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Author(s):
Ravets, Sylvain; Knüppel, Patrick; Fält, Stefan; Cotleţ, Ovidiu; Kroner, Martin; Wegscheider, Werner; Imamoglu, Atac

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Editors' Suggestion

Polaron Polaritons in the Integer and Fractional Quantum Hall Regimes

Sylvain Ravets,[1] Patrick Knüppel,[1] Stefan Faelt,[1,2] Ovidiu Cotlet,[1] Martin Kroner,[1]
Werner Wegscheider,[2] and Atac Imamoglu[1]
[1]*Institute of Quantum Electroncis, ETH Zürich, CH-8093 Zürich, Switzerland*
[2]*Solid State Physics Laboratory, ETH Zürich, CH-8093 Zürich, Switzerland*

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Elementary quasiparticles in a two-dimensional electron system can be described as exciton polarons since electron-exciton interactions ensures dressing of excitons by Fermi-sea electron-hole pair excitations. A relevant open question is the modification of this description when the electrons occupy flat bands and electron-electron interactions become prominent. Here, we perform cavity spectroscopy of a two-dimensional electron system in the strong coupling regime, where polariton resonances carry signatures of strongly correlated quantum Hall phases. By measuring the evolution of the polariton splitting under an external magnetic field, we demonstrate the modification of polaron dressing that we associate with filling factor dependent electron-exciton interactions.

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Strong coupling of excitons in a semiconductor quantum well (QW) to a microcavity mode leads to the formation of quasiparticles called cavity exciton polaritons [1]. Polaritons have played a central role in the investigation of nonequilibrium condensation and superfluidity of photonic excitations [2,3]. While polaritons acquire a finite nonlinearity due to their exciton character, interactions between polaritons in undoped QWs are not strong enough for realizing strongly interacting photonic systems [4].

Two-dimensional electron systems (2DES) evolving in large magnetic fields, in contrast, are a fertile ground for many-body physics due to the prominence of electron-electron interactions. Formation of Skyrmion excitations in the vicinity of filling factor $\nu = 1$ is a consequence of such interactions. More spectacularly, electron correlations lead to the formation of fractional quantum Hall (FQH) states where the ground state exhibits topological order [5–7]. Moreover, it has been proposed that a subclass of FQH states exhibit non-Abelian quasiparticles, which can be used to implement topological quantum computation [8].

The nature of optical excitations of a 2DES have recently generated increased interest [9,10]. Prior work investigating optical excitations out of quantum Hall states in gallium arsenide (GaAs) identified the low energy resonances as originating from a bound state of an exciton to an electron, termed a trion. While trions are likely to form in photoluminescence experiments, where an optically excited electron-hole pair can bind to a localized electron, the oscillator strength of these excitations are necessarily small as compared to collective excitations [9]. Recently, it has been demonstrated in transition metal dichalcogenide (TMD) monolayers that an accurate description of optical excitations in the presence of a degenerate electron gas is provided by the concept of Fermi polarons [11–14], which can be described as a superposition excitation of a bare exciton and all possible (zero momentum) trion Fermi-sea hole pairs [9,10]. Here, we report corresponding signatures in GaAs, where energy scales are known to differ significantly compared to TMD monolayers [15,16]. We emphasize that the exciton-polaron picture can only provide a qualitative description of GaAs 2DES optical spectra in the low magnetic field limit due to the heavy exciton mass in GaAs.

It has recently been demonstrated that embedding a 2DES inside a microcavity realizes an alternate method for probing quantum Hall (QH) states [17]. In the strong coupling regime, polariton excitations are sensitive to elementary properties of the many-body ground state, such as spin polarization and incompressibility, due to their part-exciton character. In contrast to bare excitons though, polaritons are immune to decoherence processes, such as phonon or impurity scattering, due to their ultralight mass, ensuring that they are delocalized. Consequently, the energy resolution achievable in polariton-based spectroscopy is only limited by the polariton decay rate due to mirror losses, which can be on the order of 20 mK in state-of-the-art microcavities [18]. In the present Letter, we also demonstrate a new feature of cavity-polariton spectroscopy of FQH states: by adjusting the separation distance between the 2DES and the doping layers, we substantially reduce unwanted light-induced variations of the 2DES electron density n_e [19].

Our structure consists of a 2DES in a 20 nm modulation-doped GaAs QW, embedded at the center of a 2λ $Al_{0.19}Ga_{0.81}$ microcavity [19]. The front (back) distributed Bragg reflector (DBR) is composed of 19 (25) pairs of AlAs/$Al_{0.20}Ga_{0.80}As$ layers, leading to the measured quality factor $Q \simeq (5.5 \pm 0.1) \times 10^3$ for the cavity. The QW features a double-sided silicon δ doping with a setback distance of

$3\lambda/4$ above and below the center of the cavity. From magnetotransport measurements [20], we estimate the 2DES electron density $n_e \simeq 0.33\times10^{11}$ cm^{-2} and the mobility $\mu \simeq 1.6\times10^6$ cm^2 V^{-1} s^{-1}. We deliberately choose a relatively low n_e to access the physics of the lowest Landau level (LL) in the range of magnetic fields currently available on our experimental setup ($|B| \leq 8$ T). The relatively high μ ensures that we can probe FQH physics.

We perform polarization-resolved spectroscopy of the 2DES using an infrared light-emitting diode centered around 820 nm. We shine excitation light onto the sample placed in a dilution refrigerator with a 30 mK base temperature. An aspheric lens (NA = 0.15) collects the light reflected off the sample, which is analyzed using a spectrometer. Earlier studies on the optics of 2DES have shown extreme sensitivity of n_e to optical power [17,21–23]. Increasing the optical power not only changes n_e, but also causes qualitative changes in the reflectivity spectrum [24], which is detrimental to the study of fragile QH states. These unwanted effects are attributed to photoexcitation of DX centers in Si-doped $Al_xGa_{1-x}As$ with $x > 0.2$ [25]. We minimize light-induced variations of n_e by keeping $x < 0.2$ in the structure and, more importantly, by placing the dopants in 10 nm GaAs ($x = 0$) doping quantum wells (DQWs). Further, we locate the DQWs in nodes of the electric field inside the cavity [19], which minimizes the intracavity light intensity at the position of the dopants.

We first carry out cavity spectroscopy of the 2DES [see Fig. 1(a)] when $B = 0$ T. Figure 1(b) shows the reflectivity spectrum as a function of $E_{\rm cav}$. In contrast to undoped QW structures [1], we observe coupling to three excitonlike resonances as we scan $E_{\rm cav}$. For the lowest energy anticrossing, we measure a normal mode splitting of $2\Omega \simeq 2.00 \pm 0.01$ meV. Since 2Ω is larger than the bare-cavity linewidth $\gamma_c \simeq 280 \pm 10$ μeV, the system is in the strong coupling regime of cavity QED and the elementary excitations should be characterized as cavity polaritons [1]. Since the cavity-exciton coupling in this system is comparable to energy level splittings of the three excitonlike resonances, the polariton modes observed in the reflection spectrum can only be described as a superposition of all underlying resonances [see Fig. 1(a)]. We identify the lowest energy excitonlike resonance observed in Fig. 1(b) as the heavy-hole (HH) attractive polaron ($X^{\rm HH}_{\rm att}$)—a heavy-hole exciton dressed by Fermi-sea electron-hole pair excitations [9]. Since the attractive polaron resonance is associated with the bound-molecular singlet trion channel, it was previously referred to as "trion mode" [26,27]. We assign the middle-energy excitonic resonance to the heavy hole repulsive polaron ($X^{\rm HH}_{\rm rep}$) [9,28]. The magnitude of the splitting of this mode from the attractive polaron (2.5 meV) is a factor of 2 larger than the bare trion binding energy and is fully consistent with its identification as the repulsive polaron branch. Finally, we tentatively identify the highest energy excitonic mode to the light-hole exciton [29].

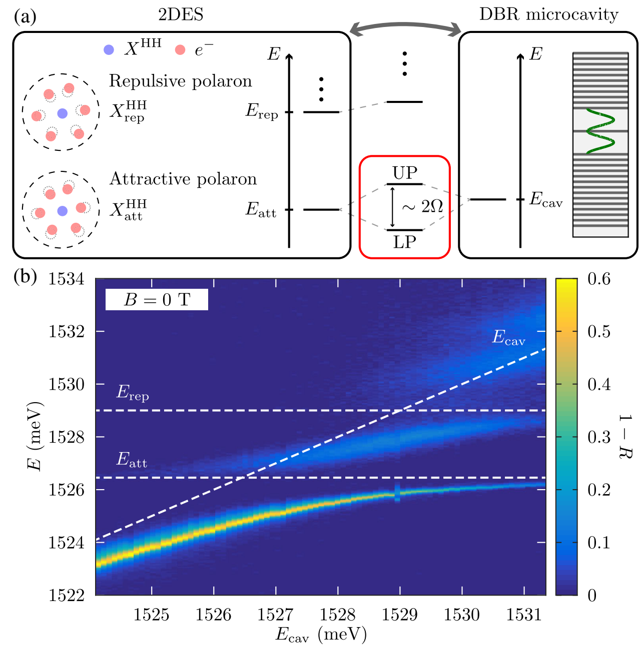

FIG. 1. Observation of polaron polaritons in a GaAs QW. (a) We couple a 2DES to the optical mode of a microcavity composed of two DBRs. In the strong coupling regime, the lowest energy eigenstates of the coupled system are the lower polariton (LP) and the upper polariton (UP). (b) Reflectivity spectrum of the system as we tune the cavity frequency.

Next, we analyze the $B \neq 0$ case, where the heavy hole valence band and the conduction band split into Landau levels LL$n_{\rm HH}$ and LLn_e [5]. To explore the interplay between quantum Hall states and polaritonic excitations, we tune $E_{\rm cav}$ to ensure that the dressed photonic mode resulting from nonperturbative coupling between the bare-cavity mode and the higher energy excitonic states is resonant with $X^{\rm HH}_{\rm att}$. Since the lowest energy polariton has predominantly $X^{\rm HH}_{\rm att}$ character, the spin state of the optically generated electron is determined by the photon polarization [17]: left-hand circularly polarized light σ^- probes transition to the lower electron Zeeman spin subband ($|\uparrow\rangle$) and right-hand circularly polarized light σ^+ probes transition to the upper electron Zeeman spin subband ($|\downarrow\rangle$). Consequently, the observed spectral signatures are strongly dependent on how the electrons are arranged in the LLs, i.e., on the spin-polarization of the different ground states of the 2DES [22,23].

Figures 2(a) and 2(b) show the white light reflection spectrum as a function of the filling factor ν, varied by scanning B. Here, we tuned $E_{\rm cav}$ close to resonance with the $|\uparrow\rangle$ transition of lowest Landau level LL0 at $\nu = 1$. The most striking feature is the collapse of Ω_{σ^-} around $B = 1.31$ T, concurrent with the enhancement of Ω_{σ^+}. We associate this feature with the $\nu = 1$ QH state, in excellent agreement with the value of the electron density

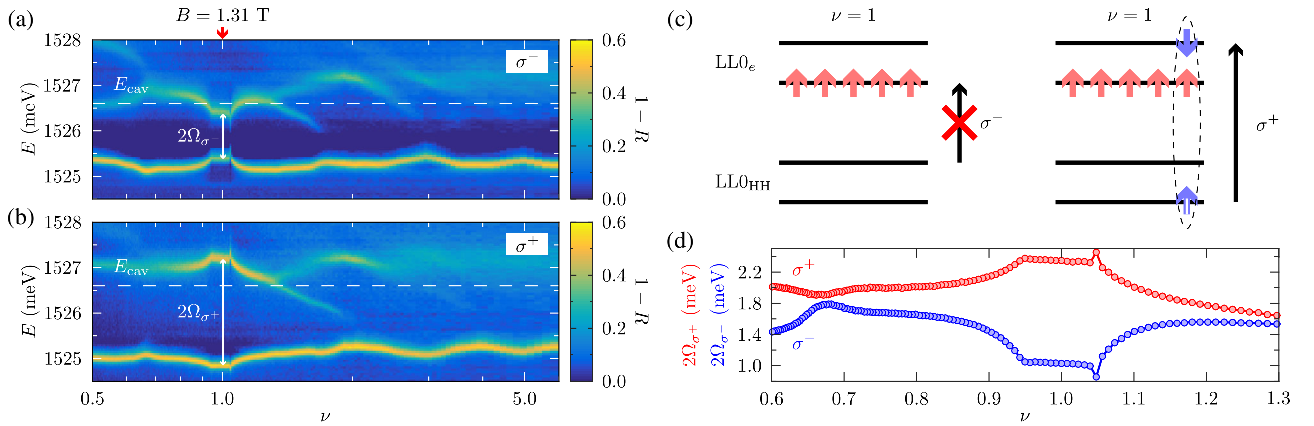

FIG. 2. Cavity spectroscopy of the system in the fractional quantum Hall regime, as we tune B for fixed E_{cav} (white dashed line). Measurement performed with (a) σ^- and (b) σ^+ polarized light. (c) Relevant energy levels and optical transitions around $\nu = 1$. Because of phase-space filling, creation of a LL0$_e$-LL0$_{HH}$ electron-hole pair is only possible in σ^+ polarization (blue arrows). (d) Polariton splitting measured in σ^- (blue) and σ^+ (red) polarizations.

measured independently. The observed behavior is a direct consequence of the high degree of spin polarization of the QH ferromagnet at $\nu = 1$: for a fully polarized state, Ω_{σ^-} is expected to collapse due to the fact that all $|\uparrow\rangle$-electron states are occupied. Phase-space filling thus prevents optical excitation of an electron to that level, and therefore, the oscillator strength for that transition collapses [see Fig. 2(c)]. Concurrently, all $|\downarrow\rangle$-electron states are free and Ω_{σ^+} increases due to the increased number of available states [30,31]. Figure 2(d) shows Ω_{σ^-} and Ω_{σ^+} extracted from fits of the reflection spectra. From this, we calculate the spin polarization $S_z \simeq (\Omega^2_{\sigma^+} - \Omega^2_{\sigma^-})/(\Omega^2_{\sigma^+} + \Omega^2_{\sigma^-})$ at $\nu = 1$ [17,23,32]. We obtain $S_z \simeq 70\%$ [19], suggesting that full polarization is not achieved at $\nu = 1$, contrary to what is expected for the quantum Hall ferromagnet. In our low n_e sample, incomplete polarization may arise due to disorder and reduced screening of impurity potentials [33]. Furthermore, the cyclotron frequency is comparable to the exciton binding energy, ensuring that exciton formation has a sizable contribution from higher LLs so that our measurements only yield a lower bound on S_z.

Tuning the filling factor away from $\nu = 1$ in Figs. 2(a) and 2(b) leads to a rich structure in the reflectivity spectrum that we can qualitatively relate to the way the electrons arrange in the different LLs as we tune B. We first observe a rapid, symmetric depolarization on both sides of $\nu = 1$, which is compatible with formation of many-body spin excitations in the ground state (Skyrmions and anti-Skyrmions) [30–36] as a consequence of the competition between Coulomb and Zeeman energies [19]. Coupling to integer QH states with $\nu \geq 2$ is also visible in Figs. 2(a) and 2(b) as variations of the lower polariton energies vs ν due to the modification of phase-space filling [19]. The upper polariton shows a more complex structure, which we attribute to coupling to higher available LLs as we tune B. The detailed study of this behavior is beyond the scope of this Letter, and we focus, in the rest of the Letter, on the evolution of the polariton splitting in the fractional quantum Hall regime, where only the lowest Landau level LL0 is filled. We emphasize that all spectral features described in this paragraph are robust against increased optical powers, which demonstrates that our sample structure provides, through "cavity protection" of the 2DES, a unique platform for optical studies of QH physics [19].

We investigate FQH states by scanning B to up to 5 T for an increased value of E_{cav} as shown in Figs. 3(a) and 3(b). Increasing B reduces ν, thus leading to absorption in a partially filled lowest LL [37–39]. Cavity coupling to several FQH states is observed in Figs. 2 and 3 as a ν-dependent normal mode splitting in both polarizations. Such spectral signatures are particularly striking when ν reaches the fractional values $\nu = 1/3$, $2/5$, $2/3$, and $5/3$. We observe that Ω_{σ^-} and Ω_{σ^+} differ significantly at $\nu = 1/3$, $2/5$, and $5/3$, which shows that these fractional QH states experience sizable spin polarization [19]. On the contrary, $\Omega_{\sigma^-} \simeq \Omega_{\sigma^+}$ at $\nu = 2/3$ shows that this state is not polarized, as expected for samples with n_e in the range of the one studied here. Increasing n_e should allow us to probe the phase transition from an unpolarized to a polarized $2/3$ state [17,40].

We now focus on filling factor $\nu = 2/5$; see Figs. 3(a) and 3(b). In stark contrast with the integer QH states, both $|\uparrow\rangle$ and $|\downarrow\rangle$ states are available and phase-space filling only plays a marginal role here. Figure 3(d) shows polariton splittings Ω_{σ^-} and Ω_{σ^+} extracted from fits of the reflectivity spectra. One striking feature is that the collapse of Ω_{σ^-} around $\nu = 2/5$ is not accompanied with an appreciable increase in Ω_{σ^+}, contrary to what was observed for $\nu = 1$. Because the LLs are partially filled, the mechanism leading to modification of the polariton splitting is indeed modified.

We argue that the decrease Ω_{σ^-} for a spin-polarized state is due to the polaron nature of optical excitations that are accessible when promoting an electron into the $|\uparrow\rangle$ state with σ^--polarized light. For a fully polarized state, all electrons are in the same $|\uparrow\rangle$ state and there are no electrons in the $|\downarrow\rangle$ state. Since the oscillator strength of the σ^-

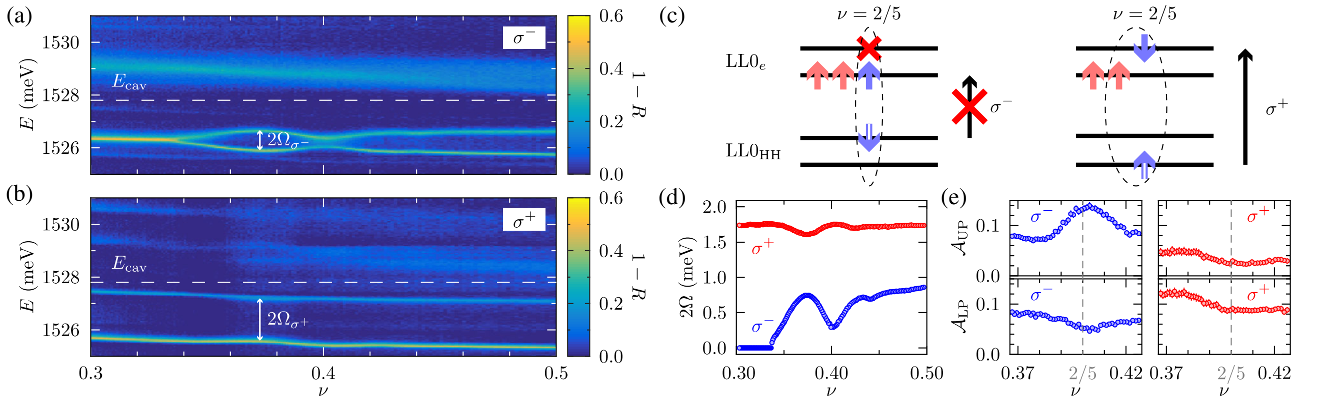

FIG. 3. Cavity spectroscopy of the system in the fractional quantum Hall regime, as we tune B for fixed E_{cav} (white dashed line). Measurement performed with (a) σ^- and (b) σ^+ polarized light. (c) Relevant energy levels and optical transitions around $\nu = 2/5$. Creation of a LL0$_e$-LL0$_{HH}$ electron-hole pair is now possible in both polarizations (blue arrows). Formation of a singlet polaron at $\nu = 2/5$ is nevertheless prevented in σ^--polarization, due to the absence of screening LL0$_e$ electrons of opposite spin. (d) Polariton splitting around $\nu = 2/5$ measured in σ^- (blue) and σ^+ (red) polarizations. (e) Lower polariton ($\mathcal{A}_{LP}$) and upper polariton ($\mathcal{A}_{UP}$) peak areas in σ^- (blue) and σ^+ (red) polarizations (arbitrary units).

singlet X_{att}^{HH} is proportional to the density of $|\downarrow\rangle$ electrons, perfect spin polarization would lead to vanishing cavity coupling. In contrast, promotion of an electron in the $|\downarrow\rangle$ state with σ^+-polarized light always leads to formation of a singlet polaron excitation, with electrons available in the $|\uparrow\rangle$ state, and the polariton splitting is only marginally modified. Figure 3(e) plots the evolution of the polariton peak areas around $\nu = 2/5$. The decrease in polariton splitting in σ^- polarization is accompanied with a loss (gain) of weight of the lower (upper) polariton. This observation is fully consistent with a reduced cavity-polaron coupling strength and a finite detuning between the bare polaron and cavity resonances, ensuring that the lower (upper) polariton has predominantly polaron (cavity) character at $\nu = 2/5$. The absence of a similar oscillator strength transfer in σ^+ polarization on resonance further supports the interpretation of our data in terms of inhibition of σ^- polaron dressing by $|\downarrow\rangle$ electrons at $\nu = 2/5$.

Finally, we address the question of the modification of the polaron-polariton effective mass in the vicinity of $\nu = 2/5$. We use a NA $= 0.68$ lens to excite a broad range of in-plane momenta $k_\parallel$ using the same broadband light-emitting diode. A low NA lens couples the reflected light into a fiber, which enables angle selective measurements. The dispersion relation in Fig. 4(a) at $\nu = 2/5$ clearly shows the anticrossings with X_{att}^{HH} and X_{rep}^{HH}, as pointed out already in Fig. 1(b) [41]. We fit a parabola to the lower polariton dispersion at $\nu = 2/5$ (dashed orange line) and compare it, in Fig. 4(b), to the dispersions measured at filling factors slightly above (green) and below (blue). Strikingly, we find an increase of the effective mass m^* at $\nu = 2/5$ (orange) by a factor of $\simeq 4 \pm 2$ compared to $\nu = 0.42$ (green) and $\nu = 0.37$ (blue) [42]. This observation illustrates further the strong reduction in the oscillator strength of the attractive-polaron resonance. which reduces the cavity character and enhances m^*.

We emphasize that theory of exciton polarons has been previously developed for excitons interacting with a 2DES in the limit $B = 0$ [9,10]. A quantitative modeling of our experiment requires extending prior theoretical work to the case of screening of excitons by electrons occupying a single LL: a significant advance in this direction was the recent development of the theory of exciton polarons in the limit of strong magnetic fields, but without taking into account electron-electron interactions leading to FQH

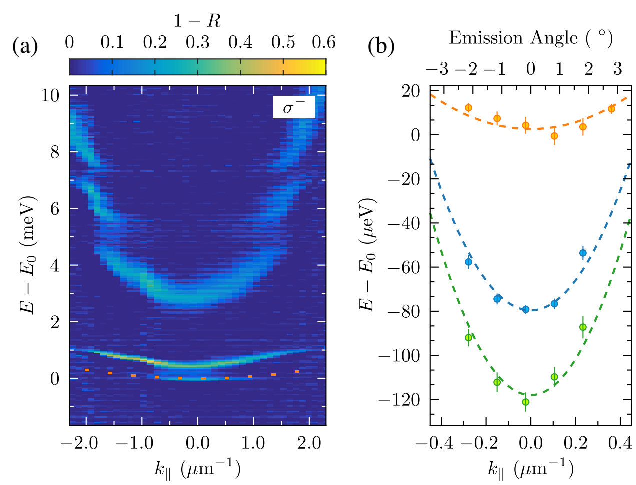

FIG. 4. Polaron-polariton dispersion around $\nu = 2/5$. (a) Cavity spectroscopy at $\nu = 0.4$ for different in-plane momenta $k_\parallel$ (σ^- polarization). The energies are plotted relative to E_0, the energy of the $k = 0$ μm^{-1} lower polariton at $\nu = 2/5$. The flat reflection signal observable between the lower and upper polaritons around $k = 0$ μm^{-1} is an experimental artifact, stemming from an etalon effect in the detection path. (b) Fitted energy of the lower polaron polariton for small $k_\parallel$ at filling factor $\nu = 0.42$ (green), $\nu = 0.4$ (orange), and $\nu = 0.37$ (blue). The error bars are statistical errors from Lorentzian fits of the lower polariton line. Dashed lines show parabolic fits to the lower polariton energies.

states [28]. Our work focused on the singlet channel, which plays a prominent role in the limit of moderate magnetic fields ($B \leq 3.5$ T) used in our experiments. Yet, we expect triplet channels to play a role in determining the full polariton spectrum, particularly at higher B fields relevant for samples with higher electron density. A more challenging problem is exciton-electron interactions in the vicinity of FQH states: polaron-polariton formation in this limit may be described using polariton dressing by fractionally charged quasiparticle hole pairs [43]. The latter problem is related to identification of signatures of incompressibility of the many-body ground state in the polariton excitation spectrum.

On the technical side, we demonstrate that cavity electrodynamics is an invaluable platform to probe fragile fractional states. This could potentially enable optical manipulation of anyonic quasiparticles associated with strongly correlated phases. Furthermore, increasing the quality factor of the cavity could further enhance the sensitivity of our measurements [18]. Finally, we note that injecting σ^- polaritons introduces (optically excited) electrons into the partially filled LL0 and thereby increases ν. Given that the polariton splitting depends on ν, this observation suggests that the system will exhibit a novel form of optical nonlinearity that depends strongly on ν. An interesting open question is if this nonlinearity can be used to enhance polariton-polariton interactions.

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