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The Infrared Emission Spectra of Uranium and Thorium

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Abstract

The region between 1 and 5.5 μm has been observed with a high-resolution Fourier transform spectrometer. See-through hollow cathode lamps with calcium fluoride windows were operated at high current. Special precautions were required to minimize interference by blackbody radiation from the hot cathode. Observed lines were measured to an absolute accuracy of about 0.001 cm^{-1} and about 5% relative intensity accuracy. The argon carrier gas lines were readily distinguished by their much wider Doppler-broadened linewidths. Many lines were assigned to neutral or singly-ionized thorium on the basis of predicted transition wavenumbers calculated from accurate level lists. However, many lines remain to be assigned. This new spectral data connects to, and extends similar, spectral information given in our uranium and thorium atlases which cover the ultraviolet and visible regions.

All spectra were taken with the Kitt Peak National Observatory Fourier transform spectrometer (FTS) which has been briefly described earlier.[1] Several precautions were taken to decrease the effects of continuous backbody radiation and atmospheric absorption in the infrared. A "see-through" hollow cathode (Figure 1) was used so that the relatively hot cathode walls would not be seen by the FTS. This required careful alignment of the cathode hole with the FTS aperture. One calcium fluoride window was purposely tipped with respect to the optic axis so that no possible reflection of the cathode wall could enter the FTS. The exit window was also slightly wedged (0.5°) to prevent interference effects between front and back surfaces. A dry-N_2 purged tube was placed between the exit window and the FTS entrance aperture to decrease absorption by atmospheric water bands. The spectrometer was evacuated to eliminate absorption in the FTS tank.

The hollow cathode (Figure 1) was constructed, where possible, of standard Varian high-vacuum parts and was based on an unpublished design.[2] The uranium or thorium cathode insert (5/8" long, 0.25" o.d. with 0.035" wall) was pressed into the demountable copper block. The quartz tube enclosing the copper cathode reduced the amount of unwanted glow discharge that was not inside the cathode hole. Operating conditions with slowly flowing argon gas

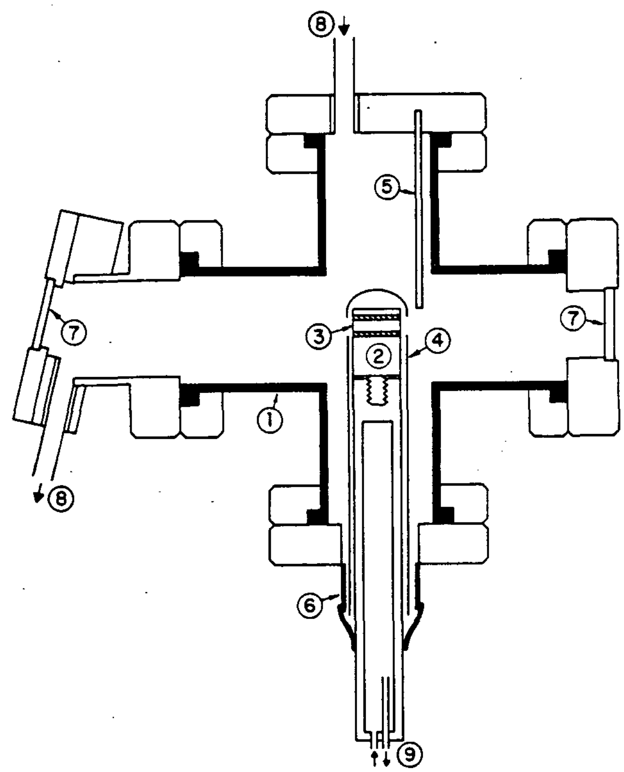

Figure 1. Hollow cathode lamp. 1) Standard 2.75" Diameter Varian Cross. 2) Demountable copper cathode block. 3) Uranium or thorium insert. 4) Quartz shield. 5) Anode rod. 6) Ceramic seal and insulator. 7) Calcium fluoride windows. 8) Argon inlet and outlet. 9) Cooling water inlet and outlet.

were 317 ma at 2.2 torr for thorium and 169 ma at 4.2 torr for uranium. After a initial warmup period of about one hour, these lamps are stable for many hours of operation. A high resolution spectrum of each lamp took about one hour and was the summation of eignt scans of the interferometer.

Results and Discussion

Line lists from the FTS data for U and Th were generated by conventional methods. Absolute wavenumber accuracy was about 0.001 cm^{-1} and relative intensity accuracy was about 5%. *Approximately 4600 and 11500 lines were found in the infrared region for* thorium and uranium, respectively. Lines were classified by using the known levels for uranium[3] and thorium.[4] About 2500 were classified to Th I, about 500 to Th II and about 50 to Th III. Assignments for uranium are not yet complete. A sample logarithmic intensity plot for thorium is shown in Figure 2. The argon emission lines are readily distingushed by their broader linewidth. The ringing on the edges of the other strong lines is due to insufficient spectrometer resolution to completely resolve the much sharper thorium lines. This ringing can be partially removed by smoothing, but with some loss of resolution. Table 1 is the line listing corresponding to Figure 2.

There has been little prior work in this area. Published work on thorium has listed some lines to about 3 µm.[5,6] Morillon[7] listed at reduced resolution 300 uranium lines in the 2.3 to 3.4 µm region, but without many assignments. A recent line list[8] does cover many of the infrared uranium lines in the present study. Unpublished work on the uranium infrared transitions are also contained in two theses,[9,10] which were analysed in a later publication.[11]

Complete thorium and uranium infrared atlases similar to our earlier works[3,4] will be issued when this work is complete. Extensions into the far infrared region (to 20 µm), a

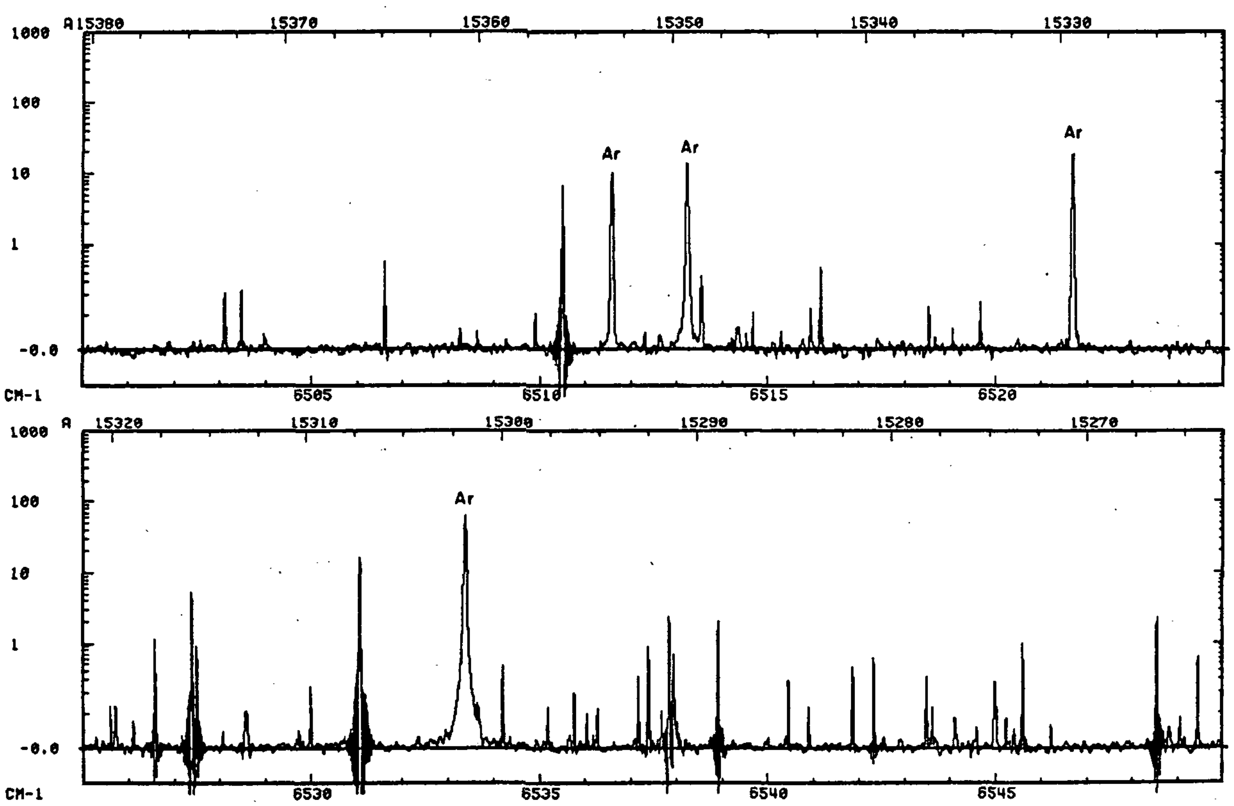

Figure 2. Sample high resolution spectrum of thorium. All lines are due to Th I or II except for the marked argon carrier gas lines.

Table 1. Sample line list for spectrum of thorium shown in Figure 2. For each line is listed the vacuum wavenumber, the air wavelength, and the relative intensity. Following the wavenumber are comments of wide (W), blend (BL), or questionable measurement (D or ?). For assigned thorium lines, the ion stage (neutral = I and singly ionized = II) and the even and odd levels and corresponding J are given.

Wavelength	Wavenumber	Int.	Ion	Even	J	Odd	J	Wavelength	Wavenumber	Int.	Ion	Even	J	Odd	J
15373.1471	6503.0720	0.16	I	32551	3	26048	4	15264.3487	6549.4233	0.49	I	18431	3	24981	3
15372.2803	6503.4387	0.19	I	33564	3	27061	2	15260.1517	6551.2246	0.26	I	5563	1	12114	2
15364.8828	6506.5698	0.45	I	28845	4	22338	3	15257.5458	6552.3435	0.07					
15357.0940	6509.8698	0.09						15254.3280	6553.7257	0.08					
15355.6872	6510.4662	5.36	I	14226	0	20737	1	15252.8222	6554.3727	0.20					
15353.1288	6511.5511	9.17						15246.1074	6557.2594	0.23	I	31326	4	24769	3
15349.2464	6513.1981	13.2						15244.1911	6558.0837?	0.06					
15348.5159	6513.5081	0.33						15242.2316	6558.9268	0.13					
15345.8265	6514.6496	0.09	I	27591	5	21077	5	15241.7789	6559.1216	0.31	II	13250	5/2	6691	3/2
15342.8654	6515.9069	0.10						15240.2517	6559.7789	13.0	II	4113	5/2	10673	5/2
15342.3514	6516.1252	0.37	I	19532	4	26048	4	15239.2866	6560.1943	1.73	I	13962	1	20522	2
15336.7582	6518.5016	0.10	I	17398	3	23916	4	15230.5477	6563.9584	0.16	I	36297	4	29733	5
15334.0882	6519.6366	0.13						15230.0326	6564.1804	0.98					
15329.3462	6521.6534	17.3						15226.6828	6565.6245	0.08					
15320.1259	6525.5783	0.10	I	16351	0	22877	1	15226.1401	6565.8585	0.14	I	33831	4	27266	4
15319.8691	6525.6877	0.12						15220.0948	6568.4664	0.08	I	37085	4	30517	4
15318.9423	6526.0825	0.07						15218.6757	6569.0789	0.32	I	33564	3	26995	3
15317.8189	6526.5611	0.98	II	4146	7/2	10673	5/2	15218.5580	6569.1297D	0.20	I	33214	5	26645	5
15315.9345	6527.3641	4.00	II	8018	3/2	14545	5/2	15215.5272	6570.4382WD	0.13					
15315.6717	6527.4761	0.60	II	10379	9/2	16906	7/2	15215.2237	6570.5693	0.12					
15309.8170	6529.9723	0.21	I	24664	3	31194	4	15215.0303	6570.6528	0.15	I	29684	5	23113	4
15307.2896	6531.0505	12.5	I	24032	4	17501	5	15214.2238	6571.0011	0.25	II	27257	7/2	20686	5/2
15301.8793	6533.3597	59.9						15212.5667	6571.7169	0.14	I	33831	4	27260	3
15301.2310	6533.6365D	0.13	I	33721	2	40254	3	15203.6232	6575.5827	0.10	I	30758	2	24182	2
15299.9594	6534.1795	0.37	I	31095	2	24561	3	15203.3415	6575.7045	0.11	I	36428	2	29853	2
15297.6452	6535.1680	0.10	I	28273	2	21738	2	15199.5008	6577.3661	0.06					
15296.2975	6535.7438	0.17	I	31715	6	25180	7	15196.9470	6578.4714	0.07	I	32963	5	26384	4
15295.6518	6536.0197	0.09	I	19273	2	25809	1	15195.2943	6579.1869	0.12	I	23990	2	17411	3
15295.1084	6536.2519	0.09	I	35216	5	28680	4	15190.7735	6581.1449	1.43	I	26796	3	20214	3
15293.0232	6537.1431	0.25	II	27526	9/2	20989	9/2	15190.3548	6581.3263	0.39	I	13962	1	20543	0
15292.4976	6537.3678	0.74	I	29552	6	23015	5	15188.8556	6581.9759	10.1	II	17727	11/2	24309	11/2
15291.8281	6537.6540	0.09	I	28679	2	22141	3	15186.2161	6583.1199	0.07	I	35633	4	29050	5
15291.4469	6537.8170	1.74	I3	0	4	6537	4	15180.3233	6585.6753	0.07	I	36297	4	29711	5
15291.2116	6537.9176	0.59	I	19713	3	13175	4	15177.7268	6586.8019	0.51					
15288.9248	6538.8955	1.52	II	8605	5/2	15144	3/2	15177.0121	6587.1121	0.07	I	32396	2	25809	1
15285.3260	6540.4350	0.25						15173.1510	6588.7883D	0.06					
15284.3015	6540.8734	0.11	I	29418	2	22877	1	15172.6914	6588.9879	54.1					
15282.0364	6541.8429	0.36	I	9804	5	16346	4	15172.0508	6589.2661WD	0.07					
15280.9684	6542.3001	0.46	II	18118	3/2	11576	3/2	15171.4063	6589.5460	0.20	I	29097	1	22508	2
15278.2543	6543.4623	0.26	I	28882	2	22338	3	15169.5044	6590.3722BL	0.06	II	24381	7/2	30972	5/2
15277.9436	6543.5954	0.09	I	30964	3	24421	3	15168.8532	6590.6551	0.13	I	38261	5	31671	4
15276.7807	6544.0935	0.08						15167.1724	6591.3855	0.17	I	33099	3	26508	3
15274.7248	6544.9743	0.26						15163.9872	6592.7700	0.07					
15274.1652	6545.2141	0.08	I	38261	5	31716	5	15163.5861	6592.9444	0.09					
15273.3261	6545.5737	0.82	I	23769	1	17224	2	15158.2261	6595.2757	0.21	I	25405	4	18809	4
15266.4473	6548.5230	1.66	II	13248	9/2	6700	9/2	15157.3337	6595.6640	0.12	I	24664	3	18069	3
15265.2596	6549.0325	0.08	I	31429	1	24880	1	15156.7610	6595.9132	0.41	I	28934	3	22338	3

region as yet uninvestigated for uranium and thorium, will require additional measures, such as liquid nitrogen cooling, to further reduce blackbody background radiation.

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