Physics 431: Modern Physics Laboratory – Condensed Matter Physics Experiments

The Oscilloscope and Function Generator Exercise. This ungraded exercise allows students to learn about oscilloscopes and function generators. Students measure digital and analog signals of different frequencies and amplitudes, explore how triggering works, and learn about the signal averaging and analysis features of digital scopes. They also explore the consequences of finite input impedance of the scope and and output impedance of the generator.

List 1

Electron Charge and Boltzmann Constants from Johnson Noise and Shot Noise Measurements. Because electronic noise is an intrinsic characteristic of electronic components and circuits, it is related to fundamental constants and can be used to measure them. The Johnson (thermal) noise across a resistor is amplified and measured at both room temperature and liquid nitrogen temperature for a series of different resistances. The amplifier contribution to the measured noise is subtracted out and the dependence of the noise voltage on the value of the resistance leads to the value of the Boltzmann constant k_B. In shot noise, a series of different currents are passed through a vacuum diode and the RMS noise across a load resistor is measured at each current. Since the current is carried by electron-size charges, the shot noise measurements contain information about the magnitude of the elementary charge e. The experiment also introduces the concept of "noise figure" of an amplifier and gives students experience with a FFT signal analyzer.

Hall Effect in Conductors and Semiconductors. The classical Hall effect is the basis of most sensors used in magnetic field measurements. Thin film samples consisting of a semiconductor (InAs) and two different metals (aluminum and gold) are investigated to determine the sign and density of the charge carriers. The sample is placed in a DC magnetic field, and the transverse (Hall) voltage is measured as a function of the current through the sample. Students observe the inverse relationship between the magnitude of the Hall voltage and charge carrier density, a relationship which accounts for the almost exclusive use of semiconductors as Hall effect/magnetic field sensing devices.

Low Temperature Superconductivity. A sample of mercury is cooled to liquid helium temperatures and the critical field as a function of temperature is recorded between 1.6 K and 4.2 K. Using a lock-in detection scheme, students record the transition of the Hg sample from normal to superconducting as they vary the vapor pressure and thus the temperature of the liquid helium bath surrounding the sample. Students are introduced to the concept of a 2nd order phase transition, where a system goes from a less ordered state to a more ordered state. Indeed, students even have the opportunity to see a visible manifestation of such a transition, as they can see the very different behavior of the liquid helium bath above and below the lambda point at about 2.2 K. With both liquid nitrogen and liquid helium used in this experiment, students have a rich opportunity to learn about the use and handling of cryogenic fluids and the operation of vacuum pumps and associated vacuum hardware.

Electron Diffraction. In this simple version of one of the most important experiments of the 20th century, students control the wavelength of electrons accelerated by an electric field to measure the diffraction pattern created by matter waves. From DeBroglie's equation and the condition for Bragg scattering, they then deduce the atomic spacing of atoms in a metal and in a single crystal of graphite. Students also explore how the Bragg diffraction spots from a single crystal become rings for multi-crystalline samples.

List 2

Surface Plasmon Resonance. If monochromatic light is shined on a thin metal film, it can under the right conditions, create many-body excitations known as surface plasmons in the electron gas of the film. Students learn that as photons excite the surface plasmons, energy and momentum are conserved, leading to the concept that many-body excitations behave in many ways like single particles. Students map out the surface plasmon resonance curve and then use a computer program to model the resonance curve and determine the best values for the film thickness and the (complex) dielectric constant.

Mössbauer Spectroscopy. The beautiful physics of the Mössbauer effect allows for energy resolutions of about one part in 10^{13}. The effect is used to measure the intrinsic magnetic field inside iron crystals and to measure the nuclear quadrupole splitting in crystals with electric field gradients at sites of iron nuclei. One can also measure the subtle "chemical" shift due to the different electronic environments of the iron nuclei in the source and absorber. Finally, relativistic effects can be observed by cooling the absorber to the temperature of liquid nitrogen, 77 K, with the source remaining at room temperature. Cooling the absorber relative to the source causes radiation from the source to be red shifted as observed by the absorber, as predicted by the second-order term in the relativistic Doppler effect; this changes the amount of first-order Doppler shift needed to observe a particular resonance.

Physical Adsorption of Nitrogen and Argon on Graphite. In this experiment students record an adsorption isotherm of N_2 molecules and a second one for Ar atoms on a graphite substrate at a temperature of 77.4 K. A characteristic monolayer feature of the N_2 isotherm corresponding to a known density of molecules on the graphite substrate allows one to calculate the total substrate area, thus allowing for determination of the Ar-Ar spacing at monolayer completion for this adsorbate. To no surprise, this number is very close to the nearest neighbor spacing in solid argon. This follows from the fact that the main force governing adsorption and adsorbate-adsorbate interaction is the dipole-dipole force, the same force governing the vapor-liquid condensation and solidification of neutral atoms.

Continuous-wave nuclear magnetic resonance (NMR). Nuclear magnetic resonance can be observed using very simple electronics and experimental hardware. A radio frequency (rf) field is applied to a proton sample (water or oil which are rich in H nuclei)) placed in a large DC magnetic field with a small AC component. As the sample passes through resonance the rf field flips the proton spins from the ground state to the excited state. The resonance signature is the signal from the proton spins relaxing back to the ground state. The resonant frequency is measured at different magnetic field values, and from these measurements the gyromagnetic ratio of the proton is derived. Similar measurements are performed on a sample containing fluorine, allowing for the determination of the gyromagnetic ratio for a second nucleus. Finally, proton (water) samples are prepared with varying concentrations of paramagnetic ions, allowing the students to observe the strong effect these ions have on the proton spin relaxation time.

Pulsed NMR. Modern NMR techniques underlying such applications as magnetic resonance imaging and mapping the structure of complicated organic molecules are explored in this experiment. Students learn how to put the sample in specific spin states, and then how to manipulate these spin states to accurately measure the longitudinal (spin-lattice) and transverse (spin- spin) relaxation times. In the process of mastering this "spin engineering," students learn how pulsed NMR techniques provide quantitative information about the spins and their environment that is not accessible using the simpler continuous wave NMR technique.