
The Ångström ($B^1\Sigma^+ \rightarrow A^1\Pi$) Band System of $^{13}\text{C}^{16}\text{O}$: New Observations and Analyses

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The emission spectrum of the Ångström system ($B^1\Sigma^+ \rightarrow A^1\Pi$) of $^{13}\text{C}^{16}\text{O}$ was recorded and analysed by classical photographic spectroscopy. Under high resolution and with a precision estimated to be $0.010\text{--}0.020\text{ cm}^{-1}$ the bands 1-2, 1-7, and 0-6 were recorded for the first time and the 0-1, 0-2, 1-1, and 1-5 bands were rephotographed and reexamined. After the rotational analysis of the bands the following constants were calculated: (1) the rotational constants B_v , D_v for the $B^1\Sigma^+$ and $A^1\Pi$ states; (2) the equilibrium constants B_e , α_e , D_e , and β_e for the $B^1\Sigma^+$ state; (3) the ν_0 band origins. A combined analysis of the currently observed Ångström bands and the previously observed Herzberg ($C^1\Sigma^+ \rightarrow A^1\Pi$) and the ($E^1\Pi \rightarrow A^1\Pi$) bands made it possible to perform a precise relative characteristic of the $B^1\Sigma^+(v=0\text{ and }1)$, $C^1\Sigma^+(v=0)$ and $E^1\Pi(v=0)$ Rydberg levels in $^{13}\text{C}^{16}\text{O}$. Numerous rotational perturbations observed in the $A^1\Pi$ state were confronted with the perturbations predicted from the theoretical calculations.

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1. Introduction

It is well known that the carbon monoxide molecule is, after H_2 , the most abundant molecule in the universe. Its occurrence has been documented in the atmospheres of planets, in comet tails, solar and stellar atmospheres and interstellar space. Therefore a precise knowledge of the spectrum, the energetic structure and molecular constants is of crucial importance in astrophysics, but it is also important in other disciplines such as chemical physics, environmental investigations etc.

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The studies of the CO molecule performed in the last two decades were focused mainly on highly excited electronic states of this molecule, including the $B^1\Sigma^+$ state. The investigations of the $B^1\Sigma^+$ Rydberg state can be performed through the analyses of the following transitions: the Hopfield–Birge ($B^1\Sigma^+ \leftrightarrow X^1\Sigma^+$) band system, the Ångström ($B^1\Sigma^+ \rightarrow A^1\Pi$) system and the $B^1\Sigma^+ \rightarrow d^3\Delta$ transition and the Amiot–Roncin–Verges ($E^1\Pi \rightarrow B^1\Sigma^+$ and $C^1\Sigma^+ \rightarrow B^1\Sigma^+$) systems and the recently observed new transitions between highly excited $W^1\Pi$, $K^1\Sigma^+$, $L^1\Pi$ and $n = 8-10$ of the s , p , d , and f Rydberg states, and the $B^1\Sigma^+$ as a lower state.

The studies of the $B^1\Sigma^+$ state in $^{13}\text{C}^{16}\text{O}$ isotopic molecule were initiated by McCulloh and Glockler [1] and Douglas and Møller [2] who performed under low resolution fragmentary observations and analyses of selected Ångström bands. Comprehensive measurements made under high resolution and a rotational analysis of the bands of this system were performed by Rytel [3]. Janjić et al. [4] completed these investigations and analyses by weaker 1–4, 1–5, and 1–6 bands belonging to the $1-v''$ progression of the Ångström system. The observations and analyses of the $B^1\Sigma^+ \leftarrow X^1\Sigma^+$ system in $^{13}\text{C}^{16}\text{O}$ were initiated in paper [5], and considerably extended and enriched in [6]. The Fourier transform record of the $C^1\Sigma^+ \rightarrow B^1\Sigma^+$ (0–0) band in the four CO isotopomers also including $^{13}\text{C}^{16}\text{O}$ was performed by Roncin et al. [7].

In this work we present three so far unobserved 1–2, 1–7, and 0–6 bands as well as the reexaminations of the 0–1, 0–2, 1–1, and 1–5 bands belonging to the $B^1\Sigma^+ \rightarrow A^1\Pi$ system in $^{13}\text{C}^{16}\text{O}$. The objective of this study was to obtain more complete and more precise spectroscopic information about the $B^1\Sigma^+$ predissociated state allowing to calculate a more precise value of the first dissociation limit [8] and to extend the information about the nearby excited electronic states in the $^{13}\text{C}^{16}\text{O}$ molecule.

2. Experimental details

The emission spectrum of the Ångström system bands was excited in water-cooled Geissler-type tube filled with carbon monoxide enriched with carbon — ^{13}C , containing about a 90% concentration of the ^{13}C isotope. The pressure in the tube was about 0.1 kPa during the exposure of the 1–1, 1–2, 1–5, and 1–7 bands and was about 0.5 kPa during the recording of the 0–1, 0–2, and 0–6 bands. The tube was operated at about 5–7 kV and 50 mA AC. The emission spectra were photographed in the 4th, 5th and 6th orders of a 2 m plane grating Ebert spectrograph (PGS-2). The grating with 651 grooves/mm for a total of 45600 grooves is blazed at 1.0 μm . The observed resolving power was near to the theoretical value which changes from about 180000 to 273000, and the reciprocal linear dispersion changed from 0.072 to 0.088 nm/mm. The exposure time on ORWO WP-1 and WT-2 spectral plates changes from 1 h for the strongest 0–1 and 0–2 bands

TABLE I
 Statistical details of the analysed Ångström ($B^1\Sigma^+ - A^1\Pi$) bands of $^{13}\text{C}^{16}\text{O}$.

Band	Remarks	Band head [cm^{-1}]	Band origin ^a [cm^{-1}]	Total number of lines	J_{max}	$\sigma_f \times 10^3$ ^b [cm^{-1}]
0-1	reanal.	20704.46	20711.067(12) 20712.48(2) ^{c*}	116	40	6.64
0-2	reanal.	19289.54	19295.516(11) 19297.02(2) ^{c*}	111	39	9.13
0-6	first obs.	13954.64	13960.591(51)	70	26	29.2
1-1	reanal.	22741.24	22748.185(19) 22749.75(3) ^{c*}	56	20	7.88
1-2	first obs.	21326.33	21332.810(10)	57	20	9.97
1-5	reanal.	17277.64	17282.658(11) 17284.064(20) ^{d*}	55	19	9.99
1-7	first obs.	14743.72	14747.9535(64)	54	19	14.6

^aValues in parentheses denote one standard deviation in units of the last quoted digit. ^bStandard deviations of individual band fits. ^cAfter Rytel [3]. ^dAfter Janjić et al. [4]. *Values calculated with included $B_v\Lambda^2$ terms of the A state.

to 12 h for the 0-6 and 1-7 bands. As a calibration spectrum the Th standard lines [9] obtained from several overlapped orders of spectrum and emitted from a hollow-cathode type tube were used. The relative position of the lines was measured using an automatic comparator built in our laboratory. The line positions on the plate were controlled interferometrically and the line profiles were scanned photoelectrically. The positions of the centre of the lines were calculated using a nonlinear least squares procedure and assuming a Gaussian profile of the lines. The typical standard deviation of the least squares fit by fifth or sixth orders polynomials for about 50 calibration lines was about $(3-4) \times 10^{-3} \text{ cm}^{-1}$. The precision of the wave numbers of molecular lines is, however, considered to be $0.010-0.020 \text{ cm}^{-1}$, excluding the blended lines. The statistical information about the 0-1, 0-2, 0-6, 1-1, 1-2, 1-5, and 1-7 bands analysed in this work is collected in Table I and the experimental wave numbers can be obtained on request from the authors.

3. Calculation and results

The vibrational identification of the recorded for the first time bands and a preliminary J -numbering of the rotational lines followed from already known information about the $B^1\Sigma^+$ state [3, 6] and the $A^1\Pi$ state [3]. The final analysis of the bands and reduction of the spectrum to molecular constants have been performed in several stages, by means of a few methods and using the well-known Hamiltonians for both states involved in this transition: for the upper $B^1\Sigma^+$ state

$$\langle H \rangle = T_v + B_v J(J+1) - D_v J^2(J+1)^2,$$

and for the lower $A^1\Pi$ state, and its both Λ -components

$$\langle H \rangle = T_v + B_v [J(J+1) - 1] - D_v [J(J+1) - 1]^2,$$

where T_v is rotationless energy calculated with respect to the lowest rovibrational level in the $X^1\Sigma^+$ ground state. In order to determine the B_v and D_v rotational constants for the $v = 0$ and 1 levels of the $B^1\Sigma^+$ state, in the first stage of the calculations a method was used allowing to separate the information concerning only the upper levels in the observed transitions, a procedure proposed by Curl and Dane [10] and Watson [11]. This method has been chosen considering the conviction that the $v = 0$ and 1 levels in the $B^1\Sigma^+$ state were so far considered as regular ones, whereas the occurrence of numerous and extensive rotational perturbations was confirmed in the $A^1\Pi$ lower state. The final constant values for the $B^1\Sigma^+$ state were calculated using stepwise merged least squares fittings of bands of the $0-v''$ and $1-v''$ progressions as described in papers [12, 13]. On the basis of the determined B_0 , B_1 and D_0 and D_1 values, the B_e , α_e , D_e , and β_e , equilibrium rotational constants have been calculated for the levels near to the minimum of the potential curve for the B state in $^{13}\text{C}^{16}\text{O}$. The results are presented in Table II.

TABLE II
Rotational constants (in cm^{-1}) of the $B^1\Sigma^+$ state of $^{13}\text{C}^{16}\text{O}^a$.

	This work	Eidelsberg et al. [6]	Rytel [3]	Tilford and Vanderslice [5]
B_0	1.862517(55)	1.86258(14)	1.8625(1)	1.8624
B_1	1.838234(49)	1.83810(20)	1.8373(6)	1.8380
$D_0 \times 10^6$	6.142(28)	6.178(48)	6.20(7)	6.3
$D_1 \times 10^6$	6.748(67)	6.69(13)	5.8(12)	5.6
B_e	1.874659(74)	1.874 ₉		
$\alpha_e \times 10^2$	2.4283(86)	2.4 ₅		
$D_e \times 10^6$	5.839(54)	6.0		
$\beta_e \times 10^7$	6.06(73)			

^aValues in parentheses denote one standard deviation excluding Eidelsberg et al. [6] data (3σ) in units of the last quoted digit.

The calculation of the B_v and D_v rotational constants of the $A^1\Pi$ state as well as the $\nu_0(v'-v'')$ band origins was based on the carefully selected band lines with negligible effects of the perturbational interactions. By using a calculation based on the least squares method and with fixed constant values for the $v = 0$ and 1 levels of the $B^1\Sigma^+$ state there were calculated the B_v and D_v effective rotational constants for the $v = 1, 2, 5, 6$, and 7 levels of the $A^1\Pi$ state, which were collected in Table III.

TABLE III
Effective rotational constants
(in cm^{-1}) of the $A^1\Pi$ state levels
of $^{13}\text{C}^{16}\text{O}^a$.

	B_v	$D_v \times 10^6$
$v = 1$	1.511540(49)	6.623(35)
$v = 2$	1.489876(54)	6.125(51)
$v = 5$	1.424995(49)	7.80(14)
$v = 6$	1.40050(28)	5.56(34)
$v = 7$	1.380473(82)	8.50(21)

^aValues of constants of not deper-
turbed levels. Values in parenthe-
ses denote one standard deviation
in units of the last quoted digit.

By combining the lines of the currently analysed bands of the Ångström system with the corresponding lines of the earlier analysed bands of the Herzberg ($C^1\Sigma^+ \rightarrow A^1\Pi$) [14] and $E^1\Pi \rightarrow A^1\Pi$ [15] systems, according to the classical Jenkins and McKellar relations [16] precise differences of the rovibronic structure parameters of the $E^1\Pi(v = 0)$, $C^1\Sigma^+(v = 0)$ and $B^1\Sigma^+(v = 0, 1)$, Rydberg levels in $^{13}\text{C}^{16}\text{O}$ were calculated. The results were collected in Table IV.

TABLE IV
Molecular constants (in cm^{-1}) of the $B^1\Sigma^+(v = 0, 1)$ levels relative to $C^1\Sigma^+(v = 0)$ and $E^1\Pi(v = 0)$ levels of $^{13}\text{C}^{16}\text{O}^a$.

	$x = B^1\Sigma^+(v = 1)$	$x = C^1\Sigma^+(v = 0)$	$x = E^1\Pi(v = 0)$
$\nu_0^{X-B}(v_x - 0)$	2037.2531(28) 2037.3 ₂ ^b 2037.320(9) ^d	5002.2319(20) 5002.204(12) ^c	6014.8354(56)
$\nu_0^{X-B}(v_x - 1)$		2964.9227(29)	3977.5652(57)
$(B_0^B - B_{v_x}^X) \times 10^2$	2.4466(37) 2.467(5) ^d	0.4022(17)	-1.5536(57) ^e -0.439(36) ^f
$(B_1^B - B_{v_x}^X) \times 10^2$		-2.0415(35)	-3.9666(53) ^e -2.8507(60) ^f
$(D_0^B - D_{v_x}^X) \times 10^7$	1.89(86)	4.46(29)	-0.98(21) ^e -9.43(38) ^f
$(D_1^B - D_{v_x}^X) \times 10^7$		5.87(85)	5.24(15) ^e 13.6(18) ^f

^aValues in parentheses denote one standard deviation in units of the last quoted digit. ^bAfter Eidelsberg et al. [6]. ^cAfter Roncin et al. [7]. ^dAfter Rytel [3]. ^{e,f}Values for the ϵ and f parity of the Λ -doubling sublevels of the $E^1\Pi$ state, respectively.

4. Perturbations of the $A^1\Pi$ state

Table V presents the comparison of the perturbations observed and predicted for both Λ -doubling components of the $A^1\Pi$ state in the $^{13}\text{C}^{16}\text{O}$ molecule.

It is known that the $A^1\Pi$ state of the CO molecule belongs to the most extensively and most intensively perturbed states among diatomic molecules. In the region of 60000 cm^{-1} in addition to the $A^1\Pi$ state, five other ($I^1\Sigma^-$, $D^1\Delta$, $e^3\Sigma^-$, $a'^3\Sigma^+$ and $d^3\Delta$) electronic states are located. Therefore in each vibrational

TABLE V
Observed and predicted perturbations of the $A^1\Pi$ state in $^{13}\text{C}^{16}\text{O}$.

$A^1\Pi(v)$	Maximum perturbation (J) of the Λ -doubling component:				Perturbing state	
	f		e		triplet component	vibrational level
	obs.	calc.	obs.	calc.		
0	11–12	7–8	8–9 14–15	4–5 10–11	$F(1)$ $F(2)$ $F(3)$	$e^3\Sigma^-(v=1)$
	23–24 27–28 31–32	23–24 27–28 31–32	23–24 27–28 31–32	23–24 27–28 31–32	$F(1)$ $F(2)$ $F(3)$	$d^3\Delta_i(v=4)$
	34–35	34 40	~ 37	37	$F(1)$ $F(2)$ $F(3)$	$a'^3\Sigma^+(v=9)$
	13–14 19–20	12–13 18–19	16–17	15–16	$F(1)$ $F(2)$ $F(3)$	$a'^3\Sigma^+(v=10)$
1	27–28 35–36	27–28 35–36	27–28	27–28		$D^1\Delta(v=1)$ $I^1\Sigma^-(v=2)$
		43–44	~ 39	40–41 46–47	$F(1)$ $F(2)$ $F(3)$	$e^3\Sigma^-(v=3)$
2	7–8	8–9				$I^1\Sigma^-(v=3)$
	28–29	28–29	25–26 31–32	25–26 31–32	$F(1)$ $F(2)$ $F(3)$	$e^3\Sigma^-(v=4)$
	33–34 37–38	33 37 41	33–34 37–38	33 37 41	$F(1)$ $F(2)$ $F(3)$	$d^3\Delta_i(v=7)$
	37	36–37 42–43	~ 40	39–40	$F(1)$ $F(2)$ $F(3)$	$a'^3\Sigma^+(v=12)$

TABLE V (cont.)

$A^1\Pi(v)$	Maximum perturbation (J) of the Λ -doubling component:				Perturbing state	
	f		e		triplet component	vibrational level
	obs.	calc.	obs.	calc.		
3	13-14	12-13	13-14	12-13	$F(1)$	$d^3\Delta_i(v=8)$
	17-18	16-17	17-18	16-17	$F(2)$	
	21-22	20-21	21-22	20-21	$F(3)$	
	20-21	20-21	23-24	23-24	$F(1)$	$a'^3\Sigma^+(v=13)$
	26-27	26-27			$F(2)$	
					$F(3)$	
	34	35	34	35		$D^1\Delta(v=4)$
		41-42				$I^1\Sigma^-(v=5)$
4	4-5	5-6	4-5	5-6		$D^1\Delta(v=5)$
	24	23-24				$I^1\Sigma^-(v=6)$
	~ 37	37	34-35	34	$F(1)$	$e^3\Sigma^-(v=7)$
				40	$F(2)$	
					$F(3)$	
				42	$F(1)$	$a'^3\Sigma^+(v=15)$
		39			$F(2)$	
		45			$F(3)$	
		39	39	$F(1)$	$d^3\Delta_i(v=10)$	
		43	43	$F(2)$		
		47	47	$F(3)$		
5	16-17	16-17	13-14	13-14	$F(1)$	$e^3\Sigma^-(v=8)$
			19-20	19-20	$F(2)$	
					$F(3)$	
	23-24	25	26-27	28	$F(1)$	$a'^3\Sigma^+(v=16)$
	29-30	31			$F(2)$	
					$F(3)$	
25-26	25-26	25-26	25-26	$F(1)$	$d^3\Delta_i(v=11)$	
29-30	29-30	29-30	29-30	$F(2)$		
33-34	33-34	33-34	33-34	$F(3)$		
38-39	38-39	38-39	38-39		$D^1\Delta(v=7)$	
6	< 1	< 1	< 1	< 1	$F(3)$	$d^3\Delta_i(v=12)$
	17-18	19-20	17-18	19-20		$D^1\Delta(v=8)$
	~ 30	31				$I^1\Sigma^-(v=9)$
		37		40	$F(1)$	$a'^3\Sigma^+(v=18)$
		43			$F(2)$	
				$F(3)$		

TABLE V (cont.)

$A^1 \Pi(v)$	Maximum perturbation (J) of the Λ -doubling component:				Perturbing state	
	f		e		triplet component	vibrational level
	obs.	calc.	obs.	calc.		
6		43		40	$F(1)$	$e^3 \Sigma^-(v = 10)$
				46	$F(2)$ $F(3)$	
7		29		26	$F(1)$	$e^3 \Sigma^-(v = 11)$
				32	$F(2)$ $F(3)$	
		27–28		30–31	$F(1)$	
		33–34			$F(2)$ $F(3)$	
		33		33	$F(1)$	$d^3 \Delta_i(v = 14)$
		37		37	$F(2)$	
	41		41	$F(3)$		
8		15–16		15–16	$F(1)$	$d^3 \Delta_i(v = 15)$
		19–20		19–20	$F(2)$	
		23–24		23–24	$F(3)$	
		22–23		22–23		$D^1 \Delta(v = 11)$
		34–35				$I^1 \Sigma^-(v = 12)$
9		40		43	$F(1)$	$a'^3 \Sigma^+(v = 20)$
		46			$F(2)$ $F(3)$	
		13–14				
		27–28		30–31	$F(1)$	$a'^3 \Sigma^+(v = 22)$
		33–34			$F(2)$ $F(3)$	
	35–36		32–33	$F(1)$	$e^3 \Sigma^-(v = 14)$	
			38–39	$F(2)$ $F(3)$		
	40		40			$D^1 \Delta(v = 13)$
10		38–39		38–39	$F(1)$	$d^3 \Delta_i(v = 17)$
		42–43		42–43	$F(2)$	
		46–47		46–47	$F(3)$	
		6–7		9–10	$F(1)$	$a'^3 \Sigma^+(v = 23)$
		12–13			$F(2)$ $F(3)$	

TABLE V (cont.)

$A^1\Pi(v)$	Maximum perturbation (J) of the Λ -doubling component:				Perturbing state	
	f		e		triplet component	vibrational level
	obs.	calc.	obs.	calc.		
10		17–18		14–15 20–21	$F(1)$ $F(2)$ $F(3)$	$e^3\Sigma^-(v=15)$
		24–25		24–25		$D^1\Delta(v=14)$
		25–26 29–30 33–34		25–26 29–30 33–34	$F(1)$ $F(2)$ $F(3)$	$d^3\Delta_i(v=18)$
		36–37				$I^1\Sigma^-(v=15)$
		38–39 44–45		41–42	$F(1)$ $F(2)$ $F(3)$	$a'^3\Sigma^+(v=24)$

level of the A state there are observed the perturbations of the rotational structure. Identification analyses and deperturbation calculations in $^{12}\text{C}^{16}\text{O}$ have also been performed repeatedly by Le Floch et al. [17]. The perturbation analyses of the $A^1\Pi$ state in isotopic molecules can provide additional information about interacting states and they also allow to verify the already known perturbations and the energetic structure constants in the $^{12}\text{C}^{16}\text{O}$ molecule. The present analysis of perturbations of the $A^1\Pi$ state in the $^{13}\text{C}^{16}\text{O}$ molecule has been performed in the aspect of the confrontation of the perturbations observed and predicted on the basis of the theoretical calculations. The identification and classification of the observed perturbations have been performed by employing the $f_x(J)$ and $g_x(J)$ where $x = Q, PR$ and \overline{PR} functions introduced by Kovacs [18]. The analysis of the course of these functions calculated by using the lines of the respective branches and bands allows to localize (J) and identify the perturbing state. In this way there were also analysed both the bands currently recorded and earlier analysed bands belonging to the Ångström [3, 4], Herzberg [14] as well as the $E^1\Pi \rightarrow A^1\Pi$ [15] systems in $^{13}\text{C}^{16}\text{O}$. The predicted perturbations for both Λ -doubling components in the region of the $v = 0-10$ and $J = 1-40$ levels were calculated by using rovibronic term crossing diagrams of the $A^1\Pi$ and nearby $I^1\Sigma^-$, $D^1\Delta$, $e^3\Sigma^-$, $a'^3\Sigma^+$, and $d^3\Delta$ states. The respective calculations were performed by making use of the rovibronic structure constants for the A , I , e , a' , and d states obtained by Field [19] and by means of the constants for the D state derived by Kittrell and Garetz [20] and recalculated for the $^{13}\text{C}^{16}\text{O}$ molecule by means of standard isotope relations.

5. Discussion and conclusion

In addition to the analysis of the observed for the first time the 1–2, 1–7, and 0–6 bands the present work gives new observations and reexaminations of the 0–1, 0–2, 1–1, and 1–5 bands belonging to the $B^1\Sigma^+ \rightarrow A^1\Pi$ system in $^{13}\text{C}^{16}\text{O}$. The applied high resolution and high precision of the measurements allowed to precise and extend the information, especially about the $B^1\Sigma^+$ state. The performed observations and analyses also confirmed the occurrence of predissociation of the $B^1\Sigma^+$ state in the $^{13}\text{C}^{16}\text{O}$ molecule for the $v = 0$ and $J_{\text{max}} = 39$ levels as well as for the $v = 1$ and $J_{\text{max}} = 19$ levels [6]. Also the application of the Jenkins and McKellar procedure for the intrasystem analysis of the Ångström system bands as well as for the analysis of the Ångström and Herzberg and $E^1\Pi \rightarrow A^1\Pi$ system bands, which is a method eliminating the effects of the $A^1\Pi$ state perturbations, allowed to determine precisely the differences of the rovibronic constants for the $B^1\Sigma^+(v = 0 \text{ and } 1)$ and $C^1\Sigma^+(v = 0)$ and $E^1\Pi(v = 0)$ Rydberg levels in the $^{13}\text{C}^{16}\text{O}$ molecule. The careful analysis of the distribution of the $B^1\Sigma^+$ state terms also confirmed the occurrence of the earlier suggested [4] rotational perturbation in the $v = 1$ level reaching a maximum of $F_{\text{obs}}^B(J) - F_{\text{calc}}^B(J) \approx -0.050 \text{ cm}^{-1}$ for $J = 7$. The analysis of the extensive $A^1\Pi$ state perturbations revealed that in the range of the observed vibrational and rotational levels there is a full agreement of perturbations observed in the $^{13}\text{C}^{16}\text{O}$ molecule and the perturbations predicted on the basis of the analyses and data concerning the $^{12}\text{C}^{16}\text{O}$ molecule.

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References

- [1] K.E. McCulloh, G. Glockler, *Phys. Rev.* **89**, 145 (1953).
- [2] A.E. Douglas, C.K. Møller, *Can. J. Phys.* **33**, 125 (1955).
- [3] M. Rytel, *Acta Phys. Pol. A* **37**, 559 (1970).
- [4] J. Janjić, J. Danielak, R. Kępa, M. Rytel, *Acta Phys. Pol. A* **41**, 757 (1972).
- [5] S.G. Tilford, J.T. Vanderslice, *J. Mol. Spectrosc.* **26**, 419 (1968).
- [6] M. Eidelsberg, J.-Y. Roncin, A.C. Le Floch, F. Launay, C. Letzelter, J. Rostas, *J. Mol. Spectrosc.* **121**, 309 (1987).
- [7] J.-Y. Roncin, A. Ross, E. Boursey, *J. Mol. Spectrosc.* **162**, 353 (1993).
- [8] R. Kępa, unpublished.
- [9] B.A. Palmer, R. Engleman Jr, *Atlas of the Thorium Spectrum*, Los Alamos National Laboratory, Los Alamos NM 1983.
- [10] R.F. Curl, C.B. Dane, *J. Mol. Spectrosc.* **128**, 406 (1988).

- [11] J.K.G. Watson, *J. Mol. Spectrosc.* **138**, 302 (1989).
- [12] D.L. Albritton, A.L. Schmeltekopf, R.N. Zare, *J. Mol. Spectrosc.* **67**, 132 (1977).
- [13] J.A. Coxon, *J. Mol. Spectrosc.* **72**, 252 (1978).
- [14] R. Kępa, *Acta Phys. Hung.* **45**, 133 (1978).
- [15] R. Kępa, M. Rytel, Z. Rzeszut, *Acta Phys. Pol. A* **54**, 355 (1978).
- [16] G. Herzberg, *Molecular Spectra and Molecular Structure*, Vol. 1, *Spectra of Diatomic Molecules*, Van Nostrand, Princeton 1950, p. 188.
- [17] A.C. Le Floch, F. Launay, J. Rostas, R.W. Field, C.M. Brown, K. Yoshino, *J. Mol. Spectrosc.* **121**, 337 (1987) and references therein.
- [18] I. Kovacs, *Rotational Structure in the Spectra of Diatomic Molecules*, Akadémiai Kiado, Budapest, Hilger, London 1969, pp. 288, 297.
- [19] R.W. Field, Ph.D. thesis, Harvard University, Cambridge, MA 1971.
- [20] C. Kittrell, B.A. Garetz, *Spectrochim. Acta A* **45**, 31 (1989).