Resymmetrizing Broken Symmetry with Hydraulic Pressure

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Recent progress in condensed matter physics, such as for graphene, topological insulators, and Weyl semimetals, often originate from the specific topological symmetries of their lattice structures. Quantum states with different degrees of freedom, e.g., spin, valley, layer, etc., arise from these symmetries, and the coherent superposition of these states form multiple energy subbands. The pseudospin, a concept analogous to the Dirac spinor matrices, is a successful description of such multisubband systems. When the electron-electron interaction dominates, many-body quantum phases arise. They usually have discrete pseudospin polarizations and exhibit sharp phase transitions at certain universal critical pseudospin energy splittings. In this Letter, we present our discovery of hydrostatic-pressure-induced degeneracy between the two lowest Landau levels. This degeneracy is evidenced by the pseudospin polarization transitions of the fragile correlated quantum liquid phases near the Landau level filling factor $\nu = 3/2$. Benefitting from the constant hole concentration and the sensitive nature of these transitions, we study the fine-tuning effect of the hydrostatic pressure at the order of 10 μeV, well beyond the meV-level state-of-the-art resolution of other techniques.

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In quantum physics, the conservation laws and energy degeneracies result from various symmetries of the system. For example, inversion and rotational symmetries protect the valley degeneracy, and states with opposite orbital angular momenta are degenerate when time-reversal symmetry exists. Energy subbands, especially their fine structures stemming from the pseudospin degree of freedom (d.o.f.), can be adjusted by symmetry-breaking effects. In 2D systems, the uniaxial strain breaks the rotational symmetry and changes the valley polarization [1–4]; the in-plane magnetic field torques the spin orientation and tunes the Zeeman splitting [5–10]. On the other hand, a moderate hydrostatic pressure of a few kilobars conserves the lattice symmetry and usually has a negligible effect on these d.o.f. [11,12].

Pseudospins are of great importance in the study of many-body systems, as they stabilize multicomponent phases. A strong perpendicular magnetic field $B_\perp$ quantizes the 2D particles' kinetic energy into a set of discrete Landau levels, which gives rise to the integer quantum Hall effect when the Landau level filling factor $\nu = nh/eB$ is close to an integer [13]. At very low temperatures, the Coulomb interaction leads to incompressible fractional quantum Hall states that are usually stable predominantly at odd-denominator fractional $\nu = i + [p/(1 \pm 2pq)]$, where p, q, i are integers [14–17]. These incompressible quantum Hall liquid phases display vanishing longitudinal resistance R_{xx} and quantized Hall resistance R_{xy}. The 2D systems with extra pseudospin d.o.f. have additional sets of Landau levels [1,10,18,19]. When two $N = 0$ Landau levels with different pseudospin flavors approach each other, the multicomponent fractional quantum Hall states form and exhibit pseudospin polarization transitions as the pseudospin energy splitting E_z^* varies [3–10,20–25].

Here, we report an experimental discovery of unexpected pseudospin degeneracy in 2D hole systems (2DHSs) confined in symmetric quantum wells. Our constant-density high-quality 2D systems [Fig. 1(b)] exhibit pronounced fractional quantum Hall states at large hydrostatic pressure P up to about 13 kbar. The isotropic hydrostatic pressure, which only compresses the lattice constant without altering any discrete symmetry, induces sharp phase transitions between states with "digitized" pseudospin polarizations. Our observation suggests that the two lowest Landau levels with opposite pseudospins are nearly degenerate at large hydrostatic pressure $P > 6$ kbar, and their energy separation is no larger than a few μeV.

The two samples used in this Letter are made from the same GaAs wafer grown by molecular beam epitaxy along the (001) direction. The wafer consists of a 17.5-nm-wide GaAs quantum well symmetrically bounded on either side by undoped $Al_{0.3}Ga_{0.7}As$ spacer layers and carbon δ-doped layers. The as-grown density of these samples is $p \simeq 1.6 \times 10^{11}$ cm^{-2}, and the low-temperature ($T \simeq 0.3$ K) mobility is above 100 m^2/V s. Each sample has a van der Pauw geometry, with eight alloyed InZn contacts at the four corners and the middle of the four edges of a 2×2 mm^2 piece cleaved from the wafer. We mount the sample on the epoxy sample stage and fill the pressure cell with oil, see Fig. 1(a). We press the piston at room temperature to apply the hydrostatic pressure. We use an *in situ* tin manometer to measure the low-temperature P via its superconducting transition temperature (~3 K). The commercial high-pressure cell is installed on the sample probe of a Leiden CF-CS81-600 dilution refrigerator. The base temperature of the dilution refrigerator is less than 8 mK, the base temperature of the sample probe is below 25 mK, and the estimated base sample temperature is less than 40 mK. We use a low-frequency (<50 Hz) lock-in technique to measure the transport coefficients.

The magnetoresistances (R_{xx} and R_{xy}) and the $\nu = 4/3$ and 5/3 fractional quantum Hall states' excitation gaps (${}^{4/3}\Delta$ and ${}^{5/3}\Delta$) in Figs. 2(a) and 2(b) highlight our discovery. At small hydrostatic pressure $P \simeq 0.3$ kbar, the fractional quantum Hall states at $\nu = 4/3$ and 5/3 are strong, and the 7/5 and 8/5 states are weak, a signature of being single-component fractional quantum Hall states [17]. When we increase P, the $\nu = 4/3$ state weakens at $P \simeq 2$ kbar and restrengthens at larger $P > 6$ kbar. Meanwhile, the $\nu = 5/3$ state is strong at $P < 2$ kbar. This state weakens monotonically, and ${}^{5/3}\Delta$ saturates at about 1/3 of its low-P value when $P > 6$ kbar. All these transitions take place between 0 and 6 kbar, and we do not see convincing evidence for further evolution as we increase the pressure up to about $P = 12.6$ kbar [26].

A tentative explanation of the above transitions is that the hydrostatic pressure changes the energy separation E_z^* between the lowest two Landau levels. In a periodic lattice without an inversion center, e.g., the zinc blende lattice, the particle's spin orientation relates to its momentum direction through the spin-orbit interaction (SOI), so the spin degeneracy splits [27]. In bulk GaAs, the SOI splits the spin $S = 3/2$ and $S = 1/2$ hole bands at $k = 0$ (the Γ point). The symmetric quantum-well confinement along the (001) (z) direction breaks the translational symmetry. The heavy-hole ($|S, S_z\rangle = |3/2, \pm 3/2\rangle$) subbands become lower in energy than the light-hole ($|S, S_z\rangle = |3/2, \pm 1/2\rangle$) subbands due to their larger effective mass along the z direction. When such a 2DHS is subjected to a strong perpendicular magnetic field $B_\perp$, the holes' orbital motions are quenched into a set of harmonic oscillators. The SOI mixes hole states with different orbital and spin indices, giving rise to a complex set of Landau levels; see Fig. 1(b). The two lowest Landau levels, or the two pseudospins, have predominantly $N = 0$ spatial wave functions but opposite $S_z = \pm 3/2$. The broken bulk inversion asymmetry elevates their energy separation E_z^* through the Dresselhaus effect [27], resulting in fully pseudospin polarized fractional quantum Hall states at $P = 0$.

The pseudospin splitting E_z^* vanishes at large hydrostatic pressure at $P > 6$ kbar, evidenced by the factor of 3 reduction of ${}^{5/3}\Delta$ from its low-P value. Such weakening is expected to happen only when the pseudospins are nearly degenerate. The Fig. 3(b) data, measured from another sample at $P = 6.6$ kbar, confirm this scenario. The fractional quantum Hall effects are weak at odd-numerator fillings $\nu = 5/3$ and 7/5, and they are strong at even-numerator fillings $\nu = 4/3$, 8/5 and 10/7. This reveals that the pseudospins are degenerate, and E_z^* is no larger than a few μeV [4,23,28]. The $\nu = 4/3$ fractional quantum Hall effect weakens and ${}^{4/3}\Delta$ vanishes at intermediate $P \simeq 1.8$ kbar. This result is also consistent with the expected first-order transition between the pseudospin fully polarized and unpolarized phases [3,5,6,20,23]; see Fig. 2(c). It is worth mentioning that we observe reduced spin-band splitting from the low-field Shubnikov–de Haas oscillations as increasing P in both samples. This observation is qualitatively consistent with our high-field findings.

The degeneracy of pseudospins at large P is broken if we tilt the magnetic field away from the highly symmetric (001) direction by an angle θ. In Fig. 3(c), data taken at $\theta = 37°$ and $P \simeq 9.9$ kbar qualitatively reproduce features of the zero pressure data such as the strength of the fractional quantum Hall states: The R_{xx} minima are deep at $\nu = 4/3$ and 5/3 and shallow at $\nu = 7/5$ and 8/5. Note that the effective Landé g factor is finite if the magnetic

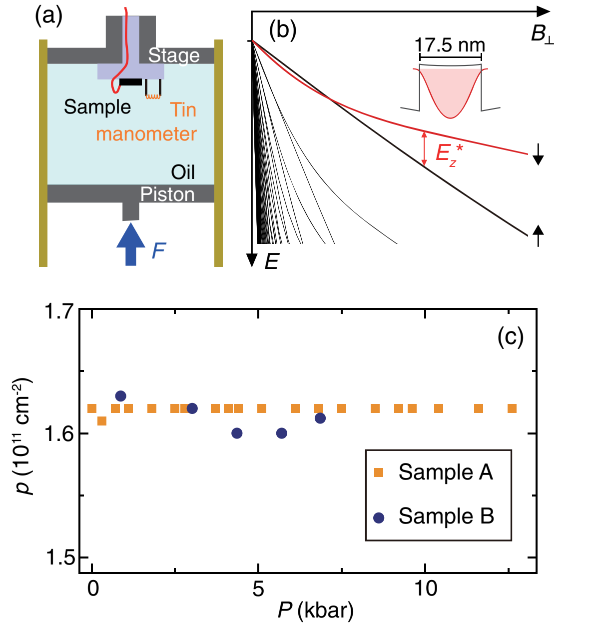

FIG. 1. (a) Experimental setup of the hydraulic pressure cell. (b) Typical Landau level diagram of 2D holes confined in symmetric, narrow quantum wells. Because of the strong SOI, the Landau levels are nonlinear with B. The single-particle wave function of the two lowest Landau levels (the thick black and red curves, which are relevant to our observations) have a predominate contribution from the $N = 0$ harmonic oscillators with $\uparrow$ and $\downarrow$ pseudospins. (c) The measured 2D hole concentration p vs the hydraulic pressure P from both samples. We see almost no density drift in our measurement.

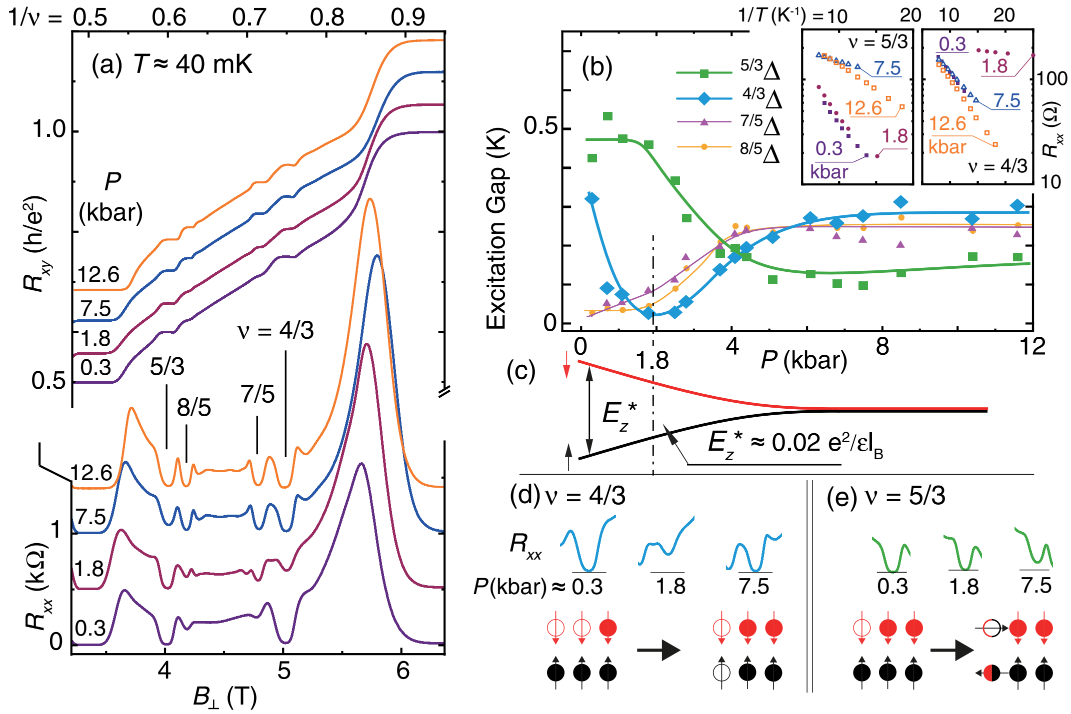

FIG. 2. (a) The longitudinal (R_{xx}) and Hall resistance (R_{xy}) measured from sample A at different hydraulic pressures P. (b) The excitation gap (${}^{\nu}\Delta$) of the $\nu = 4/3$ and 5/3 fractional quantum Hall states, evolving as a function of P, which is consistent with vanishing energy separation E_z^* between the two lowest Landau levels as P increases [see panel (c)]. (d,e) R_{xx} minima at $\nu = 4/3$ and 5/3 at different P and the cartoon charts to explain our discovery. We mark the $R_{xx} = 0$ by the thin horizontal bar. The $\nu = 4/3$ minimum is strong at $P = 0.3$ and 7.5 kbar, corresponding to pseudospin polarized (left cartoon) and unpolarized (right cartoon) fractional quantum Hall states, respectively. The polarization transition appears at $P = 1.8$ kbar, seen as a shallower minimum, when $E_z^* = 0.02(e^2/4\pi\epsilon l_B)$ [21]; l_B is the magnetic length. Meanwhile, the $\nu = 5/3$ state could be ferromagnetic [4]. Its minimum continuously weakens as the state transforms from an $\uparrow$-pseudospin-polarized state into a coherent superposition of the $\uparrow$- and $\downarrow$-pseudospin-polarized states when $\mathcal{E}$ vanishes—the left and right cartoons in panel (e), respectively.

field is not along the (001) and (111) crystal directions. The fact that a tilting magnetic field can split the pseudospin degeneracy indicates that the hydrostatic-pressure-induced degeneracy is rather fragile.

Our study offers a demonstration that the hydrostatic pressure has a direct impact on the subband structure. The transitions seen in our study can provide a semiquantitative estimation of this tuning effect. The quantum Hall effect at

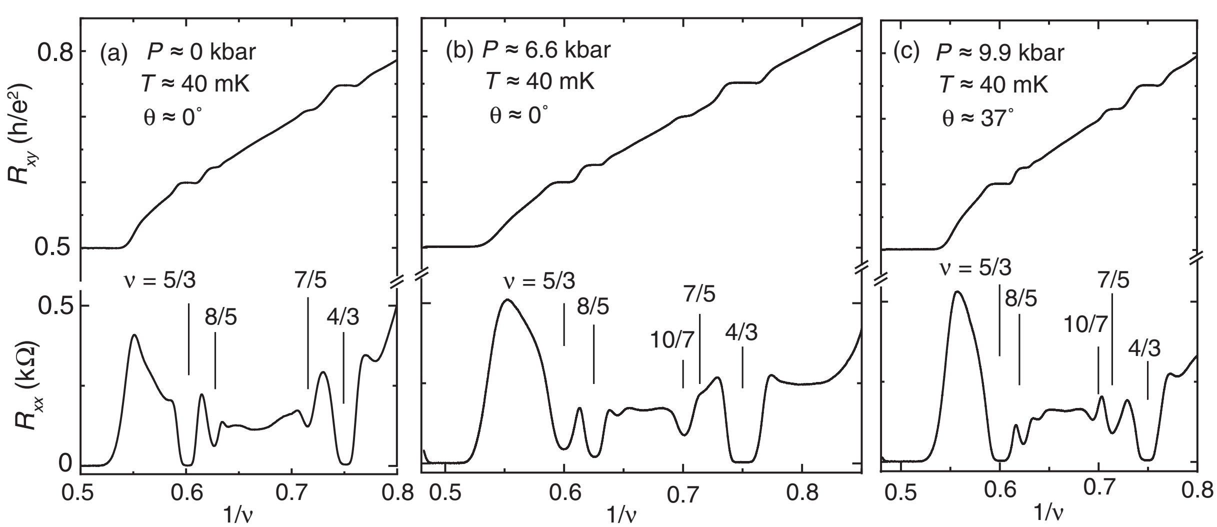

FIG. 3. (a,b) R_{xx} and R_{xy} measured from sample B at $\theta = 0°$ when $P = 0$ and 6.6 kbar, respectively. (c) Data taken at $P \simeq 9.9$ kbar and $\theta \simeq 37°$. Similar to panel (a) data, the fractional quantum Hall states closer to $\nu = 3/2$ have shallower R_{xx}.

$\nu = 4/3$ experiences a pseudospin polarization transition at $P \simeq 1.8$ kbar when E_z^* is $0.02(e^2/4\pi\epsilon l_B) \approx 200$ μeV [3,21], where l_B is the magnetic length. It is only through the sensitive many-body phase transitions that one can probe such fine-tuning effects.

It is unclear how the hydrostatic pressure can induce the pseudospin degeneracy in 2DHSs. To leading order, the isotropic hydrostatic pressure does not vary the lattice geometric symmetries. Since the finite pseudospin splitting E_z^* is primarily caused by the SOI, it is likely that large hydrostatic pressure affects its strength. This effect is extremely challenging to either explore or estimate with other approaches: The angle-resolved photoemission spectroscopy has a state-of-the-art resolution at the sub-meV level [29,30]; first principle theoretical calculations based on many-body perturbation theory, on the other hand, resolve band gaps of at most on the order of 0.1 eV [31–33]. Recent studies in 2D electron systems have seen broken rotational symmetry at large hydrostatic pressure. Unfortunately, the pressure effect tangles with effects caused by carrier density reduction [11,12,34]. Although both samples show weakening of the quantum Hall effect at $\nu = 5/3$, there are differences between data from the two neighboring samples. While the Fig. 3(b) data are perfectly consistent with vanishing E_z^*, the $\nu = 7/5$ fractional quantum Hall state that is expected to be weak appears strong at high pressure in Fig. 2. It is possible that the residue structural asymmetry of the quantum well confinement along the z direction stabilizes this state.

In conclusion, we perform transport measurements on 2DHSs confined in symmetric GaAs quantum wells grown along the (001) direction. By applying isotropic hydrostatic pressure, we discover transitions of fractional quantum Hall states near $\nu = 3/2$ and unexpected pseudospin degeneracy. Because of the zero-density drift, we can easily attribute the induced pseudospin degeneracy to the applied hydrostatic pressure. Our observation is an example in which the interaction-induced many-body states are used to study the 10-μeV-level fine-structure tuning of the underlying materials.

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