

Precision Measurement of the Helium $2^3S_1 - 2^3P/3^3P$ Tune-Out Frequency as a Test of QED

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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 that tests QED independently of traditional energy level measurements is the ‘tune-out’ frequency, where the dynamic polarizability vanishes and the atom does not interact with applied laser light. In this work, we measure the ‘tune-out’ frequency for the 2^3S_1 state of helium between transitions to the 2^3P and 3^3P manifolds and compare it to new theoretical QED calculations. The experimentally determined value of $725\,736\,700(40_{\text{stat}}, 260_{\text{syst}})$ MHz is within $\sim 2.5\sigma$ of theory ($725\,736\,053(9)$ MHz), and importantly resolves both the QED contributions ($\sim 30\sigma$) and novel retardation ($\sim 2\sigma$) 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 [1]. 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 $\mu + p$ [2], H [3, 4], and $\mu + 2p$ [5]) yield determinations of the proton radius which disagree by up to five standard deviations with other approaches (e+p scattering [6], and H spectroscopy[7]).

Helium is an exemplary testing ground for QED because its simple two-electron structure makes high-precision predictions tractable and testable. Notably helium also presents a nuclear ‘puzzle’, with precision measurement of isotope shifts of the $2^3S_1 \rightarrow 2^3P_{(0,1,2)}$ [8] and $2^3S_1 \rightarrow 2^1S_0$ [9] transitions disagreeing at two standard deviations in the derived nuclear charge radius. These ‘puzzles’ raise the possibility that the issue lies with QED itself [10]. Thus, we look to challenge QED directly by precision spectroscopy in helium beyond the usual energy interval measurements.

An atom in an optical field experiences an energy shift in proportion to the real part of the frequency dependent polarizability, a fundamental atomic property dictated by the position of energy levels and the strengths of transitions to them (Fig. 1). A ‘tune-out’ frequency (f_{TO}) occurs between transition frequencies at the point where

the contributions to the dynamic polarizability [$\alpha(f)$] by all transitions below that frequency are balanced by all those above it ($\alpha(f) = 0$) [11]. This balance point is hence fixed by the strength and frequency of every transition in the atomic spectrum and thus provides a precise constraint on the ratio of transition dipole matrix elements.

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 [12–14]. In comparison, previous tune-out measurements have been successful in measuring QED effects [15–19].

In this work we measure the tune-out of the metastable 2^3S_1 state of helium (denoted He*) which lies between transitions to the 2^3P and 3^3P manifolds (denoted $2^3S_1 - 2^3P/3^3P$) at approximately 726 THz (413 nm). We chose this particular tune-out frequency as the two neighbouring transitions are more than an octave apart in frequency, causing the gradient of atomic polarizability with optical frequency to be very small at the tune-out. Hence, this tune-out frequency is especially sensitive to higher order QED effects. We achieve a 20-fold improvement in the precision over the sole previous measurement [19].

For an unambiguous comparison we also present a new theoretical estimate of the $2^3S_1 - 2^3P/3^3P$ tune-out in helium. Following the first prediction [20] and measurement [19] of the tune-out, a vigorous campaign of theoretical studies [21–25] has reduced the uncertainty in the predicted frequency, which limited comparison with experiment. Our work represents a 10-fold improvement

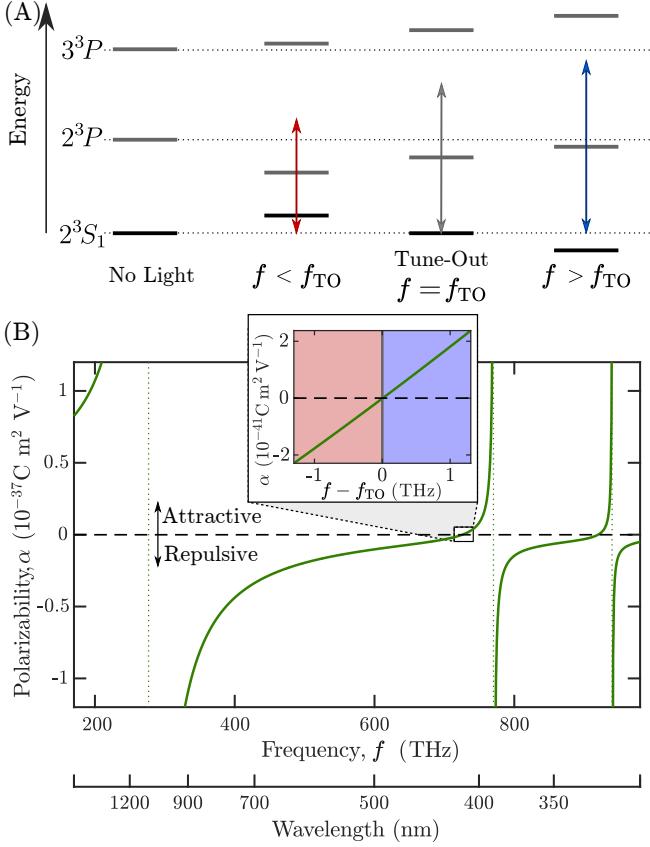


FIG. 1. Tune-out in atomic helium: (A) Atomic energy level shift of the dominant state (manifolds) about the tune-out. When an optical field of frequency f (arrows) is applied to the atom the individual levels shift dependent on the difference between f and the transition frequency. At the tune-out frequency f_{TO} (middle right), the shifts to the 2^3S_1 state energy cancel. Energy spacing and shifts not to scale. (B) Theoretical frequency dependent polarizability of 2^3S_1 helium, for a constant light polarisation, 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 2^3P , 3^3P , 4^3P manifolds. Inset shows the approximately linear polarizability with frequency about the tune-out.

in precision over previous calculations, and whose uncertainty now surpasses the experimental state-of-the-art.

Measuring a tune-out frequency amounts to measuring the potential energy of a light field interacting with an atom, known as an optical dipole potential [26], and identifying precisely the frequency at which it vanishes (see Fig. 1). The new experimental approach taken here measures the optical dipole potential via changes in the

spatial oscillation frequency (also called trap frequency) of Bose-Einstein condensates (BECs) in a harmonic magnetic trap when overlapped with a laser probe beam (see 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 consider. In this limit the oscillation frequency is given by $\Omega_{\text{net}}^2 = \Omega_{\text{mag}}^2 + \Omega_{\text{probe}}^2$ where Ω_{mag} , Ω_{probe} , and Ω_{net} denote the trap frequency of the magnetic, probe, and combined potentials respectively. For a Gaussian beam profile, as used here, the probe perturbation scales as $\Omega_{\text{probe}}^2 \propto \alpha(f)I$, where I is the intensity of the probe beam. Hence, with the probe beam power stabilized, the difference of squared trapping frequencies $\Omega_{\text{net}}^2 - \Omega_{\text{mag}}^2 \propto \alpha(f)$ produces a response which is linearly proportional to the dynamic polarizability. Having measured the transverse and longitudinal profiles of the probe beam, the shift in trapping frequency completely specifies the optical dipole potential.

We determine the trap frequency of our BECs with a novel method which repeatedly samples the momentum of an oscillating BEC with a *pulsed atom laser* [27, 28] (Fig. 2(A)). Each measurement starts by generating a new He* BEC, which is set in motion by applying a field gradient, and is then depleted over the course of the trap frequency measurement (1.2 s long, see Fig. 2(B)). The starting sample of atoms is cooled to ~ 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 alternate between measurements of trapping frequency with and without the optical potential to calibrate for any long term drift in Ω_{mag} . We then measure the change in (squared) trap frequency due to the probe beam, Ω_{probe}^2 , as a function of the probe beam (optical) frequency f near the tune-out frequency at ~ 726 THz (413 nm). The small laser frequency scan range used in our experiment allows us to determine the tune-out frequency f_{TO} via linear interpolation from the measured response of Ω_{probe}^2 (Fig. 2(C)).

The dynamic atomic polarizability consists of the frequency dependent scalar, vector, and tensor components ($\alpha^S(f)$, $\alpha^V(f)$, $\alpha^T(f)$ respectively). The total polarizability (and hence 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 \mathcal{Q}_A and V respectively, and on the angle θ_k between the laser propagation direction and the magnetic field vector [29]. The tune-out frequency for the 2^3S_1 state and arbitrary polarization is:

$$f_{TO}(\mathcal{Q}_A, V) = f_{TO}^S + \frac{1}{2}\beta^V \cos(\theta_k)V - \frac{1}{2}\beta^T \left[3 \sin^2(\theta_k) \left(\frac{1}{2} + \frac{\mathcal{Q}_A(\mathcal{Q}_L, \theta_L)}{2} \right) - 1 \right], \quad (1)$$

where f_{TO}^S is the tune-out frequency for the scalar po-

larizability $\alpha^S(f)$, $\mathcal{Q}_A(\mathcal{Q}_L, \theta_L)$ is the second Stokes pa-

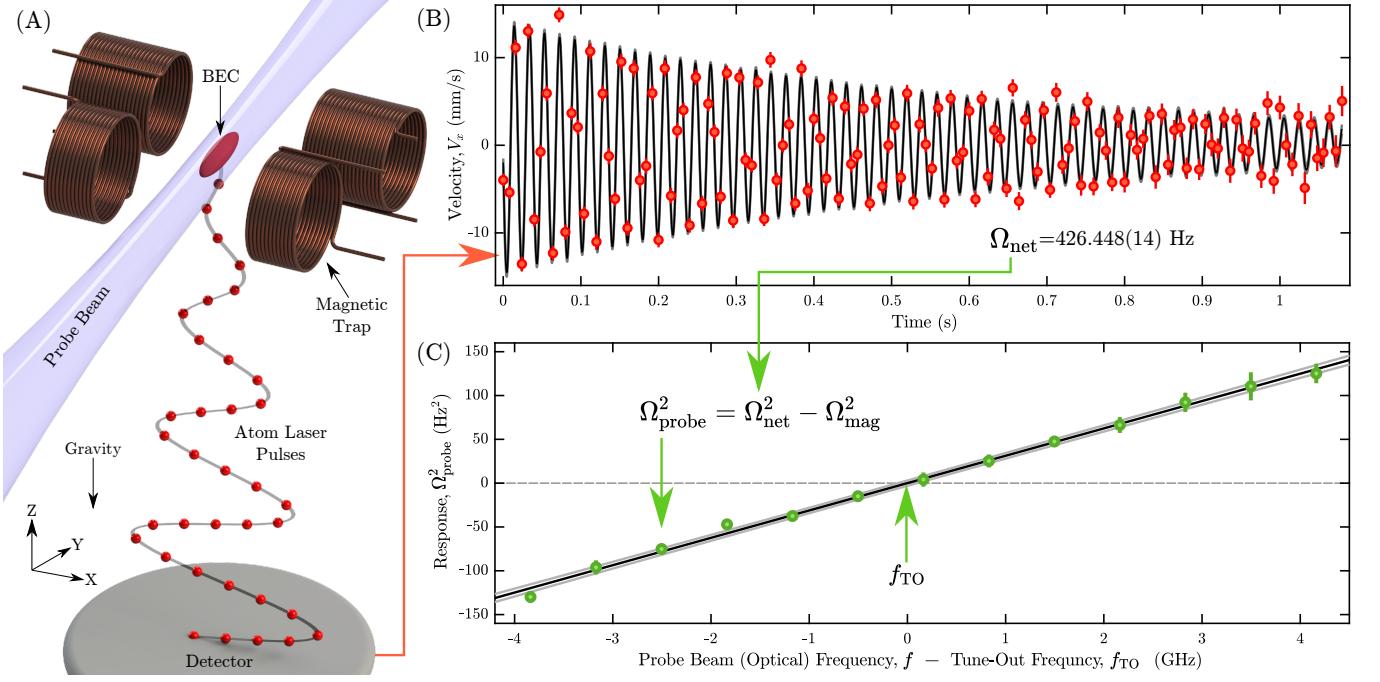


FIG. 2. Experimental procedure: Method to determine the tune-out for a fixed probe beam polarization. (A) a magnetically trapped BEC of metastable helium atoms is illuminated with a probe laser beam with an adjustable (optical) frequency. A sequence of atom laser pulses is outcoupled from the BEC to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

parameter in terms of the laboratory measurement of the second Stokes parameter $\mathcal{Q}_{\mathcal{L}}$, and the angle between the lab and atomic frames $\theta_{\mathcal{L}}$. Here, β^V and β^T are the vector and tensor polarizabilities divided by the gradient of the scalar polarizability (with respect to frequency) at the tune-out [30].

We measure the tune-out $f_{\text{TO}}(-1, 0)$, corresponding to a linearly polarised light-field whose polarisation axis is perpendicular to both the laser propagation and the magnetic field. For this configuration, the sensitivity to θ_k and $\theta_{\mathcal{L}}$ is minimized and the atomic polarizability simplifies to

$$\alpha(f) = \alpha^S(f) - \frac{1}{2}\alpha^T(f). \quad (2)$$

We measure $f_{\text{TO}}(\mathcal{Q}_{\mathcal{A}}, \mathcal{V})$ as a function of the probe beam polarization parameters $\mathcal{Q}_{\mathcal{A}}$ and \mathcal{V} and interpolate using Eq. (1) to determine $f_{\text{TO}}(-1, 0)$ (see Fig. 3). We take the sign of β^T from theory, but use no other predictions in our calculation. Thus, we determine a value of $725\,736\,700(40_{\text{stat}}, 260_{\text{syst}})$ MHz for the $f_{\text{TO}}(-1, 0)$ tune-out, including systematic effects [30].

The dominant systematic effect in our measurement is the uncertainty in the light polarization. The probe

beam passes through a vacuum window before it interacts with the atoms, which may subtly alter the laser polarization relative to measurements made outside the vacuum chamber. We constrain this error to be less than 200 MHz by measuring the probe beam polarization before entering, and after exiting, the vacuum system [30].

Separately, we improve on the state-of-the-art calculation [24] of the tune-out frequency by accounting for finite nuclear mass, relativistic, QED, finite nuclear size, negative energy states, and finite wavelength retardation effects [23, 25, 30]. We achieve a 10-fold improvement in precision and find a theoretical value of $725\,736\,053(9)$ MHz for $f_{\text{TO}}(-1, 0)$. The major contribution to the theoretical uncertainty stems from the QED contribution (± 8 MHz), which is 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 is sensitive.

To summarise, our experimental determination of $725\,736\,700(40_{\text{stat}}, 260_{\text{syst}})$ MHz is a 20-fold improvement over the first experimental determination, and is 2.5σ larger than the theoretical prediction. Our measurement

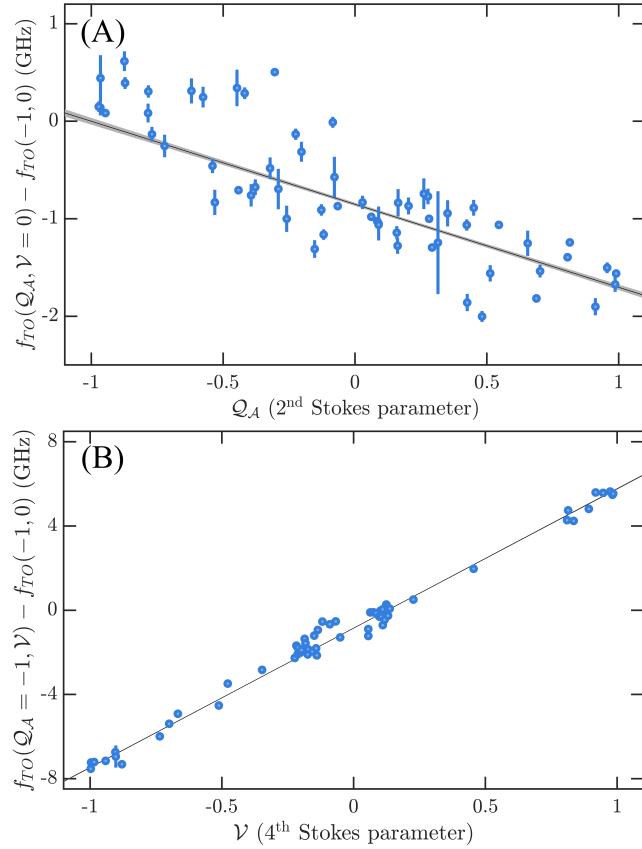


FIG. 3. Tune-out dependence on probe beam polarisation: (A) Dependence of the measured tune-out on Q_A when interpolated to $V = 0$. (B) Dependence of the measured tune-out on V when interpolated to $Q_A = -1$. The linear fits are both of the form of Eq. (1), with fit parameters $f_{TO}(-1, 0) = 725\,736\,700(40)$ MHz, $\beta^V \cos(\theta_k) = 13\,240(70)$ MHz, $\beta^T \sin^2(\theta_k) = 1\,140(20)$ MHz (uncertainties represent only statistical uncertainty; see Ref. [30] for full error budget). Error bars show the estimated standard error.

corresponds to a relative precision in oscillator strength ratio of 6 ppm [30], which is a factor of two improvement on the previous record [20]. The combined theoretical and experimental uncertainties (~ 260 MHz) are able to discern the contribution of QED effects ($\sim 30\sigma$), and are similar to the retardation corrections to the dipole interaction ($\sim 2\sigma$), but much greater than the contribution of finite nuclear size effects (5 MHz). Furthermore, our novel method for measuring the dipole potential is able to discern a peak potential energy of as little as 10^{-35} J. This is, to our knowledge, the smallest precision in a potential energy measurement reported to date [30].

This is the first measurement to be sensitive to the retardation corrections not normally included in the theory of the frequency-dependent polarizability [23, 25]. The result is a $\sim 2.5\sigma$ difference between experiment and theory, which takes into account the estimated uncertainty from terms not currently included in the theoretical cal-

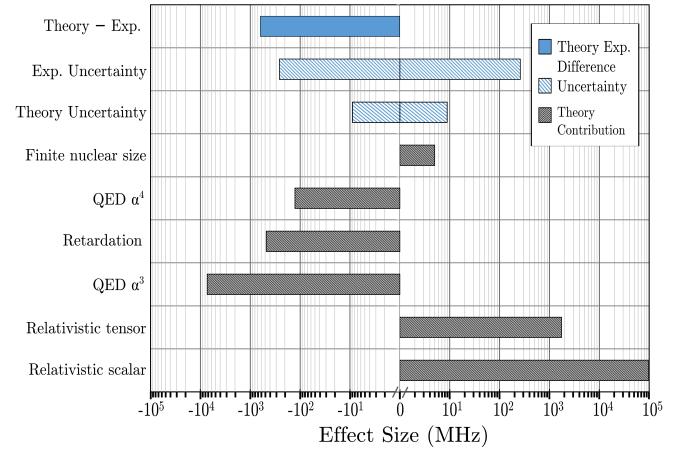


FIG. 4. Experimental and theoretical sensitivity: Comparison of uncertainties in the theoretical and experimental determinations of the $2^3S_1 - 2^3P/3^3P$ tune-out frequency and the various theoretical contributions to the tune-out value.

culation. It is notable that by ignoring the retardation correction term – first proposed in Ref. [25] and included here in tune-out frequency calculations for the first time – the difference between theory and experiment reduces to $\sim 0.5\sigma$. If the experimental precision is increased by an order of magnitude, then the effect of the retardation contribution can 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. This 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 novel method can 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 reach the MHz level, the tune-out frequency could determine the nuclear charge radius of helium. The contribution of the retardation correction is also significant in light of proposals to use the molar polarizability as a new measure of Avogadro’s number [31]. Further improvements and use of our method may thus continue to challenge and elucidate QED theory.

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