Sensitivity of Optically Enhanced Magnetic Resonance

While magnetic resonance is one of the less sensitive spectroscopic techniques, there are a number of possible means to correct this deficiency. Optical techniques provide some of the most compelling success stories, including many experiments with single electronic or nuclear spins. Compared to conventional magnetic resonance, the sensitivity can be increased by up to 20 orders of magnitude, depending on the system. Different factors contribute to this enormous gain in sensitivity, but the two most important ones are polarization and detection sensitivity.

Polarization

The magnetic resonance signal is generally proportional to the degree of polarization of the spins, i.e. to the fraction

$$p = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow},$$

where $N_\uparrow$ is the number of spins parallel to the magnetic field and $N_\downarrow$ the number of spins antiparallel to the field. In conventional magnetic resonance, this fraction is determined by the Boltzmann factor, which is of the order of $\approx 10^{-5}$ for nuclear spins. If optical pumping is used to prepare the spins, it is possible (in favorable cases), to achieve almost complete spin polarization, thus increasing the signal by up to 5 orders of magnitude.

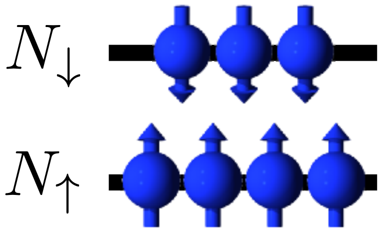

Figure 1: Spin polarization

Detection

Conventional magnetic resonance detects the spins by measuring the voltage induced by the magnetization precessing in the static magnetic field. Quantum mechanically, this corresponds to the detection of photons with an energy of $h\nu_{rf} \approx 2 \cdot 10^{-25}$ J. This signal energy is much smaller than that of the thermal energy of the system at most laboratory temperatures. It is therefore (so far) not possible to detect single radio-frequency photons, and only at very low temperature was it possible to detect individual microwave photons. In the case of optical detection, however, the signal is carried by optical photons, whose signal energy $h\nu_{opt} \approx 3 \cdot 10^{-19}$ J is significantly larger than typical thermal energies. It is therefore relatively easy to detect single optical photons and thereby single electronic or nuclear spins.