Millimeter-wave precision spectroscopy of potassium in Rydberg states

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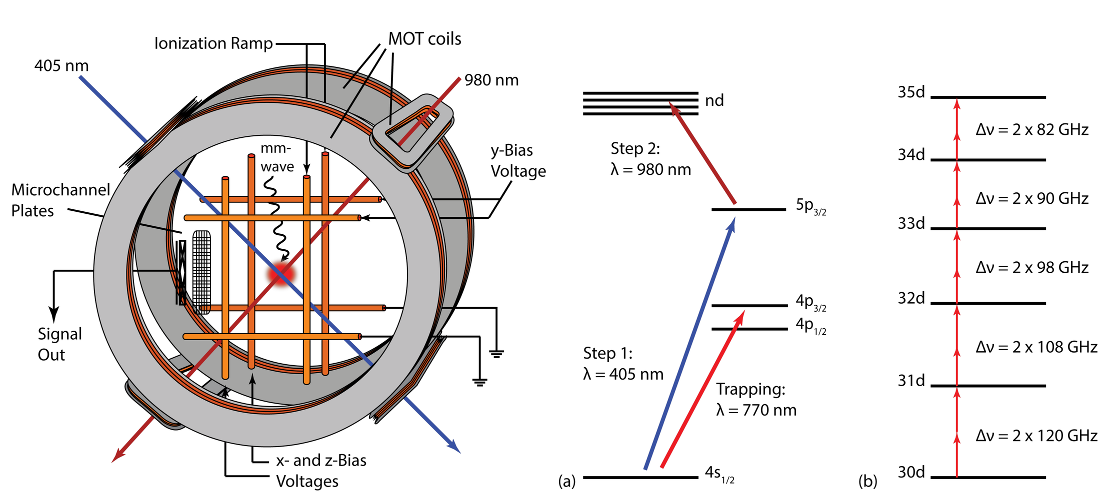
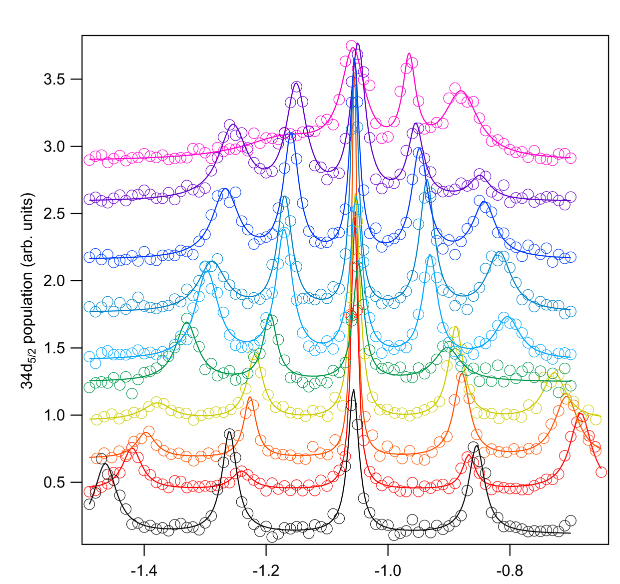
Abstract

We measure two-photon mm-wave transitions between nd$_j$ and (n+1)d$_j$ Rydberg states for $30 \leq$ n ≤ 35 in ^{39}K to an accuracy 5$\times$ 10^{-8} to determine high-n d-state quantum defects and absolute energy levels. ^{39}K atoms are trapped and cooled to 2-3 mK in a MOT, and excited from 4s$_{1/2}$ to nd$_{3/2}$ or nd$_{5/2}$ by frequency-stabilized 405 nm and 980 nm ECDL's in succession. The magnetic-field insensitive nd$_j$ $\to$ (n+1)d$_j$ Δm $= 0$ transitions are driven by a 16 μs-long pulse of mm-waves before the atoms are selectively ionized for detection. The (n+1)d population is measured as a function of mm-wave frequency. Static electric fields in the MOT are nulled in three dimensions to eliminate DC Stark shifts. The transitions exhibit small but measurable AC Stark shifts at resonance. Field-free intervals are determined both by extrapolating a sequence of measurements made as a function of mm-wave power to zero and directly without extrapolation by applying Ramsey's separated oscillating fields method. Our results give quantum defects for the high-n states that are an order of magnitude more accurate than earlier measurements of these quantities.



The MOT cloud is trapped in a magnetic field and cooled by 770 nm beams. The rods provide a static field and an ionization field. mm-waves drive nd $\to$ (n+1)d transitions. (a) 2-step trapping and excitations from 4s$_{1/2}$ to nd. (b) Two-photon transitions and approximate frequencies.

Magnetic-field insensitive Δm = 0 transitions



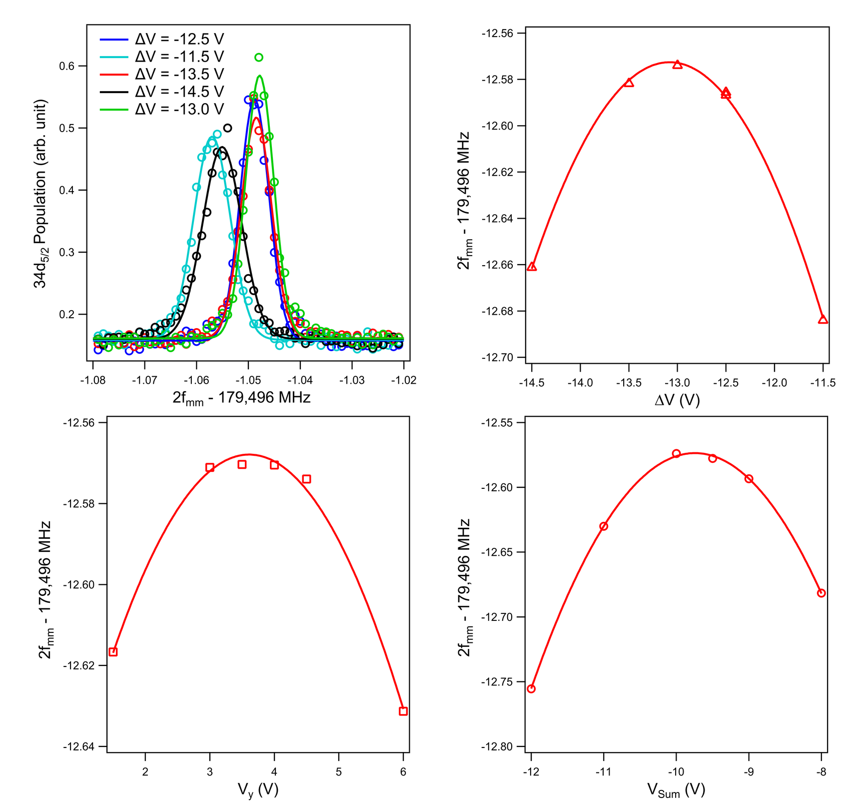
The splitting changes as we change the net magnetic field inside the MOT. However, the 33d$_{5/2}$ $\to$ 34d$_{5/2}$ Δm $= 0$ transition is not affected.

Static field elimination

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

$$\Delta\nu_{nd\to(n+1)d} = \nu_0 - \frac{1}{2}\Delta\alpha E^2,$$

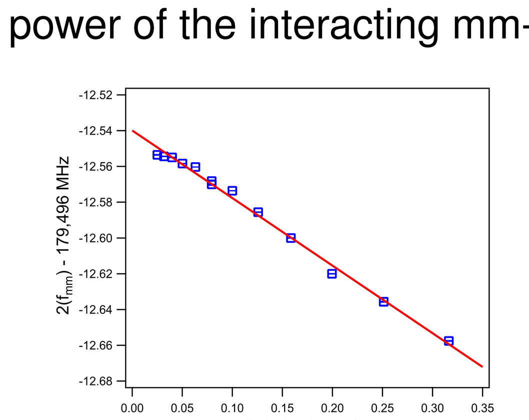
where $\Delta\alpha$ is the difference between the (n+1)d and nd polarizabilities. In general, α represents how strongly energy levels shift in response to an external static electric field.



Static field elimination for 33d$_{5/2}$ $\to$ 34d$_{5/2}$ transition. Shown are 34d$_{5/2}$ population distributions and transition frequencies at different static field values in orthogonal directions. Projected maximum frequency in one direction corresponds to a DC bias that nullifies the field in that direction.

Zero mm-wave power extrapolation

While not large, the AC Stark shift due to the mm-waves is significant at our level of precision. This shift is directly proportional to the power of the interacting mm-wave.



Zero-power extrapolation for 33d$_{5/2}$ $\to$ 34d$_{5/2}$ transition after static field elimination. 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 kHz.

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

$$\begin{aligned}\Delta\nu_0 = 2\mathrm{f}_{\mathrm{mm}} &= \text{179,496 MHz - 12.540 MHz}\\ &= \text{179,483.46 MHz}\end{aligned}$$

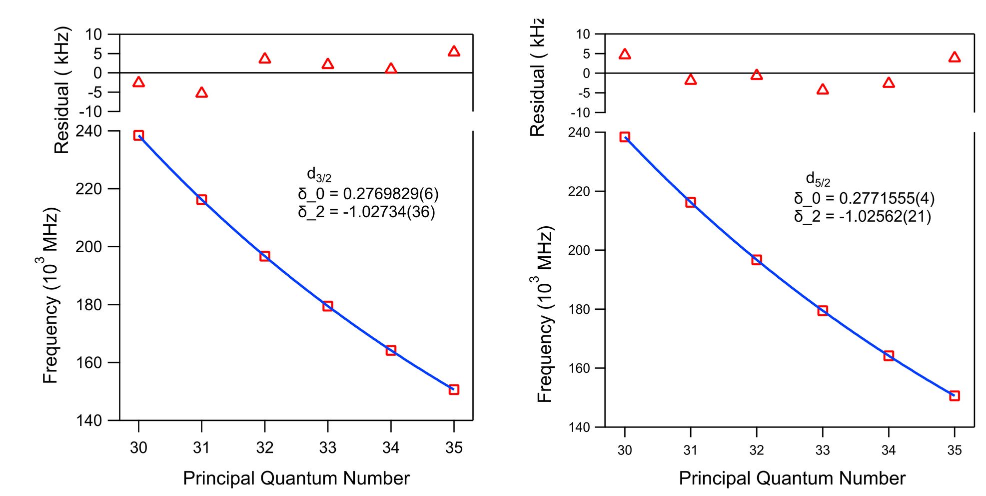
Determination of d-state quantum defects

The absolute energies are given by:

$$E_n = -\frac{hcR_K}{(n-\delta(n))^2},$$

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

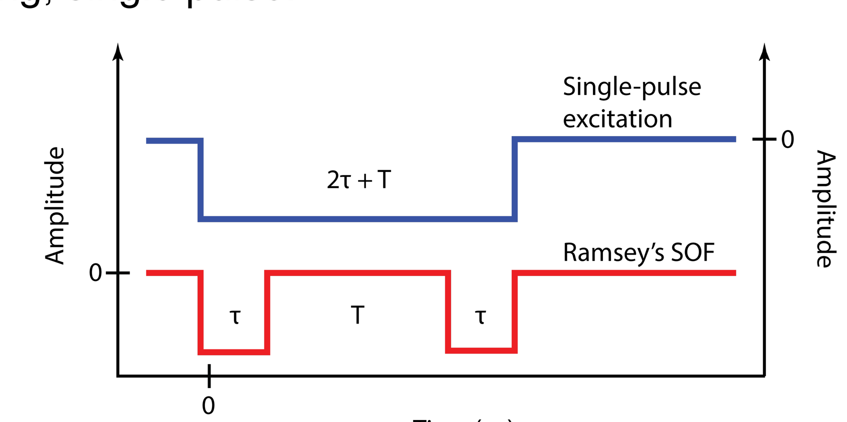
$$\delta(n) = \delta_0 + \frac{\delta_2}{(n-\delta_0)^2}.$$



nd $\to$ (n+1)d transition frequencies versus principal quantum number. A fit of the measured resonance frequencies are 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 a part in 10^7 of the transition frequencies.

Ramsey's SOF, an alternative technique

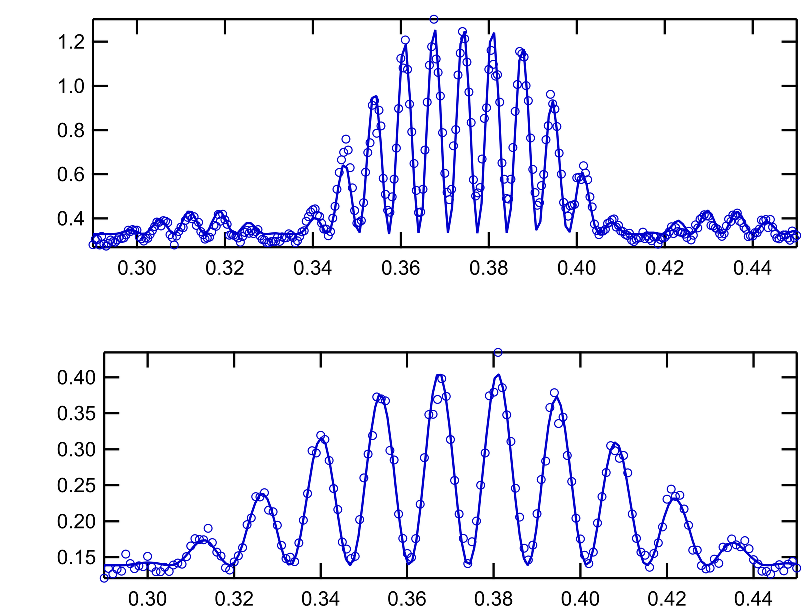
Ramsey's separated oscillating field method removes the need for zero-power extrapolation. ^{39}K atoms in the nd state are exposed to a double pulse of width τ and delay T instead of a long, single pulse.



The full expression for $P_{(n+1)d_{5/2}}$ is

$$4\sin^2\theta\sin^2\frac{\Omega'\tau}{2}\left\{\cos\frac{\Omega'\tau}{2}\cos\frac{\Delta_0 T}{2} - \cos\theta\sin\frac{\Omega'\tau}{2}\sin\frac{\Delta_0 T}{2}\right\},$$

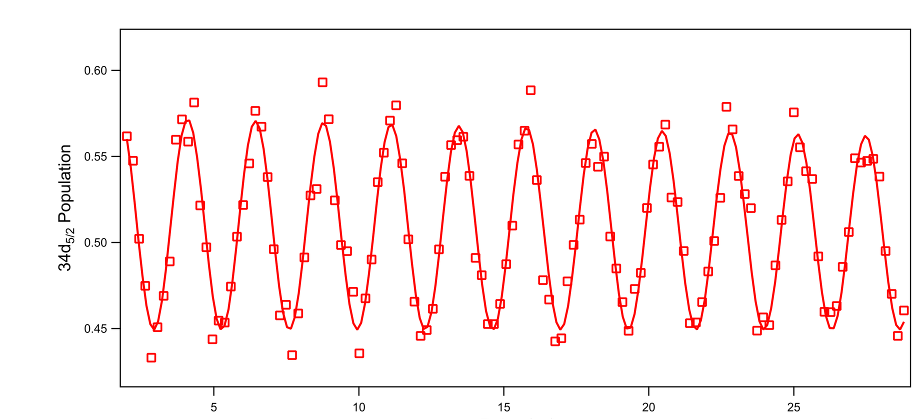
which well-models our measurements:



The final (n+1)d population oscillates as a function of T:

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

where $\Delta_0 = \omega_0 - [E_{(n+1)d} - E_{nd}]/\hbar$ is the beat frequency between the mm-wave frequency and the atomic transition frequency 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.

The fit gives $\Delta_0/2\pi$ = -0.4277 MHz. With an initial mm-wave frequency offset of -12.96 MHz, the field-free 33d$_{5/2}$ $\to$ 34d$_{5/2}$ spacing is:

$$\begin{aligned}\Delta\nu_0 &= \nu_{\text{offset}} - \Delta_0/2\pi + \text{179,496 MHz}\\ &= \text{-12.96 MHz + 0.4277 MHz + 179,496 MHz}\\ &= \text{179,483.47 MHz},\end{aligned}$$

consistent with the zero-power-extrapolated value.

Acknowledgments

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