The Franck-Hertz Experiment

Background:

The Franck-Hertz experiment was done in 1914. It was the first direct measurement of quantization of energy levels in an atom[1]. It showed a set of steps in the energy of a system that could only be explained at the time with Bohrs model of the atom which was proposed, unknowingly to Franck and Hertz, a year earlier. Fig. 1 shows the experimental set up basically consisting of a vacuum tube filled with mercury vapor, a heated cathode, an anode, and a wire mesh placed in between the two nodes. A potential difference is applied between the plates and the mesh grid. The first potential difference is used to accelerate the electrons through the vapor. The second only allows electrons with some kinetic energy to collide with the collector.

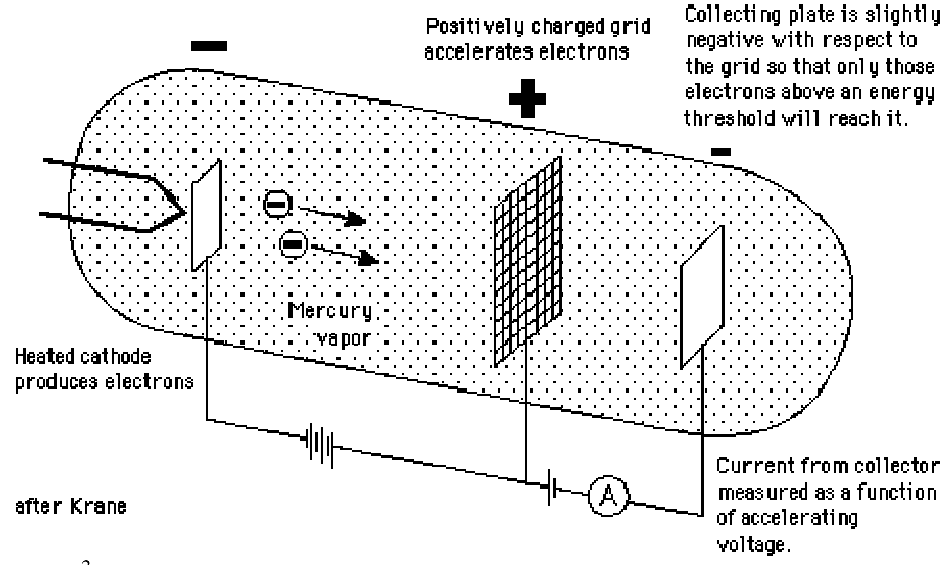


Fig 1. [3]

The Cathode produces electrons that accelerate towards the mesh grid and then collide with the collecting plate producing a current. The voltage could be adjusted to create a larger acceleration and therefore was expected to produce a larger current.

In the experiment special features were observed: if the electrons energy exceeds a value of 4.9 eV the current dropped suddenly. This effect was repeated at integer multiples of 4.9 eV. This is explained by the quantum nature of the mercury vapor. At these energies the electrons are no longer colliding with the atoms elastically. This energy of 4.9 eV is needed to excite a mercury atom. The electron is then released after the excitation with less kinetic energy due to a photon being emitted when the atom returns to the non-excited state. The integer repetition is a result of the released electron having another 4.9 eV to excite a mercury atom again.

Procedure:

Our experiment is very similar to the one described above. The Franck-Hertz tube is inside an oven that has to be maintained within a certain temperature range. The oven assures that mercury stays in vapor form, which does not occur at lower temperatures. An oscilloscope and the accelerating voltage supply allow for the data acquisition.

The first run of the experiment should be done with a temperature setting of 190^{o}C. The temperature of the unit should be allowed to rise slowly and then settle within this range. A periodic signal with linearly increasing voltage is supplied. The current is to be measured as a function of voltage.
First, make yourself familiar with the operation of the oscilloscope. Show the input voltage as a function of time, then show the output current as function of time.
Use the x-y mode to display the current as a function of voltage.
Take measurements of current and voltage at different points of the curve to accurately describe the measured curve.
The potential can be raised till the current drop of each integer voltage is reached. This procedure can be used to get an accurate reading for the current drops.

Change the oven temperature to 180^{o}C and take another measurement.
How does the oven temperature change the measured curve. What do you expect for even lower temperatures, and for higher temperatures?
Why do we not see any light being emitted from the experiment?

Preparation key words:

Bohrs model of the atom, energy levels of electrons in an atom, occupied and unoccupied states, kinetic and potential energy, vapor pressure, thermal activation

References:

1: Llewellyn, Ralph and Tipler, Paul Modern Physics 4th ed. New York:
W.H. Freeman and company, 2003

2:Valerie Gordeski, The Frank-Hertz Experiment Presentation, Massachusetts Institute of Technology

3: Department of Physics and Astronomy, Host of Hyperphysics, Georgia St. University, http://hyperphysics.phy-astr.gsu.edu/hbase/FrHz.html

Charge-To-Mass Ratio

Background:

This experiment uses a cathode's electron beam and the magnetic field of Helmholtz coils in order to observe deflection of electrons by means of magnetic force. By deflecting the electrons into a circular trajectory, we can use the equations for magnetic and centripetal forces. Using this relationship, we can isolate q/m and calculate the charge-to-mass ratio of electrons. In this setup, q/m depends on the Helmholtz coils' number of loops, their current, their radii, the accelerating voltage of the cathode and the radius of the beam's curvature.

In 1897 J.J.Thompson experimented with cathode rays, which resulted in the detection of the electron. He was unsuccessful in measuring the individual properties of the electron, however, he was able to construct a method for finding its charge-to-mass ratio.

The basic principle behind the experiment was that accelerated electrons that travel down a tube deviated from their original path in the presence of a magnetic field. The charge-to-mass ratio (q/m) could then be calculated by using the measurements of the deflections.

Essentially, a charged particle experiences a force when moving through a magnetic field. The uniform magnetic field in this experiment is created due to the application of Helmholtz coils. The Helmholtz coils are constructed of two identical and parallel coils of wire, which are set up along the same axis and separated by a distance that is equivalent to their individual radii. The equation to calculate this field is obtained by applying the Biot-Savart Law: $B = 8\mu NI / 5^{3/2}R$

The force acting upon the charged particle as a result of this field is: $F = qvB\cdot\sin\theta$

Since the electrons are traveling perpendicular to the magnetic field, their path was curved, forming a circle. In the presence of a magnetic field, the force that is exerted on an electron can be determined by applying the right hand rule. Due to the uniformity of the magnetic field, the electron's path always remained perpendicular to the magnetic field, causing the electron to travel in a circle. The equation to calculate this result pertains to the centripetal force: $F = mv^2/r$

In order to visualize, and thus measure, the deflected path of the electron, the experiment includes a sealed chamber filled with mercury gas. When the electrons excited the gas, the beam starts to glow and is then visible.

Since the electrons are accelerated by being passed through a potential difference, V, the equation for the kinetic energy in terms of voltage is also required: $Vq = (1/2)\, mv^2$.

This results in $q/m = 2V/B^2r^2$.

Procedure:

To start the experiment, consult with the instructor to see if the cables are connected correctly. Then, activate the cathode check if you can see a blue line of electrons straight upward in the glass chamber. To get the beam focused, you should raise the cathode's accelerating voltage until the electrons were only negligibly scattered. Then, switch on the power for the Helmholtz coils. They produce identical magnetic fields perpendicular to their path that complement each other greatest at the center between them, where we'd set up our electron beam. Depending on the current's orientation, the electrons are either deflected in a soft arc toward or away from the viewer. A cardboard box with a viewing slit should be utilized to diminish outside light and make the electron beam more visible.

There are marker circles on the fluorescent screen. Make the electron beam hit these circles by changing acceleration voltage and current through the coils. This way you can measure the diameter of the electron beam path. Make several measurements.

Also, measure the magnetic field using the hand-held apparatus provided. Hold the magnetometer in different orientations to see in which direction the magnetic field lines are aligned. This magnetometer utilizes the Hall effect.

Preparation key words:

Calculation of e/m, magnetic field induced by a current, fields by coils, Biot-Savart law, Maxwell equations, Hall effect

References:

Serway, Raymond, John Jewett, Jr.. Physics For Scientists and Engineers. Vol. 2. California: Brooks and Cole, 2004.

Shankar, Ramaruti. Principles of Quantum Mechanics. 2nd ed. New York: Springer, 1994.

Tipler, Paul A., Ralph Llewellyn. Modern Physics. 4th ed. New York: W.H. Freeman and Company, 2003.

Optical Diffraction

Background (from Wikipedia.org):

A diffraction grating is an optical component with a regular pattern, which splits and diffracts light into several beams traveling in different directions. The directions of these beams depend on the spacings between the lines of the grating and the wavelength of the light. A diffraction grating acts as a dispersive element used in monochromators and spectrometers.

A photographic slide with a fine pattern of black lines forms a simple grating. Gratings generally have parallel grooves or rulings on their surface with spacings between the lines of constant distance. Such periodic gratings can be either transparent or reflective.

The principles of diffraction gratings were discovered by James Gregory, about a year after Newton's Prism experiments, initially with artifacts such as bird feathers. The first man-made diffraction grating was made around 1785 by Philadelphia inventor David Rittenhouse, who strung hairs between two finely threaded screws. This was similar to notable German physicist Joseph von Fraunhofer's wire diffraction grating in 1821.

The relationship between the grating spacing and the angles of the incident and diffracted beams of light is known as the grating equation. When a wave propagates, each point on the wavefront can be considered to act as a point source, and the wavefront at any subsequent point can be found by adding together the contributions from each of these individual point sources.

An idealized grating is considered here which is made up of a set of long and infinitely narrow slits of spacing d. When a plane wave of wavelength λ is incident normally on the grating, each slit in the grating acts as a point source propagating in all directions. The light in a particular direction, θ, is made up of the interfering components from each slit. Generally, the phases of the waves from different slits will vary from one another, and will cancel one another out partially or wholly. However, when the path difference between the light from adjacent slits is equal to the wavelength, λ, the waves will all be in phase. This occurs at angles θ_m which satisfy the relationship $d\sin\theta_m/\lambda=|m|$ where d is the separation of the slits and m is an integer. Thus, the diffracted light will have maxima at angles θ_m . It is straightforward to show that if a plane wave is incident at an angle θ_i, the grating equation becomes $\sin\theta_m + \sin\theta_i = |m|\lambda/d$.

Procedure:

Use the laser to set up an experiment to measure the diffraction of the light on a periodic lattice.
Use lenses to spread the laser beam on an optical bench and produce a parallel beam on the spectrometer.
Measure the scattering angles of diffraction maxima for the incident beam perpendicular to the optical grating.
Repeat this measurement for a tilted grating.
Calculate the lattice spacing if the wavelength is known.

Preparation key words:

Lasers, characteristic emission lines from gases, absorption, diffraction, interference, coherence, diffraction grating, single slit experiment, Fraunhofer approximation, Huygens principle, explanation of diffraction maxima and minima in the far-field.

References:

Serway, Raymond, John Jewett, Jr.. Physics For Scientists and Engineers. Vol. 2. California: Brooks and Cole, 2004.

Hutley, Michael, Diffraction Gratings (Techniques of Physics), Academic Press (1982).
Loewen, Erwin & Evgeny Popov, Diffraction Gratings and Applications, CRC; 1 edition (1997).

AC Circuits

Background:

A circuit is a path between two or more points along which an electrical current can travel. Circuits are used in a growing variety of industrial settings and functions. In many applications it is desirable to constrain the frequencies that are transmitted through the circuit. Low, high and mid pass filters are used for this purpose.

A low pass filter includes a capacitor in parallel and a resistor in series with the signal path. The capacitor exhibits a reactance and blocks low frequency signals. A high pass filter works under the same principle as a low pass filter. In a high pass filter, the capacitor is in series and the resistor in parallel with the signal path. Where a low pass filter attenuates high frequencies, a high pass filter blocks low frequencies.

A low-pass filter with a resistor and a capacitor can be used to block high frequency signals. A high-pass filter is rejecting low-frequency signals. A band pass can be used to transmit a specific frequency range.

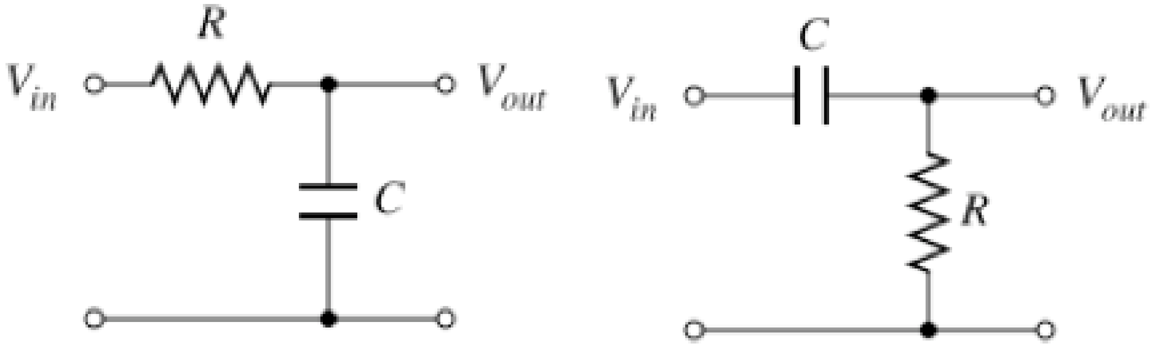


Figure 1: Diagram of a Low Pass Filter (left) and high pass filter (right) (from www.wikipedia.org)

Procedure:

A Proto Board PB-503 is available. You can generate a signal through the right TTL pins (the left are used for the ground). There are two outputs for the Oscilloscope signal. Use the ‘Pin’ for the signal and ‘shell’ for the ground. There are vertical lines of pins available, which are all on the same level for each individual vertical line. There are also horizontal sets of pins on the same level.

Build a high-pass filter and measure V(out)/V(in) as function of frequency.
Build a low-pass filter and measure V(out)/V(in) as function of frequency.
Build a bandpass filter and measure V(out)/V(in) as function of frequency.
Measure the characteristics I(V) of a diode. You need to think about the design of this experiment before you do it. You may be able to use the math (+-) option of the oscilloscope.

Preparation key words:

RC circuits and their mathematical description, complex numbers, phase shift, measurement of currents and voltages, differential equations describing electric circuits (and their solutions in the presence of a periodic input signal and in the case of off-on DC input), Physics of a pn-junctions, diode characteristics, principle of a transistor.

References:

Serway, Raymond, John Jewett, Jr.. Physics For Scientists and Engineers. Vol. 2. California: Brooks and Cole, 2004.

Wolfson and Pasachoff. Physics. 3rd ed. Reading, MA: Addison Wesley, 1999.

Temperature dependence of electrical resistivity

Background (from wikipedia.org):

The temperature dependence of the specific resistivity R is a simple test for models of electric conductivity in conductors (metals and alloys) and semiconductors. In general, electrical resistivity of metals increases with temperature, while the resistivity of semiconductors decreases with increasing temperature. In both cases, electron–phonon interactions can play a key role. At high temperatures, the resistance of a metal increases linearly with temperature. As the temperature of a metal is reduced, the temperature dependence of resistivity follows a power law function of temperature. Mathematically the temperature dependence of the resistivity ρ of a metal is given by the Bloch–Grüneisen formula:

$$\rho(T) = \rho(0) + A\left(\frac{T}{\Theta_R}\right)^n \int_0^{\frac{\Theta_R}{T}} \frac{x^n}{(e^x-1)(1-e^{-x})}dx$$

where ρ(0) is the residual resistivity due to defect scattering, A is a constant that depends on the velocity of electrons at the Fermi surface, the Debye radius and the number density of electrons in the metal. Θ_R is the Debye temperature as obtained from resistivity measurements and matches very closely with the values of Debye temperature obtained from specific heat measurements. n is an integer that depends upon the nature of interaction:
n=5 implies that the resistance is due to scattering of electrons by phonons (as it is for simple metals)
n=3 implies that the resistance is due to s-d electron scattering (as is the case for transition metals)
n=2 implies that the resistance is due to electron–electron interaction.

For noble metal resistors the the resistivity can be approximated by $\rho(T) = \rho(0^{o}C)\,(1+\alpha T)$.

As the temperature of the metal is sufficiently reduced (so as to 'freeze' all the phonons), the resistivity usually reaches a constant value, known as the residual resistivity. This value depends not only on the type of metal, but on its purity and thermal history. The value of the residual resistivity of a metal is decided by its impurity concentration. The Matthiesen rule can be used to describe the temperature dependence at low temperatures: $r=r_{imp}+AT^2+BT^5+CT$. Some materials lose all electrical resistivity at sufficiently low temperatures, due to an effect known as superconductivity.

Intrinsic semiconductors become better conductors as the temperature increases; the electrons are bumped to the conduction energy band by thermal energy, where they flow freely and in doing so leave behind holes in the valence band, which also flow freely. The electric resistance of a typical intrinsic (non doped) semiconductor decreases exponentially with the temperature: $\rho=\rho_0 \exp(E_g/kT)$. Here, E_g is the energy gap between valence and conduction band.

Extrinsic (doped) semiconductors have a far more complicated temperature profile. As temperature increases starting from absolute zero they first decrease steeply in resistance as the carriers leave the donors or acceptors. After most of the donors or acceptors have lost their carriers the resistance starts to increase again slightly due to the reducing mobility of carriers (much as in a metal). At higher temperatures it will behave like intrinsic semiconductors as the

carriers from the donors/acceptors become insignificant compared to the thermally generated carriers.
The electric resistance of electrolytes and insulators is highly nonlinear, and case by case dependent, therefore no generalized equations are given.

Procedure:

An oven is available for heating. Put the metallic conductor assembly (part 58680) in the opening of the oven. Place the thermocouple through the hole on the other side of the oven. Connect the conductor assembly to the Wheatstone bridge. Measure the resistance of the metal at room temperature by zeroing the ampmeter with the appropriate resistor settings and the rheostat. Switch on the oven and monitor resistance as a function of temperature.
Warning: Switch of the oven heater at 350°C. Make sure the resistor temperature stays below 400°C. If 400°C is exceeded remove the metal conductor assembly immediately from the oven. There is a tool to grab the assembly and put it on the opening of a metal pipe.
For the semiconductor, never exceed 200°C. Switch off the oven at 170°C.

Measure the resistance while the oven cools down.

Repeat the experiment with the semiconductor assembly. Make sure the oven temperature never exceeds 200°C.

Repeat both experiments using a voltmeter with capacity to measure resistivity.

Preparation key words:

Resistance and resistivity; energy levels of electrons in solids; differences between insulators, semiconductors, metals; Pauli principle; band structure; Fermi distribution; density of states; scattering of free electrons; phonons.

References:

Charles Kittel, Introduction to Solid State Physics
Neil Ashcroft, David Mermin, Solid State Physics

Nuclear Spectroscopy

Background:

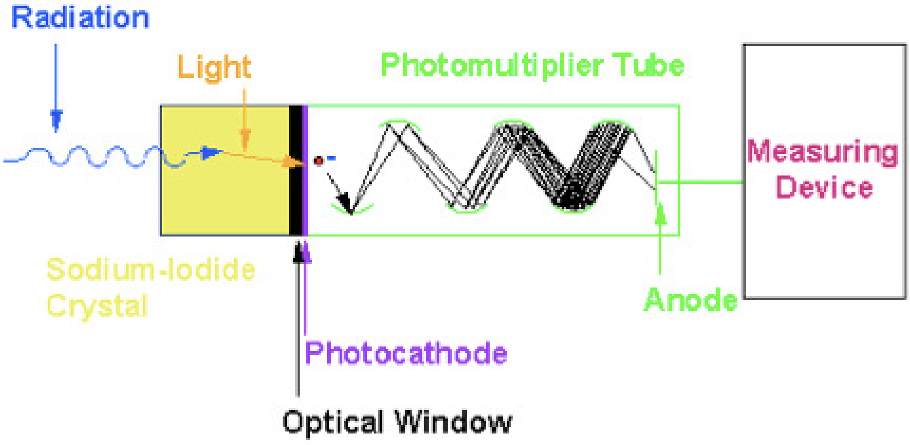
Radiation is the process of emitting energy in the form of waves or particles, and is generally produced when particles interact, decay or change their energy state. By the end of the 1800s, it was known that certain isotopes (two or more varieties of an element having the same number of protons but different numbers of neutrons) emit penetrating rays in three forms of radiation. These are known as alpha (helium nuclei), beta (electron or positron), and gamma (high energy light) ray emission.

Because the radiation process is described in probabilistic terms, we cannot with certainty predict when a particle will decay or change its energy state. With a large enough sample, however, we can measure the percentage of particles that have experienced decay/change in energy and thus infer the half-life and decay rate of the substance.

Half-life and decay rate are described by:
$N/N_0=e^{-t/\tau}$
where N/N_0 is the fraction of particles remaining after time t, and τ is the decay rate.

Procedure:

In the experiment γ radiation is detectible via a sodium iodide (NaI) scintillation detector. The instrument contains a special material (here, the salt sodium iodide), which glows when radiation interacts with it. The electromagnetic radiation (light) generated by this process is then directed to a device called a photomultiplier tube. Within the tube, a photocathode produces electrons when light strikes its surface. The electrons are pulled toward plates called dynodes. By releasing several electrons for each one that hits the surface, the dynodes magnify the pulse of electrons, allowing them to be detected.



The signal is pre-amplified and later amplified before it enters a multi channel analyzer (MCA). The analyzer separates different energies into different channels. In order to correlate the various channels to the actual energies, a sample emitting a known energy must also be used. It is known that Cesium-137 radiates at 0.662 MeV, so after locating the peak of the spectrum, this information has to be used to calibrate the MCA.

After calibrating the MCA, keep the Cesium-137 sample placed as closely as possible in front of the detector and measure the count rate for different intervals. Next, measure the absorption parameters of a 0.250-inch polyethylene filter and 0.032 and 0.062-inch lead filters.

Place an Indium-115 sample in front of the detector and measured the counts at approximately 1.64 MeV. This is a freshly activated sample. Measure the decay rate of this energy state.

Tasks:

- Make yourself familiar with the software to acquire spectra
- Measure the background signal without any radioactive source
- Measure the spectra of the radioactive sources, determine the counts per second, their statistical distribution (repeat one experiment several times), and determine the FWHM of a peak
- Measure the absorption parameters for two different filters
- Ask Raj for the neutron-activated In sample
- Measure the lifetime of the radioactive isotope (it's about 2 minutes, so think about the way to measure this before you execute this experiment).

Preparation key words:

Types of radiation and its detection, NaI detectors, photomultipliers (how do they work?), gamma-ray emission, Compton effect, lifetime of isotopes and its measurement, stability of isotopes and types of nuclear decay, radiation protection for different types of radiation.

References:

Shankar, Ramaruti. Principles of Quantum Mechanics. 2nd ed. New York: Springer, 1994.
Llewellyn, Ralph, and Paul A. Tipler. Modern Physics. 4th ed. New York: W.H. Freeman and Company, 2003.
Idaho State University Department of Physics. www.physics.isu.edu

Optical Spectroscopy

Background:

The characteristic spectral lines in a spectrum are due to the quantum nature of energy levels of an excited atom. When an atom gets excited the electron jumps to the next energy level. If the electron returns to a lower energy level the excess energy is released in the form of photons. These photons have a certain wavelength associated with this change in energy.

$$\lambda = hc/(E^1 - E^2)$$

Here λ equals the wavelength, h and c are constants and the difference of E is the change in energy. For atoms there are unique energy differences correlated to the wavelength of light emitted. However, there is more than one energy level for each atom and henceforth more than one wavelength being emitted. This is where a prism or diffraction grating comes in to separate the light into its unique wavelengths and making spectrum analysis possible. The emitting material is defined by its unique spectral lines. In fig. 1 the spectrum of helium below is shown. Each of the spectral lines coincide with excited energy level of the helium atom.

Fig. 1. Optical emission spectrum of Helium

This is analogous to absorption lines. If you have a source light that emits a continuous spectra with an elemental gas in between you and the source, the gas will absorb any light that excites the atoms within that gas. Because the photon that gets emitted does not necessarily go in the direction of the observation you are left with empty sections of the spectrum shown in the figure below.

Fig. 2. Optical absorption spectrum of Helium

Procedure:

An Ocean Optics spectrometer is available for the experiment. You can use a Tungsten halogen lamp for transmission and scattering experiments with the CUV sample holder. On the computer, start the OOIBase32 software. With the go button, you can start a measurement.m You can adjust integration time and number of readouts to average for optimum display of data below the saturation level of the spectrometer. To save data, use ‘edit’, ‘copy spectral data’, ‘all spectrometer channels’, copy this in an excel file for further data analysis.

Measure the emission spectra of the different lamps available.
Measure the characteristic maxima of the room lights.
Measure the transmission through several foils and through selected liquids with the sample holder.

Measure the scattered signal from liquids with the sample holder.

Preparation key words:

Lasers, characteristic emission lines from gasses, absorption, diffraction, interference, coherence, diffraction grating, calculation of interference maxima and minima for gratings and for a single slit, prism spectrometer, dispersion, refractive index.

References:

Llewellyn, Ralph and Tipler, Paul; Modern Physics 4th ed., New York:
W.H. Freeman and company, 2003
Haliday/Resnick/Walker, Fundamentals in Physics 6th ed., New Jersey:
John Wiley & Sons Inc., 2003

Electron Spin Resonance

Background (from http://www.chemistry.nmsu.edu/studntres/chem435/Lab7/intro.html, Wikipedia.org):

Electron paramagnetic resonance (EPR) or electron spin resonance (ESR) spectroscopy is a technique for studying chemical species that have one or more unpaired electrons, such as organic and inorganic free radicals or inorganic complexes possessing a transition metal ion. The basic physical concepts of EPR are analogous to those of nuclear magnetic resonance (NMR), but it is electron spins that are excited instead of spins of atomic nuclei. Because most stable molecules have all their electrons paired, the EPR technique is less widely used than NMR. However, this limitation to paramagnetic species also means that the EPR technique is one of great specificity, since ordinary chemical solvents and matrices do not give rise to EPR spectra.

EPR was first observed in Kazan State University by a Soviet physicist Yevgeny Zavoisky in 1944, and was developed independently at the same time by Brebis Bleaney at Oxford University.

Energy Level Structure, g-factor and hyperfine interaction

In EPR, because of the interaction of the unpaired electron spin moment (given by two projections, $m_s = \pm 1/2$, for a free electron) with the magnetic field, the so-called Zeeman effect, different projections of the spin gain different energies, as shown below and on the figure to the right:

$$E_{ms} = g \mathrm{m}_B \mathbf{B_o} m_s \qquad (1)$$

Here $\mathbf{B_o}$ is the field strength of the external magnetic field. The SI units for magnetic field is tesla,T, but, historically in EPR, gauss (1 G = 0.0001 T) is still used. Other terms in Eq.(1): m_s - is a spin projection on the field ($m_s = \pm 1/2$ for a free electron), m_B is the Bohr magneton:

$$\mathrm{m}_B = |eh/4\pi \mathrm{m}_e| = 9.2740 \times 10^{-24}\ \mathrm{J/T} \qquad (2)$$

with e and m_e being electron charge and mass, respectively, and h-Planck's constant. Parameter g for free electron, g_e, has the value close to two: $g_e = 2.0023193$. If the electron has nonzero orbital angular moment, L, the g-value (sometimes called Landé factor) becomes:

$$g = 1 + \frac{S(S + 1) - L(L + 1) + J(J + 1)}{2J(J + 1)} \qquad (3)$$

The overall magnetic momentum, m_{eff}□, can be expessed via the overall angular momentum, J, and the g-value:

$$\mathrm{m}_{eff}□ = g \mathrm{m}_B [J(J + 1)]^{1/2} \qquad (4)$$

For most of organic radicals and radical ions, unpaired electrons have L close to zero and the total electron angular momentum quantum number J is pretty much the spin quantum number, S. As result, their g-values are close to 2. Situation becomes much more complicated with transition metals. Not only they have large L's and S's, but these values depend on the surrounding electric fields of ligands, making everything messier but also more interesting. If the molecule contains nuclei with magnetic moments, such as protons, their interaction with external field and the electronic magnetic moment will change stationary energies of Eq.(1). The nuclear angular momentum quantum number I determines the nuclear magnetic moment the same way as for the electron:

$$m\square = g_N m_N [I(I + 1)]^{1/2} \qquad (5)$$

with m_N now being the nuclear Bohr magneton:

$$m_N = eh/4\pi m_p = 5.051 \text{ x } 10^{-27} \text{ J/T} \qquad (6)$$

much smaller value because of the ~2000 times more heavier proton m_p. The nuclear g factor, g_N, is obtained from a knowledge of the structure of the nucleus. Interaction with external field splits the nuclear sublevels due to Zeeman interaction the same way as for electron spin:

$$E m_I = g_N m_N \mathbf{Bo} m_I \qquad (7)$$

where m_I is one of the 2I + 1 projections of the nuclear spin.

To measure ESR we can make use of the alignment of electron spins parallel and antiparallel to the external magnetic field. For unpaired electrons one set of energy levels will be less occupied than the other in an external field. With increasing field, the difference in energy increases.

The parallel alignment corresponds to the lower energy state, and the separation between it and the upper state is $\Delta E = g_e \mu_B B_0$, where g_e is the electron's so-called g-factor (see also the Landé g-factor) and μ_B is the Bohr magneton. This equation implies that the splitting of the energy levels is directly proportional to the magnetic field's strength.

An unpaired electron can move between the two energy levels by either absorbing or emitting electromagnetic radiation of energy $\varepsilon = h\nu$ such that the resonance condition, $\varepsilon = \Delta E$, is obeyed. Substituting in $\varepsilon = h\nu$ and $\Delta E = g_e \mu_B B_0$ leads to the fundamental equation of EPR spectroscopy: $h\nu = g_e \mu_B B_0$. Experimentally, this equation permits a large combination of frequency and magnetic field values, but the great majority of EPR measurements are made with microwaves in the 9000 – 10000 MHz (9 – 10 GHz) region, with fields corresponding to about 3500 G (0.35 T). In principle, EPR spectra can be generated by either varying the photon frequency incident on a sample while holding the magnetic field constant, or doing the reverse. In practice, it is usually the frequency which is kept fixed. A collection of paramagnetic centers, such as free radicals, is exposed to microwaves at a fixed frequency. By increasing an external magnetic field, the gap between the $m_s = +1/2$ and $m_s = -1/2$ energy states is widened until it matches the energy of the microwaves, as represented by the double-arrow in the diagram above. At this point the unpaired electrons can move between their two spin states. Since there typically are more electrons in the lower state, due to the Maxwell-Boltzmann distribution, there is a net absorption of energy, and it is this absorption, which is monitored and converted into a spectrum.

Procedure:

Make yourself familiar with the setup of the equipment, how to control field, field modulation, and frequency, as well as monitoring the two latter signals on the oscilloscope. Select the largest high-frequency coil and insert one of the two samples with metal ions.

Select a high frequency, and scan through the available range of the magnetic field.

Calculate the field near the sample, and check this value with the Hall probe.

Find a field range where the ESR signal appears and lower the field modulation amplitude to identify the magnitude of the field. Determine the Bohr magneton.

Repeat the procedure for both samples at different frequencies.

Preparation key words:

Principles of ESR and NMR, electrons in magnetic fields, Pauli principle, energy levels of electrons in a magnetic field, Zeeman effect, Quantum mechanical hydrogen model

References:

Altshuler, S. A.; Kozirev, B. M. (1964). *Electron Paramagnetic Resonance*. Academic Press.
Carrington, A., McLachlan, A. (1967). *Introduction to Magnetic Resonance*. Harper & Row.