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P. S. KIREEV

FINE STRUCTURE AND THE LAMB SHIFT OF THE $2s_{1/2}$ LEVEL OF THE T_α LINE OF TRITIUM, $\lambda 6560$ Å

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The investigation of the fine structure of the lines of the third isotope of hydrogen —tritium—is of considerable scientific interest. The theory of the fine structure and of the Lamb shift of the $ns_{1/2}$ levels can be tested on tritium lines with greater accuracy than on hydrogen or deuterium lines, since the Doppler width of tritium lines is, respectively, 1.73 and 1.22 times smaller than the width of lines emitted by hydrogen and deuterium under identical conditions. Of great interest are studies of the intensities of the fine-structure components of tritium lines and the investigation of the isotope shift due to the difference in the nuclear masses of the isotopes H, D, and T. Information on spectroscopic studies of tritium lines is practically absent from the literature.

Table 1

Designation	Transition	$\delta\nu$ according to Dirac, in $1 \cdot 10^{-3}$ cm^{-1}	$\delta\nu$ (Lamb shift), $1 \cdot 10^{-3}$ cm^{-1}	I_{theor}
a	$3d_{5/2} - 2p_{3/2}$	0.0000	0.0000	9.00
g	$3d_{3/2} - 2p_{1/2}$	328.6	328.6	5.00
f	$3p_{3/2} - 2s_{1/2}$	328.6	293.6	2.08
e	$3p_{1/2} - 2s_{1/2}$	220.8	185.8	1.04
d	$3s_{1/2} - 2p_{1/2}$	220.8	230.8	0.10
	$3d_{3/2} - 2p_{3/2}$	−36.0	−36.0	1.00
c	$3s_{1/2} - 2p_{3/2}$	−144.2	−134.2	0.195

Fig. 1. Structure of the T_α line according to Dirac theory (A) and taking account of the Lamb shift of the $nS_{1/2}$ levels (B)

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In the present work, investigations were carried out of the fine structure of the first line of the Balmer series in tritium, T_α–λ6560 Å, of the intensities of the fine-structure components of this line, and of the isotope shift in the $H_\alpha - T_\alpha$ lines.

Table 1 gives the structure of the T_α line, obtained on the basis of Dirac's electron theory. The separations of the components from the most intense component a are given according to Dirac theory and with allowance for the Lamb shift of the $2s_{1/2}$ and $3s_{1/2}$ terms. The intensities of the components are given in certain conventional units obtained on the basis of Dirac' s radiation theory. Table 1 contains information on the fine structure of the α-line of the Balmer series for any isotope of hydrogen. For the shifts of the $2s_{1/2}$ and $3s_{1/2}$ terms, the values 0.035 and 0.010 cm^{-1} ([1]) were adopted (Fig. 1).

As the light source in the present work, a U-shaped discharge tube was used, with a capillary of diameter about 3 mm and length $\sim$ 120 mm. The tube was carefully evacuated with heating of the walls and electrodes, after which it was filled with pure tritium to a pressure of 2–3 mm Hg. The glow of tritium was excited by a current of several milliamperes (2.5–10 mA) from a high-voltage transformer, to which a resistance of $\sim$ 200,000 ohms was connected in series with the tube.

To resolve the fine structure of the T_α line, a Fabry–Perot etalon with spacings of various thicknesses was used, placed in front of the slit of an ISP-51 spectrograph with a camera $f = 270$ mm. The interference pat-

projected onto the spectrograph slit by an objective with $f = 300$ mm. The reflection coefficient of the etalon mirrors in the region studied was 0.92. The source, positioned vertically, was immersed in liquid nitrogen in order to reduce the Doppler width of the lines. With the aid of a rotating prism, the light from the source was directed onto the etalon. The secondary images produced by the etalon were removed by an additional slit placed after the rotating prism and projected onto the spectrograph slit with the aid of additional objectives. The spectrum was photographed on highly sensitive panchromatic film with exposures from 2–3 to 30–40 min. The spectrograms were measured on an IZA-2 comparator; the measurement results were processed by the method of rectangular tables.

Fig. 1. Structure of the T_α line according to Dirac theory (A) and taking account of the Lamb shift of the $nS_{1/2}$ levels (B)

Control photographs taken with etalons of different thicknesses showed that the

T_α line consists of three well-resolved components. Most of the photographs were taken with an etalon thickness of 7.0 mm and a dispersion region of 0.7148 cm^{-1}. After the tube had operated for some time, traces of hydrogen were detected in the spectrum; this was checked by photographing the radiation of hydrogen in the hollow cathode. After this, the T_α line was photographed with etalons of thickness 4.0 and 5.0 mm; in this case the H_α line is situated between the orders of the T_α line. The small amount of hydrogen made it possible to measure more accurately the distances between the components of the H_α and T_α lines (Figs. 2 and 3).

The mean values of the distances between the complexes (by a complex we mean a group of unresolved components) $a-e$, $e-g$, and $a-g$ are, respectively, 192.3, 129.0, and 321.3 (in $1 \cdot 10^{-3}$ cm^{-1}). The results obtained do not agree with the results of Dirac' s fine-structure theory, which is explained by the shift of the $2s_{1/2}$ and $3s_{1/2}$ levels relative to $2p_{1/2}$ and $3p_{1/2}$. To estimate the magnitude of the shift one may use a calculation based on the position of the center of gravity, assuming that the center of gravity of the complex coincides with the maximum of blackening, the position of the maximum of blackening being determined only by those components which enter into the given complex. In first approximation we neglect the influence of neighboring complexes. Denoting the displacement of the $2s_{1/2}$ level by x, and assuming that the displacement of the $3s_{1/2}$ term is in accordance with the law n^{-3}, we can find the value of the displacement x by comparing the experimentally obtained distances between the complexes with the theoretical values. In this case, for the value of x we obtain (in $1 \cdot 10^{-3}$ cm^{-1}): $x = 35.4$, $x = 34.9$, $x = 36.4$, found, respectively, from the distances $a - e$, $a - g$, $g - e$, taking account of the theoretical values of the intensities of the components. The mean value of the displacement of the $2s_{1/2}$ level is equal to $35.5 \cdot 10^{-3}$ cm^{-1}, which is in good agreement with the theory of the shift of the $nS_{1/2}$ levels in hydrogen and deuterium ([1]). However, for a more accurate calculation of the displacement of the levels it is necessary to take into account the influence of neighboring complexes. The influence of complex g on complex e can be taken into account under the assumption that the line contour is purely Doppler. Taking account of the experimentally determined half-widths and intensities of lines, which differ from the theoretical values (see below), one can estimate the shift of the $2s_{1/2}$ level as 0.037 cm^{-1}. The allowance for the influence of neighboring components on the position of the maximum in the case of a Doppler contour depends very strongly on the line half-width; therefore the magnitude of the shift in this case is determined with an accuracy of 0.002–0.003 cm^{-1}. Thus,

Fig. 2. Structure of the T_α line. Etalon $t = 7.0$ mm

Fig. 3. Isotopic shift $T_\alpha - H_\alpha$. Etalon $t = 4.0$ mm

we may assert that the displacement of the term $2s_{1/2}$ lies within the limits $0.033 < \delta E_{2s} < 0.039$ cm^{-1}. To obtain a more accurate value it is necessary to reduce the line width by using hydrogen cooling.

Fig. 4. Intensity curve of the T_α line and its decomposition into the contours of complexes. Standard $t = 7.0$ mm.

Figure 2: Fig. 4. Intensity curve of the T_α line and its decomposition into the contours of complexes. Standard $t = 7.0$ mm.

The isotopic shift $H_\alpha - T_\alpha$ was investigated in the work of Terranova and Pomeranz ([2]) on a spectrograph with a diffraction grating having a dispersion of 0.14 mm/Å. They obtained for the distance $H_\alpha - T_\alpha$ the value (2.36 ± 0.05) Å, or (5.475 ± 0.116) cm^{-1}. The use of a standard makes it possible to reduce the measurement error considerably and to obtain a more accurate result.

The measurement of the distances between the corresponding components was carried out in our work from spectrograms taken with a standard of thickness 4.0, 4.3, and 5.0 mm. For the value of the isotopic shift between the corresponding components of the H_α and T_α lines, $\delta\nu = (5.5321 \pm 0.0025)$ cm^{-1} was obtained (in air). Taking into account the refractive index of air and introducing a correction for the value of the isotopic shift in vacuum, we obtain $\delta\nu = (5.5305 \pm 0.0025)$ cm^{-1}, which is 0.006 cm^{-1} greater than the theoretical value ([3]), which takes into account the simple mass effect. The discrepancy lies outside the limits of error. The reason for the discrepancy has not been clarified.

Fig. 4. Intensity curve of the T_α line and its decomposition into the contours of complexes. Standard $t = 7.0$ mm.

The measurement of the intensities of the fine-structure components of the T_α line was carried out from the areas of the contours within one order. For this purpose the microphotogram obtained from the spectrogram, with the aid of the characteristic curve of the film $S(\lg I)$, is converted into an intensity curve. However, the intensity curve of the line obtained with the standard cannot be used to determine the intensities of the complexes, since the dispersion of the standard is nonlinear and the intensity curve cannot be decomposed into the contours of the complexes. Therefore the intensity curve obtained from the spectrogram is converted into a curve with linear dispersion. Figure 4 gives the intensity curve of the T_α line, where ε is the magnitude of the order of interference counted from some maximum. To determine the relative intensity of the complexes from the total intensity curve, the contours of the complexes are separated out (in Fig. 4 the contours of the complexes are given by thin lines). The ratio of the areas of the contours of the complexes within one order ($\Delta\varepsilon = 1$) gives the relative intensity of the complexes; in this case the area of a complex is proportional to the sum of the intensities of the components entering into the complex.

Table 2

Complex	Composition of the complex	I_{exp}	I_{theor}
a	$a,\ b,\ c$	1.000	1.000
g	$g,\ f$	0.772	0.694
e	$e,\ d$	0.218	0.112

The intensity of the complex a, consisting of the components $a,\ b,\ c$, has been taken as unity. As Table 2 shows, the intensity of the complex g, consisting of the components g and f, is somewhat greater than the theoretical value; the intensity of the complex e, consisting of the components e and d, exceeds the theoretical value by almost a factor of two.

The increased values of the intensities of the components $e,\ d$ and $g,\ f$ are explained by processes in the light source. Self-absorption of light in the source cannot be responsible for the anomaly in the distribution of the line intensity among the components, since self-absorption should lead to a decrease in the intensity of the components e and f, since the indicated components ari-

arise when the atom passes into the $2s_{1/2}$ state, which is metastable, and, consequently, the indicated components must undergo considerably greater self-absorption than the other components. The results obtained when photographing the light across the capillary coincide, within the limits of error, with the results obtained when observing the light along the capillary. Thus, our results for tritium confirm the strong dependence, observed many times earlier, of the relative intensity of the fine-structure components of the hydrogen and deuterium lines on the excitation conditions ([4]).

Noteworthy is the fact that an increase in intensity is observed for components associated with s-levels, which undergo a significant vacuum shift. A similar situation was observed by us ([5]) in the case of the He II line $\lambda\,4686$ Å. Kuhn and Series ([6]) observed an increase in the intensity of complex e in deuterium, whose intensity exceeded the theoretical value by a factor of 1.7. All this permits the assumption that the theoretical data for the intensities of the fine-structure components are incorrect, since they do not take into account certain additional interactions between the atomic electron and the electromagnetic and electron-positron vacuum, as a result of which the transition probability for components associated with s levels increases, leading to an increase in the intensity of these components in comparison with the others, for which this interaction is less pronounced. It is possible that in the present case there is a superposition of a kind of "vacuum effect" for the intensities and of effects associated with the excitation conditions. A final conclusion can be obtained after a detailed study of the course of the intensities when the excitation conditions are varied, in order to take account of the dependence on the excitation conditions and to isolate the possible "vacuum effect for the intensities" in pure form.

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Moscow State University
named after M. V. Lomonosov

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CITED LITERATURE

1. *The Latest Development of Quantum Electrodynamics* (collection of articles), IL, 1954.
2. H. Pomerance, D. Terranova, Ann. J. Phys., **18**, 466 (1950).
3. C. E. Moore, *Atomic Energy Levels*, 1, Washington, 1949, pp. 1–3.
4. H. Bethe, *Quantum Mechanics of the Simplest Systems*, 1935.
5. P. S. Kireev, DAN, **106**, No. 4 (1956).
6. H. Kuhn, C. W. Series, Proc. Roy. Soc., A **202**, 127 (1950).

Note: Figure translations are in progress. See original paper for figures.