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

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Abstract

We measured two-photon millimeter-wave transitions between nd$_j$ and (n+1)d$_j$ Rydberg states in ^{39}K for principal quantum number n from 30 to 35. Transition frequencies between 150 and 240 GHz were measured to an accuracy of 10 kHz ($\simeq 5 \times 10^{-8}$). Using these measurements we are able to determine high-n d-state fine-structure intervals, quantum defects, and absolute energy levels. In the experiment around 10^6 ^{39}K atoms were magneto-optically trapped and cooled to 2-3 mK with a peak density of approximately 2×10^8 atoms/cm^3 using a 30 mW 767 nm laser modulated at 455 MHz to drive the repumping transition. The trapped atoms were excited with 5-10 μs pulses of light from frequency-stabilized external-cavity diode lasers in a stepwise sequence from the ground 4s$_{1/2}$ F = 1 state to the 5p$_{3/2}$ state with a 405 nm laser and subsequently to the nd$_{3/2}$ or nd$_{5/2}$ state with a 980 nm laser. The magnetic-field insensitive nd$_j$ $\rightarrow$ (n+1)d$_j$ Δm $= 0$ transitions were driven by 16 μs-long pulses of mm-waves before the populations of both states were measured using selective field ionization with a 0.5 μs risetime electric field. The fraction of atoms in the (n+1)d$_j$ state was measured as a function of mm-wave frequency. Measured transitions have widths of 40-50 kHz, consistent with the transform limit. Static electric fields in the MOT were nulled to less than 50 mV/cm in three dimensions using voltages applied to sets of mutually orthogonal stainless steel rods around the MOT cloud to eliminate DC Stark shifts. Measurements of the d-state polarizabilities show that the residual electric fields are the main factor limiting the measurement's accuracy to 10 kHz. The two-photon transitions exhibit small but measurable AC Stark shifts in the resonance frequencies. We determined the field-free intervals in two ways. First, we extrapolated a sequence of measurements made as a function of mm-wave power to zero power. Second, we applied Ramsey's method of separated oscillatory fields to determine the field-free intervals without extrapolation. In the latter method we scanned the delay (0-32 μs) between two short (1-2 μs), intense, nearly resonant mm-wave pulses and measured the beat frequency between the coherent evolution of the superposition state and the mm-wave source. Fitting the measured frequencies to a function including the first two terms in the quantum defect expansion for the energy levels gives quantum defect parameters for the high-n states that are an order of magnitude more accurate than earlier measurements of these quantities.

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