A Tabletop Measurement of the Quantization of Electrical Conductance in Gold Nanowires

David Tam, Kiyohito Iigaya, Morgan May

E.K.A. Advanced Laboratory, Columbia University Department of Physics, New York, NY

Introduction

At a quantum point contact, electrons flow ballistically (without scattering) rather than diffusively. When a potential is applied, the electronic transport can be modeled as modes in a waveguide, such that only quantized values of current are allowed. The total current is a sum of these noninteracting modes. As the size of the contact is diminished, fewer modes are admitted, until only a single mode is observed. The quantization value of conductance is given by the Landauer formula,

$$G_0 = \frac{I}{\Delta V} = \frac{2e^2}{h}\,,$$

with e the charge of an electron and h Planck's constant. The factor of 2 arises from the spin degeneracy of modes.

We report on a successful implementation of a teaching laboratory at the advanced undergraduate level. Working for several hours every Friday afternoon, groups of two students typically take 4-6 weeks to complete the experiment. The first two weeks are spent familiarizing themselves with preparing the apparatus and collecting sample datasets. After they fabricate their own gold contact, the following weeks are devoted to taking and analyzing data.

Facilities

A student operates the thermal evaporator in the Columbia University Clean Room.

Clean Room Performing this experiment is extremely useful to students at the advanced undergraduate level because it brings them into actual research facilities. One part of the gold contact is made in the Columbia University Clean Room, a 3000-square foot shared space with a large array of state-of-the-art equipment. Exposing students to the Clean Room introduces them to many active areas of nanoscience research that are being conducted at the university, and is therefore of great pedagogical value unto itself.

In The Laboratory The remainder of the work is carried out back in the E.K.A. Advanced Laboratory, where the students have an opportunity to learn important concepts and techniques. Introduced in this lab are:

- Measurement devices with exceptional sensitivity
- Vibration isolation
- Protection of equipment against static electricity
- Computer-controlled data acquisition
- Appreciation for the delicacy required in sample preparation
- Noise and how to overcome its effects
- Statistical analysis
- A laboratory that is driven by experimental techniques, not complicated theoretical descriptions

Preparing the Gold Contact

Making Gold-Plated Wafers The gold contact is made between a dangling wire above and a gold-coated mica substrate below. The mica is plated by thermal evaporation, which takes place in the Clean Room. Students pump out a bell jar to high vacuum ($\leqslant 10^{-5}$ Torr, generated with an automated turbomolecular pump). When current is passed through a tungsten boat, a sample of ultrapure gold is heated to the point of vaporization. The gold evaporates onto the inner surface of the vacuum chamber, coating the mica wafers. Using a properly-arranged deposition monitor, the students plate the samples to a thickness of approximately 100 nanometers.

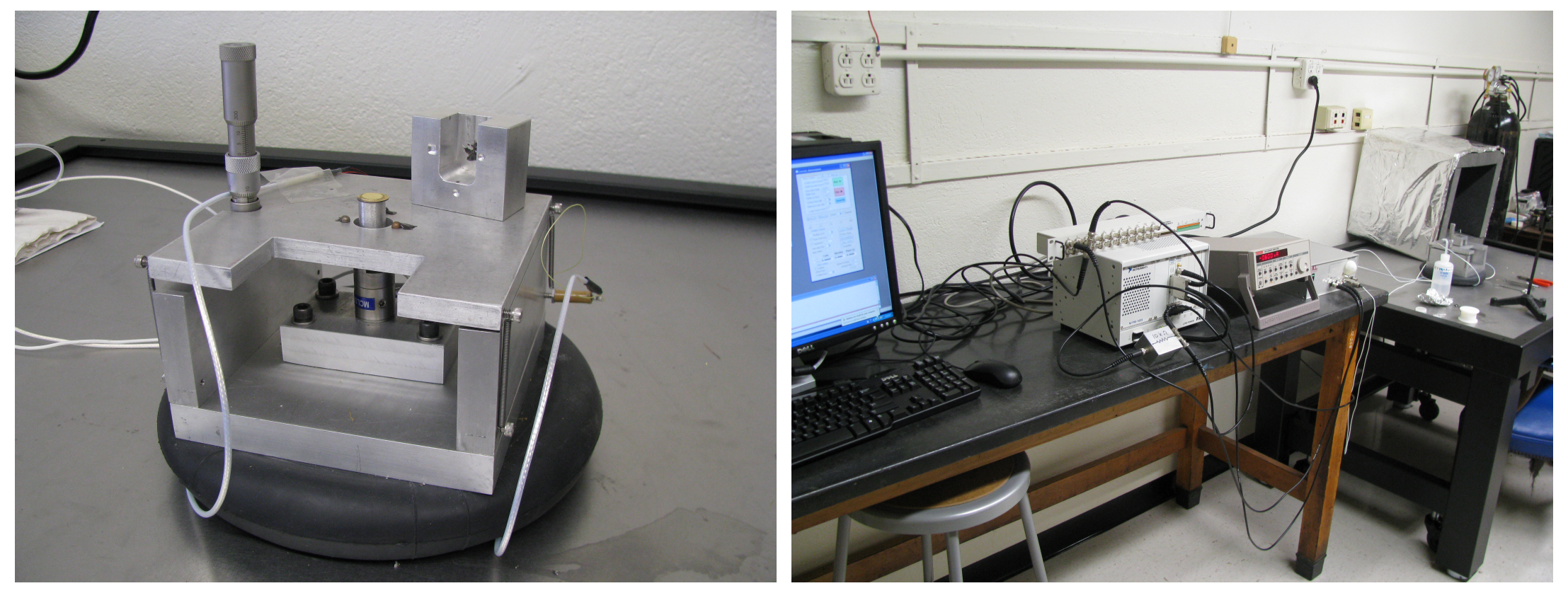
Arranging the Wire Students spend at least several hours learning and practicing a suitable arrangement of the ultrapure gold wire into an existing sheath in the apparatus. The sheath is a 10-mil (0.010") syringe needle which is electrically isolated from the main housing. The inner diameter of the small needle exactly matches the outer diameter of the wire, so slightly crimping or "kinking" the wire before insertion is necessary. Then, an extremely pointed tip must be cut using a very sharp blade. Often, the students do not appreciate the delicacy with which this contact must be prepared until they begin to see the direct correlation of their effort and the quality of the data.

The Apparatus

The measurement relies on four essential pieces of hardware. From left to right in the picture below:

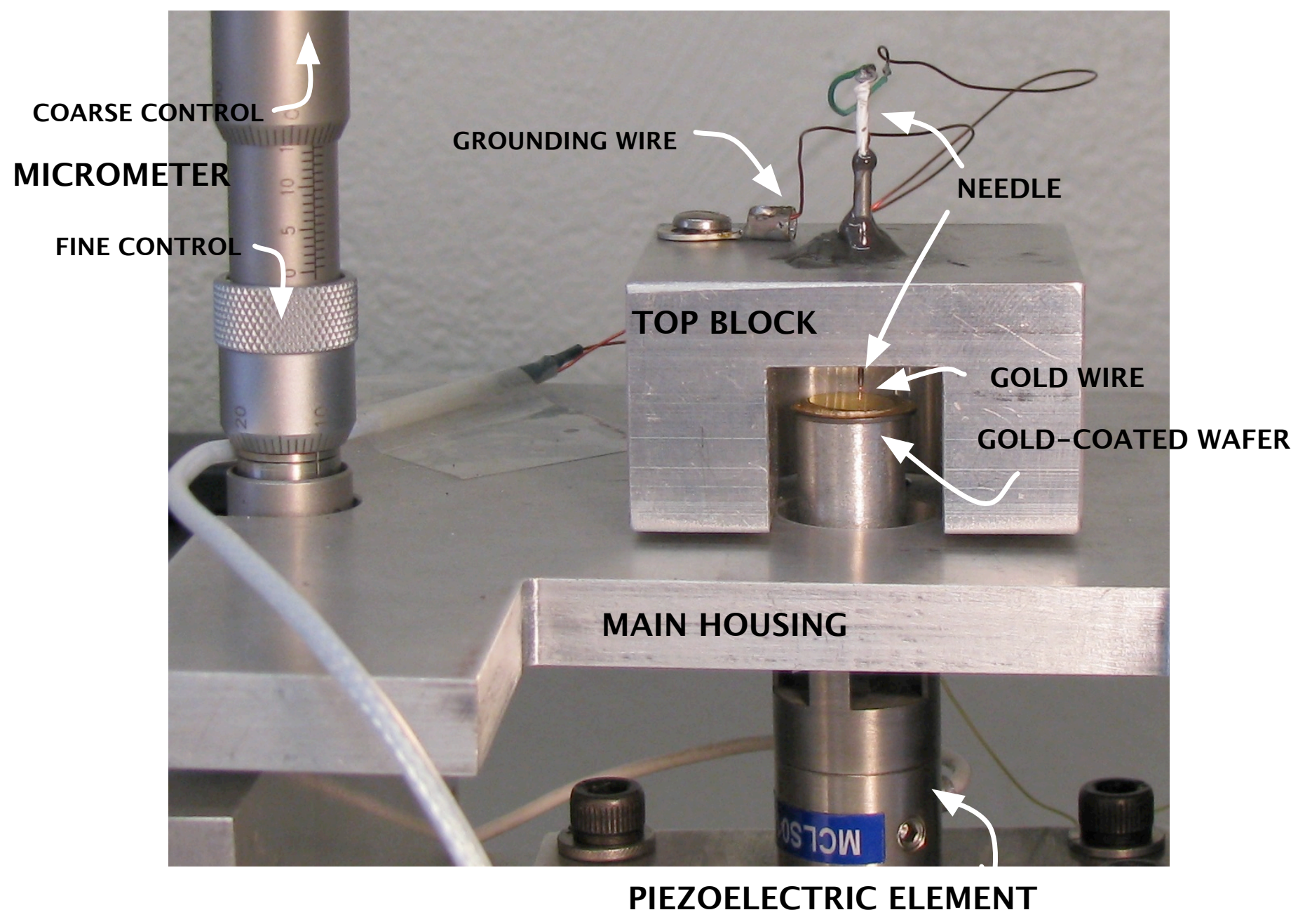
- Within the National Instruments PXI card chassis (with GPIB connection to PC)
  - NI M-Series 6289 card, High-Accuracy Multifunction DAQ
  - NI PCI-4461 card, 24-bit Analog-Digital Converter
- Keithley precision current amplifier
- MCL piezoelectric controller (attached to piezoelectric element)

A precision voltage is applied across the gold contact using the ADC card, and the current is measured using the same card after amplification by the Keithley. The devices are controlled and data is collected within the software program *Igor*. Each time the program is loaded, the code is re-compiled; this prevents any edits to the control routine that might produce unwanted effects. Hardware-level interfacing is performed through the National Instruments NI-DAQmx platform.



The central apparatus in the experiment. Left: the main housing for construction of the quantum point contact. Right: measurement devices and controllers used in the experiment, with the housing and vibration isolation table in background.

The chief apparatus is a 6" x 6" x 4" aluminum housing with an adjustable top plate, also shown above. Raising and lowering the plate by hand, using a micrometer, achieves a rough positioning for the gold contact. Once in place, the gold wafer is raised and lowered from below by a piezoelectric element, which is controlled in the software with sub-nanometer precision.



A diagram of the main housing with labels.

Vibration Isolation

This lab provides the students (and instructors!) with excellent appreciation for various sources of noise that are omnipresent in the lab. Vibrations in the floor are the largest source, and they are somewhat attenuated with a heavy-duty isolation table from Technical Manufacturing Company, which is pressurized with compressed air to 60 psi. In addition, the students experiment with constructing an acoustic shield over the apparatus. While sample data is collected, the students observe the differences between a heavy box, acoustic foam, aluminum foil (for electrical shielding), and various combinations thereof. Even so, it is still sometimes necessary for students to come in to collect data outside of the designated lab time, which is Friday rush hour along a truck route in New York City.

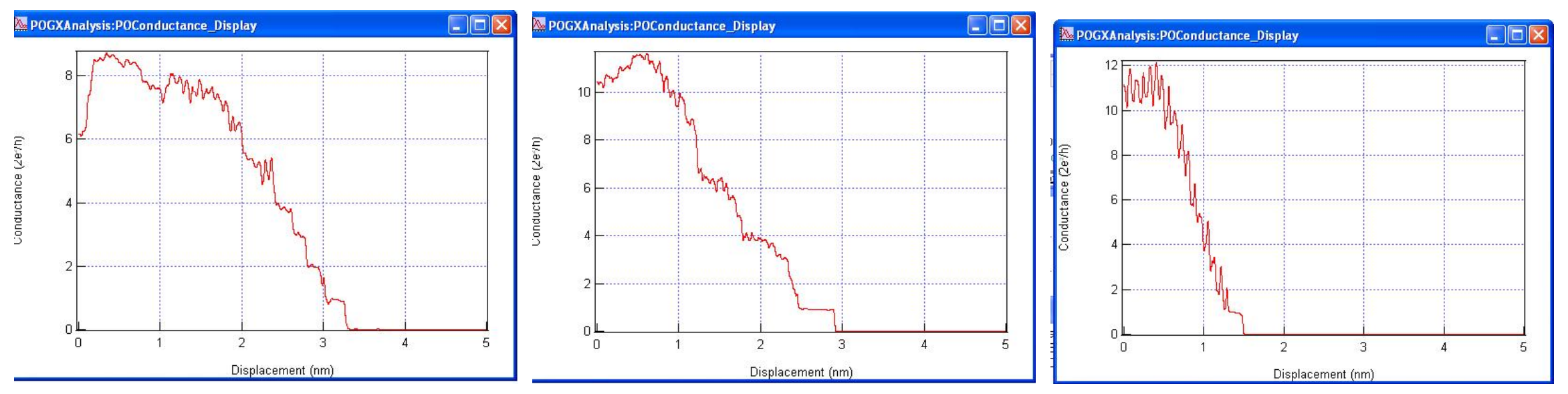
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Procedure

There are several important controls which allow the students to precisely position the gold wafer and then perform automated "traces." During a single trace, the gold wafer is brought up and into contact with the dangling wire, and then pulled away a set distance, typically five nanometers. After the wafer and wire are brought into rough contact by eye, the students apply sufficient voltage to the piezo to bring it even closer to contact. Sample traces are collected about once per second and displayed on the screen. It is easy to tell by eye if the data is behaving as it should; namely, as the contact size is decreased, the conductance should approach zero. Often, this is not the case, and the students determine whether to re-set the wire and cut the gold tip, reposition the wafer, adjust the acoustic shielding, or correct a number of other problems.

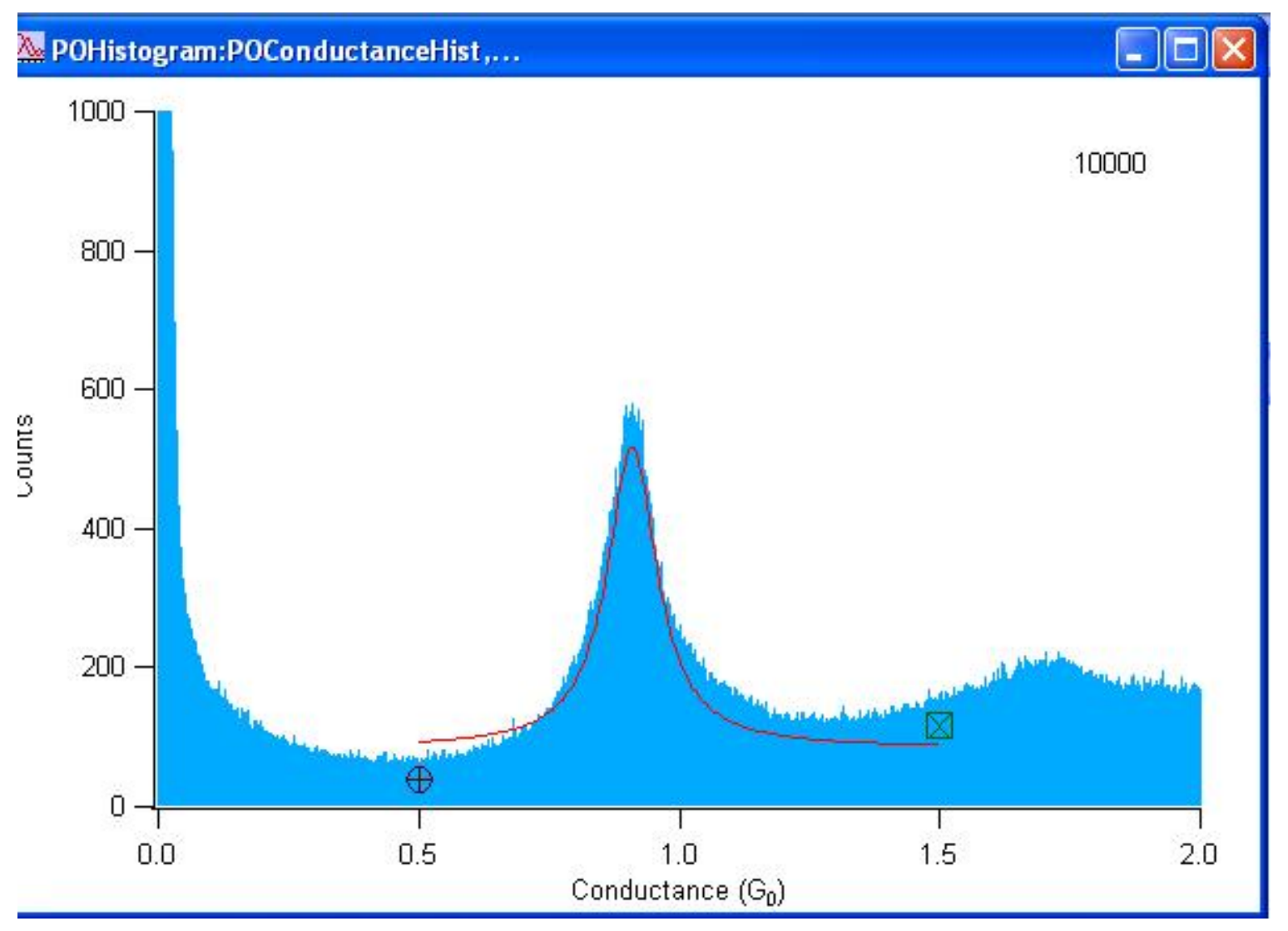
Data and Analysis

Collecting Traces The following picture is a screenshot of a three sample traces, with the lower axis showing the position of the wafer in nanometers, and the left conductance in units of the fundamental quantum, G_0. The first shows the most typical behavior during data collection: the first quantum is visible but noisy, and several additional plateaus are visible and roughly integer multiples. The second trace shows exceptional precision at the first plateau, but a lack of other features. The third trace demonstrates that the first plateau can often be seen even during noisy conditions.



Three traces.

Statistical Analysis The core of the statistical analysis is the construction of a histogram of hundreds to thousands of traces. Since the data files are a collection of sample points, this is achieved with a simple computer algorithm. The students also have the option to use a smoothing algorithm on each trace before compilation; this serves to eliminate random noise, but if too much smoothing is attempted, it can actually amplify periodic noises, and should be avoided.



A typical histogram of conductance values collected over many traces. The peak corresponding to a two-point contact is just visible on the right.

The histogram routine automatically fits a Lorentzian distribution to the peak centered at G_0, corresponding to the first plateau in the traces. The peak of the curve is reported as the observed value of quantized conductance, the the goodness of fit can be inferred from the fit parameters. It is instructive for the students to note that the background noise can and should interfere with the value.

Nanowire Chains Under the most noise-reduced conditions we have encountered, it is possible to observe some quantization of the physical lengths of the first (G_0) plateau. Apparently gold is malleable enough to stretch long chains of atoms between the two surfaces. We hope in the future to improve our conditions such that a statistical observation of this phenomenon is possible. We also hope to follow in the footsteps of research groups at Columbia who use this setup to investigate the conductive properties of organic molecules.

Resources and Acknowledgments

- E.K.A. Advanced Laboratory `http://www.phys.columbia.edu/~w3081/EKA_Org.html`
- E.K.A. Resources page `http://tesla.phys.columbia.edu/EKA_Laboratory`
- An exceptional overview of the subject: Hank van Houten and Carlo Beenakker, Phys. Today **49**, 22 (1996).
- We are very grateful to Professor Latha Venkataraman and her graduate students, particularly Maria Kamenetska, who operate almost identical equipment in a research lab in the Department of Applied Physics at Columbia, for inspiring the creation of this lab and for donating their software.