Journal and Proceedings of the Royal Society of New South Wales, vol. 146, nos. 449 & 450, pp. 136-141.
ISSN 0035-9173/13/020136-6.

Jak Kelly Award Winner, 2012

Highly Charged Ions and the Search for the Variation of Fundamental Constants

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Abstract

We discuss the search for a variation in the fine-structure constant α using highly-charged ions. In particular, we examine how highly-charged ions could be used to construct highly-accurate atomic clocks that could be used to detect the terrestrial variation of α due to the motion of the solar system relative to the observed "α-dipole". Furthermore, we show that highly-charged Fe and Ni ions in G191-B2B, a white-dwarf star could be used to probe non-linearities in the possible coupling of α-variation to the gravitational scalar potential.

Introduction

The idea to search for a variation in the constants of physics is not a new one. In fact, Dirac's Large Number Hypothesis was probably the progenitor of our fascination with the possible non-constancy of our physical constants (Dirac, 1937).

A measured variation in a constant with dimensions (units) is impossible to distinguish from a variation in the dimensions themselves. Therefore, we will limit our discussion to the dimensionless constants, namely, the fine-structure constant, $\alpha = e^2/\hbar c \sim 1/137$. Here e is the electron charge, $\hbar$ is the reduced Planck constant, and c is the speed of light.

The fine-structure constant is a physical constant that characterises the strength of the electromagnetic interaction. Analogies exist, such as $\alpha_G \sim 10^{-45}$, which characterises the strength of the gravitational interaction. As gravity is a much weaker interaction compared to electromagnetism, we see that α_G is very much smaller than α.

The quasar absorption spectra analysed by Webb et al. (2011) using data collected from the Keck and Very Large Telescopes (King et al., 2012) suggests that the fine-structure constant α takes on a gradient of values across the sky. This result has come to be known as the "Australian dipole" (Berengut and Flambaum, 2012).

Due to the motion of the Sun relative to the measured dipole (towards a region of larger α), the spatial gradient translates to a temporal variation of around $\dot{\alpha}/\alpha \sim 10^{-18} - 10^{-19}\,\mathrm{yr}^{-1}$ to an Earth-based observer, with a further small modulation incurred by the annual motion of the Earth around the Sun.

In order to detect this possible temporal variation, we turn to the most accurate instruments ever built – atomic clocks. The best current limit on terrestrial α-variation of $\dot{\alpha}/\alpha \sim (1.6 \pm 2.3) \times 10^{-17}\,\mathrm{yr}^{-1}$ was obtained by Rosenband et al. in 2008 by comparing Hg^+ and Al^+ optical atomic clocks. In their experiment, the transition used in the Hg^+ clock is strongly dependent on the value of α, whereas the transition used in the Al^+ is relatively insensitive.

As we note, their experimental result still falls about two orders of magnitude short of detecting the level of α-variation as predicted from astronomy. To confirm the dipole model of α-variation thus requires finding more sensitive systems, which is parameterised for an energy level within an atom or ion by

$$q = \frac{d\omega}{dx}\Big|_{x=0}, \tag{1}$$

where $x = (\alpha/\alpha_0)^2 - 1$ is the (small) fractional change in α^2 from its present value of α_0^2. Systems known to have large q values include optical clocks in Yb^+ (Porsev et al., 2009) and Th^{3+} (Flambaum and Porsev, 2009). In fact, an approximation for the sensitivity in Eq. (1) may be written as (Dzuba et al., 1999)

$$q \sim -I_n \frac{(Z\alpha)^2}{\nu(j+1/2)}, \tag{2}$$

where Z is the charge of the atom or ion, I_n is the ionization energy, ν is the effective principal quantum number, and j is the angular momentum of the energy level.

From Eq. (2), we see quickly why ions such as Yb^+ and Th^{3+} would be more sensitive to a variation in α – they possess combination of a larger nuclear charge and ionization energy compared to lighter ions such as Al^+ and Hg^+. In general, the more highly-charged the ion, the greater its sensitivity to a variation in α – a guiding principle we will use when searching for the most sensitive system later.

Eq. (2) can also be applied to searches for α-variation in astrophysical systems. By using spectral lines of highly-charged ions, we should be able to place more stringent limits on α-variation.

Flambaum and Shuryak (2007) suggest that the underlying mechanism for the variation of fundamental constants may be the coupling of the constants to scalar fields. An example of scalar fields is the gravitational potential. Highly-charged ions observed in systems with a much different gravitational potential than that available on Earth, such as white-dwarf stars, could be used to investigate such theories.

Level Crossings

As electrons are removed from atoms, the energy of transitions usually quickly grows out of the range of optical lasers. This necessitates the use of different types of spectroscopy, which can be up to 10 orders of magnitude less precise than optical spectroscopy, simply because optical spectroscopy is well-studied and widely used in the large majority of existing atomic clocks. Any gains in sensitivity to the variation of constants by using highly charged ions would quickly disappear unless a way to mitigate this problem is found. Thankfully, the phenomenon of level crossings may be used to solve this issue (Berengut et al., 2010).

A level crossing is the energy-reordering of two or more atomic levels within an atom or ion when one or more parameters are changed. This occurs because the ordering of energy levels initially follows the Madelung (periodic table) filling order. As electrons are removed from the atom, it begins to increasingly resemble atomic hydrogen, albeit with a larger nuclear charge. However, the order of energy levels in atomic hydrogen differs from that predicted by the Madelung filling scheme. This implies that upon removing a sufficient number of electrons from an atom, its energy levels will be reordered so as to reflect the energy level ordering in atomic hydrogen – a level crossing!

For ions near such level crossing points, the energy of transition of electrons between the crossing levels is small, and we find that optical transitions exist even in these highly-charged ions (see Figure 1). Therefore, by identifying ions near level crossings, we are able to preserve the gains in sensitivity to α-variation from using highly-charged ions and at the same time, retain the use of highly accurate optical spectroscopy.

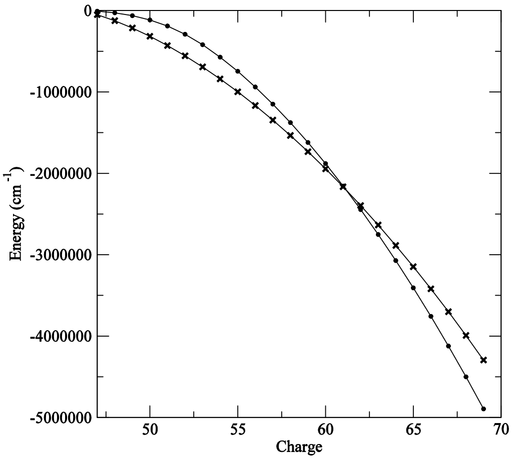

Figure 1: The energy of the 4f and 5s atomic orbitals for a 62 electron system against nuclear charge Z. The ordering of the energy levels switch near $Z = 77$.

Systematic effects in highly-charged ions

To achieve high-accuracy using atomic clocks in laboratories, experimentalists need to account for the systematic effects that affect the frequency of their atomic transitions very carefully. Examples of such effects that are routinely taken into account are the blackbody radiation shift, which accounts for the non-zero temperature of the system, and electromagnetic fields which cause Stark and Zeeman shifts.

There are two good parameterizations to describe a system's evolution from and towards the regime of highly-charged ions: isonuclear sequences (the number of electrons changes) or isoelectronic sequences (the number of protons changes). Whilst isonuclear sequences are how such ions would be produced in a laboratory, we find isoelectronic sequences more convenient for they allow more straightforward comparisons of fixed energy levels.

One further point to note is that the while the ion charge Z_i is a whole number, the external electrons that we are interested in "see" a screened (effective) charge Z_a instead. Relativistic effects would instead depend on the unscreened nuclear charge Z. One may turn to tables for values of Z_a to obtain estimates for these systematics.

The general trend is that the size of systematics tends to be much smaller than they would be for neutral atoms. This is because the electrons are more tightly bound to the nucleus, resulting in the relative size of external effects being much smaller when compared to the tighter binding.

Table 1: Scaling laws for highly-charged ions for various sources of systematic shifts in atomic clocks.

Effect	Scaling
2nd order Stark shift	$\sim 1/Z_a^4$
Blackbody shift	$\sim 1/Z_a^4$
2nd order Zeeman shift	Suppressed
Electric quadrupole shift	$\sim 1/Z_a^2$
Fine-structure	$\sim Z^2 Z_a^3/(Z_i+1)$
Hyperfine *A* coeff.	$\sim Z Z_a^3/(Z_i+1)$

Californium – the basis for a superior atomic clock

Based on our findings, we have identified highly-charged californium ions, Cf^{16+} and Cf^{17+}, as the most promising candidates for building atomic clocks that are both highly accurate and sensitive to the variation of α (Berengut et al., 2012). Californium is one of the heaviest elements with relatively long-lived isotopes that can be practically utilized in an atomic clock – this assures us the large charge and ionization energy as required for a large sensitivity in accordance with Eq. (2).

The lowest-lying energy levels as calculated using configuration interaction and many-body perturbation theory for Cf^{16+} are presented in Table 2. We see that the ion is near the 5f-6p level crossing, as the energies of the transitions between the two orbitals are well within the range of optical lasers. Table 2 also reveals that the transitions with the largest sensitivities to α-variation are two electron transitions between $5f^2$ states and $6p^2$ (the *q* value of a transition is simply the difference between the *q* values of the upper and lower levels) – of which the strongest are E2 and M1 transitions (ΔJ is at most 2). For comparison, the sensitivities of the transitions used in the Hg+ clock is *q* ~ 50000 cm^{-1}, thus Cf^{16+} can potentially provide a factor of 13 improvement over the current-day best limits on α-variation.

Table 2: Selected energy levels of Cf^{16+} and their sensitivities to α-variation *q*.

Configuration	*J*	Energy [cm^{-1}]	*q* [cm^{-1}]
$5f^1 6p^1$	3	0	0
$6p^2$	0	5267	370928
$5f^1 6p^1$	2	6104	106124
$5f^2$	4	9711	414876
$5f^1 6p^1$	4	24481	162126
$5f^2$	2	24483	354444
$5f^1 6p^1$	3	25025	59395
$5f^2$	5	29588	451455

Fe^{4+} and Ni^{4+} in White Dwarves

In this section, we will examine how highly-charged ions can be used to probe the relationship between the gravitational potential and the variation of α (Maguijo et al., 2002). Theories (Berengut et al. 2013) write

$$\frac{\Delta\alpha}{\alpha} \equiv k_\alpha \Delta\phi = k_\alpha \Delta\left(\frac{GM}{rc^2}\right) \qquad (3)$$

for a dimensionless gravitational potential $\Delta\phi$ and a proportionality constant k_α.

Existing studies of the relationship between the variation of constants and their coupling to the gravitational scalar potential has been limited to Earth-based studies. These studies rely on the ellipticity in the Earth's orbit, which gives a 3% seasonal variation in the potential at Earth due to the Sun. Due to the high precision of atomic clocks, k_α can be determined despite the small variation in the gravitational potential ϕ.

The observation of Fe^{4+} and Ni^{4+} spectral lines in G191-B2B using the Hubble Space Telescope Space Telescope Imaging Spectrograph presents an opportunity to probe Eq. (3) in the regime of a much stronger gravitational potential – about 5 orders of magnitude larger.

This not only allows us to verify the coupling as described by Eq. (3), but it also allows us to probe any non-linearities that may arise in the coupling of α to ϕ which certain models predict (Bekenstein, 1982).

Fe^{4+} and Ni^{4+} also have relatively high ion charges – referring against to Eq. (2), any limits we place on α-variation using these ions would have an advantage over other spectra due to the innately higher sensitivities these transitions have to α. At the moment, our analysis of the results has been mainly limited by the lack of accuracy in the laboratory-measured spectra for these ions, which are needed to provide a reference for calculating the shift in relative positions of the lines in the astronomical spectra. The results as shown in Figure 2 reveal that the α-variation in G191-B2B is consistent with zero at the 1.05σ level.

Conclusion

The use of highly-charged ions in the search for the variation of fundamental constants has been shown to have much potential. Atomic clocks based on highly-charged ions would not only be highly-sensitive to a variation in the fine-structure constant, but would also result in more accurate clocks with smaller systematic errors. Highly-charged iron and nickel ions in white-dwarf stars also have the potential to probe the relationship between the gravitational potential and the variation of constants.

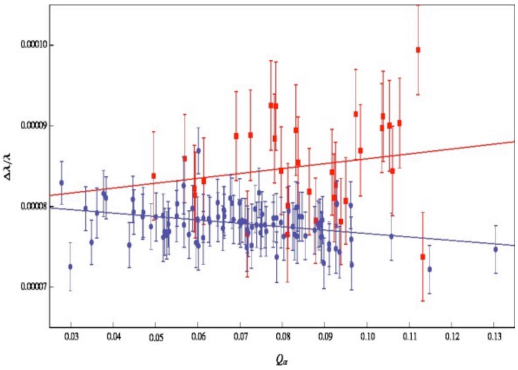

Figure 2: Scaled wavelength versus relative sensitivity to α*-variation for* Fe^{4+} *(blue circles) and* Ni^{4+} *(red squares). The slope of the lines give* $\Delta\alpha/\alpha = (4.2 \pm 1.6) \times 10^{-5}$ *for* Fe^{4+} *and* $\Delta\alpha/\alpha = (-6.1 \pm 5.8) \times 10^{-5}$ *for* Ni^{4+}*, respectively.*

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Received 16 July 2013, Accepted 8 August 2013.

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