Millimeter-wave precision spectroscopy of potassium in Rydberg states

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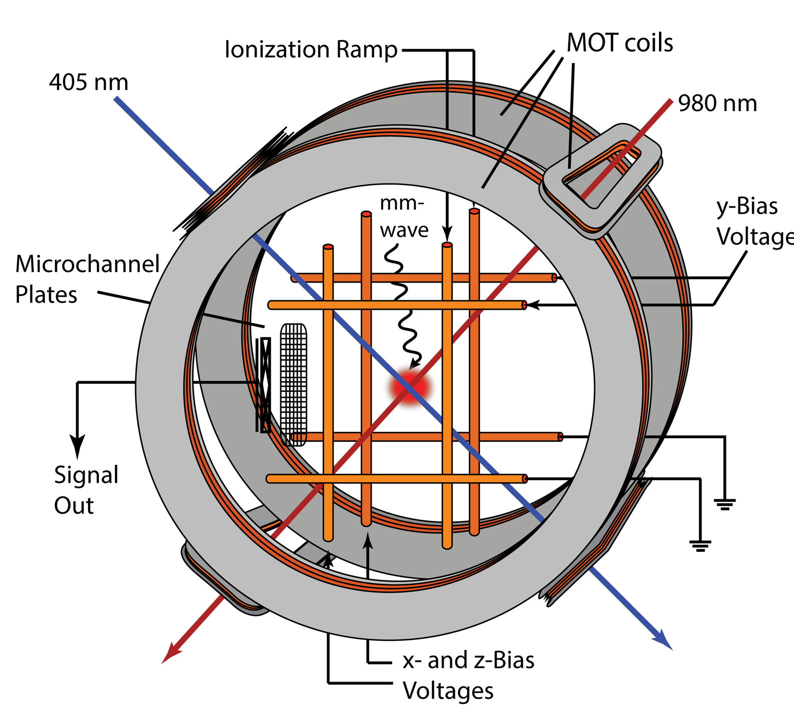
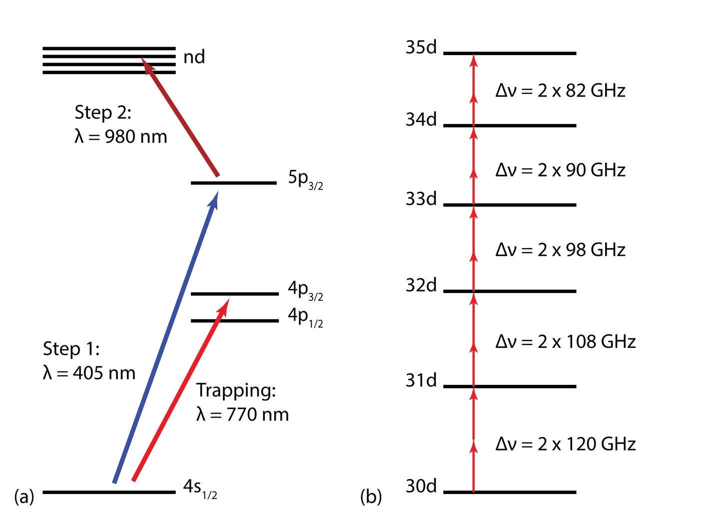
Abstract

We measure energy spacings between highly excited states in potassium to a part in 10^7 to determine d-state quantum defects and absolute energy levels of potassium. K-39 atoms are magneto-optically trapped (MOT) and cooled to 1 mK, and excited from $4s_{1/2}$ to $nd_{3/2}$ or $nd_{5/2}$ by a 405 nm and 980 nm diode laser in succession. nd $\to$ (n+1)d transitions are driven by a μs-long pulse of millimeter-wave, and the atoms are selectively ionized. The (n+1)d population is measured as a function of mm-wave frequency. Static fields in the MOT are nullified in three dimensions. Zero-oscillatory-field transition energies can be measured in two ways: (1) extrapolating zero-mm-wave resonance frequency and (2) Ramsey's separated oscillatory field (SOF) method.



Sketch of the MOT, with the MOT cloud trapped in a magnetic field created by 6 MOT coils and cooled by a 770 nm laser (not shown). The rods provide a static field and an ionization field. A mm-wave drives nd $\to$ (n+1)d transitions.



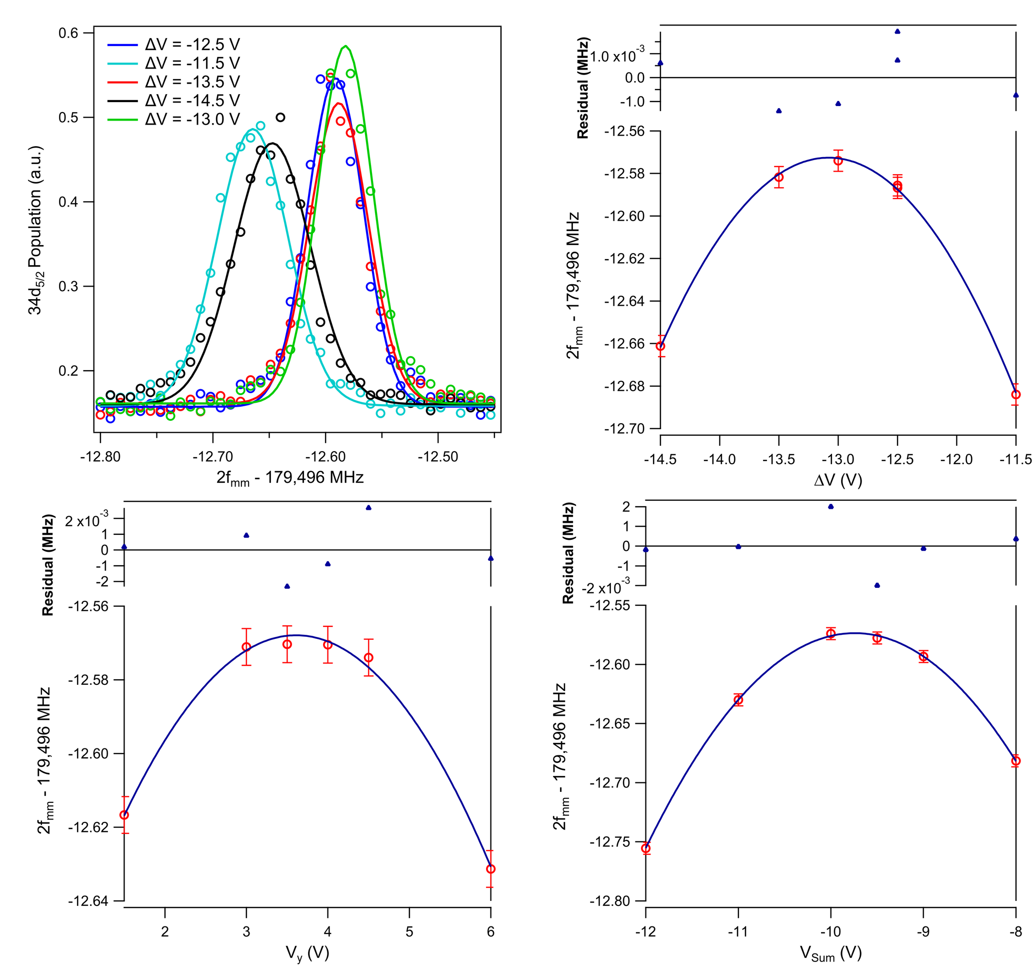
(a) Trapping and excitations from $4s_{1/2}$ to nd states in 2 steps. (b) Two-photon mm-wave transitions and their approximate frequencies.

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:

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

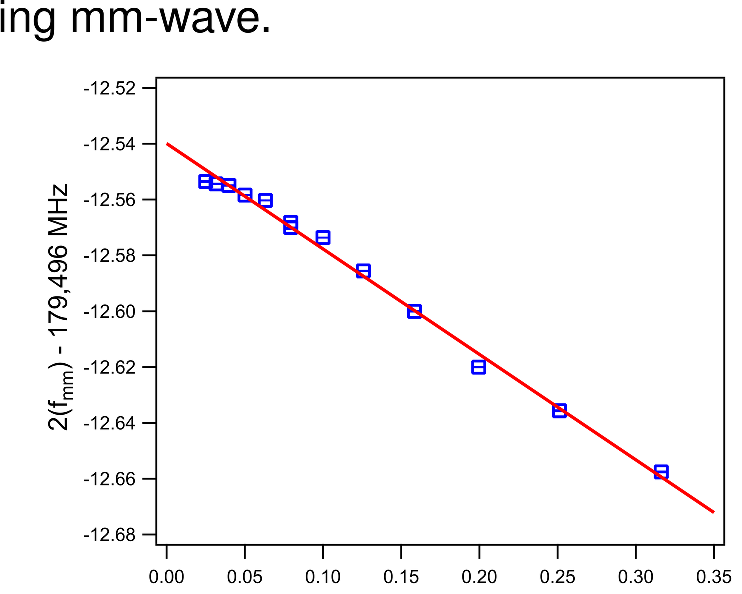
where $\Delta\alpha$ is the difference between the (n+1)d and nd polarizabilities. In general, α represents how strongly energy levels shift in response to an external static electric field.



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 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.



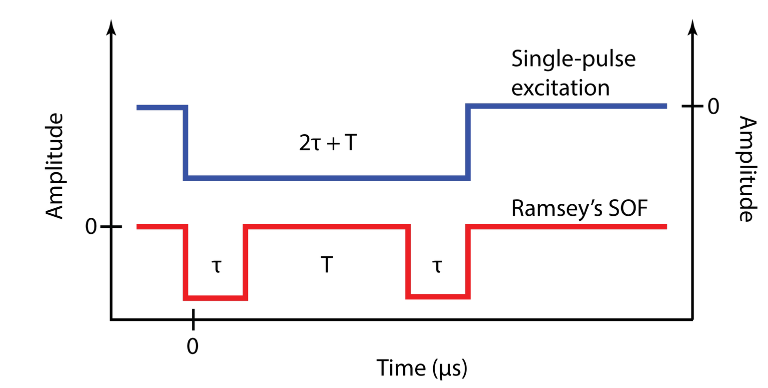
Zero-power extrapolation for $33d_{5/2} \to 34d_{5/2}$ transition after static field elimination. The y-intercept of the linear fit of the measured transition frequencies is the mm-wave-free transition frequency. The energy shifts from 0.35 to 0 relative intensity are on the order of a few kHz.

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

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

Ramsey's SOF, an alternative technique

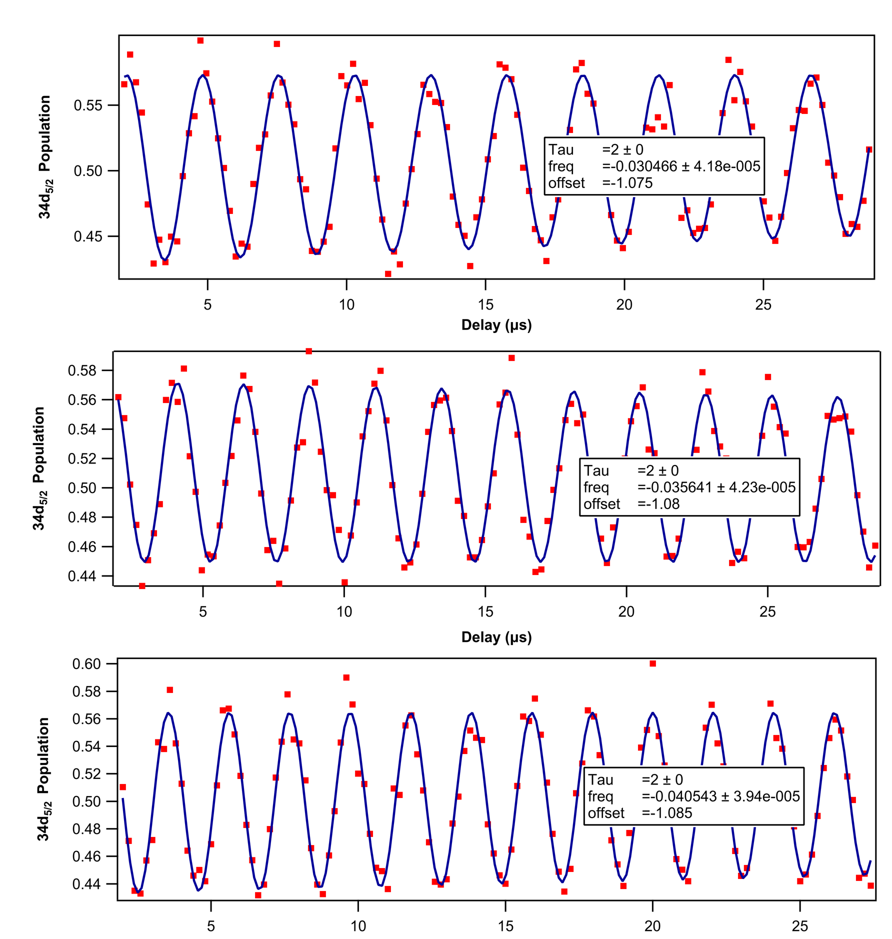
Ramsey's separated oscillatory field method removes the need for zero-power extrapolation. K atoms in the nd state are exposed to a double pulse of width τ and delay T instead of a long, single pulse.



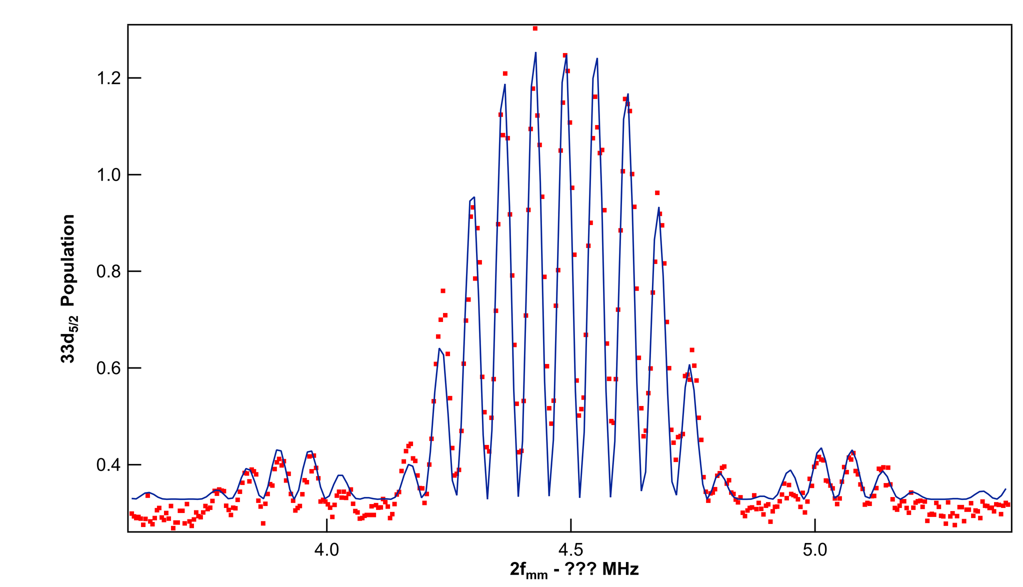
The final (n+1)d state population oscillates as a function of T:

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

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.



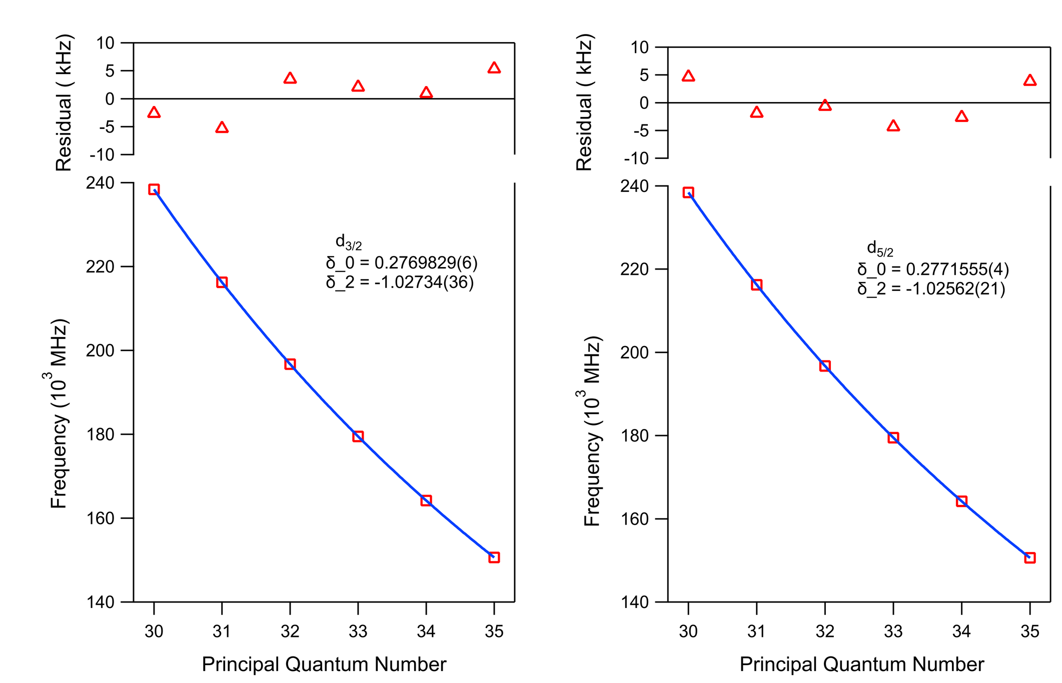
Determination of d-state quantum defects

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 transition energies can 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 a part in 10^7 of the transition frequency.

Acknowledgments

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