HANLE EFFECT

This experiment is useful in several ways: (1) it provides precise measurements of atomic lifetimes; (2) the method of precessing a radiation pattern to measure the product of magnetic moment x magnetic field is also used in nuclear and high energy physics ("perturbed angular correlation"); and (3) the phenomenon can be interpreted either quantum mechanically or classically, such dual interpretations deepening our understanding of quantum mechanics. This experiment is a particular case of a more general method used in atomic physics called the "level crossing technique" for measuring the width (lifetime) of atomic states.

THEORY:

The principle of this experiment can be understood by reference to Figure 1. Light polarized in the OY direction is incident along the X-axis on a scattering atom at the origin. The light is of just the right wavelength to induce a transition in the target atom. The excited atom then re-radiates after a characteristic lifetime τ,

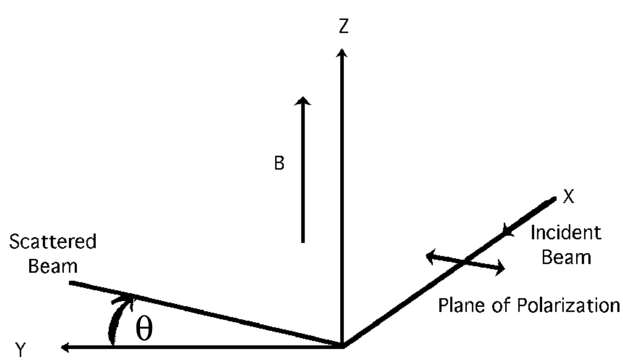

Figure 1. Geometry of the Hanle Effect experiment.

in a classical dipole distribution proportional to $\sin^2\theta$. If a B-field is applied in the OZ direction, the excited atom will precess about the OZ axis with a Larmor frequency $\omega_L = \mu B / J\hbar$, where μ is the magnetic moment of the excited state which has angular momentum $J\hbar$. The radiation field distribution precesses with the excited atom. The likelihood that the atom will radiate in the OY direction during the interval (t, t + dt) will now be given by $(e^{-t/\tau})(\sin^2\omega_L t)dt$ where the first factor reflects the exponential decay of the excited state, and the second factor makes allowance for the precession of the atom about the vertical axis. The observed intensity is given by integrating the expression above to infinity.

Radiation observed along 0Y;

$$\int_0^{\infty} e^{-t/\tau} \sin^2 \omega_L t dt = \frac{2\tau}{1/(\omega_L \tau)^2 + 4} \tag{1}$$

A plot of the intensity observed along the OY axis, as a function of B, has its minimum value at B (or ω_L) = 0, with an increase to one-half of its asymptotic value at $\omega_L t = 1/2$ or:

$$B_{1/2} = \frac{\hbar}{2 g_J \mu_0 \tau} \tag{2}$$

where μ_0 is the Bohr magneton and g_J is the electronic g factor for the excited state. The mean life τ can be determined from $B_{1/2}$ if μ is known ($\mu = g_J \mu_0 J$). These measurements always detect the product $\mu\tau$ and one must have additional information to get individual values of τ and μ. We will calculate the value of μ on the assumption that the state is described approximately by $\vec{L} \bullet \vec{S}$ coupling, in which case:

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

See the *Optical Pumping* writeup (Experiment 8) for the derivation. [The Lurio paper expression for I(τ) is incorrect. The correct expression is discussed by V. Leyva in the Hanle Effect Experiment Reference binder.]

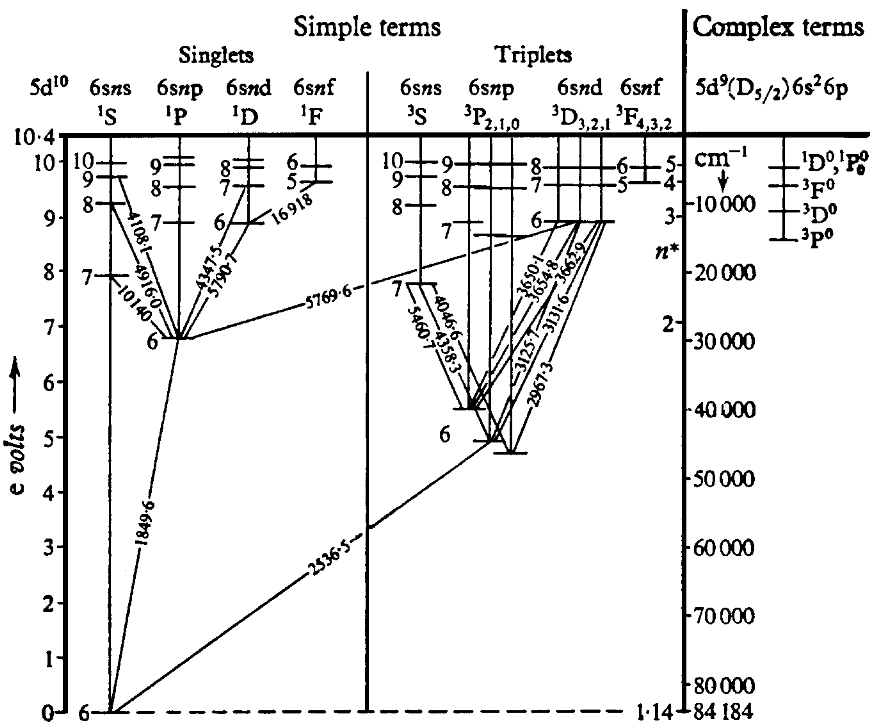

Figure 2. Term Diagram for Mercury (Hg).

THE EXPERIMENT

The optical system consists of a source arm and an orthogonal detector arm. The source arm contains a low-pressure mercury discharge lamp, a quartz collimating lens, and a UV-transmitting polarizing filter. The absorption/scattering cell is located at the intersection of the optical axes of the two arms. The detector arm contains a second UV-polarizing filter, a quartz lens to focus scattered light onto a detector, an interference bandpass filter centered on 253.7 nm (15.0 nm FWHM), and a UV-sensitive photomultiplier. Polarizing filters that function efficiently at the short UV wavelengths are used (ordinary "Polaroid" filters are totally opaque at UV wavelengths.) in both the lamp and detector arms. The description above of the principle of the experiment leaves out details such as incident line shape, trapping, collision broadening, etc. The reprint by de Zafra describes these complications and the analysis of results. The Franken and Happer papers go further into the theory.

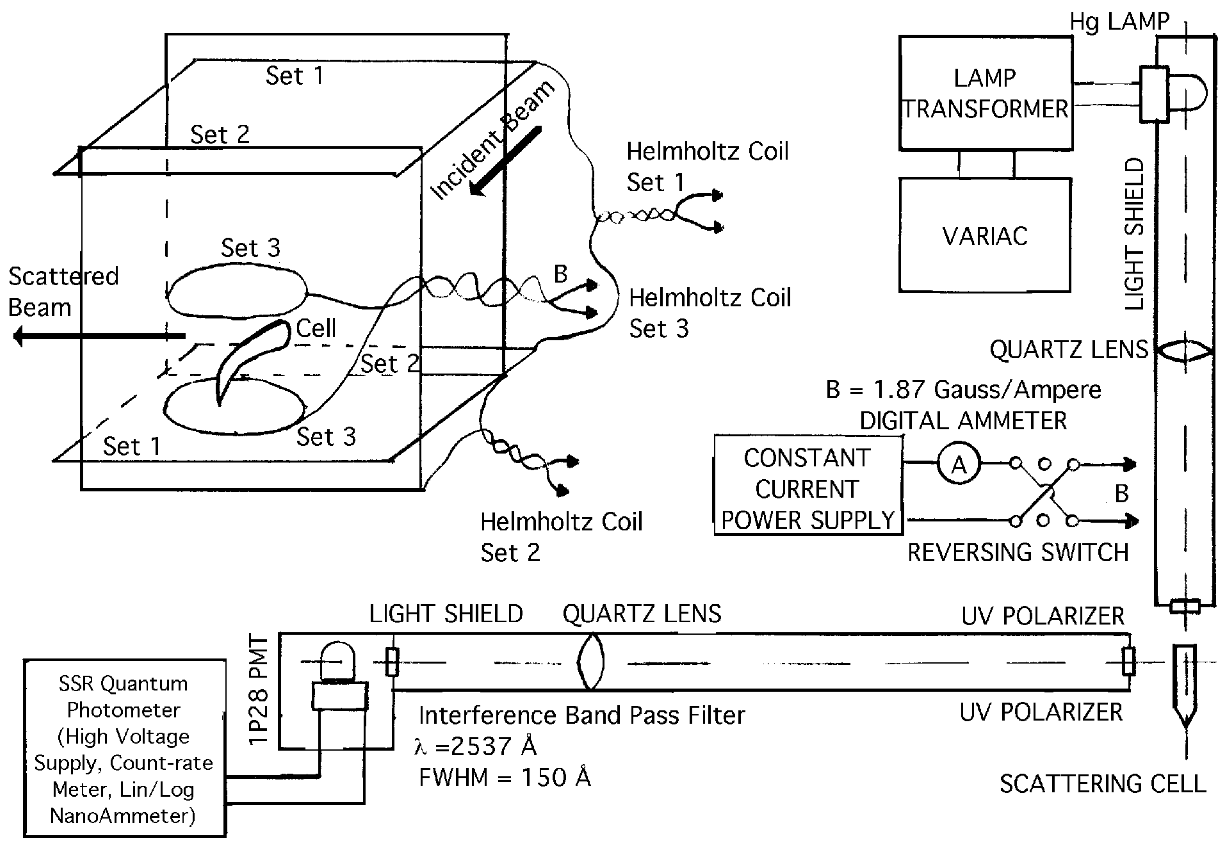

Figure 3. Experimental setup for the Hanle Effect experiment.

INSTRUMENTATION AND APPARATUS

LAMP:

The lamp consists of a pair of electrodes sealed into a synthetic quartz capillary that is folded into a hairpin shape. It is filled with natural abundance Hg at a low pressure (~1 atmosphere at operating temperature). An ideal light source would emit a spectrum that exhibits the natural width of the upper radiating $^3P_1$ state. (See the term diagram Figure 2.) However, if there are unexcited Hg atoms in the $^1S_0$ ground state, populating the hollow sheath surrounding the excited cylindrical core of the radiating source, these unexcited atoms will absorb some of the emitted radiation. If the absorbing atoms are cold, and the radiating atoms hot (the usual situation since the temperature will decrease from the centerline to the lamp wall), the spectral line emitted from the hot atoms is wider than the absorption line of the cooler atoms, and what escapes from the source has a dip in the middle. This phenomenon is called self-reversal. We can minimize this problem by running the source as cool as possible (by reducing the operating voltage). That action has the further benefit of reducing Doppler broadening by keeping the internal lamp pressure from rising excessively. **Caution:** The Hg lamp emits 95% of its energy in the 253.7 nm line. Don't look directly at the bare lamp for extended periods of time without eyeglasses. It also produces copious quantities of O_3 (ozone) when operated in open air. It is mounted in a closed housing to completely shield the UV from the user and minimize the production of O_3.

ABSORPTION/SCATTERING CELL:

The absorption cell, constructed from UV transmitting synthetic quartz, is known as a Wood's Horn. It is entirely covered with a black light-absorbing coating except for the entrance and exit windows. The shape, plus coating, insures a minimum of internal reflections so that incident light will encounter the resident Hg atoms only once before reflections alter its plane of polarization. Isotopically pure ^{198}Hg has been used for the absorption/scattering material, unlike the lamp which is filled with natural-abundance Hg (10% ^{198}Hg).

DETECTOR:

The detector (SSR Quantum Photometer) consists of a UV-sensitive photomultiplier (PMT), a high voltage power supply, and a count-rate meter/nano-ammeter. The operating voltage for the 1P28 PMT has been carefully adjusted to produce the maximum gain at minimum noise (i.e., the optimum signal-to-noise ratio), and is not altered by the user. The count-rate meter mode is used for very low intensities ($<10^8$ cps), while the nano-Ammeter (nA) mode (normally used) extends measurement capability to higher intensities. The nA mode allows selection of several integration times to average out statistical fluctuations and noise. The integration time constant chosen will be a compromise between low statistical uncertainty and realistic response time. An adjustable zero offset is also available that allows easy examination of a small percentage change in signal strength. The UV interference filter installed at the PMT entrance window passes only the wavelength of interest, substantially improving the signal-to-noise ratio of the system, while insuring that room lighting will neither damage the PMT photocathode nor seriously influence the intensity data.

FIELD COMPENSATION COIL SETS 1 & 2:

It is necessary to cancel out the ambient magnetic field at the Hg cell. This is accomplished with two pairs of rectangular coils (Sets 1 & 2), in the Helmholtz configuration, driven by two independently adjustable power supplies. Careful positioning of the plane of one pair normal to the horizontal component of the ambient field (rotating the entire experiment on the table), allows the use of only two pairs of coils instead of three. The two power supplies are operated in their Constant Voltage mode, since the current required is too small for sensitive current adjustment or regulation when the supply is in the Constant Current mode..

MAGNETOMETER:

An air-driven magnetometer is used for the adjustment of the currents through the field-canceling coils. This is a sphere of copper [Oxygen-Free High-Conductivity (OFHC) grade], supported on non-magnetic copper-beryllium ball bearings and rotated about its axis by two jets of air. A central hole has been drilled through the rotor at right angles to the axis of rotation. Two 10,000 turn coils, connected in series-aiding, closely surround the rotor. When the Cu sphere rotates, it is a single turn that cuts any magnetic field lines that may be present. Large eddy currents are induced in the low-resistance single turn which then induce a signal in the fixed coils. It is this signal that is displayed on the Oscilloscope (CRO). *The ball bearings are not as hard or durable as ordinary hardened steel (magnetic) ball bearings, which limits the speed of rotation to <600 rps, i.e., a driving air pressure of less than 2-3 psi.* The Tektronix 503 CRO is operated in the Differential Input mode to suppress rather large common-mode signals at line frequency and its harmonics.

HELMHOLTZ COIL SET 3:

A known magnetic field can be applied to the scattering cell by means of a third set of coils (Set 3), a circular pair, also in the Helmholtz configuration. A stable regulated power supply (in Constant-Current mode), a reversing switch, and a digital Ammeter complete this system. ***The field conversion factor for this pair is 1.87 Gauss/Ampere.***

DATA ANALYSIS:

The laboratory PCs contain useful programs for analyzing the data from this experiment. Math CAD and FFIT are available, and Curvefit (Mathematica) and FFIT are quite capable of fitting a Lorentzian.

PRELAB EXERCISE

1. Read the de Zafra paper to understand the principles of the experiment.

2. Estimate $B_{1/2}$ for the $^3P_1$ state of Hg (τ = ~10^{-7} sec [See TASK 7.]) for the current geometry. How does this compare to the earth's magnetic field and any stray fields expected in the laboratory?

EXPERIMENTAL TASKS:

1. Replace the Hg cell with the Vantson magnetometer by rotating the support. A manual describing the magnetometer is available. In essence, it is a generator with output voltage:

$$V(peak-to-peak) = \left(2.86x10^{-4}\,\tfrac{V\cdot S}{Gauss}\right) B/T, \tag{4}$$

where T is the period of the AC output of the generator. Drive the magnetometer with compressed air at about 2-3 psi pressure. Trigger the CRO from the 60 Hz LINE and "tweak" the rotor speed (air pressure) to obtain a stable display at a precise harmonic of 60 Hz. Adjust the currents in the horizontal and vertical bucking coils to minimize the output voltage when the magnetometer axis is oriented properly. The axis of rotation is perpendicular to the disk containing the air inlet and output connector. A small AC field will persist and cannot be canceled with the present arrangement. What is the source of this field? What is the minimum DC field you can produce at the absorption cell? What are the magnitudes of the two components of the ambient DC magnetic field? Record the voltage settings for the two bucking coils and keep them constant for the duration of the experiment.

2. Familiarize yourself with the operation of the photometer. A separate manual on the SSR photometer is available.

3. Turn on the Hg lamp, beginning with a Variac voltage of 100 V. If the lamp starts to flicker, increase the voltage slightly (1-2 V) until the flicker stops. Wait 15-20 minutes for equilibrium to be reached. The lamp should be run at a voltage that is low enough to produce narrow emission lines without flicker, but high enough (<105 V) to give a good signal-to-noise ratio.

4. Adjust the magnetic field produced by the Helmholtz coils (Set #3) to find the minimum and maximum photometer readings. Set the magnetic field such that photometer reads halfway between minimum and maximum

values and check the peak symmetry when the field is reversed. If asymmetry is more than a few percent, and if the earth's magnetic field has been properly minimized, the polarizer(s) probably needs adjustment. Ask instructor for help.

5. Measure and plot the yield of photons scattered at 90° as a function of B (vertical) produced by the Set #3 Helmholtz coils. Repeat the measurements enough to make certain that lamp intensity and scattering cell temperature are not drifting rapidly with time. Even if you have evidence of a slow time dependence, you can make an accurate measure of the half-width of the current dip by measuring the depth of the dip and then setting the current quickly to give a signal at half the full magnitude. Reverse the current to see whether the dip is symmetrical about $B_{vert} = 0$·

6. Repeat step (5) when the tip of the cell is placed in ***cool** water from a refrigerated water cooler*. Ice water, or colder baths, will be too cold, reducing the Hg vapor pressure in the absorption cell to a level too low to produce a usable signal.

7. Compute the lifetime of the $^3P_1$ state of Hg. Explain the temperature dependence of your results. Compare with the accepted value of τ = 118 ns ± 3% (Radzig & Smirnov). Mathematica 3.0, Math CAD and FFIT, on the PC's, are available for fitting Lorentzians.

QUESTIONS:

(1) How much of your B = 0 signal is due to dark current? How much to room lights? Where does the rest come from?

(2) Why do you want the Hg lamp cool?

(3) How will self reversal of the 253.7 nm line from the Hg lamp affect the shape of the light curve? How will it affect the determination of the $^3P_1$ lifetime?

(4) How does the number of Hg vapor (atoms/cm^3) vary with temperature? How does this affect the coherent-trapping process? How does this in turn influence the "lifetime" that you observe? Could you remove one of the polarizers and still get good data? Which one is most important? How would you correctly set the UV Polarizers when setting up an experiment for the first time?

(5) Why was expensive isotopically pure ^{198}Hg used to fill the scattering cell? How would the data be altered if natural abundance Hg were substituted?

(6) Why is the scattering cell shaped, and coated, the way it is? Would satisfactory results be obtained if the simpler right-cylindrical geometry had been used?

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