Laboratory spectroscopy and the search for space-time variation of the fine structure constant using QSO spectra.

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Abstract

Theories unifying gravity with other interactions suggest spatial and temporal variation of fundamental "constants" in the Universe. A change in the fine structure constant, $\alpha = e^2/\hbar c$, could be detected via shifts in the frequencies of atomic transitions in quasar absorption systems. Previous studies of three independent samples of data, containing 143 absorption systems spread from 2 to 10 billion years after big bang, hint that α was smaller 7 – 11 billion years ago [1, 2, 3, 4, 5, 6].

To continue this study we urgently need accurate laboratory measurements of atomic transition frequencies. The aim of this paper is to provide a compilation of transitions of importance to the search for α variation. They are $E1$ transitions to the ground state in several different atoms and ions, with wavelengths ranging from around 900 – 6000 Å, and require an accuracy of better than 10^{-4} Å. We also discuss isotope shift measurements that are needed in order to resolve systematic effects in the study.

Researchers who are interested in performing these measurements should contact the authors directly.

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Current theories that seek to unify gravity with the other fundamental interactions suggest the possibility of spatial and temporal variation of fundamental constants in the Universe (see, for example the review [7]). Several studies have tried to probe the values of constants at earlier stages in the evolution of the universe. One method compares atomic transition frequencies on Earth and in quasar (QSO) absorption spectra, and recent studies of these spectra have revealed hints that the fine structure constant, α, was smaller in the early universe [1, 2, 3, 4, 5, 6]. The latest results of this group, which combine data from 143 absorption systems over the redshift range $0.2 < z_{\rm abs} < 3.7$, show $\Delta\alpha/\alpha = (-0.543 \pm 0.116) \times 10^{-5}$ [6]. However, attempts to replicate this result using a similar analysis, but different data sets from different telescopes, indicate no variation of α [8, 9, 10, 11].

To continue this work and resolve the discrepancies, several new transitions are being considered. In Table I we present a list of lines commonly observed in high-resolution QSO spectra. Those transitions for which high-accuracy laboratory data are needed are marked with either 'A' (very important) or 'B' (mildly important). Some of the lines marked 'A' have already been measured quite accurately (references are given), but even in these cases confirmation and improvement is still urgently required. Predominantly, the wavelengths given in Table I come from the compilation [12, 13] and have errors of about 0.005 Å, although it is possible that some errors are closer to 0.05 Å. Note that the oscillator strengths presented are not as accurate as the wavelengths: these measurements are much more difficult. As a general rule, the lines are more important for α variation if they lie above 1215.67 Å (the Lyman-α line of hydrogen) due to the "Lyman-α forest" seen in QSO spectra.

Isotope shift measurements for these transitions are also needed in order to resolve a source of systematic error in the variation of α studies: the isotope abundance ratios in the gas clouds sampled in the quasar absorption spectra may not match those on Earth [14, 15]. Accurate measurements of the isotope shift are required to quantify these systematic effects. They can also be used to determine the abundances in the early universe directly, to test models of nuclear processes in stars. In addition to the transitions previously mentioned, in Table I, we present lines that were used in previous studies (and have precise wavelength measurements), but for which the isotopic structure has not been measured. These transitions are marked with an 'I'.

We previously calculated the relativistic energy shifts, or q values [16, 17, 18, 19]. We have presented them here for easy reference. The difference between the transition frequencies in QSO spectra (ω) and in the laboratory (ω_0) depends on the relative values of α. The dependence of the frequencies on small changes in α is given by the formula $\omega = \omega_0 + qx$, where $x = (\alpha/\alpha_0)^2 - 1$. The q values are calculated using atomic physics codes. The atomic energy levels are calculated to a first approximation using relativistic Hartree-Fock (Dirac-Hartree-Fock). Higher order effects are taken into account using many-body perturbation theory for single-valence-electron systems, or using configuration interaction for many-valence-electron systems. Both methods assume a frozen Hartree-Fock core. The value of α is varied in the computer codes and the energy levels are recalculated, and hence the transition frequencies. The q values are extracted as

$$q = \left.\frac{d\omega}{dx}\right|_{x=0}$$

We also account for complications due to level pseudo-crossing [16].

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TABLE I: High-priority lines observed in QSO spectra. The first column is the ion; the second and third columns are the rest wavelength and the transition frequency, respectively; the fourth column is the oscillator strength; the relativistic shift (q value) is shown in the fifth column, where known. Those transitions for which high-accuracy laboratory data are needed are marked with either 'A' (very important) or 'B' (mildly important). Lines for which there is no measured isotopic structure are marked 'I'. Additionally, there are some lines for which both the transition frequency and isotope shift are known; these are marked with an 'M'. They are included here for reference only (of course, verification would still be useful). References for precisely measured lines are given in the last column. The second set of references are for isotope shift measurements, where available. The wavelengths and oscillator strengths are taken from the compilation by Morton [12, 13].

Atom/ Ion	Wavelength λ (Å)	Frequency ω_0 (cm^{-1})	Oscillator Strength	q value (cm^{-1})		Refs.
C I	945.188	105799.1	0.272600	130 (60)	M	[20]
	1139.793	87735.30	0.013960	0 (100)	B	
	1155.809	86519.47	0.017250	”	B	
	1157.186	86416.55	0.549500	”	B	
	1157.910	86362.52	0.021780	”	B	
	1188.833	84116.09	0.016760	”	B	
	1193.031	83820.13	0.044470	”	B	
	1193.996	83752.41	0.009407	”	B	
	1260.736	79318.78	0.039370	30 (10)	A	
	1276.483	78340.28	0.004502	17 (10)	A	
	1277.245	78293.49	0.096650	−13 (10)	A	
	1280.135	78116.74	0.024320	−21 (10)	A	
	1328.833	75253.97	0.058040	117 (10)	A	
	1560.309	64089.85	0.080410	137 (10)	A	
	1656.928	60352.63	0.140500	−24 (10)	A	
C II	1037.018	96430.32	0.123000	168 (10)	A	
	1335.662	74869.20	0.012770	178 (10)	A	
	1335.707	74866.68	0.114900	181 (10)	A	
C III	977.020	102352.0	0.762000	165 (10)	B	
C IV	1548.204	64590.99	0.190800	232 (20)	A	[21]
	1550.781	64483.65	0.095220	104 (20)	A	[21]
O I	1025.762	97488.54	0.020300	0 (20)	B	
	1026.476	97420.72	0.002460	”	B	
	1039.230	96225.05	0.009197	”	B	
	1302.168	76794.98	0.048870	”	A	

TABLE I: (continued)

Atom/ Ion	Wavelength λ (Å)	Frequency ω_0 (cm^{-1})	Oscillator Strength	q value (cm^{-1})		Refs.
Na I	3303.320	30272.58	0.013400	59 (4)	B	
	3303.930	30266.99	0.006700	53 (4)	B	
	5891.583	16973.37	0.655000	63 (4)	M	[22][23, 24]
	5897.558	16956.17	0.327000	45 (4)	M	[22][25]
Mg I	2026.477	49346.73	0.112000	87	I	[26]
	2852.963	35051.27	0.181000	86 (10)	M	[26, 27][28, 29]
Mg II	1239.925	80650.04	0.000267		B	
	2796.354	35760.85	0.612300	211 (10)	M	[26, 27][30]
	2803.532	35669.30	0.305400	120 (10)	I	[26, 27]
Al II	1670.789	59851.97	1.880000	270 (30)	M	[21]
Al III	1854.718	53916.54	0.539000	464 (30)	M	[21]
	1862.791	53682.88	0.268000	464 (30)	M	[21]
Si II	1190.416	84004.26	0.250200		B	
	1193.290	83801.95	0.499100		B	
	1260.422	79338.50	1.007000		A	
	1304.370	76665.35	0.094000		A	
	1526.707	65500.45	0.117094	50 (30)	I	[21]
	1808.013	55309.34	0.002010	520 (30)	I	[21]
Si IV	1393.760	71748.64	0.528000	862	A	[21]
	1402.773	71287.54	0.262000	346	A	[21]
S II	1250.583	79962.61	0.005350		A	
	1253.808	79756.83	0.010700		A	
	1259.518	79395.39	0.015900		A	
Ca II	3934.775	25414.41	0.688000	452	A	[13]
	3969.590	25191.52	0.341000	224	A	[13]
Ti II	1910.600	52339.58	0.202000	−1564 (150)	A	
	1910.938	52330.32	0.098000	−1783 (300)	A	
	3067.245	32602.55	0.041500	791 (50)	I	[26]
	3073.877	32532.21	0.104000	677 (50)	I	[26]
	3230.131	30958.50	0.057300	673 (50)	I	[26]
	3242.929	30836.32	0.183000	541 (50)	I	[26]
	3384.740	29544.37	0.282000	396 (50)	I	[26]
Cr II	2056.256	48632.06	0.105000	−1110 (150)	I	[26, 31]
	2062.236	48491.05	0.078000	−1280 (150)	I	[26, 31]
	2066.164	48398.87	0.051500	−1360 (150)	I	[26, 31]
Mn II	1197.184	83529.35	0.156600	−2556 (450)	B	
	1199.391	83375.65	0.105900	−2825 (450)	B	
	1201.118	83255.77	0.088090	−3033 (450)	B	
	2576.877	38806.66	0.288000	1420 (150)	I	[26]
	2594.499	38543.08	0.223000	1148 (150)	I	[26]
	2606.462	38366.18	0.158000	986 (150)	I	[26]

TABLE I: (continued)

Atom/ Ion	Wavelength λ (Å)	Frequency ω_0 (cm^{-1})	Oscillator Strength	q value (cm^{-1})		Refs.
Fe II	1063.176	94057.80	0.060000		B	
	1063.971	93987.52	0.003718		B	
	1096.877	91167.92	0.032400		B	
	1121.975	89128.55	0.020200		B	
	1125.448	88853.51	0.016000		B	
	1143.226	87471.77	0.017700		B	
	1144.939	87340.98	0.106000		B	
	1260.533	79331.52	0.025000		A	
	1608.450	62171.63	0.058000	−1300 (300)	A	[32]
	1611.200	62065.53	0.001360	1100 (300)	A	[32]
	2249.877	44446.88	0.001821		A	
	2260.780	44232.51	0.002440		I	[26]
	2344.212	42658.24	0.114000	1210 (150)	I	[26, 33]
	2367.589	42237.06	0.000212	1904	A	
	2374.460	42114.83	0.031300	1590 (150)	I	[26, 33]
	2382.764	41968.06	0.320000	1460 (150)	I	[26, 33]
	2586.649	38660.05	0.069180	1490 (150)	I	[26, 33]
	2600.172	38458.99	0.238780	1330 (150)	I	[26, 33]
Ni II	1317.217	75917.64	0.146000		A	
	1370.132	72985.67	0.076900		A	
	1393.324	71770.82	0.022220		A	
	1454.842	68735.99	0.032300		A	
	1467.259	68154.29	0.009900		A	
	1467.756	68131.22	0.006300		A	
	1502.148	66571.34	0.006000		A	
	1703.412	58705.71	0.012240		A	[31]
	1709.604	58493.07	0.032400	−20 (250)	A	[31]
	1741.553	57420.01	0.042700	−1400 (250)	A	[31]
	1751.915	57080.37	0.027700	−700 (250)	A	[31]
Zn II	2026.137	49355.00	0.489000	2479 (25)	M	[26, 31][34]
	2062.660	48481.08	0.256000	1584 (25)	I	[26, 31]

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