

# Atomic spectroscopy and the search for variation of fundamental constants

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We urgently need accurate laboratory measurements of atomic transition frequencies to search for variation of the fine structure constant, by comparison of these frequencies with those in quasar (QSO) absorption spectra. 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 frequencies of atomic transitions in QSO systems. We previously studied three independent samples of data containing 143 absorption systems spread from 2 to 10 billion years after the Big Bang. All three data samples hint that  $\alpha$  was smaller 7 – 11 billion years ago.

**To continue this study** we need accurate laboratory wavelengths for E1 transitions to the ground state in a variety of atoms and ions. The wavelengths range from around 900 – 6000 Å, and require an accuracy of better than  $10^{-4}$  Å.

Isotope shift measurements for these transitions are also needed in order to resolve systematic effects in the study: the isotope abundance ratios in the gas clouds sampled may not match those on earth. Accurate measurements of the isotope shift are required to quantify these systematic effects in the variation of  $\alpha$  study. They can also be used to determine the abundances in the early universe directly, to test models of nuclear processes in stars.

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## Transitions that need wavelength measurements and isotope shift

This list was originally compiled by Michael Murphy 29/06/04

We present a list of high-priority lines commonly observed in high-resolution QSO absorption spectra. The first column is the ion; the second and third columns are the rest wavelength and energy; the fourth column is the oscillator strength; the fifth column shows the upper state of the transition (all transitions are to the ground state); the relativistic shift (q-value) is shown in the sixth column, where known. For lines that still require accurate laboratory wavelength measurements, the relative importance of the transition for determining variation in the fine structure constant is also shown in last column ("A" = very important; "B" = mildly important; "isotope shift" = wavelength is known to required accuracy, but isotopic structure is still needed).

Note that the oscillator strengths are not accurate. Predominantly, these wavelengths come from the compilation by Morton and so have errors of about  $0.005\text{Å}$ , although it would not be surprising to have errors of  $0.05\text{Å}$  in some cases. Hence the general need to improve the situation.

The isotopic (and, in some cases, hyperfine) structure is very important for all of these lines. As a general rule, metal lines are more important for alpha-variation if they lie above  $1215.67\text{Å}$  (the Lyman- $\alpha$  line of hydrogen) due to the “Lyman- $\alpha$  forest” seen in QSO spectra.

Atom/ Ion	Wavelength $\lambda$ (Å)	Frequency $\omega$ (cm <sup>-1</sup> )	Oscillator Strength	Upper State	q-Value (cm <sup>-1</sup> )	Measurement Needed (Importance)
C I	945.193	105798.7	0.272600	2s2p <sup>3</sup> <sup>3</sup> S <sub>1</sub> <sup>o</sup>	130 (60)	B
	1139.793	87735.30	0.013960	2s <sup>2</sup> 2p6d <sup>3</sup> D <sub>1</sub> <sup>o</sup>	~ 0 (100)	B
	1155.809	86519.47	0.017250	2s <sup>2</sup> 2p5d <sup>3</sup> P <sub>1</sub> <sup>o</sup>	"	B
	1157.186	86416.55	0.549500	2s <sup>2</sup> 2p6s <sup>1</sup> P <sub>1</sub> <sup>o</sup>	"	B
	1157.910	86362.52	0.021780	2s <sup>2</sup> 2p5d <sup>3</sup> D <sub>1</sub> <sup>o</sup>	"	B
	1188.833	84116.09	0.016760	2s <sup>2</sup> 2p4d <sup>3</sup> P <sub>1</sub> <sup>o</sup>	"	B
	1193.031	83820.13	0.044470	2s <sup>2</sup> 2p4d <sup>3</sup> D <sub>1</sub> <sup>o</sup>	"	B
	1193.996	83752.41	0.009407	2s <sup>2</sup> 2p5s <sup>3</sup> P <sub>1</sub> <sup>o</sup>	"	B
	1260.736	79318.78	0.039370	2s <sup>2</sup> 2p3d <sup>3</sup> P <sub>1</sub> <sup>o</sup>	"	A
	1276.483	78340.28	0.004502	2s <sup>2</sup> 2p4s <sup>1</sup> P <sub>1</sub> <sup>o</sup>	"	A
	1277.245	78293.49	0.096650	2s <sup>2</sup> 2p3d <sup>3</sup> D <sub>1</sub> <sup>o</sup>	"	A
	1280.135	78116.74	0.024320	2s <sup>2</sup> 2p4s <sup>3</sup> P <sub>1</sub> <sup>o</sup>	"	A
	1328.833	75253.97	0.058040	2s <sup>2</sup> 2p <sup>3</sup> <sup>3</sup> P <sub>1</sub> <sup>o</sup>	111 (60)	A
	1560.309	64089.85	0.080410	2s <sup>2</sup> 2p <sup>3</sup> <sup>3</sup> D <sub>1</sub> <sup>o</sup>	145 (60)	A
	1656.928	60352.63	0.140500	2s <sup>2</sup> 2p3s <sup>3</sup> P <sub>1</sub> <sup>o</sup>	~ 0 (100)	A
	C II	1037.018	96430.32	0.123000	2s2p <sup>2</sup> <sup>2</sup> S <sub>1/2</sub> <sup>o</sup>	161 (30)
1335.662		74869.20	0.012770	2s2p <sup>2</sup> <sup>2</sup> D <sub>3/2</sub> <sup>o</sup>	176 (20)	A
1335.707		74866.68	0.114900	2s2p <sup>2</sup> <sup>2</sup> D <sub>5/2</sub> <sup>o</sup>	179 (20)	A
C III	977.020	102352.0	0.762000	2s2p <sup>1</sup> P <sub>1</sub> <sup>o</sup>	162 (20)	B
C IV	1548.203	64590.99	0.190800	2p <sup>2</sup> P <sub>3/2</sub> <sup>o</sup>	232 (20)	A
	1550.780	64484.00	0.095220	2p <sup>2</sup> P <sub>1/2</sub> <sup>o</sup>	104 (20)	A
O I	1025.762	97488.54	0.020300	2s <sup>2</sup> 2p <sup>3</sup> 3d <sup>3</sup> D <sub>1-3</sub> <sup>o</sup>	~ 0 (20)	B
	1026.476	97420.72	0.002460	2s <sup>2</sup> 2p <sup>3</sup> 3d <sup>5</sup> D <sub>0-4</sub> <sup>o</sup>	"	B
	1039.230	96255.05	0.009197	2s <sup>2</sup> 2p <sup>3</sup> 4s <sup>3</sup> S <sub>1</sub> <sup>o</sup>	"	B
	1302.168	76794.98	0.048870	2s <sup>2</sup> 2p <sup>3</sup> 3s <sup>3</sup> S <sub>1</sub> <sup>o</sup>	"	A
Na I	3303.320	30272.58	0.013400	4p <sup>2</sup> P <sub>3/2</sub> <sup>o</sup>	59 (4)	A
	3303.930	30266.99	0.006700	4p <sup>2</sup> P <sub>1/2</sub> <sup>o</sup>	53 (4)	A
	5891.583	16973.37	0.655000	3p <sup>2</sup> P <sub>3/2</sub> <sup>o</sup>	63 (4)	A
	5897.558	16956.17	0.327000	3p <sup>2</sup> P <sub>1/2</sub> <sup>o</sup>	45 (4)	A
Mg I	1239.925	80650.04	0.000267	3p3d <sup>1</sup> D <sub>2</sub> <sup>o</sup>		B
	2026.477	49346.73	0.112000	3s4p <sup>1</sup> P <sub>1</sub> <sup>o</sup>		A
Si II	1190.416	84004.26	0.250200	3s3p <sup>2</sup> <sup>2</sup> P <sub>3/2</sub>		B
	1193.290	83801.95	0.499100	3s3p <sup>2</sup> <sup>2</sup> P <sub>1/2</sub>		B
	1260.422	79338.50	1.007000	3s <sup>2</sup> 3d <sup>2</sup> D <sub>3/2</sub>		A
	1304.370	76665.35	0.094000	3s3p <sup>2</sup> <sup>2</sup> S <sub>1/2</sub>		A
	1526.707	65500.45	0.117094	3d <sup>2</sup> 4s <sup>2</sup> S <sub>1/2</sub>	50 (30)	isotope shift
	1808.013	55309.34	0.002010	3d3p <sup>2</sup> <sup>2</sup> D <sub>3/2</sub>	520 (30)	isotope shift
Si IV	1393.760	71748.64	0.528000	3p <sup>2</sup> P <sub>3/2</sub> <sup>o</sup>	862	A
	1402.773	71287.54	0.262000	3p <sup>2</sup> P <sub>1/2</sub> <sup>o</sup>	346	A
S II	1250.583	79962.61	0.005350	3s3p <sup>4</sup> <sup>4</sup> P <sub>1/2</sub>		A
	1253.808	79756.83	0.010700	3s3p <sup>4</sup> <sup>4</sup> P <sub>3/2</sub>		A
	1259.518	79395.39	0.015900	3s3p <sup>4</sup> <sup>4</sup> P <sub>5/2</sub>		A
Ca II	3934.777	25414.40	0.688000	4p <sup>2</sup> P <sub>3/2</sub> <sup>o</sup>	452	A
	3969.591	25191.51	0.341000	4p <sup>2</sup> P <sub>1/2</sub> <sup>o</sup>	224	A
Ti II	1910.600	52339.58	0.202000	3d4s4p <sup>4</sup> D <sub>1/2</sub> <sup>o</sup>	-1564 (150)	A
	1910.938	52330.32	0.098000	3d4s4p <sup>4</sup> F <sub>3/2</sub> <sup>o</sup>	-1783 (300)	A

Atom/ Ion	Wavelength $\lambda$ (Å)	Frequency $\omega$ (cm <sup>-1</sup> )	Oscillator Strength	Upper State	q-Value (cm <sup>-1</sup> )	Measurement Needed (Importance)
Ti II	3067.245	32602.55	0.041500	3d <sup>2</sup> 4p <sup>4</sup> D <sub>3/2</sub> <sup>o</sup>	791 (50)	A
	3073.877	32532.21	0.104000	3d <sup>2</sup> 4p <sup>4</sup> D <sub>1/2</sub> <sup>o</sup>	677 (50)	A
	3230.131	30958.50	0.057300	3d <sup>2</sup> 4p <sup>4</sup> F <sub>5/2</sub> <sup>o</sup>	673 (50)	A
	3242.929	30836.32	0.183000	3d <sup>2</sup> 4p <sup>4</sup> F <sub>3/2</sub> <sup>o</sup>	541 (50)	A
	3384.740	29544.37	0.282000	3d <sup>2</sup> 4p <sup>4</sup> G <sub>5/2</sub> <sup>o</sup>	396 (50)	A
Cr II	2056.256	48632.06	0.105000	3d <sup>4</sup> 4p <sup>6</sup> P <sub>7/2</sub> <sup>o</sup>	-1110 (150)	isotope shift
	2062.236	48491.05	0.078000	3d <sup>4</sup> 4p <sup>6</sup> P <sub>5/2</sub> <sup>o</sup>	-1280 (150)	isotope shift
Mn II	2066.164	48398.87	0.051500	3d <sup>4</sup> 4p <sup>6</sup> P <sub>3/2</sub> <sup>o</sup>	-1360 (150)	isotope shift
	1197.184	83529.35	0.156600	3d <sup>4</sup> 4s4p <sup>7</sup> P <sub>4</sub> <sup>o</sup>	-2556 (450)	A
	1199.391	83375.65	0.105900	3d <sup>4</sup> 4s4p <sup>7</sup> P <sub>3</sub> <sup>o</sup>	-2825 (450)	A
Fe II	1201.118	83255.77	0.088090	3d <sup>4</sup> 4s4p <sup>7</sup> P <sub>2</sub> <sup>o</sup>	-3033 (450)	A
	2576.877	38806.66	0.288000	3d <sup>5</sup> 4p <sup>7</sup> P <sub>4</sub> <sup>o</sup>	1420 (150)	A
	2594.499	38543.08	0.223000	3d <sup>5</sup> 4p <sup>7</sup> P <sub>3</sub> <sup>o</sup>	1148 (150)	A
	2606.462	38366.18	0.158000	3d <sup>5</sup> 4p <sup>7</sup> P <sub>2</sub> <sup>o</sup>	986 (150)	A
	1063.176	94057.80	0.060000	3d <sup>5</sup> 4s4p <sup>6</sup> D <sub>9/2</sub> <sup>o</sup>		B
	1063.971	93987.52	0.003718	3d <sup>5</sup> 4s4p <sup>6</sup> D <sub>7/2</sub> <sup>o</sup>		B
	1096.877	91167.92	0.032400	3d <sup>6</sup> 5p <sup>6</sup> P <sub>7/2</sub> <sup>o</sup>		B
	1121.975	89128.55	0.020200	3d <sup>6</sup> 5p ? <sub>7/2</sub> <sup>o</sup>		B
Fe II	1125.448	88853.51	0.016000	3d <sup>6</sup> 5p <sup>6</sup> D <sub>7/2</sub> <sup>o</sup>		B
	1143.226	87471.77	0.017700	3d <sup>5</sup> 4s4p <sup>6</sup> F <sub>9/2</sub> <sup>o</sup>		B
	1144.939	87340.98	0.106000	3d <sup>5</sup> 4s4p <sup>6</sup> F <sub>11/2</sub> <sup>o</sup>		B
	1260.533	79331.52	0.025000	3d <sup>5</sup> 4s4p <sup>6</sup> P <sub>7/2</sub> <sup>o</sup>		A
	1608.450	62171.63	0.058000	3d <sup>5</sup> 4s4p <sup>6</sup> P <sub>7/2</sub> <sup>o</sup>	-1300 (300)	isotope shift
	1611.200	62065.53	0.001360	3d <sup>6</sup> 4p <sup>4</sup> F <sub>7/2</sub> <sup>o</sup>	1100 (300)	isotope shift
	2249.877	44446.88	0.001821	3d <sup>6</sup> 4p <sup>4</sup> D <sub>7/2</sub> <sup>o</sup>		isotope shift
	2260.780	44232.51	0.002440	3d <sup>6</sup> 4p <sup>4</sup> F <sub>9/2</sub> <sup>o</sup>		isotope shift
	2344.212	42658.24	0.114000	3d <sup>6</sup> 4p <sup>6</sup> P <sub>7/2</sub> <sup>o</sup>	1210 (150)	isotope shift
	2367.589	42237.06	0.000212	3d <sup>6</sup> 4p <sup>6</sup> F <sub>7/2</sub> <sup>o</sup>	1904	A
Ni II	2374.460	42114.83	0.031300	3d <sup>6</sup> 4p <sup>6</sup> F <sub>9/2</sub> <sup>o</sup>	1590 (150)	isotope shift
	2382.764	41968.06	0.320000	3d <sup>6</sup> 4p <sup>6</sup> F <sub>11/2</sub> <sup>o</sup>	1460 (150)	isotope shift
	2586.649	38660.05	0.069180	3d <sup>6</sup> 4p <sup>6</sup> D <sub>7/2</sub> <sup>o</sup>	1490 (150)	isotope shift
	2600.172	38458.99	0.238780	3d <sup>6</sup> 4p <sup>6</sup> D <sub>9/2</sub> <sup>o</sup>	1330 (150)	isotope shift
	1317.217	75917.64	0.146000	3d <sup>8</sup> 4p <sup>2</sup> F <sub>7/2</sub> <sup>o</sup>		isotope shift
	1370.132	72985.67	0.076900	3d <sup>8</sup> 4p <sup>2</sup> P <sub>3/2</sub> <sup>o</sup>		isotope shift
	1393.324	71770.82	0.022220	3d <sup>8</sup> 4p <sup>2</sup> D <sub>5/2</sub> <sup>o</sup>		A
	1454.842	68735.99	0.032300	3d <sup>8</sup> 4p <sup>2</sup> D <sub>5/2</sub> <sup>o</sup>		A
	1467.259	68154.29	0.009900	3d <sup>8</sup> 4p <sup>2</sup> D <sub>3/2</sub> <sup>o</sup>		A
	1467.756	68131.22	0.006300	3d <sup>8</sup> 4p <sup>2</sup> F <sub>7/2</sub> <sup>o</sup>		A
	1502.148	66571.34	0.006000	3d <sup>8</sup> 4p <sup>4</sup> P <sub>5/2</sub> <sup>o</sup>		A
	1703.411	58705.74	0.012240	3d <sup>8</sup> 4p <sup>2</sup> D <sub>3/2</sub> <sup>o</sup>		A
Ni II	1709.604	58493.07	0.032400	3d <sup>8</sup> 4p <sup>2</sup> F <sub>5/2</sub> <sup>o</sup>	-20 (250)	isotope shift
	1741.553	57420.01	0.042700	3d <sup>8</sup> 4p <sup>2</sup> D <sub>5/2</sub> <sup>o</sup>	-1400 (250)	isotope shift
	1751.915	57080.37	0.027700	3d <sup>8</sup> 4p <sup>2</sup> F <sub>7/2</sub> <sup>o</sup>	-700 (250)	isotope shift
Zn II	2062.660	48481.08	0.256000	4p <sup>2</sup> P <sub>1/2</sub> <sup>o</sup>	1584 (25)	isotope shift