

Precision measurement of lifetime and branching ratios of the $4f^{13}5d6s^1[5/2]_{5/2}$ state in Yb^+ ions

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We report spectroscopic and time-resolved experimental observations to characterize the $[\text{Xe}]4f^{13}(^2F_{5/2})5d6s(^1D)^1[5/2]_{5/2}^o$ state in $^{172}\text{Yb}^+$ ions. We access this state from the metastable $4f^{14}5d(^2D_{3/2,5/2})$ manifold and observe an unexpectedly long lifetime of $\tau = 37.9(9)\mu\text{s}$ that allows visible Rabi oscillations and resolved-sideband spectroscopy. Using a combination of coherent population dynamics, high-fidelity detection and heralded state preparation, and optical pumping methods, we measure the branching ratios to the $^2D_{3/2}$, $^2D_{5/2}$, and $^2S_{1/2}$ states to be 0.359(2), 0.639(2), and 0.0023(16), respectively. The branching ratio to the $4f^{13}6s(^2F_{7/2})$ is compatible with zero within our experimental resolution. We also report measurements of Landé g -factor of the $^1[5/2]_{5/2}^o$ state. Further, the branching ratio of the $^2D_{5/2}$ to $^2S_{1/2}$ decay in $^{172}\text{Yb}^+$ was measured to be 0.188(3), improving its relative uncertainty by an order of magnitude. Our measurements provide experimental benchmarks for better understanding the atomic structure of Yb^+ ions, which still lacks accurate numerical descriptions, and the use of high-lying excited states for partial detection and qubit manipulation in the *omg* architecture.

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I. INTRODUCTION

Trapped ions are a pristine quantum platform used for diverse applications, including quantum information processing [1], quantum simulation [2], and quantum metrology [3]. In particular, Yb^+ ions are a workhorse for these applications: They feature long-lived quantum memory [4] and high-fidelity single- and two-qubit gates [5], and are routinely used for the quantum simulation of spin [6–8] and spin-boson models [9–11]. Yb^+ ions also provide multiple clock transitions [12], making them one of the most attractive ions to develop optical frequency standards [13]. Additionally, they feature a large number of stable isotopes, making them a promising candidate for new boson searches via nonlinearities in King’s plots [14–16].

Despite its prominence in many applications, the atomic levels of singly ionized Yb atoms still cannot be accurately predicted by existing numerical methods [18,19] due to their extremely complex electronic structure that involves 13 or 14 electrons occupying the inner-shell $4f$ orbital. Since low-lying core-excited configurations, such as $4f^{13}6s^2$ and $4f^{13}5d6s$, strongly mix with valence configurations, core-valence correlations have to be accurately taken into account

to predict the matrix elements and energy levels [18,20–24]. For example, the theoretical prediction of the lifetime of the $4f^{13}6s(^2F_{7/2})$ state (1×10^8 s) [25] is 20σ away from the latest measured experimental value ($4.98(25) \times 10^7$ s) [26]. In the case of high-lying excited states, predictions of the matrix elements are even more challenging because an untreatable number of electron configurations, including both valence and core-excited ones, strongly mix and need to be considered [27].

One of these high-lying atomic levels, $4f^{13}(^2F_{5/2})5d6s(^1D)^1[5/2]_{5/2}^o$ (in the following, abbreviated as $^1[5/2]_{5/2}$), has recently attracted interest [28] as it could provide a convenient way to dissipatively initialize the metastable state qubit in the *omg* architecture with $^{171}\text{Yb}^+$ [29], potentially faster than relying on the natural decay from $^2D_{5/2}$ state to $^2F_{7/2}$ state [30,31]. The $^1[5/2]_{5/2}$ state forms an almost perfect “rhomboid” of frequencies with the $^2S_{1/2}$, $^2D_{3/2}$, and $^2D_{5/2}$ states as all the four transitions connecting them lie in the same spectral region (410, 411, 434, and 435 nm) and, therefore, can be excited by tuning the same lasers used for the $E2$ $^2S_{1/2} \leftrightarrow ^2D_{3/2}$, $^2D_{5/2}$ transitions (see Fig. 1). In Ref. [32], the absolute frequencies, isotope shifts, and hyperfine splittings of the $^1[5/2]_{5/2}$ state have recently been measured by exciting the $^2D_{3/2} \rightarrow ^1[5/2]_{5/2}$ transition at 410 nm. However, no detectable branching ratio to the $^2F_{7/2}$ state has been reported.

In this work, we report the direct measurement of the lifetime and branching ratios of the $^1[5/2]_{5/2}$ state by using a combination of heralded state preparation, optical pumping, and coherent drive of the $^2D_{5/2} \leftrightarrow ^1[5/2]_{5/2}$ and $^2D_{3/2} \leftrightarrow ^1[5/2]_{5/2}$ transitions at 434 and 410 nm, respectively

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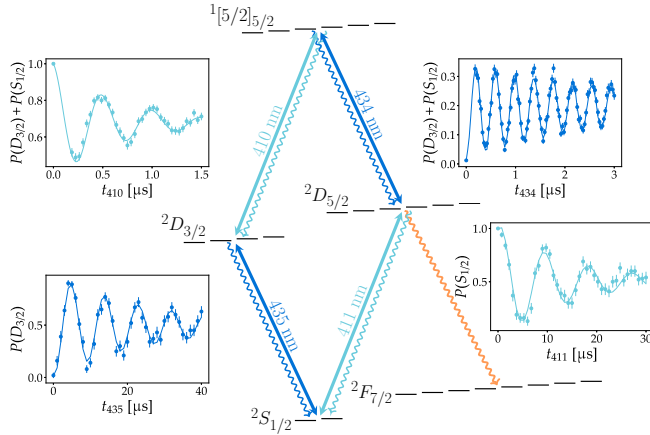


FIG. 1. Level scheme: Rabi oscillations observed on $^2S_{1/2} \leftrightarrow ^2D_{3/2} (^2D_{5/2})$ and $^2D_{3/2} (^2D_{5/2}) \leftrightarrow ^1[5/2]_{5/2}$ transitions. The maximum population inversion of the $^2D_{3/2} (^2D_{5/2}) \rightarrow ^1[5/2]_{5/2}$ transitions is limited by the total branching ratio to the $^2D_{3/2}$ and $^2S_{1/2}$ states, $b_{D_{3/2}} + b_{S_{1/2}} = 0.361(2)$. The solid lines are the OBE fits with the Rabi frequencies as free parameters, resulting in $\Omega/2\pi = (110.3, 112.3, 2609.5, 2013.8)$ kHz for the four (435, 411, 434, and 410 nm) transitions (see the Supplemental Material [17] for the relevant pulse sequences). Each data point is the average of 500 experimental runs, and the error bars are ± 1 standard deviation from the mean.

(see Fig. 1). The $^1[5/2]_{5/2}$ state is thought to have a 0.12 mixing with the $4f^{13}(^2F_{7/2})5d^2(^3F)$ configuration [33,34]. Therefore, the naive expectation is that the $^2D_{3/2,5/2} \leftrightarrow ^1[5/2]_{5/2}$ transitions are dipole allowed since they also have opposite parity and $\Delta J = 0, 1$. However, we measure a long lifetime ($\tau = 37.9(9)\mu\text{s}$), which allows the observation of distinct Rabi oscillations on both $^2D_{3/2,5/2} \leftrightarrow ^1[5/2]_{5/2}$ transitions, when driving them with a narrow-linewidth laser locked to an ultralow-expansion (ULE) cavity (~ 2 kHz linewidth) with an intensity higher than the saturation intensity of the transition. We further quantify the branching ratios to the $^2D_{3/2}$, $^2D_{5/2}$, $^2S_{1/2}$, $^2F_{7/2}$ states and also perform a measurement of the Landé factor g_J of the $^1[5/2]_{5/2}$ state. So far, there is no theoretical prediction available for the lifetime and branching ratios of the $^1[5/2]_{5/2}$ state.

II. LIFETIME MEASUREMENT

The experiments are performed on a single $^{172}\text{Yb}^+$ ion confined in a Paul trap with radial trap frequencies $(\omega_x, \omega_y)/2\pi = (3.31, 3.86)$ MHz and axial trap frequency $\omega_z/2\pi = 0.93$ MHz (see Ref. [10] for more details). The ion is Doppler cooled using the near-cycling transition $^2S_{1/2} \leftrightarrow ^2P_{1/2}$ at 370 nm, together with a 935 nm repumper addressing the $^2D_{3/2} \leftrightarrow ^1[3/2]_{3/2}$ transition (see Fig. 2 and Ref. [35]). Doppler cooling leads to a thermal population of $\bar{n} \sim 6.5$ in the radial direction and $\bar{n} \sim 22$ in the axial direction, which causes the decay of the oscillations in Fig. 1 due to the dependence of the Rabi frequency on phonon average occupation number [36].

Two laser beams at 411 nm (435 nm) and 434 nm (410 nm) are used to resonantly address the $^2S_{1/2} \leftrightarrow ^2D_{5/2} (^2D_{3/2})$ and

the $^2D_{5/2} (^2D_{3/2}) \leftrightarrow ^1[5/2]_{5/2}$ transitions, respectively. Both lasers are Pound-Drever-Hall (PDH)-locked [37] to the ULE cavity with a finesse of 9500. Since the $^2D_{5/2}$ state has an 83% branching ratio to the $^2F_{7/2}$ state [38] (in this work, we measure 81.2%, see below), a 760 nm repumper to the $4f^{13}(^2F_{7/2}^o)5d6s(^1D)^1[3/2]_{3/2}^o$ state is used at the end of every experiment to re-initialize the population in the $^2S_{1/2}$ ground state [31,39]. The population in the $^2S_{1/2}$ and $^2D_{3/2}$ states is measured by collecting the ion fluorescence with a 0.6 numerical aperture (NA) objective under 370 and 935 nm illumination for 100 μs . In this case, the Poissonian distributions of the detected photons for bright ($^2S_{1/2}$ and $^2D_{3/2}$) and dark ($^2D_{5/2}$, $^2F_{7/2}$, and $^1[5/2]_{5/2}$) states are well separated, allowing the use of threshold discrimination, where the dark fidelity of 99.7% and the bright fidelity of 100% are given by averaging over 2000 experimental repetitions. Conversely, the $^2S_{1/2}$ population alone can be detected at the end of the experiment by illuminating the ion only with the 370 nm beam for 60 μs , which results in the collection of the photons scattered during the optical pumping to the $^2D_{3/2}$ state.

The pulse sequence used to measure the decay rate of $^1[5/2]_{5/2}$ consists of the following steps [see Fig. 2(c)]: (1) The ion is prepared in the $|m_j = -1/2\rangle$ Zeeman sublevel of $^2D_{5/2}$ with a 411 nm π pulse. To significantly increase the state-preparation fidelity, we use a heralding scheme by applying a detection step with 370 and 935 nm, measuring the population in $^2S_{1/2}$ and $^2D_{3/2}$ states after the 411 nm π pulse. If the 370 nm photon counts are below the threshold, the $^2D_{5/2}$ state preparation is considered to be successful, and we move on to the next experimental pulse. Conversely, if the 370 nm detection photon counts exceed the threshold, the heralding scheme is iterated until the state preparation is successful. This procedure results in a dark fidelity of 99.7(1)%, corresponding to a 98.7(1)% fidelity in the $^2D_{5/2}$ state, which is limited primarily by the decay from the $^2D_{5/2}$ state during the 0.1 ms detection time. (2) A 434 nm π pulse (0.33 μs) is applied to populate the $|^1[5/2]_{5/2}, m_j = -3/2\rangle$ Zeeman sublevel. (3) Then, a wait time is scanned to allow the decay of the population from the $^1[5/2]_{5/2}$ state. (4) We then measure the $^2D_{3/2}$ population by first transferring it to the $^2S_{1/2}$ state with a 935 nm clearout pulse (2 μs). This is much faster than the overall $^1[5/2]_{5/2} \rightarrow \{^2D_{5/2}, ^2D_{3/2}\}$ decay timescale and thus sufficient to completely transfer the $^2D_{3/2}$ population to the $^2S_{1/2}$ state. (5) Finally, we detect only the $^2S_{1/2}$ population using the 370 nm light for 60 μs . This procedure is adopted because the 100 μs detection of both $^2S_{1/2}$ and $^2D_{3/2}$ populations is longer than the decay lifetime τ and, therefore, would affect the decay measurement. A fast population transfer from $^2D_{3/2}$ to $^2S_{1/2}$ has the advantage of allowing a direct measurement in real time of the decay probability, but it has the drawback that the number of photon counts acquired during detection is low (the total bright counts of 4.98 over the background counts of 0.34 within the detection window), hindering the application of thresholding.

The raw photon counts as a function of wait time are reported in Fig. 2. We fit the data with both an exponential function and a QuTiP [40] numerical integration of the optical Bloch equations (OBEs; see the Supplemental Material [17]) to take into account the finite 935 nm clearout time (2 μs)

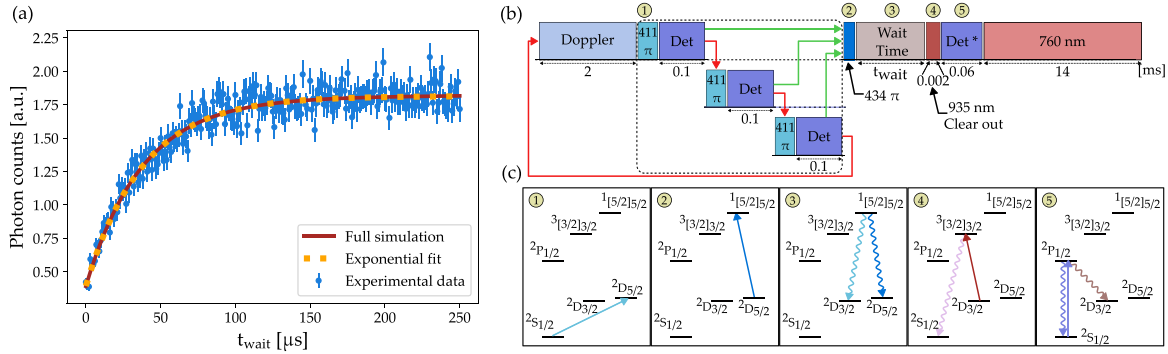


FIG. 2. (a) Lifetime measurement: Observation of the decay from $1[5/2]_{5/2}$ state to $2D_{3/2}$ and $2S_{1/2}$ states as a function of t_{wait} . The solid line is the solution of the OBEs using QuTiP. A scaling parameter and an offset are added to the simulation result to fit the unthresholded photon counts of the experimental scan. Each data point is the average of 2000 experimental repetitions, and the error bars are ± 1 standard deviation from the mean. (b), (c) Pulse sequence consisting of the heralded 411 nm state-preparation steps, 434 nm π pulse (0.33 μs), variable wait time t_{wait} , 935 nm clearout pulse (2 μs), and detection without 935 nm step (60 μs , labeled as Det*).

and the $2D_{5/2}$ and $2D_{3/2}$ decays to the $2S_{1/2}$ and $2F_{7/2}$ states. The two fitting methods agree within 1%, showing that the 935 nm clearout time and the decays from the $2D_{5/2}$ and $2D_{3/2}$ metastable states are much faster and slower than the decay time, respectively. The fit of the data to the full simulation results in the $1[5/2]_{5/2}$ state lifetime of $\tau = 37.9(9) \mu\text{s}$, which is the result of five independent measurements with the error bar being the weighted standard deviation (see the Appendix A).

In order to make the signal as stable as possible, we set the Rabi frequency of the 434 nm pulse $\Omega_{434}/2\pi = 1.519$ MHz. On the one hand, this allows us to address a single Zeeman state as $\Omega_{434}/2\pi < \Delta f_{\text{Zeeman}} = 6.806$ MHz; on the other hand, it makes the pulse sequence largely insensitive to the ULE cavity frequency drifts (0.175 Hz/s) and the magnetic field fluctuations (see the Appendix A). However, the fluctuations in the raw detection counts and the imperfect π pulses due to 434 nm laser intensity fluctuations cause the statistical error bar to underestimate the error in each data point. This results in an average reduced $\chi^2/(N-1) = 4.37$ over the five measurements. We take this into account by rescaling the statistical error bar of each point in Fig. 2 to set $\chi^2/(N-1) = 1$, as suggested in Ref. [41].

III. BRANCHING RATIO MEASUREMENTS

Precision measurements of the branching ratios have been done in trapped ions with multilevel systems by observing the scattering fluorescence given by the population being pumped to a dark state or by directly measuring the fraction of population in the pumped dark state [42–45]. Collecting the emitted 410 or 434 nm photons would result in very long experimental runs because of the very low scattering rate ($\gamma_{5/2}/2\pi = 1/2\pi\tau = 4.2(1)$ kHz) and the fact that we can collect only $\sim 10\%$ of the emitted photons.

Hence, for our measurement, we prepare the population in $|2D_{5/2}, m_j = -3/2\rangle$ with the heralding protocol and drive the $|2D_{5/2}, m_j = -3/2\rangle \rightarrow |1[5/2]_{5/2}, m_j = -5/2\rangle$ transition at low power for a variable time t_{434} . The steady-state population will accumulate in only two states, $|2D_{5/2}, m_j = -5/2\rangle$ and $|2D_{3/2}, m_j = -3/2\rangle$, as shown in Fig. 3. The next closest Zeeman transition relative to $|2D_{5/2}, m_j = -3/2\rangle$, corresponding

to $|2D_{5/2}, m_j = -3/2\rangle \rightarrow |1[5/2]_{5/2}, m_j = -3/2\rangle$, is 6 MHz away and thus not driven at sufficiently low power. We then wait for 500 μs to allow for the decay of the $1[5/2]_{5/2}$ state to be complete before detecting the probability of populating the $2S_{1/2}$ and $2D_{3/2}$ states (see the Supplemental Material [17]). If we assume that the decays to the $2S_{1/2}$ and $2F_{7/2}$ states are negligible, the steady-state population can be approximated as

$$P_{ss}(2D_{3/2}) = \frac{b_{D_{3/2}}}{b_{D_{3/2}} + b_{D_{5/2}|m=-5/2}},$$

$$b_{D_{5/2}|m=-5/2} = |\langle 5/2, -5/2; 1, 0 | 5/2, -5/2 \rangle|^2 b_{D_{5/2}}. \quad (1)$$

Here, $b_{D_{5/2}|m_j=-5/2}$ is the branching ratio of $|1[5/2]_{5/2}, m_j = -5/2\rangle \rightarrow |D_{5/2}, m_j = -5/2\rangle$ weighted by the relevant Clebsch-Gordan coefficient $\langle 5/2, -5/2; 1, 0 | 5/2, -5/2 \rangle$. However, there is a slight increase of the measured population at long times due to slow decays of the $2D_{5/2}$ ($\tau_{D_{5/2}} = 7.2(3)$ ms [38]) and $2D_{3/2}$ states ($\tau_{D_{3/2}} = 54.83(18)$ ms [46]) to the $2S_{1/2}$ and $2F_{7/2}$ states [Fig. 3(b)] that is not captured by Eq. (1). To take these corrections into account, we perform a numerical simulation of the OBEs (see the Supplemental Material [17]), including all the atomic levels involved as well as the known decay rates of $2D_{3/2}$ and $2D_{5/2}$ states. We perform the measurements at four different laser powers with Rabi frequencies [see inset in Fig. 3(b)] much smaller than the Zeeman splitting to the closest transition but larger than $\gamma_{5/2}/2\pi$. All four datasets converge to the same long-time behavior, confirming the low-power regime. Using the measured lifetime as a fixed parameter, the total branching ratio to $2D_{3/2}$ and $2S_{1/2}$ states given by the fit to the full OBEs is $b_{D_{3/2}} + b_{S_{1/2}} = 0.361(2)$.

In order to quantify the direct branching ratios to the $2S_{1/2}$ and $2F_{7/2}$ states ($b_{S_{1/2}}$ and $b_{F_{7/2}}$ in the following), we drive the $2D_{3/2} \rightarrow 1[5/2]_{5/2}$ and $2D_{5/2} \rightarrow 1[5/2]_{5/2}$ transitions at high power ($\Omega_{410}/2\pi \approx 2.8$ MHz and $\Omega_{434}/2\pi \approx 7.8$ MHz) and low magnetic field ($B = 0.448(2)$ G), such that the Rabi frequencies are much larger than the total Zeeman splitting bandwidths, where $\Delta f_z^{(410)} = 1.636$ MHz and $\Delta f_z^{(434)} = 1.974$ MHz separate the two extreme Zeeman transitions, respectively. In this regime, all the Zeeman states of the $2D_{3/2}$

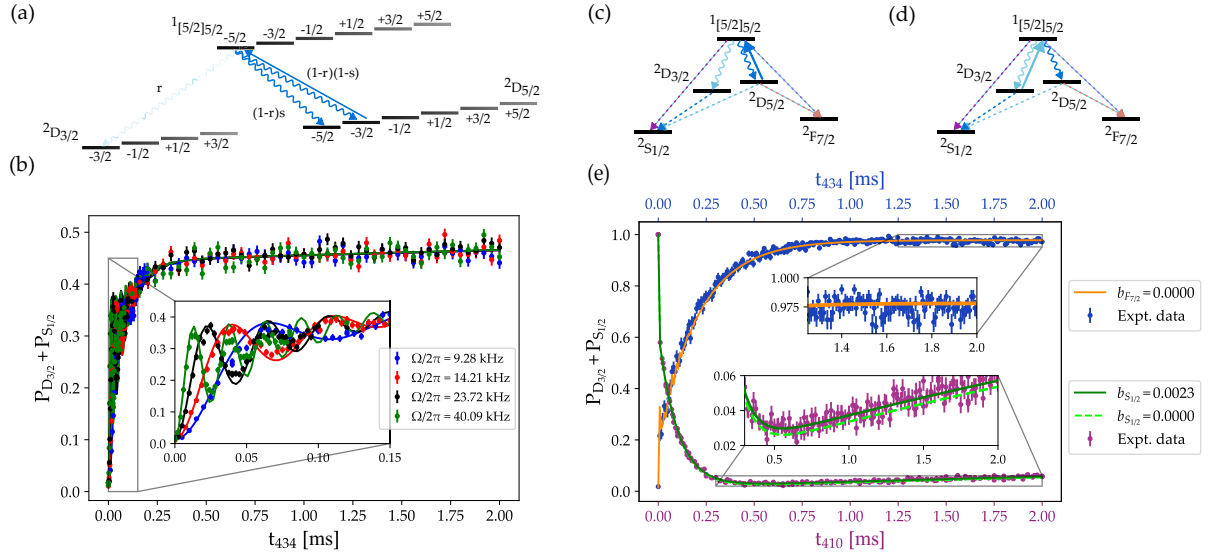


FIG. 3. Branching ratio measurements: (a) level scheme highlighting the Zeeman sublevels involved in the experiment. $r = b_{D_{3/2}}$ is the branching ratio to the $^2D_{3/2}$ state and $s = |cb|^2$, where cb is the Clebsch-Gordan coefficient (see text). (b) Low-power evolutions at $B = 4.839(1)$ G as a function of t_{434} for four different laser powers. The independently calibrated Rabi frequencies ($\Omega_{434}/2\pi = 9.28, 14.21, 23.72, 40.09$ kHz) are in the inset. Level scheme for low magnetic field ($B = 0.448(2)$ G) with high-power 434 nm [panel (c)] and 410 nm [panel (d)] drives, corresponding to blue and purple points in panel (e), respectively. (e) High-power and low-magnetic-field evolutions as a function of t_{434} (blue points) and t_{410} (purple points) with $\Omega_{434}/2\pi \approx 7800$ kHz, and $\Omega_{410}/2\pi \approx 2800$ kHz. The solid lines are fits to the OBEs with the only fit parameter being $b_{S_{1/2}}$ and $b_{F_{7/2}}$, respectively. The dashed green line is the result of the simulation assuming $b_{S_{1/2}} = 0$. In plots, each point is the average of 500 (blue) and 2000 (purple) repetitions, with the error bars being ± 1 standard deviation from the mean.

($^2D_{5/2}$) manifold are depopulated during the 410 (434) nm pulse. By measuring the total population in $^2S_{1/2} + ^2D_{3/2}$ as a function of 410 (434) nm pulse time, we can fit the data assuming the previously estimated values of $\gamma_{[5/2]}$ and $b_{D_{3/2}} + b_{S_{1/2}}$ and leaving $b_{S_{1/2}}$ ($b_{F_{7/2}}$) as the only fit parameter.

In the case of $b_{S_{1/2}}$, we use the 410 nm high-power pumping scheme [Fig. 3(d)]. As shown in Fig. 3(e), any final population in addition to the direct $^2D_{3/2}, ^2D_{5/2} \rightarrow ^2S_{1/2}$ decays can be attributed to the direct E2 $^1[5/2]_{5/2} \rightarrow ^2S_{1/2}$ decay. The comparison of the data (purple points) with the numerical results assuming $b_{S_{1/2}} = 0$ (dashed line) suggests a nonzero value for the branching ratio of this E2 decay. Since the uncertainty of $b_{S_{1/2}}$ is limited by the known accuracy of the lifetime and branching ratio of the $^2D_{5/2} \rightarrow ^2S_{1/2}$ decay, we performed a separate measurement of the lifetime $\tau_{D_{5/2}} = 7.3(3)$ ms and branching ratio $b_{D_{5/2} \rightarrow S_{1/2}} = 0.188(3)$. While our measurement of $\tau_{D_{5/2}}$ is in agreement with previous works on $^{172}\text{Yb}^+$ ions [38], we improved the relative uncertainty of $b_{D_{5/2} \rightarrow S_{1/2}}$ by an order of magnitude. Combining this uncertainty with other systematic effects (see the Appendix A), we obtain $b_{S_{1/2}} = 0.0023(16)$.

On the other hand, the blue data points, measured using the 434 nm pumping scheme shown in Fig. 3(c), closely follow the simulation assuming $b_{F_{7/2}} = 0$. The fit result of $b_{F_{7/2}} = 0.0000(3)$ is also statistically compatible with zero, inferring that the missing population in the steady state can be entirely attributed to the direct $^2D_{5/2} \rightarrow ^2F_{7/2}$ decay. Considering the error budget analysis (see the Appendix A), our experimental resolution is insufficient for precisely determining the branching ratio to $^2F_{7/2}$.

For both pumping schemes, we independently determine the Rabi frequencies by fitting coherent oscillations at short times (see the Supplemental Material [17]). The estimated values of $b_{F_{7/2}}$ and $b_{S_{1/2}}$ yield $b_{D_{3/2}} = 0.359(2)$ and $b_{D_{5/2}} = 0.639(2)$.

IV. $^1[5/2]_{5/2}$ STATE LANDÉ g-FACTOR MEASUREMENT

To estimate the Landé g-factor, we measure the frequencies of several Zeeman transitions of $^2S_{1/2} \rightarrow ^2D_{5/2}$ and $^2D_{5/2} \rightarrow ^1[5/2]_{5/2}$ using low-power Rabi spectroscopy at 411 and 434 nm at different magnetic fields (see the Appendix B). Once the ratio of Zeeman splittings is known, we can estimate the Landé g-factor of the $^1[5/2]_{5/2}$ state as follows:

$$\frac{g_{D_{5/2}}}{g_{S_{1/2}}} = \frac{\Delta f_{D_{5/2}}}{\Delta f_{S_{1/2}}}, \quad \frac{g_{[5/2]_{5/2}}}{g_{S_{1/2}}} = \frac{\Delta f_{[5/2]_{5/2}}}{\Delta f_{S_{1/2}}}, \quad (2)$$

where Δf_a is the Zeeman splitting between states with $\Delta m_j = 1$ for $a = \{^2S_{1/2}, ^2D_{5/2}, ^1[5/2]_{5/2}\}$. The ratio between the Zeeman splittings of $^2D_{5/2}$ and $^2S_{1/2}$ ($^1[5/2]_{5/2}$ and $^2S_{1/2}$) is $0.5994(2)$ ($0.4922(2)$), where the uncertainty is mainly due to magnetic field fluctuations (see the Appendix B). This ratio can be used along with previous $^2S_{1/2}$ or $^2D_{5/2}$ measurements [47] or theoretical predictions [48] to estimate the Landé g-factor of $^1[5/2]_{5/2}$. Assuming $g_{S_{1/2}} = 1.998$ [47], we obtain $g_{D_{5/2}} = 1.1976(4)$ and $g_{[5/2]_{5/2}} = 0.9834(4)$. Alternatively, assuming the recent theoretical estimate [48] of $g_{S_{1/2}} = 2.002615$, we obtain $g_{D_{5/2}} = 1.2003(4)$ and $g_{[5/2]_{5/2}} = 0.9856(4)$. Both estimated values are $0.0066(4)$ and $0.0044(4)$.

lower than the Landé g -value (0.990) of the $^1[5/2]_{5/2}$ state reported in Refs. [34,47], respectively.

V. DISCUSSION

In this work, we have reported the first precision measurement of the lifetime, branching ratios, and g -factor of the high-lying $^1[5/2]_{5/2}$ state in $^{172}\text{Yb}^+$ ions. The relatively long lifetime measured here questions the degree of mixing between the $4f^{13}6s5d$ and $4f^{13}5d^2$ configurations in the $^1[5/2]_{5/2}$ state [33,34]. Our work also paves the way to new schemes for Yb^+ qubit manipulation in the *omg* architecture, as it shows how high-lying “bracket” states can be used for quantum information processing. The fact that the $^2D_{5/2}$, $^2D_{3/2}$, and $^1[5/2]_{5/2}$ states form a quasiclosed lambda system (up to the slow decays to the $^2S_{1/2}$ and $^2F_{7/2}$ states) suggests that high-lying states might be used for midcircuit measurements by scattering photons directly in the metastable $4f^{14}5d$ manifold. For example, Yb^+ ions feature multiple odd parity states belonging to the $4f^{13}5d^2$ configuration that might exhibit broader linewidths and closed cycling transitions, more suitable for photon collection and high-fidelity detection than the $^1[5/2]_{5/2}$ state studied here.

Another use of the $^1[5/2]_{5/2}$ state studied here is optical pumping the $^2D_{3/2}$ population into the $^2D_{5/2}$ state to circumvent the fundamental limit to the shelving fidelity represented by the M1 decay from the $^2D_{5/2}$ to the $^2D_{3/2}$ state during optical pumping with 411 nm light [30,31]. Additionally, the presence of potentially three excitation paths, all leading to the relatively narrow-linewidth $^1[5/2]_{5/2}$ state, opens intriguing possibilities in tests of the foundation of quantum mechanics [49,50].

Finally, we point out that there are currently no numerical methods available to predict and explain our observations. Our work will therefore serve as a test bed to benchmark numerical methods and to better understand the atomic structure of Yb^+ ions, a workhorse of quantum information science.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [51].

APPENDIX

APPENDIX A: SYSTEMATIC ERRORS

The systematic errors for the quantities measured in this work are listed in Table I. All measurements are affected by frequency fluctuations of the relevant atomic transitions, induced by magnetic field variations, drifts in the ULE cavity, and laser intensity variations. To quantify the magnetic field fluctuations, we measure a magnetically sensitive microwave transition ($|F = 0, m_F = 0\rangle \rightarrow |F = 1, m_F = +1\rangle$) in the ground state $^2S_{1/2}$ of a $^{171}\text{Yb}^+$ (effective g -factor = 0.999) ion over the span of 30 min, observing a slow oscillatory fluctuation with a fractional rms instability of 0.5×10^{-5} . We also characterize the ULE drift by measuring the two clock transitions of $^2S_{1/2} \rightarrow ^2D_{3/2}$, $^2D_{5/2}$ over several months and find it to be 0.175 Hz/s. The Stark shift of the 410 nm transition could not be resolved in the power range explored in this work, in agreement with the OBE model predicting a few tens of kilohertz for the maximum Rabi frequency of ~ 2.8 MHz. In the case of the 434 nm transition, we verified the OBE model prediction experimentally (~ 150 kHz Stark shift at 1.5 MHz Rabi frequency) and characterized the fluctuations of the laser power to be 2% over the course of a typical experimental run. Another source of systematic error is the rms fluctuations of the SPAM (state preparation and measurement) fidelity over time, which we measured to be 1×10^{-3} .

Furthermore, we fit the data to an OBE model, which uses the lifetimes of the $^2D_{3/2}$ and $^2D_{5/2}$ states ($\tau_{D_{3/2}}$ and $\tau_{D_{5/2}}$) and the branching ratio of the $^2D_{5/2} \rightarrow ^2S_{1/2}$ decay ($b_{D_{5/2} \rightarrow S_{1/2}}$) as inputs. Therefore, we also have to consider their known uncertainties [38,46]. For $b_{D_{5/2} \rightarrow S_{1/2}}$, we use the value and uncertainty measured in this work.

Finally, we consider the truncation errors caused by fitting only selected portions of the datasets. We neglect the systematic effects of quantum beats, as our measurements are largely insensitive to them because we detect the population resulting from the decay tracing over the final Zeeman states and not the photons emitted by the decay.

To estimate the systematic errors for the reported quantities, we use the sources of error (ULE frequency, magnetic field, Stark shift, SPAM, and $\tau_{D_{3/2}}$, $\tau_{D_{5/2}}$, $b_{D_{5/2} \rightarrow S_{1/2}}$) as Gaussian random variables with experimentally characterized variance to perform Monte Carlo sampling and fit the measured data with each Monte Carlo sample. With the resulting samples of fitted quantities $\{\tau, b_{D_{3/2}}, b_{D_{5/2}}, b_{S_{1/2}}, b_{F_{7/2}}\}$, we extract the weighted standard deviation to estimate the systematic error of that particular parameter. Similarly, when appropriate, we perform a truncation analysis to extract the systematic effect on how we select the data subset. In the case of the lifetime measurement (Fig. 2), we consider 13 truncation windows from $\sim 3\tau$ to the last timestamp, increasing by $10.5 \mu\text{s}$ per window. For the measured branching ratio $b_{D_{3/2}} + b_{S_{1/2}}$ [Fig. 3(b)], we truncate from $320 \mu\text{s}$ to the last timestamp, using nine truncation windows, each with a span of $80 \mu\text{s}$. We also truncate the initial point from 0.5 to 1.5 ms with 20 truncation windows ($5 \mu\text{s}$ each) and from 0.5 to 1.25 ms with 12 truncation windows ($12.5 \mu\text{s}$ each) for $b_{F_{7/2}}$ and $b_{S_{1/2}}$, respectively.

TABLE I. Error budget for lifetime τ and branching ratios $b_{D_{3/2}}$, $b_{S_{1/2}}$, and $b_{F_{7/2}}$. The errors on the branching ratios are in absolute percentages.

Noise source	τ (ms)	$b_{D_{3/2}}$ (%)	$b_{F_{7/2}}$ (%)	$b_{S_{1/2}}$ (%)
τ		1.1×10^{-2}	6.9×10^{-3}	1.4×10^{-3}
ULE cavity drift	2.1×10^{-4}	3.6×10^{-3}	1.6×10^{-7}	5.8×10^{-7}
Magnetic field	1.3×10^{-8}	1.6×10^{-3}	8.4×10^{-3}	3.2×10^{-3}
Stark shift	1.9×10^{-4}	2.1×10^{-3}	4.8×10^{-7}	8.5×10^{-5}
SPAM	1.3×10^{-8}	4.0×10^{-2}	3.7×10^{-3}	4.4×10^{-2}
$\tau_{D_{3/2}}$, $\tau_{D_{5/2}}$, and $b_{D_{5/2} \rightarrow S_{1/2}}$	2.8×10^{-4}	0.14	6.9×10^{-3}	0.15
Truncation errors	3.2×10^{-4}	1.5×10^{-2}	1.2×10^{-2}	1.4×10^{-2}
Total systematic	5.2×10^{-4}	0.15	1.8×10^{-2}	0.16
Statistical	7.8×10^{-4}	8.8×10^{-2}	2.0×10^{-2}	2.9×10^{-2}
Total	0.0009	0.17	2.6×10^{-2}	0.16

Finally, we note that we verify with Monte Carlo sampling that the experimental protocol of the lifetime measurement is insensitive to the values of the branching ratios ($<1.1 \times 10^{-4}$, not reported in Table I), as their variations would affect the scale of the overall signal and not the decay time. At the same time, in the case of the datasets used to extract the branching ratios [Fig. 3(b)], we truncate the data to make sure that the first part of the decay, which is more sensitive to the value of τ , is removed, and we measure the branching ratios using only the plateau at the end of the evolution that is mostly affected by the branching ratios and the values of $\tau_{D_{3/2}}$, $\tau_{D_{5/2}}$, and $b_{D_{5/2} \rightarrow S_{1/2}}$. We check that this procedure guarantees a systematic error induced by the uncertainty of τ for the branching ratios of $<1.1 \times 10^{-4}$ in absolute scale, as shown in Table I.

APPENDIX B: LANDÉ g -FACTOR MEASUREMENT

The magnetic field is controlled by tuning the current in the electromagnetic coils placed symmetrically around the vacuum chamber in the Helmholtz configuration. For each magnetic field, we first use the 411 nm beam to measure the transition frequencies from both the

$|^2S_{1/2}, m_j = -1/2\rangle$ and $|^2S_{1/2}, m_j = 1/2\rangle$ to the $|^2D_{5/2}, m'_j = -3/2, -1/2, 1/2\rangle$ and $|^2D_{5/2}, m'_j = -1/2, 1/2, 3/2\rangle$ Zeeman states, respectively. Each measurement is quickly followed by a similar spectroscopy at low 434 nm power, starting from $|^2D_{5/2}, m_j = -1/2\rangle$ and $|^2D_{5/2}, m_j = 1/2\rangle$ to $|^1[5/2]_{5/2}, m'_j = -3/2, -1/2, 1/2\rangle$ and $|^1[5/2]_{5/2}, m'_j = -1/2, 1/2, 3/2\rangle$ states, respectively. Finally, the $^2S_{1/2} \rightarrow ^2D_{5/2}$ transition is measured again to account for drifts in the magnetic field and ULE cavity, and the average of the two values is taken for each subtransition. The observed Zeeman splittings are shown in Fig. 4.

APPENDIX C: MEASUREMENT OF LIFETIME AND BRANCHING RATIO OF THE $^2D_{5/2}$ STATE

To measure the lifetime of $^2D_{5/2}$ and its branching ratio to $^2S_{1/2}$, we prepare the ion in the $^2D_{5/2}|m_j = -3/2\rangle$ state using the heralding procedure and observe the total population in $^2S_{1/2}$ and $^2D_{3/2}$ as a function of wait time as shown in Fig. 5. We measure the $^2D_{5/2}$ lifetime of 7.3(3) ms and the branching ratio from $^2D_{5/2}$ to $^2S_{1/2}$ to be 0.188(3). The error bars include the systematic effects of SPAM fluctuations.

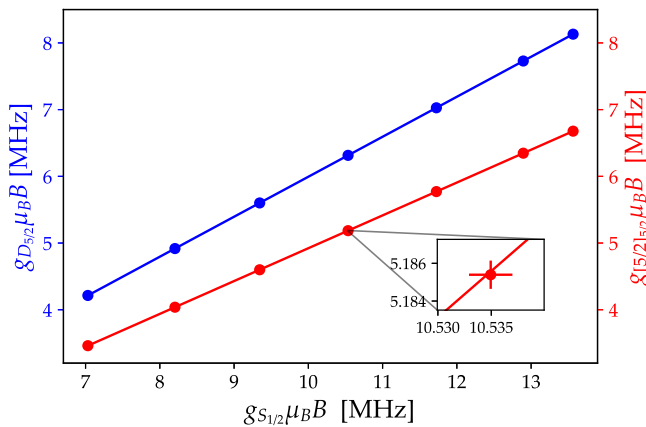


FIG. 4. Relative Zeeman frequency splitting of $^2D_{5/2}$ and $^1[5/2]_{5/2}$ as a function of $^2S_{1/2}$ Zeeman splitting for different magnetic fields. The solid line is a linear fit of the experimental values. The error bars are shown in the inset.

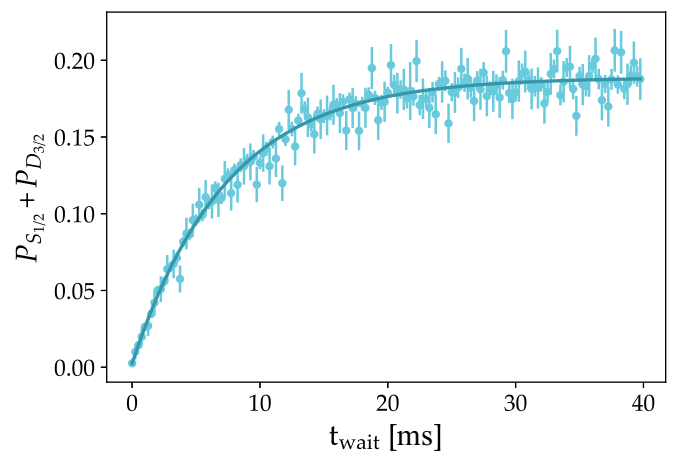


FIG. 5. Decay of population from $^2D_{5/2}$ to $^2S_{1/2}$. Each point is the average of 4000 repetitions taken over multiple datasets. The solid line is the fit to an exponential curve.

- [1] C. D. Bruzewicz, J. Chiaverini, R. McConnell, and J. M. Sage, Trapped-ion quantum computing: Progress and challenges, *Appl. Phys. Rev.* **6**, 021314 (2019).
- [2] C. Monroe, W. C. Campbell, L.-M. Duan, Z.-X. Gong, A. V. Gorshkov, P. W. Hess, R. Islam, K. Kim, N. M. Linke, G. Pagano, P. Richerme, C. Senko, and N. Y. Yao, Programmable quantum simulations of spin systems with trapped ions, *Rev. Mod. Phys.* **93**, 025001 (2021).
- [3] A. D. Ludlow, M. M. Boyd, J. Ye, E. Peik, and P. O. Schmidt, Optical atomic clocks, *Rev. Mod. Phys.* **87**, 637 (2015).
- [4] P. Wang, C.-Y. Luan, M. Qiao, M. Um, J. Zhang, Y. Wang, X. Yuan, M. Gu, J. Zhang, and K. Kim, Single ion qubit with estimated coherence time exceeding one hour, *Nat. Commun.* **12**, 233 (2021).
- [5] S. A. Moses, C. H. Baldwin, M. S. Allman, R. Ancona, L. Ascarrunz, C. Barnes, J. Bartolotta, B. Bjork, P. Blanchard, M. Bohn *et al.*, A race-track trapped-ion quantum processor, *Phys. Rev. X* **13**, 041052 (2023).
- [6] W. L. Tan, P. Becker, F. Liu, G. Pagano, K. S. Collins, A. De, L. Feng, H. B. Kaplan, A. Kyprianidis, R. Lundgren, W. Morong, S. Whitsitt, A. V. Gorshkov, and C. Monroe, Domain-wall confinement and dynamics in a quantum simulator, *Nat. Phys.* **17**, 742 (2021).
- [7] A. De, A. Lerose, D. Luo, F. M. Surace, A. Schuckert, E. R. Bennewitz, B. Ware, W. Morong, K. S. Collins, Z. Davoudi, A. V. Gorshkov, O. Katz, and C. Monroe, Observation of string-breaking dynamics in a quantum simulator, *arXiv:2410.13815*.
- [8] M. K. Joshi, F. Kranzl, A. Schuckert, I. Lovas, C. Maier, R. Blatt, M. Knap, and C. F. Roos, Observing emergent hydrodynamics in a long-range quantum magnet, *Science* **376**, 720 (2022).
- [9] K. Sun, M. Kang, H. Nuomin, G. Schwartz, D. N. Beratan, K. R. Brown, and J. Kim, Quantum simulation of spin-boson models with structured bath, *Nat. Commun.* **16**, 4042 (2025).
- [10] V. So, M. D. Suganthi, A. Menon, M. Zhu, R. Zhuravel, H. Pu, P. G. Wolynes, J. N. Onuchic, and G. Pagano, Trapped-ion quantum simulation of electron transfer models with tunable dissipation, *Sci. Adv.* **10**, eads8011 (2024).
- [11] V. So, M. D. Suganthi, M. Zhu, A. Menon, G. Tomaras, R. Zhuravel, H. Pu, P. G. Wolynes, J. N. Onuchic, and G. Pagano, Quantum simulation of charge and exciton transfer in multi-mode models using engineered reservoirs, *arXiv:2505.22729*.
- [12] N. Huntemann, M. Okhapkin, B. Lipphardt, S. Weyers, C. Tamm, and E. Peik, High-accuracy optical clock based on the octupole transition in $^{171}\text{Yb}^+$, *Phys. Rev. Lett.* **108**, 090801 (2012).
- [13] J. Stuhler, M. Abdel Hafiz, B. Arar, A. Bawamia, K. Bergner, M. Biethahn, S. Brakhane, A. Didier, J. Fortágh, M. Halder *et al.*, Opticlock: Transportable and easy-to-operate optical single-ion clock, *Meas. Sens.* **18**, 100264 (2021).
- [14] J. C. Berengut, C. Delaunay, A. Geddes, and Y. Soreq, Generalized King linearity and new physics searches with isotope shifts, *Phys. Rev. Res.* **2**, 043444 (2020).
- [15] J. Hur, D. P. L. Aude Craik, I. Counts, E. Knyazev, L. Caldwell, C. Leung, S. Pandey, J. C. Berengut, A. Geddes, W. Nazarewicz, P.-G. Reinhard, A. Kawasaki, H. Jeon, W. Jhe, and V. Vuletić, Evidence of two-source King plot nonlinearity in spectroscopic search for new boson, *Phys. Rev. Lett.* **128**, 163201 (2022).
- [16] M. Door, C.-H. Yeh, M. Heinz, F. Kirk, C. Lyu, T. Miyagi, J. C. Berengut, J. Bieroń, K. Blaum, L. S. Dreissen *et al.*, Probing new bosons and nuclear structure with ytterbium isotope shifts, *Phys. Rev. Lett.* **134**, 063002 (2025).
- [17] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/mwwc-kng1> for more experimental details.
- [18] S. G. Porsev, M. S. Safronova, and M. G. Kozlov, Correlation effects in Yb^+ and implications for parity violation, *Phys. Rev. A* **86**, 022504 (2012).
- [19] E. Kahl and J. Berengut, Ambit: A programme for high-precision relativistic atomic structure calculations, *Comput. Phys. Commun.* **238**, 232 (2019).
- [20] J. Migdalek and W. Siegel, Collapse of d and f orbitals in the isoelectronic sequence of singly ionized ytterbium, *Phys. Rev. A* **61**, 062502 (2000).
- [21] U. I. Safronova and M. S. Safronova, Third-order relativistic many-body calculations of energies, transition rates, hyperfine constants, and blackbody radiation shift in $^{171}\text{Yb}^+$, *Phys. Rev. A* **79**, 022512 (2009).
- [22] J. Migdalek and W. Siegel, Relativistic E1 transition probabilities and lifetimes along Yb isoelectronic sequence, *J. Phys. B: At. Mol. Opt. Phys.* **45**, 145002 (2012).
- [23] L. Radžiūtė, G. Gaigalas, D. Kato, P. Rynkun, and M. Tanaka, Extended calculations of energy levels and transition rates for singly ionized lanthanide elements. II. Tb-Yb, *Astrophys. J. Suppl. Ser.* **257**, 29 (2021).
- [24] X.-T. Guo, Y.-M. Yu, Y. Li, and B.-B. Suo, Finite-field calculation of electric quadrupole moments of $^2\text{P}_{3/2}$, $^2\text{D}_{3/2,5/2}$, and $^2\text{F}_{5/2}$ states for Yb^+ ion, *Chin. Phys. B* **29**, 053101 (2020).
- [25] V. A. Dzuba and V. V. Flambaum, Hyperfine-induced electric dipole contributions to the electric octupole and magnetic quadrupole atomic clock transitions, *Phys. Rev. A* **93**, 052517 (2016).
- [26] R. Lange, A. A. Peshkov, N. Huntemann, C. Tamm, A. Surzhykov, and E. Peik, Lifetime of the $^2\text{F}_{7/2}$ level in Yb^+ for spontaneous emission of electric octupole radiation, *Phys. Rev. Lett.* **127**, 213001 (2021).
- [27] E. Biémont, J.-F. Dutrieux, I. Martin, and P. Quinet, Lifetime calculations in Yb II, *J. Phys. B: At. Mol. Opt. Phys.* **31**, 3321 (1998).
- [28] M. Schacht, J. R. Danielson, S. Rahaman, J. R. Torgerson, J. Zhang, and M. M. Schauer, $^{171}\text{Yb}^+ 5D_{3/2}$ hyperfine state detection and $F = 2$ lifetime, *J. Phys. B: At. Mol. Opt. Phys.* **48**, 065003 (2015).
- [29] D. T. C. Allcock, W. C. Campbell, J. Chiaverini, I. L. Chuang, E. R. Hudson, I. D. Moore, A. Ransford, C. Roman, J. M. Sage, and D. J. Wineland, *omg* blueprint for trapped ion quantum computing with metastable states, *Appl. Phys. Lett.* **119**, 214002 (2021).
- [30] C. Roman, Expanding the $^{171}\text{Yb}^+$ toolbox: The $^2\text{F}_{7/2}$ state as resource for quantum information science, Ph.D. thesis, University of California, 2021, <https://escholarship.org/uc/item/0mx6t24p>.
- [31] C. L. Edmunds, T. R. Tan, A. R. Milne, A. Singh, M. J. Biercuk, and C. Hempel, Scalable hyperfine qubit state detection via electron shelving in the $^2\text{D}_{5/2}$ and $^2\text{F}_{7/2}$ manifolds in $^{171}\text{Yb}^+$, *Phys. Rev. A* **104**, 012606 (2021).
- [32] N. A. Diepeveen, C. Robalo Pereira, M. Mazzanti, Z. E. D. Ackerman, L. P. H. Gallagher, T. Timmerman, R. Gerritsma, and R. X. Schüssler, Single-ion spectroscopy of four

- metastable-state clear-out transitions in Yb^+ : Isotope shifts and hyperfine structure, *Phys. Rev. A* **110**, 042809 (2024).
- [33] W. C. Martin, R. Zalubas, and L. Hagan, *Atomic Energy Levels—The Rare-Earth Elements*, National Standard Reference Data Series (U.S. Department of Commerce, National Bureau of Standards, 1978), Vol. 60.
- [34] A. Kramida, Yu Ralchenko, J. Reader, and NIST ASD Team, NIST Atomic Spectra Database (ver. 5.12) [Online], National Institute of Standards and Technology, Gaithersburg, MD, 2024, <https://physics.nist.gov/asd>.
- [35] S. Olmschenk, K. C. Younge, D. L. Moehring, D. N. Matsukevich, P. Maunz, and C. Monroe, Manipulation and detection of a trapped Yb^+ hyperfine qubit, *Phys. Rev. A* **76**, 052314 (2007).
- [36] D. Leibfried, B. DeMarco, V. Meyer, D. Lucas, M. Barrett, J. Britton, W. M. Itano, B. Jelenković, C. Langer, T. Rosenband *et al.*, Experimental demonstration of a robust, high-fidelity geometric two ion-qubit phase gate, *Nature (London)* **422**, 412 (2003).
- [37] E. Black, An introduction to Pound–Drever–Hall laser frequency stabilization, *Am. J. Phys.* **69**, 79 (2001).
- [38] P. Taylor, M. Roberts, S. V. Gateva-Kostova, R. B. M. Clarke, G. P. Barwood, W. R. C. Rowley, and P. Gill, Investigation of the $^2S_{1/2} - ^2D_{5/2}$ clock transition in a single ytterbium ion, *Phys. Rev. A* **56**, 2699 (1997).
- [39] K. Sugiyama, Laser cooling of single $^{174}\text{Yb}^+$ ions stored in a RF trap, *Jpn. J. Appl. Phys.* **38**, 2141 (1999).
- [40] J. Johansson, P. Nation, and F. Nori, QuTiP 2: A Python framework for the dynamics of open quantum systems, *Comput. Phys. Commun.* **184**, 1234 (2013).
- [41] S. Navas, C. Amsler, T. Gutsche, C. Hanhart, J. J. Hernández-Rey, C. Lourenço, A. Masoni, M. Mikhasenko, R. E. Mitchell, C. Patrignani *et al.*, Review of particle physics, *Phys. Rev. D* **110**, 030001 (2024).
- [42] R. Gerritsma, G. Kirchmair, F. Zähringer, J. Benhelm, R. Blatt, and C. F. Roos, Precision measurement of the branching fractions of the $4p^2P_{3/2}$ decay of Ca II, *Eur. Phys. J. D* **50**, 13 (2008).
- [43] M. Ramm, T. Pruttivarasin, M. Kokish, I. Talukdar, and H. Häffner, Precision measurement method for branching fractions of excited $P_{1/2}$ states applied to $^{40}\text{Ca}^+$, *Phys. Rev. Lett.* **111**, 023004 (2013).
- [44] H. Zhang, M. Gutierrez, G. H. Low, R. Rines, J. Stuart, T. Wu, and I. Chuang, Iterative precision measurement of branching ratios applied to $5P$ states $^{88}\text{Sr}^+$, *New J. Phys.* **18**, 123021 (2016).
- [45] K. J. Arnold, S. R. Chanu, R. Kaewuam, T. R. Tan, L. Yeo, Z. Zhang, M. S. Safronova, and M. D. Barrett, Measurements of the branching ratios for $6P_{1/2}$ decays in $^{138}\text{Ba}^+$, *Phys. Rev. A* **100**, 032503 (2019).
- [46] H. Shao, H. Yue, Z. Ma, Y. Huang, H. Guan, and K. Gao, Precision determination of the $5d^2D_{3/2}$ state lifetime of single $^{174}\text{Yb}^+$ ion, *Phys. Rev. Res.* **5**, 023193 (2023).
- [47] W. F. Meggers, The second spectrum of ytterbium (Yb II), *J. Res. Natl. Bur. Stand. Sect. A Phys. Chem.* **71A**, 396 (1967).
- [48] J. Han, B. Lu, Y. Yu, J. Li, Z. Huang, J. Wen, L. Qian, and L. Wang, Determination of the Landé g_J factor and Zeeman coefficients in ground-state $^{171}\text{Yb}^+$ and their applications to quantum frequency standards, *Phys. Rev. A* **111**, 012814 (2025).
- [49] S. Weinberg, Lindblad decoherence in atomic clocks, *Phys. Rev. A* **94**, 042117 (2016).
- [50] M. G. Raizen, G. Gilbert, and D. Budker, Proposed test of quantum mechanics with three connected atomic clock transitions, *Phys. Rev. A* **106**, 032209 (2022).
- [51] M. Duraisamy Suganthi, Dataset for “Precision Measurement of Lifetime and Branching Ratios of the $4f^{13}5d6s^1[5/2]_{5/2}$ state in Yb^+ ions” [Data set], Zenodo (2025), doi:10.5281/zenodo.17358392.