

E-3 Quantum Hall Effect

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THE QUANTUM HALL EFFECT

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first experiment: II

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LEARNING GOALS

- Understand how Landau levels contribute to quantization of transverse resistivity for a GaAs/AlGaAs sample in high magnetic fields.
- Measure the quantized Hall resistance $R_H = h / ne^2$ of a 2D electron gas at low temperature.
- Observe minima in longitudinal conductivity at magnetic fields where Hall plateaus occur.
- Learn low-temperature techniques.
- Handle cryogenic liquids safely.

INTRODUCTION

The integer quantum Hall effect (http://en.wikipedia.org/wiki/Quantum_Hall_effect) was discovered in 1980 by Klaus von Klitzing (http://en.wikipedia.org/wiki/Klaus_von_Klitzing), who won the Nobel prize for his discovery shortly afterward. He found that the Hall resistance of a two-dimensional electron gas (2DEG) in a Si MOSFET at liquid helium temperatures was accurately quantized for certain ranges of magnetic field in steps with values determined entirely by fundamental constants: $R_H = h/ne^2$, where h is Planck's constant, e is the electronic charge, and n is an integer. The accuracy of this quantization was found to be quite remarkable: better than 1 part in 10^6 . This discovery was reproduced shortly afterward in more nearly ideal 2D electron gases in GaAs/AlGaAs heterostructures. At low temperatures $T < 1$ K, the form of the Hall and magnetoresistance in high mobility GaAs samples is quite remarkable: the Hall resistance increases with magnetic field in a series of steps, accurately quantized at values $R_H = h/ne^2$, and the magnetoresistance accurately falls to zero at the centers of each step and oscillates to non-zero values between steps. In 1982, shortly after von Klitzing's original discovery, the fractional quantum Hall effect was discovered for the 2DEG in GaAs/AlGaAs heterostructures by Stormer (http://en.wikipedia.org/wiki/Horst_Ludwig_Stormer), Tsui (http://en.wikipedia.org/wiki/Horst_Ludwig_St%C3%B6rmer), and Gossard. For the fractional effect, the magnetic field dependence of the Hall resistance and the magnetoresistance is very similar to that described above, but steps also occur at fractional values of the filling factor $n = p/q$, where p and q are integers and q is odd.

One can understand the structure of the Hall and magnetoresistance for both the integer and fractional quantum Hall effect according to the following picture, due largely to Prof. Halperin (<http://www.physics.harvard.edu/people/facpages/halperin.html>) here at Harvard. We start with the integer effect. The energy of electrons in a 2D electron gas in a strong magnetic field is completely quantized into Landau levels with energies $E_\ell = \ell h\omega_c$, where $\omega_c = eB/mc$ is the cyclotron frequency. For a perfect gas at temperatures much lower than the Landau level spacing $k_B T \ll h\omega_c$, the electron gas is degenerate, and the Fermi level must lie on one of the Landau levels. The number of filled Landau levels in this simple picture is called the filling factor n . Real samples always possess disorder, which creates localized quantum states with energies between Landau levels. As one changes the magnetic field for a given sample, the Fermi level makes regular transitions between Landau levels, and passes through these regions of localized states. When the Fermi level lies in a region of extended states on a Landau level, scattering occurs just as for normal metals, giving rise to resistance. However, when the Fermi level lies in a region of localized states between Landau levels, scattering is completely suppressed at sufficiently low temperatures, and the magnetoresistance goes to zero. One might naively think that the sample was somehow like a superconductor, but this is not true. What happens is that the electron current density J is everywhere exactly perpendicular to the electric field E , so that the component of electric field parallel to J , which is measured in the magnetoresistance is exactly zero. [The average motion of a charged particle with no scattering in crossed electric and magnetic fields is a simply a drift with velocity $v_d = cE/B$ in the direction perpendicular to both \vec{E} and \vec{B} ; see Jackson, Classical Electrodynamics, for example]. This description explains why the magnetoresistance falls to zero on Hall steps.

The Hall voltage is determined by the perpendicular component of the electric field E in an applied field B perpendicular to the electron gas layer. From elementary theory one can easily show that the Hall resistance for a 2DEG is $R_H = h/ne^2$, with the filling factor n a real number equal to the number of filled Landau levels plus the fractional filling of the highest level. When the Fermi level lies between Landau levels, n is approximately equal to an integer in this simple picture. The surprising fact, which was not anticipated before von Klitzing's discovery, is that n is *exactly* an integer when the Fermi level lies in a region of localized states; this integer is just the number of filled Landau levels below the Fermi energy. Thus when the Fermi level lies in localized states between Landau levels in a magnetic field sweep, the Hall voltage is fixed, creating the Hall steps described above.

The integer quantum Hall effect is a single-particle phenomenon. By contrast, the fractional quantum Hall effect is a collective phenomenon for which Coulomb interactions between electrons are essential. The structure of fractional quantum Hall effect data is similar to that for the integer effect, and can be understood according to a picture similar to that given above, in which the Fermi level passes through a gap between the energies of allowed quantum states. For the integer effect this gap is just the separation between Landau levels. For the fractional effect the energy gap is created by the condensation of electrons into a new type of collective electronic state. Thus, while the form of the data for the two effects is very similar, the physical origins are quite different. The theory of the fractional quantum Hall effect has been developed by R. Laughlin and by B. Halperin, among others.

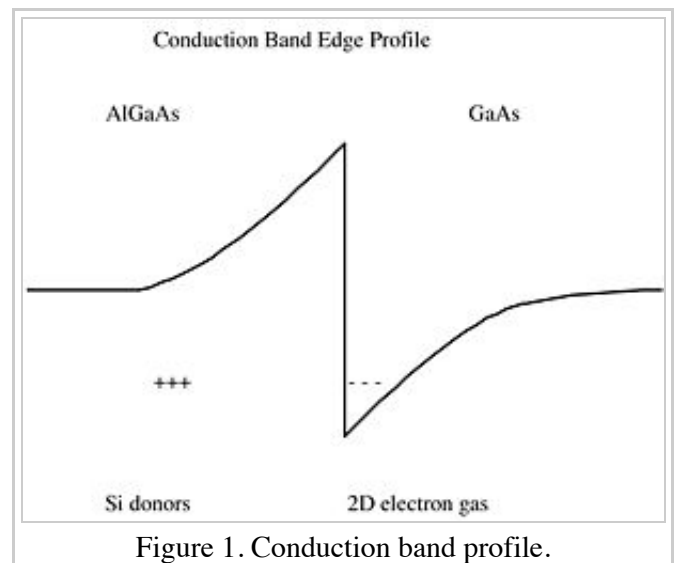
In this experiment, you will measure the integer quantum Hall effect for the 2D electron gas in a GaAs/AlGaAs heterostructure.

APPARATUS

- GaAs/AlGaAs two-dimensional electron gas sample
- Liquid He Dewar with vacuum pump and gauges
- 5 tesla superconducting solenoid
- High current power supply and ramp generator
- Lockin amplifiers (two) with built-in oscillator
- Sine-wave voltage source
- Series resistors in Pomona boxes
- Computer-based dual XY recorder
- Oscilloscope
- Multimeter

The sample for this experiment is a GaAs/AlGaAs heterostructure grown by molecular beam epitaxy (MBE). In the MBE process a crystal is grown one atomic layer at a time in an ultrahigh vacuum system; the alloy composition can be changed during growth by uncovering shutters in front of separate Ga, As, Al, and Si sources. Silicon forms a donor in $Al_xGa_{1-x}As$ and is used as a source of electrons. Because the conduction band edge in the random alloy $Al_xGa_{1-x}As$ increases linearly with Al content x , this growth technique can be used to create a wide variety of conduction band profiles along the growth direction, for example square wells and superlattices.

The conduction band profile for the sample used in this experiment, shown below, is a step created by growing an undoped $Al_{0.3}Ga_{0.7}As$ barrier on top of a high mobility layer of pure GaAs. Electrons are introduced by doping the AlGaAs barrier with Si in a layer set back from the GaAs by 200 Å. Electrons from these donors flow into the GaAs region in order to lower their energy and form a 2D electron gas at the GaAs/AlGaAs interface. The total potential shown is the sum of the step in the conduction band edge and the electrostatic potential created by separating the electrons from the ionized donors. The combined trick of using a step in the conduction band edge profile with remote doping was developed in the early 1980's to produce 2DEG's with extremely high mobility.



The sample is rectangular, approximately 3 mm x 5 mm.

Six electrical contacts are made to the sample; these are available at the box with BNC connectors on the lab bench. Pinouts are in the Bench Notes. Voltage measurements are made using a 4-contact technique to minimize the effects of contact resistance. For magnetoresistance measurements, voltage contacts on the same side of the bar are used, and for Hall measurements, voltage contacts on opposite sides are used.

The sample is mounted inside a superconducting solenoid inside a liquid He Dewar. When the Dewar is warm before you start the experiment, ask one of the laboratory assistants to remove the Dewar insert, and inspect the sample and superconducting solenoid. *Do not touch the sample or any of the electrical leads: they are very delicate and easily damaged.* The sample should be located roughly halfway down inside the superconducting solenoid, inside a protective ring.

The Dewar will have been precooled with liquid nitrogen when you arrive in lab. Ask one of the lab assistants to help you cool the Dewar with liquid helium. Before you transfer helium for the first time, read Appendix 4 (https://coursewikis.fas.harvard.edu/phys191r/How_to_Transfer_Liquid_Helium) carefully and watch the Liquid Helium Transfer Video (<http://stream.fas.harvard.edu/ramgen/permanent/physics190r/LiquidHeliumTransfer.rm>). The transfer procedure is sketched below. First remove all of the nitrogen by overpressuring the Dewar through the small vacuum manifold with nitrogen or helium gas to blow the nitrogen out through the stainless tube provided for that purpose. Make sure that the tube is inserted all the way to the bottom of the Dewar. Next flush the inside of the Dewar with helium gas by first pumping out the inside to a good vacuum (<1 Torr on the pressure gauge) then filling the Dewar with warm He gas through the small manifold. If there is still liquid nitrogen left in the Dewar, you will not be able to get a good vacuum. From this point on, be careful not to admit air into the Dewar, because it will freeze onto the various components inside and cause trouble. Finally, fill the Dewar with liquid He, using the insulated transfer tube. First flush out the transfer tube with warm He gas. Then insert the tube into both the Dewar and the storage Dewar, and transfer liquid by pressurizing the storage Dewar slightly. You should use 0.25psi until the Dewar starts to fill with helium, then you can increase the pressure to about 1 psi. You can tell when the Dewar starts to fill, because the blow off rate of helium gas will slow considerably. Stop transferring when the Dewar is full, as indicated by the helium level gauge. Remove the transfer tube from both Dewars and immediately close the tops of both the experiment and storage Dewars to prevent air from entering and freezing.

The magnetic field in this experiment is accurately controlled by the current through the superconducting solenoid. For the AMI 5 tesla solenoid used in this experiment, the constant relating current and field is: $B(\text{tesla}) = .1172 \times I(\text{amps})$ and the maximum rated current is 42.7 amps at 4.2 K. [Note that there is a 12 to 15% increase in the critical current by cooling to 2 to 1.5 K. Thus, when pumping below 2 K, the current may be run up to 47 amps if (and only if) there is at least 10% registered on the helium level gauge (so that there is enough helium to absorb the energy in case of a quench).] The magnet current is monitored by measuring the voltage across a 1 m Ω series resistor.

An interface box which includes a ramp controller regulates the output from the 50 Amp Hewlett Packard power supply. The controller is integrated with the LabVIEW virtual instrument (vi) called qh2.vi, which also acts as a dual XY recorder (Figure 2-1). See the figure below for more information. A potentiometer (Figure 2-2) in the interface box programs the HP current output remotely. A small dc motor (Figure 3-3) rotates the potentiometer under control of the LabVIEW vi. Do not try to move the motorized potentiometer by hand. The software allows you to hold the magnet current at a fixed value, sweep up, or sweep down slowly at a fixed rate. Turn the vi and interface box on before the power supply, and turn them off after the power supply. The

potentiometer knob must read zero before the power supply is turned on or off. If the power supply is ever on while the controller is off, it can suddenly apply a large current to the magnet and possibly cause damage. The green LED (Figure 2-4) indicates zero current.

Because the inductance L of the magnet is very large, it can generate a substantial voltage $V = -L(di/dt)$ during sweeps. Keep the sweep rate (di/dt) slow to minimize this back EMF. Typical sweep time is on the order of 100 sec. Never disconnect the current leads with current flowing through the magnet, or you risk damage to the apparatus and possibly to yourself from the high voltages generated.

LabVIEW vi (qh2.vi)

qh2.vi ramps the magnetic field and records analog data from the lockin amplifiers. The user sets the maximum magnet current and controls the sweep direction.



Figure 2. Quantum Hall interface panel.

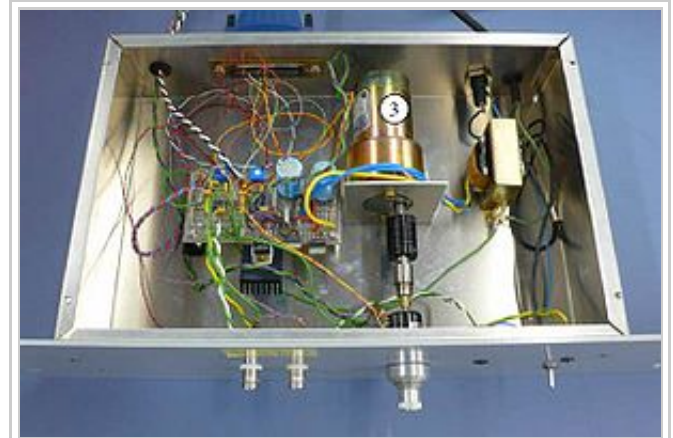


Figure 3. Quantum Hall interface circuit.



Figure 4. LabVIEW vi.

- (Figure 4-1). Control # 1, sets the maximum magnet current.
- (Figure 4-2). SWEEP RATE control is the voltage applied to the dc motor that rotates the current-controlling potentiometer. Due to static friction, voltages below about 2 V cause no rotation. The maximum recommended sweep rate is achieved at 5 V.
- (Figure 4-3). Control # 3 sets the time interval at which the analog voltage inputs are sampled.
- (Figure 4-4). Indicators # 4 display the latest values of the analog input voltages, the programmed magnet current and actual magnet current. Programmed current is derived from the voltage across the motorized potentiometer. Actual current comes from the 1 m Ω series resistor. The difference is displayed on the analog meter below. The LR time constant of the magnet with its 2 Ω parallel resistance causes hysteresis.
- (Figure 4-5). SWEEP CONTROL works in conjunction with SWEEP RATE, control # 2. The numeric value of SWEEP RATE is multiplied by +1 or -1 for increasing or decreasing sweep, or zero to hold the current. The indicator displays the voltage applied to the motor.
- (Figure 4-6). Indicators #6 are part of the magnet safety system. qh2.vi should never terminate while there is current flowing in the magnet nor should it rotate the potentiometer unless the HP power supply is on. The CURRENT ZERO? LED turns green when the magnet current decreases below a threshold, typically 50mA. This allows the STOP button (above # 5) to terminate the program. The HP On indicator uses a voltage internal to the HP power supply to sense whether it is powered on.
- (Figure 4-7). In order to save data to a text file, the SAVE DATA? switch must be set to YES BEFORE

- running the program.
- (Figure 4-8). Graphs # 8 display the two analog inputs as functions of magnet current.
- (Figure 4-9). Graph # 9 shows magnet current as a function of time.

Temperature Control

The temperature of the sample is controlled via the vapor pressure of He gas over the liquid. At atmospheric pressure, liquid He boils at $T = 4.2\text{K}$. The liquid He bath can be cooled via evaporation by reducing the He gas pressure over the liquid using a vacuum pump. The temperature of the He bath is then determined from the saturated vapor pressure measured with a pressure gauge using tables from the AIP handbook. To hold the temperature of the sample at 4.2K simply allow the He gas to boil out of the overpressure vent at the top of the Dewar. To cool below 4.2K, make sure all openings on the top of the Dewar are closed, and then pump down through the mechanical pressure regulator. This pressure regulator works like those on gas cylinders: to increase the pressure you turn the knob clockwise. Start with the knob turned fully clockwise near atmospheric pressure, then cool down slowly by turning the regulator knob counter clockwise in increments, waiting after each step for the pump to cool the bath down to the new lower temperature. When the desired temperature is reached, leave the knob as it is and the pressure will be regulated at the present value. The total time required to cool down from 4.2K to 2.0K should be at least 20 min, or you will waste liquid He. To raise the temperature, turn the regulator knob clockwise to increase the pressure. This will initially stop the flow of gas completely and the temperature of the bath will drift upward due to residual heating. To increase the pressure of the bath to atmospheric pressure at the end of a run, one can slowly admit He gas through the small manifold over a period of several minutes. Never allow air or any gas other than He inside the Dewar, or it will freeze and cause trouble.

EXPERIMENTAL PROCEDURE

Hook up the electronics to the sample, using the cable ending with a box with BNC connectors. Current bias the sample using a current source constructed from a sine wave voltage source and a relatively large series resistor in a Pomona box (typically $1\text{ M}\Omega$). The low end of the current source should be grounded. One can easily wire the circuit by connecting the Pomona box to the BNC output of the sine-wave source, and connecting the BNC output of the Pomona box to the BNC for the I+ current lead of the sample using a BNC cable, and placing a shorting BNC cap on the I- current lead to complete the circuit. Connect both inputs of the lockin amplifier to two voltage leads along one side of the sample for magnetoresistance measurements, or to two voltage leads on opposite sides of the sample for Hall measurements. Optionally, two lockins can be used at the same time to measure Hall voltage and magnetoresistance simultaneously. To avoid heating or damaging the sample, you should adjust the measuring current to be less than $10\ \mu\text{A}$ which will produce voltages less than $\sim 0.1\text{ V}$. Connect the analog output(s) of the lockin amplifier(s) to the vertical (Y) axis (axes) of the XY recorder. Note that the lockin analog output will be 10 V for full-scale deflection. It is important to note the lockin scale to convert the measurements into actual sample voltages. The horizontal (X) axis input is connected across the $1\text{m}\Omega$ series resistor internally in the control/interface box. A National Instruments multifunction interface card (PCI-6011E also known as PCI-MIO-16XE-50, NI part number 777385-01) is used to record the data.

Classical Hall effect: First measure the electron concentration and mobility using the classical Hall effect at low magnetic fields $B < 1$ tesla. See Kittel, Introduction to Solid State Physics for a discussion of the classical Hall effect.

Shubnikov de Haas oscillations: Because the energy levels of the 2D electron gas are quantized in a magnetic field, the magnetoresistance oscillates with increasing magnetic field, as Landau levels pass through the Fermi

surface (see Kittel, Introduction to Solid State Physics, for a good discussion of the physics). These oscillations are periodic in $1/B$, and the period is determined by Fermi wavevector in zero field, and thus the carrier concentration. Compare your results for the electron concentration using these two methods. Shubnikov de Haas oscillations are generally a more reliable measure of the carrier concentration than the classical Hall effect.

Quantum Hall Effect: Measure the quantum Hall effect at 4.2 K by making magnetoresistance and Hall sweeps over the full range of magnetic field available $B = 0$ to 5 tesla. It is convenient to adjust the XY recorder so that sweeps for the magnetoresistance and Hall resistance overlap with the same origin. Repeat your measurements at the lowest temperature available, for which the Hall steps should be wider and the resistance minima deeper. One can investigate several different aspects of the quantum Hall effect:

- 1) How accurate is the quantization of the Hall resistance $R_H = h / ne^2$, when compared with the known values of h and e ?
- 2) How accurately does the magnetoresistance approach zero in the center of a Hall step?
- 3) How can one understand the relative sizes of Hall steps at different filling factors n ?
- 4) What is the temperature dependence of the resistance minima at different fields?

PAPER

In your paper, include XY recorder data for the classical Hall effect, Shubnikov de Haas oscillations, and the quantum Hall effect. For the Shubnikov de Haas data find the position of minima of the resistance oscillations and make a plot of $1/B$ vs. n for the n^{th} position to extract the period in $1/B$. Make a table comparing your measurements of the electron concentration from the Hall effect and the Shubnikov de Haas oscillation data and comment on any differences. For the quantum Hall effect describe the measurements you made, and show whatever data is appropriate. Be careful to analyze the sources of experimental error in your measurements, including possible sources of systematic errors, especially for the measurements of the accuracy of the quantum Hall effect.

NOTES

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BENCH NOTES

- Liquid Helium: Pressure (mTorr) vs. Temperature (K) (http://www.fas.harvard.edu/~phys191r/Bench_Notes/pt.txt)
- The 1958 Helium-4 Scale of Temperatures (P vs. T for lHe4) (http://www.fas.harvard.edu/~phys191r/Bench_Notes/HeScale.pdf)
- Liquid Helium Transfer Video (<http://stream.fas.harvard.edu/ramgen/permanent/physics190r/LiquidHeliumTransfer.rm>)
- Appendix 4: How to Transfer Liquid Helium (http://www.fas.harvard.edu/~phys191r/pdf/ap4_09.pdf)
-
- **Helium Transfer Quick Checklist**
- 1. Remove liquid nitrogen
- 2. Remove liquid nitrogen residue
- 3. Measure level in storage dewar
- 4. Precool transfer tube
- 5. Transfer helium into cryostat
- 6. Remeasure level in storage dewar
-

THERMOMETER PINOUT

diode function -- amphenol connector -- white cable -- DRC80 controller 5-pin connector

I+	A	red	E
I-	B	black	D

V+	H	clear	A
V-	D	green	B

- Precision Cryogenics Cryostat (http://www.fas.harvard.edu/~phys191r/Bench_Notes/E3/Cryostat.pdf)
- Liquid Helium Level Meter (http://www.fas.harvard.edu/~phys191r/Bench_Notes/E3/HEmeter.pdf)
- Model 179A Multimeter (http://www.fas.harvard.edu/~phys191r/Bench_Notes/E3/Keithley179.pdf)
- Interface Card Pinout (http://www.fas.harvard.edu/~phys191r/Bench_Notes/E3/NIpinout.pdf)
- Interface Card Catalog Entry (http://www.fas.harvard.edu/~phys191r/Bench_Notes/E3/nicardspecs.pdf)
- Interface Card Specifications (6011E)
(http://www.fas.harvard.edu/~phys191r/Bench_Notes/E3/6011e.pdf)
- Power Buffer Specifications (LT1010)
(http://www.fas.harvard.edu/~phys191r/Bench_Notes/E3/LT1010.pdf)
- Model 400A Magnet Controller
(http://www.fas.harvard.edu/~phys191r/Bench_Notes/E3/MagnetController.pdf)
- Magnet Power Supply (http://www.fas.harvard.edu/~phys191r/Bench_Notes/E3/MagnetPwrSupply.pdf)
- Sample Connections (http://www.fas.harvard.edu/~phys191r/Bench_Notes/E3/SampleConnection.pdf)
- SR510 Lock-in Amplifier (http://www.fas.harvard.edu/~phys191r/Bench_Notes/SR510.pdf)
- Model DRC-80 Cryogenic Thermometer
(http://www.fas.harvard.edu/~phys191r/Bench_Notes/E3/Thermometer.pdf)
- Model 21 Wavetek Function Generator
(http://www.fas.harvard.edu/~phys191r/Bench_Notes/E3/wavetek21.pdf)
- Dell Optiplex 980 Technical Guide (http://www.fas.harvard.edu/~phys191r/Bench_Notes/optiplex-980-tech-guide.pdf)

PHOTOS



magnet, side view



magnet, end view



sample holder assembly



sample holder



sample holder closeup

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