



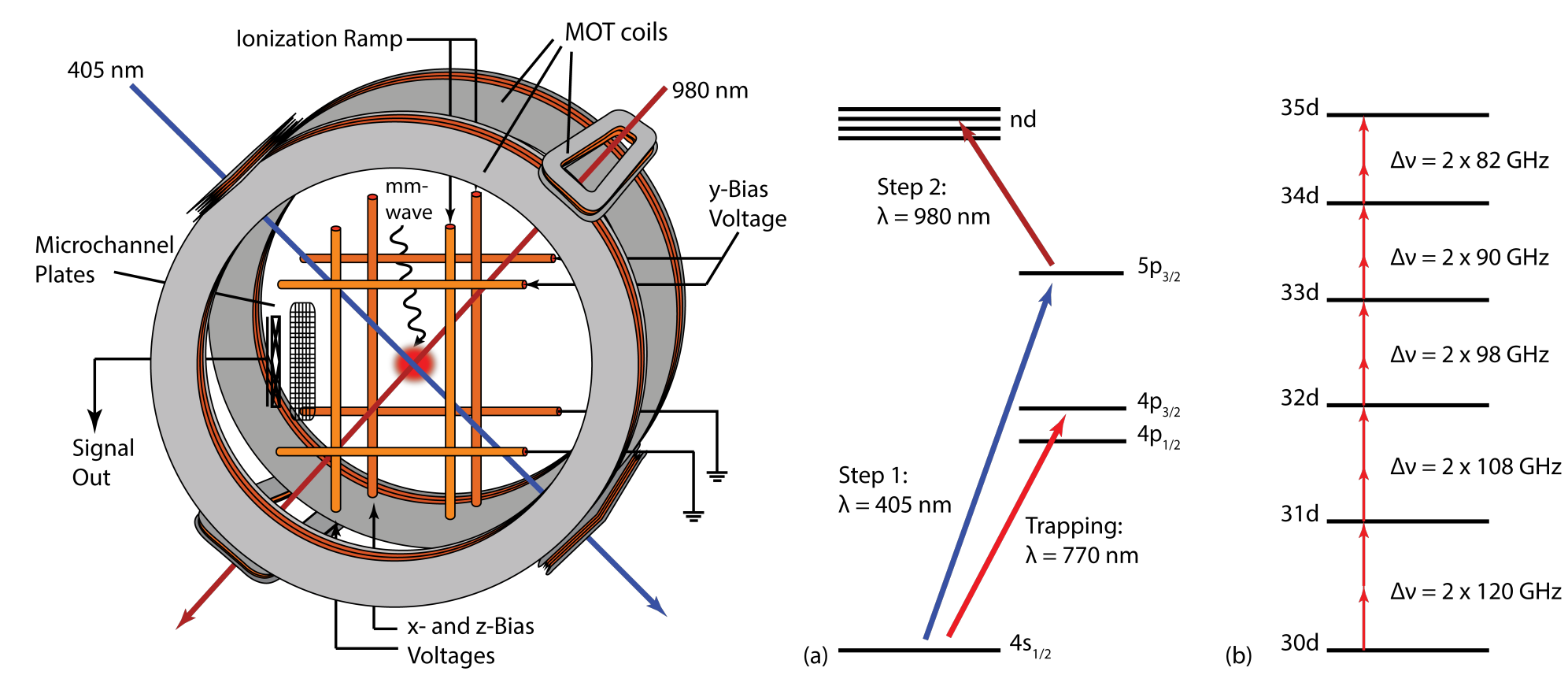
# Millimeter-wave precision spectroscopy of potassium in Rydberg states

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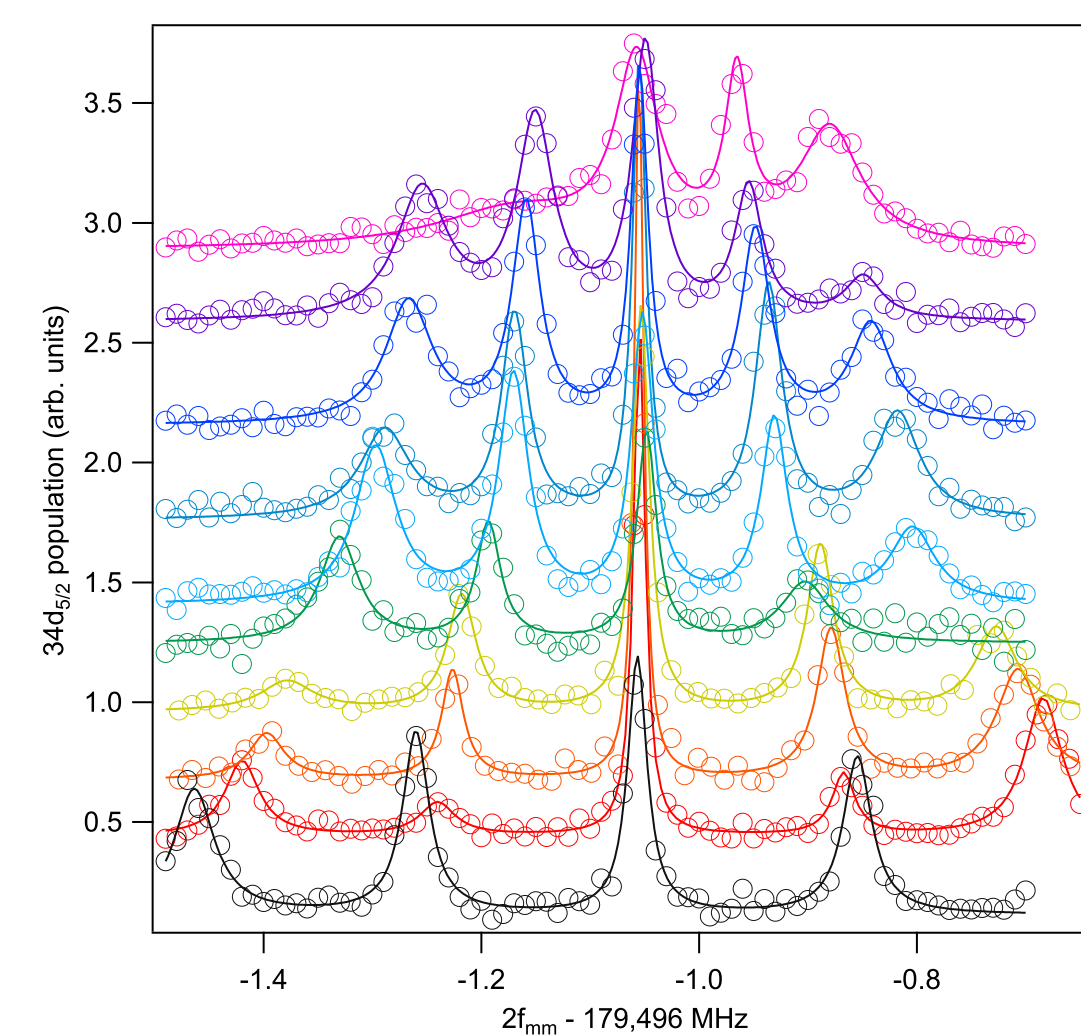
## Abstract

We measure two-photon mm-wave transitions between  $nd_j$  and  $(n+1)d_j$  Rydberg states for  $30 \leq n \leq 35$  in  $^{39}\text{K}$  to an accuracy  $5 \times 10^{-8}$  to determine high- $n$  d-state quantum defects and absolute energy levels.  $^{39}\text{K}$  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  $nd_j \rightarrow (n+1)d_j$   $\Delta m = 0$  transitions are driven by a 16  $\mu\text{s}$ -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 a 770 nm laser (not shown). The rods provide a static field and an ionization field. A mm-wave drives  $nd \rightarrow (n+1)d$  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.

## Magnetic-field insensitive $\Delta m = 0$ transitions

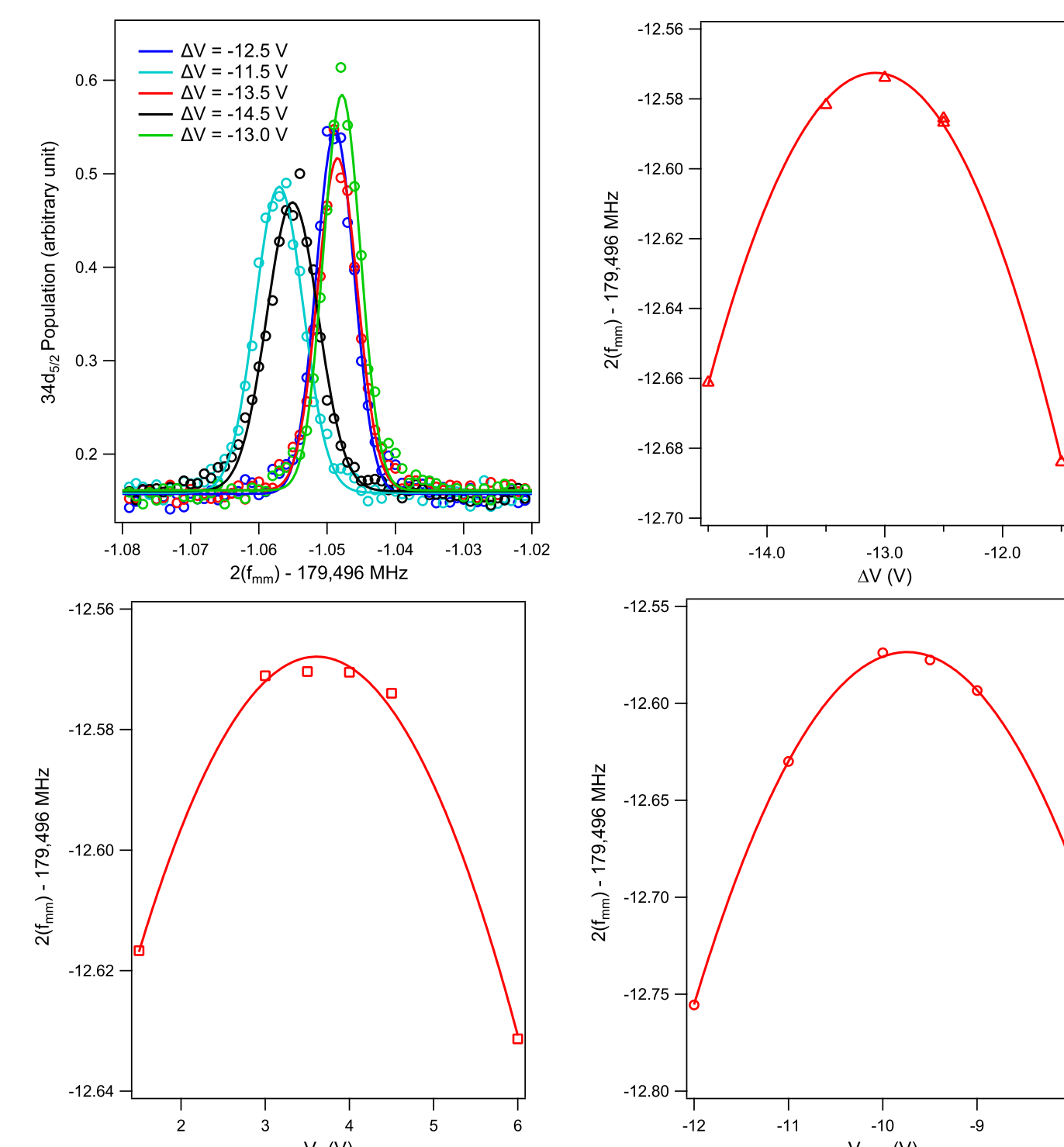


## Static field elimination

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

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

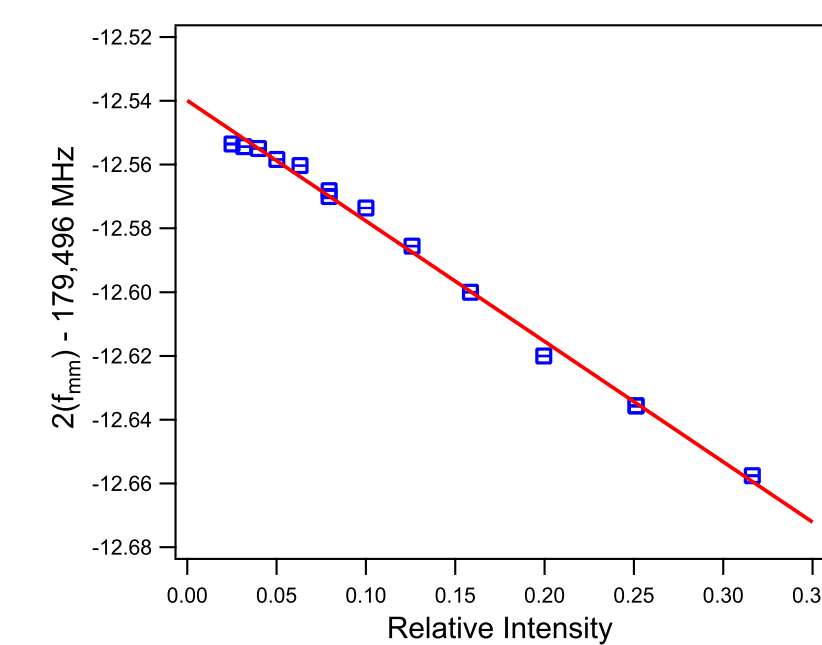
where  $\Delta\alpha$  is the difference between the  $(n+1)d$  and  $nd$  polarizabilities. In general,  $\alpha$  represents how strongly energy levels shift in response to an external static electric field.



Static field elimination for  $33d_{5/2} \rightarrow 34d_{5/2}$  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  $33d_{5/2} \rightarrow 34d_{5/2}$  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.

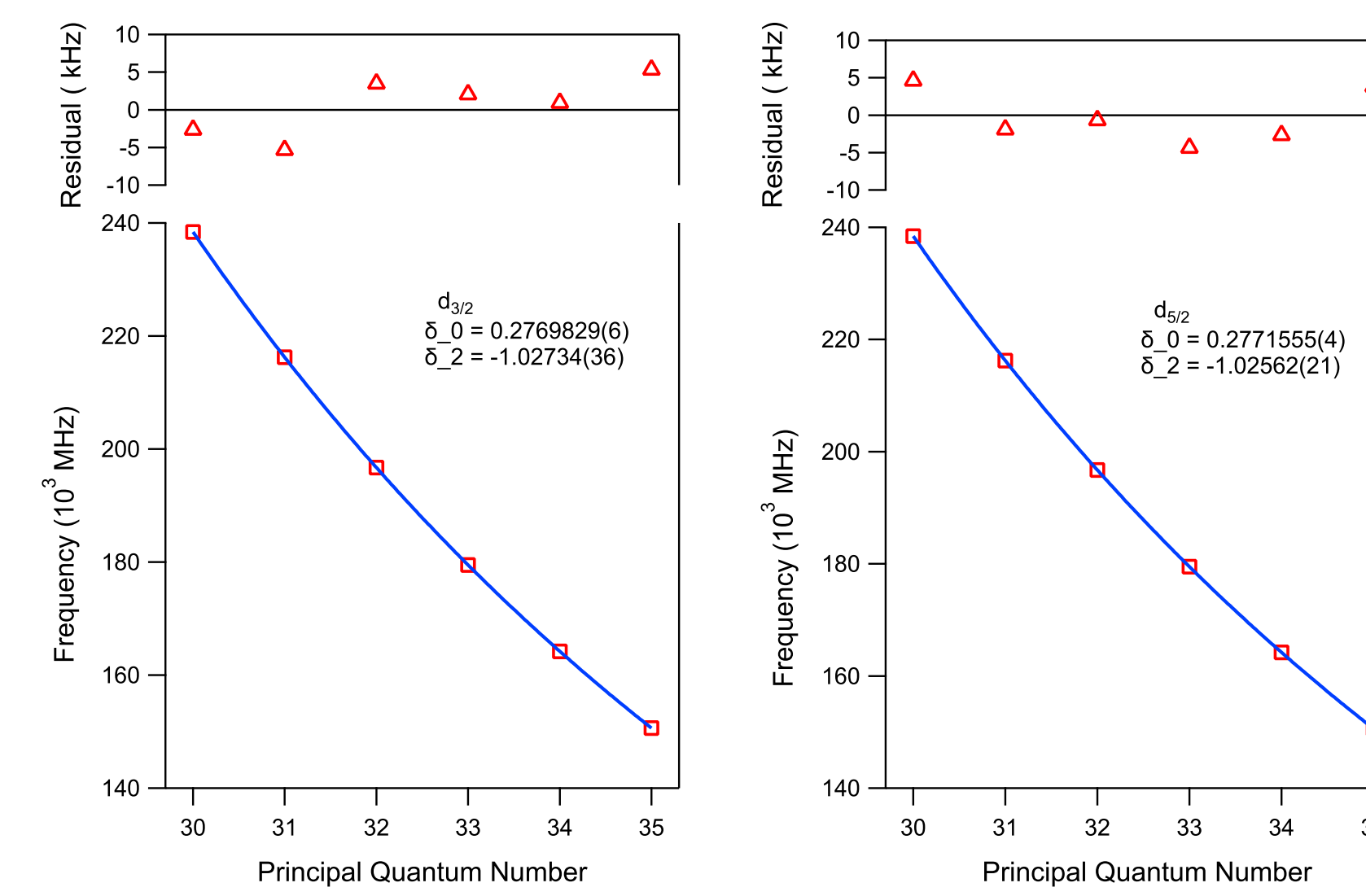
## Determination of d-state quantum defects

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,  $\delta_0$  and  $\delta_2$ , as:

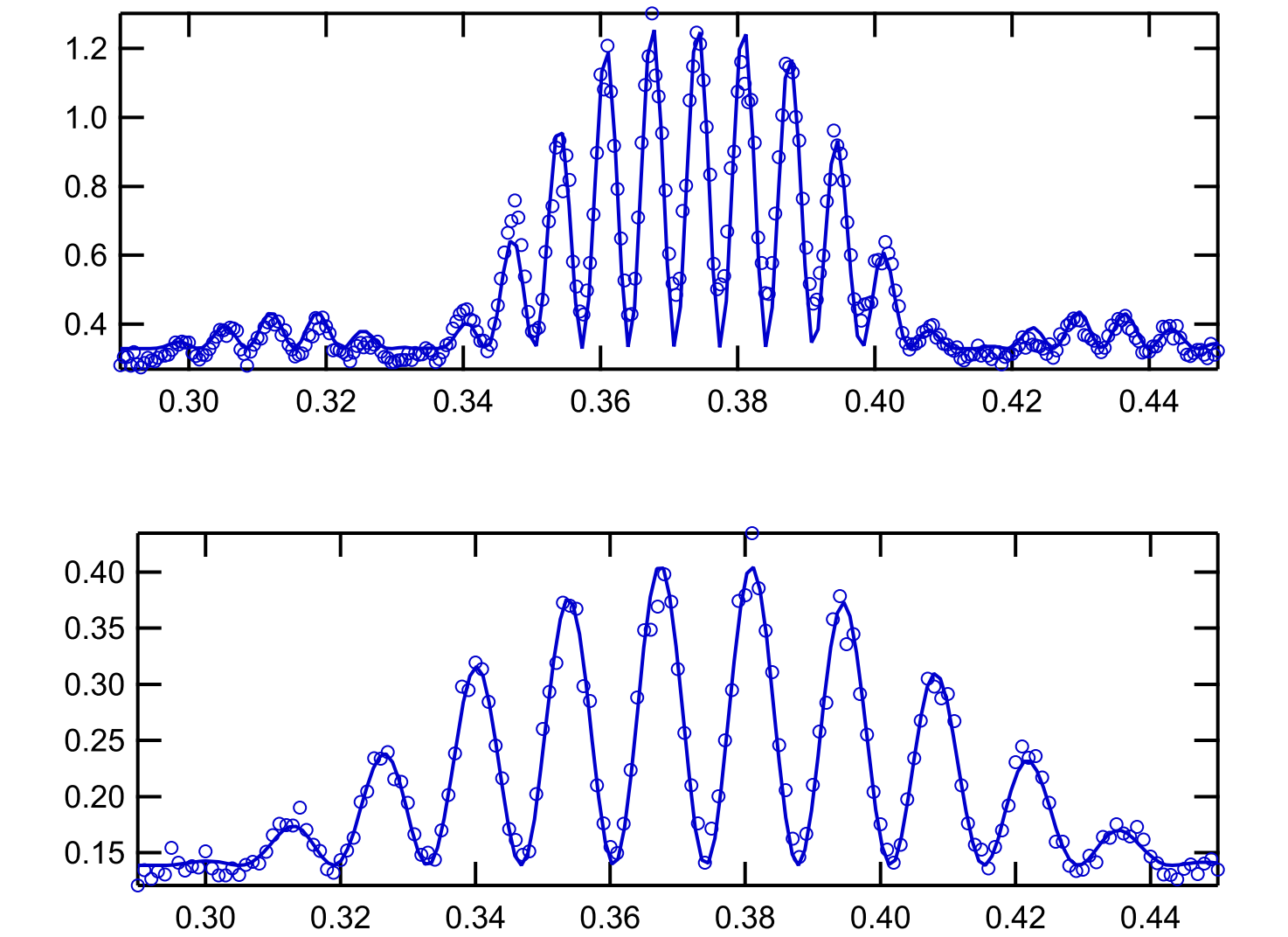
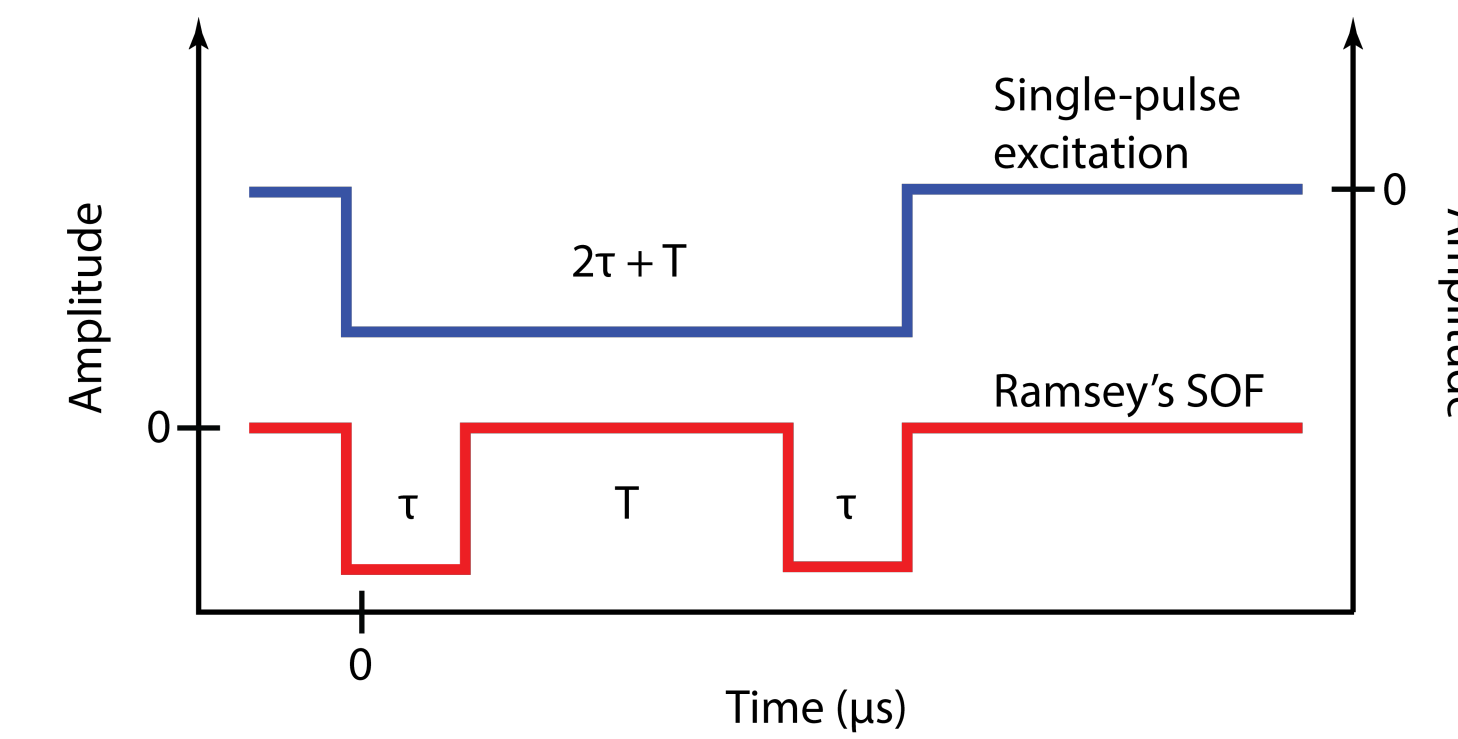
$$\delta(n) = \delta_0 + \frac{\delta_2}{(n - \delta_0)^2}.$$



$nd \rightarrow (n+1)d$  transition frequencies versus principal quantum number. A fit of the measured resonance frequencies are used to determine  $\delta_0$  and  $\delta_2$  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

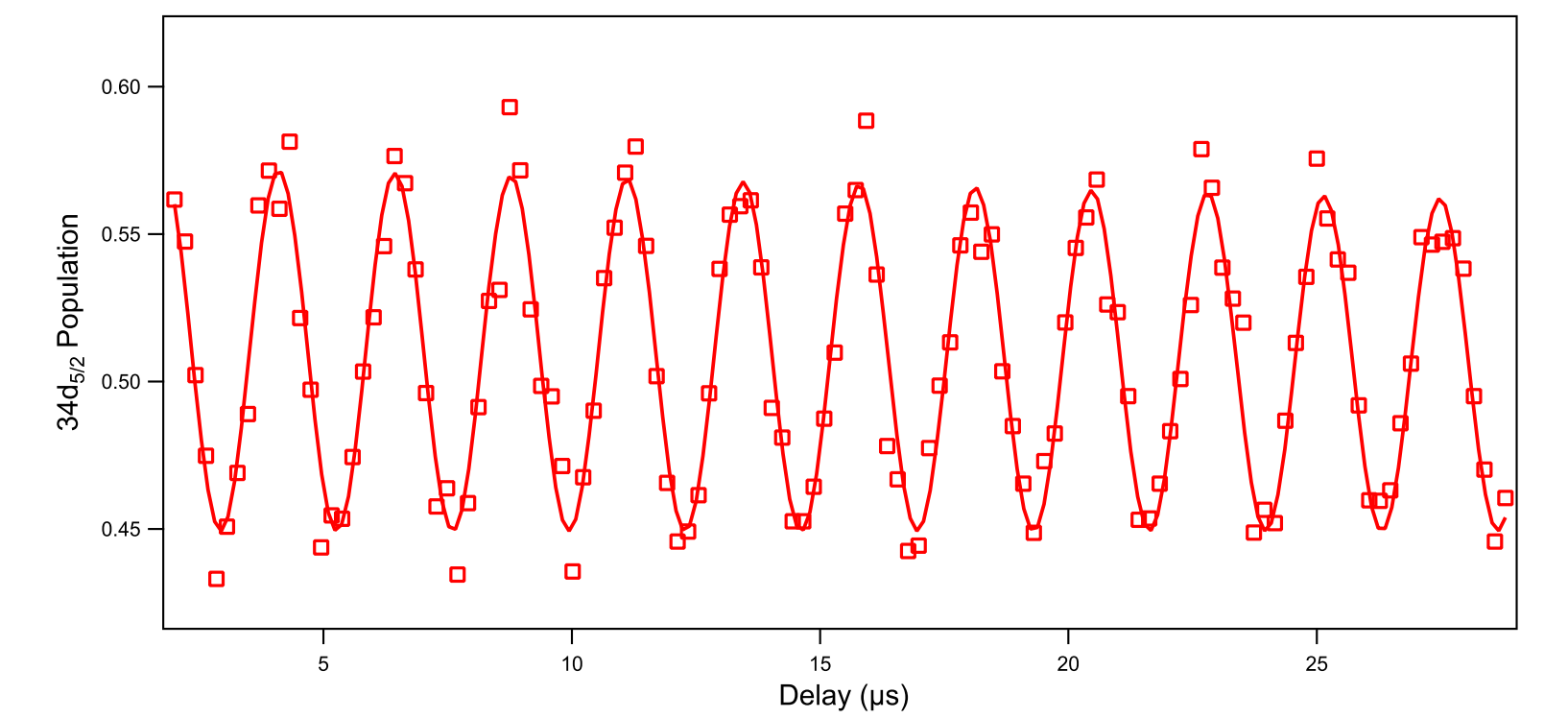
Ramsey's separated oscillatory field method removes the need for zero-power extrapolation. K atoms in the  $nd$  state are exposed to a double pulse of width  $\tau$  and delay  $T$  instead of a long, single pulse.



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  $33d_{5/2} \rightarrow 34d_{5/2}$  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  $33d_{5/2} \rightarrow 34d_{5/2}$  spacing is:

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

consistent with the zero-power-extrapolated value.

## Acknowledgments

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