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More Wavelengths From Thorium Lamps

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For the purpose of supplementing or superseding the spectroscopic secondary standards of wavelength derived since 1910 from an iron arc, Meggers and Stanley, in 1958, reported the first interferometric determinations of wavelengths emitted by a thorium lamp. Those determinations were restricted to 222 intense radiations of thorium with wavelengths ranging from 3288.7356 Å to 6991.5839 Å. Now the same, and additional, interference spectrograms have been measured to provide improved wavelengths for 510 radiations ranging in wavelength from 3269.6089 Å to 7020.504 Å. The present list includes many lines of lower intensity than those previously published and fills most of the large intervals in our first report. The accuracy in relative wavelength values of 163 classified thorium lines is tested by the combination principle which indicates that the average error is less than 1 part in 20 to 40 million. Similar measurements of wavelengths emitted by iron-halide lamps have errors that are 3 to 5 times greater.

1. Introduction

After forty years of intermittent effort to extend and improve the international standards of wavelengths used in spectroscopy, Meggers [1][1] suggested, in 1955, that secondary standards, superior in sharpness and distribution, could be obtained by replacing the standard iron arc with a modern thorium lamp as a light source. Such improvement was demonstrated by Meggers and Stanley [2] who first measured the wavelengths of 222 intense radiations emitted by a thorium-iodide lamp. Those wavelengths extended from 3288.7356 Å to 6991.5839 Å in vacuum; they were measured interferometrically relative to wavelengths emitted by a Meggers mercury 198 lamp. In the meantime, those measurements have found favor among all spectroscopists who specialize in making accurate descriptions of complex spectra, especially of chemical elements whose atoms are more massive than those of iron. Moreover, those spectroscopists have suggested that more wavelengths of thorium radiations be accurately measured to increase the range of intensity and decrease the average interval, thus removing handicaps on account of overexposure and/or expanded dispersion in modern photographic spectrograms. Consequently, the same, and additional, interference spectrograms have been measured to provide improved values of wavelengths for 510 thorium radiations (including 222 reported earlier) ranging in value from 3263.6089 Å to 7020.504 Å in vacuum. The purpose of this paper is to present a new list of thorium wavelengths including many lines of lower intensity than those previously published [2] and also to reduce the average interval between standards. Because of the increase in the number of carefully measured wavelengths, the combination principle is applied as an internal test of the accuracy in relative value of a considerable fraction of them.

2. Experiments

In our first paper [2], full details concerning light sources, interferometers, spectrograph, measurements, and computations were given for the first determinations of thorium wavelengths from Fabry-Perot etalons. Briefly, the thorium radiations were emitted by a small electrodeless lamp containing a few milligrams of thorium iodide and several torr of helium. The wavelengths of selected thorium lines were measured relative to adopted standards emitted by a similar lamp containing 1 mg of mercury-198 and 3 torr of argon. Both lamps were excited by magnetrons generating 2450 Mc/s. One lamp was imaged in the other and both simultaneously illuminated a Fabry-Perot etalon interferometer to avoid errors usually entailed by alternate exposures to different light sources.

The enclosed and evacuated Fabry-Perot interferometer consisted of two flat plates of crystalline quartz whose facing surfaces were coated with thin aluminum films and separated by invar etalons of 25, 40, or 50 mm length. The 25 and 40 mm spacers were relied upon to insure the correct integral order of interference for any given line, assuming that available values of the wavelength obtained from diffraction-grating spectrograms had no errors greater than ±0.02 Å.

The interference patterns (Haidinger fringes) were photographed with a concave grating of 22 feet radius in a (stigmatic) Wadsworth mounting. The spectral range 4400 Å to 7000 Å was photographed in the first-order spectrum with a slit width of 0.30 mm and plate factor of 5 Å/mm. Because

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[1] Figures in brackets indicate the literature references at the end of this paper.

of a greater density of thorium lines in the unltraviolet, the region from 3250 Å to 4500 Å was recorded in the second-order grating spectrum with a plate factor of 2.5 Å/mm and slit width of 0.15 mm. In each wavelength range, several spectrograms were made with different times of exposure, and with slightly different spacing of the interferometer plates to alter the interference configurations or fractional orders for all spectral lines. The green (5462.2705 Å) and violet (4047.7144 Å) lines of Hg^{198} were chosen as standards, respectively, for the long- and short-wave interference spectrograms described above. The wavelengths of Hg^{198} radiations used for the calibration of etalons were previously measured [3] relative to red radiation (6438.4696 Å) of cadmium, the primary standard of wavelength prior to 1960.

In our first report [2] ,the fractional order at the center of an interference pattern was determined from measurements of five interference fringes for each line and least-squares calculations according to the formula

$$\epsilon=\frac{2(3D_1+2D_2^2+D_3^2-D_5^2)}{-2D_1^2-D_2^2+D_4^2+2D_5^2},$$

first discussed by Rolt and Barrell [4]. After taking squares from a table, all computations were by mental arithmetic except the final quotient which was obtained from a desk calculator. About 12,000 interference fringes were thus used to derive the wavelengths of 222 intense radiations in thorium spectra, 172 from Th I and 50 from Th II.

The results reported in the present paper were obtained by Meggers from spectrograms made by Stanley in 1956 and described jointly in 1958 [2]. In addition, several spectrograms that were overexposed, and, therefore, unsuitable for measurement of the stronger lines, were salvaged by dissolving the dense background in solutions of sodium thiosulphate and potassium ferricyanide, thereby making them ideal for measurement of the weaker lines.

In this series of measurements, the diameters of six interference circles (Haidinger fringes) were determined from readings of the distances between twelve fringes for each line. In most cases, two readings were made on each fringe and the mean was recorded. Since the fringes on 510 thorium lines and several mercury 198 lines were measured on two to six spectrograms, the average being four, it appears that more than 40,000 readings were made. The recorded readings were transferred to IBM cards in a punch machine and transmitted to an electronic computer that calculated wavelengths after determining the fractional and integral orders of interference for each line in a given interferometer.

The fractional order, ϵ, at the center of an interference pattern was calculated from 6 diameters according to the formula:

$$\epsilon=\frac{5}{3}\left(\frac{11D_1^2+8D_2^2+5D_3^2+2D_4^2-D_5^2-4D_6^2}{-5D_1^2-3D_2^2-D_3^2+D_4^2+3D_5^2+5D_6^2}\right).$$

The final calculations of wavelength, λ, were made from the relation $\lambda=2t/(p+\epsilon)$, where t is the separation of the interferometer plates, p is the integral order, and ϵ the fractional order of interference at the center of a pattern. In this series of measurements, the wavelengths of 510 thorium radiations were determined relative to Hg^{198} wavelengths (5462.2706 Å, 4359.5625 Å, and 4047.7147 Å) which in turn were measured by Kaufman [5] in terms of the new primary standard of length, 6057.80211 Å, radiated by Kr^{86}.

3. Results

Our latest measurements of vacuum wavelengths for 510 radiations from thorium lamps are presented in table 1. The vacuum values in column 1 were converted to appropriate values in standard air, column 2, by using the Table of Wavenumbers of Coleman, Bozman, and Meggers [6]. The estimated relative intensities, column 3, and assignment to spectrum, Th I or Th II, are quoted from a *New Description of Thorium Spectra* by Zalubas [7]. Table 1 contains data for 510 radiations, 395 from Th I and 115 from Th II. Wavelength values given to 8 figures have estimated errors less than 0.0005 Å, 34 given to 7 figures are included to suggest that they are suitable for further refinement.

Although the Kr^{86} wavelength (6057.80211 Å in vacuum) was derived from the Cd wavelength (6438.46960 Å, in air), the wavelengths of identical Hg^{198} lamps (3 torr Ar) measured relative to the former are slightly greater (0.0001 to 0.0003 Å) than those derived from the latter. Consequently, the wavelengths of 222 thorium radiations reported in our first paper [2] have now increased by 0.0001 Å on the average. We are unable to explain the source of this small discrepancy. Fortunately for spectroscopic use as standards, the absolute values of thorium wavelengths are less important than their relative values for calibrating spectrograms.

Because the number of independent determinations of each thorium wavelength is, in general, too small to yield a true probable error, we have extensively applied the combination principle as a rigid test of the accuracy of measured wavelengths in relative value. Two radiations resulting from combinations of a highly excited atomic (or ionic) level with two low-energy levels will exhibit in their wavenumbers the energy difference of the low levels. Any other high levels that combine with the same low levels will exhibit the same difference within the accuracy of measurement. In table 2, we present typical examples of 21 low-energy differences, 20 involving wavenumber differences between designated low-energy levels for Th I [8], and 1 for Th II [9]. The total number of line pairs in table 2 is 111 but, since some radiations participate two or three times in pairing with others, only 163 different lines are involved. However, these are randomly distributed throughout the list and comprise nearly 63 percent of the classified Th I wavelengths given to 8 figures.

We may expect, therefore, that the remainder will satisfy these tests when other wavelengths are measured and the present partial analyses of these spectra are greatly extended.

The critical test of our thorium wavelengths is shown in the last two columns of table 2, where recurring wavenumber differences and their deviations from the mean are listed.

The deviations of the measured level separations from the mean range from 0 to ± 4 m K (milli-Kayser $= 10^{-3}$ cm^{-1}). The average deviation of all tested pairs of lines is ± 0.0012 K, and if we assume the errors are shared equally by all lines, the individual average error is 0.0006 K, or one part in 20 to 40 million, depending on the spectral region. These tests indicate that our thorium wavelengths qualify as Class A standards defined as having accuracy of 0.001 K according to a suggestion by Littlefield [10]. Calculated probable errors, as well as atomic energy intervals, for similar measurements of wavelengths from iron-halide lamps [11] indicate that the relative values are uncertain by 1 part in 7 or 8 million.

Recently, additional measurements of thorium wavelengths have been reported by Littlefield and Wood [12], by Davison, Giacchetti, and Stanley [13], and by Giacchetti, Gellarado, Garavaglia, Gonzalez, Valero, and Zakowicz [14]. The first [12] used a hollow-cathode light source and reflection-echelon interferometer to measure the wavelengths of 484 thorium radiations ranging from 2566.3615 Å to 9050.7361 Å; the results have been reported in the Transactions of the I A U but no further experimental details have been published. The others, [13, 14], used electrodeless thorium lamps and Fabry-Perot interferometers similar to ours. Davison et al. [13] published the wavelengths of 68 radiations ranging from 2651.3722 Å to 3394.9671 Å, and Giacchetti et al. [14] gave 129 values from 2687.9304 Å to 4596.7088 Å. Unfortunately, none of the above-mentioned observers tested their results by means of the combination principle; there are many serious discrepancies between values reported by two or more observers and it will be important to seek the source of the larger differences.

The senior author gladly and gratefully acknowledges the assistance of Mrs. John B. Peterson who transferred written readings to punched cards, and thanks Victor Kaufman for presenting these data to an electronic computer that produced wavelengths by using a code previously prepared by Karl G. Kessler.

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TABLE 1. *Wavelengths of thorium lines*

λvac	λair	Relative intensity	Spectrum
Å	Å		
3263.6089	3262.6682	3000	II
3272.9913	3272.0482	800	I
3274.8374	3273.8938	600	II
3276.011	3275.067	400	II
3286.6984	3285.7518	900	I
3288.7358	3287.7887	1600	II
3292.6868	3291.7387	3000	II
3293.4688	3292.5205	3000	II
3302.207	3301.256	600	II
3305.1895	3304.2382	3000	I
3310.3178	3309.3652	800	I
3314.022	3313.068	400	I
3321.4317	3320.4763	400	I
3325.7088	3324.7523	2000	II
3326.0767	3325.1201	3000	II
3331.4345	3330.4765	1800	I
3334.0872	3333.1285	1000	I
3338.8297	3337.8698	2000	II
3349.7310	3348.768	3000	I
3352.1912	3351.2279	2500	II
3359.5667	3358.6015	2000	II
3368.7860	3367.8185	1200	II
3375.9440	3374.9747	1600	I
3379.5433	3378.5730	400	II
3381.8300	3380.8592	900	I
3386.5031	3385.5311	800	II
3393.0082	3392.0345	6000	II
3397.7023	3396.7274	1400	I
3399.5201	3398.5447	1600	I
3406.5348	3405.5576	1400	I
3413.9919	3413.0128	1800	I
3422.1909	3421.2097	2500	I
3424.9714	3423.9895	1600	I
3434.9827	3433.9983	3000	II
3438.2923	3437.3070	2500	I
3443.5653	3442.5787	800	I
3452.6909	3451.7019	900	I
3458.0588	3457.0685	800	I
3463.8419	3462.8501	2000	II
3469.2125	3468.2193	2000	II
3480.1683	3479.1723	800	II
3487.5248	3486.5269	3500	II
3494.5176	3493.5179	2000	II
3499.6217	3498.6207	900	I
3504.7880	3503.7857	500	I
3512.1610	3511.1568	1000	I
3519.4096	3518.4035	1000	I
3522.0660	3521.0592	500	I
3531.5236	3530.5144	500	II
3532.4595	3531.4501	1000	I
3540.3335	3539.3220	800	II
3540.5985	3539.5870	4000	II
3545.0303	3544.0176	1500	I
3550.6096	3549.5955	1200	I
3552.4160	3551.4014	1000	I
3556.0284	3555.0129	1500	I
3560.4658	3559.4491	2500	II
3564.3930	3563.3753	800	I
3568.2824	3567.2637	1200	I
3573.4119	3572.3919	1000	II

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TABLE 1. *Wavelengths of thorium lines*—Continued

λvac	λair	Relative intensity	Spectrum
Å	Å		
3577.5785	3576.5574	1000	I
3585.1986	3584.1756	800	I
3592.4771	3591.4522	1000	I
3593.8042	3592.7790	2000	I
3599.1464	3598.1198	2000	I
3605.711	3604.683	800	I
3606.222	3605.194	500	I
3609.4067	3608.3774	1200	I
3613.4576	3612.4273	1400	I
3616.1634	3615.1324	2000	II
3623.8281	3622.7951	800	I
3626.6612	3625.6275	500	II
3633.8656	3632.8300	1000	I
3636.9796	3635.9432	1900	I
3643.2867	3642.2487	2200	I
3650.7746	3649.7346	1200	I
3657.7354	3656.6936	1000	I
3662.6653	3661.6223	500	II
3669.1843	3668.1396	1000	I
3671.0138	3669.9686	750	I
3672.5853	3671.5397	700	I
3676.6136	3675.5670	1000	II
3683.5345	3682.4861	1000	I
3691.6742	3690.6237	1000	I
3693.6172	3692.5662	1200	I
3699.1584	3698.1059	1300	I
3702.0314	3700.9782	300	I
3707.8219	3706.7672	2400	I
3712.3597	3711.3038	600	II
3720.4927	3719.4347	3000	I
3728.9626	3727.9024	800	I
3734.0467	3732.9852	500	I
3734.7340	3733.6723	500	I
3742.2464	3741.1828	3000	II
3743.9873	3742.9232	1100	I
3748.6040	3747.5387	900	II
3753.6352	3752.5686	3500	II
3758.7620	3757.6941	1000	I
3764.0030	3762.9337	1200	I
3771.1268	3770.0557	1300	I
3772.4419	3771.3704	1500	I
3777.3435	3776.2708	600	I
3782.0398	3780.9659	350	I
3786.6751	3785.5999	1000	II
3790.2449	3789.1688	1500	I
3796.4632	3795.3855	500	II
3804.1547	3803.0750	4000	I
3808.9554	3807.8745	1200	II
3814.1499	3813.0676	1200	II
3819.7690	3818.6853	500	I
3829.4708	3828.3845	3200	I
3831.8604	3830.7735	800	I
3838.9638	3837.8751	2000	I
3840.7835	3839.6943	2500	I
3843.0499	3841.9601	1200	II
3853.2278	3852.1354	600	I
3855.6037	3854.5106	1200	II
3860.9341	3859.8396	500	II
3864.5011	3863.4057	1200	II
3870.7604	3869.6634	600	I

TABLE 1. *Wavelengths of thorium lines*—Continued

λvac	λair	Relative intensity	Spectrum
Å	Å		
3875.9602	3874.8618	1800	I
3876.4723	3875.3738	500	I
3880.7435	3879.6439	1000	I
3885.9251	3884.8241	400	II
3896.5229	3895.4192	400	I
3904.2082	3903.1025	1500	I
3905.169	3904.063	1000	II
3906.2923	3905.1860	1500	II
3913.0171	3911.9091	600	I
3917.5266	3916.4174	500	I
3920.1336	3919.0239	800	I
3924.9106	3923.7995	400	I
3926.2046	3925.0932	1000	I
3930.7818	3929.6692	2500	II
3934.0244	3932.9109	1400	I
3938.1548	3937.0402	400	II
3944.5112	3943.3950	400	II
3950.0814	3948.9637	1000	II
3953.8796	3952.7609	500	I
3960.4204	3959.3000	1000	I
3968.5146	3967.3921	2000	I
3973.2783	3972.1546	1400	I
3974.3200	3973.1960	1100	I
3981.2151	3980.0893	1100	I
3988.3509	3987.2232	600	I
3991.6206	3990.4921	800	I
3995.6788	3994.5492	1200	I
4002.1893	4001.0580	800	I
4003.0253	4001.8938	150	I
4009.3433	4008.2102	1600	I
4010.190	4009.057	1600	I
4013.6295	4012.4952	2000	I
4019.2344	4018.0987	400	I
4020.2649	4019.1289	1200	II
4028.1470	4027.0089	1000	I
4031.4314	4030.2925	200	I
4031.9815	4030.8424	1800	I
4037.1879	4036.0475	1800	I
4037.7056	4036.5650	400	II
4044.5369	4043.3946	800	I
4052.0315	4050.8872	800	I
4054.6727	4053.5277	1000	I
4060.3994	4059.2529	1000	I
4064.5547	4063.4071	800	II
4065.4793	4064.3315	400	I
4068.5994	4067.4508	400	I
4070.3508	4069.2017	750	II
4070.6098	4069.4606	400	I
4073.7787	4072.6287	400	I
4076.6536	4075.5029	400	I
4082.5200	4081.3677	800	I
4087.6742	4086.5206	1600	II
4089.8815	4088.7273	400	I
4090.2920	4089.1377	400	I
4995.9029	4094.7471	1600	II
4098.9042	4097.7476	800	I
4101.4985	4100.3413	1100	I
4109.5792	4108.4198	800	II
4110.4832	4109.3236	400	I
4113.9150	4112.7545	700	I

TABLE 1. *Wavelengths of thorium lines*—Continued

λvac	λair	Relative intensity	Spectrum
Å	Å		
4116. 9203	4115. 7590	800	I
4117. 8754	4116. 7139	600	II
4128. 5761	4127. 4118	1000	I
4132. 1675	4131. 0022	800	I
4133. 9192	4132. 7535	600	II
4141. 4028	4140. 2351	400	II
4151. 1570	4149. 9868	800	II
4159. 7076	4158. 5351	800	I
4166. 9406	4165. 7662	1000	I
4171. 7090	4170. 5334	500	I
4179. 2377	4178. 0601	3000	II
4185. 3170	4184. 1378	500	I
4194. 1984	4193. 0169	900	I
4196. 1178	4194. 9358	350	I
4203. 0308	4201. 8469	500	II
4210. 0764	4208. 8907	3000	I
4211. 9511	4210. 7649	400	I
4212. 1096	4210. 9234	200	I
4214. 2542	4213. 0674	400	I
4216. 0158	4214. 8285	200	I
4221. 253	4220. 064	750	I
4228. 5780	4227. 3874	400	I
4231. 6184	4230. 4271	600	I
4236. 6565	4235. 4638	600	I
4249. 1853	4247. 9893	400	II
4251. 511	4250. 314	1200	I
4254. 7362	4253. 5388	800	I
4258. 6948	4257. 4963	700	I
4259. 719	4258. 520	500	I
4261. 5322	4260. 3327	800	I
4271. 1445	4269. 9428	200	I
4274. 5603	4273. 3577	1000	II
4278. 5178	4277. 3141	1200	II
4283. 2464	4282. 0415	2000	II
4293. 0177	4291. 8102	400	I
4298. 5155	4297. 3066	400	I
4301. 0492	4299. 8396	600	I
4308. 3879	4307. 1764	700	I
4316. 4680	4315. 2543	400	I
4319. 6302	4318. 4157	700	I
4321. 3414	4320. 1265	300	II
4330. 1329	4328. 9156	400	I
4332. 0619	4330. 8441	300	I
4338. 4971	4337. 2777	900	I
4343. 4765	4342. 2557	300	II
4345. 5479	4344. 3266	300	II
4347. 6587	4346. 4368	500	I
4350. 2950	4349. 0724	400	I
4354. 6724	4353. 4487	500	I
4360. 5972	4359. 3719	600	I
4367. 1575	4365. 9305	600	I
4371. 1038	4369. 8758	200	I
4375. 3536	4374. 1244	600	I
4379. 4071	4378. 1769	500	I
4383. 0917	4381. 8605	900	I
4392. 3443	4391. 1107	3000	II
4394. 2084	4392. 9743	400	I
4402. 8178	4401. 5814	400	I
4404. 1639	4402. 9272	400	I
4410. 1211	4408. 8828	600	I

TABLE 1. *Wavelengths of thorium lines*—Continued

λvac	λair	Relative intensity	Spectrum
Å	Å		
4415. 7260	4414. 4862	400	I
4423. 2900	4422. 0482	350	I
4434. 2077	4432. 9640	600	II
4440. 370	4439. 124	400	II
4442. 114	4440. 867	400	II
4446. 5562	4445. 3083	300	I
4447. 1495	4445. 9014	200	I
4453. 8148	4452. 5650	200	I
4459. 2531	4458. 0018	600	I
4462. 4933	4461. 2412	600	I
4466. 5940	4465. 3408	300	II
4470. 7800	4469. 5257	400	I
4483. 4270	4482. 1694	300	I
4488. 1563	4486. 8974	200	I
4494. 5943	4493. 3337	1200	I
4500. 2022	4498. 9401	800	I
4501. 2459	4499. 9836	500	I
4506. 4799	4505. 2162	400	I
4511. 7910	4510. 5259	800	II
4516. 3845	4515. 1182	300	I
4522. 489	4521. 221	500	I
4531. 5895	4530. 3192	160	I
4536. 5265	4535. 2549	300	I
4542. 2720	4540. 9988	300	I
4547. 1900	4545. 9155	350	I
4557. 0903	4555. 8132	500	I
4562. 6266	4561. 3481	500	I
4572. 2528	4570. 9717	500	I
4589. 7124	4588. 4267	400	I
4593. 953	4592. 666	400	I
4596. 7082	4595. 4207	600	I
4604. 461	4603. 171	175	I
4622. 4565	4621. 1621	200	I
4633. 0585	4631. 7613	300	II
4641. 344	4640. 045	500	II
4652. 857	4651. 555	500	II
4664. 5080	4663. 2025	200	I
4669. 4785	4668. 1717	700	I
4671. 2916	4669. 9843	400	I
4674. 9693	4673. 6611	600	I
4687. 5060	4686. 1944	400	I
4696. 3520	4695. 0380	400	I
4705. 3063	4703. 9900	500	I
4713. 7713	4712. 4528	500	I
4719. 9363	4718. 6162	200	II
4730. 4507	4729. 1278	250	I
4741. 8552	4740. 5293	400	II
4753. 7432	4752. 4141	500	II
4762. 4415	4761. 1101	400	II
4767. 9332	4766. 6003	200	I
4779. 6300	4778. 2940	300	I
4790. 7256	4789. 3867	300	I
4809. 4775	4808. 1336	350	I
4810. 9583	4809. 6140	300	I
4824. 2027	4822. 8549	300	I
4828. 0490	4826. 7002	300	I
4832. 4710	4831. 1210	350	I
4842. 195	4840. 843	400	I
4849. 7168	4848. 3623	250	I
4859. 6895	4858. 3323	300	II

Table 1. *Wavelengths of thorium lines*—Continued

λvac	λair	Relative intensity	Spectrum
Å	Å		
4864. 5305	4863. 1720	1000	II
4866. 8363	4865. 4772	350	I
4880. 0955	4878. 7329	200	I
4896. 3218	4894. 9549	350	I
4908. 5795	4907. 2093	150	I
4921. 1892	4919. 8157	600	II
4929. 1564	4927. 7808	140	I
4941. 0208	4939. 6420	350	I
4946. 8387	4945. 4584	140	I
4967. 1169	4965. 7312	250	I
4981. 5757	4980. 1862	600	I
4986. 7636	4985. 3727	300	I
4990. 7005	4989. 3085	200	I
5003. 4924	5002. 0970	400	I
5018. 6541	5017. 2547	500	II
5030. 0586	5028. 6562	400	II
5040. 6359	5039. 2307	200	I
5046. 1263	5044. 7196	400	I
5051. 2040	5049. 7960	400	I
5061. 2716	5059. 8609	200	I
5069. 3870	5067. 9741	900	I
5086. 411	5084. 994	150	I
5097. 9046	5096. 4842	200	I
5102. 0426	5100. 6210	200	I
5116. 4702	5115. 0448	250	I
5127. 3781	5125. 9498	150	I
5129. 9184	5128. 4894	125	I
5136. 1764	5134. 7458	150	I
5145. 3493	5143. 9162	200	I
5153. 0472	5151. 6121	400	II
5155. 6791	5154. 2433	400	I
5160. 0414	5158. 6044	700	I
5164. 8968	5163. 4585	300	I
5178. 4026	5176. 9607	400	I
5183. 9704	5182. 5270	200	II
5197. 2605	5195. 8136	400	I
5200. 6116	5199. 1638	800	I
5212. 6816	5211. 2306	400	I
5220. 5630	5219. 1099	500	I
5232. 6161	5231. 1598	900	I
5234. 6822	5233. 2253	350	II
5249. 1148	5247. 6541	400	II
5259. 8240	5258. 3604	300	I
5268. 1760	5266. 7102	200	I
5278. 9688	5277. 5001	400	II
5297. 7529	5296. 2792	200	I
5299. 2158	5297. 7417	250	I
5308. 9423	5307. 4657	300	II
5313. 4795	5312. 0016	400	I
5326. 6264	5325. 1450	300	II
5328. 4577	5326. 9758	400	I
5345. 0677	5343. 5814	500	I
5352. 6146	5351. 1263	120	I
5361. 6410	5360. 1503	250	I
5370. 773	5369. 280	200	I
5374. 1973	5372. 7033	200	I
5388. 1085	5386. 6107	300	I
5396. 2608	5394. 7609	400	I
5409. 1571	5407. 6537	200	I
5412. 2733	5410. 7691	180	I

Table 1. *Wavelengths of thorium lines*—Continued

λvac	λair	Relative intensity	Spectrum
Å	Å		
5418. 9918	5417. 4858	200	I
5427. 1864	5425. 6782	250	II
5432. 6214	5431. 1118	300	I
5437. 4039	5435. 8930	400	II
5450. 9935	5449. 4790	150	II
5453. 7341	5452. 2188	250	I
5465. 7236	5464. 2051	75	I
5472. 2790	5470. 7588	100	I
5494. 168	5492. 642	100	I
5500. 7831	5499. 2553	250	I
5505. 8312	5504. 3020	160	I
5511. 5245	5509. 9938	300	I
5516. 4051	5514. 8731	160	I
5526. 1178	5524. 5832	100	I
5540. 8005	5539. 2620	400	I
5549. 7170	5548. 1761	300	I
5558. 5886	5557. 0453	200	I
5559. 8863	5558. 3427	400	I
5572. 7389	5571. 1919	300	I
5574. 9017	5573. 3541	350	I
5580. 9078	5579. 3586	300	I
5588. 5781	5587. 0268	500	I
5596. 6168	5595. 0634	200	I
5603. 1587	5601. 6035	150	I
5613. 6262	5612. 0682	100	I
5616. 8788	5615. 3200	350	I
5631. 8595	5630. 2967	60	I
5641. 3117	5639. 7463	250	II
5659. 4958	5657. 9256	100	I
5666. 7532	5665. 1810	140	I
5676. 561	5674. 986	120	I
5686. 7695	5685. 1920	150	I
5702. 4993	5700. 9176	150	II
5708. 6868	5707. 1034	150	II
5721. 2097	5719. 6230	200	I
5721. 7704	5720. 1835	400	I
5726. 9767	5725. 3884	250	I
5750. 3347	5748. 7402	150	I
5754. 6225	5753. 0268	100	I
5762. 1489	5760. 5512	600	I
5765. 1270	5763. 5285	80	I
5769. 7813	5768. 1816	150	I
5775. 5478	5773. 9465	150	I
5791. 2500	5789. 6445	200	I
5794. 0363	5792. 4301	150	I
5797. 6759	5796. 0687	150	I
5802. 4380	5800. 8295	175	I
5805. 7507	5804. 1414	300	I
5814. 5842	5812. 9725	150	I
5817. 0346	5815. 4222	175	II
5833. 9875	5832. 3706	125	I
5854. 3043	5852. 6820	200	I
5855. 7424	5854. 1197	100	I
5861. 2904	5859. 6662	140	II
5869. 9996	5868. 3731	125	I
5887. 3330	5885. 7018	120	I
5893. 0838	5891. 4511	70	I
5907. 2068	5905. 5703	100	I
5916. 3095	5914. 6706	140	I
5927. 8744	5926. 2324	100	I

TABLE 1. *Wavelengths of thorium lines*—Continued

λvac	λair	Relative intensity	Spectrum
Å	Å		
5940.4706	5938.8252	140	I
5946.2946	5944.6476	75	II
5975.3199	5973.6652	250	I
5976.7203	5975.0652	250	I
5990.7034	5989.0445	150	II
5995.7897	5994.1295	200	I
6008.7362	6007.0725	180	I
6011.8253	6010.1608	90	I
6022.7038	6021.0364	140	I
6039.3697	6037.6978	140	I
6050.7257	6049.0507	100	I
6055.0569	6053.3808	300	I
6074.7856	6073.1042	50	II
6079.554	6077.871	75	I
6087.0596	6085.3749	100	I
6089.7162	6088.0308	125	I
6104.2840	6102.5947	90	I
6114.5300	6112.8379	125	II
6123.1031	6121.4087	75	I
6126.178	6124.483	75	I
6153.6960	6151.9934	125	I
6163.0585	6161.3534	50	I
6166.1856	6164.4797	75	I
6171.5299	6169.8226	500	I
6180.1417	6178.4320	100	I
6184.3331	6182.6223	400	I
6189.8381	6188.1258	160	I
6193.6189	6191.9056	100	I
6199.9380	6198.2230	80	I
6205.2095	6203.4931	100	I
6208.9377	6207.2203	160	I
6226.2496	6224.5276	100	I
6236.5804	6234.8556	200	I
6259.1550	6257.4241	100	I
6263.1498	6261.4179	180	I
6275.8522	6274.1169	100	II
6292.9314	6291.1915	30	I
6304.9940	6303.2508	40	I
6328.117	6326.368	60	II
6329.0285	6327.2789	180	I
6339.3728	6337.6204	40	I
6344.6140	6342.8602	300	I
6350.4928	6348.7374	40	I
6357.6686	6355.9113	40	I
6370.9008	6369.1409	120	I
6373.7056	6371.9440	50	I
6378.6942	6376.9313	350	I
6389.1624	6387.3967	50	I
6390.583	6388.817	40	I
6408.2173	6406.4464	75	I
6413.6720	6411.8997	250	I
6415.3879	6413.6151	200	I
6426.5890	6424.8132	30	II
6439.5405	6437.7612	50	I
6448.5530	6446.7713	50	I
6459.0677	6457.2832	500	I
6464.4002	6462.6142	400	II
6492.5315	6490.7380	120	I
6494.9922	6493.1980	75	I
6514.1635	6512.3642	75	I

TABLE 1. *Wavelengths of thorium lines*—Continued

λvac	λair	Relative intensity	Spectrum
Å	Å		
6523.8458	6522.0439	40	II
6533.1470	6531.3426	400	I
6555.9711	6554.1605	100	I
6579.0336	6577.2168	50	I
6585.7251	6583.9065	200	I
6590.3598	6588.5400	200	I
6593.3058	6591.4852	100	I
6595.7612	6593.9399	200	I
6607.2410	6605.4167	30	II
6621.7752	6619.9470	20	II
6640.7452	6638.9119	100	I
6646.488	6644.653	30	II
6660.5164	6658.6777	50	I
6664.1092	6662.2696	250	I
6676.5400	6674.6970	30	I
6680.5511	6678.7071	30	I
6715.824	6713.969	100	I
6729.3159	6727.4587	200	I
6758.3180	6756.4530	250	I
6780.183	6778.312	80	I
6782.285	6780.414	140	I
6793.110	6791.236	80	I
6826.561	6824.678	100	I
6830.9202	6829.0357	150	I
6836.8112	6834.9251	75	I
6913.1336	6911.2270	400	I
6945.5265	6943.6112	600	I
6991.5839	6989.6562	900	I
7002.735	7000.804	300	I
7020.504	7018.568	200	I

TABLE 2. *Test of thorium wavelengths*

Line pair	Wave-length	Wave-number	Wave-number difference	Deviaiton from mean
	Å	*K*	*K*	*mK*
1	5164.8968 5212.6816	19361.471 19183.984	177.487	0
2	5345.0677 5396.2608	18708.837 18531.350	177.487	0
3	5975.3199 6039.3697	16735.506 16558.019	177.487	0
4	6514.1635 6590.3598	15351.165 15173.678	177.487	0
5	3288.7358 3325.7088	30406.821 30068.778	338.043	0
6	5990.7034 6114.5300	16692.531 16354.487	338.044	0
7	5472.2790 5686.7695	18273.922 17584.678	689.244	0
8	5574.9017 5797.6759	17937.536 17248.291	689.245	+1

TABLE 2. *Test of thorium wavelengths*—Continued

Line pair	Wave-length	Wave-number	Wave-number difference	Deviation from mean
	Å	K	K	mK
9	5769. 7813 6008. 7362	17331. 679 16642. 435	689. 244	0
10	3960. 4204 4089. 8815	25249. 844 24450. 586	799. 258	+3
11	5775. 5478 6055. 0569	17314. 375 16515. 121	799. 254	−1
12	5940. 4706 6236. 5804	16833. 683 16034. 428	799. 255	0
13	6208. 9377 6533. 1470	16105. 815 15306. 559	799. 256	+1
14	6373. 7056 6715. 824	15689. 460 14890. 206	799. 254	−1
15	3413. 9919 3512. 1610	29291. 224 28472. 499	818. 725	−3
16	3519. 4096 3623. 8281	28413. 857 27595. 128	818. 729	+1
17	3585. 1986 3693. 6172	27892. 458 27073. 731	818. 727	−1
18	4379. 4071 4542. 2720	22834. 141 22015. 414	818. 727	−1
19	4664. 5080 4849. 7168	21438. 488 20619. 761	818. 727	−1
20	5136. 1764 5361. 6410	19469. 736 18651. 006	818. 730	+2
21	5465. 7236 5721. 7704	18295. 839 17477. 108	818. 731	+3
22	5765. 1270 6050. 7257	17345. 672 16526. 943	818. 729	+1
23	6184. 3331 6514. 1635	16169. 892 15351. 165	818. 727	−1
24	5558. 5886 5887. 3330	17990. 178 16985. 620	1004. 558	+1
25	6492. 5315 6945. 5265	15402. 313 14397. 757	1004. 556	−1
26	5432. 6214 5791. 2500	18407. 320 17267. 429	1139. 891	−2
27	5750. 3347 6153. 6960	17390. 292 16250. 397	1139. 895	+2
28	5976. 7203 6413. 6720	16731. 584 15591. 692	1139. 892	−1
29	6193. 6189 6664. 1092	16145. 650 15005. 757	1139. 893	0
30	4488. 1563 4767. 9332	22280. 864 20973. 448	1307. 416	−1
31	4880. 0955 5212. 6816	20491. 402 19183. 984	1307. 418	+1

TABLE 2. *Test of thorium wavelengths*—Continued

Line pair	Wave-length	Wave-number	Wave-number difference	Deviation from mean
	Å	K	K	mK
32	5040. 6359 5396. 2608	19838. 767 18531. 350	1307. 417	0
33	5232. 6161 5616. 8788	19110. 899 17803. 482	1307. 417	0
34	5097. 9046 5580. 9078	19615. 903 17918. 232	1697. 671	+3
35	5259. 8240 5775. 5478	19012. 043 17314. 375	1697. 668	0
36	5396. 2608 5940. 4706	18531. 350 16833. 683	1697. 667	−1
37	5616. 8788 6208. 9377	17803. 482 16105. 815	1697. 667	−1
38	6039. 3697 6729. 3159	16558. 019 14860. 352	1697. 667	−1
39	3585. 1986 3875. 9602	27892. 458 25800. 059	2092. 399	−1
40	3728. 9626 4044. 5369	26817. 110 24724. 710	2092. 400	0
41	4098. 9042 4483. 4270	24396. 764 22304. 367	2092. 397	−3
42	4687. 5060 5197. 2605	21333. 306 19240 906	2092. 400	0
43	4842. 1950 5388. 1085	20651. 791 18559. 389	2092. 402	+2
44	5003. 4924 5588. 5781	19986. 040 17893. 639	2092. 401	+1
45	5136. 1764 5754. 6225	19469. 736 17377. 334	2092. 402	+2
46	5465. 7236 6171. 5299	18295. 839 16203. 438	2092. 401	+1
47	5765. 1270 6555. 9711	17345. 672 15253. 270	2092. 402	+2
48	3691. 6742 4076. 6536	27087. 980 24529. 924	2558. 056	−1
49	3804. 1547 4214. 2542	26287. 049 23728. 991	2558. 058	+1
50	5762. 1489 6758. 3180	17354. 637 14796. 581	2558. 056	−1
51	3592. 4771 3974. 3200	27835. 946 25161. 537	2674. 409	0
52	3764. 0030 4185. 3170	26567. 460 23893. 053	2674. 407	−2
53	4828. 0490 5549. 7170	20693. 347 18018. 937	2674. 410	+1
54	5313. 4795 6193. 6189	18820. 059 16145. 650	2674. 409	0

TABLE 2. *Test of thorium wavelengths*—Continued

Line pair	Wave-length	Wave-number	Wave-number difference	Deviation from mean
	Å	K	K	mK
55	5345.0677 6236.5804	18708.837 16034.428	2674.409	0
56	5361.6410 6259.1550	18651.006 15976.597	2674.409	0
57	3310.3178 3657.7354	30208.580 27339.320	2869.260	0
58	3331.4345 3683.5345	30017.099 27147.839	2869.260	0
59	3458.0588 3838.9638	28917.958 26048.696	2869.262	+2
60	3599.1464 4013.6295	27784.366 24915.105	2869.261	+1
61	3643.2867 4068.5994	27447.744 24578.483	2869.261	+1
62	3840.7835 4316.4680	26036.354 23167.090	2869.264	+4
63	4113.9150 4664.5080	24307.746 21438.488	2869.258	−2
64	4251.5110 4842.195	23521.049 20651.791	2869.258	−2
65	4375.3536 5003.4924	22855.296 19986.040	2869.256	−4
66	4494.5943 5160.0414	22248.949 19379.689	2869.260	0
67	4946.8387 5765.1270	20214.930 17345.672	2869.258	−2
68	5127.3781 6011.8253	19503.145 16633.883	2869.262	+2
69	5603.1587 6676.5400	17847.076 14977.818	2869.258	−2
70	4483.4270 5220.5630	22304.367 19155.022	3149.345	0
71	5588.5781 6782.285	17893.639 14744.293	3149.346	0
72	3512.1610 4019.2344	28472.499 24880.360	3592.139	+2
73	3920.1336 4562.6266	25509.335 21917.200	3592.135	−2
74	4596.7082 5505.8312	21754.698 18162.562	3592.136	1
75	3305.1895 3764.0030	30255.451 26567.460	3687.991	+4
76	3424.9714 3920.1336	29197.324 25509.335	3687.989	+2
77	3829.4708 4459.2531	26113.269 22425.280	3687.989	+2
78	3831.8604 4462.4933	26096.984 22408.997	3687.987	0
79	4003.0253 4696.3520	24981.106 21293.122	3687.984	−3
80	4101.4985 4832.4710	24381.333 20693.347	3687.986	−1
81	4113.9150 4849.7168	24307.746 20619.761	3687.985	−2
82	4212.1096 4986.7636	23741.073 20053.086	3687.987	0
83	4338.4971 5164.8968	23049.456 19361.471	3687.985	−2
84	4516.3845 5418.9918	22141.605 18453.617	3687.988	+1
85	4779.6300 5802.4380	20922.122 17234.135	3687.987	0
86	4896.3218 5975.3199	20423.494 16735.506	3687.988	+1
87	4946.8387 6050.7257	20214.930 16526.940	3687.990	+3
88	5046.1263 6199.9380	19817.181 16129.194	3687.987	0
89	3458.0588 3991.6206	28917.958 25052.481	3865.477	+4
90	4258.6948 5097.9046	23481.373 19615.903	3865.470	−3
91	4330.1329 5200.6116	23093.979 19228.508	3865.471	−2
92	4338.4971 5212.6816	23049.456 19183.984	3865.472	−1
93	4371.1038 5259.8240	22877.517 19012.043	3865.474	+1
94	4896.3218 6039.3697	20423.494 16558.019	3865.475	+2
95	3532.4595 4261.5321	28308.888 23465.739	4843.149	+1
96	4216.0158 5297.7529	23719.076 18875.928	4843.148	0
97	4350.2950 5511.5245	22986.947 18143.800	4843.147	−1
98	3381.8300 4110.4832	29569.789 24328.040	5241.749	0
99	3438.2923 4194.1984	29084.206 23842.458	5241.748	0
100	3349.7310 4116.9203	29853.143 24290.001	5563.142	0

TABLE 2. *Test of thorium wavelengths*—Continued

Line pair	Wave-length	Wave-number	Wave-number difference	Deviation from mean
	Å	K	K	mK
101	3599.1464 4500.2022	27784.366 22221.224	5563.142	0
102	4258.6948 5580.9078	23481.373 17918.232	5563.141	+1
103	4371.1038 5775.5478	22877.517 17314.375	5563.142	0
104	4705.3063 6373.7056	21252.602 15689.460	5563.142	0
105	4896.3218 6729.3159	20423.494 14860.352	5563.142	0
106	3305.1895 4185.3170	30255.451 23893.053	6362.398	+2
107	4037.1879 5432.6214	24769.717 18407.320	6362.397	+1
108	4101.4985 5549.7170	24381.333 18018.937	6362.396	0
109	4330.1329 5976.7203	23093.979 16731.584	6362.395	−1
110	4371.1038 6055.0569	22877.517 16515.121	6362.396	0
111	4705.3063 6715.824	21252.602 14890.206	6362.396	0

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