Observation of Quantum Hall Valley Skyrmions

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(Dated: January 1, 2022)

We report measurements of the interaction-induced quantum Hall effect in a spin-polarized AlAs two-dimensional electron system where the electrons occupy two in-plane conduction band valleys. Via the application of in-plane strain, we tune the energies of these valleys and measure the energy gap of the quantum Hall state at filling factor $\nu = 1$. The gap has a finite value even at zero strain and, with strain, rises much faster than expected from a single-particle picture, suggesting that the lowest energy charged excitations at $\nu = 1$ are "valley Skyrmions".

PACS numbers: 73.43.-f, 73.21.-b, 71.70.Fk

In a two-dimensional electron system (2DES) with a spin SU(2) symmetry, electron-electron interaction causes a dramatic deviation from the single-particle physics. For example, the large Coulomb energy cost of a spin flip results in a large excitation gap for the $\nu = 1$ quantum Hall state (QHS) even in the limit of zero Lande g-factor. Another consequence of this energy cost is that the charged excitations at $\nu = 1$ have a non-trivial long-range spin order, with a slow rotation of the spin along the radial direction. The size (s) of such a spin texture, or "Skyrmion", is the number of electrons participating in the excitation, and depends on the strain. The larger the Zeeman energy, the less preferable it is for the Skyrmion to form, and s tends to one as the g-factor of the 2DES is sufficiently increased. While in the context of a 2DES a Skyrmion is usually associated with the spin degree of freedom, these excitations should exist in any system whose Hamiltonian has an SU(2) symmetry.

In a 2DES with two equivalent and energy degenerate conduction band valleys, there is a direct analogy between the valley index (isospin) and the electron spin. Indeed, it has been argued that, since rotations in the valley isospin space leave the electron Hamiltonian unchanged, a 2DES with a valley degree of freedom contains a hidden SU(2) symmetry. In a two-valley system, an externally applied strain has the same effect on the valleys as the magnetic field has on the electron spins; the strain breaks the isospin SU(2) symmetry by lifting the energy degeneracy between the valleys. In this Letter, we directly probe the effects of interaction on a 2DES confined to AlAs quantum well where the electrons occupy two valleys. Via the application of symmetry breaking in-plane strain, we tune the energies of these valleys and measure the $\nu = 1$ QHS energy gap. The gap's dependence on strain provides experimental evidence that the excitations of this QHS are valley Skyrmions (valley textures).

AlAs is an indirect gap semiconductor in which the electrons occupy multiple valleys at the X-point of the Brillouin zone. The constant energy surface in bulk AlAs consists of three highly anisotropic ellipsoids (six half-ellipsoids) with their major axes along the <100> crystal directions; we designate these valleys by their major axis' direction. The longitudinal and transverse effective masses of the electrons in these valleys are 1 and 0.2, respectively, in units of the free electron mass. While the valleys in bulk AlAs are energy degenerate, this degeneracy is lifted when the electrons are confined to a 2D layer. In a quantum well grown on top of a GaAs (001) wafer, only the [100] and [010] valleys are occupied for well widths greater than $\sim 5$ nm. This is different from the Si (001) MOSFET (metal oxide semiconductor field-effect transistor), in which the two valleys with the out-of-plane major axes are occupied.

We study 2D electrons in an 11 nm-wide, modulation doped AlAs quantum well grown on a GaAs (001) substrate using molecular beam epitaxy. The electrons are confined to AlAs by two Al$_{0.4}$Ga$_{0.6}$As barrier layers. We inject current into the 2DES through alloyed AuGeNi contact pads and measure the longitudinal resistance on an etched Hall bar mesa aligned with [100]. The sample is cooled in a pumped $^3$He system that allows us to perform measurements in the temperature ($T$) range between 0.3 K and 6 K. The typical mobility of our samples is between 8 and 15 m$^2$/Vs for the electron concentration $n = 2.6 \times 10^{11}$ cm$^{-2}$ at $T = 0.3$ K.

To control the energy splitting between the valleys, we strain the sample by gluing it to one side of a PZT-5H piezoelectric stack (piezo) with the sample's [100] direction aligned with the poling direction of the piezo, as shown in Fig. (a). The voltage-induced strain change of the piezo allows us to in situ and continuously vary the in-plane strain applied to the sample and thereby lift the valley degeneracy. As shown schematically in Fig. (a), by applying tension along the [100] direction, we induce a transfer of electrons from the [100] valley into the [010] valley; the total density of the 2DES, however, remains constant to better than 1%. The single-particle valley splitting, $\Delta E_{v}$, can be expressed in the form $E_{2\pi \times y}$, where $E_{2\pi \times y}$ is the energy of the $2\pi \times y$ state and $\epsilon_{xy}$ is the difference in the strain along [100] and [010]. We determine $\Delta E_{v}$ to within an accuracy of...
Before presenting the experimental data, it is instructive to describe the fan diagram of the AlAs 2DES as a function of strain-induced valley splitting in a non-interacting, single-particle picture [Fig. 1(b)]. The magnetic field perpendicular to the plane of the 2DES quantizes the orbital motion of the electrons and forces them to occupy a discrete set of energy levels separated by the cyclotron energy, \( \hbar \omega_c = \hbar eB/m^* \), where \( m^* = 0.46 \) is the cyclotron effective mass in AlAs [12]. There are four sets of these Landau levels, one for each spin and valley combination. The energy splitting between oppositely polarized spins is controlled through \( \Delta E_z = g_B \mu_B B \) (band g-factor \( g_B = 2 \)), while the levels corresponding to different valleys are separated by \( \Delta E_v \). When \( \epsilon_{xy} = 0 \), in the single-particle picture of Fig. 1(b), the energy degeneracy of the Landau levels associated with different valleys implies that there is no \( \nu = 1 \) QHS. As the applied strain increases and breaks the valley degeneracy, the \( \nu = 1 \) QHS gap (\( 1\Delta \)) develops. For \( \Delta E_v < \Delta E_z \), \( 1\Delta \) should increase linearly with strain and be equal to \( \Delta E_v \). For sufficiently large strains such that \( \Delta E_v \) exceeds \( \Delta E_z \), \( 1\Delta \) should be equal to \( \Delta E_Z \), independent of strain.

The results of our measurements are in sharp contrast to the simple, non-interacting picture described above. Experimentally, we determine \( 1\Delta \) from the activated T-dependence of the longitudinal resistance, \( R_{xx} \), according to \( R_{xx} \sim \exp(-1\Delta/2k_BT) \). This gap is plotted in Fig. 1(c) as a function of \( \Delta E_v \). The measured \( 1\Delta \) differs from the single-particle picture [dashed curve in Fig. 1(c)] in three important aspects: (1) \( 1\Delta \) is finite even when there is no applied strain, (2) rises with the applied strain much faster than expected, and (3) saturates at a value which is closer to \( \hbar \omega_c \) than to \( \Delta E_Z \). As we discuss in the remainder of the paper, these features of the data are all consistent with the many-body origin of \( 1\Delta \) and the presence of valley Skyrmions at small values of strain [10].

Since there are no explicit calculations for the dependence of \( 1\Delta \) on \( \Delta E_v \), we compare our data to the de-
dependence of $\Delta$ on $\Delta E_Z$ in a system which has a spin degree of freedom but no valley degree of freedom [1, 2]. In Fig. 1(d), we show the theoretical prediction for $\Delta$ (solid line) that includes the effects of electron-electron interaction [6]. Even when $\Delta E_Z = 0$, $\Delta$ is nonzero and has a value of 0.63 in units of the Coulomb energy. This is an interaction-induced gap, and rises rapidly as a function of $\Delta E_Z$, with the slope of the $\Delta$ vs. $\Delta E_Z$ curve equal to the Skyrmin size $s$. The qualitative agreement between the theoretical predictions and the measured $\Delta$ in GaAs and AlGaAs 2DESs [filled symbols in Fig. 1(d)] are widely interpreted as evidence for the existence of QHS spin Skyrmions [1, 3]. The striking resemblance between the data of Figs. 1(c) and (d) suggests the presence of QHS “valley Skyrmions” in AlAs 2DESs. With this interpretation, the value of $s$ for the valley Skyrmions in our 2DES is $4.3 \Delta E_v/(e^2/AepB) = 0.01$, comparable to $s = 5$ for the spin Skyrmions in GaAs 2DESs at $\Delta E_Z/(e^2/4AepB) = 0.01$ [3].

In our experiments, as in previous measurements of spin Skyrmions in single-valley systems [1, 2, 4], we find that the measured values for $\Delta$ are only a small fraction of the Coulomb energy, in sharp contrast to the theoretical prediction [see Fig. 1(d)]. The strongly depressed experimental gap for $\nu = 1$ in a non-idealized 2DES is attributed to the combination of the effects of the finite wavefunction thickness along the confinement direction, Landau level mixing, and disorder [1, 17]. In AlAs, the effect of Landau level mixing should be particularly important since the Coulomb energy in our experiment is much larger than the separation between the single-particle energy levels.

We now address whether the spin degree of freedom affects the strength of the $\nu = 1$ QHS in our samples at both large and small values of $\Delta E_v$. In Fig. 1(c) we note that, for large values of $\Delta E_v$, where the electrons occupy only the [010] valley, the measured $\Delta$ saturates at a value that is close to $h\omega_c$ rather than $\Delta E_Z$, contrary to what we would expect from the fan diagram of Fig. 1(b). We have measured this saturation value as a function of the 2DES density (Fig. 2 inset), and we find that it is indeed always close to $h\omega_c$ in our accessible density range. This observation is not surprising. It is consistent with previous measurements [14, 19] which indicate that, thanks to interaction, $\Delta E_Z$ is greatly enhanced in AlAs 2DESs and is indeed larger than $h\omega_c$ for the parameters of our sample. Therefore, in the limit of very large $\Delta E_v$, the nearest single-particle energy level is $h\omega_c$ above the ground state energy. Our data indicate that once $\Delta$ reaches $h\omega_c$, it remains fixed at $h\omega_c$ and no longer shows an enhancement over the single-particle gap.

To further understand the role of electron spin in our 2DESs, and to ensure that our data of Fig. 1(c) are not influenced by the spin degree of freedom, we performed the following experiment. We measured $\Delta$ as we increased the Zeeman energy by tilting the normal of the 2DES by $\theta$ degrees with respect to the magnetic field while keeping the perpendicular component of the field $B_\perp$ (and thus $h\omega_c$) constant [20]. In Fig. 2 we show the measured $\Delta$ for $\theta = 0$ (squares) and $\theta = 46^\circ$ (triangles). We display the data at $\theta = 46^\circ$ shifted by +0.27 meV in $\Delta E_v$ with respect to the $\theta = 0^\circ$ data [21]. As can be clearly seen, $\Delta$ in unaffected by a 43% increase of $\Delta E_Z$. These data thus indicate that the dependence of $\Delta$ on $\Delta E_v$ seen at small values of strain in Fig. 1(c) is primarily a result of the valley interaction and not spin effects.

Our $R_{xx}$ vs. magnetic field data (Fig. 3), taken at various values of strain, reveal additional interesting features. The low temperature ($T = 0.3 \text{ K}$) traces shown in the main figure exhibit several strong QHSs at various fillings, including one at the fractional filling $\nu = 2/3$. The strongest QHS clearly occurs at $\nu = 1$ in the entire range of applied strains, attesting to the robustness of this QHS even in the limit of zero strain. In traces taken at higher temperature ($T = 2 \text{ K}$), plotted in the inset, the $\nu = 1$ minimum is indeed the most prominent feature of the data. The $T = 2K$ data show a weakening of the $\nu = 1$ minimum when the strain is small, consistent with $\Delta$ values of Fig. 1(c). More remarkably, we observe that for small strains there are in fact two minima near $\nu = 1$, one exactly at $\nu = 1$ and the other at a slightly lower field. The side minimum, whose resistance value does not follow a simple, thermally activated behavior, disappears with increasing magnitude of $\Delta E_v$. The appearance of a double minimum near a QHS has been previously associated with a phase transition between two competing QHSs, such as between spin-polarized and unpolarized QHSs at $\nu = 8/5$ [22] or at $\nu = 2/3$ [23] in GaAs 2DESs. We do not know if the double minimum we observe is
a signature of a phase transition in the AlAs 2DES; we note however, that competing states in 2DESs with (spin) SU(2) symmetry have been theoretically suggested [17].

In conclusion, we find that electron-electron interaction strongly modifies the excitations of the υSU(2) symmetry have been theoretically suggested [17].

We thank the NSF for support, and E. Tutuc, S. Sondhi, A. H. MacDonald, and D. P. Arovas for illuminating discussions.

[1] A. Usher, R. J. Nicholas, J. J. Harris, and C. T. Foxon, Phys. Rev. B 41, 1129 (1990).