Accurate laboratory wavelengths of some ultraviolet lines of Cr, Zn and Ni relevant to time variations of the fine structure constant

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ABSTRACT

The quality of astronomical spectroscopic data now available is so high that interpretation and analysis are often limited by the uncertainties of the laboratory data base. In particular, the limit with which space–time variations in the fine structure constant \( \alpha \) can be constrained using quasar spectra depends on the availability of more accurate laboratory rest wavelengths. We recently measured some transitions in magnesium by high-resolution Fourier transform spectroscopy for this purpose, and we now report measurements on some ultraviolet resonance lines of Zn\( \text{II} \) (2062 and 2026 Å), Cr\( \text{II} \) (2066, 2062 and 2056 Å) and Ni\( \text{II} \) (1751, 1741, 1709 and 1703 Å). Apart from the last line, which is very weak, the uncertainty of these measurements is 0.002 cm\(^{-1}\) (0.08 mA) for the lines around 2000 Å and 0.004 cm\(^{-1}\) (0.12 mA) for the lines around 1700 Å.


1 INTRODUCTION

Echelle spectroscopy of high-redshift quasars provides a high-precision technique for studying the physics of the young universe. The quality of the observational data is now so high that the limits on measurement accuracy are set by the precision of the available laboratory data. For example, redshifts of two of the Ni\( \text{II} \) transitions for which we report measurements in this paper, seen in the spectrum of the quasar GB1759+7539, have been attributed statistical uncertainties of \( 3 \times 10^{-6} \) (e.g. Outram et al. 1999). This corresponds to an uncertainty in the rest wavelength of 1.4 mA. However, the laboratory wavelengths used to derive those redshifts were known to a precision of only 2 mA (Morton 1991).

The astrophysical application that motivates the measurements we describe here is a search for any space–time variation in the fine structure constant, \( \alpha \), where \( \alpha = (1/\hbar c)(e^2/4\pi\epsilon_0) \). Kaluza–Klein and higher dimensional unification theories such as string theories require the presence of additional dimensions (other than the usual 3+1), ‘compatified’ on small scales. In these models, the values of the fundamental constants are linked to the scalelengths of the extra dimensions. Any cosmological evolution in these scalelengths may be revealed through a change in the values of the constants (Marciano 1984; Barrow 1987). Another potential source of variation of fundamental constants is associated with temporal and spatial evolution of a dilaton field, generic to all superstring theories (Damour & Polyakov 1994).

At present, no mechanism for preventing evolution of the additional dimensions is known. Static cosmological models are also, in general, rather contrived. Indeed, one has to introduce unusual behaviours of a cosmological scalar field in order to prevent unified theories from predicting time-dependent gauge coupling constants (Damour & Polyakov 1994; Fujii, Omote & Nishioka 1994) (reminiscent of Einstein’s motivation for introducing the cosmological constant, yielding only a pseudo-static universe).

Varying speed of light models have received much recent attention, and provide another form of expressing varying \( \alpha \) (Clayton & Moffat 1999; Barrow & Magueijo 1999). It is interesting to note that varying \( \alpha \) may be able to explain the supernovae results for a non-zero cosmological constant \( \Lambda \) (Barrow & Magueijo 2000). These theories may also solve other cosmological problems (e.g. the horizon, flatness, monopole problems) (Barrow & Magueijo 1998; Albrecht & Magueijo 1999).

The ratio of the fine structure splitting to the mean transition frequency in a simple spectrum such as an alkali-type doublet is proportional to \( \alpha^2 \). Therefore, a test for the variation of \( \alpha \) is to
compare this ratio in quasar spectra with the laboratory value. The precision achievable from this test has been limited by the quality of the quasar spectra, the accuracy of the laboratory wavelengths, and the constant of proportionality linking the frequency shift and $\alpha^2$ for the particular species examined.

In fact, the relativistic corrections to all atomic transition frequencies (not just alkali-type doublets) are also proportional to $\alpha^2$ (to first order), but the idea was previously restricted to using alkali doublets alone because of the complexity in computing the proportionality constants for more complex species. However, recent relativistic many-body calculations (Dzuba, Flambaum & Webb 1999a,b) have shown that a dramatically increased sensitivity to variation of $\alpha$ can be obtained by comparing suitably chosen species, since both the magnitude and the direction of the correction can vary from one atom or ion to another and from one transition to another within the same species (Webb et al. 1999). The resonance lines of Zn $\text{II}$, Cr $\text{II}$ and Ni $\text{II}$ are of particular interest in this respect because these species are commonly observed in damped Lyman-alpha absorption systems and because they span a wide dynamic range in proportionality coefficients and exhibit both negative and positive shifts.

In this paper we describe the results of experiments at both Imperial College (IC) and Lund University (LU) to measure accurately the wavelengths of these Zn, Cr and Ni lines, together with a confirmation at LU of the earlier measurements on Mg at IC (Pickering, Thorne & Webb, 1998). Although the measurements in the two laboratories were made independently, they used similar high resolution UV Fourier transform (FT) spectrometers, with hollow cathode lamps as light sources. The measurement precision for a single resolved line is determined by its signal-to-noise ratio, but the absolute accuracy depends also on the wavenumber calibration. The reference wavenumbers used in both laboratories derive from the same set of Ar $\text{II}$ lines, via a set of ‘standard’ lines in the spectrum of Fe $\text{II}$ (Nave et al. 1991) that were also used to calibrate the Mg lines in the earlier paper.

## 2 EXPERIMENTAL METHOD

The wavelengths were measured by Fourier transform spectrometry (FTS), using the two UV FT instruments at IC (Thorne et al. 1987) and a similar instrument at LU. The resolution, between 0.05 and 0.065 cm$^{-1}$ above 2000 Å and 0.08 cm$^{-1}$ below, was sufficient to resolve the lines fully. Sufficient scans were co-added to achieve signal-to-noise ratios of more than 200 except for the Ni $\text{II}$ lines (see detailed results below).

Both laboratories used hollow cathode discharge lamps as sources, with cathodes about 8 mm in diameter and 35 mm long. Ar or Ne was the carrier gas, and currents ranged from 150 to 600 mA. At Lund a ‘composite’ cathode was made by placing small pieces of Mg, Cr and Zn in a pure Fe cathode so that all four spectra were recorded simultaneously. At IC the Zn spectrum was excited in a similar way (a small piece of Zn in a stainless steel cathode), but the Cr and Ni spectra were obtained from cathodes made of pure Cr and Ni, respectively. (Mg in a Ni cathode was used for the earlier IC experiment.) At high currents and/or with anything more than a trace of zinc in the cathode, the resonance doublet of Zn $\text{II}$ is significantly self-absorbed. In both laboratories, runs were taken at different currents and vapour density to reduce the self-absorption. The effects of the residual self-absorption are discussed in Section 3 below.

In FTS the noise (predominantly photon noise in our case) is transformed along with the spectrum, and white noise is distributed uniformly through the spectrum. Thus every line seen by the detector contributes to the noise at every point in the spectrum, and it is disadvantageous to record lines outside the region of interest. The spectra above 2000 Å were recorded with solar-blind photomultipliers (R166), which have a long-wavelength cut-off at about 3000 Å. Although the interferometers themselves are evacuated, the air path between the source and the interferometer imposed an effective short-wavelength limit of about 1900 Å. The Ni $\text{II}$ lines below 1800 Å were recorded with a R1259 photomultiplier, which has a cut-off at about 1850 Å, and auxiliary spectra were taken to provide the wavelength calibration as described in Section 3. These VUV spectra are beyond the range of the LU spectrometer and were taken at IC only.

## 3 ANALYSIS AND RESULTS

### 3.1 Wavenumber calibration

The wavenumber scale of an FT spectrum derives from the stabilised He–Ne laser that is used to determine the sampling intervals for the interferogram, and it is accurately linear – i.e. $\sigma_{\text{exp}} = \sigma_0 (1 - \epsilon)$, where $\sigma_{\text{exp}}$ and $\sigma_0$ are the observed and true wavenumbers respectively. The ‘stretch factor’ $(1 - \epsilon)$ is due to the finite size of the interferometer entrance aperture and any possible offsets in the angle of the laser beam through the interferometer; $\epsilon$ is of the order of the reciprocal of the resolving power. In principle a single reference line is sufficient to evaluate $\epsilon$. In practice, a number of reference lines are used, and the mean value of $(\sigma_0 - \sigma_{\text{exp}})/\sigma$ determines $\epsilon$. It is not necessary to have the reference lines distributed through the spectrum, as is the case for a grating, and the calibration can be carried through from one spectral region to another provided the overlap region contains suitable transfer lines (Learner & Thorne 1988).

In all of these experiments the calibration lines came directly (or, in the case of Ni, indirectly) from the recommended Fe $\text{I}$ and Fe $\text{II}$ ‘standards’ of Nave et al. (1991), which in turn derive from a selected set of 26 Ar $\text{II}$ lines in the blue region (Learner & Thorne 1988), originally measured against the $^{89}$Kr standard by Norlén (1973). A subset of 17 Fe $\text{II}$ lines from the list of Nave et al. was used to calibrate the Mg, Cr and Zn lines at LU and the Zn lines at IC. The IC Cr wavelengths were taken from the spectra of J.E. Murray, recorded some 10 yr ago (Murray 1992). Murray used the Fe lines in spectra taken with a stainless steel hollow cathode (70 per cent Fe, 18 per cent Cr, 10 per cent Ni) to calibrate the stronger Cr lines, which then became the reference lines for the pure Cr spectra. The calibration uncertainty of all these lines is estimated to be between 1 and 2 mK, where 1 mK = 0.001 cm$^{-1}$.

The calibration of the VUV Ni $\text{II}$ spectra presented some difficulties because we were not able to excite simultaneously good (low noise) Fe $\text{II}$ and Ni $\text{II}$ spectra in this region. A reliable set of Ni $\text{II}$ wavelengths down to about 2000 Å is available from the work of Litzén, Brault & Thorne (1993), but it was necessary to take further spectra with an R1220 photomultiplier and two different interference filters to bridge satisfactorily the gap between 2000 and 1750 Å, in which there are few strong Ni lines. The wavelengths of the reference Ni $\text{II}$ lines were obtained from the stainless steel spectra in the same way as those of the Cr lines. We estimate the cumulative calibration uncertainty for the VUV Ni $\text{II}$ lines to be 2.5 mK.
3.2 Line fitting

The profiles of emission lines, for both neutral and ionic species, generated in a hollow cathode discharge are usually well described by Voigt functions with small damping factors. The line-fitting programs written for FT spectra by Brault (1987) use an iterative least-squares procedure to evaluate the Voigt parameters. For a symmetric isolated line, the uncertainty \( \epsilon \) in the central wavenumber of the fitted Voigt profile is given by (Brault 1987)

\[
\epsilon = W/\sqrt{n \times \text{SNR}}
\]

where \( W \) is the full width at half maximum of the line in the same units as \( \epsilon \), \( n \) is the number of independent spectral points across \( W \), and \( \text{SNR} \) is the signal-to-noise ratio for the line.

The fitting of the Cr lines is straightforward because any isotope or hyperfine structure should be negligible compared to the Doppler width (Cr has 84 per cent of the even isotope \(^{52}\text{Cr}\)). The \( \text{Ni} \) resonance doublet presents a potential problem because some degree of self-absorption in all the spectra was indicated by the departure of the two components from the theoretical 2:1 intensity ratio. Whereas the centre of a truly symmetric line is not shifted by modest self-absorption, the presence of unresolved isotope structure (Zn has three even isotopes of comparable abundance) might give rise to a small shift. As shown in the next subsection, we believe any such shift to be within the other uncertainties. Ni has two abundant isotopes, \(^{58}\text{Ni} \) at 68 per cent and \(^{60}\text{Ni} \) at 26 per cent, but no asymmetry was observable in the \( \text{Ni} \) lines of interest here. As there was also no evidence of self-absorption, the potential problem noted for Zn does not arise for Ni.

The signal-to-noise ratios for the Cr and Zn lines both at LU and at IC lead to wavenumber uncertainties of less than 1 mK, and the results from the two laboratories agree to within this uncertainty. In Table 1 we present the weighted means of the two sets of results. Taking into account the calibration uncertainty that they have in common, we ascribe an absolute uncertainty of 2 mK to these values.

The signal-to-noise ratios for the VUV \( \text{Ni} \) lines are significantly poorer. The measurements on two spectra, one taken recently and one nearly 4 yr ago, agree to well within their respective uncertainties, and the weighted means are presented in Table 1. (As these spectra were taken at two different currents, 600 and 200 mA, respectively, this agreement confirms our assumption that any shifts from unresolved isotope structure lie within the other uncertainties.) For the three lines the combined measurement and calibration uncertainty is 4 mK, and for the fourth (rather weak) line it is 15 mK.

Figure 1 shows the line profiles of all the Cr, Zn and Ni lines in Table 1. The intensity scale is set to make the rms noise equal to 1 in each case.

Table 1. Wavelengths of ultraviolet lines. Columns 2–4 give the weighted means of the IC and LU results for Cr, Zn and Ni. Column 4 is the value given by Morton (1991). For \( \text{Mg} \) the previously published IC measurements are given.

<table>
<thead>
<tr>
<th></th>
<th>( \lambda_{\text{air}} ) (Å)</th>
<th>( \lambda_{\text{vac}} ) (Å)</th>
<th>Wavenumber (cm(^{-1}))</th>
<th>( \lambda_{\text{vac}} ) (Morton 1991) (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr(\text{II} )</td>
<td>2065.5041</td>
<td>2066.1640 ± 0.0001</td>
<td>48398.868 ± 0.002</td>
<td>2066.161</td>
</tr>
<tr>
<td>Cr(\text{II} )</td>
<td>2061.5769</td>
<td>2062.2361 ± 0.0001</td>
<td>48491.053 ± 0.002</td>
<td>2062.234</td>
</tr>
<tr>
<td>Cr(\text{II} )</td>
<td>2055.3988</td>
<td>2056.2569 ± 0.0001</td>
<td>48532.055 ± 0.002</td>
<td>2056.254</td>
</tr>
<tr>
<td>Zn(\text{II} )</td>
<td>2062.0011</td>
<td>2062.6604 ± 0.0001</td>
<td>48481.077 ± 0.002</td>
<td>2062.664</td>
</tr>
<tr>
<td>Zn(\text{II} )</td>
<td>2025.4845</td>
<td>2026.1371 ± 0.0001</td>
<td>49355.002 ± 0.002</td>
<td>2026.136</td>
</tr>
<tr>
<td>Ni(\text{II} )</td>
<td>1751.9157 ± 0.0001</td>
<td>1750.387 ± 0.004</td>
<td>57080.373 ± 0.004</td>
<td>1751.910</td>
</tr>
<tr>
<td>Ni(\text{II} )</td>
<td>1741.5531 ± 0.0001</td>
<td>1740.013 ± 0.004</td>
<td>57420.013 ± 0.004</td>
<td>1741.549</td>
</tr>
<tr>
<td>Ni(\text{II} )</td>
<td>1709.6042 ± 0.0001</td>
<td>1708.071 ± 0.004</td>
<td>58493.071 ± 0.004</td>
<td>1709.600</td>
</tr>
<tr>
<td>Ni(\text{II} )</td>
<td>1703.4119 ± 0.0004</td>
<td>1702.057 ± 0.015</td>
<td>58705.707 ± 0.015</td>
<td>1703.405</td>
</tr>
<tr>
<td>Mg(\text{II} )</td>
<td>2852.1251</td>
<td>2852.9631 ± 0.0001</td>
<td>35051.277 ± 0.001</td>
<td>2852.126</td>
</tr>
<tr>
<td>Mg(\text{II} )</td>
<td>2795.5301</td>
<td>2796.3543 ± 0.0001</td>
<td>35760.848 ± 0.002</td>
<td>2796.352</td>
</tr>
<tr>
<td>Mg(\text{II} )</td>
<td>2802.7056</td>
<td>2803.5315 ± 0.0001</td>
<td>35669.298 ± 0.002</td>
<td>2803.531</td>
</tr>
</tbody>
</table>

1–2 mK, suggesting a larger field shift than that estimated above. These strongly self-absorbed lines have not been used in arriving at our final results.

Table 1 sets out our weighted mean values for all the lines, together with the values from Morton’s compilation (Morton 1991), and our previous measurements of Mg. Morton’s values have been given to seven digits because the vacuum wavelengths in his compilation are given to three decimal places of Å corresponding to two decimal places of cm$^{-1}$.

As is frequently the case, most of the actual data are much older – up to 20 yr – than the latest compilation. Morton’s 1991 values for Cr and Ni are taken from Sugar & Corliss (1985). The Cr$^{II}$ energy levels were redetermined by Johansson in 1983 (private communication to Sugar & Corliss), but the measurements and spectral analysis for Ni$^{II}$ are the work of Shenstone (1970). Sugar & Corliss (1985) estimate the accuracy to be about 0.05 cm$^{-1}$, or 2 mÅ. The Zn$^{II}$ doublet was measured by Martin & Kaufmann (1970) to about the same accuracy.

### 4 CONCLUSIONS

Motivated by recent advances in spectroscopy of high-redshift gas clouds, we have made accurate laboratory measurements of Cr$^{II}$, Zn$^{II}$ and Ni$^{II}$ transitions, which are observed in quasar spectra. The importance of the new laboratory wavelengths, in the context
of searches for space–time variation of the fine structure constant \( \alpha \), is that they can now be incorporated into analyses similar to that of Webb et al. (1999), enabling a reduction of systematic effects. We note also that the new laboratory wavelengths presented here and in our earlier paper will also prove valuable for spectroscopy of stars and the inter-stellar medium, as well as for quasar spectroscopy.

Confidence in the accuracy of the Cr and Zn measurements we report here is increased by the good agreement (within the stated uncertainties) between independent measurements from two laboratories. Some of these measurements extend over many years. The Ni lines were measured only at IC. The IC wave-numbers for the Mg lines reported in our previous paper (Pickering et al. 1998) have also been confirmed at LU. However, it should be noted that the absolute wavenumber scales for the Mg, Cr, Zn and Ni lines, as well as that for the Fe lines given by Nave et al. (1991), all originate from the same set of \( \text{Ar} \, \text{II} \) reference lines. Any error in the calibration factor derived from these lines will be a systematic multiplicative error in all the IC and LU measurements: \( \Delta \sigma = \varepsilon \sigma \) where \( \Delta \sigma \) is the error in the wavenumber \( \sigma \) and \( \varepsilon \) is certainly not greater than \( 4 \times 10^{-8} \).

The results of the earlier IC measurements of \( \text{Fe} \, \text{II} \) (Nave et al. 1991) and \( \text{Mg} \, \text{II} \) and \( \text{Mg} \, \text{I} \) (Pickering et al. 1998), combined with new theoretical developments (Dzuba et al. 1999a,b) enabled an order-of-magnitude increase in the precision with which one can constrain changes in \( \alpha \) (Webb et al. 1999). Those particular transitions effectively restrict the maximum observed redshift range to \( \sim 1.5 \) or so. At higher redshifts, the redshifted transitions fall at observed wavelengths where emission and absorption features in the sky and atmosphere reduce the reliability of the results. The new IC and LU measurements presented in this paper will now allow that redshift range to be extended to at least \( z \sim 2.5 \), using \( \text{Ni} \, \text{II} \), \( \text{Cr} \, \text{II} \), \( \text{Zn} \, \text{II} \) and other transitions of lower rest wavelength.

The fact that the magnitudes of the shifts vary according to the species/transition by at least one order of magnitude, and also that the direction of the shift can be of opposite sign for a given change in \( \alpha \) (Dzuba et al. 1999a,b), means that transitions with small relativistic corrections act as ‘wavelength anchors’, against which shifts in species with larger relativistic corrections can be measured. Large shifts of opposite signs are important in that these will assist in negating systematic uncertainties in the quasar spectra. Comparing results from different species with relativistic corrections of opposite sign must yield different inferred variations in \( \alpha \) if systematic errors in the data are significant. If, on the other hand the comparison yields consistent variations in \( \alpha \), it would be hard to attribute the results to anything other than a genuine change in \( \alpha \). Considerations like these strongly motivated the measurements we describe here and will allow an important check on the very tentative indication that \( \alpha \) may actually have varied with time (Webb et al. 1999).

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