(or bluer) than the magic-zero wavelength may produce light (or dark) solitons. Studying vortex excitation probability from a laser stir stick [26] may provide another way to measure $\lambda_{\rm zero}$ in Bose-Einstein condensate systems. Atoms can diffract from an optical lattice near (but not at) $\lambda_{\rm zero}$, and atom beam deflections can be induced by light detuned from $\lambda_{\rm zero}$ [12]. But all of these methods essentially rely on changes to the center of mass motion for atoms or, equivalently, changes to the de Broglie wave that represents this motion. Atomic clocks provide similar (picometer) precision for measurements of the magic wavelengths ($\lambda_{\rm magic}$) that depend on the differential light shift for two states [7,8], but, because clocks are affected by shifts in both ground and excited states, they are less ideal for measurement of magic-zero wavelengths ($\lambda_{\rm zero}$) discussed here. Furthermore, all of these proposed experiments are limited by decoherence or heating due to photon scattering.

To quantify this fundamental limitation due to decoherence in our experiment, let Δ_i be the detuning from resonance i, Ω_i be the Rabi frequency, and T be the time that an atom is exposed to the laser beam. In the large detuning limit ($\Delta_i^2 \gg \Omega_i^2$), the slope $d\phi/d\lambda$ is proportional to $\sum_i T\Omega_i^2/\Delta_i^2$, whereas the phase uncertainty increases exponentially with the same factor [27]. This indicates that a more powerful laser or a longer interaction time offers diminishing returns for the experimental sensitivity to $\lambda_{\rm zero}$. To minimize the shot noise limited uncertainty in $\lambda_{\rm zero}$, we should increase the pulse area (IT) until we obtain a contrast reduction of $C/C_0 = e^{-1}$.

Our experiment could be significantly improved by increasing the atom interferometer path separation so the laser can be entirely focused (with homogeneous irradiance) on one interferometer path. The elliptical polarization could be reduced by a factor of 10^5 by passing the laser beam through a high quality polarizer immediately before it crosses the atom beam, and the broadband light component could be reduced by using a different type of laser or filtering the light with a grating and aperture. In this more ideal situation, decoherence is the only remaining source of contrast loss. We calculated a maximum achievable slope $d\phi/d\lambda$ of

$$\frac{d\phi}{d\omega} \approx \frac{1}{2\Gamma} P_s, \tag{5}$$

where P_s is the probability that an atom scatters one or more photons and Γ is the excited state decay rate. With optimized contrast loss due to scattering ($P_s = 1 - e^{-1}$), the slope becomes as large as $d\phi/d\lambda = 40$ rad/pm. In this way, future measurements of magic-zero wavelengths can be made with very high precision, possibly with accuracy limited by a shot noise sensitivity better than picometers per $\sqrt{\rm Hz}$ with current technology. Perhaps this can be achieved in an ultracold atom interferometer [11]; however, such experiments typically would measure the magic-zero wavelength of a particular $|F, m_F\rangle$ state and therefore may be more sensitive to uncertainties in the laser polarization and magnetic fields.

As an outlook, the $\lambda_{\rm zero}$ measurement presented here provides a foundation for a new set of experimental benchmarks that can be used to test atomic structure calculations. Future measurements of several other magic-zero wavelengths in potassium and other atoms can be accomplished with similar techniques. For example, in potassium atoms, two additional magic-zero wavelengths occur near the $4s$ to $5p_j$ transitions. One magic-zero wavelength near 405.96 (4) nm is between the $4s - 4p$ and $4s - 5p$ transitions, while the other magic-zero wavelength near 404.72(4) nm is between the $4s - 5p_{1/2}$ and $4s - 5p_{3/2}$ transitions. Therefore, measurements of two other $\lambda_{\rm zero}$ combined with the one reported here could be used to specify ratios of four line strengths. However, $\alpha_{\rm core}$ [the largest component of the semiempirical parameter A in Eq. (2)] more strongly affects $\lambda_{\rm zero}$ near 405 nm [9]. Therefore, new $\lambda_{\rm zero}$ measurements will also provide benchmark tests for the contributions from core electrons to polarizabilities. Magic-zero wavelength measurements in heavier atoms, where the fine-structure splitting is larger, will be more sensitive to both core-electron contributions and relativistic corrections to the line strength ratio R. Measurements of hyperpolarizability may also be accomplished by measuring energy shifts at magic-zero wavelengths that depend on intensity squared (i.e., E^4).

In summary, we measured the longest magic-zero wavelength of potassium with 1.5 pm uncertainty. The measured phase shifts and resulting precision in $\lambda_{\rm zero}$ could be increased by 3 orders of magnitude in future work by focusing a laser beam entirely on one path of the atom interferometer, more accurate measurements of the laser spectrum, and more careful control of the laser polarization.

We thank M. S. Safronova and B. P. Anderson for enlightening discussions and J. D. Ronan and J. O. Kessler for help starting this experiment. This work is supported by NSF Grant No. 0969348 and a NIST PMG. W. F. H. thanks the Arizona TRIF and R. T. thanks NSF GRFP Grant No. DGE-1143953 for additional support.

Note added.—Recently, we became aware of a recent $\lambda_{\rm zero}$ measurement in rubidium [28].

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