Millimeter-wave precision spectroscopy of d-d transitions in potassium Rydberg states

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Abstract

We measured two-photon millimeter-wave nd$_j$ $\to$ (n+1)d$_j$ Rydberg state transitions in potassium to an accuracy of 10 kHz ($\approx 5\times10^{-8}$) for $30 \le n \le 35$ to determine d-state quantum defects and absolute energy levels of potassium. K-39 atoms are magneto-optically trapped and laser-cooled to 2-3 mK, then excited from 4s$_{1/2}$ to nd$_{3/2}$ or nd$_{5/2}$ by 405 nm and 980 nm diode lasers in succession. nd$_j$ $\to$ (n+1)d$_j$, Δm = 0 transitions are driven by a 16 μs-long pulses of millimeter-wave before atoms are selectively ionized. The (n+1)d$_j$ population is measured as a function of mm-wave frequency. Static fields in the MOT are nulled to $<$ 50 mV/cm in three dimensions to eliminate DC Stark shifts. Zero-oscillatory-field transition energies can be measured in two ways: extrapolating zero-mm-wave resonance frequency and Ramsey's separated oscillatory field (SOF) method.

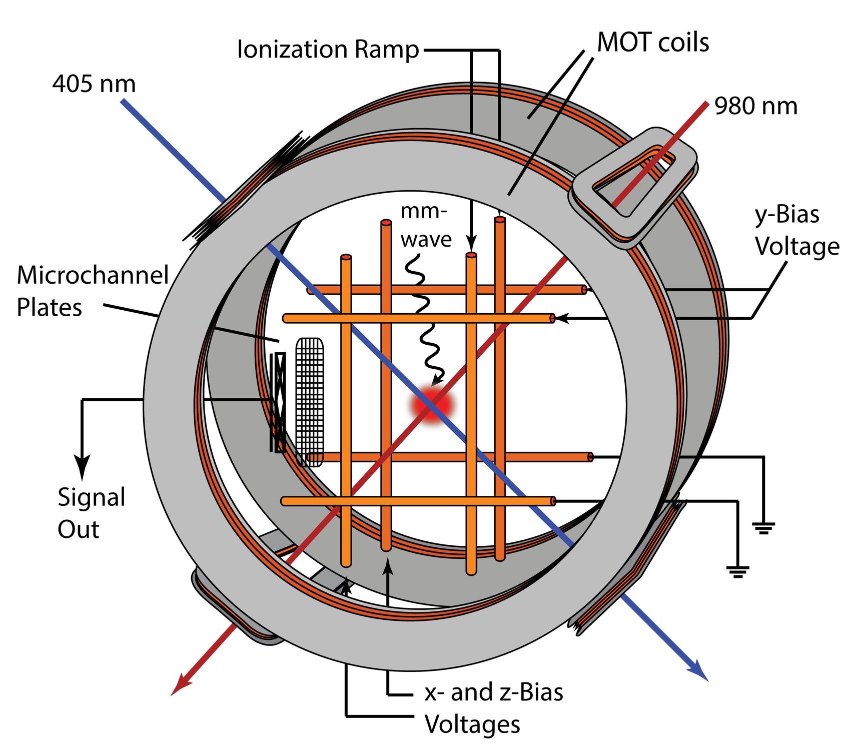

Figure 1: Drawing of the apparatus, with the MOT cloud trapped in a magnetic field created by 2 MOT coils and cooled by a 770 nm laser (not shown). The rods provide a static field and an ionization field. A mm-wave from outside the vacuum chamber drives nd$_j$ $\to$ (n+1)d$_j$ transitions.

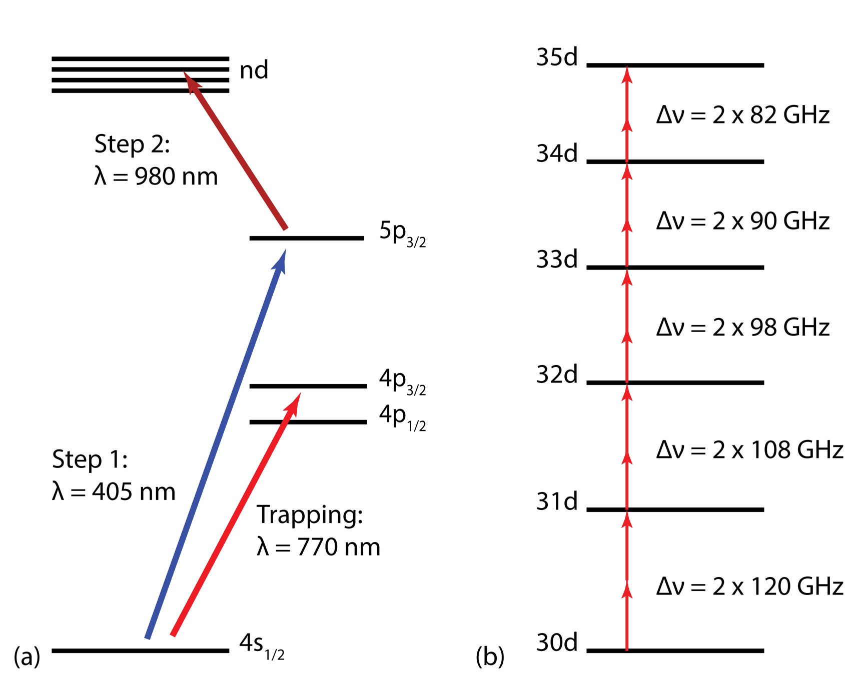

Figure 2: (a) Rydberg excitation, trapping, and (b) d-d excitation schemes.

Static field elimination

Energy levels of Rydberg states are sensitive to external static electric fields. Measured nd$_j$ $\to$ (n+1)d$_j$ transition frequencies vary quadratically with static field amplitude:

$$\boxed{\Delta\nu_{nd_j\to(n+1)d_j} = \nu_0 - \frac{1}{2}\Delta\alpha E^2}$$

where $\Delta\alpha$ is the difference between the (n+1)d$_j$ and nd$_j$ polarizabilities, representing how strongly energy levels shift due to an external static electric field.

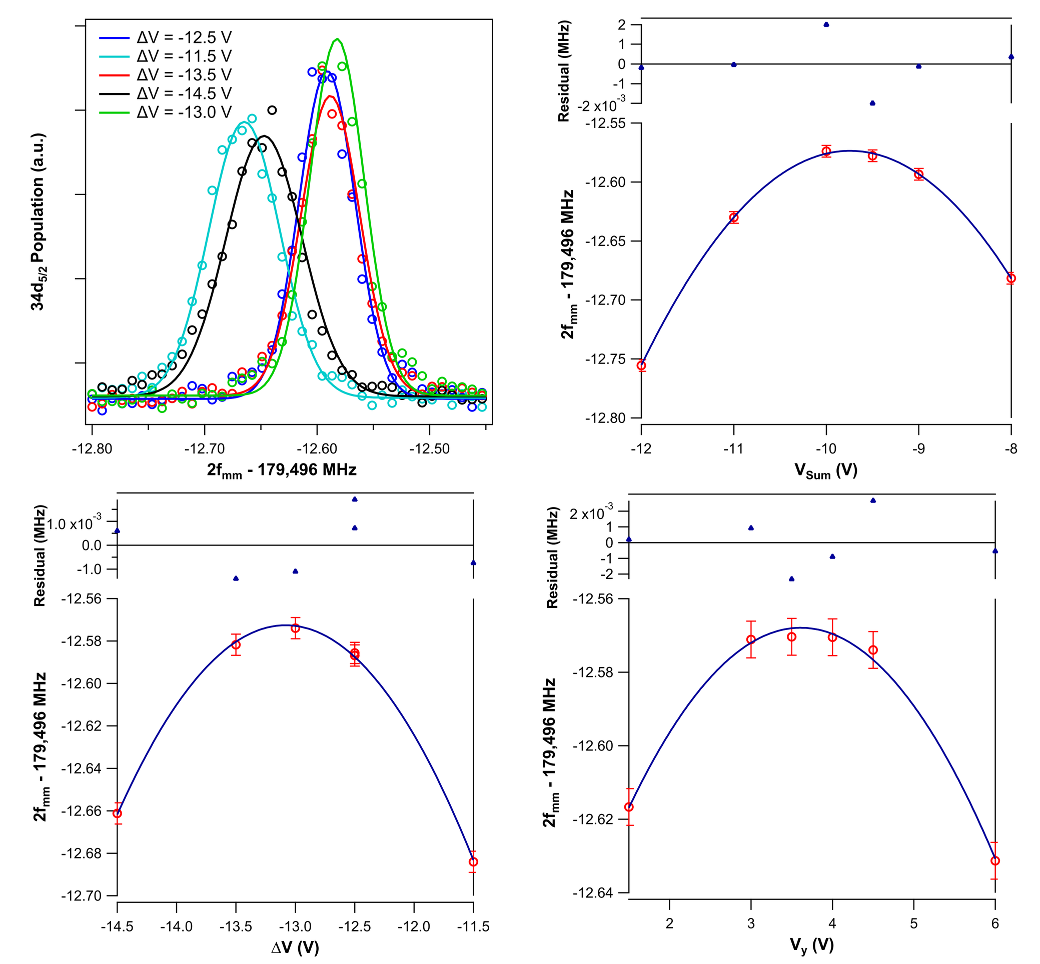

Figure 3: 33d$_{5/2}$$\to$34d$_{5/2}$ DC Stark shifts and field nulling as a function of voltages on the rods.

Transition frequency is maximized when the static field components in each of the orthogonal directions is zero. A DC bias in each direction nulls the field in that direction.

Zero mm-wave power extrapolation

While not a large effect, the energy shift caused by the mm-wave source is significant at our level of precision. This shift is directly proportional to the intensity of the interacting mm-wave.

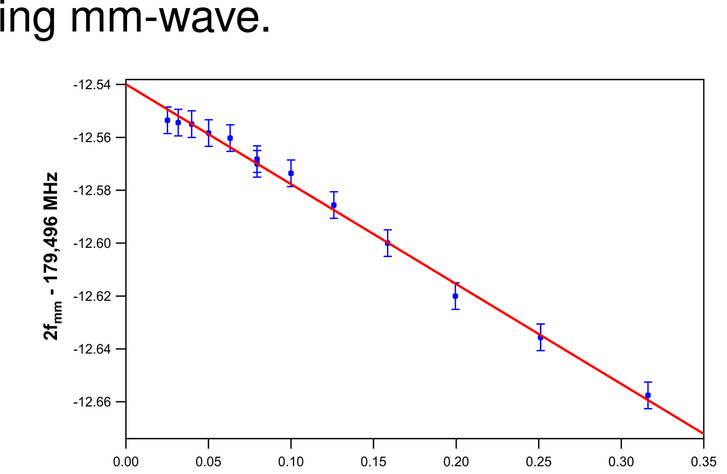

Figure 4: Zero-power extrapolation for 33d$_{5/2}$ $\to$ 34d$_{5/2}$

The y-intercept of the linear fit of the measured transition frequencies is the mm-wave-free transition frequency. The energy shifts from 0.35 to 0 relative intensity are on the order of a few tens of kHz.

The 33d$_{5/2}$ $\to$ 34d$_{5/2}$ spacing can then be calculated:

$$\begin{aligned}\Delta\nu_0 = 2\mathrm{f_{mm}} &= 179{,}496 \text{ MHz - } 12.540(6) \text{ MHz}\\ &= 179{,}483.460(6) \text{ MHz.}\end{aligned}$$

Ramsey's SOF, an alternative technique

Ramsey's separated oscillatory field method removes the need for zero-power extrapolation. K atoms in the nd$_j$ state are exposed to a double pulse of width τ and delay T instead of a long, single pulse.

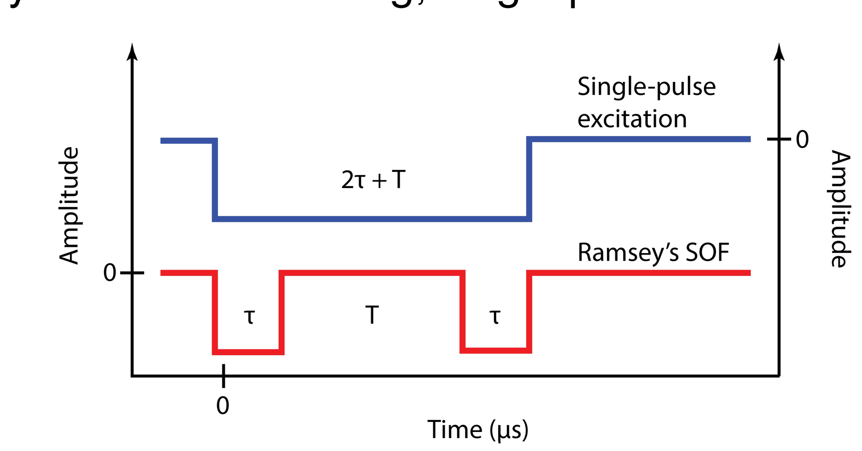

Figure 5: Single-pulse v. Ramsey's SOF scheme.

A detuning scan reveals Ramsey fringes, as expected.

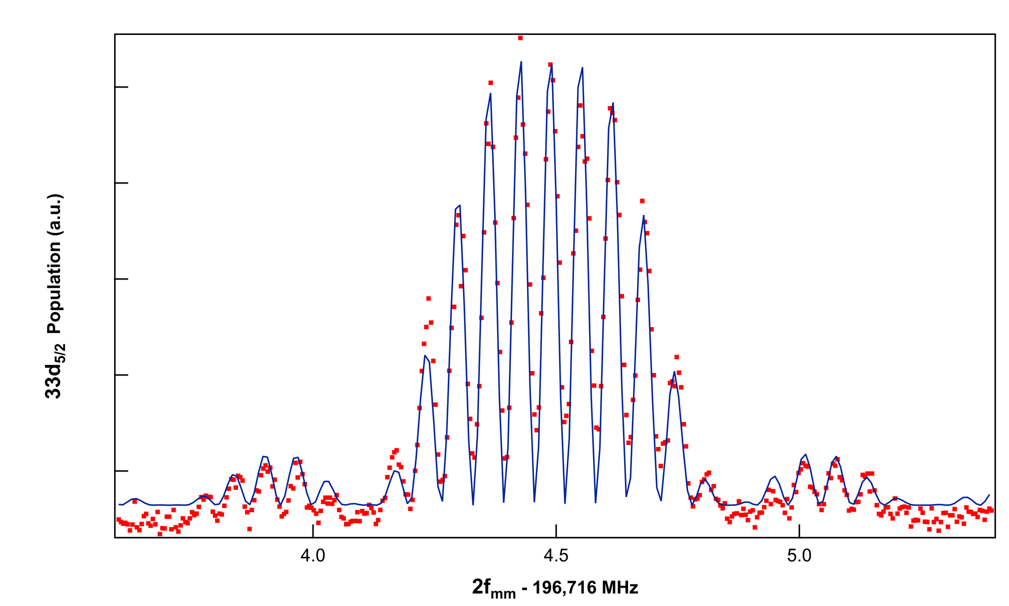

Figure 6: Ramsey fringes & fit for 32d$_{5/2}$$\to$33d$_{5/2}$. Field-free spacing can be detected from the fit.

(n+1)d$_j$ state population oscillates as a function of T:

$$\boxed{P_{(n+1)d_j} \propto \cos^2\left(\frac{\Delta_0 T}{2}\right)}$$

where $\Delta_0 = \omega_0 - (E_{(n+1)d_j} - E_{nd_j})/\hbar$ is the beat frequency between the mm-wave and the atomic transition frequencies in zero oscillatory field. With known mm-wave frequency offset, fitting a cosine squared to a delay scan signal allows for determining the zero-power frequency for the 33d$_{5/2}$ $\to$ 34d$_{5/2}$ transition.

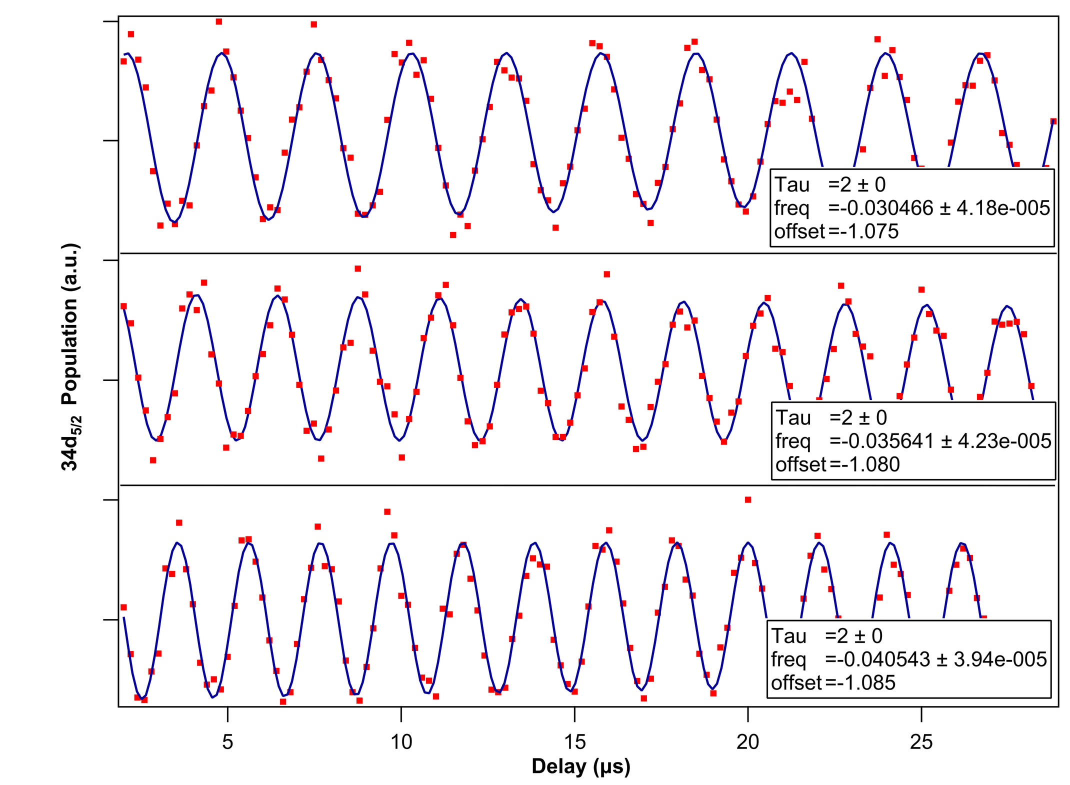

Figure 7: Delay (T) scans at different ω_0's. Each corresponds to the same field-free interval 179,483.467(10) MHz.

Determination of d-state quantum defects

The absolute energies are given by:

$$\boxed{E_n = -\frac{hcR_K}{(n-\delta(n))^2}, \quad \delta(n) = \delta_0 + \frac{\delta_2}{(n-\delta_0)^2}}$$

where n is the principal quantum number, and $\delta(n)$ is the quantum defect, parameterized by two coefficients, δ_0 and δ_2.

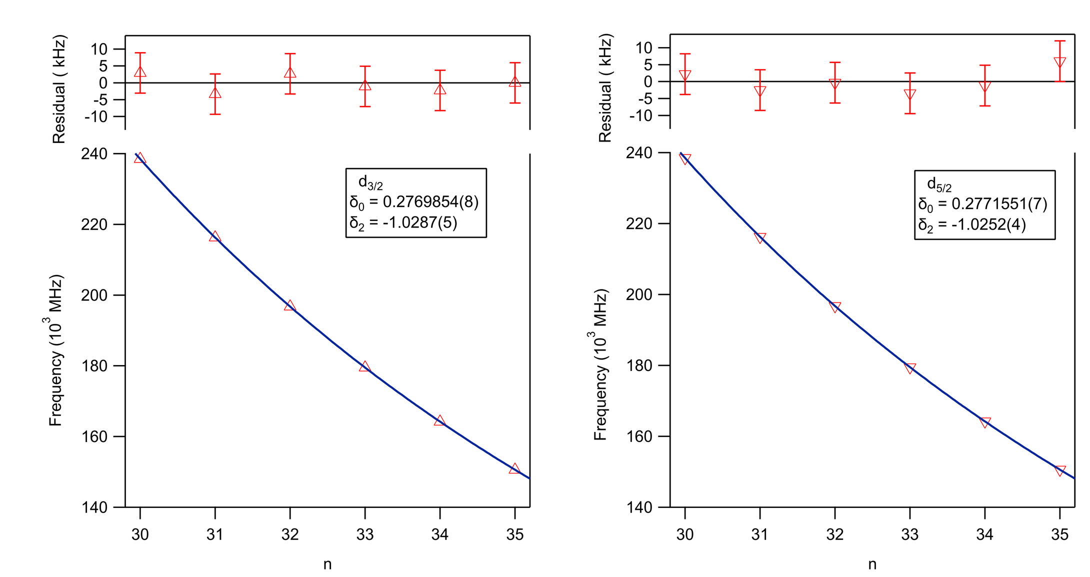

Figure 8: nd$_j$ $\to$ (n+1)d$_j$ transition frequencies versus principal quantum number. A fit of the measured transition energies is be used to determine δ_0 and δ_2 for the d$_{3/2}$ and d$_{5/2}$ states. Residuals of the fit are less than 5×10^{-8} of the transition frequency.

Acknowledgments

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