Scientific background to subbin code

Sandeep Mavadia

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Qubit projection estimation

We use the photon information we collect from the ion to determine the projected state of the qubit after each repetition of an experiment. This is done via a Markov model initially published for $^{171}\mathrm{Yb}^+$ in ref. [1]. For the RB experiments described in the main text we combine this information over r repetitions to calculate the most likely projection of the Bloch vector on the z-axis. This methodology has a reduced measurement error compared to a simple threshold detection technique that assigns a state based on whether the total number of detected photon counts is above or below a certain level.

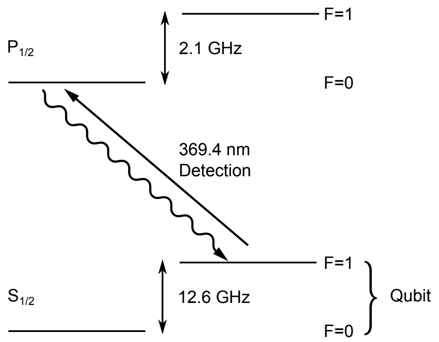

Figure 1: Relevant energy levels for $^{171}\mathrm{Yb}^+$ and their energy splitting, with the Zeeman structure omitted. The qubit is encoded in the $\mathrm{S}_{1/2}$, $F = 0, m_F = 0$ and $\mathrm{S}_{1/2}$, $F = 1, m_F = 0$ states and controlled via microwave radiation resonant with a magnetic dipole transition at 12.64 GHz.

To detect the state of the ion at the end of a sequence of microwave-driven rotations, we apply light at 369.4 nm resonant with the optical dipole transition between the $\mathrm{S}_{1/2}$, $F = 1$ and $\mathrm{P}_{1/2}$, $F = 0$ states (Figure 1). During this detection period, an avalanche photodiode registers photons that are scattered if the qubit was projected into the $|F = 1, m_F = 0\rangle$ state, hence denoted "bright state", and no photons if the qubit was projected into the $|F = 0, m_F = 0\rangle$ "dark" state.

Due to the proximity of the other electronic levels in the S and P manifolds, off-resonant excitations (proportional to the applied laser power) can occur and change the state of the qubit during the detection period, adversely affecting the detection fidelity. The rate at which these changes occur can be expressed in terms of a bright (dark) state lifetime τ_{B} (τ_{D}).

Rather than simply considering a single transition between the bright and dark states (or vice versa) we can generalise this to multiple transitions within a single measurement detection period [1]. To identify these individual transitions we split the photon detection time into equal length sub-bins and make the assumption that there is at most one transition between bright and dark state per sub-bin. We then use the number of photons within each sub-bin and the distribution of photons across sub-bins within a single detection period to determine the likelihood of the ion initially having been projected into the bright or the dark state. For full details of this procedure and a mathematical derivation, see [1].

In this work we employed a detection time of 800 µs split into 5 sub-bins of 160 µs length. In each experimental repetition we calculate the mean detected photon rate in the bright state, R_B, and the dark state, R_D, by fitting a double Poisson function to a histogram of the entire data set. Typical values are $R_D \approx 0.5\,\mathrm{kHz}$ (resulting from laser scatter and detector dark counts) and $R_B \approx 40\,\mathrm{kHz}$. For a given detection laser power, the decay rates $\tau_{B,D}^{-1}$ are obtained from a separately performed calibration where we initialise the ion in either the bright or dark state and then observe the average photon count rate over many repetitions as a function of detection time. Average rates are calculated to be $\tau_B^{-1} \sim 264\,\mathrm{Hz}$ and $\tau_D^{-1} \sim 20\,\mathrm{Hz}$.

In addition to analysing photons in the detection period using sub-bins, we also remove experimental repetitions which do not emit a certain number of photons during the laser cooling period prior to the microwave rotations. This accounts for the rare occurrences when the ion is subject to a collision or other heating effect that may impact the efficacy of the experiment.

This procedure is carried out for both RB and GST experiments. However, from this point on, the data are treated differently between the two classes of experiments. For GST experiments we take the most likely outcome for each single repetition, either bright or dark at the beginning of the detection period, and use these outcomes to produce a dataset to input into the pyGSTi software package. For each sequence in the RB experiments, by contrast, we calculate the most likely projection ϕ along the z-axis, in this context related to the RB survival probability $\mathcal{P}$ as $1-\mathcal{P}$. To do this we implement a Bayesian approach to find the probability distribution over all possible projections. The distribution is discretised in steps of 10^{-3} and initialised such that the likelihood of measuring any projection along the z-axis is equal,

$$\Pr(\phi) = 1/K, \tag{1}$$

where K is a normalisation term. We then condition this probability on the observed photon distribution, p_φ, such that

$$\Pr(\phi|p_\varphi) = K^{-1} \prod \Pr(p_\varphi|\phi) \tag{2}$$

where $\Pr(p_\varphi|\phi)$ is calculated from the likelihood of finding the qubit in either the $|1\rangle$ or $|0\rangle$ state,

$$\Pr(p_\varphi|\phi) = \Pr(p_\varphi||1\rangle)\Pr(|1\rangle|\phi) + \Pr(p_\varphi||0\rangle)\Pr(|0\rangle|\phi). \tag{3}$$

The terms $\Pr(p_\varphi||1\rangle)$ and $\Pr(p_\varphi||0\rangle)$ are the likelihoods of measuring the photon distribution p_φ given that we start in the bright or dark state respectively and are calculated via the Markov model described above. The values $\Pr(|1\rangle|\phi)$ and $\Pr(|0\rangle|\phi)$ are the probabilities of projecting the qubit into either the $|1\rangle$ or $|0\rangle$ state during detection given a particular ϕ. We incrementally update $\Pr(\phi|p_\varphi)$ by adding information for each repetition across all of the noise realisations. To find the most likely outcome for a particular sequence we then calculate the mean of this distribution.

References

[1] S. Wölk, C. Piltz, T. Sriarunothai, Theeraphot, C. Wunderlich, J Phys B, State selective detection of hyperfine qubits, **48**, 7, 075101, 2015.