Simultaneous Excitation of Spins and Pseudospins in the Bilayer \(\nu = 1\) Quantum Hall State

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The tilting angular dependence of the energy gap was measured in the bilayer quantum Hall state at the Landau level filling \(\nu = 1\) by changing the density imbalance between the two layers. The observed gap behavior shows a continuous transformation from the bilayer balanced density state to the monolayer state. Even a sample with 33 K tunneling gap shows the same activation energy anomaly reported by Murphy et al. \cite{1}. We discuss a possible relation between our experimental results and the quantum Hall ferromagnet of spins and pseudospins.

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I. INTRODUCTION

In the \(\nu = 1\) bilayer quantum Hall (QH) state, when both layers have the same electron density and sufficiently close together, interlayer Coulomb interactions can produce a many-body state even in the absence of interlayer tunneling \cite{1, 2, 3}. This collective state is thought to have a broken symmetry, which is viewed as an easy-plane ferromagnet in the pseudospin space. Pseudospin “up” (“down”) refers to an electron in the “front” (“back”) layer. The huge tunneling conductance observed in this collective state is considered as the Goldstone mode of this broken symmetry \cite{4, 5}. Intriguingly, this collective state has a remarkable tilting angular dependence reported by Murphy et al. \cite{1}, which is characterized as a rapid decrease of energy gap before crossing over into a roughly angular independent region. This dependence is explained as a commensurate-incommensurate (CIC) transition \cite{6}, a change in pseudospin ferromagnetic properties of the ground state. The lowest-energy charged excitation has been considered as a pair of pseudospin vortices called meron \cite{7}. In contrast, the monolayer \(\nu = 1\) state is also a broken symmetry ferromagnetic ground state. In this case, the spontaneous ferromagnetic order is in the spin space, which leads to the system possessing an unusual spin excitation known as skyrmion \cite{8, 9, 10, 11}. The energy gap increases with tilting because the Zeeman energy, \(g^* \mu_B B_{\text{tot}}\), is increased \cite{11}. Here \(g^*\) is the gyromagnetic ratio \((g^* = -0.44)\), \(\mu_B\) is the Bohr magneton and \(B_{\text{tot}}\) is the total magnetic field.

II. EXPERIMENTAL RESULT

Samples used in this experiment are GaAs/Al\(_x\)Ga\(_{1-x}\)As double-quantum-well heterostructures grown by molecular beam epitaxy. We used mainly two samples; they both have two 20 nm wide GaAs wells separated by a 3.1 nm Al\(_x\)Ga\(_{1-x}\)As barrier layer. Their tunneling gap \(\Delta_{\text{SAS}}\) are 1 K \((x = 1)\) and 11 K \((x = 0.33)\). We additionally prepared a sample with extremely large tunneling gap. Having the barrier layer thickness of 1 nm and the Al concentration of 0.33, the tunneling gap of this sample is 33 K. A unique feature of these sample structures is that the modulation doping is carried out only on the front side of the double quantum well, and electrons in the other side of the layer is fully field-induced by applying a positive bias to an underlying \(n^+\)-GaAs back gate.

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The total density ($\Delta$) of the magnetic field from the normal line of the sample.

\[ \sigma_t \text{ activation energy at various density differences (a) for } \Delta. \]

In both samples, the activation energy behavior at $\sigma = 0$ transforms into that at $\sigma = 1$ continuously in both samples. The solid thin curves are guides to the eye.

FIG. 1: The angular dependence of the activation energy (a) for $\Delta_{\text{SAS}} = 11$ K and (b) for $\Delta_{\text{SAS}} = 1$ K. It looks like that the behavior at $\sigma = 0$ transforms into that at $\sigma = 1$ continuously in both samples. The solid thin curves are guides to the eye.

This method enables us to control the electron density without deteriorating the mobility \[13\]. The low temperature mobility of all samples is $2 \times 10^9$ cm$^2$/Vs, except for $\Delta_{\text{SAS}} = 33$ K sample $5.4 \times 10^9$ cm$^2$/Vs at electron density $1.0 \times 10^{11}$ cm$^{-2}$.

Measurements were performed with the sample mounted in a mixing chamber of a dilution refrigerator. Standard low-frequency ac lock-in techniques were used with a current of 20 nA to avoid heating effects. A goniometer with a superconducting stepper motor was used to rotate the samples in the magnetic field \[14\]. The activation energy gap $\Delta$ was determined from the temperature dependence of the magnetoresistance $R_{xx} \sim \exp(-\Delta/2T)$.

In Fig. 1 we show the angular dependence of the activation energy at various density differences (a) for $\Delta_{\text{SAS}} = 11$ K and (b) for 1 K. Here $\theta$ is the tilting angle of the magnetic field from the normal line of the sample. The total density ($n_f + n_b$) is fixed to $0.6 \times 10^{11}$ cm$^{-2}$. In both samples, the activation energy behavior at $\sigma = 0$ is substantially the same as the result of Murphy et al. \[13\]. The gaps drop until they reach the CIC transition angle $\theta_c$, and then go into a roughly angle-independent regime. The transition angle $\theta_c$ is 43° for 11 K sample and 27° for 1 K sample. At the monolayer point, the gaps indicate a typical skyrmion-like behavior. The number of flipped spins is approximately 7, according to the method employed by Schmeller et al. \[11\]. Yet the most remarkable results of this measurement is that the energy gaps transform continuously from the balanced point to the monolayer limit. It seems that there is no clear transition from meron-pair excitations to skyrmion excitations. Furthermore, the changes at $\sigma = 0$ and 0.7 in the sample of $\Delta_{\text{SAS}} = 11$ K are somewhat unexpected and yet more noteworthy. They drop before the CIC transition angle, which is not different from $\sigma = 0$, then they start increasing with further tilting. The numbers of flipped spins in the region of starting to increase are 2.4 at $\sigma = 0$ and 2.5 at $\sigma = 0.7$, indicating a possible excitation of skyrmions.

The energy gap of the sample with a large tunneling gap exhibited in Fig. 2 is very intriguing. We expected an increasing behavior because the Zeeman gap $g \mu_B B_{\text{tot}}$ ($\approx 1$ K) is much smaller than the tunneling gap $\Delta_{\text{SAS}}$ ($\approx 33$ K), which affects pseudospins as a 'pseudomagnetic field' \[12\] in the one-particle state. However, the observed angular dependence at the balance point decreases by tilting and shows the characteristic change of the meron-pair excitation.

### III. DISCUSSIONS

Our experimental result is well reproduced by the following equation [Fig. 3]

\[ \Delta(\sigma, \theta) = (1 - \sigma^2)\Delta(0, \theta) + \sigma^2\Delta(1, \theta) + b(\sigma), \]  

(1)

where $\Delta(\sigma, \theta)$ is the activation energy at density difference $\sigma$ and tilting angle $\theta$. Here $\Delta(0, \theta)$ and $\Delta(1, \theta)$ are polynomial fit to the data at $\sigma = 0$ and 1, respectively, while $b(\sigma)$ is a phenomenological bias term. Values of $b(\sigma)$ are described in the figure. Here we show the result of the $\Delta_{\text{SAS}} = 11$ K sample only, but we have obtained substantially the same fitting result for the $\Delta_{\text{SAS}} = 1$ K sample.
Equation (1) indicates two essential points. First, the excitation gap of the meron-pair and that of the skyrmion are proportional to $1 - \sigma^2$ and $\sigma^2$, respectively. Second, a quasiparticle must have the properties of both the meron-pair and the skyrmion at an intermediate value of $\sigma$.

We argue the dependence of the excitation gap on $\sigma$ by studying how the spin and pseudospin stiffnesses depend on it. By increasing $\sigma$ from zero, the effects of the intralayer Coulomb interaction becomes larger in the state dominated by the interlayer Coulomb exchange interactions. Being accompanied by this Coulomb interactions, the spin stiffness $\rho_s$, for being originated in the exchange energy between the spins, increases as $\sigma^2$ because the exchange energy is proportional to the probability of the adjacent electron existance. In contrast, the meron-pair excitation gap becomes smaller since the interlayer Coulomb interaction decreases with increasing $\sigma$. The pseudospin stiffness $\rho_{ps}$ is calculated within the Hartree-Fock Approximation as $\rho_{ps} = (1 - \sigma^2) \rho_E$, where $\rho_E$ is the interlayer exchange stiffness when the layers are balanced. Therefore, the $\sigma$-dependence of the skyrmion excitation gap and the meron-pair excitation gap are expected to be proportional to $\sigma^2$ and $1 - \sigma^2$, respectively.

We also have to consider the enhancement of the direct Coulomb energy concomitant with the excitation. This could be the origin of the term $b(\sigma)$ in equation (1). To suppress this Coulomb energy enhancement at the minimum, both spins and pseudospins must be excited simultaneously. Indeed, our experimental result shows that, in imbalanced density states at $\nu = 1$, the charged excitation carries both the spin and pseudospin components. The reason reads as follows. Let us assume either the meron-pair or the skyrmion is excited. If a level crossing occurs as the sample is tilted, we can argue that it occurs only as in Fig 4. In this case, a naive expectation is that skyrmions and meron-pairs are excited for $\theta < \theta_{cr}$ and $\theta > \theta_{cr}$, with a certain critical value $\theta_{cr}$, respectively. Then the activation energy must be realigned along the solid line in the figure. On the contrary, our experimental result is against a simple level crossing between a skyrmion and a meron-pair excitations. Thus, to realize the experimental curve, it is necessary that there exists a single excitation carrying both spins and pseudospins which is reduced to the skyrmion in the monolayer limit ($\sigma = 1$) and to the meron-pair at the balanced point ($\sigma = 0$). Such a simultaneous flip of spins and pseudospins may be the predicted SU(4) skyrmion in the $\nu = 1$ bilayer QH state.

Finally, the present experiment suggests that pseudospins are excited at $\sigma = 0$ even in a sample with very large tunneling gap [Fig. 2]. An intriguing behavior of this activation energy as a function of the tilting angle in Fig. 4 is yet to be explained.

In conclusion, we measured the tilting angular dependence of the energy gap by changing the density difference in the $\nu = 1$ bilayer QH state. We have found a simultaneous excitation of spins and pseudospins in imbalanced density states.

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