

Physics 432: Modern Physics Laboratory – Atomic and Molecular Physics Experiments

List 1

Optical Spectrum of Hydrogen and Deuterium. Students measure the Balmer series emission lines of hydrogen and deuterium. Results of the measurements are used to derive a value of the Rydberg constant for each of the isotopes. The concept of reduced mass is introduced and the dependence of the Rydberg constant on this parameter is noted. A value for the H-D mass ratio is then derived from the values of the two Rydberg constants.

Moseley’s Law and the X-ray Spectra of Atoms. Students measure the x-ray emission lines of multi-electron atoms using a high resolution solid state detector. They learn how the simple physics of the hydrogen atom is generalized to describe the major features of x-ray spectra for $Z > 1$. Students record the spectra from several samples of unknown composition, thus seeing first-hand how x-ray fluorescence can be used to determine the elemental composition of such samples. They are introduced to the physics of solid state detectors, thus acquiring insight into the remarkable resolving power of these devices.

Hanle Effect. The Hanle effect in mercury atoms is used to make a Doppler-free measurement of the lifetime of the first excited state. Light from a secondary mercury source is shown onto a primary mercury vapor cell located in a slowly varying magnetic field. This field induces a Larmor precession in the excited atoms, and as they decay to the ground state the precession results in a time varying spatial distribution of the decay radiation. The magnitude of the decay radiation is measured as a function of magnetic field strength. The data are fit to a Lorentzian lineshape, thus allowing the students to determine the lifetime as one of the fitting parameters. For many decades this method was the only Doppler-free way to measure atomic lifetimes.

Phase-sensitive Detection. In this exercise, students are introduced to the so called “lock-in” detector, one of the experimentalist’s most useful and powerful tools for recovering signals otherwise hopelessly buried in noise. The “signal” of interest is generated by a light emitting diode (LED) driven at the lock-in reference frequency, and the noise signal is generated by a second LED driven by a random noise generator. Light from both LED’s is detected by a photodiode and in this process the signal and noise are mixed. Students observe that the light from the signal diode can easily be distinguished from the noise, even when the noise power exceeds the signal power by a factor of several hundred or more. The inevitable trade-off between lock-in response time and output stability is explored, showing that even with this remarkable instrument there is no free lunch when noise is at the table.

Franck-Hertz Effect in Mercury and Neon. In this experiment students repeat the original measurement that demonstrates the quantization of atomic energy levels using a probe other than photons. Electrons emitted from a heated cathode are accelerated by a potential difference as they pass through a mercury vapor. When they have gained sufficient energy, the electrons collide inelastically with mercury atoms, exciting them from the ground state. Electrons are collected at the anode, and the anode current shows minima and maxima at potential differences related to the energy difference between the ground state and the lowest lying excited states of the mercury atom. Thus, the students see striking evidence for energy quantization simply by watching the current meter. The Franck-Hertz effect is also used to investigate neon atoms where bright emission bands are visually observed in the regions where the electron have sufficient energy to excite neon atoms from the ground state.

List 2

Inversion Spectrum of Ammonia. This experiment is a beautiful realization of the effects of the quantum mechanical double well potential. The ammonia molecule is pyramidal shaped with the three hydrogen atoms forming the base and the nitrogen atom at the apex. The nitrogen atom sees a double-well potential with one well on either side of the plane defined by the H atoms. The wave function for the N atom can be either symmetric or anti-symmetric, the two states being split by a small energy difference. When a RF (microwave) field is applied at this energy difference, the resulting wavefunction (a combination of the symmetric and anti-symmetric functions) shows the N atom to be tunneling back and forth from one well to the other at the frequency of the applied field. The shape of the molecule and therefore that of the double well potential is a function of the rotational state of the molecule, with the result that the tunneling is observed at many different frequencies depending on the particular rotational state. Students measure a number of these frequencies and fit them to a model accounting for the rotational effects. Students also observe and measure hyperfine splitting due to the quadrupole moment of the N nucleus.

Optical Pumping in Rubidium. This elegant experiment introduces the double resonance technique, whereby magnetic resonance transitions are detected by optical absorption. Circularly polarized light from a Rb lamp passes through a cell containing Rb vapor. A weak magnetic field is applied to the cell, splitting the ground state sublevels. Transition rules are invoked to explain how the population of these sublevels becomes inverted, with the result that optical transitions from the ground state to the first excited state are greatly reduced. Re-distribution among the ground state sublevels is achieved by application of a radio-frequency field, resulting in increased optical absorption in the cell. The magnitude of the magnetic field is thus measured by frequency, a parameter readily measured to high accuracy, making this double resonance technique useful as a highly sensitive magnetic field probe.

Normal and Anomalous Zeeman Effects in Mercury. Students measure the magnetic splitting of the yellow (normal) and green (anomalous) lines of mercury, and learn about the physics accounting for the two quite different spectra. A high resolution Fabry-Perot interferometer is used to measure the spectral splitting as a function of applied magnetic field. Students also learn the physics of the Fabry-Perot interferometer, thereby gaining an understanding of how this device can provide such high resolving power.

Lamb Shift in Hydrogen. According to Arthur Schawlow, "The spectrum of the hydrogen atom has proved to be the Rosetta stone of modern physics: once this pattern of lines had been deciphered much else could also be understood." In the early 20th century the spectrum of atomic hydrogen was a key factor in the development of quantum mechanics. As experimentalists made more detailed measurements, increasingly refined theoretical models kept pace with explanations of the proliferating number of features in the hydrogen spectrum. But some measurements made in the 1930's hinted at a discrepancy for which even the Dirac theory could not account. In 1947 Lamb and Retherford measured the energy difference between the lowest $n = 2$, $S_{1/2}$ and $P_{1/2}$ states, predicted to be degenerate by the Dirac theory. This measurement provided one of the first tests for the now well-established theory referred to as quantum electrodynamics (QED), which continues to provide a benchmark against which increasingly refined versions of this theory are tested even today. In this experiment, atomic hydrogen is generated in a discharge tube, and students initially observe the Doppler broadened fine structure lines of the Balmer alpha transition at 656 nm. Then, deploying the technique of saturation spectroscopy, students record the Doppler-free spectrum, easily resolving the fine structure components of this line, and also the Lamb shift.

In addition to measuring the fine structure splittings and the Lamb shift, one can use the recorded linewidths to estimate the lifetimes of the various excited states.

Pulsed NMR. In this experiment students are introduced to the modern NMR techniques underlying such applications as magnetic resonance imaging and mapping the structure of complicated organic molecules. 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.