Disentangling Pauli Blocking of Atomic Decay from Cooperative Radiation and Atomic Motion in a 2D Fermi Gas

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The observation of Pauli blocking of atomic spontaneous decay via direct measurements of the atomic population requires the use of long-lived atomic gases where quantum statistics, atom recoil, and cooperative radiative processes are all relevant. We develop a theoretical framework capable of simultaneously accounting for all these effects in the many-body quantum degenerate regime. We apply it to atoms in a single 2D pancake or arrays of pancakes featuring an effective $\Lambda$ level structure (one excited and two degenerate ground states). We identify a parameter window in which a factor of 2 extension in the atomic lifetime clearly attributable to Pauli blocking should be experimentally observable in deeply degenerate gases with $\sim 10^4$ atoms. We experimentally observe a suppressed excited-state decay rate, fully consistent with the theory prediction of an enhanced excited-state lifetime, on the $^1S_0 \rightarrow ^3P_1$ transition in $^{87}$Sr atoms.

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Introduction.—Spontaneous emission emerges from the interaction of an excited atom with the vacuum of electromagnetic field modes [1,2]. It depends on the atomic internal structure but also on the density of states of the joint atom-photon system, which can be engineered by shaping the environment as widely demonstrated in cavity [3–7], circuit [8–13], and waveguide QED [14–16].

The emission rate can also be modified by Fermi statistics and Pauli blocking of the motional states into which an excited atom can decay. Since this effect was first pointed out [17], there have been a variety of subsequent theoretical explorations [18–26]. However, the experimental observation of Pauli blocking of radiation has been difficult due to the complex interplay of cooperative effects and atomic motion. Cooperative effects, arising from the virtual exchange of photons between atoms and the resulting dipolar interactions, can also enhance or suppress the radiative decay rate of the system [27–39], especially at the high densities required for Pauli blocking. At the same time, the emission process couples the internal dynamics to the motional states, leading to competition between the recoil kick during emission and the extent of the Fermi sea that blocks the decay.

Recent experiments have for the first time observed Pauli blocking through measurements of light scattered by atomic ensembles [40–42]. There, the mentioned undesirable competing effects were minimized by performing angular-resolved measurements to select low momentum transfer processes and by using a far detuned probe to minimize cooperative dipolar processes and suppress the number of excited atoms.

However, an observation of enhanced lifetimes due to Pauli blocking by direct measurements of the excited-state population has yet to be demonstrated. Resonantly exciting a significant fraction of atoms to the excited state to subsequently measure their decay may result in significant dipolar interaction effects in striking contrast to scattering experiments. Moreover, working on a slow transition enabling time-resolved observation of the excited-state population poses the challenge that radiative decay rates and cooperative effects become comparable with the Fermi energy and associated motional degrees of freedom, which all need to be taken into account.

In this Letter, we develop a theoretical framework based on a master equation formulated in momentum space capable of describing the full dipolar dynamics of optically excited atoms confined in two dimensions (see Fig. 1) or in stacks of two-dimensional pancakes. While the few-body two-level problem can be treated exactly [26], our framework goes beyond this limit and, instead, is developed to tackle multilevel atomic ensembles in the interacting quantum degenerate regime. There, prior approaches fail since they account for Pauli blocking in a semiclassical noninteracting setting [23–25], include interactions for atoms at frozen positions, neglecting the recoil momentum [27–39], treat two-level systems in static motional states [43,44], neglecting motional dynamics, and do not account for the multilevel structure required for the Pauli blocking mechanism described here.
Our key finding is that a highly imbalanced ultracold Fermi gas excited by a resonant $\pi$ pulse (which suppresses coherences) can feature at $T/T_F \sim 0.1$ (with $T_F$ the Fermi temperature) up to 50\% Pauli suppression at peak densities of $10^{14}$ cm$^{-3}$ in a parameter regime where cooperative effects only affect the lifetime weakly. We perform measurements on the $^1S_0 - ^3P_1$ transition in fermionic $^{87}\text{Sr}$ at $T/T_F = 0.6$ with a natural lifetime of $\Gamma^{-1} = 21.3$ $\mu$s. Working with this long-lived narrow transition enables our experiment to spectroscopically resolve the multilevel structure and implement time-resolved measurements of the excited-state population dynamics. We observe an up to 20\% reduction of the decay rate of the excited-state population, thus providing both theoretical predictions and direct experimental evidence for an enhanced lifetime of an optically excited state due to Pauli blocking.

Model.—We analyze first the case of a Fermi gas in a single pancake in the regime where only the ground-state coherences (if any) can feature at low temperatures up to 50\% Pauli suppression at peak densities $\bar{n}_g$.

We consider an effective $\Lambda$-type internal level structure $[\text{Fig. 1(a)}]$ with two internal ground states as the minimal system, allowing strong Pauli blocking even under full excitation of one of the states, but note that our results can be straightforwardly extended to more general multilevel systems. For specificity we focus on the $^1S_0(F = 9/2)$ to $^3P_1(F = 11/2)$ transition of $^{87}\text{Sr}$, with the $m_F = -9/2$ excited state as $e$ and the $m_F = -9/2, -7/2$ ground states as $g_0$ and $g_1$, respectively, and set the quantization axis along $x$. We assume the presence of a magnetic field large enough to suppress transitions to other levels (which are omitted in the figure). The atoms are initially in an incoherent mixture with $N_{g0}$ atoms in $g_0$ and $N_{g1}$ in $g_1$.

This configuration features $x$ and $\sigma^-$ polarized decay, at rates $\Gamma_{g0} = 2/11\Gamma$ and $\Gamma_{g1} = 9/11\Gamma$, respectively, with $\Gamma^{-1} = 21.3$ $\mu$s [45].

Atoms are excited by a short laser pulse with pulse area $\theta$ and then let to evolve and decay for some time $t$ in the dark, after which the total excited-state population is measured [Fig. 1(c)]. We focus on the effective decay rate $\gamma_{\text{eff}}(\theta) = \lim_{t\rightarrow\infty}N_{ee}(t)/N_{ee}(0)$ obtained at initial time for the total number of excitations $N_{ee}(t)$. While the decay rate can change with time, in the cases discussed here, the decay at early times is well approximated by an exponential decay with rate $\gamma_{\text{eff}}$.

The initial excitation laser with wave number $k_L$ is propagating along the strongly confined $z$ direction and linearly polarized $(\mathbf{n}_L)$ along $x$ so that it only excites $g_0$ atoms to $e$ [Fig. 1(b)]. Because of the strong confinement along $z$, the motional state does not change during excitation: the Rabi pulse transfers a population, thus providing both theoretical predictions and direct experimental evidence for an enhanced lifetime of an optically excited state due to Pauli blocking.
Here, $\sigma^{kq}_{\alpha \delta \epsilon} = c_{k\alpha}^\dagger c_{q\delta} c_{q\epsilon}$ and $c_{k\alpha}^\dagger (c_{k\alpha})$ creates a fermion in the $e (g_0)$ state with in plane momentum $k = (k_x, k_y)$ in the harmonic oscillator ground state $n_{0z}$ along $z$.

The terms $\Delta_{\alpha \beta}^{kq} (\Gamma_{\alpha \beta}^{kq})$ describe coherent (incoherent) exchange of photons of the relevant transitions $\alpha, \beta = 0, 1$ between two atoms in the corresponding internal and motional states [Figs. 1(d) and 1(e)]. They are defined as projections of the real (Re) and imaginary part (Im) of Green’s tensor $G$ as $\Delta_{\alpha \beta}^{kq} = d_{q} G^{\alpha \beta}_{Re}(k_{\alpha}, k_{\beta})$, $\Gamma_{\alpha \beta}^{kq} = d_{q} G^{\alpha \beta}_{Im}(k_{\alpha}, k_{\beta})$, where $d_{q} = C_{\alpha} n_{\epsilon}$ given in terms of the Clebsch-Gordan coefficient $C_{\alpha}$ and the polarization vector $n_{\epsilon} [n_{0} = e_{x}, n_{1} = (e_{y} + i e_{z})/\sqrt{2}]$, and $d^{T}$ and $d$ denote the transpose and complex conjugate, respectively. Green’s tensor is $G(r) = (3\Gamma/4)\{[1 - R \otimes \tilde{R}](e^{ik_0 r}/k_0 r) + [1 - 3 R \otimes \tilde{R}](i[e^{ik_0 r}/(k_0 r)]^3)\}$, with the wave vector $k_0$ of the ground-excited-state transition. The matrix elements $G_{\alpha \beta}^{kq}$ are defined as $G_{\alpha \beta}^{kq} = \int d r dr' \phi_{\alpha}^*(r) \phi_{\beta}^*(r) G(r-r') \phi_{\alpha}^*(r') \phi_{\beta}^*(r')$, where $\phi_{\alpha}(x,y,z) = (1/\sqrt{V}) \phi_{\alpha}(x,y,k)$ is the ground state in the presence of a Fermi sea of ground-state atoms, the decay rate will be reduced. The degree of Pauli blocking will depend on the ratio of $k_0$ to $k_F$ (controlled by the density) and the mean occupation within the Fermi sea (set by the temperature of the gas).

To illustrate this phenomenology, we show in Fig. 2 the rate $\gamma^{\text{nonint}}/\Gamma$ for an initially balanced Fermi gas with $N_0 = N_1$ noninteracting atoms and full excitation of all $g_0$ atoms to the $e$ state (i.e., $\theta = \pi$), as a function of the temperature $T/T_F$. In this case the maximal Pauli suppression achievable is $\Gamma_{11}/\Gamma \sim 81\%$ when all decay channels into $g_1$ are blocked. We compare the 3D (dashed) to the strongly confined 2D system (solid) for a range of $N$ (colors), i.e., of $k_0/k_F$. Most notably, we observe a strong enhancement of Pauli blocking in 2D compared to 3D, over a significantly larger range of temperatures.

This can be understood as follows. First, the axial confinement changes the energy spectrum and thus the
density of states. This results in a higher mean occupation fraction in 2D and, consequently, stronger Pauli blocking than in 3D for the same $k_0/k_F$. Second, the initial laser excitation imparts a momentum kick to the atoms in 3D that displaces the excited population away from the unexcited ground-state Fermi sea, facilitating decay to unoccupied states (inset of Fig. 2). In contrast, in 2D for laser excitation along the strongly confined direction, the motional states are unaffected, enhancing the probability to decay to an already occupied state.

Interplay of dipolar interactions with Pauli blocking.— In Fig. 3 we study how $\gamma_{\text{eff}}^{\text{nom}}$ (dashed lines) is modified by dipolar induced cooperative effects using the full ME (solid lines) as a function of the pulse area $\theta$ for a balanced gas, $N_0 = N_1$. At $\theta = \pi$, interactions have no effect on $\gamma_{\text{eff}}$ due to the absence of initial coherences. However, for smaller $\theta$ and increasing $N$, there is an intricate competition between interactions and Pauli blocking. Note the modifications from $\theta$ affect exclusively the $e \rightarrow g_0$ transition. On the one hand, lowering $\theta$ results in a higher population in the $g_0$ ground state $\sim \cos^2(\theta/2)$, which increases Pauli blocking of the $e \rightarrow g_0$ decay channel for noninteracting atoms. On the other hand, interaction effects become stronger at low $\theta$, leading to an enhanced normalized superradiant decay that scales as $\sim \cos^2(\theta/2)$ [47]. Importantly, the superradiant enhancement also scales with $N$. This interplay leads to dominant Pauli blocking and thus lower decay rates at low atom numbers and dominant cooperatively enhanced emission and faster radiative decay at high densities as $\theta$ decreases.

To demonstrate the importance of including atomic motion and its interplay with quantum statistics, we also compare the ME in momentum space to the usual frozen atom approximation (FA) [27–38], which is derived for atoms assumed to be at fixed positions in real space. We show the resulting $\gamma_{\text{eff}}$ for a $\theta = \pi/2$ excitation as a function of the atom number $N$ and temperature $T/T_F$ in Fig. 3(b). The FA properly captures the superradiantly enhanced decay rate due to dipolar interactions. However, its inability to account for Pauli blocking results in incorrect predictions in the quantum degenerate regime and an incorrect scaling of the decay rate with $N$.

Finally, Figs. 3(c) and 3(d) explore the role of the imbalance $N_1/N_0$ of the initial populations of the two ground states on the effective decay rate. For noninteracting atoms it is highly advantageous to only excite a small fraction of atoms [24] to maximize Pauli blocking. This is demonstrated in Fig. 3(c), which shows the decay rate $\gamma_{\text{eff}}^{\text{nom}}/\Gamma$ at $T/T_F = 0.1$ for $\theta = \pi$, predicting the largest suppression in the $N_1 \gg N_0$ regime. Interestingly, for the 2D system, even in the presence of superradiance as $\theta \rightarrow 0$, it is possible to minimize interaction effects while maintaining significant Pauli suppression ($\sim 66\%$) by choosing $N_1 \gg N_0$ as shown in Fig. 3(d). This is because only the $N_0$ atoms feature coherences and experience dipolar interactions at early times.

Comparison with experiment.—We compare our predictions to experimental measurements done on the $^1S_0 - ^3P_1$ transition in fermionic $^{88}$Sr. The 7.5 KHz natural linewidth of this transition allows us to spectroscopically resolve the multilevel structure and to track the excited-state population dynamics in a time-resolved fashion. We consider an array of two-dimensional pancakes (inset of Fig. 4), realized by confining the initially 3D Fermi gas in a deep optical lattice along $z$. The extension of the theory and

![FIG. 3. Interplay of dipolar interactions and Pauli blocking in 2D. (a) $\gamma_{\text{eff}}(\theta)/\gamma_{\text{eff}}^{\text{nom}}(\pi)$ comparing the full ME (solid) to the noninteracting part (dashed) at $T/T_F = 0.1$ for different $N = N_0 = N_1$. (b) Decay rate $\gamma_{\text{eff}}/\Gamma$ at $\theta = \pi/2$ vs $N$ at different temperatures comparing the full ME (solid) to the frozen atom approximation (dash-dotted lines). (c) Decay rate $\gamma_{\text{eff}}^{\text{nom}}(\pi)$ vs $N_0$ and $N_1$. (d) Interaction effects quantified by $\gamma_{\text{eff}}/\gamma_{\text{eff}}^{\text{nom}}$ for $\theta \rightarrow 0$ vs $N_0,N_1$. (c),(d) In thermal equilibrium for $T_0 = T_1$ and $T/T_{F,1} = 0.1$.](image)

![FIG. 4. Decay rates in stacked pancakes geometry. (a) Scaling of the decay rate $\gamma_{\text{eff}}$ with $N$ comparing the balanced case (dotted), $N_0 = N_1 = N$, to the highly imbalanced case (solid), $N_0 = 200, N_1 = N$, for a $\theta = \pi$ pulse. The gray shading denotes the fixed $N = 1500$ used in (b) $\gamma_{\text{eff}}/\Gamma$ vs $\theta$. Temperatures indicated in the legend in (b), in the imbalanced case $T_0 = T_1$ and $T/T_{F,1}$ given with respect to $T_{F,1}$. Points with error bars are experimental data taken under the same conditions as the solid green lines.](image)
details on the experimental preparation and measurement protocol are provided in the Supplemental Material [47].

Figure 4 shows experimental data available for the highly imbalanced scenario, demonstrating agreement with our predictions within errors (green points and lines). Figure 4(a) shows the effective decay rate $\gamma_{\text{eff}}/\Gamma$ as a function of the atom number, pulse area, and temperature, comparing a balanced (dotted) to the imbalanced case (solid) for a $\pi$ pulse excitation. For $N \approx 4 \times 10^5$ and $T/T_F = 0.1$ corresponding to peak densities of $10^{19}$ cm$^{-3}$, we predict up to a factor of 2 enhancement in the atomic lifetime. In Fig. 4(b) we demonstrate the strong interaction effects present for balanced gases when preparing initial coherences due to superradiance. In contrast, we emphasize the weak dependence on $\theta$ in the imbalanced case, which demonstrates the lack of significant cooperative effects.

**Outlook.**—We theoretically predict enhanced lifetimes attributable to Pauli blocking. This prediction is supported by experimental observation of excited-state populations in imbalanced multilevel 2D Fermi gases. The good agreement of our theory treatment, which neglects many-body correlations, and the experimental observations support the validity of our treatment in the investigated regime and motivates further experimental work. Important future directions include the preparation of a deeply degenerate Fermi gas in 2D, where the differences between balanced and imbalanced cases become rather striking, as well as the exploration of conditions where the interplay of quantum statistics and correlations could modify more dramatically the radiative decay dynamics.

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