Measurement of the Electron "g-factor" $g_e$ via Electron Spin Resonance

Theoretical Background:

The electron is a fundamental particle which can be characterized by its mass ($m_e$), charge ($-e$), and intrinsic magnetic moment ($\mu$). The latter quantity can be written in terms of the electron spin as $\mu = g_e(-e/2m_e)S$ where $g_e$ is the electron "g-factor". In a magnetic field (oriented in the $z$-direction) the electron experiences an interaction energy of $U_B = -\mu \cdot B = -\mu_z B_z = g_e(e/2m_e)S_z B_z$ where $S_z = +h/2$ or $-h/2$. Note that the low energy state is the one in which the electron spin is aligned against the magnetic field ("spin-down"). It is convenient to describe magnetic moments in atomic systems in terms of the Bohr magneton which is defined as $\mu_B = e h / 2 m_e = 9.274 \times 10^{-24}$ J/T. Thus, the magnetic moment of a spin-up electron is $\mu_z = -(g_e/2) \mu_B$ and the energy difference between the spin-up and spin-down states for an electron in a magnetic field is simply given by $|\Delta U_B| = 2\mu_z B_z = g_e \mu_B B_z$. A transition from the low energy spin-down state to the high energy spin-up state can be driven by the absorption of a photon of energy $E_{\text{photon}} = hf = |\Delta U_B|$. This induced spin-flip process is known as electron spin resonance or ESR. In this experiment we will use ESR to measure the value of the electron's g-factor.

Experimental Apparatus:

The ESR apparatus consists of a set of Helmholtz coils that produce a milli-Tesla magnetic field and a radio frequency (MHz) oscillator which drives a small probe coil. This probe coil is positioned in the center of the magnetic field (i.e., between the Helmholtz coils) in a perpendicular orientation such that a sample can be inserted inside it. The probe coil can be run at three different fixed frequencies of about 45, 60, and 75 MHz (corresponding to the LO, MID, and HI settings on the console). The exact oscillator frequency can be read from the attached digital frequency counter (set to 1 MΩ input; reading is in MHz, but console outputs frequency/1000). The Helmholtz coils are driven with a linear ramp current which varies from 0 to 250 mA in a sweep time of 40 ms. This produces a magnetic field at the center of the coils which varies linearly from 0 to $3.67 \times 10^{-3}$ Tesla (when the two Helmholtz coils are maximally separated). A voltage signal (0 to 1.0 V) proportional to this magnetic field is output on channel 1 of the console and should be monitored on Channel 1 of the oscilloscope. An inverted voltage signal from the high frequency oscillator circuit is output on channel 2 of the console and should be monitored on channel 2 of the oscilloscope. A peak is observed when energy is being drawn from the oscillator (which happens when the electron spin-flip resonance condition is met). The sample used in this experiment is the paramagnetic compound diphenyl-picri-hydrazyl (DPPH) which contains a loosely bound, unpaired electron.

*Dirac's original relativistic treatment of quantum theory predicts that $g_e = 2$. A lack of agreement between this prediction and experimental measurements led to the development of Quantum Electrodynamics (QED) by Feynman and others.*
**Procedure:**

The DPPH sample is in a glass tube with an orange cap. The sample tube should be inserted into the high frequency probe coil (from the back side of the apparatus). The two console output channels should be attached to the oscilloscope and the initial oscilloscope setup should be as follows:

Both channels: 200 mV/division; dc coupled; probe=1X. Timebase: 5 ms/division.

Trigger: source=CH 1; type=edge; mode=normal (or noise reduce), coupling=DC (or HF reject).

When the console and the ESR apparatus are powered up you should get a linear ramp voltage on channel 1 of the scope. You should also see a peak in the channel 2 output. You may have to adjust the trigger level control to get a stable trace.

If no peak is evident on Channel 2 (or the peak is small) you will need to adjust the sensitivity of the oscillator circuit. You do this by turning the small screw marked SENS on the high frequency oscillator unit. (CAUTION: be VERY CAREFUL in adjusting the SENS screw). The circuit is tuned to maximum sensitivity (corresponding to "marginal" oscillation) when the signal level LED on the console begins to dim. The more marginal the oscillator, the better the peak signal-to-noise ratio. If the oscillator is made too marginal it will stop running and the console signal level LED will go out. If this happens turn the SENS screw on the oscillator counterclockwise until the LED is re-illuminated.

Once you have a good signal peak, use the cursors on the oscilloscope to determine the peak location (relative to the voltage ramp) and thus the magnetic field strength. For this you need to measure the time difference between the start of the voltage ramp ($t_0$) and the resonance peak ($t_R$) in order to compute the magnetic field at resonance $B_R$. You may want to freeze the scope display (by pressing the "run/stop" button) to make accurate measurements. Use the width of the resonance peak (at "half max") to estimate an uncertainty for these $B_R$ values. You can save the scope display to a flash drive to include with your write-up. Verify that your signal is due to the DPPH sample by removing the sample and inserting an empty sample tube (black cap) into the probe coil.

**Analysis and Write-up:**

For data analysis, use LinReg to make a plot of the frequency at resonance $f_R$ versus magnetic field strength at resonance $B_R$. Include error bars for $B_R$. From the slope of the resulting line obtain a value for the electron $g$-factor $g_e$ (including an uncertainty estimate).

Your write-up should include a typed table of your data (i.e., $f_R$, $t_0$, $t_R$, and $B_R$). You need to show how you correlate the time data with the channel-2 voltage ramp to determine the magnetic field $B_R$ at the absorption peak. This is best done by clearly annotating the printouts of the scope display.