Simultaneous Excitation of Spins and Pseudospins in the bilayer $\nu = 1$ Quantum Hall State

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Introduction

In a bilayer $\nu = 1$ quantum Hall state, when both layers have the same electron density, a characteristic tilting angular dependence of the excitation gap has been reported by Murphy *et al.* [1]. The observed behavior is considered to reflect a change in the pseudospin ferromagnetic properties of the $\nu = 1$ ground state [2], and the excitation attributes to a pair vortices excitation of pseudospins called meron [3]. Pseudospin "up" ("down") refers to an electron in the "front" ("back") layer. In contrast, we see the spin vortex excitation known as skyrmion in a monolayer $\nu = 1$ quantum Hall state [4]. However, bilayer $\nu = 1$ states with different density configuration have scarcely been investigated so far, especially the angular dependence of the energy gap. Thus it is interesting how the energy gap change when there is a density difference between the two layers in the bilayer $\nu = 1$ state.

Results and Considerlations

Samples used in this experiment are double quantum well GaAs/Al_xGa_{1-x}As heterostructures. The sample's tunneling gap Δ_{SAS} is 11 K ($x = 0.33$) and 1 K ($x = 1$), and the mobility is 2×10^6 cm^2/Vs [5]. Throughout this work, the total density was fixed to 0.6×10^{11} cm^{-2}.

In Figure 1, we show the angular dependence of the activation energies Δ at several density differences $\sigma = (n_f - n_b)/(n_f + n_b)$, where $n_f(n_b)$ is the electron density in the front (back) layer. Δ was determined from the temperature dependence of the magnetoresistance $R_{xx} \sim \ln(-\Delta/2T)$. At $\sigma = 0$, we see essentially the same behavior observed in [1] in both samples. The gap drops then turns into a roughly constant regime beyond the transition angle $\theta_c \approx 43^\circ$ for Δ_{SAS}=11K and $\theta_c \approx 21^\circ$ for Δ_{SAS}=1 K. While at the monolayer point ($\sigma = 1$), the gaps increase as we tilt the samples.

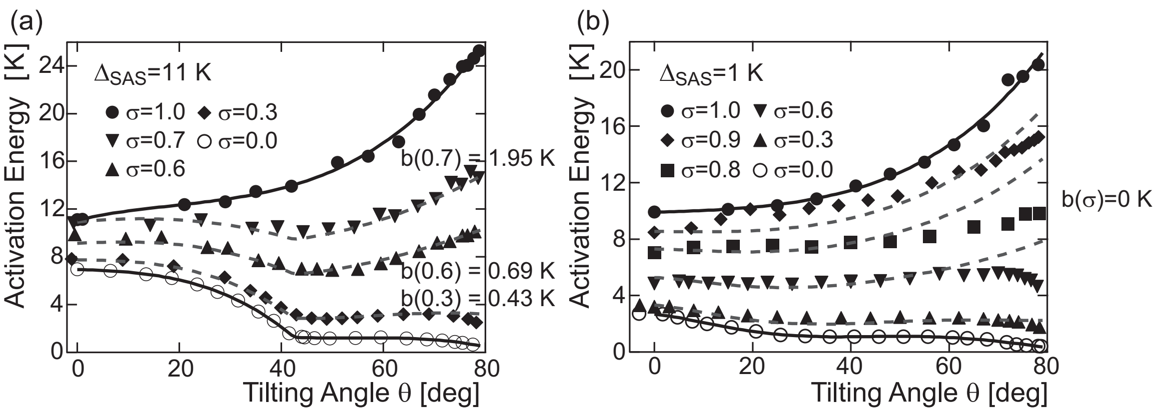

Figure 1: The energy gap as a function of tilting angle θ. (a) is for Δ_{SAS} = 11K and (b) is for 1K. The solid lines are polynomial fitting of the data and the broken lines are obtained curves by the equation (1) in the text.

These changes at $\sigma = 0$ and $\sigma = 1$ are the typical behavior of the meron excitation and the skyrmion excitation respectively. Moreover, we find the energy gap at $\sigma = 0$ continuously transforms to the gap at $\sigma = 1$ as increasing σ, though the angle at which the decrease of gap stops is almost the same as that of $\sigma = 0$ in both samples. In particular, at intermediate density diferences $\sigma = 0.6$ and 0.7 of Δ_{SAS}=11K, the energy gaps increase after the transition angle. This change is inconsistent with a simple level crossing of the skyrmion excitation and the meron excitation as we show in Figure 2.

However, we noticed the following aspect. The overall behavior is well reproduced by a sum of the energy gaps at $\sigma = 0$ and 1 in the ratio of $1-\sigma^2$ to σ^2 in the both samples, that is,

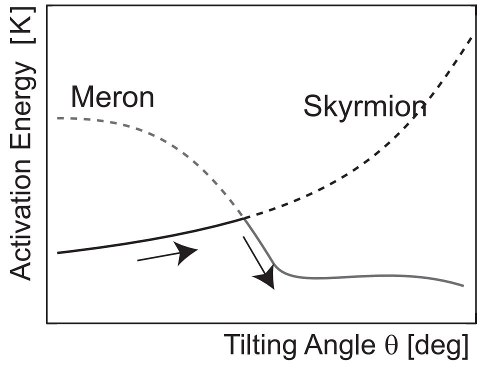

Figure 2: An illustration of a typical level crossing of a meron and a skyrmion excitations. The activation energy is expected to realize along the solid line. Actually, it looks like the experimental results rather trace the dotted line.

$$\Delta(\sigma,\theta) = (1-\sigma^2)\Delta(0,\theta) + \sigma^2\Delta(1,\theta) + b(\sigma) \quad (1)$$

Here $\Delta(\sigma,\theta)$ is the tilting behavior of the activation energy at the density difference σ, and $b(\sigma)$ is for biasing. This formula indicates two essential points. First, the excitation gap of a meron and a skyrmion varies in proportional to $1-\sigma^2$ [6] and σ^2 respectively when we change σ. We consider these σ dependence attributes to the pseudospin and the spin stiffness because the meron and the skyrmion need energy to break their stiffness. Second, at the intermediate σ, the meron and the skyrmion excite simultaneously. In this regime, Coulomb energy affects both spins and pseudospins, hence they excite simultaneously. Therefore the elementary excitation is the compound quasiparticle of a meron and skyrmion. This result may reflect the predicted SU(4) skyrmions in the $\nu = 1$ bilayer quantum Hall state [7].

Conclusion

To summarize, we have presented an experimental result of the angular dependence of the energy gap in the bilayer $\nu = 1$ quantum Hall state. At intermediate σ state, the change in the energy gap is described by a sum of the gap at $\sigma = 0$ and $\sigma = 1$ in the ratio of $1-\sigma^2 : \sigma^2$. We conclude that the excitation in this state is a simultaneous excitation of the pseudospins and the spins, that is, the compound quasiparticle of a meron and skyrmion.

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