Rapid Single-Shot Measurement of a Singlet-Triplet Qubit

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Accessibility
In one of the experiments described in the accompanying Letter, “Rapid Single-Shot Measurement of a Singlet-Triplet Qubit”, two electrons in a double quantum dot are initialized in the singlet state, then brought to the antiresonance the lower branch of the hybridized singlet, $S$, and the $m = +1$ triplet, $T_+ = |1 + 1\rangle$. The hyperfine interaction felt by the electrons due to the large number ($\sim 10^6$) of nuclei in the host material is treated as an effective classical Zeeman (Overhauser) field acting on the electrons. The Overhauser field is further assumed to be static on time scales of the electron dynamics. Near the $S - T_+$ resonance, the difference in transverse components of the Overhauser fields in the left (L) and right (R) dots, $\Delta B_z(x) = |B_z^L(x) - B_z^R(x)|/2$ mix singlet and triplet state, while the average longitudinal Overhauser field, $B_z = \langle B_z^L + B_z^R \rangle/2$, acts as a random energy detuning. An external magnetic field, $B$, defines the quantization axis $z$. This supplementary note presents a derivation of the triplet probability, $P_T$, used to fit experimental data in Fig. 4(b), following Ref. [3]. The Hamiltonian in the basis $(S, T_+)$ is [1, 2]

$$H = g^* \mu_B \left( -\frac{J}{(g^* \mu_B)} \cos \theta \frac{B+/\sqrt{2}}{B + B_±} \right),$$

(1)

where $\cos \theta$ is the (1,1) component of the hybridized singlet ground state, $|S⟩ = \cos \theta |(1,1)S⟩ + \sin \theta |(0,2)S⟩$ and $B_± = \Delta B_x ± i\Delta B_y$. The effective electron $g$-factor is $g^* = -0.44$. An additional factor $\sqrt{2}$ in the numerator of the off-diagonal term stems from constructive interference of two electron spin flip - pathways, since there are two electrons participating [1]. The exchange, $J$, the external magnetic field, $B$, and the nuclear Overhauser $z$-component, $B_z$, are combined to the energy mismatch $\delta = -g^* \mu_B (B + B_z) - J$. In the described experiment the exchange is tuned to resonance, leaving $\delta = -g^* \mu_B B_z$. For an initial singlet $c_T(\tau_1) = 0$ the solution for the probability amplitude, $c_T(\tau_1)$, is [4]

$$c_T(\tau_1) = \frac{\cos \theta (\Delta B_x + i\Delta B_y)}{\sqrt{2} \hbar \omega |g^* \mu_B|} \sin (\omega \tau_1),$$

(2)

with the precession frequency, $\omega$,

$$\omega = \frac{1}{2\hbar} \sqrt{\delta^2 + 2 \cos^2 \theta (g^* \mu_B)^2(\Delta B_x^2 + \Delta B_y^2)} = \frac{|g^* \mu_B|}{2\hbar} \sqrt{B_z^2 + 2 \cos^2 \theta (\Delta B_x^2 + \Delta B_y^2)}.$$

(3)

The nuclear Overhauser field $z$-component, $B_z$, and the gradient fields, $\Delta B_x$ and $\Delta B_y$, are not known and constant, but distributed according to the distribution function $\rho(B) = (2\pi B_{\text{nuc}})^{-3/2} e^{-|B/(B_{\text{nuc}})|^2/2}$, with $B = (\Delta B_x, \Delta B_y, B_z)$. The evolution of the nuclear fields is slower than the evolution of the electron spin, hence the triplet probability for an ensemble of measurements, $P_T^{\text{ideal}}(\tau_1)$, can be written as the integral of all probabilities for a single constant Overhauser field, weighted by $\rho(B)$,

$$P_T^{\text{ideal}}(\tau_1) = \int d^3B \rho(B) c_T(\tau_1)c_T^*(\tau_1) = \int d^3B \rho(B) \frac{\cos^2 \theta (\Delta B_x^2 + \Delta B_y^2)}{2(\hbar \omega |g^* \mu_B|)^2} \sin^2 (\omega \tau_1).$$

(4)

The evolution occurs far detuned from the (1,1)-(0,2) charge degeneracy, therefore the hybridized singlet is approximately identical to the (1,1) singlet, and $\cos \theta \sim 1$. Furthermore allowing an offset, $P_T^0$, of $P_T$, because of imperfect preparation or miscounting of singlets as triplets and a smaller than one visibility, $V$, yields the equation in the paper:

$$P_T = P_T^0 + V \int d^3B \rho(B) \frac{\Delta B_x^2 + \Delta B_y^2}{2(\hbar \omega |g^* \mu_B|)^2} \sin^2 (\omega \tau_1).$$

(5)
which describes the measured triplet probability, averaged over many singleshot measurements.