

# Measurement of a Wavelength of Light for Which the Energy Shift for an Atom Vanishes

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Light at a magic-zero wavelength causes a zero energy shift for an atom. We measured the longest magic-zero wavelength for ground state potassium atoms to be  $\lambda_{\text{zero}} = 768.9712(15)$  nm, and we show how this measurement provides an improved experimental benchmark for atomic structure calculations. This  $\lambda_{\text{zero}}$  measurement determines the ratio of the potassium atom *D1* and *D2* line strengths with record precision. It also demonstrates a new application for atom interferometry, and we discuss how decoherence will fundamentally limit future measurements of magic-zero wavelengths.

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The light-induced energy shift of an atom depends on the light wavelength, and there exist *magic-zero wavelengths* for which the energy shift vanishes [1,2]. A magic-zero wavelength ( $\lambda_{\text{zero}}$ ) is found between atomic resonances, where the light is red-detuned from one resonance and blue-detuned from another. Opposing contributions from these resonances produce a root in the energy shift spectrum at  $\lambda_{\text{zero}}$ . In this Letter, we report a measurement of a magic-zero wavelength made with an atom interferometer.

LeBlanc and Thywissen [1] referred to  $\lambda_{\text{zero}}$  as *tune-out wavelengths* and discussed their utility for multispecies atom traps. Since then, various  $\lambda_{\text{zero}}$  have been used in experiments to study entropy exchange [3], quantum information processing [4], and diffraction of matter waves from an ultracold atom crystal [5]. However, the light used in experiments [3–5] to minimize energy shifts can be hundreds of picometers different than the  $\lambda_{\text{zero}}$  values calculated in Refs. [1,2] due to impure optical polarization. LeBlanc and Thywissen predicted a  $\lambda_{\text{zero}}$  for each alkali atom with 10 pm precision based on the wavelengths of their principal (*D1* and *D2*) transitions. More recently, Arora, Safronova, and Clark [2] predicted magic-zero wavelengths by using state-of-the-art atomic theory calculations of dipole matrix elements for several transitions in each atom, including core electron excitations. For the  $\lambda_{\text{zero}}$  we measured, Arora, Safronova, and Clark stated a theoretical uncertainty of 3 pm. In comparison, our measurement has an uncertainty of 1.5 pm. Because calculations of dipole matrix elements similar to those used in Ref. [2] are needed to calculate static polarizabilities, state lifetimes, line strengths, van der Waals potentials, and magic wavelengths [6–8], we are motivated to explore how measurements of magic-zero wavelengths can serve as new benchmark tests of atomic structure calculations.

In this Letter, we present a measurement of the magic-zero wavelength for potassium between the 770 (*D1*) and 767 nm (*D2*) transitions. Our measurement of  $\lambda_{\text{zero}} = 768.9712(14)_{\text{stat}}(6)_{\text{sys}}$  is a novel test of atomic structure calculations and provides the most precise determination

yet of the ratio of the *D1* and *D2* line strengths  $S_1$  and  $S_2$ . We find the ratio

$$R = \frac{S_2}{S_1} = \frac{|\langle 4s || D || 4p_{3/2} \rangle|^2}{|\langle 4s || D || 4p_{1/2} \rangle|^2} = 2.0005(40). \quad (1)$$

The ratio of degeneracies for the excited states would make  $R = 2$ ; however, relativistic corrections slightly reduce the predicted ratio to  $R = 1.9987$  [9]. Our measurement is consistent with the prediction in Ref. [2], and our measurement uncertainty is half as much as the theoretical uncertainty quoted in Ref. [2].

Most measurements of static and dynamic polarizabilities [10–14] are limited by uncertainty in the electric field strength and uncertainty in the time an atom interacts with the field. However, our measurement of the wavelength at which the polarizability is zero is not subject to uncertainty from these factors. Instead, we will discuss systematic errors in  $\lambda_{\text{zero}}$  measurements caused by laser spectra and statistical limitations caused by contrast loss and small (mrad/pm) phase shifts near  $\lambda_{\text{zero}}$ .

The longest magic-zero wavelengths for alkali atoms are determined mostly by the transition energies  $\hbar\omega_1$  and  $\hbar\omega_2$  and the ratio  $R$  of the line strengths. We use the sum-over-states approach to describe the dynamic polarizability  $\alpha(\omega)$  near these two transitions by

$$\alpha(\omega) = \frac{1}{3\hbar} S_1 \left( \frac{\omega_1}{\omega_1^2 - \omega^2} + R \frac{\omega_2}{\omega_2^2 - \omega^2} \right) + A, \quad (2)$$

where  $A$  accounts for contributions from core excitations, higher energy valence transitions, and core-valence coupling [6,15]. At the longest magic-zero wavelength of potassium,  $A$  is 0.02% of the nearly equal and opposite contributions from the principal transitions to the polarizability and  $A$  changes  $\lambda_{\text{zero}}$  by 0.15(1) pm [9]. Therefore, the uncertainty in this magic-zero wavelength calculation is nearly entirely determined by uncertainty in the ratio of the line strengths,  $R$ .