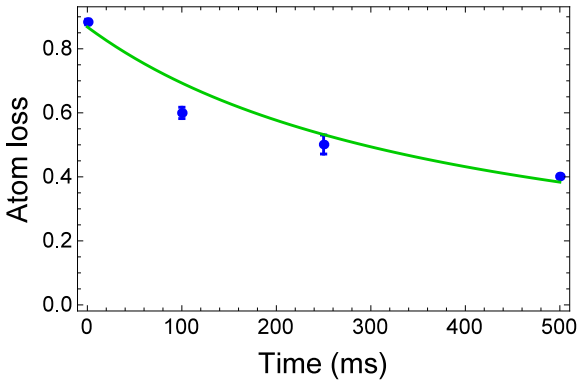

FIG. 5: Number of atoms in state $|1\rangle$ versus time with $\Omega_1 = 0.65\,\gamma_e$ and ω_1 tuned to cause loss at 841 G. $\Omega_2 = 0.9\,\gamma_e$ and ω_2 is tuned to suppress loss near 841 G. With $\Omega_1 = 0.65\,\gamma_e$ and $\Omega_2 = 0$, the corresponding decay time is $\simeq 0.5$ ms. $\gamma_e = 2\pi \times 11.8$ MHz is the radiative decay rate; $T = 4.5\,\mu$K. Solid green curve: $N(t) = N(0)/(1+\gamma t)$, where $\gamma = 2.5\,s^{-1}$.

ment of quantum degeneracy and many-body effects to future work.

The loss rate constant $K_2(k)$ is calculated from the optically-modified scattering state in the continuum-dressed state basis [16]. In previous calculations [7, 12, 13], interaction of the colliding atom pair with the optical fields is described in the "bare" state basis, Fig. 6a, with singlet states, $|g_1\rangle$, $|g_2\rangle$, and $|e\rangle$, and triplet continuum $|T,k\rangle$. Using the continuum-dressed state basis, Fig. 6b, the bare states $|g_1\rangle$ and $|T,k\rangle$, are replaced by the dressed bound state $|E\rangle$ and the Feshbach resonance scattering state $|E_k\rangle$. These dressed states already contain the hyperfine coupling constant V_{HF}, permitting consistent adiabatic elimination of the excited state amplitude $|e\rangle$, even for broad Feshbach resonances where V_{HF} is large compared to γ_e. From the scattering state, we determine the corresponding two-body scattering amplitude $f(k)$, which yields $K_2(k)$ from the inelastic cross section. The new model shows that the light-shifts arising from the Ω_1 beam have a different relative momentum dependence for broad resonances than for narrow resonances and reproduces previous calculations [7, 12, 13] that are valid only for narrow resonances. For broad resonances, the new model avoids a fixed loss point at B_∞, which is incorrectly predicted by narrow resonance models [7, 12, 13].

In conclusion, we have demonstrated that closed-channel dark-state methods can produce large shifts of magnetic Feshbach resonances and strong suppression of spontaneous scattering, enabling flexible control of the tradeoff between loss and tunability. We have established a continuum-dressed state model that fits our measured loss spectra in shape and magnitude, using the measured Rabi frequencies and trap parameters. A key result of this model is the prediction of the relative momentum dependence of the light-induced level shifts for both broad and narrow resonances, resolving a long-standing issue with predictions for broad resonances. Using the predicted relative momentum dependence of the scattering amplitude, the model predicts not only optical control of the scattering length [16], but of the effective range [16], which will be experimentally studied in future work.

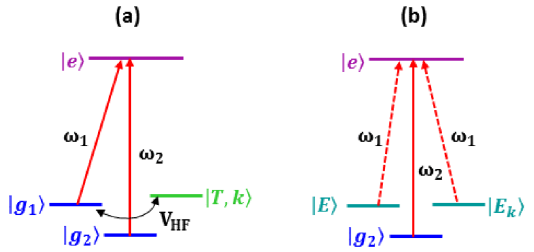

FIG. 6: Level schemes in (a) "bare-state" and (b) "continuum-dressed-state" bases. $|g_1\rangle$, $|g_2\rangle$, and $|e\rangle$ are the bare molecular states in the energetically closed (singlet) channel. $|T,k\rangle$ is a bare continuum state in the open (triplet) channel. The hyperfine interaction V_{HF} couples the bare molecular state $|g_1\rangle$ and the continuum states $|T,k\rangle$, creating the "continuum-dressed" bound state $|E\rangle$ and the (Feshbach resonance) scattering state $|E_k\rangle$.

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