Spin Polarization and Zeeman Splitting Simulation

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Introduction

Spintronics (spin transport electronics) explores the manipulation of the electron's spin degree of freedom in addition to its charge. One fundamental concept in spintronics is the control of spin polarization under external magnetic fields, governed by the Zeeman effect.

Zeeman Effect

The Zeeman effect refers to the splitting of degenerate energy levels in an atom or a system of electrons when an external magnetic field B is applied. For a free electron:

$$\Delta E = g\mu_B B \tag{1}$$

Here,

- $g \approx 2$ is the Landé g-factor,
- $\mu_B = 9.274 \times 10^{-24}$ J/T is the Bohr magneton,
- B is the applied magnetic field in Tesla.

This causes the energy levels for spin-up (↑) and spin-down (↓) states to split as:

$$E_\uparrow = -\mu_B B \tag{2}$$
$$E_\downarrow = +\mu_B B \tag{3}$$

Spin Polarization

The spin polarization P is a measure of imbalance in population between spin-up and spin-down electrons. It is defined as:

$$P = \frac{n_\uparrow - n_\downarrow}{n_\uparrow + n_\downarrow} \tag{4}$$

Assuming thermal equilibrium, the populations follow Boltzmann distribution:

$$n_\uparrow \propto \exp\left(\frac{-E_\uparrow}{k_B T}\right) = \exp\left(\frac{\mu_B B}{k_B T}\right) \tag{5}$$
$$n_\downarrow \propto \exp\left(\frac{-E_\downarrow}{k_B T}\right) = \exp\left(-\frac{\mu_B B}{k_B T}\right) \tag{6}$$

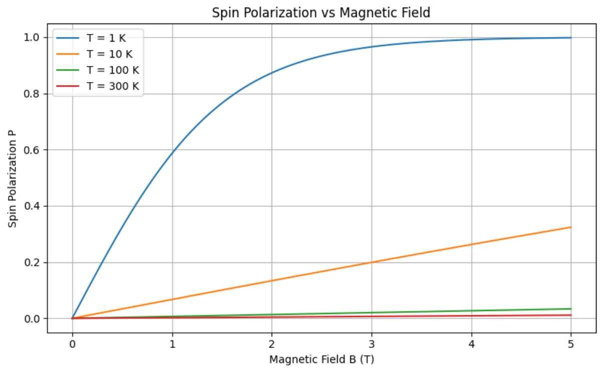

Figure 1: Spin Polarization vs Magnetic field at different T values

Substituting these into the expression for P:

$$P = \tanh\left(\frac{\mu_B B}{k_B T}\right) \quad (7)$$

Observations

- At low temperatures ($T \to 0$), $P \to 1$, indicating full spin polarization.
- At high temperatures ($T \to \infty$), $P \to 0$, indicating nearly equal spin populations.
- The spin polarization increases with increasing magnetic field strength B.

1 Simulations

Spin Polarisation and Magnetic field dependence were simulated using Python programming. Behaviour was observed for T = 1K, 10K, 100K and 300K.

Conclusion

This theoretical framework of Zeeman splitting and spin polarization forms the foundation of various spintronic phenomena. By controlling the external magnetic field and temperature, one can manipulate the spin populations in a material — a core principle leveraged in devices like spin valves, magnetic tunnel junctions, and spin transistors.

2 References

Yuan, H., Bahramy, M., Morimoto, K. et al. Zeeman-type spin splitting controlled by an electric field. Nature Phys 9, 563–569 (2013). https://doi.org/10.1038/nphys2691