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Experimental oscillator strengths in U II of cosmological interest

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Abstract. Oscillator strengths for 57 U II lines in the region 3500–6700 Å have been derived by combining new branching fraction measurements with recently measured lifetimes. The lines combine six upper levels with numerous low levels having excitation energies of 0–1.5 eV. The data include the U II line at 3859 Å, which is used for cosmochronology.

Key words. atomic data – stars: evolution – Galaxy: evolution

1. Introduction

Determination of stellar ages using radiative dating requires a high accuracy in the determination of chemical abundances, which is based on the analysis of spectral lines. The crucial atomic parameter is the oscillator strength. The method of radioactive dating is based upon the change with time in the abundance ratio of two elements, either a radioactive and a stable isotope, or two radioactive isotopes with different half-lifes. Cayrel et al. (2001) determined the age of the metal poor star CS 31082–001, using a uranium-thorium cosmochronometer. In order to increase the accuracy in this age determination, new f-values for Th II have been reported by Nilsson et al. (2001), and in the present paper we present new f-values for U II.

Previous measurements of relative line intensities in U II were made by Meggers et al. (1961), using an arc as a light source. Corliss & Bozman (1962) put the measurements of Meggers et al. on an absolute scale by estimating the plasma parameters in the arc. Voigt (1975) measured oscillator strengths from an arc, which enabled Corliss (1976) to rescale the line intensities from Meggers et al. (1961). In a study by Palmer et al. (1980), relative line intensities and accurate wavenumbers were measured from uranium hollow cathode (HC) spectra recorded with the Fourier transform spectrometer (FTS) at Kitt Peak National Observatory. That work also includes a semi-empirical formula for putting the relative intensities on a absolute scale using the values reported by Corliss (1976). Values of the oscillator strengths of the $\lambda\lambda$ 3859.6 and 4050.0 lines were later reported by Chen & Borzileri (1981), who measured the lifetimes of the 5f^{3}6d7p ^{6}M$_{13/2}$ level at 26191 cm^{-1}, the upper level of the 3859.6 line, and the 5f^{3}7s7p ^{6}I level at 24 684 cm^{-1}, the upper level of the 4050.0 line, and combined them with unpublished branching fractions (BF). Henrion et al. (1987) measured relative intensities from a HC and scaled them to the values of Corliss (1976).

In the present paper we present relative intensities of 57 U II lines measured in FTS spectra and recalculated to BFs. Combining these BFs with radiative lifetimes (Lundberg et al. 2001) yields oscillator strengths for the 57 lines.

2. Branching fractions

The BFs are derived from line intensities, which have been measured in spectra recorded with a Chelsea Instrument FT500 FTS in the wavelength interval 3300–7000 Å. As a light source we ran a HC at different currents between 0.1 and 0.5 A and with argon as a carrier gas. The cathode is a 3 cm long iron tube with an inner diameter of 0.5 cm, in which a piece of uranium was inserted. The U II transitions with $\lambda > 5000$ Å are predicted to be weak, and they were not observed in the spectra as the FTS response is low above 5000 Å. However, a spectrum recorded at Kitt Peak National Observatory and extracted from the Kitt Peak FTS archive could be used to measure the intensities of these lines. The Kitt Peak spectrum was recorded from a HC with a discharge current of 0.3 A and argon as a carrier gas in the wavelength interval 2400–12 800 Å. In order to get relative intensities the FTS spectra were corrected for the instrument response by using known branching ratios in argon (Whaling et al. 1993).

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Table 1. U II branching fractions (BFs) and gf-values. The lines are sorted by the upper level.

Upper	Lower	$\lambda_{\rm air}$	σ	BF	gf	log gf				Unc.
level	level	(Å)	(cm^{-1})			This work	K[a]	C[b]	C&B[c]	(% in gf)
23315.090	7166	6190.822	16148.460	0.003	0.002	−2.632				27
$\tau = 84$ ns	5401	5580.801	17913.586	0.04	0.022	−1.668	−2.345	−1.94		12
$J = 4.5$	914	4462.965	22400.325	0.17	0.059	−1.229	−1.782	−1.65		11
	289	4341.683	23026.049	0.59	0.199	−0.700	−1.161	−1.24		7
	0	4287.858	23315.090	0.20	0.065	−1.184	−1.709	−1.62		11
24684.132	9690	6667.728	14993.471	0.002	0.003	−2.534				51
$\tau = 49$ ns	8379	6131.603	16304.436	0.004	0.004	−2.393				41
$J = 4.5$	7598	5851.199	17085.777	0.01	0.011	−1.949				17
	7547	5833.792	17136.759	0.01	0.008	−2.105				17
	7166	5706.993	17517.502	0.03	0.026	−1.591	−2.148			9
	6445	5481.204	18239.097	0.13	0.116	−0.937	−1.677	−1.51		9
	5790	5291.356	18893.491	0.01	0.009	−2.061				10
	5667	5257.045	19016.801	0.06	0.051	−1.289	−1.924	−1.70		9
	5401	5184.571	19282.628	0.09	0.076	−1.120	−1.855	−1.66		9
	4420	4933.662	20263.262	0.06	0.047	−1.330	−2.212	−1.92		9
	2294	4465.139	22389.436	0.06	0.035	−1.453	−1.944	−1.78		9
	289	4098.029	24395.091	0.15	0.076	−1.117	−1.239	−1.34		9
	0	4050.041	24684.132	0.39	0.197	−0.706	−0.713	−0.99	−0.675	7
25714.049	10740	6676.804	14973.092	0.01	0.023	−1.638				26
$\tau = 35$ ns	8510	5811.266	17203.183	0.02	0.036	−1.438		−1.72		17
$J = 6.5$	8276	5733.237	17437.316	0.01	0.026	−1.590	−1.976	−1.71		17
	6283	5145.083	19430.618	0.02	0.024	−1.615	−2.117	−2.85		17
	5259	4887.559	20454.397	0.003	0.004	−2.371				43
	4585	4731.594	21128.615	0.09	0.125	−0.902	−1.509	−1.48		18
	4420	4695.026	21293.179	0.01	0.010	−2.022				26
	1749	4171.589	23964.926	0.32	0.336	−0.474	−0.606	−0.92		14
	289	3932.022	25425.008	0.52	0.482	−0.317	−0.528	−0.89		12
26191.309	10740	6470.556	15450.352	0.01	0.032	−1.494				34
$\tau = 18.6$ ns	8510	5654.397	17680.443	0.01	0.030	−1.516				18
$J = 6.5$	8276	5580.497	17914.576	0.003	0.010	−2.021				52
	6283	5021.736	19907.878	0.01	0.022	−1.650				22
	5790	4900.432	20400.668	0.01	0.023	−1.647				19
	5526	4837.851	20664.561	0.002	0.004	−2.349				52
	4585	4627.075	21605.875	0.11	0.255	−0.593	−1.178	−1.27		14
	4420	4592.098	21770.439	0.002	0.006	−2.241				43
	1749	4090.132	24442.187	0.35	0.655	−0.184	−0.377	−0.78		13
	289	3859.571	25902.269	0.51	0.856	−0.067	−0.105	−0.62	−0.204	12

Intensities of strong lines to low energy levels can be affected by self absorption. In order to check for this effect spectra were recorded at different currents through the HC, and the intensity ratio between two lines coming from the same upper level was plotted as a function of the current. A linear fit was applied, and the extrapolated intensity ratio at zero current was adopted. The study of self absorption effects was performed in two ways. Firstly, we ran the HC with high currents and high density of uranium ions to force the strong lines to be self absorbed, and the intensities were corrected as described above. Secondly we removed the uranium piece from the cathode leaving only the layers of sputtered uranium deposited on the cathode walls. This gives a plasma having a low density of uranium ions. By plotting intensity ratios as a function of discharge current we get a constant value and hence no indication of self absorption. A comparison of the results of the two different sets of runs gave a difference of <10% for the strong lines, which is within the experimental uncertainties.

In the recorded spectrum it was possible to measure all lines from a given level having a $BF > 0.004$, but some lines may occur outside the observed wavelength interval. This residual intensity can in some cases be estimated from calculations, but in the case of U II there are no calculations available probably due to the complex atomic structure. In the wavelength interval 2020 to 24 600 Å it was possible to check for "missing" lines in the atlas by Steinhaus et al. (1971). The spectra in this atlas were recorded on photographic plates which are more sensitive and therefore include weaker lines. The atlas contains

Table 1. continued.

Upper level	Lower level	$\lambda_{\rm air}$ (Å)	σ (cm^{-1})	BF	gf	log gf This work	K[a]	C[b]	C&B[c]	Unc. (% in gf)
28154.450	8755	5153.520	19398.810	0.002	0.009	−2.053				41
$\tau = 12.4$ ns	8510	5089.302	19643.584	0.003	0.012	−1.917				46
$J = 5.5$	8379	5055.543	19774.754	0.01	0.029	−1.533				17
	7166	4763.336	20987.820	0.004	0.012	−1.937				41
	6283	4570.979	21871.019	0.03	0.082	−1.084		−1.68		9
	4585	4241.664	23569.016	0.30	0.789	−0.103	−0.431	−0.83		8
	4420	4212.253	23733.580	0.06	0.154	−0.811	−1.294	−1.42		9
	2294	3865.917	25859.754	0.18	0.380	−0.421	−0.273	−0.77		9
	914	3670.069	27239.685	0.33	0.642	−0.192	−0.173	−0.72		7
	0	3550.822	28154.450	0.09	0.164	−0.785	−0.584	−1.01		9
30341.675	12629	5644.217	17712.325	0.01	0.040	−1.400				26
$\tau = 24.0$ ns	9626	4825.914	20715.562	0.02	0.041	−1.391				9
$J = 7.5$	8521	4581.717	21819.753	0.05	0.098	−1.010				9
	8394	4555.087	21947.313	0.11	0.224	−0.650	−1.167	−1.34		9
	8276	4530.802	22064.942	0.01	0.014	−1.854				41
	6283	4155.404	24058.244	0.14	0.248	−0.606	−0.759	−1.10		9
	5526	4028.691	24814.927	0.004	0.006	−2.241				51
	5259	3985.789	25082.023	0.33	0.528	−0.278	−0.165	−0.71		8
	4585	3881.451	25756.241	0.21	0.310	−0.509	−0.279	−0.80		9
	1749	3496.411	28592.552	0.12	0.151	−0.821	−0.691	−1.12		9

[a] Value from the Kurucz (1993).
[b] Value measured by Corliss (1976).
[c] Value measured by Chen & Borzileri (1981).

no lines outside the wavelength interval and from the energy levels studied in the present investigation. However, we found some extra lines in the interval covered in our recordings. Since these lines do not appear in our spectra, they should have a $BF < 0.004$. These facts imply that the residual is small and has no significant impact on the BF value of the strongest lines.

The wavenumbers and line identifications are taken from the analysis of Palmer et al. (1980) and Steinhaus et al. (1971).

3. Oscillator strengths

The oscillator strength (f) of a line can be derived from the relation,

$$f = 1.4992 \times 10^{-16} \frac{g_i}{g_k} \lambda^2 A_{ik}, \quad (1)$$

where g_i and g_k are the statistical weights for the upper and lower level, respectively, λ is the wavelength of the transition in Å and A_{ik} the transition probability in s^{-1}. The transition probability of the line can be derived from the observed BF and lifetime (τ),

$$A_{ik} = \frac{(BF)_{ik}}{\tau_i}. \quad (2)$$

The experimental lifetimes used to derive the f-values were measured by Lundberg et al. (2001) with the laser induced fluorescence technique. In Table 1 the measured BFs, gf and log gf-values are reported. For comparison, Table 1 also include values from the Kurucz database (Kurucz 1993) (K) based on estimates from line intensities measured by Meggers et al. (1961), the values reported by Corliss (1976) (C), and the values reported by Chen & Borzileri (1981) (C&B). The uncertainties given in Table 1 are calculated using the method suggested by Sikström et al. (2001), which includes the uncertainty in the intensity measurements and intensity calibration, the uncertainty introduced by the combination of different spectral regions, the uncertainty in the self absorption correction and the uncertainty in the lifetimes.

4. Conclusion

The method of Cayrel et al. (2001) to use uranium for radioactive dating of a star provides a spectacular illustration of atomic astrophysics. An accurate value of the oscillator strength for a specific line λ 3859.6 of ionized uranium, U II, is needed to derive the present uranium abundance in the star CS 31082–001. The decay rate of uranium and the change in abundance define together a time scale for the evolution of the star.

We present in this paper the results of branching fraction measurements of 57 U II lines, including the line λ 3859.6. By combining these BFs with previously measured lifetimes by Lundberg et al (2001) we can derive oscillator strengths for the lines. The atomic structure of U II is very complex with five valence electrons in three open shells, which makes theoretical calculations of the atomic structure and the line strengths very difficult. It is, therefore, natural that most of the experimental energy levels have not been assigned and no calculated gf-values have been published.

The uncertainties in the f-values have contributions from various sources and vary substantially in size. In general, strong lines have the smallest uncertainty. (However, they are in general the lines, which are most sensitive to self absorption.) The experimental method used has for other complex spectra, e.g. Fe II (Sikström et al. 1999; Nilsson et al. 2000), given consistent results. The agreement with theoretical data are typically within the error bars. The difference between measurements in Fe II and U II is that all energy levels and all transitions of relevance are known in Fe II. In the case of Fe II, it has been posssible to estimate the contributions from unobserved lines in the BF measurements, "the residual", to a high degree of accuracy. This is not the case for U II, but there is no indication, experimental or theoretical, of a residual that would add an extra uncertainty in the gf-value of the cosmochronometer line, λ 3859.6. It is one of the strongest lines in the spectrum, but we find no signs of self absorption that would affect the BF outside the error bar.

The oscillator strength obtained for λ 3859.6 is $gf = 0.86 \pm 0.10$ (log $gf = -0.067 \pm 0.05$), which is 36% higher than the value of 0.62 (log $gf = -0.204$) given by Chen & Borzileri (1981).

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