THE BAND SPECTRA OF SCANDIUM-, YTTRIUM-, AND LANTHANUM MONOXIDES

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ABSTRACT

The ordinary arc spectra of scandium, yttrium, and lanthanum show, in addition to lines characteristic of neutral and ionized atoms, complex banded structures which are ascribed to a molecular compound of the atoms with oxygen. These bands have the same general appearance as those due to well-known diatomic molecules and are, therefore, attributed to ScO, YO, and LaO, rather than to the chemically stable oxides Sc_2O_3, Y_2O_3, and La_2O_3.

Electric arcs between silver electrodes with some salt of the element under investigation placed on the lower electrode were employed as sources, the salt being either pure scandium oxide, yttrium chloride, or yttrium oxalate, or lanthanum chloride or oxalate. The spectra were photographed with concave gratings of 21½ feet radius of curvature, the gratings and order of spectrum being chosen so that the dispersion was 1.8 A/mm in the ultra-violet and blue, 3.7 A/mm in the remainder of the visible, and 10.4 A/mm in the infra-red. Wave lengths of band heads were measured relative to standards in the arc spectrum of iron, and the relative intensities of the various bands were estimated.

The band spectra of these oxides are so complex that the fine structure of the individual bands has not been sufficiently well resolved to permit analysis of the rotation energies, consequently only a description of band heads and their classification in various systems resulting from transitions between a number of vibration levels of initial and final electronic states can be given. Examination of the ScO spectrograms revealed 139 band heads, all of which are degraded to red. These bands have been divided into 5 systems, the 0,0 transitions giving heads at I, 4857.79 A, 4858.09 A; II, 6017.07 A; III, 6036.17 A; IV, 6064.31 A; V, 6079.30 A. In the YO spectrum 120 band heads have been recognized, and all of them are degraded redwards. The structure of the YO spectrum is very similar to that of ScO; analysis shows that it also consists of 5 systems, the 0,0 transitions of which are at I, 4817.38 A, 4818.20 A; II, 5939.08 A; III, 5972.04 A; IV, 6096.78 A; V, 6132.06 A. The spectrum emitted by the LaO molecule is exceedingly complex; more than 300 band heads have been measured, and it is very likely that all of the bands are close doubles separated by about half a wave number. The complete molecular spectrum can be divided into 9 systems, 7 of which include all of the bands shaded to red, and the remaining 2 consist of groups of weaker bands shaded in the opposite direction. The former systems have their 0,0 bands at I, 4371.872 A, 4371.968 A; II, 4418.142 A, 4418.240 A; III R, 5599.89 A, 5600.02 A, III, Q, 5602.36 A, 5602.50 A; IV, 7379.84 A; V, 7403.52 A; VI, 7876.87 A, 7877.27 A; VII, 7910.19 A, 7910.54 A.

CONTENTS

I. INTRODUCTION

The atomic spectra of scandium, yttrium, and lanthanum have been under investigation at this bureau since 1925, and it was found necessary in each case to make new descriptions [1] of the spectra before their structures could be satisfactorily analyzed. The ordinary arc spectrum of each of these elements is encumbered with a complex band spectrum which is ascribed to a molecular compound of the element with oxygen. The experimental proof for this is that the bands can be suppressed in a vacuum arc or in a hydrogen atmosphere and they do not appear in vacuum furnace spectra. The observed bands are believed to be due to ScO, YO, and LaO rather than to the chemically stable oxides Sc_2O_3, Y_2O_3, and La_2O_3 because the bands have the same appearance as those due to known diatomic molecules and are very different from the few which are known to be emitted by polyatomic molecules, and which as far as we know have never been obtained in an electric arc. These bands are very much subdued in a high potential condensed spark discharge in which the molecular compounds are dissociated and the atoms mostly ionized. Their presence in ordinary arc spectra is a great annoyance, making it very difficult to find the weaker arc lines in regions covered by the bands. In making the new descriptions of atomic spectra referred to above the more or less sharply defined heads of the unavoidable bands were measured and assigned in the wave-length tables to the molecular spectrum. Although these molecular spectra are very prominent and beautiful and some of the principal band heads have been in the literature for many years, no effort was made to interpret them until recently.

In 1927 Mecke and Guillery [2] presented one system of ScO bands, but we find that this analysis is a mixture of two different systems. We shall give in this paper an analysis of five different systems of bands due to ScO. To the best of our knowledge nothing has been published on the interpretation of YO bands; we shall present an analysis of five systems of bands. The spectrum of LaO is considerably more complex than either ScO or YO; an analysis of seven systems was first published by Mecke,[3] and a revised and more extended analysis has been given by Jevons.[4] In some cases our spectrograms show even more bands than Jevons has published, and since our photographs were made with larger dispersion we feel that our wave-length measurements of band heads may be somewhat more accurate. We are accordingly presenting an analysis of seven systems of LaO bands which agrees in the main with that of Jevons.

By way of introduction, a brief general description of electronic band spectra of diatomic molecules is included here, so that readers unfamiliar with the nature and theory of these spectra can more readily understand them. The entire spectrum of 1 molecule can always be subdivided into a number of "systems," each system consisting of a number of "sequences" of band heads. These sequences are easily recognized in many spectra; they usually consist of a group of neighboring bands distributed over a limited range of spectrum with obvious

[1] Meggers, Wave Length Measurements in the Arc Spectrum of Scandium, B. S. Sci. Paper No. 549, 22, p. 61; 1927. Wave Lengths and Zeeman Effects in Yttrium Spectra, B. S. Research Paper No. 12, 1, p. 319; 1928. Wave Lengths and Zeeman Effects in Lanthanum Spectra (to be published soon).
[2] Mecke and Guillery, Physikalische Zeitschrift, 28, p. 514; 1927.
[3] Mecke, Naturwissenschaften, 17, p. 86; 1929.
[4] Jevons, Proc. Phys. Soc., London, 41, p. 520; 1929.

regularity in spacing and relative intensity. These sequences of band heads are the starting point for the analysis of band systems. The individual band heads are characteristic of molecular spectra and are quite different from atomic spectral lines. Each band has a fairly sharp edge or "head" from which the intensity falls off on one side or the other. If the intensity diminishes with decreasing wave number the band is said to degrade or shade to the red; if it declines toward increasing wave numbers the band is said to degrade or shade to the violet. In some cases the band heads are most favorably seen in spectra of relatively low dispersion; with very high dispersion and large resolving power the bands are seen to consist of many fine lines packed immeasurably close at the head and spaced more widely with increasing distance from the head. In some cases high resolving power shows that what appeared under low dispersion to be a single head may in reality be two or more heads. The fine lines of a band can often be recognized as belonging to two or more "branches," the number and arrangement of which, depend essentially upon the electronic configurations of the molecule.

The very excellent account of molecular spectra given by Jevons [5] is quoted here, with the notation changed to conform with that recommended by Mulliken,[6] and with certain minor changes made in the text:

The theory of molecular spectra attributes the emission of a line of wave number νcm^{-1} (frequency νc per second) to a transition in the molecule from an excited state (or energy level) in which the energy is E' to a less excited, or the unexcited level, of energy E'', in accordance with the quantum condition $\nu=(E'-E'')/hc=T'-T''$, where T' and T'' are the term-values of the more excited and less excited states, respectively. The absorption of the same line accompanies the opposite transition $E'\leftarrow E''$. The energy of a molecule is regarded somewhat arbitrarily as the sum of three parts, the electronic energy ($E_e=hcT_e$), energy of nuclear vibration ($E_v=hcG$), and energy of molecular rotation ($E_r=hcF$), where $E_e \gg E_v \gg E_r$. In other works, a molecule has a number of fairly widely spaced electronic energy levels (specified by a group of electronic quantum numbers abbreviated by e); each electronic level has associated with it a set of more closely spaced vibrational energy levels (specified by successive integral values of a vibrational quantum number v), and each of these has a set of much more closely spaced rotational energy levels (specified by successive values of a rotational quantum number J, of which Ω is the component measuring the nuclear angular momentum in units $h/2\pi$). Thus the wave number of the line emitted in a transition $T'\rightarrow T''$ is

$$\begin{aligned}\nu &= (T'_e - T''_e) + (G' - G'') + (F' - F'') \\ &= \nu_e + \nu_v + \nu_r,\end{aligned} \qquad (1)$$

where $\nu_e \gg \nu_v \gg \nu_r$ in the general case (that is, that of electronic bands) when E_e, E_v, and E_r all change. For a given band ν_r varies from line to line, while $\nu_e+\nu_v$ is constant and defines the band origin ($\nu_r=0$). For a given system ν_v varies from band to band, ν_e being constant and defining the system origin.

The energy of a molecular vibration is given approximately by the new quantum mechanics as

$$E_v = hcG = hc[\omega_0(v+\tfrac{1}{2}) - \omega_0 x\,(v+\tfrac{1}{2})^2],\ (v=0,\ 1,\ 2,\ 3,\ \text{---}) \qquad (2)$$

where $c\omega_0$ per second is called the frequency of vibration of infinitesimal amplitude for the nonrotating molecule, and x is a small constant. The electronic transition accompanying the emission of light by the molecule involves changes in both ω_0

[5] Jevons, Proc. Phys. Soc. London, 41, p. 538; 1929.
[6] Mulliken, Phys. Rev., 36, p. 911; 1930.

and $\omega_0 x$, and for the band origins ($\nu_r=0$) in the system arising from the transition we have

$$\begin{aligned}\nu_{\text{origin}} &= \nu_e + G' - G'' \\ &= \nu_e + [\omega_0'(v'+\tfrac{1}{2}) - \omega_0' x'(v'+\tfrac{1}{2})^2] - \\ &\quad [\omega'_0{}'(v''+\tfrac{1}{2}) - \omega_0'' x''(v''+\tfrac{1}{2})^2]\end{aligned} \tag{3}$$

There is no selection rule limiting the amount of the change $v'-v''$.

As the positions of the origins are known for comparatively few bands, we must consider the positions of the band heads, by discussing briefly the line structure of a simple type of electronic band. The energy of rotation of a molecule may be written as $E_r=hcF\ (J)$ where $F\ (J)$ is a function which differs in form from one electronic state of a molecule to another. Its simplest form is $F\ (J)=B_v(J+\tfrac{1}{2})^2$, where B_v is a function of v which can be expanded in a power series

$$\begin{aligned}B_v &= B_e - \alpha_e(v+\tfrac{1}{2}) + \gamma_e(v+\tfrac{1}{2})^2 - \cdots \\ &= \frac{h}{8\pi^2 c I_e} - \alpha_e(v+\tfrac{1}{2}) + \cdots\end{aligned} \tag{4}$$

I_e being the moment of inertia of the molecule in the electronic state in question. Usually for a first approximation we may use Ω for J and write

$$F(J) \doteq B_v \Omega^2 \doteq B_e \Omega^2 \tag{5}$$

The electronic change is accompanied by a change in I_e as well as in ω_0, $\omega_0 x$, and other molecular constants. Hence, the wave number of the $\Omega \rightarrow \Omega$ line of the $N' \rightarrow N''$ band is given by

$$\nu = \nu_e + \nu_v + F'(J') - F''(J'') \doteq \nu_e + \nu_v + B_e'\Omega'^2 - B_e''\Omega''^2 \tag{6}$$

The change $J'-J''$ is always restricted to 1, 0, and -1, and the series of lines corresponding to each of these three values is called a branch, distinguished, respectively, by the names R or "positive," Q or "zero," and P or "negative." Putting $(\Omega''+1)$, Ω'', and $(\Omega''-1)$ in turn for Ω' in formula (6) we obtain approximate expressions for the branches:

$$\begin{aligned}\nu_R &\doteq \nu_e + \nu_v + B_e' + 2\ B_e'\Omega'' + (B_e' - B_e'')\Omega''^2 \\ 2_Q &\doteq \nu_e + \nu_v + (B_e' - B_e'')\Omega''^2 \\ \nu_P &\doteq \nu_e + \nu_v + B_e' - 2\ B_e'\Omega'' + (B_e' - B_e'')\Omega''^2\end{aligned} \tag{7}$$

Now if there is a decrease in the moment of inertia during the emission of light, $I_e' > I_e''$ and $(B_e' - B_e'')$ is negative; accordingly as Ω is given increasing values, formula (7) shows that the lines in the P and Q branches draw away from the origin toward longer wave lengths (smaller frequencies) at a constantly increasing rate; on the other hand, the lines of the R branches start out toward shorter wave lengths, get closer and closer together, forming a head, and then start back to longer wave lengths at an increasing rate. The value of Ω giving the maximum excursion of the R lines to the violet is from formula (7) approximately $\frac{B_e'}{B_e'' - B_e'}$, and the separation between the R head and the origin is accordingly

$$\nu_{R\ \text{head}} - \nu_{\text{origin}} \doteq \frac{B_e' B_e''}{B_e'' - B_e'} \tag{8}$$

Such a band degrades toward the red.

If, on the other hand, the moment of inertia increases during the emission, $B_e' > B_e''$ and the R and Q branches draw away at an increasing rate from the origin toward shorter wave lengths (higher frequencies); the P branch, however, drawing away to longer wave lengths, soon comes to a head and then returns toward shorter wave lengths. In this case the separation between the P head and the band origin is

$$\nu_{P\ \text{head}} - \nu_{\text{origin}} = \frac{B_e' B_e''}{B_e' - B_e''} \tag{9}$$

This type of band is said to degrade to the violet.

With this knowledge of the separation between band heads and band origins, we should be able to correct equation (3) for origins to fit the observed band heads. Doing so, we have to a first approximation

$$\nu_{\text{head}} \doteq \nu_{\text{origin}} + \frac{B_e' B_e''}{B_e'' - B_e'} \tag{10}$$

$$\doteq \nu_e + [\omega_0'(v'+\tfrac{1}{2}) - \omega_0' x'(v'+\tfrac{1}{2})^2] -$$

$$[\omega_0''(v''+\tfrac{1}{2}) - \omega_0'' x''(v'+\tfrac{1}{2})^2] + \frac{B_e' B_e''}{B_e'' - B_e'}$$

In general, this approximation is not very good, because we have been using B_v instead of $B_v \equiv B_e - \alpha_e(v+\tfrac{1}{2}) + \cdots$. We can improve it by substituting B_v for B_e in (10):

$$\nu_{\text{head}} \doteq \nu_e + [\omega_0'(v'+\tfrac{1}{2}) - \omega_0' x'(v'+\tfrac{1}{2})^2] - [\omega_0''(v''+\tfrac{1}{2}) - \omega_0'' x''(v''+\tfrac{1}{2})^2]$$

$$+ \frac{[B_e' - \alpha_e'(v'+\tfrac{1}{2})]\ [B_e'' - \alpha_e''(v''+\tfrac{1}{2})]}{B_e'' - B_e' + \alpha_e''(v''+\tfrac{1}{2}) - \alpha_e'(v'+\tfrac{1}{2})}$$

$$\doteq (\nu_e + k) + [a'(v'+\tfrac{1}{2}) - b'(v'+\tfrac{1}{2})^2] - [a''(v''+\tfrac{1}{2}) - b(v''+\tfrac{1}{2})^2] + \theta(v'+\tfrac{1}{2})\ (v''+\tfrac{1}{2}) \tag{11}$$

where k, θ, a', a'', b', and b'' are constants, depending on the values of B_e', B_e'', α_e', α_e'', ω_0', ω_0'', $\omega_0' x'$, and $\omega_0'' x''$. For the majority of cases encountered in band spectra, equation (11) fits the observed band heads rather well. [7]

Bands for which v' (or v'') is constant and v'' (or v') varies constitute a v'' (or v') progression; thus the bands for which v', v'' are, respectively, 0,0, 0,1, 0,2, 0,3 $\cdots$ form the v'' progression $v'=0$, and the 0,2, 1,2, 2,2, 3,2 $\cdots$ bands form the v' progression $v''=2$. Bands for which the change $v''-v'$ is constant form a sequence, thus the $v''-v'=+1$ sequence consists of the 0,1, 1,2, 2,3, 3,4 $\cdots$ bands. In analyzing a system it is usually expedient to arrange the wave numbers of the heads in a table such that the 0,0 band appears in, say, the left-hand top corner, each v'' progression runs horizontally, each v' progression runs vertically and each sequence runs diagonally from top left to bottom right. The vibrational quantum analysis may, indeed be said to consist of the correct construction of such a table, for when this is achieved, the values of v' and v'' can be assigned with almost complete certainty, and the coefficients in equation (11) often evaluated.

Criteria for the v', v'' assignments are:

1. ν increases with decreasing v'' in a v'' progression and with increasing v' in a v' progression.

2. The intervals $\Delta\nu$ between successive bands of a progression decrease with increasing v' or increasing v'', very nearly in arithmetical progression if Q heads or band origins are tabulated, and less nearly in arithmetical progression if R or P heads are used.

3. A decrease of I is accompanied by an increase of ω_0, and vice versa; hence, if the bands degrade toward the infra-red, $I''<I'$, $\omega_0''>\omega_0'$, and the above intervals $\Delta\nu$ are larger in a v'' progression than in a v' progression; the reverse is true if the bands degrade toward the ultra-violet.

4. As a consequence of (1) and (3), along a sequence v' and v'' increase in the direction in which the bands degrade.

5. When the directions of increase of v' and v'' are thus settled, their values are decided by the sudden cessation of a v'' progression (say $v'=0$ or 1) at its low-ν end, and of a v' progression (say $v''=0$ or 1) at its high-ν end; the test is applied by verification of the entire absence from the spectrogram of bands whose ν's are obtained by extrapolations beyond the top row and left-hand columns of the above table.

6. If the bands have measurable Q heads, in bands degraded to the red the interval $\nu_{R\ \text{head}} - \nu_{Q\ \text{head}}$ increases with diminishing v' along a v' progression and with increasing v'' along a v'' progression, and in bands degraded to the violet $\nu_{Q\ \text{head}} - \nu_{P\ \text{head}}$ decreases in these directions. These facts, which follow from equations (7), (8), and (9), are more useful in the recognition of Q heads than as evidence for the v', v'' assignment.

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[7] For the observations which we have made on the spectra of scandium, yttrium, and lanthanum monoxides, there is, however, a definite and systematic departure from the type of formula implied by the term $\theta(v'+\tfrac{1}{2})(v''+\tfrac{1}{2})$. We plan at a later time to make observations on the positions of the band origins, to determine the causes of this discrepancy.

7. The distribution of intensity among the bands of a system is normally of the type in which a progression (say $v'=4$ or $v''=4$) has two intensity maxima separated by a minimum, and the locus of all the maxima is a curve of nearly parabolic form (the Franck-Condon parabola) such that (*a*) its axis approximately coincides with the 0 sequence, and represents a rapid decline of intensity from a maximum to zero; (*b*) if the change $I''-I'$ or $\omega_0''-\omega_0'$ is very small, its vertex coincides with the 0,0 band (which is the strongest of the system), and its two limbs are close to one another and to the 0 sequence (which is the strongest, if not the only, sequence present); (*c*) as the change $I''-I'$ or $\omega_0''-\omega_0'$ increases, the vertex of the curve recedes from the 0,0 band, and the limbs of the curve become wider apart; thus the wide curve of maxima which characterizes a large change cuts the 0 sequence not at the 0,0 band, but at a higher v', v'' band.

8. The vibrational isotope effect, if present and precisely measurable, furnishes an absolute check on the v', v'' numeration and is, in fact, the experimental evidence for the use of $(v+\frac{1}{2})$ instead of v in the vibrational energy terms in equations (2), (3), and (11).

As a result of the analysis of different band systems of the same molecule, and as a demonstration of the Ritz combination principle as applied to band spectra, it is frequently found that a given electron level (recognized usually by its associated vibrational energies, and less often by the moment of inertia I_0 and internuclear distance r_0 for that state) is involved in two or more systems, either as a common initial state, or as a common final state, or as the initial state for one system and the final for another. Thus, in the "red" and "violet" systems of CN, the band origin equations (3) have common values of ω_0'' and $\omega_0'' x''$, indicating that the final electronic state for each system has a common set of vibrational energy levels. In the spectrum of CO there are about 9 systems involving only 11 electronic states, the final state for the visible Ångstrom system, for instance, being both the initial state for the extensive ultra-violet "fourth positive" system, and also the final state for another system; while for CO^+ (as also for $B^{11}O$ and $B^{10}O$) there are 3 known systems with only 3 electronic states. In spectra containing many known systems, for example, H_2 and He_2, the system origins form series of the Rydberg-Ritz type already well known in atomic line spectra.

A certain correspondence exists between the spectra and electronic states of many of the lighter molecules and those of the atoms containing two less extranuclear electrons, and it is inferred that in the molecule each atom retains its own K electrons, while the remaining electrons form an outer configuration similar to that in the comparable atom. Thus corresponding to the 11-electron atom Na, which has $2K$, $8L$, and $1M$ electrons, each of the 13-electron molecules BeF, BO, CN, CO^+, N_2^+ contains, besides its $2+2K$ electrons, 9 outer electrons which are regarded as an outer structure of a group of 8 electrons, together with 1 outermost or valence electron. Similarly, the 21-electron molecules, MgF, AlO, SiN, have, like the 19-electron atom K, $8+8+1$ electrons outside the K electrons and the nuclei, and are thus also "one-valence-electron" molecules. Again, CO and N_2 (14 electrons) are, by comparison with Mg (12), "two-valence-electron" molecules.

Aided by this correspondence, detailed theoretical study of the fine structure of bands of different types has led to the classification of molecular electronic levels into singlet, doublet, triplet, ... levels, and into types which are to some extent analogous to the term-types S, P, D, F already known in atomic spectra. As in the case of atoms, the electronic levels of odd and even molecules have even and odd multiplicities, respectively. The molecular electronic levels were until recently designated by the same capital letters, but it is sometimes necessary to discuss the electronic levels of molecules in relation to those of their constituent atoms, and to indicate the differences between the two types of levels the above letters are now reserved for atomic levels, and Σ, Π, Δ, Φ are used for molecular levels.

This new notation also serves to emphasize the fact that the electronic levels in the two cases are not completely analogous. While transitions between similar states; for example, $S\rightarrow S$, $P\rightarrow P$, are never found in atomic spectra, such transitions as $\Sigma\rightarrow\Sigma$, $\Pi\rightarrow\Pi$, are frequently represented in molecular spectra. Thus, the normal and lowest two excited states are ^2S, ^2P, ^2S, respectively, for Na (11) and K (19), and $^2\Sigma$, $^2\Pi$, $^2\Sigma$, respectively, for the 13-electron and 21-electron molecules already mentioned; and in the CN spectrum, for instance, the "red" system is attributed to the transition $^2\Pi\rightarrow{}^2\Sigma$, and corresponds to the Na yellow doublet $^2P\rightarrow{}^2S$, while the "violet" system is due to $^2\Sigma\rightarrow{}^2\Sigma$ (the final state being, as for the "red" system, the normal $^2\Sigma$ state) and has no corresponding line

$^2S \rightarrow {}^2S$ in the Na spectrum. Again, three band systems which are well known in laboratory and stellar spectroscopy, namely, the "second positive" of N_2, the Swan system of C_2 and the blue-green (Antarian) system of TiO, are each attributed to a transition $^3\Pi \rightarrow {}^3\Pi$, which has no counter part $^3P \rightarrow {}^3P$ in atomic spectra.

II. EXPERIMENTAL

The spectra herein described were produced in electric arcs between silver electrodes with some salt of the element under investigation placed on the lower electrode. The silver electrodes were rods of 7 mm diameter, and the arc was operated on a 220 volt d. c. circuit with the current limited to 5 or 6 amperes, because with larger current the electrodes were in danger of melting. Silver electrodes are preferred to carbon for the study of the spectra of rare and precious pure salts because the spectra of carbon impurities and the bands of carbon and of carbon compounds obscure much of the spectrum under investigation unless large quantities of the salts are used.

The salts employed in this investigation were pure scandium oxide, yttrium chloride or yttrium oxalate and lanthanum chloride or oxalate. When small quantities of these salts are fused and vaporized in a silver arc they produce a distinct change in the color of the flame of the arc; instead of the green flame characteristic of silver one sees a red flame[8] in the first two cases and a white flame in the last. These changes in color are mainly due to the intense radiation of molecular spectra, the strongest bands of ScO and YO being in the orange and red, while strong bands of LaO occur in the blue, green, and red.

The spectra were studied with 6-inch concave gratings of 21½-foot radius mounted in parallel light so as to give stigmatic images.[9] Two gratings were used interchangeably in this mounting, one with 7,500 lines per inch gave a dispersion of 10.4 A/mm in the first order and the other with 20,000 lines per inch gave a scale of 3.7 A/mm in the first order. The first grating was used mainly in the red and infra-red regions; all the spectra in the region 3,000 to 7,000 A were photographed in the first order of the second grating, and the ultra-violet, blue, and green bands of LaO were also photographed with a scale of 1.8 A/mm in the second order of the last-named grating. Wave lengths of the stronger bands in the ScO and YO have already been published in papers describing the arc spectra of Sc and Y, and these values are essentially unchanged in the present publication. In order to give a more complete description of the molecular spectra it was found necessary to make additional spectrograms in which the stronger bands were greatly overexposed so that fainter bands could be recorded. This necessitated a revision of the arbitrary scale of estimated relative intensities. In the present paper complete lists of all measured band heads and more consistent estimates of relative intensity are presented. It should be remembered that the measurement of an unsymmetrical image, such as a band head, is not susceptible of the same precision as the measurement of a sharp symmetrical spectral line. If one attempts to measure the sharp edge of a band the wave-length value will depend on exposure time because of photographic spreading of the image. We have tried to measure the line of maximum density in the image and let

[8] Meggers, B. S. Sci. Papers (S 549), **22**, p. 62; 1927.
[9] Meggers and Burns, B. S. Sci. Papers (S441), **18**, p. 191; 1922.

such measurement represent the effective wave length of a band head. The probable error in the mean value of band heads measured in this way on different spectrograms is usually less than 0.05 A, so that we feel justified in retaining the second decimal place for such values. Occasionally the rotation structure of another band or a line characteristic of atomic spectra may nearly coincide with a band head; in such cases systematic errors in the wave lengths and intensities of the latter may occur. Although it is possible, by choosing the proper conditions, to excite atomic spectra without the molecular spectra, it is unfortunately impossible to do the reverse. The molecular spectra are no doubt relatively more intense in the outer flame than in the core of the arc, but even in the flame the molecular dissociation and atomic excitation are so great that all easily excited arc and spark lines are present.

The spectra dealt with in this paper are so complex that the fine structure of the individual bands has not been sufficiently well resolved to permit analysis of the rotation energies. Even in the second order spectrum of our largest grating (dispersion 1.8 A/mm, resolving power 150,000) the rotation structure of the blue LaO bands was not satisfactorily resolved, although the doubling of the band heads was clearly shown. For the present we are, therefore, concerned only with the measurement of band heads and their classification in various systems resulting from transitions between various vibrational levels of initial and final electronic states.

Typical sequences in various systems of bands in the ScO, YO, and LaO spectra are reproduced in Figures 1, 2, and 3, respectively.

III. RESULTS

1. SCANDIUM MONOXIDE

About 60 band heads appearing in arc spectra of scandium were previously measured by Fowler [10] and by Eder and Valenta.[11] Examination of our spectrograms has revealed 139 band heads; their wave lengths, estimated relative intensities, and vacuum wave numbers are shown in Table 1. The wave lengths of 92 of these bands were published by Meggers [12] several years ago. All of the observed bands are degraded toward the red. The complete molecular spectrum has been divided into five systems, one of which extends from blue to green and the remainder overlap one another in the orange and red. The first attempt to analyze the ScO bands was made by Kayser [13] in 1912, and we find that his identification of the main sequences among the orange and red bands is correct. More recently Mecke and Guillery [14] published a system of bands, but it appears that they used parts of two different systems. Our analysis of these bands is presented in Table 2, where the wave numbers, intensities, and differences between progressions are shown. If the wave numbers corresponded to band origins instead of heads the differences would be expected to be constant and would represent the separations of vibration levels in the initial and final electronic states.

[10] Fowler, Phil. Trans., A **209**, p. 47; 1908.
[11] Eder and Valenta, Wien, Ber., **119**, IIa, p. 519; 1910.
[12] Meggers, B. S. Sci. Paper (S549), **22**, p. 61; 1927.
[13] Kayser, Handbuch der Spectroscopie, **6**, p. 454; 1912.
[14] Mecke and Guillery, Physikalische Zeitschrift, **28**, p. 514; 1927.

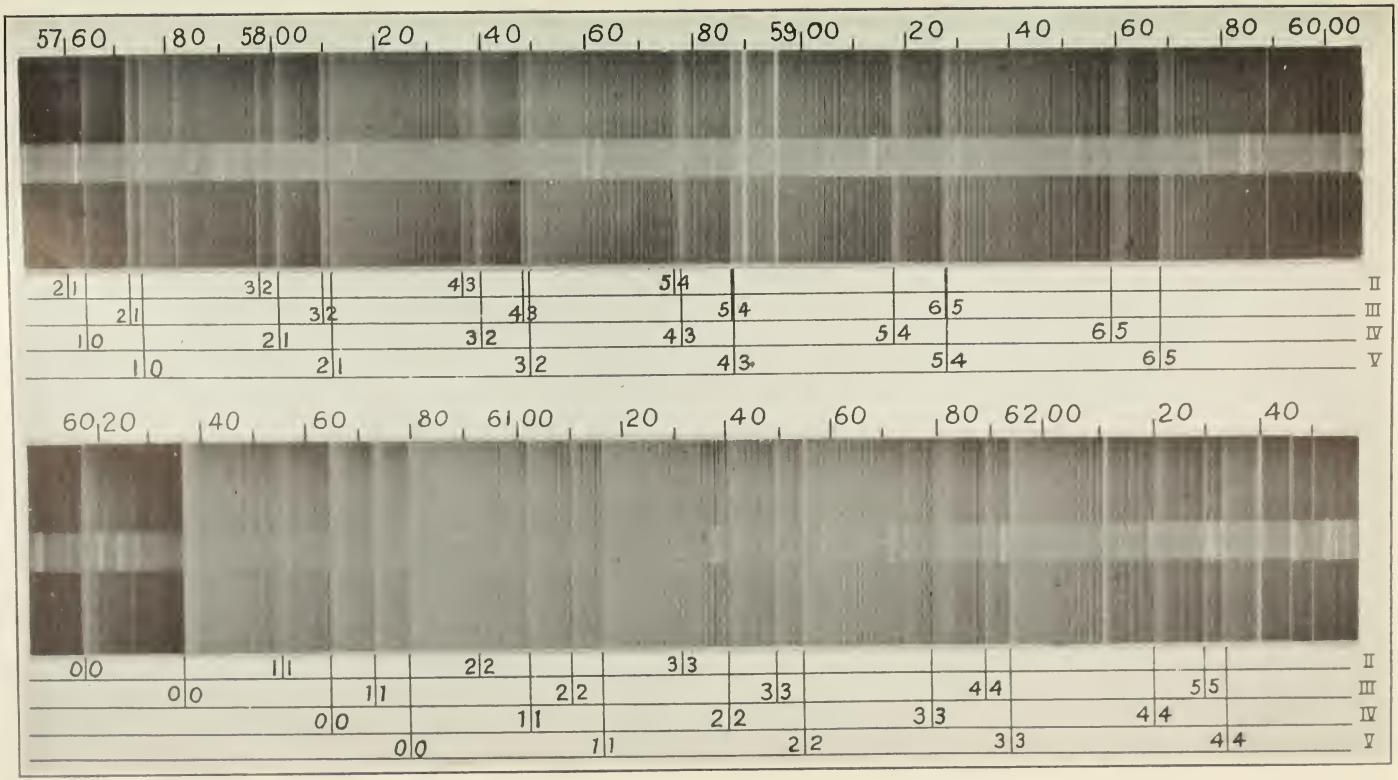

FIGURE 1.—*Scandium monoxide bands (ScO)*

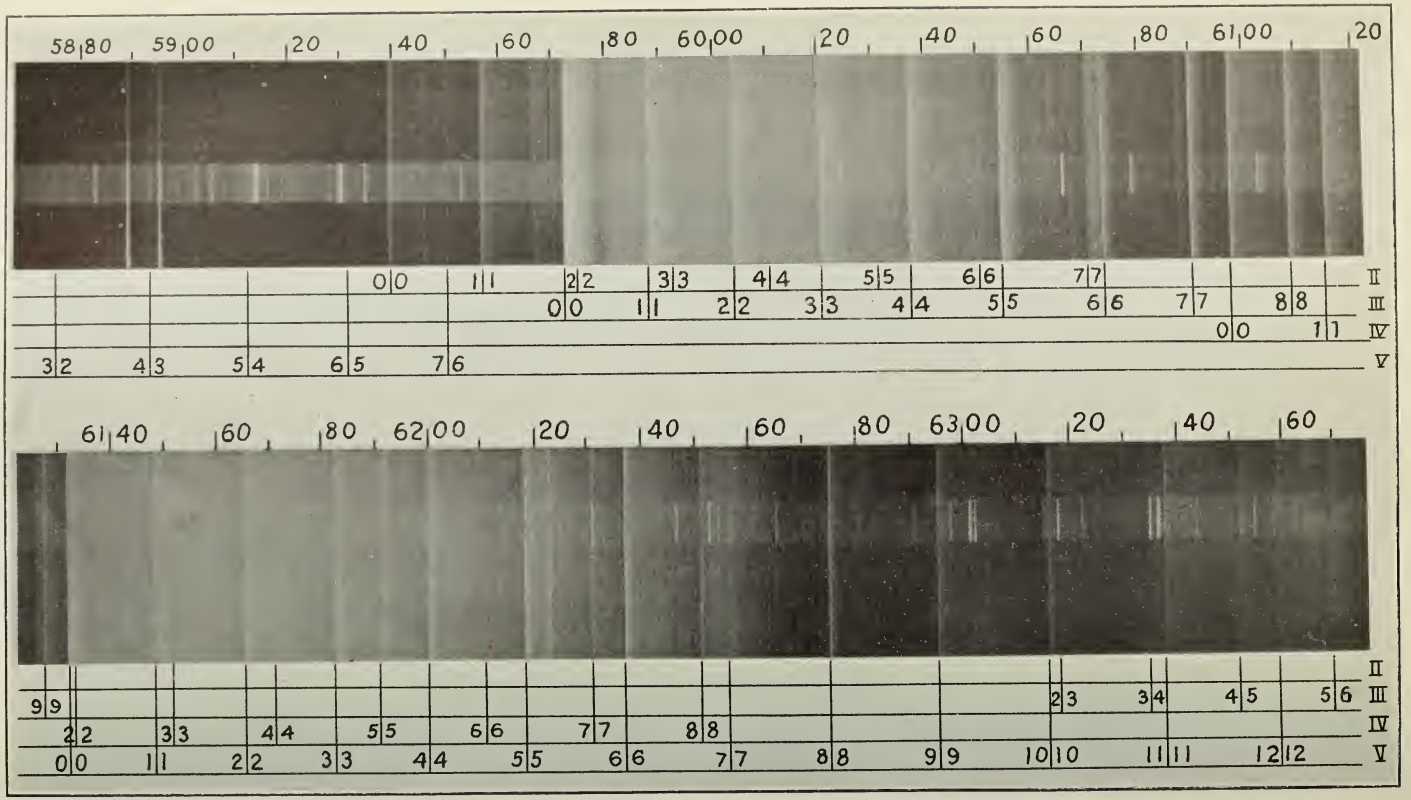

FIGURE 2.—*Yttrium monoxide bands (YO)*

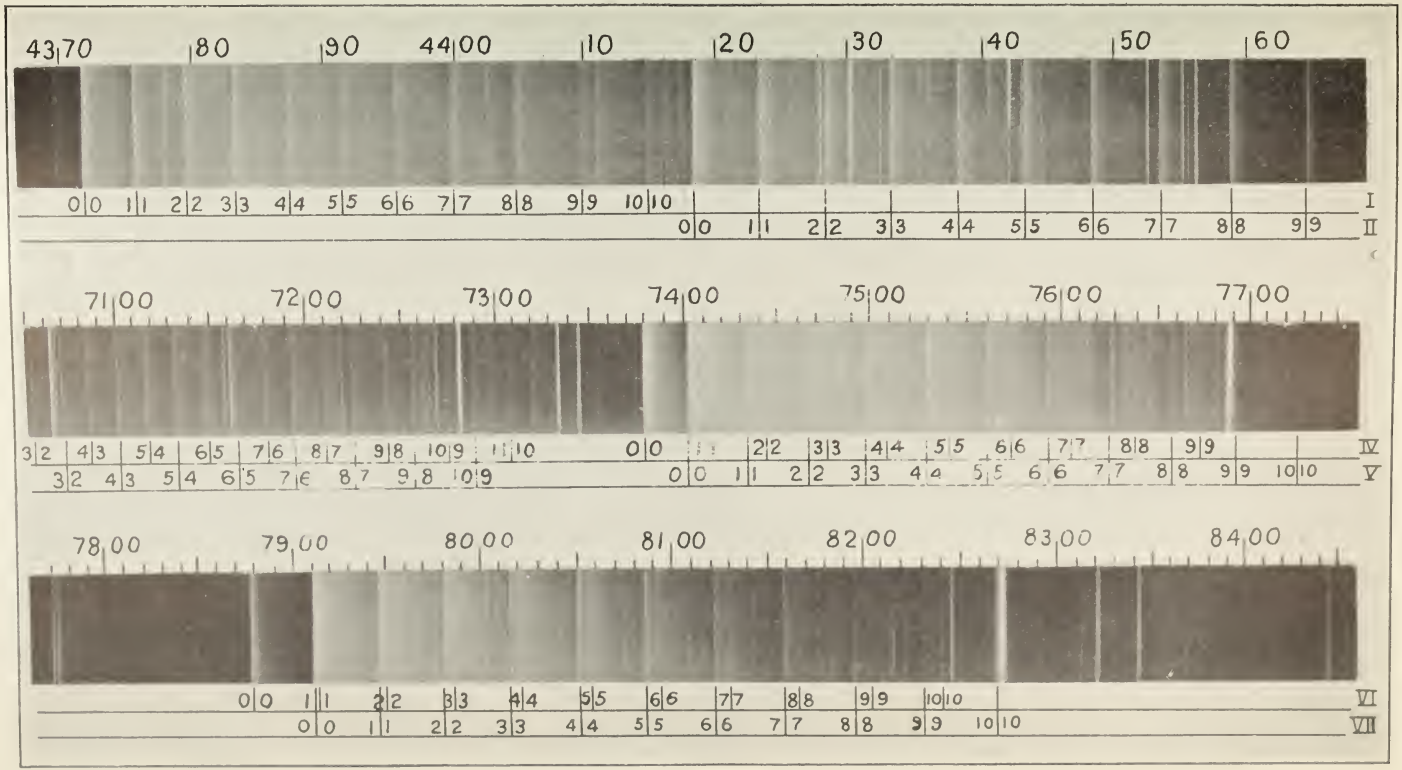

FIGURE 3.—*Lanthanum monoxide bands (LaO)*

TABLE 1.—*Band heads in the spectrum of scandium monoxide (ScO)*

λ I. A.	Intensity	ν_{vac} cm^{-1}	System and v', v''
4,502.79	5	22,202.3	I 2,0
36.59	8	22,202.6	I 3,1
4,571.30	10	21,869.5	I 4,2
4,606.78	5	701.1	I 5,3
72.62	10	395.3	I 1,0
4,673.10	10	393.1	I 1,0
4,706.97 [1]	10	239.2	I 2,1
07.26	5	237.9	I 2,1
42.45	5	21,080.3	I 3,2
4,778.50	3	20,921.2	I 4,3
4,857.79	20	579.8	I 0,0
58.09	30	578.3	I 0,0
92.98 [2]	3	431.8	I 1,1
4,893.31	4	20,430.4	I 1,1
5,096.73 [3]	20	19,615.0	I 0,1
5,133.29	3	475.3	I 1,2
33.68	5	473.8	I 1,2
5,171.06	4	19,333.0	I 2,3
5,358.03	1	18,658.4	I 0,2
96.00	1	527.1	I 1,3
5,396.37	2	525.8	I 1,3
5,435.47	1	18,392.6	I 2,4
5,736.85	10	17,426.3	III 1,0
59.0	2	359.3	II 2,1
64.45	8	342.9	IV 1,0
72.74	15	318.0	III 2,1
75.32	10	310.3	V 1,0
5,797.60	4	243.7	II 3,2
5,801.32	10	232.7	IV 2,1
09.84	20	207.4	III 3,2
11.60	15	202.2	V 2–1
36.46	6	128.9	II 4,3
39.61	10	119.7	IV 3,2
47.73	20	095.9	III 4,3
49.07	20	092.0	V 3,2
76.90	3	011.4	II 5,4
77.83	10	17,008.4	IV 4,3
5,887.38	20	16,980.8	V 4,3 III 5,4
5,918.04	10	892.8	IV 5,4
28.10	15c	864.2	V 5,4 III 6,5
59.01	6	776.7	IV 6,5
68.5	10c	750.0	V 6,5
5,970.5	5c	744.4	III 7,6
6,002.34	3	655.6	IV 7,6
17.07	40	614.8	II 0,0
36.17	200	562.2	III 0,0
55.2	10?	510.2	II 1,1
64.31	80	485.4	IV 0,0
72.65	100	462.7	III 1,1
79.30	100	444.7	V 0,0
6,092.50	5?	409.1	II 2,2
6,101.87	30	383.9	IV 1,1
09.93	40	362.3	III 2,2
15.97	40	346.1	V 1,1
32.3	3	302.6	II 3,3
40.32	10c	281.3	IV 2,2
48.70	20	259.1	III 3,3
53.93	20	245.3	V 2,2
73.05	2	195.0	II 4,4
80.6	4	175.2	IV 3,3
88.09	10	155.6	III 4,4
6,192.90	10	143.1	V 3,3
6,220.16	6	16,072.3	IV 4,4
6,229.42	5	16,048.4	III 5,5
33.1	6	16,039.0	V 4,4
62.3 [4]	6	15,964.2	IV 5,5
71.8	2	940.0	III 6,6
6,274.6	4	932.9	V 5,5
6,316.1	2	828.2	III 7,7
17.5	3	824.7	V 6,6
61.7	2	714.7	V 7,7 III 8,8
86.6	1	635.5	II 0,1
6,408.41	2	600.2	V 8,8 III 0,1
20.3	2	571.3	
24.0	2	562.3	II 1,2
37.08	10	530.7	IV 0,1
46.24	30	508.6	III 1,2
57.78	15	480.9	V 0,1
61.11	3	473.0	
62.81	3	468.9	II 2,3
76.53	10	436.1	IV 1,2
85.40	20	415.0	III 2,3
6,495.90	15	390.1	V 1,2
6,503.1	4	373.0	II 3,4
17.66	6	338.7	IV 2,3
25.62	15	320.0	III 3,4
35.30	10	297.3	V 2,3
57.84 [5]	10	244.7	IV 3,4
66.88	10	223.7	III 4,5
6,575.85	10	203.0	V 3,4
6,600.81	10	145.5	IV 4,5
09.99	8	124.4	III 5,6
17.94	8	106.3	V 4,5
45.08	6	044.6	IV 5,6
54.42	7	023.5	III 6,7
61.01	7	15,008.6	V 5,6
6,691.15	4	14,941.0	IV 6,7
6,700.48	5	920.2	III 7,8
05.93	6	908.1	V 6,7
35.42	2	842.8	IV 7,8
48.25	3	814.6	III 8,9
52.62	4	805.0	V 7,8
83.98	3	736.6	IV 8,9
6,798.22	2	705.7	III 9,10
6,800.52	3	700.7	V 8,9
37.60	4	621.0	II 1,3
50.46	4?	593.5	V 9,10 III 10,11
64.57	6	563.6	
74.30	4	542.9	II 2,4
77.40	4	536.4	
81.14	5	528.5	
6,885.29	8	519.7	
6,914.46	4	458.5	II 3,5
36.70	4	412.1	IV 2,4
48.30	2	388.0	III 3,5
61.63	4	360.5	III 4,6
63.12	4	357.4	V 2,4
80.59	5	321.5	IV 3,5
85.49	6	311.4	
6,990.68	7	300.8	III 4,6
7,005.52	5	270.5	V 3,5
25.72	5	229.5	IV 4,6
35.77	6	14,209.2	III 5,7

[1] Sc_I line at 4,706.97 A.
[2] Sc_I line at 4,893.00 A.
[3] Sc_I line at 5,096.73 A.
[4] Sc_I line at 6,262.26 A.
[5] Sc_I line at 6,557.84 A.

TABLE 1.—*Band heads in the spectrum of scandium monoxide (ScO)*—Con.

λ I. A.	Intensity	ν_{vac} cm^{-1}	System and v', v''	λ I. A.	Intensity	ν_{vac} cm^{-1}	System and v', v''
7,049.41	5	14,181.7	V 4,6	7,180.68	4	13,922.4	III 8,10
72.37	5	135.6	IV 5,7	7,189.70	3	905.0	V 7,9
82.39	5	115.6	III 6,8	7,221.63	3	843.5	IV 8,10
7,094.38	5	091.8	V 5,7	33.17	3	821.3	III 9,11
7,120.45	4	040.2	IV 6,8	40.25	3	807.9	V 8,10
30.64	4	14,020.1	III 7,9	75.55[6]	10?	740.9	IV 9,11
41.22	5	13,999.4	V 6,8	87.86	2	717.7	III 10,12
7,170.15	3	13,942.7	IV 7,9	7,293.35	2	13,707.3	V 9,11

[6] Sc_I line at 7,275.55 A.

TABLE 2.—*Wave numbers, intensities, and differences between progressions of ScO bands*

ScO BANDS, SYSTEM I

v′ \ v″	0	1	2	3	4	5	6	7	8
0	20, 579. 8(20) 964 20, 578. 5(30) 815	19, 615. 0(20) 956. 6 816	18, 658. 4(1) 816						
1	21, 395. 3(10) 963. 5 21, 393. 1(10) 962. 7 808	20, 431. 8(3) 956. 1 20, 430. 4(4) 956. 6 807	19, 475. 3(3) 948. 2 19, 473. 8(5) 948. 0	18, 527. 1(1) 18, 525. 8(2) 807					
2	22, 202. 3(5) 963	21, 239. 2(10) 21, 237. 9(5) 798		19, 330. 0(4) 940. 4	18, 392. 6(1) 798				
3		22, 036. 8(8) 956. 5	21, 080. 3(5) 789. 2		[1] 19, 190				
4			21, 869. 5(10) 948. 3	20, 921. 2(3) 779. 9					
5				21, 701. 1(5)					

ScO BANDS, SYSTEM II

v′ \ v″	0	1	2	3	4	5	6	7	8
0	16, 641. 8(40) 961. 3	15, 653. 5(10″) 856. 8							
1		16. 510. 3(10) 947. 9 849. 0	15, 562. 4(2) 941. 4 846. 7	14, 621. 0(4) 847. 9					
2		17, 359. 3(2) 950. 2	16, 409. 1(5) 940. 2 834. 7	15, 468. 9(3) 926. 0 833. 7	14, 542. 9(4) 830. 2				
3			17, 243. 8(4) 941. 2	16, 302. 6(3) 929. 5 826. 3	15, 373. 1(4) 914. 6 822. 0	14, 458. 5(4)			
4				17, 128. 9(6) 933. 8	16, 195. 1(2) 816. 3		14, 360. 5(4)		
5					17, 011. 4(3)				

[1] Masked by Ag 5209.0 A

TABLE 2.—*Wave numbers, intensities, and differences between progressions of ScO bands*—Continued

ScO BANDS, SYSTEM III

v′ \ v″	0	1	2	3	4	5	6	7	8
0	16, 562. 2(200) 962. 0 864. 2	15, 600. 2(20) 862. 5							
1	17, 426. 4(10) 963. 7	16, 462. 7(100) 954. 0	15, 508. 7(30)						
2		855. 3 17, 318. 0(15) 955. 7	853. 6 16, 362. 3(40) 947. 3 845. 1	15, 415. 0(20) 844. 1					
3			17, 207. 4(20) 948. 3	16, 259. 1(20) 939. 1 836. 8	15, 320. 0(15) 931. 9 835. 6	14, 388. 1(2) 835. 6			
4				17, 095. 9(20) 940. 3	16, 155. 6(10) 931. 9 825. 2	15, 223. 7(10) 922. 9 824. 7	14, 300. 8(7) 823. 6		
5					16, 980. 8(20) 932. 4	16, 048. 4(5) 924. 0 815. 8	15, 124. 4(8) 915. 2 815. 6	14, 209. 2(6) 814. 3	
6						16, 864. 2(15) 924. 2	15, 940. 0(2) 916. 5 804. 4	15, 023. 5(7) 907. 8 804. 7	14, 115. 7(5) 804. 5
	8	9	10	11	12				
7	14, 920. 2(5) 900. 1 794. 5	14, 020. 1(4) 794. 5					16, 744. 4(5) 916. 2	15, 828. 2(2) 908. 0	14, 920. 2(5) 794. 5
8	15, 714. 7(2) 900. 1	14, 814. 6(3) 892. 2	13, 922. 4(4) 783. 3						15, 714. 7(2)
9			14, 705. 7(2) 884. 3	13, 821. 4(3) 772. 1					
10				14, 593. 5(4)? 875. 8	13, 717. 7(2)				

v' \ v''	0	1	2	3	4	5	6	7	8
0	16,485.4(80) 954.7 857.5	15,530.7(10) 853.2							
1	17,342.9 (8) 959.0	16,383.9(30) 947.8 848.8	15,436.1(10) 845.2						
2		17,232.7(10) 951.4	16,281.3(10) 942.6 838.4	15,338.7 (6) 926.7 836.8	14,412.2 (4) 832.5				
3			17,119.7(10) 944.2	16,175.5 (4) 930.8 832.9	15,244.7(10) 922.2 827.5	14,321.5 (5) 824.0			
4				17,008.4(10) 936.2	16,072.2 (6) 926.7 820.6	15,145.5(10) 916.0 818.6	14,229.5 (5) 815.1		
5					16,892.8(10) 928.7	15,964.1 (6) 919.5 812.6	15,044.6 (6) 909.0	14,135.6 (5) 805.4	
	8	9	10	11					
6	14,040.2 (4) 802.6					16,776.7 (6)		14,941.0 (4) 900.8	14,040.2(4) 802.6
7	14,842.8 (2) 900.1	13,942.7 (3) 793.9					16,655.6 (3)		14,842.8(2)
8		14,736.6 (3) 893.1	13,843.5 (3)						
9				13,740.9(10?)					

TABLE 2.—*Wave numbers, intensities, and differences between progressions of ScO bands*—Continued

ScO BANDS, SYSTEM V

v' \ v''	0	1	2	3	4	5	6	7	8
0	16,444.7(100) 963.8 865.6	15,480.9(15) 865.2							
1	17 310.3(10) 964.2	16,346.1(40) 956.0 856.1	15,390.1(15) 855.2						
2		17,202.2(15) 956.9	16,245.3(20) 948.0 846.7	15,297.3(10) 939.9 845.8	14,357.4 (4) 845.6				
3			17,092.0(20) 948.9	16,143.1(10) 940.1 837.7	15,203.0(10) 932.5 836.0	14,270.5 (5) 835.8			
4				16,980.8(20) 941.8	16,039.0 (6) 932.7 825.5	15,106.3 (8) 924.6 826.6	14,181.7 (5) 826.9		
5					16,864.5(15) 931.6	15,932.9 (4) 924.3 817.1	15,008.6 (7) 916.8 816.1	14,091.8 (5) 816.3	
	8	9	10	11					
6	13,999.4 (5) 805.6					16,750.0(10) 925.3	15,824.7 (3) 916.6	14,908.1 (6) 908.7 806.6	13,999.4(5) 805.6
7	14,805.0 (4) 900.0 795.2	13,905.0 (3) 795.7						15,714.7 (2) 909.7	14,805.0(4) 795.2
8	15,600.2 (2) 899.5	14,700.7 (3) 892.8	13,807.9 (3) 785.6						15,600.2(2)
9			14,593.5 (4) 886.2	13,707.3 (2)					

The first analysis indicated the presence of only three red systems, III, IV, and V. Faint traces of new bands in the blue led to longer exposures which made possible the analysis of System I. These blue bands are distributed in a relatively large number of sequences, in each of which the intensity of successive bands falls off rather rapidly. Such an intensity distribution is characteristic of electronic transitions in which there is a considerable difference between the mean molecular radii in the initial and final states. Two heads, separated by about 1.4 cm^{-1}, were observed for a number of the blue bands. The average wave number of the two was taken in forming differences with the wave numbers of bands having unresolved heads.

Analogy with the four red systems of YO and LaO later indicated the presence of a fourth red system in ScO. This system (II) is considerably weaker than the three other long wave-length systems, so that many of its bands are probably hidden by the other systems.

The tables of the ScO band heads and wave-number systems show, as do those of YO and LaO to an even greater extent, a "combination deficit" or variation with v' of the difference between the v'' vibration level and $v''+1$ vibration level. If this "combination deficit" is the same throughout a band system, it gives, and in fact is equal to, 0 in band-head formula (11); but in all the systems analyzed in the present investigation, as may be seen from the differences in the tables here given, the combination deficit definitely decreases with increasing v'', and (11) is accordingly inapplicable.

2. YTTRIUM MONOXIDE

The first extensive list of band heads occurring in yttrium spectra was published by Exner and Haschek [15]; they gave 43 bands between 4,562.1 and 6,387.1 A. About 35 band heads were measured by Kiess [16] and 50 by Meggers [17] in a new description of yttrium spectra. Longer exposures have revealed a large number of fainter bands, so that we are now able to present in Table 3, data for 120 band heads characteristic of the YO molecule. The structure of this spectrum is strikingly similar to that of ScO; analysis shows that it consists of five systems of bands, one in the blue and the others overlapping in the yellow, orange, and red. To the best of our knowledge no analysis of any of these band systems has heretofore been published. Our analysis is presented in Table 4, which is constructed in the same manner as Table 2.

[15] Exner and Haschek, Die Spectren der Elemente bei normalem Druck, Deuticke, Leipzig; 1911, 1912.
[16] Kiess, B. S. Sci. Papers (S421), 17, p. 322; 1921.
[17] Meggers, B. S. Jour. Research, 1, (RP12), p. 319; 1928.

TABLE 3.—*Band heads in the spectrum of yttrium monoxide (YO)*

λ I. A.	Intensity	ν_{vac} cm−1	System and v', v''	λ I. A.	Intensity	ν_{vac} cm−1	System and v', v''
4,496.38	5	22,233.9	I 2,0	5,987.64	300	16,696.5	III 1,1
4,525.29	5	091.8	I 3,1	5,992.10	10	684.0	II 3,3
25.66	2	22,090.0	I 3,1	6,003.60	200	652.1	III 2,2
4,561.81	6	21,915.0	I 4,2	[2] 09.15	8	636.7	II 4,4
4,603.70	5	715.6	I 5,3				
				11.06	2	631.4	II 1,0
46.89	5	513.8	I 6,4	19.87	150	607.1	III 3,3
49.54	10	501.5	I 1,0	30.48	6	577.9	II 5,5
50.21	15	498.4	I 1,0	36.60	100	561.0	III 4,4
76.3	5	378.5	I 2,1	49.17	3	526.6	II 6,6
4,676.9	3	375.7	I 2,1				
				53.81	50	514.0	III 5,5
4,706.27	4	242.3	I 3,2	70.02	5	469.9	II 7,7
06.74	10	240.2	I 3,2	72.78	15	462.4	III 6,6
44.53.	5	071.0	I 4,3	89.35	30	417.6	III 7,7
4,744.94	6	21,069.2	I 4,3	6,096.78	30	397.6	IV 0,0
4,817.38	20	20,752.4	I 0,0				
				6,107.82	15	367.9	III 8,8
18.20	30	748.9	I 0,0	14.73	20	349.4	IV 1,1
42.02	5	646.8	I 1,1	27.38	8	315.7	III 9,9
4,842.52	3	20,644.7	I 1,1	32.06	200	303.2	V 0,0
5,024.30	10	19,897.7	I 0,1	48.36	100	260.0	V 1,1
25.25	20	894.0	I 0,1				
				51.72	5	251.1	IV 3,3
49.71	8	797.6	I 1,2	65.08	80	215.9	V 2,2
50.61	10	794.1	I 1,2	70.82	4	200.8	IV 4,4
77.92	4	687.6	I 2,3	82.23	60	16,170.9	V 3,3
5,078.65	6	684.8	I 2,3	90.72	5	16,148.8	IV 5,5
5,249.5	1	19,044.1	I 0,2				
				6,199.82	50	125.0	V 4,4
74.26	1	18,954.7	I 1,3	6,209.94	5	098.8	IV 6,6
5,275.37	1	950.8	I 1,3	17.96	40	078.0	V 5,5
5,303.54	1	850.1	I 2,4	21.84	6	068.0	
04.49	1	846.7	I 2,4	30.76	5	045.0	IV 7,7
33.24	1	745.1	I 3,5				
				36.72	30	16,029.6	V 6,6
5,333.93	1	18,742.7	I 3,5	51.04	5	15,992.9	IV 8,8
5,693.99	1	17,557.5	II 2,1	55.85	4	980.6	V 7,7
5,697.80	5	545.8	III 1,0	75.01	15	931.8	V 8,8
5,712.44	1	500.8	II 3,2	87.5	1	900.2	III 0,1
13.81	10	496.6	III 2,1				
				6,295.46	10	880.1	V 9,9
30.12	15	446.8	III 3,2	6,302.7	2	861.8	III 1,2
30.65	1	445.2	II 4,3	16.20	8	827.9	V 10,10
46.93	20	395.8	III 4,3	18.4	3	822.4	III 2,3
64.22	20	343.6	III 5,4	35.5	4	779.7	III 3,4
5,782.70	10	288.2	III 6,5	38.10	10	773.2	V 11,11
5,800.00	15	236.6	III 7,6	52.30	5	738.0	III 4,5
18.58	15	181.6	III 8,7	59.48	8	720.2	V 12,12
19.28	5	179.5	IV 1,0	69.87	10	694.6	III 5,6
37.17	6	126.8	IV 2,1	6,387.06	10	652.3	III 6,7
38.07	10	124.2	III 9,8				
				6,405.63	5	606.9	III 7,8
41.91	8	113.0	V 1,0	24.14	2	562.0	III 8,9
55.31	5	073.8	IV 3,2	44.04	1	513.9	III 9,10
58.83	10	063.5	V 2,1	68.19	8	456.0	V 0,1
73.99	5	019.5	IV 4,3				
76.14	10	013.3	V 3,2	6,484.56	10	417.0	V 1,2
				[3] 6,501.23	15	377.5	V 2,3
			{ IV 5,4	18.33	15	337.1	V 3,4
5,893.94	10	16,961.9	{ V 4,3	35.84	10	296.0	V 4,5
5,912.19	10	909.5	V 5,4				
12.74	3	908.0	IV 6,5	53.84	8	254.0	V 5,6
31.10	6	855.6	V 6,5	72.53	6	210.6	V 6,7
				6,591.38	2	167.2	V 7,8
33.18	2	849.7	IV 7,6	6,610.45	4	123.4	V 8,9
39.08	100	833.0	II 0,0				
[1] 49.99	4	802.1	V 7,6	31.27	2	075.9	V 9,10
56.41	80	784.0	II 1,1	51.61	1	15,029.8	V 10,11
69.63	4	746.8	V 8,7	73.32	1	14,980.9	V 11,12
72.04	600	16,740.0	III 0,0	6,694.27	1	14,934.0	V 12,13

[1] Y_I line at 5950.02 A. [2] Y_I line at 6009.19 A. [3] Y_I line at 6501.3 A.

TABLE 4.—*Wave numbers, intensities, and differences between progressions of YO bands*

YO BANDS, SYSTEM I

v'' / v'	0	1	2	3	4	5	6	7	8
0	20, 752. 4(20) 854. 7 20, 748. 9(30) 854. 9 749. 1 749. 5	19, 897. 7(10) 19, 894. 0(20) 852 749. 1 750. 7	19, 044. 1(1) 751						
1	21, 501. 5(10) 854. 7 21, 498. 4(15) 853. 7 734	20, 646. 8(5) 849. 2 20, 644. 7(3) 850. 6 731. 7 731. 0	19, 797. 6(8) 842. 9 19, 794. 1(10) 843. 3	18, 954. 7(1) 18, 950. 8(1) 732. 9 734. 0					
2	22, 233. 9(5) 857	21, 378. 5(5) 21, 375. 7(3) 713. 3 714. 3		19, 687. 6(4) 837. 5 19, 684. 8(6) 838. 1	18, 850. 1(1) 18, 846. 7(1)				
3		22, 091. 8 (5) 849. 5 22, 090. 0 (2) 849. 8	21, 242. 3 (4) 21, 240. 2(10) 674						
4			21, 915. 0(6) 845	21, 071. 0(5) 21, 069. 2(6) 645					
5				21, 715. 6(5)					
6					21, 513. 8(5)				

TABLE 4.—*Wave numbers, intensities, and differences between progressions of YO bands*—Continued

YO BANDS, SYSTEM II

v' \ v''	0	1	2	3	4	5	6	7	8
0	16, 833. 0(100) 840. 1 798. 4	15, 992. 9(5) 791. 1							
1	17, 631. 4(2) 847. 4	16, 784. 0(80) 773. 5							
2		17, 557. 5(1)	[1] 16, 728						
3			17, 500. 8(1) 816. 8	16, 684. 0(10?) 761. 2					
4				17, 445. 2(1) 808. 5	16, 636. 7(8)				
5						16, 577. 9(6)			
6							16, 526. 6(3)		
7								16, 469. 9(5)	

YO BANDS, SYSTEM III

v' \ v''	0	1	2	3	4	5	6	7	8
0	16, 740. 0(600) 839. 9 805. 8	15, 900. 2(1)							
1	17, 545. 8(5) 849. 3	16, 696. 5(300) 834. 7 800. 1	15, 861. 8(2)						
2		17, 496. 6(10) 844. 5	16, 652. 1(200) 829. 7 794. 7	15, 822. 4(3)					
3			17, 446. 8(15) 839. 7	16, 607. 1(150) 827. 4 788. 7	15, 779. 7(4)				
4				17, 395. 8(20) 834. 8	16, 561. 0(100) 823. 0 782. 6	15, 738. 0(5) 776. 0			
5					17, 343. 6(20) 829. 6	16, 514. 0(50) 819. 4 774. 2	15, 694. 6(10) 767. 8		
6						17, 288. 2(10) 825. 8	16, 462. 4(15) 810. 4 774. 2	15, 652. 0(10) 765. 6	

	8		9		10											
7	15,606.9(5) 701.0												17,236.6(15)	819.0	16,417.6(30) 764.0	810.7	15,606.9(5) 761.0
8	16,367.9(15) 756.3	805.9	15,562.0(2) 753.7												17,181.6(15)	813.7	16,367.9(15) 756.3
9	17,124.2(10)	808.5	16,315.7(8)	801.8	15,513.9(1)												17,124.2(10)

YO BANDS, SYSTEM IV

v'' / v'	0		1		2		3		4		5		6		7		8
0	16,397.6(30) 781.9																
1	17,179.5(5)	830.1	16,349.4(20) 774.4														
2			17,126.8(6)		[2]16,300												
3					17,073.8(5)	822.7	16,251.1(5) 768.4										
4							17,019.5(5)	818.7	16,200.8(4) 761.1								
5									16,961.9(10?)	813.1	16,148.8(5) 759.2						
6											16,908.0(3)	809.2	16,098.8(5) 750.9				
7													16,849.7(2)	804.7	16,045.0(5)		

[1] Masked by 16,740.0(600) III 0, 0.

[2] Marked by 16,303.2(200), V 0, 0.

TABLE 4.—*Wave numbers, intensities, and differences between progressions of YO bands*—Continued

YO BANDS, SYSTEM V

v' \ v''	0	1	2	3	4	5	6	7	8
0	16,303.2(200) 847.2 809.7	15,456.0(8) 804.0							
1	17,113.0(8) 853.3	16,260.0(100) 843 803.5	15,417.0(10) 798.9						
2		17,063.5(10) 847.6	16,215.9(80) 838.4 797.4	15,377.5(15) 793.4					
3			17,013.3(10) 842.4	16,170.9(60) 833.8 791.0	15,337.1(15) 787.9				
4				16,961.9(10) 836.9	16,125.0(50) 829.0 784.5	15,296.0(18) 782.0			
5					16,909.5(10) 831.5	16,078.0(40) 824.0 777.6	15,254.0(8) 775.6		
6						16,855.6(6) 826.0	16,029.6(30) 819.0 772.5	15,210.6(6) 770.0	
	8	9	10	11	12	13			
7	15,167.2(2) 764.6						16,802.1(4) 821.5	15,980.6(4) 813.4 766.2	15,167.2(2) 764.6
8	15,931.8(15) 808.4	15,123.4(4) 756.7						16,746.8(4) 815.0	15,931.8(15)
9		15,880.1(10) 804.2	15,075.9(2) 752.0						
10			15,827.9(8) 798.1	15,029.8(1) 743.4					
11				15,773.2(10) 792.3	14,980.9(1) 739.3				
12					15,720.2(8) 786.2	14,934.0(1)			

The bands in the blue systems of yttrium (I) have a head doubling of about 3.5 cm^{-1}. The bands of maximum intensity in this system are distributed in a wide parabola. Of the four red systems analyzed, Systems II and IV are considerably weaker than III and V, making it difficult to identify with absolute certainty any but the bands in their zero sequences. In general, the zero sequences are longest and strongest in all of the YO band systems except System I in the blue, where, as already stated, the intensity maximum follows a wide parabola. This distribution of intensity in the red systems as compared with the blue indicates a smaller change of vibration frequency and of moment of inertia in passing from the initial to the final state of the molecule. System III exhibits a remarkable intensity anomaly in one of its v'' progressions, $v'=6$. The 6,6 transition has only about one-third its expected intensity, and the other transitions involving the same initial state are also affected. A still more striking intensity defect occurs in the v'' progression, $v'=7$, in System V. The relative number of molecules in these particular initial states must be greatly depressed by some disturbing force, but the exact nature of this force is still unknown.

3. LANTHANUM MONOXIDE

An exceedingly complex spectrum is emitted by the LaO molecule, and it has been a serious obstruction in making a complete description of the La_I spectrum produced in the ordinary arc. A few of the stronger sequences in the blue and yellow were known [18] in 1905, and two groups in the red were listed [19] in the Tabelle der Bandenspectra in 1912. No further data were published until 1921, when Kiess [20] reported waves longer than 5,500 A. In 1929 Auerbach [21] gave the wave lengths for two groups in the infra-red. This accumulation of data was analyzed by Mecke [22] who resolved it into seven band systems having 0,0 heads at (I) 4,372 A, (II) 4,418 A, (III) 5,600 A, (IV) 7,380 A, (V) 7,404 A, (VI) 7,877 A, and (VII) 7,910 A. All of the bands in these systems are degraded to red. In the meantime the spectrum of LaO was being studied also by Jevons [23], who published wave lengths for about 250 band heads, extending the seven systems analyzed by Mecke and suggesting an eighth system of bands in the ultra-violet, whose heads are shaded to shorter wave lengths. Under high dispersion the 0 sequences of Systems I and II have been observed [24] to have double heads with a separation of about 0.5 cm^{-1}. We have confirmed this doubling and also observed it in the $+1$ sequence of System II and in the stronger heads of System III. Similar doubling of heads has been reported by Auerbach [25] and by Querbach [26] for the 0,0 band of System VI and for the 0 and $+1$ sequences of system 7. If all of the LaO bands are in reality double the total number of band heads in this spectrum will approximate 500.

[18] Kayser, Handbuch der Spectroscopie, **5**, p. 667; 1910.
[19] Kayser, Handbuch der Spectroscopie, **6**, p. 1036; 1912.
[20] Kiess, B. S. Sci. Papers (S 421), **17**, p. 324; 1921.
[21] Auerbach, Naturwissenschaften, **17**, p. 84; 1929.
[22] Mecke, Naturwissenschaften, **17**, p. 86; 1929.
[23] Jevons, Proc. Phys. Soc. London, **41**, p. 520; 1929.
[24] Okubu, Tôhoku Univ. Sci. Rep., **11**, p. 95; 1922.
[25] Auerbach, Naturwissenschaften, **17**, p. 84; 1929
[26] Querbach, Zeitschr. f. Phys. **60**, p. 109; 1930.

Our observations and analysis of the LaO bands agree for the most part with those given by Jevons. The differences may be noted as follows: The spectrographs which we employed gave from three to five times the dispersion used by Jevons, and we feel that on this account our measurements may be somewhat more accurate. By using plates sensitized in the laboratory instead of commercial plates we have been able to extend some of the sequences in the infra-red. We have occasionally found faint hazy lines appearing near the positions indicated by Jevons as band heads for the +2 and +3 sequences of System III, but, in general, we have been unable to confirm these sequences. Jevons listed 19 ultra-violet bands (3,457.11 to 3,709.64 A) degraded toward the further ultra-violet, 8 of which he tentatively assigned to a new system, VIII. Only 13 of his bands were found on our spectrograms; some of these are complex and others do not appear to be band heads, so that we are not able to confirm his analysis of this group. Between System III and IV, two new sequences of bands degraded to the violet appeared on our spectrograms. We are unable to identify these bands with impurities and are, therefore, presenting them as characteristic of LaO with a suggestion that they represent the *P* and *Q* heads of a new system, IX. No other sequences have been observed in this system, but this may be due to the fact that, compared with the average intensity of LaO bands degraded to red, those observed with violet degradation are extremely weak.

TABLE 5.—*Band heads in the spectrum of lanthanum monoxide (LaO)*

λ I. A.	Intensity	ν_{vac} cm [1]	System and v', v''	λ I. A.	Intensity	ν_{vac} cm [1]	System and v', v''
3,565.81	4 hv	28,036.2		4,391.490	4	22,764.94	I 5,5
3,566.12	5 h	28,033.7		91.592	8	764.41	I 5,5
3,604.45	5 hv	27,735.6		95.634	3	743.48	I 6,6
07.84	5 hv	709.5		95.740	6	742.93	I 6,6
08.08	3 h	707.7		4,399.990	2	720.96	I 7,7
11.13	6 hv	684.3		4,400 085	4	720.47	I 7,7
11.39	4 d	682.3		04.800	1	696.15	I 8,8
13.76	3 h	664.1		04.904	3	695.62	I 8,8
14.22	3 h	660.6		09.642	4c	671.23	I 9,9
14.41	4 h	659.2		14.549	1	646.03	I 10,10
14.77	5 hv	656.4		14.648	3	645.52	I 10,10
16.26	3 h	645.0		18.142	25	627.62	II 0,0
19.40	4 h	621.0		18.240	50	627.11	II 0,0
20.13	6 h	615.5		23.070	20	602.41	II 1,1
20.59	2 h	612.0		23.170	40	601.89	II 1,1
20.78	3 h	610.5		28.002	15	577.23	II 2,2
21.24	4h	607.0		28.101	30	576.73	II 2,2
22.04	4h	600.9		[2] 32.950	15?	552.03	II 3,3
3,622.63	6hv	27,596.4		33.040	30?	551.57	II 3,3
4,369.70	5	22,878.4		37.908	15	526.83	II 4,4
71.872	20	867.09	I 0,0	38.008	30	526.32	II 4,4
71.968	40	866.59	I 0,0	42.900	12	501.53	II 5,5
75.739	15	846.89	I 1,1	43.001	25	501.01	II 5,5
75.837	30	846.38	I 1,1	47.939	10	476.03	II 6,6
79.625	10	826.61	I 2,2	48.036	20	475.54	II 6,6
79.723	20	826.10	I 2,2	53.086	8	450.06	II 7,7
[1] 83.421	8?	806.85	I 3,3	53.182	20	449.57	II 7,7
83.520	15	806.33	I 3,3	58.375	5	423.43	II 8,8
87.488	5	785.70	I 4,4	58.477	15	422.91	II 8,8
4,387.587	10	22,785.19	I 4,4	4,464.072	3	22,394.81	II 9,9

[1] La II line at 4,383.44 A.

[2] La II line at 4,432.95 A

TABLE 5.—*Band heads in the spectrum of lanthanum monoxide (LaO)*—Continued

λ I. A.	Intensity	ν_{vac} cm^{-1}	System and v', v''
4,464.172	10	22,394.31	II 9,9
71.216	3	359.03	II 10,10
4,471.315	10	22,358.53	II 10,10
4,580.707	1	21,824.59	II 0,1
80.798	3	824.16	II 0,1
85.024	1	804.05	II 1,2
85.121	4	803.58	II 1,2
89.369	2	783.41	II 2,3
89.467	5	782.94	II 2,3
93.752	1	762.62	II 3,4
93.846	5	762.17	II 3,4
98.143	1	741.84	II 4,5
4,598.244	4	741.36	II 4,5
4,602.629	1	720.65	II 5,6
02.723	3	720.20	II 5,6
07.192	1	699.14	II 6,7
07.285	3	698.70	II 6,7
11.885	1	677.05	II 7,8
11.990	3	676.56	II 7,8
4,616.926	1	21,653.39	II 8,9
4,617.023	3	652.93	II 8,9
22.609	1	626.77	II 9,10
22.706	3	626.31	II 9,10
4,627.339	3h	21,604.66	II 10,11?
5,380.48	10	18,580.6	III R 1,0
5,382.48	20	573.6	III Q 1,0
5,405.66	20	494.0	III R 2,1
07.69	30	487.1	III Q 2,1
31.05	20	407.5	III R 3,2
33.07	30	400.7	III Q 3,2
56.63	10	321.3	III R 4,3
[3] 58.66	20	314.4	III Q 4,3
[4] 82.27	5?	235.6	III R 5,4
5,484.30	10	228.8	III Q 5,4
5,508.44	10	148.9	III R 6,5
10.22	8	143.1	III Q 6,5
34.23	8	064.4	III R 7,6
36.35	10	18,057.4	III Q 7,6
60.40	8	17,979.3	III R 8,7
62.57	5	972.3	III Q 8,7
86.91	6	894.0	III R 9,8
88.84	2	887.8	III Q 9,8
5,599.89	50	852.6	III R 0,0
5,600.02	100	852.1	III R 0,0
02.36	100	844.7	III Q 0,0
02.50	200	844.2	III Q 0,0
26.03	100	769.6	III R 1,1
28.60	100	761.5	III Q 1,1
52.34	50c	686.9	III R 2,2
54.82	50c	679.1	III Q 2,2
78.56	20H	605.2	III R 3,3
79.18	10h	603.3	
5,681.10	20H	597.4	III Q 3,3
5,705.3	8?	522.7	III R 4,4
5,707.9	10?	514.7	III Q 4,4
5,866.42	40	041.5	III R 0,1
69.50	50	17,032.5	III Q 0,1
93.57	60	16,963.0	III R 1,2
5,896.67	80	954.0	III Q 1,2
5,920.84	50	884.8	III R 2,3
23.97	70	875.9	III Q 2,3
48.28	40	806.9	III R 3,4
51.26	50	798.5	III Q 3,4
[5] 75.82	30?	729.5	III R 4,5
5,978.83	40	16,721.1	III Q 4,5
6,003.62	30	16,652.0	III R 5,6
06.66	40	643.6	III Q 5,6
[6] 31.45	20?	575.2	III R 6,7
34.52	30	566.8	III Q 6,7
59.5	10h	498.4	III R 7,8
62.59	20h	490.3	III Q 7,8
87.99	10h	421.2	III R 8,9
6,090.90	10h	413.4	III Q 8,9
6,116.11	5h	345.8	III R 9,10
18.78	5h	338.6	III Q 9,10
43.99	2	271.6	III R 10,11
46.95	2	263.7	III Q 10,11
61.5	4	225.3	III Q 0,2
85.88	2	161.4	III R 1,3
6,189.83	7	151.1	IIIQ 1,3
6,214.32	15	087.4	III R 2,4
[7] 18.19	10?	077.4	III Q 2,4
26.35	5v	056.3	IX?
28.53	5v	050.7	IX?
42.93	25	013.7	III R 3,5
46.75	20	16,003.9	III Q 3,5
71.61	10	15,940.5	III R 4,6
6,275.46	8	930.7	III Q 4,6
6,300.30	8	867.9	III R 5,7
04.20	10	858.1	III Q 5,7
29.45	8	794.8	III R 6,8
33.25	8	785.3	III Q 6,8
[8] 58.12	40?	723.6	III R 7,9
62.33	8	713.2	III Q 7,9
87.8	4	650.5	III R 8,10
6,391.53	10	641.4	III Q 8,10
[9]6,417.22	3	578.8	III R 9,11
6,420.87	5	569.9	III Q 9,11
6,562.46	2hv	234.0	IX 4,4
6,573.23	3v	209.0	IX Q 3,3
6,575.69	4v	203.3	IX P3,3
83.81	4v	184.6	IX Q2,2
86.33	5v	178.8	IX P2,2
94.45	6v	160.1	IX Q1,1
6,597.01	6v	154.2	IX P1,1
6,605.12	8v	135.6	IX Q0,0
6,607.73	7v	15,129.6	IX P0,0
6,867.27	1	14,557.8	V 9,7
6,929.50	1	427.1	V 11,9
61.17	1	361.4	V 12,10
94.50	10	293.0	IV 1,0
6,996.89	5	288.1	
7,011.22	20	258.9	V 1,0
[10] 23.65	10?	233.7	IV 2,1
24.56	2	231.7	
40.84	20	199.0	V 2,1
54.80	15	170.8	IV 3,2
70.79	25	138.8	V 3,2
7,085.40	15	109.6	IV 4,3
7,101.02	20	078.6	V 4,3
16.40	15	048.2	IV 5,4
31.58	25	14,018.3	V 5,4
47.48	10	13,987.1	IV 6,5
62.60	10	957.6	V 6,5
79.00	10	925.7	IV 7,6
7,193.70	15	897.2	V 7,6
7,210.95	8	864.0	IV 8,7
25.24	10	836.6	V 8,7
42.88	5	802.9	IV 9,8
7,257.16	8	13,775.7	V 9,8

[3] LaII line at 5.458.68 A.
[4] LaII line at 5,482.27 A.
[5] LaI line at 5,975.75 A.
[6] LaI line at 6,031.46 A.
[7] LaI line at 6,218.19 A.
[8] LaII line at 6,358.12 A.
[9] LaI line at 6,417.23 A.
[10] LaI line at 7,023.67 A.

TABLE 5.—*Band heads in the spectrum of lanthanum monoxide (LaO)*—Contd.

λ I. A.	Intensity	ν_{vac} cm^{-1}	System and v', v''
7,275.40	4	13,741.2	IV 10, 9
7,289.22	4	715.1	V 10, 9
7,308.40	3	679.1	IV 11, 10
22.04	3	653.6	V 11,
41.3	2	617.8	IV 12,
54.90	3	592.6	V 12, 11
74.80	1	556.0	IV 13, 12
79.84	150	546.7	IV 0, 0
7,387.9	1	531.9	V 13, 12
7,403.52	200	503.4	V 0, 0
11.34	80	489.1	IV 1, 1
34.28	100	447.5	V 1, 1
42.92	60	431.9	IV 2, 2
65.25	80	391.7	V 2, 2
72.5	1	378.7	VI 2, 1
74.83	50	374.5	IV3, 3
7,496.50	60	335.9	V 3, 3
7,506.79	40	317.6	IV 4, 4
28.21	40	279.7	VI 3, 2
29.64	2	277.2	V 4, 4
[11] 39.21	10?	260.3	VII 3, 2
60.09	20	223.7	IV 5, 5
63.44	4	217.9	V 5, 5
72.49	5	202.1	VII 4, 3
75.10	2	197.5	IV 6, 6
92.26	15	167.7	VI 5, 4
7,597.47	4	158.7	V 6, 6
7,605.12	5	145.4	VII 5, 4
10.11	2	136.8	IV 7, 7
24.99	10	111.2	VI 6, 5
32.15	5	098.9	V 7, 7
38.28	2	088.4	VII 6, 5
45.23	4	076.5	IV 8, 8
57.83	8	054.9	VI 7, 6
66.73	2	039.8	V 8, 8
72.50	2	030.0	VII 7, 6
80.87	2	13,015.8	IV 9, 9
7,691.08	5	12,998.5	VI 8, 7
7,701.94	5	980.2	V 9, 9
06.20	2	973.0	VII 8, 7
16.66	3	955.4	IV 10, 10
24.29	4	942.6	VI 9, 8
37.74	1	920.1	V 10, 10
40.60	1	915.3	VII 9, 8
52.88	5	894.9	IV 11, 11
58.76	2	885.1	VI 10, 9
7,789.31	3	834.6	V 11, 11
7,809.77	5	801.0	VI 11, 10
42.55	2	747.5	VII 11, 10
7,846.4	3	741.2	IV 0, 1
75.53	2	694.1	VII 12, 11
[12] 76.867		691.91	IV 1, 2
[12] 77.22		691.35	VI 0, 0
7,877.18	100	691.4	
7,908.77	5	640.7	IV 2, 3
[12] 10.19		638.43	V 1, 2
[12] 10.54		637.89	VII 0. 0
10.50	150	638.0	
12.29	50	635.1	VI 1, 1
41.23	1	589.0	V 2. 3
42.70	1	586.7	IV 3, 4
[12] 44.61		583.70	VII 1, 1
[12] 44.95		583.16	
7,944.93	100	12,583.2	

λ I. A.	Intensity	ν_{vac} cm^{-1}	System and v', v''
7,947.86	20?	12,578.6	VI 2, 2
73.98	2	537.3	V 3, 4
[12] 79.35		528.91	VII 2, 2
[12] 79.70		528.36	
79.68	80	528.4	
7,983.30	10	522.7	VI 3, 3
8,007.40	2	485.0	V 4, 5
[12] 14.43		474.07	VII 3, 3
[12] 14.79		473.51	
14.78	60	473.5	
19.48	4	466.2	VI 4, 4
40.50	2	433.6	V 5, 6
[12] 49.92		419.07	VII 4, 4
[12] 50.26		418.55	
50.16	40	418.7	
55.84	3	410.0	VI 5, 5
73.79	2	382.4	V 6, 7
[12] 85.75		364.04	VII 5, 5
[12] 86.09		363.52	
[13] 86.10	20	363.5	
8,093.00	1?	353.0	VI 6, 6
8,108.13	2	329.9	V 7, 8
[12] 21.87		309.05	VII 6, 6
[12] 22.24		308.50	
22.20	10	308.6	
29.45	2	297.6	VI 7, 7
42.26	2	278.2	V 8, 9
[12] 58.76		253.40	VII 7, 7
[12] 59.10		252.89	
59.02	15	253.0	
66.84	2	241.3	VI 8, 8
77.26	2	225.7	V 9, 10
84.86	2	214.3	IV 10, 11
[12] 95.60		198.22	VII 8, 8
[12] 96.00		197.72	
8,196.12	10	197.5	
8,203.41	3	186.7	VI 9, 9
33.07	8	142.8	VII 9, 9
39.32	2	133.6	VI 10, 10
70.72	5	087.5	VII 10, 10
8,275.46	3	080.6	VI 11, 11
8,308.85	4	12,032.0	VII 11, 11
45.1	3	11,979.8	VII 12, 12
8,386.15	2	921.2	VII 13, 13
8,406.05	10	892.9	VI 0, 1
43.33	25	840.4	VI 1, 2
[12] 53.41		826.30	VII 0, 1
[12] 53.74		825.83	
53.55	50	826.1	
81.02	10	787.8	VI 2, 3
89.63		775.86	VII 1, 2
89.99		775.35	
8,490.00	40	775.3	
8,519.00	5	735.2	VI 3, 4
[12] 26.22		725.31	VII 2, 3
[12] 26.62		724.76	
26.59	35	724.8	
57.32	5	682.7	VI 4, 5
63.54	30	674.2	VII 3, 4
[12] 64.05		673.54	
[12] 64.37		673.08	
81.52	3	649.7	V 5, 7
8,595.88	6	630.3	VI 5, 6
[12] 8,600.46		11,624.10	VII 4, 5
[12] 00.81		623.62	
8,600.81	30	11,623.6	

[11] Lai line at 7,539.24 A.
[12] Measured by Auerbach and by Querbach.
[13] Lai line at 8,086.10 A.

TABLE 5.—*Band heads in the spectrum of lanthanum monoxide (LaO)*—Contd.

λ I. A.	Intensity	ν_{vac} cm^{-1}	System and v', v''	λ I. A.	Intensity	ν_{vac} cm^{-1}	System and v', v''
8,616.63	2	11,602.3	V 6,8	8,753.55	12	11,420.8	VII 8,9
35.52	2	576.9	VI 6,7	61.66	2	410.2	V 10,12
				8,792.77	10	369.9	VII 9,10
[12] 38.13		573.40		8,801.32	2	358.8	V 11,13
[12] 38.46		572.96	VII 5,6	32.33	5	318.9	VII 10,11
38.46	20	573.0					
52.17	2	554.6	V 7,9	8,872.12	4	268.2	VII 11,12
76.60	15	522.1	VII 6,7	8,912.42	3	217.2	VII 12,13
				8,953.59	2	11,165.6	VII 13,14
8,688.11	3	506.8	V 8,10	9,149.92	1	10,926.1	VII 2,4
8,713.43	2	473.4	VI 8,9				
14.92	15	471.4	VII 7,8				
27.1	2	455.5	V 9,11				
8,750.34	1	11,425.0	VI 9,10				

TABLE 6.—*Wave numbers, intensities, and differences between progressions of LaO bands*

LaO BANDS, SYSTEM I

v'' / v'	0	1	2	3	4	5	6	7	8
0	22, 867. 09(20) 22, 866. 59(40)								
1		22, 846. 89(15) 22, 846. 38(30)							
2			22, 826. 61(10) 22, 826. 10(20)						
3				22, 806. 85(8) 22, 806. 33(15)					
4					22, 785. 70(5) 22, 785. 19(10)				
5						22, 764. 94(4) 22, 764. 41(8)			
6							22, 743. 48(3) 22, 742. 93(6)		
7								22, 720. 96(2) 22, 720. 47(4)	
	8	9	10						22, 696. 15(1) 22, 695. 52(3)
8	22, 696. 15(1) 22, 695. 62(3)								
9		22, 671. 23(4)							
10			22, 646. 03(1) 22, 645. 52(3)						

LaO BANDS, SYSTEM II

v' \ v''	0	1	2	3	4	5	6	7
0	22, 627. 62(25) 803. 03 22, 627. 11(50) 802. 95	21, 824. 59(1) 21, 824. 16(3) 777. 82 777. 73						
1		22, 602. 41(20) 798. 36 22, 601. 89(40) 798. 31	21, 804. 05(1) 21, 803. 58(4) 773. 18 773. 15					
2			22, 577. 23(15) 793. 82 22, 576. 73(30) 793. 79	21, 783. 41(2) 21, 782. 94(5) 768, 62 768. 63				
3				22, 552. 03(15?)789. 41 22, 551. 57(30?)789. 40	21, 762. 62(1) 21, 762. 17(5) 764. 21 764. 15			
4					22, 526. 83(15) 784. 99 22, 526. 32(30) 784. 96	21, 741. 84(1) 21, 741. 36(4) 759. 69 759. 65		
5						22, 501. 53(12) 780. 88 22, 501. 01(25) 780. 81	21, 720. 65(1) 21, 720. 20(3) 775. 38 755. 34	
6							22, 476. 03(10) 777. 89 22, 475. 54(20) 777. 84	21, 699. 14(1) 21, 698. 70(3) 750. 92 750. 87

TABLE 6.—*Wave numbers, intensities, and differences between progressions of LaO bands*—Continued

LaO BANDS, SYSTEM II—Continued

v' \ v''	7	8	9	10	11			
6	21, 699. 14(1) 21, 698. 70(3) 750. 92 750. 87							
7	22, 450. 06(8) 773. 01 22, 449. 57(20) 773. 01	21, 677. 05(1) 21, 676. 56(3) 746. 35 746. 35						
8		22, 423. 40(5) 770. 01 22, 422. 91(15) 769. 98	21, 653. 39(1) 21, 652. 93(3) 741. 42 741. 38					
9			22, 394. 81(3) 768. 04 22, 394. 31(10) 768. 00	21, 626. 77(1) 21, 626. 31(3) 732. 26 732. 22				
10				22, 359. 03(3) 22, 358. 53(10) 753. 87	21, 604. 66(3?)			

LaO BANDS, SYSTEM III (R HEADS ABOVE, Q HEADS BELOW)

v' \ v''	0	1	2	3	4	5	6	7
0	17, 852. 4(200d) 810. 9 17, 844. 5(250d) 812. 0 728. 2 729. 1	17, 041. 5(40) 17, 032. 5(50) 807. 2 728. 1 729. 0	16, 225. 3(4) 728. 7					
1	18, 580. 6(10) 811. 0 18, 573. 6(20) 812. 1	17, 769. 6(100) 806. 6 17, 761. 5(100) 807. 5 724. 4 725. 6	16, 963. 0(60) 801. 6 16, 954. 0(80) 802. 9 723. 9 725. 1	16, 161. 4(2) 16, 151. 1(7) 723. 4 724. 8				
2		18, 494. 0(20) 807. 1 18, 487. 1(30) 808. 0	17, 686. 9(50) 802. 1 17, 679. 1(50) 803. 2 720. 6 721. 6	16, 884. 8(50) 797. 4 16, 875. 9(20) 798. 5 720. 4 721. 5	16, 087. 4(15) 16, 077. 4(10?) 719. 5 721. 1			
3			18, 407. 5(20) 802. 3 18, 400. 7(30) 803. 3	17, 605. 2(20) 798. 3 17, 597. 4(20) 798. 9 716. 1 717. 0	16, 806. 9(40) 793. 2 16, 798. 5(50) 794. 6 715. 8 716. 2	16, 013. 7(25) 16, 003. 9(20) 715. 8 717. 2		
4				18, 321. 3(10) 798. 6 18, 314. 4(20) 799. 7	17, 522. 7(8?) 793. 2 17, 514. 7(10?) 793. 6 712. 9 714. 1	16, 729. 5(60?) 789. 0 16, 721. 1(40) 790. 4	15, 940. 5(10) 15, 930. 7(8) 711. 5 712. 9	
5					18, 235. 6(?) 18, 228. 8(10)		16, 652. 0(30) 784. 1 16, 643. 6(40) 785. 5	15, 867. 9(8) 15, 858. 1(10) 707. 3 708. 7

TABLE 6.—*Wave numbers, intensities, and differences between progressions of LaO bands*—Continued

LaO BANDS SYSTEM III (R HEADS ABOVE, Q HEADS BELOW—Continued

v′ \ v″	4	5	6	7	8	9	10	11
6		18, 148. 9(10) 18, 141. 8(8)		16, 575. 2(20) 780. 4 16, 566. 8(30) 781. 5	15, 794. 8(8) 15, 785. 3(8) 703. 6 704. 7			
7			18, 064. 4(8) 18, 057. 4(10)		16, 498. 4(10) 774. 8 16, 490. 0(20) 776. 8	15, 723. 6(40?) 15, 713. 2(8) 697. 6 700. 2		
8				17, 979. 3(8) 17, 972. 3(5)		16, 421. 2(10) 770. 7 16, 413. 4(10) 772. 0	15, 650. 5(4) 15, 641. 4(10) 695. 3 697. 2	
9					17, 894. 0(6) 17. 887. 8(2)		16, 345. 8(5) 767. 0 16, 338. 6(5) 768. 7	15, 578. 8(3) 15, 589. 9(5) 692. 8 693. 8
10								16, 271. 6(2) 16, 263. 7(2)

v' \ v''	0	1	2	3	4	5	6	7	8
0	13, 546. 7(150) 799. 2 746. 3	12, 747. (2) 5 741. 6							
1	14, 293. 0 (10) 803. 9	13, 489. 1(80) 795. 0 744. 6	12, 694. 1(2) 737. 8						
2		14, 233. 7(40?) 801. 8	13, 431. 9(60) 791. 2 738. 9	12, 640. 7(5?) 733. 8					
3			14, 170. 8(15) 796. 3	13, 374. 5(50) 787. 8 735. 1	12, 586. 7(1) 730. 9				
4				14, 109. 6(15) 792. 0	13, 317. 6(40) 730. 6				
5					14, 048. 2(15) 787. 9	13, 260. 3(40) 726. 8			
6						13, 987. 1(10) 785. 0	13, 202. 1(5) 723. 6		
7							13, 925. 7(10) 780. 3	13, 145. 4(5) 718. 6	
	8	9	10	11	12				
8	13, 088. 4(2) 715. 5							13, 864. 0(8) 775. 6	13, 688. 4(2) 714. 5
9	13, 802. 9(5) 772. 9	13, 030. 0(2) 711. 2							13, 802. 9(5)
10		13, 741. 2(4) 768. 2	12, 973. 0(2) 758. 7 706. 1	12, 214. 3(2) 701. 0					
11			13, 679. 1(3) 763. 8	12, 915. 3(1) 702. 5					
12				13, 617. 8(2)					
13					13, 556. 0(1)				

TABLE 6.—*Wave numbers, intensities, and differences between progressions of LaO bands*—Continued

LaO BANDS, SYSTEM V

v′ \ v″	0	1	2	3	4	5	6	7	8
0	13, 503. 4(200) 809. 3 755. 5	12, 694. 1(2?) 753. 4							
1	14, 258. 9(20) 811. 4	13, 447. 5(100) 806. 8 751. 5	12, 640. 7(5?) 751. 0						
2		14, 199. 0(20) 807. 3	13, 391. 7(80) 802. 7 747. 1	12, 589. 0(1) 746. 9					
3			14, 138. 8(25) 802. 9	13, 335. 9(60) 798. 6 742. 7	12, 537. 3(2) 742. 4				
4				14, 078. 6(20) 798. 9	13, 279. 7(40) 794. 7 738. 6	12, 485. 0(2) 738. 7			
5					14, 018. 3(25) 794. 6	13, 223. 7(20) 790. 1 733. 8	12, 433. 6(2) 783. 9 734. 1	11, 649. 7(3) 732. 7	
6						13, 957. 5(10) 789. 8	13, 167. 7(15) 785. 3 729. 5	12, 382. 4(2) 780. 1 728. 8	11, 602. 3(2) 727. 6
	8	9	10	11	12	13			
7	12, 329. 9(2) 775. 3 725. 0	11, 554. 6(1) 723. 6					13, 897. 2(15) 786. 0	13, 111. 2(10) 781. 3 725. 4	12, 329. 9(2) 725. 0
8	13, 054. 9(8) 776. 7 720. 8	12, 278. 2(2) 771. 4 720. 3	11, 506. 8(3) 718. 9					13, 836. 6(10) 781. 7 721. 2	13, 054. 9(8) 720. 8
9	13, 775. 7(8) 777. 2	12, 998. 5(5) 772. 8 716. 6	12, 225. 7(2) 770. 2 716. 9	11, 455. 5(2)				14, 557. 8(1) 781. 9	13, 775. 7(8)
10		13, 715. 1(4) 772. 5 712. 0	12, 942. 6(4) 711. 0		11, 410. 2(2)				
11		14, 427. 1(1) 773. 8	13, 653. 6(3) 707. 8	768. 5 12, 885. 1(2) 707. 5		11, 358. 8(2)			
12			14, 361. 4(1) 768. 8	13, 592. 6(3)					
13					13, 531. 9(1)				

LaO BANDS, SYSTEM VI

v' \ v''	0	1	2	3	4	5	6	7	8
0	12, 691. 4(100) 798. 5	11, 892. 9(10) 742. 2							
1	[1] 13, 437	12, 635. 1(50) 794. 7 743. 6	11, 840. 4(25) 738. 2						
2		13, 378. 7(1) 800. 1	12, 578. 6(20) 789. 8 739. 0	11, 787. 8(10) 734. 9					
3			13, 317. 6(10) 794. 9	12, 522. 7(10) 787. 5	11, 735. 2(5) 731. 0				
4				[2] 13, 257	12, 466. 2(4) 783. 5 731. 3	11, 682. 7(5) 727. 2			
5					13, 197. 5(2) 787. 6	12, 409. 9(3) 779. 6 726. 9	11, 630. 3(6) 722. 7		
6						13, 136. 8(2) 783. 8	12, 353. 0(1) 776. 1 723. 5	11, 576. 9(2) 720. 7	
7							13, 076. 5(4) 778. 9	12, 297. 6(2) 718. 2	
	8	9	10	11					
8	12, 241. 3(2) 757. 9 714. 1	11, 473. 4(2) 713. 3						13, 015. 8(2) 771. 5	12, 241. 3(2) 714. 1
9	12, 955. 4(3) 768. 7	12, 186. 7(3) 761. 7 708. 2	11, 425. 0(1) 708. 6						12, 955. 4(3)
10		12, 894. 9(5) 761. 3	12, 133. 6(2) 701. 0						
11			12, 834. 6(3) 754. 0	12, 080. 6(3)					

[1] Masked by 13,447.5(100) V 1, 1.

[2] Masked by 13,260.3(40) IV 5, 5 and LaI.

TABLE 6.—*Wave numbers, intensities, and differences between progressions of LaO bands*—Continued

LaO BANDS, SYSTEM VII

v′ \ v″	0	1	2	3	4	5	6	7	8
0	12, 638. 0(150) 811. 9	11, 826. 1 (50) 757. 1							
1	[1] 13, 395	12, 583. 2(100) 807. 9	11, 775. 3(40) 753. 1						
2		[2] 13, 336	12, 528. 4(80) 803. 6 748. 8	11, 724. 8(35) 798. 7 748. 7	10, 926. 1 (1) 748. 1				
3			13, 277. 2 (2) 803. 7	12, 473. 5(60) 799. 3 744. 4	11, 674. 2(30) 744. 5				
4				13, 217. 9 (4) 799. 2	12, 418. 7(40) 795. 1 740. 0	11, 623. 6(30) 739. 9			
5					13, 158. 7 (4) 795. 2	12, 363. 5(20) 790. 5 735. 4	11, 573. 0(20) 735. 6		
6						13, 098. 9 (5) 790. 3	12, 308. 6(10) 786. 5 731. 2	11, 522. 1(15) 730. 9	
7							13, 039. 8 (2) 786. 8	12, 253. 0(15) 781. 6	11, 471. 4(15)
	8	9	10	11	12	13	14	727. 2	726. 1
8	12, 197. 5(10) 776. 7 722. 6	11, 420. 8(12) 722. 0						12, 980. 2 (5) 782. 7	12, 197. 5(10) 722. 6
9	12, 920. 1 (1) 777. 3	12, 142. 8 (8) 722. 9	11, 369. 9(10) 717. 6						12, 920. 1 (1)
10			12, 087. 5 (5) 768. 6 713. 5	11, 318. 9(5) 713. 1					
11			12, 801. 0 (5) 769. 0	12, 032. 0(4) 763. 8 709. 2	11, 268. 2(4) 711. 6				
12				12, 741. 2(3) 761. 4	11, 979. 8(3)? 762. 6	11, 217. 2(3) 704. 0			
13						11, 921. 2(2) 755. 6	11, 165. 6(2)		

LaO BANDS, SYSTEM IX (Q HEADS ABOVE, P HEADS BELOW)

v'' / v'	0	1	2	3	4	5	6	7	8
0	15, 135. 6(8) 15, 129. 6(7)								
1		15, 160. 1(6) 15, 154. 2(6)							
2			15, 184. 6(4) 15, 178. 8(5)						
3				15, 209. 0(3) 15, 203. 3(4)					
4					15, 234. 0(ed)				

[1] Masked by 13,395.6 LaI.

[2] Masked by 13,335.9(60) v. 3, 3.

Wave lengths, intensities, and vacuum wave numbers for the bands observed in the LaO spectrum are given in Table 5, and the analysis into various systems is shown in Table 6. The values of infra-red bands measured double by Auerbach and by Querbach are quoted to show that a constant separation of about 0.5 cm^{-1} probably occurs in all of the band heads. The cause of this doubling is unknown. All bands are shaded to red except those marked *V*, which are shaded to violet.

By setting up formulas which approximately represent the band heads of the seven systems, and then comparing coefficients, both Mecke and Jevons have drawn certain conclusions as to the initial or final states held in common by the different systems. Thus Mecke's conclusion that Systems III, V, and VII have a common final state is approximately confirmed by Jevons, but Mecke's suggestion that the initial state of I may be the final of IV is not accepted by Jevons, who holds that if these systems have a state in common it can only be the final of each. Similarly, while Mecke suggests that the initial state of II may be the final of VI, Jevons believes that these two systems probably have a common final state. It appears to be impossible to settle these points without more accurate information as to band origins.

IV. DISCUSSION

In the ScO, YO, and LaO bands which we have investigated, the (probably) large discrepancies between the values of a', b', a'', and b'' in band head equation (11) and the quantities ω_0', $\omega_0'x'$, ω_0'', and $\omega_0''x''$ in band origin equation (3) have precluded the possibility of unambiguous assignment of electronic states to the various systems. Band-origin measurements will make possible definite electronic level assignments, and will permit the accurate determination of molecular dissociation energies. Jevons and Pearce [27] have suggested that there may be an analogy between the electronic levels of the ScO, YO, and LaO molecules and those of the K, Rb, and Cs atoms, respectively, arising from a sharing between the constituent atoms of the molecule all but each one's own $2K$ and $8L$ electrons, with the result that the atom corresponding to a given molecule should have 10 less electrons. If in accordance with this idea we interpret the four red systems of each molecule as being the *R* and *Q* heads of $^2\Pi_{1\frac{1}{2}} \rightarrow {}^2\Sigma_{\frac{1}{2}}$ and $^2\Pi_{\frac{1}{2}} \rightarrow {}^2\Sigma_{\frac{1}{2}}$ transitions, we may classify the systems as follows:

Molecule	*R* head of (0, 0) band of $^2\Pi_{1\frac{1}{2}} - {}^2\Sigma_{\frac{1}{2}}$	*Q* head of (0, 0) band of $^2\Pi_{1\frac{1}{2}} - {}^2\Sigma_{\frac{1}{2}}$	*R* head of (0, 0) band of $^2\Pi_{\frac{1}{2}} - {}^2\Sigma_{\frac{1}{2}}$	*Q* head of (0, 0) band of $^2\Pi_{\frac{1}{2}} - {}^2\Pi_{1\frac{1}{2}}$
Sc (21) O (8)	16,615 cm^{-1} System II	16,562 cm^{-1} System III	16,485 cm^{-1} System IV	16,445 cm^{-1}. System V.
Y (39) O (8)	16,833 cm^{-1} System II	16,741 cm^{-1} System III	16,398 cm^{-1} System IV	16,303 cm^{-1}. System V.
La (57) O (8)	13,547 cm^{-1} System IV	13,503 cm^{-1} System V	12,691 cm^{-1} System VI	12,638 cm^{-1}. System VII.

Molecule	Approximate *R* head − *Q* head separations	Approximate doublet separations	Analogous atom	Atomic doublet separations	$^2P_{1\frac{1}{2}} - {}^2S_{\frac{1}{2}}$
Sc (21) O (8)	47 cm^{-1}	124 cm^{-1}	K (29)	57.8 cm^{-1}	13,042 cm^{-1}.
Y (39) O (8)	94 cm^{-1}	437 cm^{-1}	Rb (47)	236.0 cm^{-1}	12,816 cm^{-1}.
La (57) O (8)	49 cm^{-1}	860 cm^{-1}	Cs (65)	553.9 cm^{-1}	11,732 cm^{-1}.

[27] Proc. Phys. Soc. London, **41**, p. 531; 1929.

Whether this classification has any reality is doubtful because of the large R head-Q head separations it implies; the approximate separation calculated from an empirical formula was only 10 to 20 cm^{-1} for the four YO systems. Another argument to be brought against it is that Q heads should not show the large "combination deficit" present in Systems III and V of YO.

It is known that the vibrational energy levels in a few electronic states of some molecules show marked deviations from formula (2). Considerable departures of this type are evident in the fourth, fifth, and sixth vibrational levels of the initial state of System I of YO. Also perturbations in intensity are evident in several cases; that is, bands arising from the seventh vibrational level of the initial state of YO System III have about one-third the estimated intensity to be expected; the eighth vibrational level of the intital state of YO System V has about one-fifth the expected intensity; and the seventh vibrational level of the final state of LaO System VII shows a weakening, although it is not much greater than the probable error in intensity estimates.

The rotational fine structure of bands is in general, not so simple as is indicated in the introductory theory given above. In particular, the rotational fine structure of the monoxides of the elements in the third column of the periodic table of the elements may be expected to show complications arising from one outer nonvalence electron and from the interaction of its angular momentum, l, and its spin, $s=1/2$ with each other and with the rotational motion of the molecule and will give rise to $^2\Sigma$, $^2\Pi$, ..., etc., terms. The theory of $^2\Sigma \rightarrow {}^2\Pi$ and $^2\Pi \rightarrow {}^2\Sigma$ combinations has been given by Mulliken.[28] According to his treatment, a number of different types of rotational structure may be expected in such transitions, varying from a situation where there are 6 strong branches, showing four heads, and accompanied by 4 weak satellite branches, to a case where there are 12 strong branches. In the first case, where 4 heads are present, the first head should, in general, be the weakest. LaO System III shows exactly this behavior; the estimated intensities of the heads of the (0, 0) band at 5,600 A. proceeding in order from shorter wave lengths to longer are 50, 100, 100, 200. An attempt to analyze the (0, 0) band was made, using a second order spectrogram taken with a dispersion of 1.8 A/mm. and a resolving power of 150,000. Two of three branches were traced out amidst the fine structure, but the complete analysis of the LaO rotational structure will require higher resolving power. The doubling is only $0.5-^1$ in the presumable R and Q heads of System III; we have also measured the same doubling in Systems I and II, and Auerbach [29] and Querbach [30] have, in addition, found it in one band of System VI and in System VII.

Systems I of ScO and YO, analogous to System III of LaO, differ from it in showing under our present resolutions only two heads. It is planned to carry out with higher resolving power fine structure analysis for all three molecules and to trace the variations in the rotational levels as the atomic number increases.

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[28] Mulliken, Phys. Rev. **32**, p. 338; 1928.
[29] Auerbach, Die Naturwissenschaften, **17**, p. 84; 1929.
[30] Querbach, Zeitsch. f. Phys., **60**, p. 109; 1930.