PHYSICS

Measurement of a helium tune-out frequency: an independent test of quantum electrodynamics

B. M. Henson1†, J. A. Ross3†, K. F. Thomas3, C. N. Kuhn2, D. K. Shin1, S. S. Hodgman1, Yong-Hui Zhang2, Li-Yan Tang3†, G. W. F. Drake4†, A. T. Bondy4, A. G. Truscott1, K. G. H. Baldwin1†

Despite quantum electrodynamics (QED) being one of the most stringently tested theories underpinning modern physics, recent precision atomic spectroscopy measurements have uncovered several small discrepancies between experiment and theory. One particularly powerful experimental observable is the measurement uncertainty and resolves both the QED contributions and retardation corrections.

Quantum electrodynamics (QED) describes the interaction between matter and light. It is so ubiquitous that the theory is considered a cornerstone of modern physics. QED has been remarkably predictive in describing fundamental processes, such as spontaneous emission rates of photons from atoms and the anomalous electron magnetic moment. However, as the precision of atomic spectroscopy approaches the part-per-trillion level, discrepancies between such predictions and experiments have come to light, such as the "proton radius puzzle." Spectroscopic measurements of muonic hydrogen, hydrogen, and muonic deuterium yield determinations of the proton radius that disagree with other approaches. These factors have previously limited the precision of direct transition strength measurements. As a test of QED, a tune-out frequency is advantageous because it is a null measurement, which does not require calibration of the light intensity or a measurement of excitation probability. These factors have previously limited the precision of direct transition strength measurements. In this work, we measured the tune-out frequency for the 23S1 state of helium between transitions to the 2P and 3P manifolds and compare it with new theoretical QED calculations. The experimentally determined value of 725.736.700(260) megahertz differs from theory [725.736.252(9) megahertz] by 1.7 times the measurement uncertainty and resolves both the QED contributions and retardation corrections.

Fig. 1. Tune-out in atomic helium. (A) Atomic energy level shift of the dominant state (manifolds) around the tune-out. When an optical field of frequency \( f \) (arrows) is applied to the atom, the individual levels shift depending on the difference between \( f \) and the transition frequency. At the tune-out frequency, \( f = f_{TO} \) (middle right), the shift to the 23S1 state energy cancels. Energy spacing and shifts are not to scale. (B) Theoretical frequency-dependent polarizability of 23S1 helium, for a constant light polarization, indicating that the polarizability vanishes near 726 THz, the tune-out frequency measured in this paper. Vertical dotted lines show, from left to right, the transitions to the 2P, 3P, and 4P manifolds. Inset shows the approximately linear polarizability with frequency around the tune-out.

1Department of Quantum Science and Technology, Research School of Physics, The Australian National University, Canberra, ACT 2601, Australia. 2Centre for Quantum and Optical Science, Swinburne University of Technology, Melbourne, VIC 3122, Australia. 3State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences, Wuhan 430071, People’s Republic of China. 4Department of Physics, University of Windsor, Windsor, Ontario N9B 3P4, Canada. *Corresponding author. Email: kenneth.baldwin@anu.edu.au (K.G.H.B.); gdrake@uwindsor.ca (G.W.F.D.); lytang@whpim.ac.cn (L.-Y.T.). †These authors contributed equally to this work.

Henson et al., Science 376, 199–203 (2022) 8 April 2022
the tune-out, a vigorous campaign of theoretical studies (25–29) has reduced the uncertainty in the predicted frequency, which limited comparison with experiment. Our work represents a 10-fold improvement in precision over previous calculations, and its uncertainty now surpasses the experimental state-of-the-art.

Measuring a tune-out frequency involves measuring the potential energy of a light field interacting with an atom, known as an optical dipole potential (30), and precisely identifying the frequency at which it vanishes (Fig. 1). The experimental approach taken here measures the optical dipole potential via changes in the optical dipole potential via changes in the

---

**Fig. 2. Experimental procedure.** Method to determine the tune-out for a fixed probe beam polarization. (A) A magnetically trapped BEC of metastable helium atoms was illuminated with a probe laser beam with an adjustable (optical) frequency. A sequence of atom laser pulses was outcoupled from the BEC to sample the oscillation. (B) The mean velocity of each pulse in the x direction (\(v_x\)) was used to trace out the oscillation over time (red points) and extract the oscillation frequency with a dampened sine wave fit (solid line). A single experimental realization is shown. (C) The squared probe beam trap frequency (response) was found using a separate measurement of the magnetic trap frequency. This measurement was repeated over a small range of optical frequencies. The tune-out was extracted by finding the x intercept of the response as a function of probe beam frequency using a linear fit (solid black line). Light-gray lines show the model 1σ confidence intervals. All error bars represent the standard error in the mean.

---

**Fig. 3. Tune-out dependence on probe beam polarization.** (A) Dependence of the measured tune-out on \(Q_A\) when interpolated to \(\nu = 0\). (B) Dependence of the measured tune-out on \(\nu\) when interpolated to \(Q_A = 0\). The linear fit to all scans is in the form of Eq. 1, with fit parameters \(f_{TO(-1.0)} = 725,736,700(40)\) MHz, \(\beta^x\cos(\theta_0) = 13,240(70)\) MHz, \(\beta^y\sin^2(\theta_0) = 1140(20)\) MHz, and \(\chi^2/\text{degree of freedom} = 0.9968\). Horizontal error bars show polarization state uncertainty, and vertical error bars show the standard error of the measurement combined with the propagated polarization state uncertainty from the interpolated axis. For a visualization of the combined dependence, see fig. S4. The shaded regions in (A) show the model 1σ confidence interval, which is too small to be visible in (B). The point marked with a red cross in (A) shows the reference value \(f_{TO(-1.0)}\) (error bar not visible at this scale).
spatial oscillation frequency (also called the trap frequency) of Bose-Einstein condensates (BECs) in a harmonic magnetic trap when overlapped with a laser probe beam (Fig. 2). The net potential energy is the sum of a harmonic magnetic potential and a Gaussian optical potential, which is approximately harmonic for the small oscillation amplitudes we considered. In this approximation, the oscillation frequency is given by $f_{\text{net}} = \Omega_{\text{mag}}^2 + \Omega_{\text{probe}}^2$, where $\Omega_{\text{mag}}$, $\Omega_{\text{probe}}$, and $\Omega_{\text{net}}$ denote the trapping frequencies of the magnetic, probe, and combined potentials, respectively. For a Gaussian beam profile, as used here, the probe perturbation scales as $\Omega_{\text{probe}}^2 \propto a(f) J$, where $J$ is the intensity of the probe beam. With the probe beam power stabilized, the difference of squared trapping frequencies $\Omega_{\text{net}}^2 - \Omega_{\text{mag}}^2 \propto a(f)$ produces a response that is linearly proportional to the dynamic polarizability. Having measured the transverse and longitudinal profiles of the probe beam, we find that the shift in trapping frequency completely specifies the optical dipole potential.

We determined the trap frequency of our BECs with a novel method (31) that repeatedly samples the momentum of an oscillating BEC with a pulsed atom laser (32) (Fig. 2A). Each measurement was started by generating a new He$^*$ BEC, which was set in motion by applying a field gradient, and was then depleted over the duration of the trap frequency measurement (1.2 s) (Fig. 2B). The starting sample of atoms was cooled to $\sim$80 nK, well below the critical temperature, to reduce the damping that ultimately limits the interrogation time and, in turn, uncertainty in the trapping frequency. We alternated between measurements of trapping frequency with and without the optical potential to calibrate for any long-term drift in $\Omega_{\text{mag}}$. We then measured the change in (squared) trap frequency due to the probe beam, $f_{\text{probe}}^2$, as a function of the probe beam (optical) frequency $f$ near the tune-out frequency at $\sim$726 THz (413 nm). The small laser frequency scan range used in our experiment allowed us to determine the tune-out frequency, $f_{\text{TO}}$, through linear interpolation from the measured response of $f_{\text{probe}}^2$ (Fig. 2C).

The dynamic atomic polarizability consisted of the frequency-dependent scalar, vector, and tensor components $[a^S(f), a^V(f), a^T(f)]$, respectively. The total polarizability (and therefore the tune-out) also depends on the degree of linear and circular polarization in the atom’s reference frame, given by the second and fourth Stokes parameters, $Q_A$ and $V$, respectively, and on the angle $\theta_b$ between the laser propagation direction and the magnetic field vector ($\mathbf{B}^\text{m}$). The tune-out frequency for the $2^3S_1$ state and arbitrary polarization is

$$f_{\text{TO}}(Q_A, V) = f_0^B + \frac{1}{2} b^V \cos(\theta_b) V - \frac{1}{2} b^T \left[ 3 \sin^2(\theta_b) \left( \frac{1}{2} + \frac{Q_A(Q_C, \theta_C)}{2} \right) - 1 \right]$$

where $f_0^B$ is the tune-out frequency for the scalar polarizability $a^S(f)$, and $Q_A(Q_C, \theta_C)$ is the second Stokes parameter in terms of the laboratory measurement of the second Stokes parameter, $Q_C$, and the angle between the lab and atomic frames, $\theta_C$. Here, $b^V$ and $b^T$ are the vector and tensor polarizabilities divided by the gradient of the scalar polarizability (with respect to frequency) at the tune-out [see supplementary materials (SM) section 2.3].

We measure the tune-out $f_{\text{TO}}(\sim-1.0)$, corresponding to a linearly polarized light field whose polarization axis is perpendicular to both the laser propagation and the magnetic field. For this configuration, the sensitivity to $\theta_b$ and $\theta_C$ is minimized, and the atomic polarizability simplifies to

$$a(f) = a^S(f) - \frac{1}{2} a^T(f)$$

We measured $f_{\text{TO}}(Q_A, V)$ as a function of the probe beam polarization parameters $Q_A$ and $V$ and interpolated using Eq. 1 to determine $f_{\text{TO}}(\sim-1.0)$ (Fig. 3). We took the sign of $b^T$ from theory but used no other predictions in our calculation. We determined a value of 725,736,700 MHz for the $f_{\text{TO}}(\sim-1.0)$ tune-out with a statistical uncertainty of 40 MHz and a systematic uncertainty of 260 MHz (SM section 4).

The dominant systematic effect in our measurement was the uncertainty in the light polarization. The probe beam passed through a vacuum window before it interacted with the atoms, which may have subtly altered the laser polarization relative to measurements made outside the vacuum chamber. We constrained this error to be $<200$ MHz by measuring the probe beam polarization before entering, and after exiting, the vacuum system (SM section 4.1).

Separate improvements in the state-of-the-art calculation (28) of the tune-out frequency by accounting for finite nuclear mass, relativistic, QED, finite nuclear size, and finite wavelength retardation effects (27, 29). We achieved a 10-fold improvement in precision and found a theoretical value of 725,736,252 (9 MHz for $f_{\text{TO}}(\sim-1.0$). The major contribution to the theoretical uncertainty stems from the nonradiative QED corrections ($\pm 6$ MHz) of order $\alpha^2$ Ry, which was an order of magnitude less than the systematic experimental uncertainty. We show a comparison of our experimental and theoretical uncertainties to the main contributions of interest to the theoretical value in Fig. 4, to demonstrate the contributions to which our measurement was sensitive.

Our experimental determination is a 20-fold improvement over the previous experimental determination and is larger than the theoretical prediction by 1.7 times the measurement uncertainty (herein, $\sigma$). Our measurement corresponds to a relative precision in oscillator...
strength ratio of 6 parts per million (SM section 6), which is a factor of two improvement over the previous record (17). The combined theoretical and experimental uncertainties (~260 MHz) were able to discern the contribution of QED effects (~30σ) and are similar to the retardation corrections to the dipole interaction (~2σ) but much greater than the contribution of finite nuclear size effects (5 MHz). Furthermore, our method for measuring the dipole potential was able to discern a peak potential energy of as little as 10−26 J. This is, to our knowledge, the most sensitive measurement of potential energy reported to date.

Our measurement was sensitive to the retardation corrections not normally included in the theory of the frequency-dependent polarizability (27, 29). The result was an ~1.7σ difference between experiment and theory, which took into account the estimated uncertainty from terms not currently included in the theoretical calculation. It is notable that by ignoring the retardation correction term—proposed in (29) and included here in tune-out frequency calculations—the difference between theory and experiment fell to ~0.1σ. If the experimental precision is increased by an order of magnitude, then the effect of the retardation contribution could be more stringently tested.

Future experimental improvements could include more precise laser polarization calibrations, likely using in-vacuum optics, and a finer measurement of the angle between the laser propagation and the magnetic field. These would allow an independent comparison of the predicted and measured scalar, vector, and tensor polarizabilities, providing further information on the structure of the helium atom and QED theory itself.

Our method could be easily applied to other tune-out frequencies in helium and used as an investigative tool for other problems in QED theory. If the precision of future measurements reaches the megahertz level, the tune-out frequency could determine the nuclear charge radius of helium. Further improvements and use of our method may thus continue to challenge and elucidate QED theory.

REFERENCES AND NOTES

1. T. Aoyama, M. Hayakawa, T. Kinoshita, M. Nio, Phys. Rev. D 91, 033006 (2015).
2. H. Gao, M. Van der Haegen, Rev. Mod. Phys. 94, 015002 (2022).
3. R. Pohl et al., Nature 466, 213–216 (2010).
4. N. Bezginov et al., Science 365, 1007–1012 (2019).
5. A. Beyer et al., Science 358, 79–85 (2017).
6. R. Pohl et al., Science 353, 669–673 (2016).
7. X. Zhan et al., Phys. Rev. B 90, 59–64 (2011).
8. H. Fleuret et al., Phys. Rev. Lett. 120, 183001 (2018).
9. X. Zheng et al., Phys. Rev. Lett. 119, 263002 (2017).
10. R. J. Rengelink et al., Nat. Phys. 14, 1132–1137 (2018).
11. G. Clausen et al., Phys. Rev. Lett. 127, 053001 (2021).
12. V. Patiño, V. A. Yerokhin, K. Pachucki, Phys. Rev. A 103, 042809 (2021).
13. R. J. Hill, EPJ Web Conf. 137, 01023 (2017).
14. L. J. LeBlanc, J. H. Thywissen, Phys. Rev. A 75, 053612 (2007).
15. Y.-H. Zhang, L.-Y. Tang, J.-Y. Zhang, T.-Y. Shi, Phys. Rev. A 103, 032810 (2021).
16. C. D. Herold et al., Phys. Rev. Lett. 109, 243003 (2012).
17. R. H. Leonard, A. J. Fallon, C. A. Sackett, M. S. Safronova, Phys. Rev. A 92, 052501 (2015).
18. N. Bouloufa, A. Crubellier, O. Dulieu, Phys. Scr. 134, 014034 (2020).
19. F. Vogt et al., Eur. Phys. J. D 44, 73–79 (2007).
20. K. F. Thomas et al., Phys. Rev. Lett. 125, 013002 (2020).
21. W. F. Holmgren, R. Trubko, I. Hromada, A. D. Cronin, Phys. Rev. Lett. 109, 243004 (2012).
22. F. Schmidt et al., Phys. Rev. A 93, 022507 (2016).
23. B. M. Henson et al., Phys. Rev. Lett. 115, 043004 (2015).
24. J. Mitzry, L.-Y. Tang, Phys. Rev. A 88, 052515 (2013).
25. Y.-H. Zhang, L.-Y. Tang, X.-Z. Zhang, T.-Y. Shi, Phys. Rev. A 93, 052516 (2016).
26. J. Manalo, thesis, University of Windsor, Ontario, Canada (2017).
27. G. W. F. Drake, J. G. Manalo, P. P. Zhang, K. G. H. Baldwin, Hypertone Interact. 240, 31 (2019).
28. Y.-H. Zhang et al., Phys. Rev. A 99, 040502 (2019).
29. K. Pachucki, M. Puchalski, Phys. Rev. A 99, 041803 (2019).
30. R. Grimm, M. Weidemüller, Y. B. Ovchinnikov, Adv. At. Mol. Opt. Phys. 42, 95–170 (2000).
31. B. M. Henson et al., arXiv:2201.10021 [cond-mat.quant-gas] (2022).
32. M.-O. Mewes et al., Phys. Rev. Lett. 78, 582–585 (1997).
33. F. Le Kien, P. Schneeweiss, A. Rauschenbeutel, Eur. Phys. J. D 67, 92 (2013).
34. B. M. Henson, K. F. Thomas, Replication data for: Testing quantum electrodynamics by measuring a tune-out frequency in atomic helium, version 1, Harvard Dataverse (2022); https://doi.org/10.7910/DVN/KQEW.
35. B. M. Henson, J. A. Ross, K. F. Thomas, Tune out v2 code, GitHub (2022); https://github.com/HeBECAN/U-Tune_out-v2.

ACKNOWLEDGMENTS

We thank Mr. Bromley for instructive discussion regarding the hyperpolarizability, D. Cocks for careful reading of the manuscript, C. J. Vale and S. Hoinka for the loan of the laser, T.-Y. Shi for helpful discussions regarding the theoretical calculations, and K. Pachucki for helpful correspondence concerning the relativistic and retardation corrections to the tune-out frequency. Funding: This work was supported through Australian Research Council (ARC) Discovery Project grants DP160103337 and DP180100983, as well as Linkage Project LE180100342. K.F.T. and D.K.S. were supported by Australian Government Research Training Program (RTP) scholarships. S.S.H. was supported by ARC Discovery Early Career Researcher Award DE150100335. L.-Y.T. was supported by the National Key Research and Development Program of China under grant 2017YFA0303402, the Strategic Priority Research Program of the Chinese Academy of Sciences under grant XDB20030300, and the National Natural Science Foundation of China under grants 12174402 and 12121004. G.W.F.D. acknowledges support by the Natural Sciences and Engineering Research Council of Canada (NSERC) and by SHARCNET. Author contributions: B.M.H., J.A.R., K.F.T., L.-Y.T., G.W.F.D., A.G.T., and K.G.H.B. conceived the work. B.M.H., J.A.R., K.F.T., A.G.T., and K.G.H.B. designed the experiments. B.M.H., J.A.R., K.F.T., C.N.K., and D.K.S. ran the experiments. B.M.H., J.A.R., and K.F.T. analyzed and visualized the data. Y.-H.Z., L.-Y.T., G.W.F.D., and A.T.B. developed the theoretical methods. B.M.H., J.A.R., K.F.T., S.S.H., L.-Y.T., G.W.F.D., A.G.T., and K.G.H.B. wrote the manuscript. All authors reviewed the results and commented on the manuscript. S.S.H., A.G.T., and K.G.H.B. secured funding for and supervised the project. Competing interests: None declared.

Data and materials availability: All experimental data along with the associated processing code are available online (34, 35). All other data needed to evaluate the conclusions in the paper are present in the paper or the supplementary materials.

SUPPLEMENTARY MATERIALS

science.org/doi/10.1126/science.abc2502
Materials and Methods
Supplementary Text
Figs. S1 to S7
Tables S1 to S3
References (36–66)
5 July 2021; resubmitted 8 March 2022
Accepted 8 March 2022
10.1126/science.abc2502