Supplemental Material: "Observation of Fermi Polarons in a Tunable Fermi Liquid of Ultracold Atoms"

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In this supplemental material we state, starting with the variational Ansatz by Chevy, key properties of the polaron, such as the energy $E_\downarrow$ and the quasiparticle residue Z, and we calculate its RF spectrum using Fermi's Golden Rule. We connect this approach and its implication for finite impurity concentration to the results of Fermi liquid theory and the T-matrix formalism used in [1–4]. Furthermore, details are provided about the extraction of the quasiparticle residue Z.

Polaron wavefunction, energy and quasiparticle residue

We start with the hamiltonian for a dilute two component mixture of fermionic atoms interacting via the van-der-Waals potential $V(\mathbf{r})$ [5]. Thanks to the diluteness of the system, the potential is of short range R compared to the interparticle distance $1/k_F$, so $k_F R \ll 1$. Its Fourier transform $V(\mathbf{k})$ is thus essentially constant, g_0, below k_F and rolls off to zero at a momentum on the order of $1/R \gg k_F$. The many-body Hamiltonian for the system is then

$$\hat{H} = \sum_{\mathbf{k},\sigma} \epsilon_{\mathbf{k}} c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \frac{g_0}{\mathcal{V}} \sum_{\mathbf{k},\mathbf{k}',\mathbf{q}} c^\dagger_{\mathbf{k}+\frac{\mathbf{q}}{2}\uparrow} c^\dagger_{-\mathbf{k}+\frac{\mathbf{q}}{2}\downarrow} c_{\mathbf{k}'+\frac{\mathbf{q}}{2}\downarrow} c_{-\mathbf{k}'+\frac{\mathbf{q}}{2}\uparrow} \tag{1}$$

Here, the label σ denotes the spin state $\uparrow,\downarrow$, $\epsilon_{\mathbf{k}} = \hbar^2 k^2/2m$, $\mathcal{V}$ is the volume of the system and the $c^\dagger_{k\sigma}$,$c_{k\sigma}$ are the usual creation and annihilation operators for fermions with momentum $\mathbf{k}$ and spin σ. The trial wavefunction for the Fermi polaron with zero momentum proposed by F. Chevy in [6] is

$$|\Psi\rangle = \varphi_0 \left|\mathbf{0}\right\rangle_\downarrow |FS\rangle_\uparrow + \sum_{q<k_F}^{k>k_F} \varphi_{\mathbf{kq}} c^\dagger_{\mathbf{k}\uparrow} c_{\mathbf{q}\uparrow} \left|\mathbf{q}-\mathbf{k}\right\rangle_\downarrow |FS\rangle_\uparrow \tag{2}$$

The energy is then minimized under variation of the parameters φ_0 and $\varphi_{\mathbf{kq}}$, with the constraint of constant norm $\langle\Psi|\Psi\rangle = |\varphi_0|^2 + \sum_{q<k_F}^{k>k_F} |\varphi_{\mathbf{kq}}|^2 = 1$. That is, the quantity to minimize is $\left\langle \Psi|\hat{H}|\Psi \right\rangle - E_\downarrow \langle\Psi|\Psi\rangle$. The derivation can be found in [6], here we quote the result for the particle-hole excitation amplitudes $\varphi_{\mathbf{kq}}$, the quasiparticle weight $|\varphi_0|^2 = Z$, and the energy $E_\downarrow$ due to addition of the down spin impurity:

$$\varphi_{\mathbf{kq}} = \varphi_0 \frac{1}{\mathcal{V}} \frac{f(E_\downarrow, \mathbf{q})}{E_\downarrow - \epsilon_{\mathbf{k}} + \epsilon_{\mathbf{q}} - \epsilon_{\mathbf{q}-\mathbf{k}}} \tag{3}$$

$$\frac{1}{|\varphi_0|^2} \equiv \frac{1}{Z} = \left(1 - \frac{\partial}{\partial E} \frac{1}{\mathcal{V}} \sum_{q<k_F} f(E,\mathbf{q})\right)_{E=E_\downarrow} \tag{4}$$

$$E_\downarrow = \frac{1}{\mathcal{V}} \sum_{q<k_F} f(E_\downarrow, \mathbf{q}) \tag{5}$$

These all depend on the function $f(E,\mathbf{q})$ with

$$f^{-1}(E,\mathbf{q}) = \frac{1}{g_0} + \frac{1}{\mathcal{V}} \sum_{k>k_F} \frac{1}{\epsilon_{\mathbf{k}} - \epsilon_{\mathbf{q}} + \epsilon_{\mathbf{q}-\mathbf{k}} - E} \tag{6}$$

It is a measure of the interaction strength between spin up and spin down, modified by the presence of the spin up Fermi sea. As usual, g_0 can be replaced by the physically observable scattering length a for collisions between spin up and down via [5] $\frac{1}{g_0} = \frac{m}{4\pi\hbar^2 a} - \frac{1}{\mathcal{V}} \sum_{\mathbf{k}} \frac{1}{2\epsilon_{\mathbf{k}}}$.

$$f^{-1}(E,\mathbf{q}) = \frac{m k_F}{2\pi^2\hbar^2} \left(\frac{\pi}{2k_F a} - 1\right) + \frac{1}{\mathcal{V}} \sum_{k>k_F} \left(\frac{1}{\epsilon_{\mathbf{k}} - \epsilon_{\mathbf{q}} + \epsilon_{\mathbf{q}-\mathbf{k}} - E} - \frac{1}{2\epsilon_k}\right) \tag{7}$$

The integral in above expression is convergent and gives

$$f^{-1}(E,\mathbf{q}) = \frac{m k_F}{2\pi^2\hbar^2} \left\{\frac{\pi}{2k_F a} - 1 + I\left(\frac{E}{E_F}, \frac{q}{k_F}\right)\right\} \tag{8}$$
$$I(\epsilon, y) = \int_1^\infty \mathrm{d}x \left(\frac{x}{2y} \ln\left(\frac{2x^2 + 2xy - \epsilon}{2x^2 - 2xy - \epsilon}\right) - 1\right)$$

An analytic expression for the integral exists but does not provide additional insight. The equation for $E_\downarrow$ becomes

$$\frac{E_\downarrow}{E_F} = -2 \int_0^1 \mathrm{d}y \frac{y^2}{1 - \frac{\pi}{2k_F a} - I\left(\frac{E_\downarrow}{E_F}, y\right)} \tag{9}$$

This implicit equation for $E_\downarrow$ can be easily solved numerically. The result is shown as the dashed line in Fig. 3 of the main paper. Clearly, $E_\downarrow$ is negative due to the attractive interactions with the medium. In the weakly interacting limit $1/k_F a \to -\infty$, we can neglect the integral in the denominator and immediately obtain $E_\downarrow = \frac{2}{3} \frac{2k_F a}{\pi} E_F = 4\pi\hbar^2 a n_\uparrow/m$, which is the mean field result [7].

The approach turns out to be equivalent to a T-Matrix description, as shown in [7]. In that language, $f(E,\mathbf{q})$

is (up to a constant) the scattering amplitude in the medium (i.e. the vertex) for the scattering process with total energy and momentum E and q of the colliding particles. $\Sigma(\mathbf{0}, E) \equiv \frac{1}{\mathcal{V}} \sum_{q<k_F} f(E_\downarrow + E, \mathbf{q})$ is the self-energy at zero momentum and frequency $E/\hbar$. It is real in this approximation. The expression for the quasiparticle residue Z of a *single* spin down impurity in Eq. 4 is immediately seen to be equivalent to the well-known relation [3]

$$Z_\downarrow^{-1} = \left(1 - \frac{\partial}{\partial E} \mathrm{Re}\Sigma(k_{F\downarrow}, E)\right)_{E=0} \tag{10}$$

for a spin down quasiparticle on top of a spin down Fermi sea, in the limit of vanishing Fermi momentum $k_{F\downarrow}$.

RF spectrum from the variational Ansatz

Fermi's Golden Rule allows us to directly predict the shape of the impurity RF spectrum. This topic has been studied in detail since the early days of RF spectrosocpy, and for the problem of highly imbalanced Fermi gases in [1–4], among others. Chevy's wavefunction offers a simple way of calculating the RF spectrum of a single impurity.

The RF operator $\hat{V} = \hbar\Omega_R \sum_k c_{k,f}^\dagger c_{k,\downarrow} + h.c.$ promotes the impurity into the free final state $|f\rangle$ (energy E_f) without momentum transfer [5]. In the experiment, the final internal state is the second lowest hyperfine state of ^{6}Li. Fermi's Golden Rule for the impurity starting in state $|\Psi\rangle$ is

$$\Gamma(\omega) = \frac{2\pi}{\hbar} \sum_f \left|\left\langle f|\hat{V}|\Psi\right\rangle\right|^2 \delta(\hbar\omega - (E_f - E_\downarrow)) \tag{11}$$

Where ω is the RF offset from the bare atomic transition frequency between the internal states labeled by $\downarrow$ and f. One possible final state is $|0\rangle \equiv |\mathbf{0}\rangle_f |FS\rangle_\uparrow$, i.e. a zero momentum particle in the final state plus a perfect Fermi sea of up spins, with energy $E_{|0\rangle} = 0$ relative to the Fermi energy E_F of the environment. Other possible final states are $|\mathbf{q}, \mathbf{k}\rangle \equiv |\mathbf{q} - \mathbf{k}\rangle_f c_{\mathbf{k}\uparrow}^\dagger c_{\mathbf{q}\uparrow} |FS\rangle_\uparrow$ with $q < k_F$ and $k > k_F$, i.e. a particle with momentum $\mathbf{q} - \mathbf{k}$ in the final state and a Fermi sea with a hole at $\mathbf{q}$ and an excited environment particle above the Fermi sea at $\mathbf{k}$. The energy of these states is $E_{|\mathbf{q},\mathbf{k}\rangle} = \epsilon_\mathbf{k} - \epsilon_\mathbf{q} + \epsilon_{\mathbf{q}-\mathbf{k}}$ relative to the environment Fermi energy E_F. The matrix elements are

$$\left\langle 0 \middle| \hat{V} \middle| \Psi \right\rangle = \hbar\Omega_R\, \varphi_0$$
$$\left\langle \mathbf{q}, \mathbf{k} \middle| \hat{V} \middle| \Psi \right\rangle = \hbar\Omega_R\, \varphi_{\mathbf{kq}}$$

This leaves us with two components in the RF spectrum:

$$\Gamma(\omega) = 2\pi\hbar\Omega_R^2 \left(Z\delta(\hbar\omega + E_\downarrow) + \sum_{q<k_F}^{k>k_F} |\varphi_{\mathbf{kq}}|^2 \delta(\hbar\omega + E_\downarrow - \epsilon_\mathbf{k} + \epsilon_\mathbf{q} - \epsilon_{\mathbf{q}-\mathbf{k}}) \right) \tag{12}$$

The first part is a delta-peak shifted by the quasiparticle energy. As $E_\downarrow < 0$, it is shifted to higher frequencies: The RF photon has to supply additional energy to transfer the impurity out of its attractive environment. The weight of this peak is Z, the quasiparticle residue, allowing the experimental determination of Z by simply integrating the area under the prominent peak. Such a delta-peak is typically called "coherent", as a broadband excitation around this energy would not dephase over time. The second part of the spectrum is incoherent, it consists of a broad continuum of frequencies. Broadband excitations of this continuum would rapidly dephase, over a timescale given by the inverse width of the continuum.

RF spectrum in Fermi Liquid theory

This structure of the RF spectrum is a generic feature of quasiparticle spectra. In Fermi liquid theory, the propagator of a quasiparticle is approximated as a pole at energy $E(k) > 0$ (relative to the ground state energy), lifetime $1/\gamma(k)$ and residue Z plus an incoherent spectrum [3, 8]

$$G_-^R(\mathbf{k}, \omega) = \frac{Z}{\hbar\omega + E(k) + i\hbar\gamma(k)} + G_-^{R,\mathrm{inc}}(\mathbf{k}, \omega) \tag{13}$$

The spectral function is given by $A_-(\mathbf{k}, \omega) = -\frac{1}{\pi}\mathrm{Im}G_-^R(\mathbf{k}, \omega) = Z\frac{1}{\pi}\frac{\hbar\gamma(k)}{(\hbar\omega+E(k))^2+\hbar^2\gamma(k)^2} + A_-^{\mathrm{inc}}(\mathbf{k}, \omega)$ which tends to

$$A_-(\mathbf{k}, \omega) = Z\delta(\hbar\omega + E(k)) + A_-^{\mathrm{inc}}(\mathbf{k}, \omega) \tag{14}$$

in the limit of small damping of the quasiparticle. $A_-(\mathbf{k}, \omega)$ measures the probability that removing a particle with momentum $\mathbf{k}$ will cost an energy $-\hbar\omega$. The RF spectrum in linear response is given by [2]

$$\Gamma(\omega) = 2\pi\hbar\Omega_R^2 \sum_k A_-(\mathbf{k}, \epsilon_\mathbf{k} - \mu - \hbar\omega) n_F(\epsilon_\mathbf{k} - \mu - \hbar\omega) \tag{15}$$

where μ is the chemical potential of the quasiparticle and $n_F(x) = 1/(e^{\beta x} + 1)$ is the Fermi function that tends to $\theta(-x)$ at zero temperature. This is intuitively understood: For a given momentum $\mathbf{k}$, the RF photon with energy $\hbar\omega$ has to provide the energy $\epsilon_\mathbf{k} - \mu$ (relative to the initial chemical potential μ) to create a free particle in the final state. The rest, $\hbar\omega - \epsilon_\mathbf{k} + \mu$, is used to remove a particle from the initial state (probability $A_-(\mathbf{k}, \epsilon_\mathbf{k} - \mu - \hbar\omega)$) if there exists such a particle (factor

$n_F(\epsilon_{\mathbf{k}}-\mu-\hbar\omega))$. Eq. 15 is equivalent to Fermi's Golden Rule Eq. 11 [9]. In the case where the spectral function is dominated by a quasiparticle peak, the spectrum becomes

$$\Gamma(\omega) = 2\pi\hbar\Omega_R^2 Z \sum_k \delta(\epsilon_{\mathbf{k}} + E(k) - \mu - \hbar\omega) \times n_F(\epsilon_{\mathbf{k}} - \mu - \hbar\omega) + \Gamma^{\rm inc}(\omega) \quad (16)$$

Connecting to our case of a single quasiparticle with $\mu = E_\downarrow$ and $k = 0$, this directly gives

$$\Gamma(\omega) = 2\pi\hbar\Omega_R^2 Z\delta(\hbar\omega + E_\downarrow) + \Gamma^{\rm inc}(\omega) \quad (17)$$

identical to the prediction via the trial wavefunction.

Polaron spectral function

To connect the single particle and the Fermi liquid description, we calculate the propagator $G_-^R(\mathbf{k},\omega)$ for the removal of a single spin down impurity from the wavefunction $|\Psi\rangle$. By definition,

$$iG_-^R(\mathbf{k},t) = \langle\Psi| c_{\mathbf{k}\downarrow}^\dagger e^{i\hat{H}t/\hbar} c_{\mathbf{k}\downarrow} |\Psi\rangle\, \theta(t) \quad (18)$$

Inserting a complete set of eigenstates, this gives

$$iG_-^R(\mathbf{k},t) = \sum_f |\langle f| c_{\mathbf{k}\downarrow} |\Psi\rangle|^2 e^{iE_f t/\hbar}\theta(t) \quad (19)$$

The state $c_{\mathbf{k}\downarrow}|\Psi\rangle$ is void of any spin down impurity and has non-vanishing matrix elements only with either the unperturbed spin up Fermi sea, $|FS\rangle_\uparrow$ (if $\mathbf{k}=\mathbf{0}$), or with particle-hole excitations $|\mathbf{q},\mathbf{k}'\rangle = c_{\mathbf{k}'\uparrow}^\dagger c_{\mathbf{q}\uparrow}|FS\rangle_\uparrow$ (in the case $\mathbf{k} = \mathbf{q}-\mathbf{k}'$). These matrix elements are $\varphi_0 = \sqrt{Z}$ and $\varphi_{\mathbf{k}'\mathbf{q}}$ resp., the corresponding energies $E_f = 0$ and $E_f = \epsilon_{\mathbf{k}'} - \epsilon_{\mathbf{q}}$ relative to E_F. So one has:

$$iG_-^R(\mathbf{k},t) = (Z\delta_{\mathbf{k},\mathbf{0}} + \sum_{q<k_F}^{k'>k_F} \delta_{\mathbf{k},\mathbf{q}-\mathbf{k}'} |\varphi_{\mathbf{k}'\mathbf{q}}|^2 e^{i(\epsilon_{\mathbf{k}'}-\epsilon_{\mathbf{q}})t/\hbar})\theta(t)$$

Finally, $G_-^R(\mathbf{k},\omega) = \frac{Z}{\hbar\omega+i\eta}\delta_{\mathbf{k},\mathbf{0}} + G_-^{R,\rm inc}(\mathbf{k},\omega)$ with infinitesimal $\eta > 0$. This is just the Fermi liquid form of G_-^R but for a single quasiparticle with zero momentum ($E(0) = 0$ in (13)), as described by $|\Psi\rangle$. The spectral function is

$$A_-(\mathbf{k},\omega) = Z\delta(\hbar\omega)\delta_{\mathbf{k},\mathbf{0}} + \sum_{q<k_F}^{k'>k_F} \delta_{\mathbf{k},\mathbf{q}-\mathbf{k}'} |\varphi_{\mathbf{k}'\mathbf{q}}|^2 \delta(\hbar\omega + \epsilon_{\mathbf{k}'} - \epsilon_{\mathbf{q}})$$

With Eq. 15 this exactly gives the RF spectrum of Eq. 12.

Calculation of the incoherent background

Using Eq. 3, we can write the incoherent part of the spectrum as:

$$\Gamma^{\rm inc}(\omega) \equiv 2\pi\hbar\Omega_R^2 \sum_{q<k_F}^{k>k_F} |\varphi_{\mathbf{kq}}|^2 \delta(\hbar\omega + E_\downarrow - \epsilon_{\mathbf{k}} + \epsilon_{\mathbf{q}} - \epsilon_{\mathbf{q}-\mathbf{k}})$$

$$= \frac{2\pi\Omega_R^2}{\hbar}\frac{Z}{\omega^2}\frac{1}{\mathcal{V}^2}\sum_{q<k_F}^{k>k_F} f(E_\downarrow,\mathbf{q})^2\delta(\hbar\omega + E_\downarrow - \epsilon_{\mathbf{k}} + \epsilon_{\mathbf{q}} - \epsilon_{\mathbf{q}-\mathbf{k}})$$

The integral over $\mathbf{k}$ exists in analytic form:

$$\frac{1}{\mathcal{V}}\sum_{k>k_F}\delta(\hbar\omega + E_\downarrow - \epsilon_{\mathbf{k}} + \epsilon_{\mathbf{q}} - \epsilon_{\mathbf{q}-\mathbf{k}}) = \frac{mk_F}{8\pi^2\hbar^2}K\left(\frac{\hbar\omega+E_\downarrow}{2E_F},\frac{q}{k_F}\right)$$

$$\text{with}\quad K(\epsilon,y) = \begin{cases} \frac{y_+^2-y_-^2}{y} & \text{for } y_- > 1\,, \\ \frac{y_+^2-1}{y} & \text{for } y_- < 1 < y_+\,, \\ 0 & \text{for } 1 > y_+\,. \end{cases}$$

$$\text{and}\quad y_\pm = \pm\frac{y}{2} + \sqrt{\frac{y^2}{4}+\epsilon} \quad (20)$$

The incoherent spectrum is then

$$\Gamma^{\rm inc}(\omega) = \pi\Omega_R^2\frac{ZE_F}{\hbar\omega^2}\int_0^1 {\rm d}y\frac{y^2K\left(\frac{\hbar\omega+E_\downarrow}{2E_F},y\right)}{\left(1-\frac{\pi}{2k_Fa} - I\left(\frac{E_\downarrow}{E_F},y\right)\right)^2} \quad (21)$$

One can check that the total spectrum obeys the sum rule

$$\int_{-\infty}^{\infty}{\rm d}\omega\Gamma(\omega) = 2\pi\hbar\Omega_R^2 \quad (22)$$

and in particular that the total weight of the incoherent background is proportional to $1-Z$, which is not obvious from the form in Eq. 21. For RF frequencies close to threshold $\hbar\omega + E_\downarrow \ll 2E_F$, the hole momentum $\mathbf{q}$ and the particle momentum $\mathbf{k}$ must be close to each other to fulfill energy conservation, i.e. they have to be close to the Fermi momentum. The double sum over $\mathbf{q}$ and $\mathbf{k}$ thus gives a phase space suppression on the order of $(\hbar\omega + E_\downarrow)^2$, i.e. the spectrum starts like $(\hbar\omega+E_\downarrow)^2/\omega^2$. This is in contrast to the dissociation spectrum of a molecule of binding energy E_B, where the density of states above threshold gives a spectrum proportional to $\sqrt{\hbar\omega+E_B}/\omega^2$. For large RF energies, large particle momenta $\mathbf{k}$ are involved, the suppression due to the Fermi sea becomes negligible and the spectrum behaves like $\sqrt{\hbar\omega+E_\downarrow}/\omega^2$, as for a molecule of binding energy $E_\downarrow$. This is natural as for large momenta, we are probing short-range physics which involves at most two particles, a spin up environment atom and the impurity. In particular, at RF energies $\hbar\omega \gg E_\downarrow$, we recover the $\omega^{-3/2}$ behavior of the RF spectrum that is universal for short-range interactions.

RF Spectrum of a finite concentration of impurities

Since polarons are found to be weakly interacting, they will form a Fermi sea filled up to the impurity Fermi momentum $k_{F\downarrow}$. The fact that the dispersion of polarons $E_(k) = \frac{m}{m^*}\epsilon_{\mathbf{k}}$ differs from that of a free particle due to the effective mass $m^* \neq m$ leads to broadening of the RF spectra. The RF photon has to supply the difference in kinetic energies $(1-\frac{m}{m^*})\epsilon_{\mathbf{k}}$ between the initial and the final state, with a maximal shift $(1-\frac{m}{m^*})\hbar^2 k_{F\downarrow}^2/2m$. The spectral shape is easily obtained: The spectral function at momentum $\mathbf{k}$ will be dominated by polarons that occupy that momentum state. The coherent part of the spectral function is thus $A_-^{\rm coh}(\mathbf{k},\omega) = Z\delta(\hbar\omega + E(k))$ with $E(k) = -\hbar^2k^2/2m^* = -\frac{m}{m^*}\epsilon_{\mathbf{k}}$ relative to the impurity Fermi energy. The coherent part of the spectrum then becomes

$$\Gamma^{\rm coh}(\omega) = 2\pi\hbar\Omega_R^2 \sum_k A_-^{\rm coh}(\mathbf{k}, \epsilon_k - E_\downarrow - \hbar\omega)$$

where the sum extends up to the impurity Fermi momentum $k_{F\downarrow}$. With the free, 3D density of states $\rho(\epsilon)$, this is

$$\begin{aligned}\Gamma^{\rm coh}(\omega) &= 2\pi\hbar\Omega_R^2 \int_0^{E_{F\downarrow}} {\rm d}\epsilon\, \rho(\epsilon) Z\delta(\epsilon - E_\downarrow - \hbar\omega - \frac{m}{m^*}\epsilon) \\ &= 2\pi\hbar\Omega_R^2 \frac{Z}{1-\frac{m}{m^*}} \rho\left(\frac{\hbar\omega + E_\downarrow}{1-\frac{m}{m^*}}\right) \times \\ &\quad \theta\left((1-\frac{m}{m^*})E_{F\downarrow} - \hbar\omega - E_\downarrow\right) \qquad (23)\end{aligned}$$

This coherent part of the spectrum starts at the polaron ground state energy $\hbar\omega = |E_\downarrow|$, then grows like a square root and jumps to zero when $\hbar\omega - |E_\downarrow| = (1-\frac{m}{m^*})E_{F\downarrow}$. On resonance, where $m^* \approx 1.2$, this occurs at $\hbar\omega - |E_\downarrow| = 0.2x^{2/3}E_{F\uparrow} \approx 0.04 E_{F\uparrow}$ for $x = 0.1$. This is still smaller than the Fourier width of the RF pulse used in the experiment of about $0.1E_F$. The size of the jump is given by $2\pi\hbar\Omega_R^2\frac{Z}{1-\frac{m}{m^*}}\rho(E_{F\downarrow})$ and reflects the impurity Fermi surface in the RF spectrum. This behavior of the coherent part of the spectrum was found in [1] and was discussed recently in [4]. It is intriguing that the sharpness of the Fermi surface and its discontinuity should, at least in principle, be observable in the RF spectrum.

Determination of Z from experimental spectra

In order to extract the quasiparticle residue Z, we determine the area under the peak that is not matched by the environment's response and divide by the total area under the impurity spectrum (see spectrum in the inset of Fig. 4 in the main body of the paper). Due to the Fourier width of the probe pulse, the strong response of the environment around zero RF offset (the resonance for

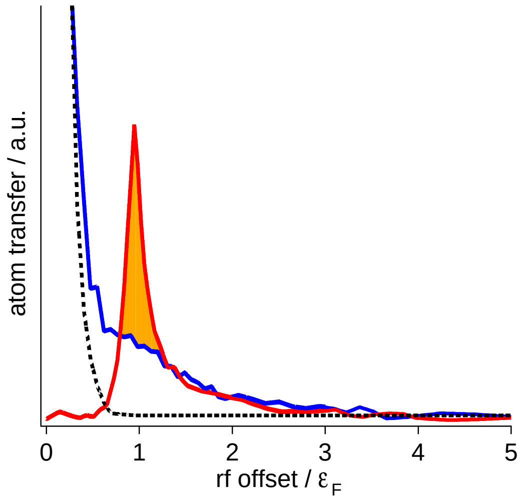

FIG. 1: Determination of the quasiparticle residue Z. Impurity spectrum (red), environment spectrum (blue) and spectral response of non-interacting atoms (black dashed), folded over from negative RF offsets.

non-interacting atoms) adds some weight to the environment background at the position of the polaron peak. To remove this effect in the determination of Z, the part of the environment's response at negative frequency offset is folded towards the positive side (dashed line in Fig. 1) and subtracted from the environment spectrum. As it turns out, this procedure changes the value for Z by less than 5% for all spectra in Fig. 2 of the main paper.

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