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OSCILLATOR STRENGTHS OF NEUTRAL AND SINGLY IONISED MOLYBDENUM

S. E. SCHNEHAGE, K. DANZMANN†, R. KÜNNEMEYER, and M. KOCK
Institut für Plasmaphysik, Universität Hannover, Callinstr. 38, 3000 Hannover, West Germany

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Abstract—Oscillator strengths of 174 Mo(I) and 58 Mo(II) lines in the range 2470–5570 Å were obtained from wall-stabilised arc and hollow cathode measurements. Sets of relative *f*-values were determined by a combination of hook and emission measurements requiring no assumptions concerning the plasma state. The sets have been enlarged considerably by evaluating spectra recorded with a Fourier spectrometer. The relative Mo(I) *f*-values were converted to an absolute scale by means of radiative lifetimes measured by P. Zimmermann and his group. The overall uncertainties are within 10–35%. Since lifetimes of Mo(II) levels are not yet available, only relative Mo(II) *f*-values are presented.

1. INTRODUCTION

In astrophysics and for fusion research, reliable oscillator strengths are needed, especially for the heavy elements. A method frequently used to obtain large sets of *f*-values for lines of different excitation potentials is that based upon emission spectroscopy on suitable plasma light sources such as cascaded arcs.[1] A more promising method, which reduces the number of assumptions required, is the combination of hook and emission measurements.[2–6] Thus, large sets of relative *f*-values can be determined without any assumptions concerning the plasma state. The absolute calibration of the relative data is preferably done by means of radiative lifetimes.

The objective of the present investigation was the determination of reliable oscillator strengths of neutral and singly ionised molybdenum.

2. EXPERIMENTAL PROCEDURE

The hook measurements were performed with a three chamber cascaded arc, which consisted of a stack of brass plates, each 10 mm thick with a central bore of 16 mm. The plates were electrically insulated from one another by 1 mm thick Pertinax sheets. The plates were cooled axially by forced water cooling. The arc length was 120 mm between a ring anode and two tapered cathodes, all made of tungsten. The arc was operated in argon at atmospheric pressure and at a current of 40 A supplied by a d.c. generator (460 V/120 A).

For the excitation of molybdenum in the arc, we used an admixture of molybdenum pentachloride ($MoCl_5$: b.p. 268°C). The vapor was generated in a small ceramic oven attached to the arc chamber.

The set-up for our hook experiment was similar to that described in an earlier paper.[3] It consisted of the cascaded arc, a high-power capillary discharge as a continuum light source, a Michelson interferometer with quartz optics, and a stigmatic spectrograph. The spectrograph was a 3.4 m Ebert configuration with a plane grating of 1200 lines mm^{-1} producing a reciprocal linear dispersion of 2.4 Å mm^{-1} in the first order. The spectra were photographed on Ilford FP 4 film. They were evaluated by means of a computer. Only hooks with a separation of at least 300 mÅ were evaluated.[7]

The emission measurements were performed with hollow cathodes. We have used commercially available hollow cathodes (Perkin–Elmer, No. 029287) which we have operated at a current of 30 mA. A problem in using this type of hollow cathode is the examination of the optical depth of the plasma layer from which the lines under investigation are emitted. Therefore, we have again used our high current hollow cathode.[6]

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†Present address: Stanford University, Department of Physics, Stanford, CA 94305, U.S.A.

The cathode has a length of 100 mm and a central bore of 8.5 mm. The discharge was operated either in argon or in neon at a current of 2 A.

The spectra were recorded photoelectrically by using a photon counting system and a 1-m McPherson monochromator with a plane grating of 2400 lines mm^{-1} having a resolution of about 55 mÅ. The line intensities were calibrated with a carbon arc as a radiation standard.[8,9] For the u.v. region below 3300 Å, we used a low-current argon arc designed and calibrated by PTB[10] in Berlin.

The present program was complemented by measurements with the 1-m Fourier transform spectrometer at the Kitt Peak National Observatory, Tucson, Arizona. Experimental details such as the calibration of the spectra are described elsewhere.[11] For molybdenum, we obtained one spectrum in the range 3000–5100 Å.

All emission lines were tested and shown to be free of self-absorption. For the Perkin–Elmer hollow cathode, we measured relative intensities of lines with the same upper level but of different strengths at various discharge currents. The constancy of the intensity ratio then was a check that the lines were emitted from an optically thin layer.

Since the lines emitted from our hollow cathode are Doppler-broadened, we have measured the widths of the lines by means of a highly resolving Fabry–Perot interferometer and estimated the maximum optical thickness by the following relationship:

$$\tau_{\max} \leq 0.94 J / \Delta\lambda_D B,$$

where J is the integrated line intensity, B the Kirchhoff–Planck function and $\Delta\lambda_D$ the FWHM of the line under investigation. Since only lines with $\tau_{\max} < 0.1$ have been evaluated, no corrections were necessary for an optically thin layer.

3. RESULTS AND DISCUSSION

For the 174 Mo(I) lines investigated, we have obtained three independent sets of relative f-values from a combination of hook measurements for lines of common lower levels, with emission measurements for lines originating from common upper levels. In the same manner, we obtained one set of relative f-values for the 58 Mo(II) lines.

For an absolute calibration of the Mo(I) sets, we used lifetimes which have been measured by P. Zimmermann[12] and his group (see Table 1). The lifetime of the $z\,^7P_4^0$ level has been published by these authors[13] together with additional Mo(I) lifetimes belonging to the septet system. We have calculated absolute f-values from the first three lifetimes of Table 1 and our measured branching ratios. The final data comprising 174 Mo(I) lines are listed in Table 2.

The accuracy of the f-values was estimated to be within 10–35% because of errors in the emission and hook measurements (the standard deviation of the mean was evaluated from up to seven independent measurements) and the uncertainty of the lifetime.

The completeness of the branching ratios has been checked by means of the Fourier spectrum. For the level $y\,^5F_1^0$, only the lines at 6812 and 6787 Å could not be measured. We have taken into account this contribution (1%) by using the calculated f-values given by Kurucz and Peytreman.[14]

Table 1. Mo(I) lifetimes measured by P. Zimmermann and his group.[12,13] The uncertainty is 5–7%.

Level	Energy (cm^{-1})	Lifetime (ns)
$z\,^7P_4^0$	26 320.38	[illegible]
$z\,^5P_2^0$	28 836.[illegible]	[illegible]
$y\,^5F_1^0$	41 011.74	[illegible]
$y\,^5F_2^0$	41 032.[illegible]	[illegible]

Table 2. Absolute oscillator strengths of Mo(I) lines: (*), determined from a Fourier spectrum; (′), wavelength corrected.

Wavelength (Å)	Transition	E_m (cm^{-1})	lg(gf)	Error (%)
2471.95	$a^5S_2 - w^5P^0_3$	51 209.92	- 0.10	25
2505.08	$a^5D_1 - v^5P^0_2$	51 049.60	- 1.20	22
2514.62	$a^5D_2 - w^5P^0_3$	51 209.92	- 0.87	25
2524.80	$a^5D_2 - v^5P^0_2$	51 049.60	- 0.48	12
2540.44	$a^5D_3 - w^5P^0_3$	51 209.92	- 0.31	19
2548.23	$a^5S_2 - v^5P^0_3$	49 999.49	- 0.21	31
2550.84	$a^5D_3 - v^5P^0_2$	51 049.60	- 0.48	22
2567.05	$a^5S_2 - w^5P^0_2$	49.711.86	- 0.31	16
2572.33	$a^5D_4 - w^5P^0_3$	51 209.92	+ 0.29	24
2582.15	$a^5S_2 - w^5P^0_1$	49 484.14	- 0.39	10
2583.22	$a^5S_2 - t^5F^0_3$	49 468.05	- 1.89	16
2591.97	$a^5D_1 - w^5P^0_2$	49 711.86	- 0.83	12
2593.59	$a^5D_2 - v^5P^0_3$	49 999.49	- 0.45	33
2595.40	$a^5D_0 - w^5P^0_1$	49 484.14	- 0.74	11
2607.37	$a^5D_1 - w^5P^0_1$	49 484.14	- 0.37	10
2611.21	$a^5D_4 - w^3G^0_5$	50 631.35	- 0.26	21
2613.09	$a^5D_2 - w^5P^0_2$	49 711.86	- 0.18	13
2615.39	$a^5D_0 - t^5F^0_1$	49 189.71	- 0.67	10
2616.78	$a^5D_1 - t^5F^0_2$	49 346.30	- 0.38	14
2621.07	$a^5D_3 - v^5P^0_3$	49 999.49	- 0.41	31
2627.55	$a^5D_1 - t^5F^0_1$	49 189.71	- 0.55	21
2628.74	$a^5D_2 - w^5P^0_1$	49 484.14	- 0.37	14
2635.56	$a^5D_3 - u^3F^0_3$	49 789.83	- 0.87	16
2638.30	$a^5D_2 - t^5F^0_2$	49 346.30	- 0.30	14
2640.99	$a^5D_3 - w^5P^0_2$	49 711.86	+ 0.05	16
2649.46	$a^5D_3 - t^5F^0_4$	49 590.83	+ 0.24	14
2655.03	$a^5D_4 - v^5P^0_3$	49 999.49	+ 0.30	21
2658.11	$a^5D_3 - t^5F^0_3$	49 468.05	- 0.12	19
2666.74	$a^5D_3 - t^5F^0_2$	49 346.30	- 1.37	13
2670.32	$a^5S_2 - v^3D^0_3$	48 205.95	- 0.92	23
2679.86	$a^5D_4 - t^5F^0_5$	49 650.58	+ 0.55	21
2681.02	$a^5D_3 - x^5G^0_4$	49 146.69	- 0.85	27
2697.80	$a^5D_0 - u^5F^0_1$	48 022.23	- 0.94	11
2701.03	$a^5D_3 - v^5D^0_4$	48 870.44	- 0.62	12
2701.09	$a^5S_2 - v^3D^0_1$	47 779.41	- 0.77	12
2706.11	$a^5D_1 - v^3D^0_2$	48 085.26	- 0.95	22
2710.74	$a^5D_1 - u^5F^0_1$	48 022.23	- 1.14	13
2720.17	$a^5D_2 - v^3D^0_3$	48 205.95	- 0.86	10
2725.15	$a^5D_1 - u^5F^0_2$	47 827.22	- 0.82	15
2733.39	$a^5D_2 - u^5F^0_3$	48 028.22	+ 0.43	66
2733.84	$a^5D_2 - u^5F^0_1$	48 022.23	- 0.33	17
2751.47	$a^5D_3 - u^5F^0_4$	48 192.05	- 0.31	23

Table 2. (*Contd*)

Wavelength (Å)	Transition	E_m (cm^{-1})	lg(gf)	Error (%)
2761.53	$a^5D_4 - u^5F_5^0$	48 547.44	- 0.25	21
2779.47	$a^5D_1 - w^3D_2^0$	47 110.24	- 1.02	26
2787.83	$a^5D_4 - v^3D_3^0$	48 205.95	- 0.27	21
2788.91	$a^5D_4 - u^5F_4^0$	48.192.05	- 0.76	21
2797.93	$a^5D_2 - w^3D_3^0$	47 184.58	- 0.50	22
2801.46	$a^5S_2 - v^5F_3^0$	46 453.42	- 0.73	11
2817.50	$a^5D_0 - v^5F_1^0$	46 447.97	- 1.10	15
2905.41	$a^5G_2 - v^5P_2^0$	51 049.60	+ 0.16	20
3038.36	$a^5G_4 - t^5F_5^0$	49 650.68	- 1.20	25
3047.32	$a^5G_5 - t^5F_4^0$	49 590.83	+ 0.14	18
3050.21*	$a^5G_3 - t^5F_3^0$	49 468.05	- 1.99	25
3055.32*	$a^5G_4 - t^5F_3^0$	49 468.05	- 0.16	24
3056.73	$a^5G_2 - t^5F_2^0$	49 346.30	- 1.49	17
3061.59*'	$a^5G_3 - t^5F_2^0$	49 346.30	- 0.53	15
3064.28	$a^5G_6 - x^5G_6^0$	49 408.54	+ 0.51	27
3070.90	$a^5G_4 - x^5G_5^0$	49 301.98	- 0.06	27
3074.37*'	$a^5G_5 - x^5G_5^0$	49 301.98	+ 0.60	18
3080.40*'	$a^5G_3 - x^5G_4^0$	49 146.69	- 0.11	27
3085.62	$a^5G_4 - x^5G_4^0$	49 146.69	+ 0.48	27
3089.14*	$a^5G_5 - x^5G_4^0$	49 146.69	- 0.50	27
3101.34	$a^5G_2 - x^5G_2^0$	48 875.84	+ 0.68	28
3112.12	$a^7S_3 - z^7D_4^0$	32 123.16	- 1.07	10
3132.59	$a^7S_3 - y^7P_4^0$	31 913.24	+ 0.34	9
3147.36	$a^5G_6 - u^5F_5^0$	48 547.44	- 0.08	23
3158.16	$a^7S_3 - z^7D_3^0$	31 654.80	- 0.33	12
3170.34	$a^7S_3 - y^7P_3^0$	31 533.27	+ 0.11	12
3176.80	$a^5S_2 - w^5D_2^0$	42 237.41	- 1.81	19
3183.04*'	$a^5G_5 - u^5F_4^0$	48 192.05	- 0.69	16
3183.26	$a^5G_5 - y^3H_5^0$	48 189.22	- 0.06	22
3187.69*	$a^5P_3 - z^5F_4^0$	49 590.83	- 0.53	19
3193.97	$a^7S_3 - y^7P_2^0$	31 299.95	+ 0.05	13
3200.22*	$a^5P_3 - t^5F_3^0$	49 468.05	- 1.04	25
3205.21	$a^5D_0 - w^5D_1^0$	42 156.14	- 0.45	20
3205.89	$a^5D_4 - x^5F_4^0$	43 529.85	+ 0.15	25
3208.83	$a^7S_3 - z^7D_2^0$	31 155.04	- 0.64	11
3215.07*'	$a^5D_1 - w^5D_2^0$	42 237.41	- 0.34	13
3228.21	$a^5D_2 - w^5D_3^0$	42 422.40	- 0.31	18
3229.80	$a^5D_4 - x^5F_5^0$	43 299.08	- 0.24	21
3233.21	$a^5G_5 - y^5G_6^0$	47 704.68	+ 0.32	20
3247.61	$a^5D_2 - w^5D_2^0$	42 237.41	- 0.72	16
3270.90*'	$a^5D_3 - w^5D_3^0$	42 422.40	- 0.34	19
3289.01	$a^5D_4 - w^5D_4^0$	42 741.82	+ 0.09	35

Table 2. (*Contd*)

Wavelength (Å)	Transition	E_m (cm^{-1})	lg(gf)	Error (%)
3290.82*'	$a^5D_3 - w^5D^{\circ}_2$	42 237.41	- 0.23	14
3303.35*'	$a^5S_2 - y^5F^{\circ}_2$	41 032.01	- 1.62	22
3305.56*'	$a^5S_2 - y^5F^{\circ}_1$	41 011.74	- 1.09	5
3325.67	$a^5S_2 - x^5D^{\circ}_2$	40 828.85	- 0.97	10
3327.31*'	$a^5D_0 - y^5F^{\circ}_1$	41 011.74	- 0.86	14
3336.51*	$a^5P_3 - u^5F^{\circ}_4$	48 192.05	- 1.62	17
3340.15	$a^5S_2 - x^5D^{\circ}_1$	40 698.46	- 1.29	10
3344.73*'	$a^5D_1 - y^5F^{\circ}_2$	41 032.01	- 0.25	21
3347.00*	$a^5D_1 - y^5F^{\circ}_1$	41 011.74	- 0.87	24
3358.12	$a^5D_2 - y^5F^{\circ}_3$	41 224.41	+ 0.03	12
3362.36	$a^5D_0 - x^5D^{\circ}_1$	40 698.46	- 1.18	17
3363.77	$a^5S_2 - x^5D^{\circ}_3$	40 488.35	- 0.56	14
3379.97*	$a^5D_2 - y^5F^{\circ}_2$	41 032.01	- 0.39	20
3382.29*	$a^5D_2 - y^5F^{\circ}_1$	41 011.74	- 1.61	21
3382.48	$a^5D_1 - x^5D^{\circ}_1$	40 498.46	- 0.78	28
3384.61	$a^5D_3 - y^5F^{\circ}_4$	41 395.54	+ 0.12	22
3389.69*	$b^5D_4 - t^5F^{\circ}_5$	49 650.68	- 1.62	23
3397.68	$a^5D_1 - z^3D^{\circ}_2$	40.566.27	- 1.47	15
3404.34	$a^5D_3 - y^5F^{\circ}_3$	41 224.41	- 0.46	16
3425.20*	$b^5D_2 - t^5F^{\circ}_3$	49 468.05	- 0.79	25
3426.79*	$a^5D_3 - y^5F^{\circ}_2$	41 032.01	- 1.28	23
3433.38*	$b^5D_3 - t^5F^{\circ}_3$	49 468.05	- 1.05	25
3434.78	$a^5D_3 - z^3D^{\circ}_3$	40 964.11	- 0.45	19
3439.56*'	$b^5D_2 - t^5F^{\circ}_2$	49 346.30	- 1.19	16
3447.12	$a^5D_4 - y^5F^{\circ}_5$	41 347.71	+ 0.50	20
3456.39	$a^7S_3 - z^5P^{\circ}_3$	28 923.66	- 1.57	16
3490.26*	$a^3G_3 - t^5F^{\circ}_4$	49 590.83	- 0.53	18
3521.42*	$b^5D_4 - u^5F^{\circ}_5$	48 547.44	+ 0.42	24
3566.06*	$b^5D_4 - u^5F^{\circ}_4$	48 192.05	- 0.73	17
3581.88	$a^5G_5 - y^5H^{\circ}_6$	44 694.93	+ 0.16	19
3590.74*'	$b^5D_3 - u^5F^{\circ}_4$	48 192.05	- 0.81	17
3614.31	$a^5G_5 - y^5H^{\circ}_5$	44 444.51	+ 0.40	55
3624.45	$a^5G_4 - z^5I^{\circ}_5$	44 330.23	+ 0.22	27
3697.43*'	$a^3G_4 - u^5F^{\circ}_4$	48 192.05	- 1.77	17
3723.50*'	$a^3G_5 - u^5F^{\circ}_4$	48 192.05	- 1.36	17
3798.26	$a^7S_3 - z^7P^{\circ}_4$	26 320.38	+ 0.12	8
3825.32*	$a^3F_4 - t^5F^{\circ}_5$	49 650.68	- 0.62	22
3826.69	$a^5D_2 - z^5D^{\circ}_2$	37 579.23	- 0.85	20
3854.91*	$a^3F_2 - t^5F^{\circ}_3$	49 468.05	- 1.26	25
3856.52*'	$a^3F_3 - t^5F^{\circ}_4$	49 590.83	- 0.79	19
3864.11	$a^7S_3 - z^7P^{\circ}_3$	25 871.86	+ 0.01	11
3885.51*'	$a^5G_3 - w^5D^{\circ}_3$	42 422.41	- 1.75	18

Table 2. (*Contd*)

Wavelength (Å)	Transition	E_m (cm^{-1})	lg(gf)	Error (%)
3902.96	$a^7S_3 - z^7P_2^0$	25 614.31	− 0.13	11
3912.12*'	$a^3H_4 - t^5F_5^0$	49 650.68	− 1.12	22
3966.23*	$a^3H_4 - x^5G_5^0$	49 301.98	− 0.49	19
4025.23*	$a^3H_5 - x^5G_5^0$	49 301.98	− 1.51	19
4069.89	$a^5G_6 - y^5F_5^0$	41 347.71	+ 0.08	49
4084.37	$a^5G_4 - y^5F_3^0$	41 224.41	− 0.15	28
4098.74*'	$a^5G_2 - y^5F_2^0$	41 032.01	− 1.26	23
4102.15*'	$a^5G_2 - y^5F_1^0$	41 011.74	− 0.94	10
4107.47*	$a^5G_3 - y^5F_2^0$	41 032.01	− 0.41	23
4131.92*'	$c^5D_4 - t^5F_5^0$	49 650.68	− 0.07	22
4142.15*	$c^5D_4 - t^5F_4^0$	49 590.83	− 0.79	23
4164.08*'	$a^5P_3 - w^5D_2^0$	42 237.41	− 1.75	16
4186.28*'	$a^5P_2 - w^5D_2^0$	42 237.41	− 1.43	16
4232.58	$a^5G_4 - z^5H_5^0$	40 367.34	+ 0.15	27
4244.81*'	$c^5D_2 - t^5F_2^0$	49 346.30	− 1.67	16
4249.50*'	$c^5D_1 - t^5F_2^0$	49 346.30	− 1.87	16
4329.34*'	$c^5D_4 - u^5F_5^0$	48 547.44	− 0.94	24
4334.83*	$a^5F_1 - t^5F_2^0$	49 346.30	− 0.001	18
4354.69*'	$a^5F_3 - x^5G_4^0$	49 146.69	− 1.15	27
4384.20*	$a^5P_3 - y^5F_2^0$	41 032.01	− 1.94	23
4412.77*'	$a^5P_2 - y^5F_1^0$	41 011.74	− 1.17	10
4415.36*	$a^5F_5 - u^5F_5^0$	48 547.44	− 1.04	24
4432.88*	$a^5P_1 - y^5F_2^0$	41 032.01	− 2.17	23
4433.34*'	$a^5F_4 - u^5F_5^0$	48 547.44	− 1.65	24
4434.94	$a^5G_4 - z^5G_4^0$	39 289.63	+ 0.27	35
4436.87*	$a^5P_1 - y^5F_1^0$	41 011.74	− 1.32	12
4468.08*'	$b^3F_2 - t^5F_3^0$	49 468.05	− 0.32	25
4490.19*	$b^5D_4 - w^5D_3^0$	42 422.40	− 1.09	20
4515.17*	$b^5D_2 - w^5D_3^0$	42 422.40	− 1.13	20
4522.19*'	$b^5D_1 - w^5D_2^0$	42 237.41	− 1.02	16
4529.40*'	$b^5D_3 - w^5D_3^0$	42 422.40	− 0.83	20
4547.53*'	$b^3D_1 - t^5F_2^0$	49 346.30	− 1.02	19
4553.22*'	$b^5D_2 - w^5D_2^0$	42 237.41	− 1.34	16
4567.68*'	$b^5D_3 - w^5D_2^0$	42 237.41	− 0.92	16
4696.51*'	$a^3D_2 - w^5D_2^0$	42 237.41	− 1.61	16
4700.49*'	$a^3G_4 - w^5D_3^0$	42 422.40	− 1.26	20
4751.11*'	$b^5D_0 - y^5F_1^0$	41 011.74	− 2.00	12
4787.63*'	$b^5D_1 - y^5F_1^0$	41 011.74	− 1.90	18
4817.70*	$b^5D_2 - y^5F_2^0$	41 032.01	− 1.32	23
4822.42*'	$b^5D_2 - y^5F_1^0$	41 011.74	− 1.71	18
4899.58*'	$a^3P_0 - y^5F_1^0$	41 011.74	− 1.82	18
4973.35*	$a^3D_1 - y^5F_2^0$	41 032.01	− 1.54	23

Table 2. (*Contd*)

Wavelength (Å)	Transition	E_m (cm^{-1})	lg(gf)	Error (%)
4977.69*'	$a^3G_3 - y^5F_2^0$	41 032.01	- 1.73	23
4983.45*'	$a^3D_2 - y^5F_1^0$	41 011.74	- 1.85	18
5114.61*	$a^3P_2 - w^5D_3^0$	42 422.40	- 2.45	20
5506.50	$a^5S_2 - z^5P_3^0$	28 923.66	+ 0.047	11
5533.03	$a^5S_2 - z^5P_2^0$	28 836.60	- 0.103	5
5570.43	$a^5S_2 - z^5P_1^0$	28 715.29	- 0.413	18

With the highly resolved Fourier spectrum, we were also able to correct wavelengths of molybdenum lines (indicated by a prime in Tables 2 and 3). The corrections are of the order ± 5 mÅ in relation to the wavelengths calculated from the energy values given by Moore.[15] We have checked our laboratory spectra for blends and misidentifications. Distorted lines have been rejected. Finally, we measured relative *f*-values from this spectrum. These transitions are marked by an asterisk in Tables 2 and 3.

Table 3. Relative oscillator strengths of Mo(II) lines: (*), determined from a Fourier spectrum; ('), wavelength corrected.

Wavelength (Å)	Transition	E_m (cm^{-1})	$\lg(gf)_{rel}$	Error (%)
2538.44	$a^6D_{9/2} - z^4F^0_{9/2}$	52 843.10	+ 0.09	11
2542.67	$a^6D_{7/2} - z^4F^0_{7/2}$	52 217.30	- 0.3	20
2542.79	$a^6D_{5/2} - z^4F^0_{5/2}$	51 732.39	- 0.61	32
2593.71	$a^6D_{3/2} - z^6D^0_{5/2}$	50 577.36	- 0.45	8
2602.80	$a^6D_{1/2} - z^6D^0_{3/2}$	50 192.00	- 0.56	6
2619.35	$a^6D_{1/2} - z^6D^0_{1/2}$	49 949.45	- 0.80	12
2636.67	$a^6D_{3/2} - z^6D^0_{1/2}$	49 949.45	- 0.3	16
2638.76	$a^6D_{5/2} - z^6D^0_{7/2}$	50 302.54	+ 0.15	11
2644.35	$a^6D_{7/2} - z^6D^0_{9/2}$	50 705.52	+ 0.18	14
2646.49	$a^6D_{5/2} - z^6D^0_{3/2}$	50 192.00	- 0.2	6
2653.35	$a^6D_{7/2} - z^6D^0_{5/2}$	50 577.36	- 0.07	9
2660.58	$a^6D_{3/2} - z^6P^0_{5/2}$	49 608.74	0	-
2672.84	$a^6D_{7/2} - z^6D^0_{7/2}$	50 302.54	+ 0.21	14
2683.23	$a^6D_{1/2} - z^6P^0_{3/2}$	49 040.82	- 0.05	8
2684.14	$a^6D_{9/2} - z^6D^0_{9/2}$	50 705.22	+ 0.41	10
2687.99	$a^6D_{5/2} - z^6P^0_{5/2}$	49 608.74	- 0.03	5
2701.41	$a^6D_{3/2} - z^6P^0_{3/2}$	49 040.82	- 0.15	7
2713.50	$a^6D_{9/2} - z^6D^0_{7/2}$	50 302.54	- 0.56	28
2729.68	$a^6D_{5/2} - z^6P^0_{3/2}$	49 040.82	- 0.59	18
2732.87	$a^6D_{7/2} - z^6P^0_{7/2}$	49 481.04	- 0.38	10
2775.39	$a^6D_{9/2} - z^6P^0_{7/2}$	49 481.04	+ 0.52	11
2784.98	$a^4D_{7/2} - z^4F^0_{9/2}$	52 843.10	+ 0.24	17
2807.75	$a^6D_{5/2} - z^4P^0_{3/2}$	48 022.45	- 0.29	14

Table 3. (*Contd*)

Wavelength (Å)	Transition	E_m (cm^{-1})	log gf_{rel}	Error (%)
2816.15	$a^6D_{9/2} - z^6F^0_{11/2}$	49 959.68	+ 0.73	14
2848.24	$a^6D_{7/2} - z^6F^0_{9/2}$	47 999.47	+ 0.51	18
2856.90	$a^4D_{5/2} - z^6D^0_{3/2}$	50 192.00	[illegible]	[illegible]
2871.31	$a^6D_{5/2} - z^6F^0_{7/2}$	47 231.98	[illegible]	14
2890.99	$a^6D_{3/2} - z^6F^0_{5/2}$	46 614.14	[illegible]	[illegible]
2894.45	$a^6D_{9/2} - z^6F^0_{9/2}$	47 999.47	[illegible]	12
2897.64	$a^4P_{5/2} - z^6D^0_{3/2}$	50 192.00	[illegible]	[illegible]
2909.11	$a^6D_{1/2} - z^6F^0_{3/2}$	46 148.12	[illegible]	[illegible]
2911.91	$a^6D_{7/2} - z^6F^0_{7/2}$	47 231.98	[illegible]	[illegible]
2923.39	$a^6D_{5/2} - z^6F^0_{5/2}$	46 614.14	[illegible]	16
2930.49	$a^6D_{3/2} - z^6F^0_{3/2}$	46 148.12	[illegible]	[illegible]
2934.30	$a^6D_{1/2} - z^6F^0_{1/2}$	45 853.08	[illegible]	8
2956.05	$a^6D_{3/2} - z^6F^0_{1/2}$	45 853.08	[illegible]	17
2960.23	$a^6D_{9/2} - z^6F^0_{7/2}$	47 231.98	[illegible]	14
2961.32*'	$a^4D_{7/2} - z^6D^0_{9/2}$	50 705.52	- 0.87	[illegible]
2963.80*'	$a^6D_{5/2} - z^6F^0_{3/2}$	46 148.12	[illegible]	5
2965.28	$a^6D_{7/2} - z^6F^0_{5/2}$	46 614.14	[illegible]	10
2972.62	$a^4D_{7/2} - z^6D^0_{5/2}$	50 577.36	[illegible]	11
2992.85*	$a^4D_{3/2} - z^6D^0_{5/2}$	50 577.36	- 1.21	[illegible]
2993.51	$a^4D_{1/2} - z^6D^0_{3/2}$	50 192.00	[illegible]	5
2997.10*'	$a^4D_{7/2} - z^6D^0_{7/2}$	50 302.54	- 2.18	[illegible]
2997.66*	$a^4P_{5/2} - z^6P^0_{3/2}$	49 040.82	- 1.38	12
3027.78	$a^4D_{3/2} - z^6D^0_{3/2}$	50 192.00	[illegible]	11
3033.23*'	$a^4D_{5/2} - z^6D^0_{7/2}$	50 302.54	[illegible]	16
3060.78	$a^4D_{7/2} - z^6P^0_{5/2}$	49 608.74	- 1.04	12
3098.47	$a^4D_{5/2} - z^6P^0_{5/2}$	49 608.74	- 1.16	16
3100.39	$a^4D_{1/2} - z^6P^0_{3/2}$	49 040.82	[illegible]	10
3169.58*	$a^4P_{5/2} - z^6F^0_{7/2}$	47 231.98	[illegible]	[illegible]
3871.89	$b^4D_{1/2} - z^6D^0_{3/2}$	50 192.00	- 1.61	11
3915.42	$b^4D_{3/2} - z^6D^0_{3/2}$	50 192.00	- 0.15	9
3925.83	$b^4D_{5/2} - z^6D^0_{5/2}$	50 577.36	- 1.13	9
3941.49*	$b^4D_{7/2} - z^6D^0_{9/2}$	50 705.52	- 1.61	20
3968.65*'	$b^4D_{5/2} - z^6D^0_{7/2}$	50 302.54	- 0.96	10
4119.63	$b^4D_{7/2} - z^6P^0_{5/2}$	49 608.74	- 1.05	8
4832.81*'	$b^4G_{7/2} - z^6D^0_{9/2}$	50 705.52	- 0.86	20

We used the fourth lifetime of Table 1 for an independent second absolute calibration of one of the three sets of relative f-values and compared that result with the first one. The consistency between both results is within 10%.

A comparison of our Mo(I) f-values with published data is shown in Fig. 1. Absolute data were published by Corliss and Bozman.[16] Their data were obtained from simplified emission measurements on free-burning arcs operated in air.

The method has been critically analysed by several authors[17,18] and was found to be prone to error. As can be seen from Fig. 1, the deviations from our data reach a factor of 100, especially for small *f*-values. In our opinion, the reason for the large discrepancies is the absence of LTE in their plasma light source together with an inadequate temperature determination. Also, the absolute scale seems too high by about 0.5 dex. Nevertheless, the comprehensive data published by Corliss and Bozman[16] are still a valuable aid for orientation when one tries to measure oscillator strengths.

Mishakov and Fogel[19] used a pulsed discharge in order to excite $MoCl_5$. They applied the hook technique to obtain relative *f*-values. We have linked their set to ours via the line 3170 Å. As may be seen in Fig. 1, the agreement is very good.

Dickerman and Deuel[20] have measured a few relative molybdenum *f*-values of which we have only two in common. We have not included these two data in our comparison.

Kwiatkowski *et al.*[13] have converted their measured Mo(I) lifetimes into absolute oscillator strengths under the assumption that the resonance transition is dominant. Their results agree very well with ours. The deviations are normally smaller than 10%. We found

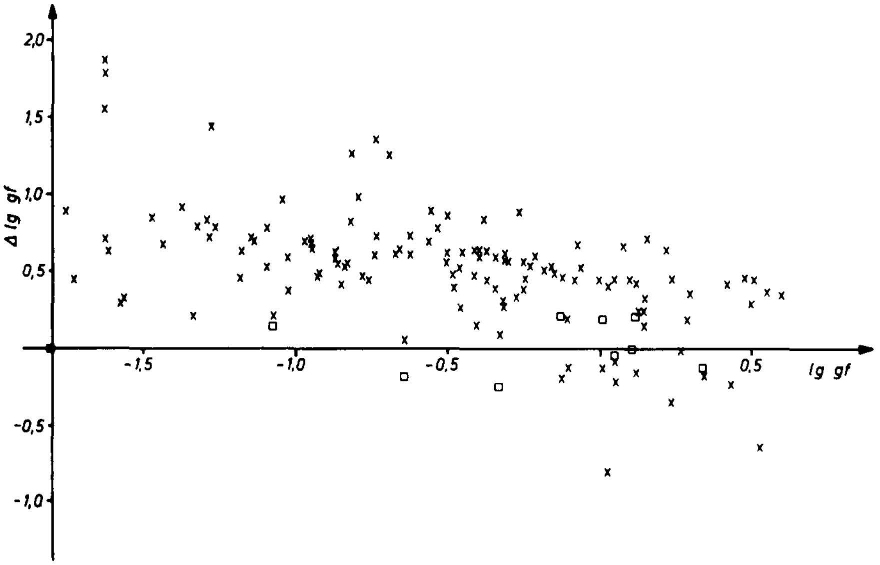

Fig. 1. Comparison of the present Mo(I) oscillator strengths with other results: ×, Corliss and Bozman;[16] □, Mishakov and Fogel.[19]

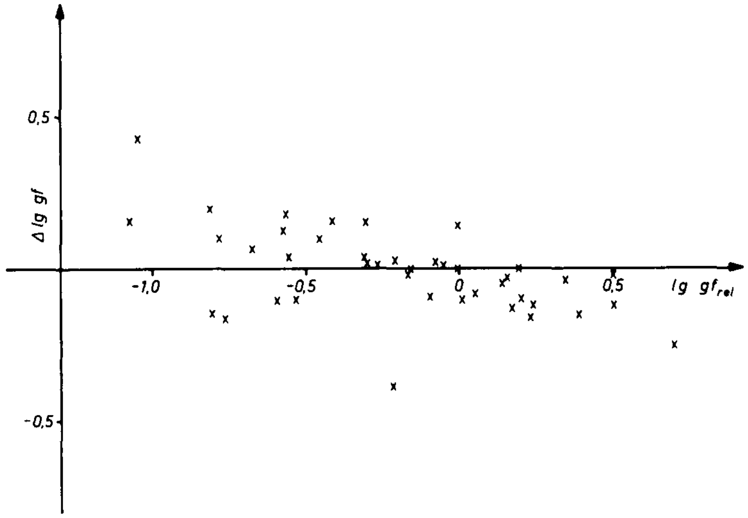

Fig. 2. Comparison of the present relative Mo(II) oscillator strengths with the results of Corliss and Bozman.[16]

deviations larger than 10% for only two lines. This result corroborates both the lifetime measurements as well as our data.

The 58 Mo(II) *f*-values are listed in Table 3. Because of missing lifetimes, the values are only on a relative scale. The quoted errors have been determined in the same way as for the Mo(I) data. For comparison, we only found the data published by Corliss and Bozman.[16] Both scales are linked together via the line 2660 Å. As can be seen from Fig. 2, the scatter is obviously smaller than for the Mo(I) data, but there is again increased deviation towards smaller *f*-values.

4. CONCLUSION

Molybdenum is a highly refractory metal with very complex spectra. We consider the absolute Mo(I) *f*-values to have satisfactory accuracy. Neither the assumption of LTE nor temperature measurements are required here. Comparisons with the few literature data show differences by factors of up to 100. For Mo(II), lifetimes are not yet available. Therefore only relative *f*-values are given.

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