Majorana fermions and non-Abelian anyons in a Kitaev quantum spin liquid

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Quantum spin liquid (QSL) is a novel state of matter that lacks long-range magnetic order all the way down to zero temperature while possesses some special patterns of quantum mechanical entanglement. The long-standing experimental challenges associated with the identification of the QSL state is the detection of fractionalized excitations, which are signatures of topological order inherent to the QSL. Recently, the Kitaev spin model of insulating magnets on two-dimensional (2D) honeycomb lattice has attracted interest, as it hosts a QSL where quantum spins are fractionalized into Majorana fermions.[1] In magnetic fields, the emergence of Majorana edge current and non-Abelian anyons in the bulk is predicted to manifest itself in the form of thermal quantum Hall effect, a feature discussed in topological superconductors and even-denominator fractional quantum Hall state. Here we report on thermal Hall conductivity κ_{xy} measurements in α-$RuCl_3$, a candidate material for Kitaev QSL on a 2D honeycomb lattice.[2,3] In magnetic field perpendicular to the 2D honeycomb planes, positive κ_{xy} develops in a spin-liquid state below the temperature characterized by the Kitaev interaction $J_K/k_B \sim 80$ K, demonstrating the presence of highly unusual itinerant excitations. Although the zero-temperature property is masked by the antiferromagnetic (AFM) ordering at $T_N = 7$ K, the sign, magnitude, and T-dependence of κ_{xy} at $T_N < T < J_K/k_B$ follows the predicted trend of the itinerant Majorana fermion excitations.[2] The application of a tilted magnetic field suppresses the AFM order, leading to a field-induced QSL ground state. In this QSL state, the 2D thermal Hall conductance per honeycomb plane κ_{xy}^{2D}/T shows a plateau behavior as a function of applied magnetic field and has a quantization value of $(\pi^2/6)(k_B^2/h)$, which is exactly half of κ_{xy}^{2D}/T in the integer quantum Hall state and conventional odd-denominator fractional quantum Hall state that hosts Abelian anyons.[4] We also show that the half-integer thermal Hall plateau is observed even when the magnetic field is applied parallel to the 2D plane. In addition, the topological Chern number determined by the sign of the quantized thermal Hall conductance is consistent with that expected in the Kitaev QSL.[5] These results provide strong evidence of topologically protected chiral currents of charge neutral Majorana fermions at the edge and and non-Abelian anyons in the bulk of the crystal.[3] Above a critical field, the quantization disappears and κ_{xy}^{2D}/T goes to zero rapidly, indicating a topological phase transition.

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