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Energy Levels of Neutral and Singly Ionized Berkelium

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ABSTRACT

Energy level analyses of the observed emission spectrum of berkelium have yielded 179 odd and 187 even levels of neutral berkelium, Bk I, and 42 odd and 118 even levels of singly ionized berkelium, Bk II. The levels are tabulated with the J-value, g-value, configuration and hyperfine constants A and B and width given for many of the levels[5-7].

The ground states of Bk I and Bk II are $[Rn]5f^9 7s^2\ {}^6H^o_{15/2}$ and $[Rn]5f^9 7s\ {}^7H^o_8$, respectively. A table lists the lowest level of each identified electronic configuration of Bk I[9] and Bk II[6].

INTRODUCTION

Berkelium (Bk) is element number 97 in the periodic table. It was discovered in December of 1949 by S. G. Thompson, A. Ghiorso and G. T. Seaborg by means of a cyclotron bombardment of ^{241}Am with helium ions.[1] The first report of the observation of the berkelium spectrum was by R. G. Gutmacher, E. K. Hulet and R. Lougheed in 1965.[2] Observation of the hyperfine structure in high resolution emission spectra of ^{249}Bk and confirmation of the nuclear spin of ^{249}Bk as 7/2 were reported in 1967.[3] Subsequently we reported the emission lines observed in the infrared[4] and the visible-ultraviolet[5] as well as energy levels for neutral berkelium, ^{249}Bk I, and singly ionized berkelium, ^{249}Bk II. Parametic studies of the $5f^97s^2$ and $5f^86d7s^2$ configurations of Bk I and of the $5f^97s$ and $5f^96d$ configurations of Bk II have been made.[6-7] We report here an extended list of energy levels of ^{249}Bk I and ^{249}Bk II.

EXPERIMENTAL

The experimental conditions to obtain the two sets of emission spectra used to find the levels reported here are covered in the original papers.[3-4-5] All spectra were observed using ^{249}Bk. Detailed experimental information may be found in Reference 8. Briefly the visible and ultraviolet lines were photographed at Lawrence Livermore National Laboratory (LLNL) on a 3.4 m Ebert spectrograph with the grating at high angles (high orders) near 60° and 30°. The infrared data were obtained with a Fourier transform spectrometer at Laboratoire Aimé Cotton. Both works used electrodeless discharge lamps (EDL) containing on the order of 30 to

100 micrograms of berkelium as the iodide. Zeeman spectra were obtained using the 9.15m Paschen-Runge spectrograph and a magnetic field of 2.4 T at the Argonne National Laboratory (ANL).

RESULTS

As a result of the nuclear spin of 7/2 and the relatively large magnetic moment, $\mu = +2.0 \pm 0.4$ n.m. of ^{249}Bk,[7-9] most lines show flag patterns of 8 diagonal components and many with up to 14 off diagonal components (for transitions between levels with $J \geq 7/2$). Except for low J values, the center of gravity of the pattern is close to the fourth component which was taken as the wave number of the line. The width of some of Bk II hyperfine patterns were observed to be as large as 6 to 8 cm^{-1}. Most of the lines have widths of the order of 1 to 4 cm^{-1}. This makes it difficult to measure Zeeman structures, particularly in the Bk II spectrum. For this reason, the analyses of the Bk I and Bk II spectra have been carried out mainly with the aid of the hyperfine structure. Figures 1, 2 and 3 illustrate how hyperfine structure can serve to confirm levels found by constant sum or difference procedures or in some cases to find new levels and help assign J values. Fig. 1 and 2 are tracings of lines at 11204.260 $cm^{-1}$and 11024.046 cm^{-1} taken on the Fourier transform spectrometer. The pattern in Fig. 1 is characteristic of a transition between levels with J's differing by one, while the pattern in Fig. 2 is for a transition between levels with the same J. The frequencies of the resolved components of these lines allow the determination of hyperfine structure of the levels involved in these transitions. Here one of the levels is common to both transitions as shown in Fig. 3.

No isotope shift experiments were possible because only one isotope was available in sufficient quantities to make EDLs. For this reason, the interpertation of the levels is based on parametric studies for the lower configurations[6] of each spectrum and on empirical considerations such as the strengths of transitions from levels without definite configuration assignment to the levels that already had configuration assignment. Landé g-values, when available, helped establish energy levels and their interpertation. Using these methods we have been able to identify nine configurations in Bk I and six configurations in Bk II. Table 1 lists the lowest levels of these 15 identified configurations along with the hyperfine widths and designations. In Bk I we have identified levels belonging to all nine configurations expected from Brewers prediction[10] to be found below 35,000 cm^{-1}. Bk II levels that belong to 6 of the 8 configurations expected[11] below 37,000 cm^{-1} have been identified.

The known energy levels of Bk I and Bk II are listed in Tables 2 through 5. In Tables 1 to 5, column 1 is the energy of the level in cm^{-1}, column 2 the J value, column 3 the Landé g factor. The configuration designation is given in column 4 and follows the notation convention used in "Atomic Energy Levels-The Rare-Earth Elements".[12] Columns 5 and 6 contain the A and B hyperfine values[4] and column 7 the overall width of the level in mK where 1 mK = $10^{-3} cm^{-1}$. Energy levels given to three significent figures (except those ending in 0 or 5) are uncertain to ± 0.003 cm^{-1} and those ending in 0 or 5 are uncertain to ± 0.01 cm^{-1}. Levels given to two significent figures have uncertainties of ± 0.02 cm^{-1} or larger. Landé g-values with three significent figures have an uncertainty of ± 0.01 cm^{-1} while those given to two figures are uncertain by ± 0.03 cm^{-1} or larger.

Table 2 lists 179 odd levels of Bk I. One hundred seven of these levels have been assigned to the odd configurations listed in Table 1. Table 3 lists the known information for the 187 Bk I even levels. There are 88 even levels assigned to the even configurations listed in Table 1. Tables 4 and 5 list the information for the 42 Bk II odd levels and 118 Bk II even levels.

CONCLUSIONS

We have identified 15 electronic configurations in Bk I and II and have determined the lowest level of each. We have found 386 levels of the Bk I and 160 levels of Bk II. For Bk I 53% of the observed levels have been assigned to configurations and for Bk II 35% have been assigned. The number of levels found represents a small fraction of the levels expected for Bk I and II. In order for the analysis to progress further it will be necessary to re-observe the spectrum to increase the total number of lines. It is especially important to re-investigate the visible-ultraviolet region taking advantage of the increased precision available with modern Fourier transform spectrometers.

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TABLES

Table 1. The lowest levels of identified configurations of neutral and singly ionized berkelium, ^{249}Bk I and II.

Table 2. The odd energy levels of neutral berkelium, ^{249}Bk I.

Table 3. The even energy levels of neutral berkelium, ^{249}Bk I.

Table 4. The odd energy levels of singly ionized berkelium, ^{249}Bk II.

Table 5. The even energy levels of singly ionized berkelium, ^{249}Bk II.

CAPTIONS

Figure 1. Tracing of the ^{249}Bk line at 11204.25 cm^{-1} taken on the Fourier transform spectrometer at Laboratoire Aimé Cotton. The transition is from the odd level 34114.485 cm^{-1}, $5f^9(^6H^o_{15/2})7s8s(^3S_1)$, J=13/2, to the even level 22910.225 cm^{-1}, $5f^9(^6H^o_{15/2})7s7p(^3P^o_2)$, J=15/2. The F values, (F=I+J) are across the top of the figure.

Figure 2. Fourier transform spectrometer tracing of the ^{249}Bk line at 11024.046 cm^{-1}. The transition is from the odd level 34114.485 cm^{-1}, $5f^9(^6H^o_{15/2})7s8s(^3S_1)$, J=13/2 to the even 23090.450 cm^{-1}, $5f^9(^6H^o_{15/2})7s7p(^3P^o_2)$, J=13/2. The same upper level as is in Fig 1 is involved. The F values are across the top of the figure.

Figure 3. Energy level diagram of transitions 11204.260 and 11024.046 cm^{-1} shown in Fig's 1 and 2. The upper level is common to both transitions and has a sign opposite to the two lower levels. The number beside each hyperfine level indicates the F value.

Table 1. The lowest levels of the identified configurations of neutral and singly ionized berkelium, ^{249}Bk I and II.

Level (cm^{-1})	J	g	Configuration	A[a] (mK)	B[a] (mK)	Width[a] (mK)
Bk I, ODD						
0.000	15/2	1.285	$5f^9 7s^2\ {}^6H^o$			1150
17182.482	17/2		$5f^9 6d7s\ {}^8H^o$	71.2	126.7	4472
17777.808	11/2		$5f^8 7s^2({}^7F_6)7p_{1/2}$	4.7	243.7	157
24652.405	13/2	1.38	$5f^8 6d7s7p$	24.1	164.	1157
32488.850	17/2		$5f^9({}^6H^o_{15/2})7s8s({}^3S_1)$	100.5	254.8	6306
Bk I, EVEN						
9141.115	13/2	1.515	$5f^8 6d7s^2\ {}^8G$	17.5	153.	836
16913.770	15/2		$5f^9({}^6H^o_{15/2})7s7p({}^3P^o_0)$	37.05	232.	3168
21506.436	13/2		$5f^8 6d^2 7s\ {}^{10}G$	73.7	123.2	3596
36952.61	13/2		$5f^9 7d7p$			1800

Bk II, ODD					
0.000	8	$5f^9 7s\ ^7H^o$	104.6	279.	6195
16360.00	8	$5f^9(^6H^o_{15/2})6d_{3/2}$			670
32025.72	6	$5f^8(^7F_6)7s7p(^3P_0)$			3445
Bk II, EVEN					
7040.98	6	$5f^8 7s^2\ ^7F$			820
12340.96	8	$5f^8 6d7s\ ^9G$			8678
26938.26	7	$5f^9(^6H^o_{15/2})7p_{1/2}$			2050

a, 1 mK = 10^{-3} cm^{-1}.

Table 2. The odd energy levels of neutral berkelium, ^{249}Bk I.

Energy Level (cm^{-1})	J odd	g odd	Configuration	Hyperfine[a] A (mK)	B (mK)	Width (mK)
0.000	15/2	1.285	$5f^9 7s^2\ ^6H^o$	20.0	277.0	1150
5416.690	11/2	1.330	$5f^9 7s^2\ ^6F^o$	19.7	35.4	823
5757.440	9/2	1.305	$5f^9 7s^2\ ^6F^o$			770
6530.720	13/2	1.255	$5f^9 7s^2\ ^6H^o$			1020
9535.130	11/2	1.275	$5f^9 7s^2\ ^6H^o$			695
10605.570	9/2	1.155	$5f^9 7s^2\ ^6H^o$			875
10985.83	7/2	1.295	$5f^9 7s^2\ ^6F^o$			550
12067.63	7/2	0.925	$5f^9 7s^2\ ^6H^o$			890
12568.38	5/2	0.95	$5f^9 7s^2\ ^6F^o$			605
17182.482	17/2		$5f^9 6d7s\ ^8H^o$	71.2	126.7	4472
17547.622	15/2		$5f^9 6d7s\ ^8H^o$	57.7	123.	3218
17777.808	11/2		$5f^8 7s^2(^7F_6)7p_{1/2}$	4.7	243.7	157
17993.628	13/2		$5f^8 7s^2(^7F_6)7p_{1/2}$	34.2	156.4	1653
18717.833	13/2		$5f^9 6d7s\ ^8H^o$	30.66	202.4	1475
19013.785	11/2		$5f^9 7s^2\ ^4G^o$	20.7	130.9	849
19373.730	19/2		$5f^9 6d7s\ ^8I^o$	67.08	226.1	4676
19993.728	13/2		$5f^9 6d7s$	34.9	184.6	1688
20021.434	15/2		$5f^9 6d7s$	-6.67	113.5	-386
20878.420	11/2		$5f^9 6d7s$	-34.9	225.8	-1503
21046.130	17/2		$5f^9 6d7s$	6.46	190.1	388
22153.005	7/2		$5f^8 7s^2(^7F_4)7p_{1/2}$	-.09	39.74	-14

22236.350	9/2			33.52	-24.46	1178
22574.380	9/2			10.9	63.6	370
22752.817	19/2		$5f^9 6d7s\ ^8K^o$	36.82	327.3	2549
22771.690	9/2		$5f^9 7s^2\ ^4F3^o$	28.10	-23.1	988
23072.085	15/2		$5f^9 6d7s$	11.98	118.	667
23185.065	9/2			92.73	60.4	3233
23225.66	13/2,15/2		$5f^9 6d7s$			3285
23226.985	11/2			33.49	40.	1400
23361.667	17/2		$5f^9 6d7s$	-9.36	294.3	-619
24005.250	11/2		$5f^9 6d7s$	13.59	66.7	560
24107.632	15/2		$5f^9 6d7s$	25.54	124.5	1416
24287.590	13/2			58.99	31.25	2886
24371.842	13/2		$5f^8 7s^2(^7F_6)7p_{3/2}$	9.8	98.8	468
24555.210	11/2		$5f^8 7s^2 7p$	57.44	58.9	2386
24652.405	13/2	1.38	$5f^8 6d7s7p$	24.1	164.	1157
24786.279	15/2	1.42	$5f^8 7s^2(^7F_6)7p_{3/2}$	38.4	309.	2118
25026.967	5/2			-28.5	-1.7	-569
25103.260	17/2		$5f^9 6d7s$	10.38	195.6	663
25104.290	15/2		$5f^8 6d7s7p$	56.48	147.3	3080
25118.035	11/2	1.44	$5f^8 6d7s7p$	26.86	63.	1118
25386.061	5/2			-38.6	-1.2	-772
25430.510	13/2		$5f^8 6d7s7p$	66.5	42.	3253
25458.445	11/2		$5f^8 7s^2 7p$	3.0	3.	126
25517.270	3/2			-12.85	-40.3	-143
25543.340	7/2			27.19	7.3	759
25664.750	11/2		$5f^8 6d7s7p$	39.36	100.8	1637
25757.890	5/2			39.57	-17.3	796

25776.560	7/2			30.82	31.7	854
25907.978	11/2		$5f^8 6d7s7p$	27.8	107.	1151
25918.845	7/2					200
25958.976	13/2		$5f^9 6d7s$	54.59	34.3	2670
26044.240	9/2		$5f^8 6d7s7p$	12.60	290.	380
26298.040	15/2		$5f^8 6d7s7p$	77.9	28.	4359
26416.478	13/2		$5f^9 6d7s$	36.88	61.7	1799
26439.838	17/2		$5f^9 6d7s$	72.23	157.8	4535
26494.905	15/2		$5f^9 6d7s$			4260
26590.332	11/2		$5f^9 7s^2 \ {}^4H1^o$	19.1	94.7	788
26598.965	9/2		$5f^8 6d7s7p$	52.73	258.	1792
26734.375	15/2		$5f^9 6d7s$	32.1	74.8	1770
27022.050	13/2		$5f^9 6d7s$			1290
27161.215	17/2		$5f^9 6d7s$			4653
27302.475	13/2		$5f^9 7s^2 \ {}^4H1^o$	-0.39	52.	-26
27550.280	13/2		$5f^9 6d7s$	22.2	81.	1232
27668.915	13/2		$5f^9 6d7s$	3.96	69.	185
27874.375	11/2		$5f^9 6d7s$	64.44	102.	2690
28223.288	17/2		$5f^8 6d7s7p$	88.8	21.3	5592
28235.018	15/2		$5f^9 6d7s$	5.9	156.	313
28319.825	11/2		$5f^9 6d7s$	80.6	135.	3363
28725.858	13/2		$5f^8 6d7s7p$	38.8	64.	1893
28728.270	7/2		$5f^8 6d7s7p$			780
28800.390	17/2		$5f^9 6d7s$	45.4	273.1	2833
28895.291	11/2	1.49		22.8	76.	944
28950.660	13/2		$5f^9 6d7s$	50.39	70.7	2460
28967.67	9/2		$5f^8 6d7s7p$	29.73	42.	1032

29135.612	9/2		$5f^8 6d7s7p$	32.24	51.8	1118
29227.335	11/2	1.390	$5f^8 6d7s7p$	21.	116.	863
29351.179	11/2			23.96	47.8	998
29465.103	13/2	1.45	$5f^8 6d7s7p$	26.94	29.1	1316
29548.720	13/2		$5f^8 6d7s7p$	41.6	233.	2006
29615.965	9/2		$5f^8 6d7s7p$			1802
29625.565	11/2			30.6	84.	1271
29671.295	13/2		$5f^8 6d7s7p$	8.5	94.5	404
29683.615	13/2		$5f^8 6d7s7p$	4.2	158.	183
29799.236	7/2					415
29912.305	13/2		$5f^8 6d7s7p$	34.2	186.	1650
29945.300	11/2		$5f^8 6d7s7p$	39.2	158.	1620
29966.22	9/2					80
30093.215	7/2	1.370				
30113.700	9/2		$5f^8 6d7s7p$	3.37	37.6	110
30119.865	15/2		$5f^8 6d7s7p$			3880
30205.283	13/2	1.25	$5f^8 6d7s7p$	12.6	127.	602
30410.000	9/2		$5f^8 6d7s7p$			400
30567.275	11/2		$5f^8 6d7s7p$	68.3	109.	2851
30660.98	7/2					380
30857.098	11/2			60.69	-38.5	2555
31033.68	11/2					590
31275.633	15/2		$5f^8 6d7s7p$	4.9	24.	253
31541.302	15/2		$5f^8 6d7s7p$	6.5	205.	343
31915.12	11/2					1060
32110.40	11/2					400
32200.355	13/2		$5f^8 6d7s7p$			3830

32454.45	9/2	1.375				
32488.850	17/2		$5f^9(^6H^o_{15/2})7s8s(^3S_1)$	100.5	254.8	6306
32553.47	9/2					620
32710.260	17/2		$5f^9 6d7s$			490
32725.42	9/2	1.295				720
32857.790	17/2		$5f^8 6d7s7p$			5264
32959.70	19/2		$5f^8 6d7s7p$			5640
33050.98	13/2		$5f^8 6d7s7p$			130
33110.280	15/2		$5f^9(^6H^o_{15/2})7s8s(^3S_1)$	76.89	242.9	4278
33177.79	13/2		$5f^8 6d7s7p$			1395
33256.455	15/2		$5f^8 6d7s7p$	91.2	268.	5077
33671.915	15/2		$5f^8 6d7s7p$			3200
33902.28	13/2					3080
33922.290	13/2					2740
34010.05	17/2		$5f^8 6d7s7p$			3506
34066.66	7/2	1.40				
34109.19	11/2	1.41				780
34114.485	13/2		$5f^9(^6H^o_{15/2})7s8s(^3S_1)$	-41.82	88.1	-2061
34157.500	13/2	1.24	$5f^8 6d7s7p$	23.47	142.	1131
34165.685	9/2	1.58	$5f^8 6d7s7p$			2880
34186.760	13/2		$5f^8 6d7s7p$	17.2	126.	824
34254.920	17/2		$5f^8 6d7s7p$			4795
34698.635	13/2					3547
34704.55	9/2	1.285				
34785.550	15/2		$5f^9(^6H^o_{15/2})7s8s(^1S_0)$	36.5	80.	2035
34837.92	11/2	1.200				
34872.925	15/2		$5f^8 6d7s7p$	14.3	195.	780

35041.46	11/2	1.350		1140
35192.24	19/2		$5f^8 6d7s7p$	5665
35287.55	15/2	1.285		1200
35374.795	11/2	1.415		2130
35491.415	11/2			2725
35670.78	15/2	1.39	$5f^8 6d7s7p$	1385
36665.84	13/2			1200
36721.245	17/2,15/2			4220
36942.78	13/2	1.32		
36958.28	13/2			
37220.44	13/2	1.34		310
37235.48	15/2		$5f^8 6d7s7p$	4585
37494.475	13/2			2015
37892.055	11/2			1300
38005.00	13/2		$5f^9(^6F^o_{11/2})7s8s(^3S_1)$	5975
38085.625	13/2		$5f^8 6d7s7p$	3237
38110.47	5/2	1.52		
38114.54	11/2		$5f^8 6d7s7p$	3440
38239.110	11/2	1.215		
38366.575	7/2	1.470		
38412.66	11/2		$5f^9(^6H^o_{11/2})7s8s(^3S_1)$	4485
38473.00	15/2	1.31		
38508.175	11/2		$5f^8 6d7s7p$	3975
38697.06	11/2		$5f^8 6d7s7p$	2567
38702.20	13/2			2950
38768.760	9/2			2000
38799.350	21/2		$5f^8 6d7s7p$	5730

39191.44	9/2	1.39				300
39291.600	15/2		$5f^9(^6H^o_{13/2})7s8s(^3S_1)$	102.4	197.	5712
39579.68	13/2					3168
39686.345	15/2					3155
39693.01	11/2	1.29				
39746.055	9/2					
39768.190	15/2					2930
39785.150	13/2		$5f^9(^6H^o_{13/2})7s8s(^3S_1)$			3400
39806.995	11/2					-100
39954.94	11/2	1.46				
40021.125	11/2	1.355				600
40040.225	13/2	1.29				1365
40049.15	15/2					2426
40145.715	13/2	1.18				
41183.685	17/2,15/2					3052
41279.48	13/2					-180
41350.965	11/2	1.31				
41353.705	13/2					-438
41601.565	9/2	1.175				
41931.920	15/2	1.26				
41983.620	15/2	1.29				
42145.715	9/2	1.25				
43134.22	5/2	1.32				0

a 1 mK = 10^{-3} cm^{-1}.

Table 3. The even energy levels of neutral berkelium, ^{249}Bk I.

Energy Level (cm^{-1})	J even	g even	Configuration	Hyperfine[a] A (mK)	B (mK)	Width (mK)
9141.115	13/2	1.415	$5f^8 6d7s^2\ ^8G$	17.5	153.	836
9300.585	11/2	1.485	$5f^8 6d7s^2\ ^8D$	19.2	132.7	785
10587.345	15/2	1.415	$5f^8 6d7s^2\ ^8G$	17.1	254.7	927
10735.955	9/2	1.575	$5f^8 6d7s^2\ ^8D$	21.3	300.	683
13191.915	7/2	1.41	$5f^8 6d7s^2\ ^8G$	20.6	33.3	567
13439.485	9/2	1.40	$5f^8 6d7s^2\ ^8G$	16.7	-11.0	585
13769.315	11/2	1.46	$5f^8 6d7s^2\ ^8G$	13.6	-3.5	571
13931.000	5/2	1.56	$5f^8 6d7s^2\ ^8G$	25.8	76.7	494
14920.166	7/2		$5f^8 6d7s^2\ ^8D$			395
15290.142	17/2	1.37	$5f^8 6d7s^2\ ^8H$	18.7	421.3	1138
15626.860	3/2		$5f^8 6d7s^2\ ^8G$	29.8	-10.	360
15987.97	11/2		$5f^8 6d7s^2\ ^8H$	16.9	118.9	689
16038.000	13/2	1.47	$5f^8 6d7s^2\ ^8F$	14.1	81.5	676
16039.840	15/2	1.31	$5f^8 6d7s^2\ ^6H$	13.8	338.3	732
16145.840	1/2		$5f^8 6d7s^2\ ^8G$	76.5		306
16276.960	5/2			13.6	-117.5	305
16541.450	9/2		$5f^8 6d7s^2$	15.4	-25.8	543
16913.770	15/2		$5f^9(^6H^o_{15/2})7s7p(^3P^o_0)$	37.05	232.	3168
17484.350	3/2		$5f^8 6d7s^2$	1.7	-82.9	44
17532.100	13/2	1.32	$5f^8 6d7s^2\ ^8H$	3.3	220.	131

17559.160	11/2	1.37	$5f^8 6d7s^2$	16.1	73.8	664
17665.980	17/2		$5f^9(^6H^o_{15/2})7s7p(^3P^o_1)$	86.5	26.6	5445
18540.750	13/2		$5f^8 6d7s^2$	-7.2	165.2	-375
18624.117	7/2		$5f^8 6d7s^2$	10.2	-109.	318
18733.630	11/2		$5f^8 6d7s^2$	13.4	9.9	559
19177.220	9/2		$5f^8 6d7s^2$	15.6	83.8	527
19179.210	15/2	1.25	$5f^9(^6H^o_{15/2})7s7p(^3P^o_1)$	-5.2	331.3	-328
19197.97	5/2		$5f^8 6d7s^2$	9.8	-74.4	218
19275.632	7/2		$5f^8 6d7s^2$	18.2	69.	490
19334.710	13/2	1.28	$5f^9(^6H^o_{15/2})7s7p(^3P^o_1)$	-10.4	150.3	-532
19439.284	9/2	1.35	$5f^8 6d7s^2$	16.0	117.5	537
20569.745	15/2		$5f^8 6d7s^2\ ^8H$	18.1	335.	976
21506.436	13/2		$5f^8 6d^2 7s\ ^{10}G$	73.7	123.2	3596
21876.700	11/2		$5f^8 6d^2 7s\ ^{10}G$	70.9	197.9	2945
21894.093	15/2		$5f^8 6d^2 7s\ ^{10}G$	73.5	116.9	4100
22016.040	11/2		$5f^8 6d7s^2$	12.4	93.2	506
22138.91	7/2		$5f^8 6d7s^2$			300
22227.670	9/2		$5f^8 6d^2 7s\ ^{10}G$	91.97	218.4	3174
22298.240	11/2		$5f^9(^6F^o_{11/2})7s7p(^3P^o_0)$	64.6	63.5	2703
22369.436	19/2		$5f^9(^6H^o_{15/2})7s7p(^3P^o_2)$	77.8	486.	5405
22382.830	17/2		$5f^9(^6H^o_{15/2})7s7p(^3P^o_2)$	66.3	221.	4154
22516.876	9/2	1.46	$5f^8 6d7s^2$	21.9	14.8	763
22602.640	13/2			33.3	242.6	1599
22686.020	9/2		$5f^9(^6F^o_{9/2})7s7p(^3P^o_0)$			2300
22861.25	9/2	1.32	$5f^8 6d7s^2$			550
22910.225	15/2		$5f^9(^6H^o_{15/2})7s7p(^3P^o_2)$	38.9	155.4	2160
22956.45	17/2		$5f^8 6d^2 7s\ ^{10}G$			4600

23090.450	13/2		$5f^9(^6H^o_{15/2})7s7p(^3P^o_2)$	54.4	-28.8	2645
23329.100	11/2	1.23		8.7	152.	340
23406.695	11/2	1.30	$5f^9(^6H^o_{15/2})7s7p(^3P^o_2)$	21.9	139.5	896
23468.810	13/2		$5f^9(^6H^o_{13/2})7s7p(^3P^o_0)$	38.3	132.7	1858
24102.207	11/2		$5f^9(^6F^o_{9/2})7s7p(^3P^o_1)$			2493
24210.030	13/2	1.32*	$5f^9(^6F^o_{11/2})7s7p(^3P^o_1)$	63.6	95.4	3114
24259.140	9/2			-24.6	17.4	-864
24290.60	9/2	1.155				598
24496.03	7/2	1.61	$5f^8 6d7s^2$			800
24521.690	15/2		$5f^9(^6H^o_{13/2})7s7p(^3P^o_1)$	94.2	20	5276
24563.01	9/2	1.32	$5f^9(^6F^o_{11/2})7s7p(^3P^o_1)$			-5
24758.590	11/2		$5f^9(^6F^o_{11/2})7s7p(^3P^o_1)$	-18.9	111.1	-811
25279.040	11/2			-14.1	156.3	-618
25493.793	13/2	1.175		17.9	181.6	852
25617.69	13/2					2400
25765.190	13/2	1.29	$5f^9(^6H^o_{13/2})7s7p(^3P^o_1)$	21.05	276.	994
25814.140	11/2		$5f^9(^6H^o_{13/2})7s7p(^3P^o_1)$	-1.1	128.3	-67
26000.831	19/2		$5f^8 6d^2 7s\ ^{10}H$			4672
26645.60	15/2	1.29	$5f^9(^6H^o_{15/2})7s7p(^1P^o_1)$	9.1	135.	495
26691.780	13/2	1.49				1540
26718.477	15/2	1.39		18.7	159.5	1030
26860.78	11/2		$5f^9(^6H^o_{11/2})7s7p(^3P^o_0)$			1505
26925.284	17/2	1.27	$5f^9(^6H^o_{15/2})7s7p(^1P^o_1)$	-12.2	327.4	-803
27021.760	17/2		$5f^8 6d^2 7s$			3160
27558.500	13/2		$5f^9(^6H^o_{15/2})7s7p(^1P^o_1)$	27.	226.2	1292
27695.870	15/2					1537
27761.265	17/2		$5f^9 7s7p$	67.4	86.4	4239

27820.04	13/2		$5f^9(^6H^o_{11/2})7s7p(^3P^o_1)$			4715
27844.730	15/2		$5f^9(^6F^o_{11/2})7s7p(^3P^o_2)$			4735
27914.22	9/2					450
27925.565	21/2		$5f^86d^27s\ ^{10}I$			5002
27956.900	13/2		$5f^97s7p$	91.7	30.2	4491
28130.21	9/2	1.41	$5f^9(^6H_{11/2})7s7p$			
28300.040	13/2		$5f^9(^6H^o_{11/2})7s7p(^3P^o_2)$			4153
28430.62	11/2					355
28484.47	9/2		$5f^9(^6F)7s7p$			1200
28520.58	9/2	1.32	$5f^9(^6F^o_{11/2})7s7p(^3P^o_2)$			2350
28682.50	7/2	1.510				
28824.415	17/2		$5f^86d^27s$			4120
29038.930	15/2		$5f^9(^6H^o_{13/2})7s7p(^3P^o_2)$	64.2	214.8	3569
29080.625	11/2		$5f^9(^6H^o_{11/2})7s7p$			2845
29172.103	17/2		$5f^9(^6H^o_{13/2})7s7p(^3P^o_2)$	80.1	357.7	5012
29504.83	11/2	1.155				
29600.310	13/2		$5f^9(^6H^o_{13/2})7s7p(^3P^o_2)$			2110
29769.92	9/2	1.170				
29787.16	7/2	1.610				
29974.04	13/2	1.12				1755
30255.690	11/2	1.310	$5f^9(^6H^o_{13/2})7s7p(^3P^o_2)$			850
30336.20	9/2	1.060				
31139.69	13/2					1490
31154.14	13/2					1018
31213.72	9/2					1815
31249.81	9/2					110
31255.72	13/2	1.32				990

31406.12	11/2	1.18		1190
31446.61	15/2	1.45		1720
31707.89	11/2	1.165		
31751.30	13/2			2055
32020.07	13/2	1.28	$5f^9(^6F^o_{11/2})7s7p(^1P^o_1)$	-1100
32075.25	9/2,11/2		$5f^9(^6F^o_{9/2})7s7p(^1P^o_1)$	
32125.29	9/2	1.37	$5f^9(^6F^o_{11/2})7s7p(^1P^o_1)$	
32147.66	11/2	1.425	$5f^9(^6F^o_{11/2})7s7p(^1P^o_1)$	
32279.32	13/2	1.26		2780
32341.42	13/2			3130
32477.01	15/2			3728
32477.06	7/2	1.060		
32533.23	9/2	1.457*		1200
32550.20	13/2	1.138	$5f^9(^6H^o_{13/2})7s7p(^1P^o_1)$	1007
32665.80	11/2	1.28	$5f^9(^6H^o_{13/2})7s7p(^1P^o_1)$	1100
32747.49	9/2	1.190		600
32799.82	11/2			1735
32903.61	11/2			1580
32956.25	9/2			1476
33191.97	13/2			3260
33229.89	15/2	1.102		870
33365.93	13/2	1.17		1173
33427.20	15/2			
33455.06	15/2			-460
33455.46	9/2			3150
33504.33	13/2			-200
33526.02	13/2	1.22		

33549.16	9/2	1.270		
33726.06	13/2			4460
33825.61	11/2			1950
33993.46	13/2	1.11		1193
34032.03	11/2			1150
34525.540	7/2	0.78		
34645.84	17/2			3470
34683.50	7/2	1.170		
34705.68	13/2			680
34861.48	13/2			
35067.51	11/2	1.135		
35467.89	11/2	1.135		
35532.58	9/2			1900
35560.37	9/2,11/2			2800
35583.27	15/2			
35814.60	13/2			1600
35827.21	9/2	1.255		465
35904.32	11/2			280
36228.48	13/2			2330
36361.78	9/2	1.40		1125
36441.24	15/2			1340
36478.43	11/2	1.21		1065
36554.62	15/2			345
36588.30	11/2			900
36817.65	13/2		$5f^9 7s7p$	740
36929.79	13/2			1670
36952.61	13/2		$5f^9 6d7p$	1800

37106.88	9/2	1.16		300
37149.29	7/2			1150
37164.49	15/2		$5f^9 6d7p$	480
37317.22	11/2	1.16		583
37613.27	11/2	1.11		-362
37789.81	11/2			
37971.67	13/2,15/2		$5f^9 6d7p$	1340
38001.89	9/2			260
38051.245	13/2			1000
38067.83	7/2	1.17		530
38193.76	9/2			
38274.69	9/2	1.285		
38329.77	11/2			563
38338.58	9/2	1.19		
38587.50	5/2	1.28		
38974.92	9/2	1.20		1183
39102.53	7/2	1.15		
39460.06	7/2			165
39569.77	19/2		$5f^9 6d7p$	1624
39620.83	9/2			1500
39628.10	7/2			65
39881.50	7/2	1.28		
39902.21	11/2			
40540.04	11/2			
41017.45	11/2			613
41093.41	9/2	1.21		
41172.48	9/2	1.27		480

41365.69	11/2	2250
41962.02	13/2	
42122.88	13/2	1260
42662.69	11/2	

a, 1 mK = 10^{-3} cm^{-1}.

* approximate value.

Table 4. The odd energy levels of singly ionized berkelium, ^{249}Bk II.

Energy Level (cm^{-1})	J odd	g odd	Configuration	Hyperfine[a] A (mK)	B (mK)	Width (mK)
0.000	8		$5f^9 7s\ ^7H^o$	104.6	279.	6195
1487.51	7		$5f^9 7s\ ^5H^o$	-65.9	241.	-3430
5598.10	6		$5f^9 7s\ ^7F^o$	126.9	61.	5800
6051.18	5		$5f^9 7s\ ^7F^o$	143.5	-45.	5645
6809.52	7		$5f^9 7s\ ^7H^o$	115.1	202.	6000
6906.07	5		$5f^9 7s\ ^5F^o$	-87.1	83.	-3290
7038.48	4		$5f^9 7s\ ^5F^o$	-120.1	23.	-3565
7786.75	6		$5f^9 7s\ ^5H^o$	-61.4	197.	-2680
10033.97	6		$5f^9 7s\ ^7H^o$			5170
10711.16	5	1.22	$5f^9 7s\ ^5H^o$			850
11080.94	4		$5f^9 7s\ ^5H^o$			-3400
11569.00	5		$5f^9 7s\ ^7H^o$			3000
11724.89	4		$5f^9 7s\ ^7F^o$			3600
16360.00	8		$5f^9(^6H^o_{15/2})6d_{3/2}$			670
16801.52	7		$5f^9(^6H^o_{15/2})6d_{3/2}$			750

18755.77	6	$5f^9(^6H^o_{15/2})6d_{3/2}$	680
19065.22	9	$5f^9 7s\ ^5K^o$	4540
19426.80	9	$5f^9(^6H^o_{15/2})6d_{3/2}$	2745
21743.92	6	$5f^9 6d$	430
22315.775	5	$5f^9(^6F^o_{11/2})6d_{3/2}$	-140
22428.94	8	$5f^9(^6H^o_{15/2})6d_{5/2}$	960
22752.20	4	$5f^9(^6F^o)6d$	1020
22967.80	10	$5f^9(^6H^o_{15/2})6d_{5/2}$	750
23400.91	9	$5f^9(^6H^o_{15/2})6d_{5/2}$	1170
23419.46	7	$5f^9 6d\ ^6H_{15/2},5/2$	640
23642.15	6	$5f^9 6d$	820
32025.72	6	$5f^8(^7F_6)7s7p(^3P^o_0)$	3445
32343.09	6		1015
33132.61	7	$5f^8(^7F_6)7s7p(^3P^o_1)$	6705
34643.65	5	$5f^8(^7F_6)7s7p(^3P^o_1)$	-3120
34664.01	5,6		-1944
35788.03	6	$5f^8(^7F_6)7s7p(^3P^o_1)$	-1265
40960.15	6		2810
41442.03	6		1084
41816.45	6,5		380

41859.13	7	1953
41950.33	5	550
42510.15	7,6	3370
43348.69	4	- 650
43665.550	6	4665
44065.44	6	100
49754.89	6,7	1250

a, 1 mK = 10^{-3} cm^{-1}.

Table 5. The even energy levels of singly ionized berkelium, ^{249}Bk II.

Energy Level (cm^{-1})	J even	g even	Not	Configuration	Hyperfine Width (mK) [a]
7040.98	6			$5f^8 7s^2\ ^7F$	820
10191.14	5			$5f^8 7s^2\ ^7F$	390
12340.96	8			$5f^8 6d7s\ ^9G$	8678
12558.97	7			$5f^8 6d7s\ ^9G$	5710
12583.03	6			$5f^8 6d7s\ ^9G$	4785
13889.43	5			$5f^8 6d7s\ ^9G$	2865
15644.42	6				-820
16240.01	6				1265
17405.79	6,5				2900
17957.73	7			$5f^8 6d7s\ ^7G$	-2250
18196.51	7,6,8				4175
21888.57	7				2080
23817.32	7				930
23861.38	7				3745
24234.54	8,7				-1945
25593.755	8			$5f^8 6d7s\ ^9H$	5710
26510.20	7				-115

26938.26	7	$5f^9(^6H^o_{15/2})7p_{1/2}$	2050
27157.155	8	$5f^9(^6H^o_{15/2})7p_{1/2}$	2085
28223.10	8	$5f^8 6d7s\ ^7H$	445
28280.11	5		740
28619.12	5		3430
28793.47	7		300
29512.29	7		2330
29969.76	6		3810
30301.30	6		735
30452.395	6		-1990
30786.30	7		4070
30998.71	5		4270
31387.425	5		1950
31529.34	4		2770
31747.47	5	$5f^9(^6F^o_{11/2})7p_{1/2}$	825
31778.43	6		-75
31921.40	5		- 100
32193.82	4	$5f^9(^6F^o_{9/2})7p_{1/2}$	850
32432.73	6	$5f^9(^6F^o_{11/2})7p_{1/2}$	1670
32815.405	5	$5f^9(^6F^o_{9/2})7p_{1/2}$	3270
32938.63	5	$5f^9(^6F^o_{9/2})7p_{1/2}$	1505
32940.15	6	$5f^9(^6H^o_{15/2})7p_{3/2}$	1805

33055.78	5			265
33566.35	7		$5f^9(^6H^o_{13/2})7p_{1/2}$	1732
33633.825	5,6			3020
33691.28	7			-923
33727.95	7,6			3300
33981.89	6			1125
34224.30	5,6			420
34594.29	8		$5f^9(^6H^o_{15/2})7p_{3/2}$	1640
34597.19	6			2140
34729.28	9		$5f^9(^6H^o_{15/2})7p_{3/2}$	2080
34808.96	6			810
34938.96	8			985
34947.72	7			2340
35157.63	7		$5f^9(^6H^o_{15/2})7p_{3/2}$	2725
35217.75	4,5			-30
35355.68	8			4355
35834.09	7			430
35938.78	5,4			-100
36064.36	9			2245
36095.62	5	1.27	$5f^9(^6H^o_{11/2})7p_{1/2}$	-130
36142.13	7,6			427
36294.88	6			1964
36344.08	6			1100
36347.20	5			2050

36379.08	7	$5f^9 7p$	950
36525.55	8,7		1390
36599.76	8,7		1650
36636.14	5,4,6		350
36765.94	6		2265
36913.33	5,6	$5f^9(^6H^o_{11/2})7p_{1/2}$	1955
37051.13	6,7		2220
37275.04	4,5	$5f^9(^6H^o_{9/2})7p_{1/2}$	420
37302.15	6,7		1865
37322.79	6		2500
37497.23	5		950
37688.35	5,6		730
38055.26	7,6		800
38185.91	5		100
38541.94	7		625
38704.84	5,6		900
38964.87	7		590
39368.45	5		2650
39600.28	7		1050
39742.20	7		1890
39848.50	7,8		1100
40057.16	7		3500
40383.76	6		2066
40463.62	3		600
40480.12	4		2460

40486.48	6	2075
40599.40	6	1345
40625.13	5	495
40637.75	6,7	1535
40747.49	5,6	2535
40880.79	7	- 150
40911.65	6	2445
40927.00	5	1375
40970.16	8	3210
41258.35	6,7	2194
41267.02	4,5	-425
41292.69	5,4	0
41333.80	6,7	1560
41489.08	7,6	2020
41496.54	7,6	500
41514.63	4,5	1240
41554.45	4,5	-200
41611.69	6	2535
41770.62	6,7	0
42011.97	7	2120
42358.38	6,7	2235
42557.58	5,6	1193
42660.32	6	1360
42923.84	5,6,7	550
43012.95	5	1400
43253.94	5,6,7	415
43481.63	6,7	1415

44149.02	6,7		1165
44555.91	5,6	$5f^9(^6H^o_{11/2})7p_{3/2}$	1810

a, 1 mK = 10^{-3} cm^{-1}.

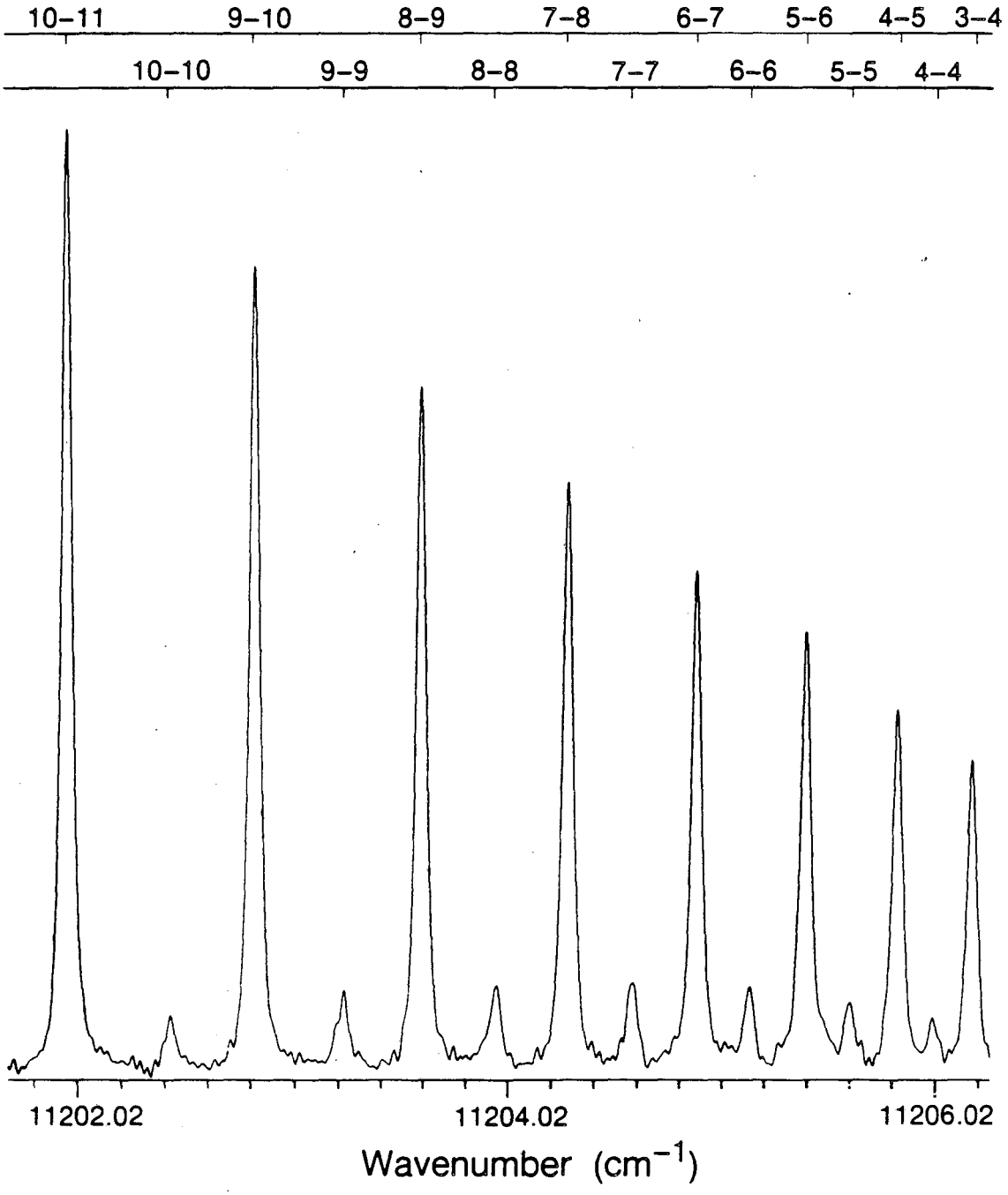

Figure 1. Tracing of the ^{249}Bk line at 11204.25 cm^{-1} taken on the Fourier transform spectrometer at Laboratoire Aime Cotton. The transition is from the odd level 34114.485 cm^{-1}, $5f^9(^6H^o_{15/2})7s8s(^3S_1)$, J=13/2, to the even level 22910.225 cm^{-1}, $5f^9(^6H^o_{15/2})7s7p(^3P^o_2)$, J=15/2. The F values, (F=I+J) are across the top of the figure.

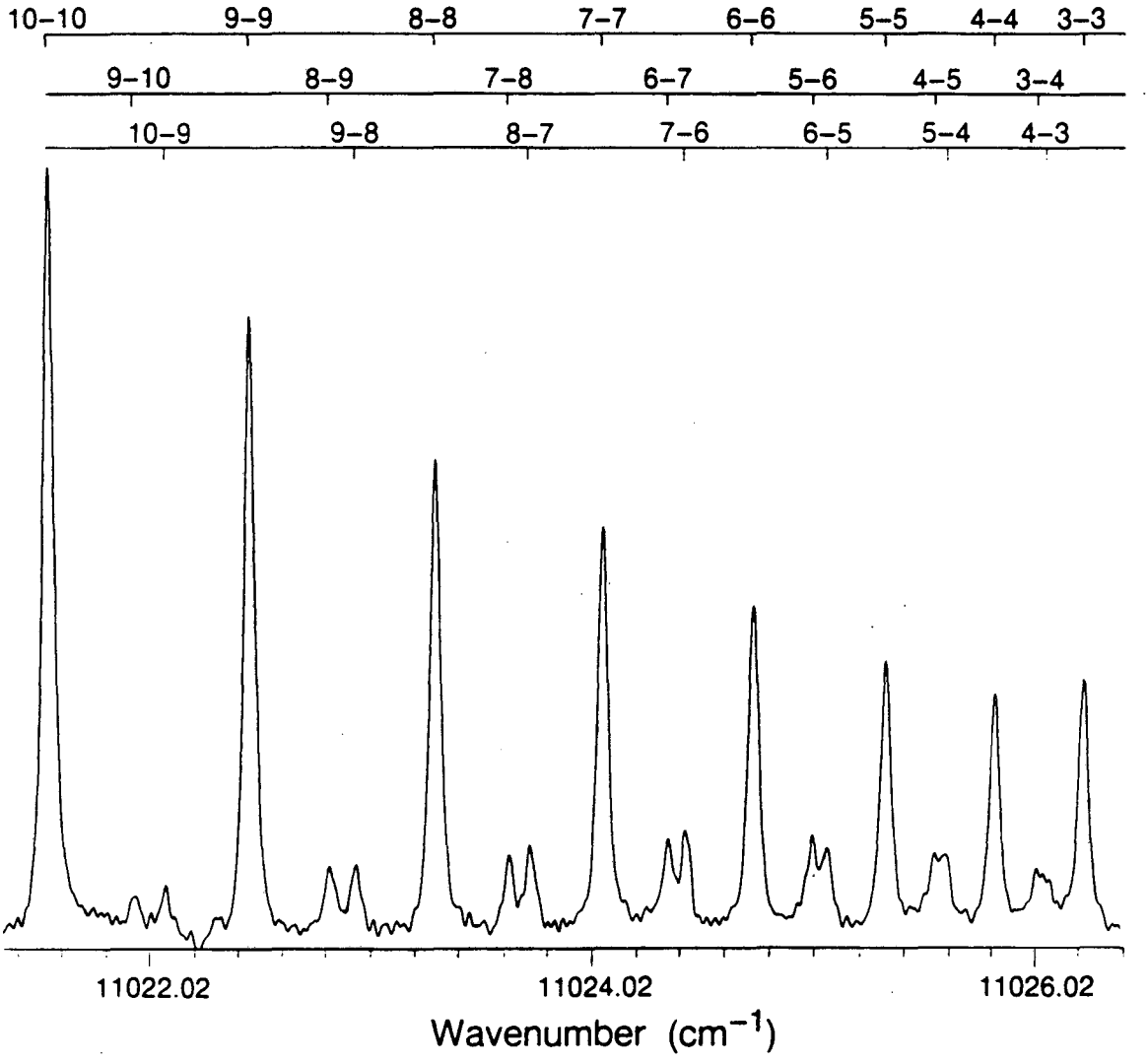

Figure 2. Fourier transform spectrometer tracing of the ^{249}Bk line at 11024.046 cm^{-1}. The transition is from the odd level 34114.485 cm^{-1}, $5f^9$ ($^6H^o_{15/2}$)7s8s($^3S_1$), J=13/2 to the even 23090.450 cm^{-1}, $5f^9$($^6H^o_{15/2}$)7s7p($^3P^o_2$), J=13/2. The same upper level as is in Fig 1 is involved. The F values are across the top of the figure.

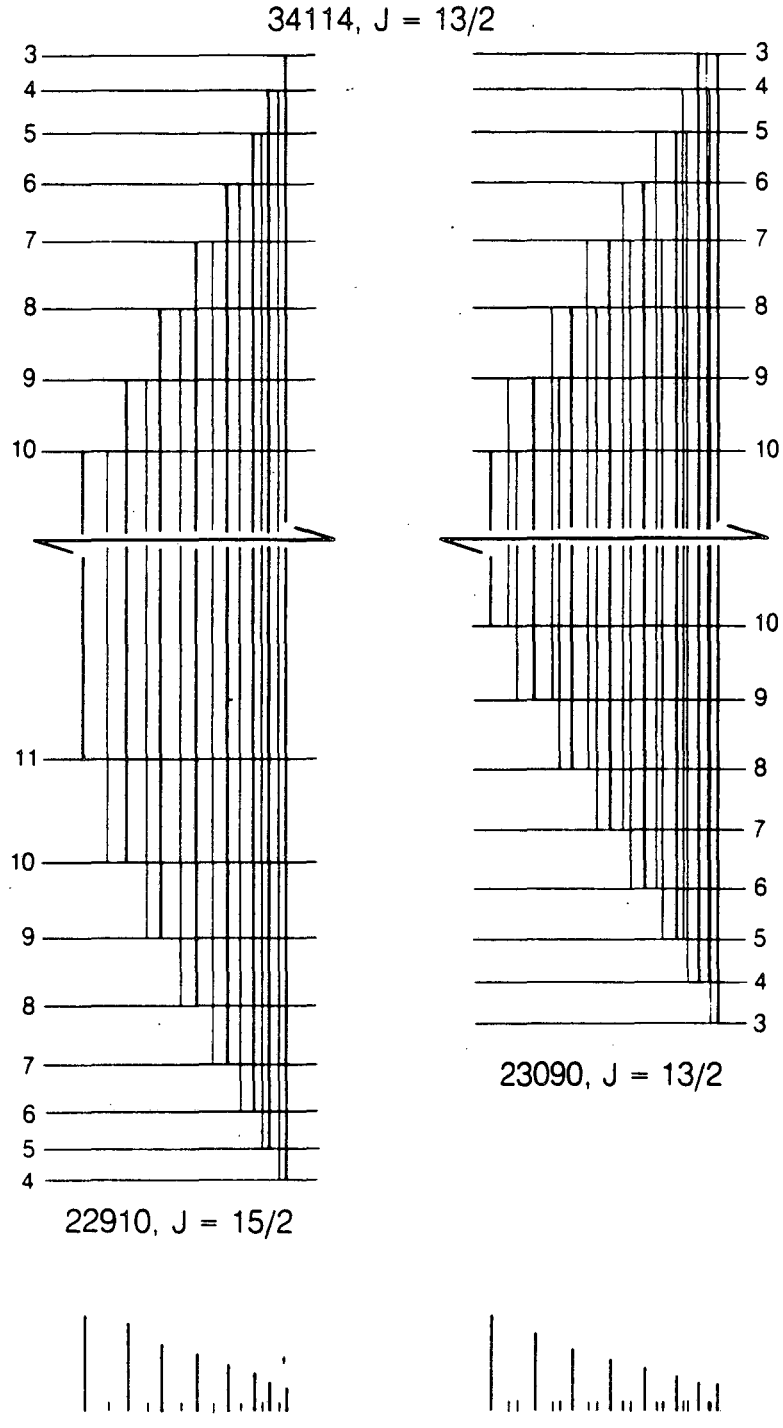

Figure 3. Energy level diagram of transitions 11204.260 and 11024.046 cm^{-1} shown in Fig's 1 and 2. The upper level is common to both transitions and has a sign opposite to the two lower levels. The number beside each hyperfine level indicates the F value.

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