Experimental atomic transition probabilities for O II lines

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We have measured the atomic transition probabilities of 80 spectral lines belonging to $3s$-$3p$, $3p$-$3d$, and $3p$-$4s$ multiplets of O II using a wall-stabilized arc. We applied recent lifetime results obtained for several $3p\ ^4D$ levels to normalize our relative data to an absolute scale, and we estimate that the uncertainties of our data are in the range from 8% to 9%. The agreement of our multiplet values with recent advanced calculations is typically in the range from 5% to 15%. For many lines of the $3p$-$3d$ multiplets, the agreement of our experimental data with intermediate coupling calculations is much better than with LS-coupling data. [S1050-2947(96)08609-X]

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I. INTRODUCTION

Two advanced atomic structure calculations were recently carried out for the spectrum of O II. A very comprehensive calculation for this spectrum, which used the R-matrix approach in conjunction with the close-coupling approximation, was performed by Lennon and Burke [1] as part of the Opacity Project [2]. These calculations were limited to multiplet data. While the extension to individual line values is readily achieved by applying LS-coupling strengths [3], the assumption of LS coupling may not be fully satisfactory for O II, an open-shell ion. Another sophisticated calculation, applied to a smaller number of lines, was carried out by Bell *et al.* [4] with the CIV 3 configuration interaction code. In this work, the strengths of numerous individual lines involving principal quantum numbers $n=2$ and $n=3$ were calculated. Bell *et al.* [4] obtained the data for these fine-structure transitions in intermediate coupling by including relativistic corrections of the Breit-Pauli type.

Numerous differences—some fairly large—are encountered between the results of these two calculations, most likely due to electron correlation effects not fully accounted for and departures from LS coupling. Since neither calculation provides intrinsic error estimates, it becomes important to provide accurate experimental comparison data with detailed consideration of the uncertainties. In this paper, we report the first photoelectric measurements for prominent near uv and visible emission lines of O II.

In an earlier emission experiment for the isoelectronic nitrogen atom [5], we have observed appreciable deviations from LS coupling for $3p$-$3d$ and higher transitions. However, in practically all cases these deviations were not nearly as large as those calculated by Hibbert and colleagues [6] in their intermediate coupling calculations with the CIV 3 code, which contain extensive configuration interaction. It is of interest to determine if this is also true for the lowest ion of the nitrogen sequence, singly ionized oxygen, which is important for numerous applications in plasma and upper atmosphere physics, astrophysics, and spectrochemistry. Between neutral nitrogen and singly ionized oxygen some significant rearrangements of the locations of various energy levels for these isoelectronic spectra occur. For example, for O II the $2s2p^4$ term is located much closer to the ground level than for N I and thus much farther away from any other levels that form the same term. On the other hand, the strongly interacting $3d\ ^4P$ and the $4s\ ^4P$ terms as well as the corresponding doublet terms still are located quite close to each other as in neutral nitrogen. They are therefore expected to lead to substantial configuration mixing and deviations from the normal LS coupling line intensities.

II. EXPERIMENT

Since we have applied an experimental technique very similar to our nitrogen work [5], we will describe our method only briefly. The O II spectrum was studied with a high current wall-stabilized arc discharge, which had a length of 50 mm and was operated in a stack of seven water-cooled disks with a central bore of 4 mm. The electrodes consisted of water-cooled tungsten for the cathode and copper for the anode. The areas close to the electrodes were operated in pure argon gas, and the midsection was run in helium with a small admixture of oxygen. The admixture of oxygen to helium was kept in the range of 0.5% to 2% by volume. This was readily achieved by a suitable arrangement of gas inlets and continuous gas mixing with flow valves. The arc was operated in a current range from 50 to 60 A. The operation of the arc in almost pure helium in the observation region has the important advantage that the electron density is kept relatively low so that the O II lines are narrow. Their relative intensities in multiplets were measured side-on, while measurements of line intensity ratios between selected lines of different multiplets were carried out end-on for reasons that will be explained later.

The arc was imaged with slight magnification onto the entrance slit of a 2.25-m Czerny-Turner monochromator. Self-absorption checks were performed experimentally with an optical imaging setup that effectively doubled the length of the arc [7]. Ratios between signals from the arc without or with its image reflected by a concave mirror were obtained across the spectral range of the lines and it was checked if this ratio remained constant from the line wings to the line

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center—the case of an optically thin plasma layer—or if the ratio decreased at the line center, indicating self-absorption. We found that optically thin conditions were obtained for all measured lines at these low concentrations of oxygen in helium. We also monitored the stability of the arc emission by utilizing a small 0.25-m monochromator, which was kept fixed at a particular O II line during the measurements. Fluctuations of the total line intensity during the measurements were found to be less than $\pm 1\%$.

All measurements of the intensity ratios between selected lines from different multiplets were performed end-on. The O II line emission was observed from an approximately homogeneous plasma layer in the midsection of the arc which was about 20 mm long. The homogeneity of this plasma layer is essential to obtain a uniform temperature, and thus to interrelate the populations of various atomic energy levels, from which the transitions originate. This is done via the Boltzmann population factors by utilizing the diagnostic technique described below.

III. METHOD AND PLASMA DIAGNOSTICS

We measured the line intensities for 80 persistent O II lines in the visible and near ultraviolet part of the spectrum. Measurements for each group of lines forming the various multiplets were carried out with side-on observations where an inhomogeneous plasma layer is viewed. For our medium density plasma, the inhomogeneity is of no consequence for lines within multiplets since the excitation energies of the upper levels E are either identical or very nearly the same. Measurements connecting selected strong lines of different multiplets (denoted X) to a reference line (R) with a significantly different excitation energy were performed in an end-on geometry. Using the $3s\ ^4P_{5/2}$–$3p\ ^4D^o_{7/2}$ line at 4649.13 Å as the reference line, we determined the line intensity ratios I_X/I_R. These ratios are, for the approximately homogeneous plasma layer along the arc axis, related to the atomic transition probability ratios A_X/A_R by the equation (see, e.g., Ref. [5])

$$\frac{I_X}{I_R}=\frac{A_X\lambda_R g_X}{A_R\lambda_X g_R}\exp\left[\frac{E_R-E_X}{kT}\right].$$

Here λ is the wavelength of the line, g the statistical weight, E the excitation energy of the upper level of the transition, and T is the plasma (excitation) temperature.

For Eq. (1) to be valid the plasma must be in partial local thermodynamic equilibrium (PLTE). PLTE is assured for the upper levels of the investigated O II transition (principal quantum numbers $n=3,4$) for our plasma conditions both from equilibrium criteria [8] and from experimental tests of PLTE conditions [9]. The critical quantity is the electron density, which must be 2×10^{14} cm^{-3} or higher. Our measurements of the intensity ratio between the forbidden and allowed components of the 4471-Å helium line as well as of the wavelength difference between the two components yielded electron densities of 1.5×10^{15} and 2×10^{15} cm^{-3}, considerably above the required limit.

We have measured the plasma excitation temperature with the Boltzmann-plot technique [10], using 7 N II lines with an excitation energy spread of 2.7 eV. The required A values for these N II lines were taken from the recent CIV 3 calculations of Bell *et al.* [11] and produced an axis temperature of 14 500$\pm$300 K.

IV. RESULTS AND COMPARISONS

We have measured the oscillator strengths for 80 lines of various $3s$-$3p$, $3p$-$3d$, and $3p$-$4s$ multiplets of O II. We first determined the relative values within each multiplet, setting the total value equal to 100 in each case. We then measured a strong line from each multiplet versus the 4649.13 Å reference line to obtain ratios of transition probabilities according to Eq. (1). Setting the A value of the reference line at unity, an arbitrary scale was established, which was subsequently extended to all measured lines with the earlier obtained relative values in multiplets.

Lifetime measurements by Coetzer *et al.* [12] for the $3p\ ^4D_{1/2,3/2,5/2,7/2}$ levels were then used to put our data on an absolute scale. In addition to the measured $3s\ ^4P-3p\ ^4D$ transitions, weak transitions occur from the $3p\ ^4D$ levels to the $2s2p^4\ ^4P$ levels. Since we were unable to observe these vacuum ultraviolet transitions at 1150 Å, we have taken them into account by utilizing the results of the CIV 3 and Opacity Project calculations. According to this work, they contribute about 7% to the total decay rate. The Coetzer *et al.* data were obtained by the beam foil spectroscopy method, which may be subject to significant systematic errors due to the nonselective nature of their excitation process, which gives rise to cascading effects. Coetzer *et al.* therefore treated the cascading problem with the well-proven ANDC (arbitrarily normalized decay curve) technique. This method requires the measurement of the temporal decay of all principal feeder levels [13]. However, they used this procedure in a simplified manner by considering only two major cascade levels. A third important level, $3d\ ^4P$, was not included because it was found to be very short lived, which led Coetzer *et al.* to the conclusion that the influence of this level may be neglected. They also state that their measured $3p\ ^4D^o_j$ lifetimes could be influenced by secondary cascades from several other higher levels, but their spectral analysis showed that these may be neglected too.

Table I lists all our results on this absolute, lifetime-based scale. The uncertainties of our data, i.e., the square root of the sum of the squares of the individual standard uncertainty components, are estimated to be $\pm 8\%$ for the $3s$-$3p$ transitions and $\pm 9\%$ for the $3p$-$3d$ and $3p$-$4s$ transitions. The individual uncertainty components arise from the line intensity measurements, the line-shape fitting procedure, possible self-absorption effects, the temperature determination, the assumption of a homogeneous plasma, the radiometric calibration procedure, and the lifetime data of Coetzer *et al.* [12] (further details of our analysis of uncertainties are given in Ref. [5]). Table I also contains for comparison the results of the two advanced calculations, the configuration interaction calculations in intermediate coupling by Bell *et al.* [4], based on the CIV 3 code, and the R-matrix calculations by Lennon and Burke [1]. The latter are for multiplet values only, and have been combined with LS-coupling line strengths so that line data can be shown. Our lifetime-normalized multiplet data agree normally with the calculated results within about 15%, and the agreement is somewhat better with the CIV 3

TABLE I. Results and comparisons. The experimental uncertainties (see text) are within ±8% for the lines of the $3s$-$3p$ multiplets and within ±9% for the other lines. Multiplet values are shown in italics. For some multiplets, data for one line are missing because of blending with another line or because of a very low signal. Numbers in brackets indicate powers of 10.

Multiplet	Wavelength (Å)	Statistical weight		This expt.	Bell *et al.*	Opacity (with *LS* coupling)
		g_i	g_k			
$3s\ ^4P-3p\ ^4D^o$	*4651.5*	*12*	*20*	*7.29[−01]*	*8.48[−01]*	*8.32[−01]*
	4649.13	6	8	7.18[−01]	8.49[−01]	8.33[−01]
	4641.81	4	6	5.43[−01]	6.26[−01]	5.86[−01]
	4638.86	2	4	3.40[−01]	3.82[−01]	3.49[−01]
	4676.23	6	6	1.87[−01]	2.22[−01]	2.46[−01]
	4661.63	4	4	3.76[−01]	4.32[−01]	4.41[−01]
	4650.84	2	2	6.21[−01]	7.20[−01]	6.94[−01]
	4696.35	6	4	2.99[−02]	3.31[−02]	4.04[−02]
	4673.73	4	2	1.22[−01]	1.27[−01]	1.37[−01]
$3s\ ^4P-3p\ ^4P^o$	*4341.3*	*12*	*12*	*8.68[−01]*	*9.76[−01]*	*9.71[−01]*
	4349.43	6	6	6.35[−01]	7.15[−01]	6.76[−01]
	4336.86	4	4	1.44[−01]	1.62[−01]	1.30[−01]
	4325.76	2	2	1.35[−01]	1.49[−01]	1.64[−01]
	4366.89	6	4	3.66[−01]	4.19[−01]	4.30[−01]
	4345.56	4	2	7.64[−01]	8.26[−01]	8.07[−01]
	4319.63	4	6	2.34[−01]	2.62[−01]	2.96[−01]
	4317.14	2	4	3.40[−01]	3.95[−01]	4.12[−01]
$3s\ ^4P-3p\ ^4S^o$	*3735.9*	*12*	*4*	*1.65[+00]*	*1.82[+00]*	*1.77[+00]*
	3749.48	6	4	8.56[−01]	9.37[−01]	8.74[−01]
	3727.32	4	4	5.34[−01]	5.95[−01]	5.93[−01]
	3712.74	2	4	2.61[−01]	2.88[−01]	3.00[−01]
$3s\ ^2P-3p\ ^2D^o$	*4418.1*	*6*	*10*	*7.73[−01]*	*9.25[−01]*	*9.50[−01]*
	4414.90	4	6	7.67[−01]	9.26[−01]	9.52[−01]
	4416.97	2	4	6.55[−01]	7.77[−01]	7.93[−01]
	4452.38	4	4	1.26[−01]	1.47[−01]	1.55[−01]
$3s\ ^2P-3p\ ^2P^o$	*3966.9*	*6*	*6*		*1.29[+00]*	*1.33[+00]*
	3973.26	4	4	9.56[−01]	1.08[+00]	1.10[+00]
	3954.36	2	2		8.57[−01]	8.94[−01]
	3982.71	4	2	3.93[−01]	4.38[−01]	4.37[−01]
	3945.04	2	4	1.88[−01]	2.14[−01]	2.25[−01]
$3p\ ^2S^o-3d\ ^2P$	*3385.8*	*2*	*6*	*1.14[+00]*	*1.50[+00]*	*1.24[+00]*
	3390.21	2	4	1.12[+00]	1.50[+00]	1.24[+00]
	3377.15	2	2	1.17[+00]	1.48[+00]	1.25[+00]
$3p\ ^4D^o-3d\ ^4F$	*4074.8*	*20*	*28*	*1.96[+00]*	*2.01[+00]*	*1.99[+00]*
	4075.86	8	10	1.94[+00]	2.01[+00]	1.99[+00]
	4072.15	6	8	1.82[+00]	1.77[+00]	1.71[+00]
	4069.88	4	6	1.41[+00]	1.55[+00]	1.50[+00]
	4069.62	2	4	1.40[+00]	1.45[+00]	1.40[+00]
	4092.93	8	8	2.44[−01]	2.46[−01]	2.80[−01]
	4085.11	6	6	4.18[−01]	4.45[−01]	4.82[−01]
	4078.84	4	4	5.07[−01]	5.35[−01]	5.57[−01]
	4106.02	8	6	1.56[−02]	1.46[−02]	1.88[−02]
	4094.14	6	4	4.32[−02]	3.37[−02]	3.93[−02]

TABLE I. *(Continued).*

Multiplet	Wavelength (Å)	Statistical weight g_i	g_k	This expt.	Bell *et al.*	Opacity (with *LS* coupling)
$3p\ ^4D^o-3d\ ^4D$	*3867.2*	*20*	*20*	*4.35[−01]*	*4.88[−01]*	*5.77[−01]*
	3882.19	8	8	5.06[−01]	5.14[−01]	4.89[−01]
	3864.43	6	6	1.98[−01]	2.13[−01]	3.31[−01]
	3851.0-3	4	4	1.46[−01]	1.58[−01]	2.34[−01]
	3847.89	2	2	1.79[−01]	1.95[−01]	2.93[−01]
	3883.14	8	6	1.04[−01]	1.10[−01]	1.0[−01]
	3864.67	6	4	1.65[−01]	2.18[−01]	2.02[−01]
	3856.13	4	2	2.10[−01]	2.80[−01]	2.91[−01]
	3863.50	6	8	5.97[−02]	6.01[−02]	8.24[−02]
	3850.80	4	6	5.50[−03]	6.26[−02]	1.36[−01]
	3842.81	2	4	6.85[−02]	9.42[−02]	1.47[−01]
$3p\ ^4P^o-3d\ ^4P$	*4151.7*	*12*	*12*		*9.63[−01]*	*9.92[−01]*
	4169.22	6	6	2.49[−01]	3.00[−01]	6.86[−01]
	4140.70	4	4	3.76[−01]	1.36[−01]	1.33[−01]
	4121.46	2	2		5.60[−01]	1.69[−01]
	4156.534	6	4	1.94[−01]	2.39[−01]	4.45[−01]
	4129.32	4	2	1.65[−01]	3.98[−01]	8.40[−01]
	4153.30	4	6	7.27[−01]	6.64[−01]	2.97[−01]
	4132.80	2	4	8.39[−01]	7.37[−01]	4.19[−01]
$3p\ ^4P^o-3d\ ^4D$	*4114.4*	*12*	*20*		*1.33*	*1.53[−01]*
	4119.22	6	8	1.22[+00]	1.40[+00]	1.52[+00]
	4104.72	4	6	2.89[−01]	4.74[−01]	1.07[+00]
	40o97.22	2	4	3.33[−01]	2.74[−01]	6.42[−01]
	4120.28	6	6	1.98[−01]	6.25[−01]	4.55[−01]
	4104.99	4	4	8.40[−01]	9.35[−01]	8.17[−01]
	4103.00	2	2	4.68[−01]	8.63[−01]	1.28[−01]
	4120.55	6	4		2.60[−01]	7.58[−01]
	4110.79	4	2	7.08[−01]	6.,03[−01]	2.54[−01]
$3p\ ^4P^o-4s\ ^4P$						
	3287.47	6	6	4.92[−01]		4.77[−01]
	3294.99	4	4	1.00[−01]		9.03[−02]
	3301.41	2	2	1.06[−01]		1.12[−01]
	3305.00	6	4	2.89[−01]		3.02[−01]
	3306.45	4	2	5.55[−01]		5.58[−01]
	3277.56	4	6	2.02[−01]		2.06[−01]
$3p\ ^2D^o-3d\ ^2F$	*4703.9*	*10*	*14*		*1.14+00*	*1.40[+00]*
	4705.35	6	8	1.01[+00]	1.24[+00]	1.40[+00]
	4699.22	4	6		9.36[−01]	1.32[+00]
	4741.70	6	6	4.33[−02]	5.80[−02]	9.14[−02]
$3p\ ^2D^o-4s\ ^2P$						
	3470.67	6	4	8.63[−01]		1.16[+00]
	3470.28	4	2	1.09[+00]		1.29[+00]
$3p\ ^4S^o-3d\ ^4P$	*4913.0*	*4*	*12*		*5.48[−01]*	*6.26[−01]*
	4924.53	4	6		5.43[−01]	6.22[−01]
	4906.83	4	4	4.17[−01]	5.40[−01]	6.29[−01]
	4890.86	4	2	4.41[−01]	5.79[−01]	6.35[−01]

TABLE I. *(Continued).*

Multiplet	Wavelength (Å)	Statistical weight g_i	g_k	This expt.	Bell *et al.*	Opacity (with LS coupling)
$3p\ ^4S^o-4s\ ^4P$	*3753.5*	*4*	*12*	*2.89[−01]*		*4.10[−01]*
	3739.76	4	6	2.97[−01]		4.15[−01]
	3762.47	4	4	3.10[−01]		4.07[−01]
	3777.42	4	2	2.25[−01]		4.02[−01]
$3p\ ^2P^o-3d\ ^2P$	*5191.0*	*6*	*6*	*4.43[−01]*	*4.64[−01]*	*6.53[−01]*
	5206.65	4	4	3.29[−01]	3.38[−01]	5.40[−01]
	5159.94	2	2	3.02[−01]	3.22[−01]	4.44[−01]
	5175.90	4	2	1.37[−01]	1.56[−01]	2.20[−01]
	5190.50	2	4	1.16[−01]	1.20[−01]	1.09[−01]
$3p\ ^2P^o-3d\ ^2P$	*4943.2*	*6*	*10*	*7.12[−01]*	*8.62[−01]*	*9.78[−01]*
	4943.01	4	6	7.15[−01]	8.61[−01]	9.78[−01]
	4941.07	2	4	5.40[−01]	6.67[−01]	8.16[−01]
	4955.71	4	4	1.67[−01]	1.96[−01]	1.62[−01]

than with the R-matrix data [4]. Also, compared to the theoretical results, our lifetime-based data appear to be systematically too low by about 10%. We should note that the omission of any significant cascading transitions from the ANDC procedure (see above) makes the ''apparent'' primary lifetime too long, because some electrons replenishing the population of the primary level are not considered. It is thus reasonable to assume that a more comprehensive ANDC procedure covering the additional levels mentioned by Coetzer *et al.* [12] would produce a slightly shorter lifetime and correspondingly higher A values.

Generally, the consistency between our experimental results for the individual lines and the intermediate coupling data of Bell *et al.* [4] is significantly better than with the LS-coupling line strengths. Our measurements show especially for the $3p$-$3d$ multiplets large departures from the LS-coupling values.

Multiplets with the $3d\ ^4P$ or ^2P and $4s\ ^4P$ or ^2P upper terms, which are energetically quite close to each other, are expected to be especially sensitive to configuration interaction effects. But, the ratios between our experiment and the two theories appear to vary no more widely for these multiplets than for the others.

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