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PICTURE OF "SPATIAL ANISOTROPY" INDUCED BY CASCADE LASER TRANSITIONS $5s'[1/2]^o_1 \to 4p'[1/2]_0 \to 3d'[3/2]^o_1$

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Anisotropy of induced changes in intensities of spectral lines emitted from the $5s'[1/2]^o_1$ and $3p'[1/2]_1$ levels has been investigated in details. The experimental results have been explained by assuming that the optical E vector of laser radiation gives an axis of quantization, and linearly polarized laser oscillations induce only π transitions $\Delta m_J = 0$. An energy transfer within m_J sublevels of the $5s'[1/2]^o_1$ and $3p'[1/2]_1$ levels has been observed.

It is a well known fact that the interaction of linearly polarized He-Ne laser radiation with excited neon atoms produces an alignment of angular momenta J of the laser levels in an optical field of E vector [1]. This alignment causes a spatial anisotropy of the spontaneous emission of spectral lines from laser levels. The effect, called "Induced Spatial Anisotropy", has been described by Javan and Hänsch and Toschek for the $3p'[3/2]_2 (J = 2)$ neon level and laser actions at 633 and 1152 nm [2–4]. However, the anisotropy of the upper laser levels $5s'[1/2]^o_1$ and $4s'[1/2^o_1 (J = 1)$ was not observed in the above mentioned works. This was explained by a destruction of the alignment due to collision transfer of the population within m_J sublevels [2]. In spite of that, such anisotropy has been obtained for the $5s'[1/2]^o_1$ level, under the same pressure conditions as in the quoted works [5]. The only difference consisted in an inducing laser action, which starting from $5s'[1/2]^o_1$ comes to a level with $J = 0$, otherwise $4p'[1/2]_0$-oscillations at 4218 nm. Analyzing the anisotropy of the $5s'[1/2]^o_1$ level, induced by laser oscillations at 4218 nm and 633 nm, we have drawn a conclusion: the anisotropy appears when linearly polarized laser radiation pumps individual sublevels of laser level — in the optical field of the E vector — at different rates. For example: all sublevels $m = \pm 1, 0$ of $5s'[1/2]^o_1$ are depopulated via π laser transitions at 633 nm, so spectral lines from that do not show any anisotropy. It is a different situation when laser oscillation $5s'[1/2]^o_1 \to 4p'[1/2_0$, at 4218 nm, induces changes in populations of the $5s'[1/2]^o_1$ level. Because the angular momentum of the lower laser level has $J = 0$, so $m = 0$, and π laser transitions depopulate only sublevel $m = 0$, and as a result,

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the anisotropy appears. The matter of the article is to present and explain results which have been obtained for the above mentioned transition $5s'[1/2]_1^0 \rightarrow 4p'[1/2]_0$. As laser oscillations on that transition induce only slight changes in the population of the $5s'[1/2]_1^0$ level, so to enhance the effect, another laser action, developing between $4p'[1/2]_0$ and $3d'[3/2]_1^0$ levels 5404 nm, has been used. Changes induced by both these simultaneous laser actions are sufficiently distinct for mesurements.

1. Theory

The problem of anisotropy we shall resolve by means of a theory of the Zeeman effect. It is known, that any level of quantum number J (total angular momentum) splits into m_J sublevels in a magnetic or electric field. The atoms emitting light in jumping from one state to another may change m_J by ± 1 or 0 only. If m_J does not change ($\Delta m_J = 0$), light emitted is polarized parallel to the field; there are π components. If m_J changes by one unit ($\Delta m = \pm 1$), components $\sigma^{\pm}$ are emitted with circular polarization about the field. In the next considerations we shall assume a field, giving a quantization axis, so weak, that it is of no use to take into account the energy splitting into sublevels. In our experiment that splitting will be considerably smaller than the Doppler level width.

Now, we consider an atom in an excited state with an angular momentum $J = 1$. There are three possible transitions of the atom to a lower states described by $J = 0, 1, 2$. For every one of those cases we can calculate the relative intensities, or transition probabilities, for particular π and σ components from the formula

$$\gamma(JM \rightarrow J'M') \sim \begin{pmatrix} J & 1 & J' \\ -M & q & M' \end{pmatrix}^2, \tag{1}$$

where $q = M - M'$, and JM; $J'M'$ are quanta numberes of the upper and lower levels (in our case $J = 1$ and $J' = 0, 1, 2$) [6]. The results of calculations for any case $\Delta J = \pm 1{,}0$ has been given in Fig. 3.

The anisotropy of intensity changes of spontaneously emitted lines we shall find by calculating those changes for the π and σ components, separately. Let us begin with the transition $(J = 1) \rightarrow (J = 0)$ (see Fig. 3). Here, we have only one π ($\Delta m_J = 0$), and two $\sigma(\Delta m_J = \pm 1)$ components. Because, the splitting is small, there are no differences in the populations of particular sublevels when there is no perturbation. Making use of probabilities, calculated from formula (1) we obtain

$$\left(\frac{\Delta I_\pi}{I_\pi^0}\right)_{1\rightarrow 0} = \frac{\Delta N_0}{N_0^0} \tag{2}$$

and

$$\left(\frac{\Delta I_\sigma}{I_\sigma^0}\right)_{1\rightarrow 0} = \tfrac{1}{2}\,\frac{\Delta N_{-1}}{N_{-1}^0} + \tfrac{1}{2}\,\frac{\Delta N_{+1}}{N_{+1}^0},$$

where $N_0^0, N_{-1}^0, N_{+1}^0$ are the populations of the respective sublevels under non-perturbed conditions; $\Delta N_0, \Delta N_{-1}, \Delta N_{+1}$ — induced changes in populations; subscript $1 \rightarrow 0$ shows the kind of transition.

Analogously for the remaining transitions $(J = 1) \rightarrow (J = 1)$ and $(J = 1) \rightarrow (J = 2$ we obtain

$$\begin{aligned} \left(\frac{\Delta I_\pi}{I_\pi^0}\right)_{1\to 1} &= \tfrac{1}{2}\frac{\Delta N_{-1}}{N_{-1}^0} + \tfrac{1}{2}\frac{\Delta N_{+1}}{N_{+1}^0}, \\ \left(\frac{\Delta I_\sigma}{I_\sigma^0}\right)_{1\to 1} &= \tfrac{1}{4}\frac{\Delta N_{-1}}{N_{-1}^0} + \tfrac{1}{4}\frac{\Delta N_{+1}}{N_{+1}^0} + \tfrac{1}{2}\frac{\Delta N_0}{N_0^0}; \end{aligned} \tag{3}$$

$$\begin{aligned} \left(\frac{\Delta I_\pi}{I_\pi^0}\right)_{1\to 2} &= \tfrac{3}{10}\frac{\Delta N_{-1}}{N_{-1}^0} + \tfrac{3}{10}\frac{\Delta N_{+1}}{N_{+1}^0} + \tfrac{4}{10}\frac{\Delta N_0}{N_0^0}, \\ \left(\frac{\Delta I_\sigma}{I_\sigma^0}\right)_{1\to 2} &= \tfrac{7}{20}\frac{\Delta N_{-1}}{N_{-1}^0} + \tfrac{7}{20}\frac{\Delta N_{+1}}{N_{+1}^0} + \tfrac{6}{20}\frac{\Delta N_0}{N_0^0}. \end{aligned} \tag{4}$$

The formulas (2)–(4) describe completely the anisotropy of induced changes in intensities of the lines starting from a level with $J = 1$.

As is seen, the anisotropy exists only when there are some differences in changes of populations of individual sublevels. These conditions may be reached if linearly polarized laser oscillations rapidly populate or depopulate the level $J = 1$. The experiments show that for an absence of a magnetic field the optical vector E gives an axis of quantization.

2. *Experimental set-up*

The measurements were performed in two directions of observation, both perpendicular to the laser tube: one was along the E vector, and another — perpendicular to it. Polarization of the light was analized by means of a polaroid located just before a monochromator slit (see Fig. 1). Fluorescence lines, coming from the $5s'[1/2]_1^0$, $4p'[1/2]_0$ and $3d'[3/2]_1^0$ levels were investigated, but only those from $5s'[1/2[_1^0$ will be discussed in details. The spectral lines emitted from that level behaved in the same manner if they corresponded to these same changes of total angular momentum J. Because of that, results of only three spectral lines chosen for $\Delta J = -1$, $\Delta J = 0$ and $\Delta J = +1$ – 635, 543 and 594 nm, respectively,

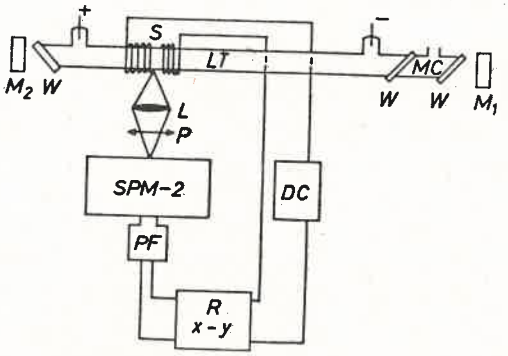

Fig. 1. Experimental set-up. LT — laser tube 1500 mm; MC — methane cell; M_1 M_2 — aluminium mirrors; W — fluorite Brewster window; S — magnetic coil 300 mm; P — polaroid; L — lens; SPM-2 — grating monochromator; PF — photomultiplier; DC — d.c. supply of magnetic coil; R — x–y recorder

are presented (see Table I and II). Induced changes in intensities for two components of linear polarization, that is, along and perpendicular to the laser tube were measured. Additionally, a magnetic field of about 50 Gauss could be produced by means of a selenoid. All data in Table I, II and III are expressed in per-cent respectively to non-perturbed conditions (when laser oscillations are supressed).

3. *Analyzation of the data*

As has been said above, there are three groups of transitions, from the $5s'[1/2]_1^0$ level, every one defined by $\Delta J = \pm 1, 0$. Let us start from the first one with $\Delta J = -1$; the spectral line at 635 nm was chosen to measure induced changes. This line, if it is observed along the E vector, shows equal changes (12%) for both components of polarization. Assuming that the optical field of the E vector determines of quantization axis, those changes are seen as the $\sigma^{\pm}$ components, and the same their values for both polarization components are comprehensible. When that line is observed perpendicularly to the E vector, the intensity of the polarization component parallel to the E vector changes by 40%, and as before, by 12% for polarization parallel to the laser tube. The last results confirm the conclusion that $\sigma^{\pm}$ components are observed, and give a new value of change in intensity of π component to be 40%.

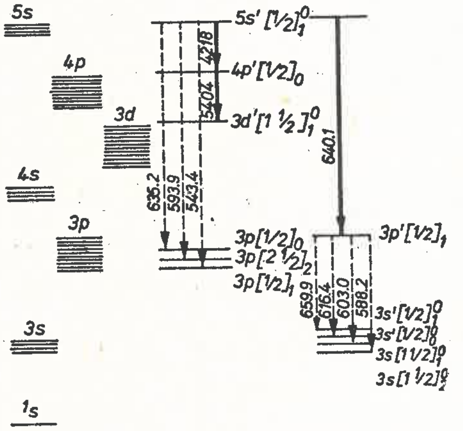

Fig. 2. Diagram of neon levels and optical transitions discussed in the work

In view of small splitting of the $5s'[1/2]_1^0$ level, there is no reason to assume that the laser oscillations to induce different changes in the population of sublevels with $m = \pm 1$; for an electrical field it is no problem, as there is no splitting between $m = \pm 1$ sublevels. It is seen from formulas (2), that above mentioned data give the changes in populations of the sublevels with $m = \pm 1$ by 12%, and $m = 0$ by 40%. Next, these values have been used in formulas (3), (4), and the obtained results have been compared with those from the experiment (see Table I). Good agreement between the results seems to confirm the previous assumptions.

TABLE I

	Polarization components (respective to the laser tube)	Components of transitions (π or σ)	Observations parallel to E vector		Components of transitions (π or σ)	Observations perpendicular to E vector	
			Measurements	Values calculated from measurements*		Measurements	Values calculated from measurements*
635.2 $\Delta J = -1$	⊥	σ	12		π	40*	
	∥	σ	12		σ	12*	
543.3 $\Delta J = 0$	⊥	σ	28	26	π	12	12
	∥	σ	28	26	σ	26	26
593.9 $\Delta J = +1$	⊥	σ	21	20	π	23	23
	∥	σ	21	20	σ	20	20

4. *Effect of magnetic field*

A magnetic field formed along the laser tube causes the aligned angular momenta J of neon atoms in the excited state $5s'[1/2^0_1]$, to start to rotate around the field. However, when the field is sufficiently strong we observe the anisotropy to change its orientation according to the direction of the magnetic field.

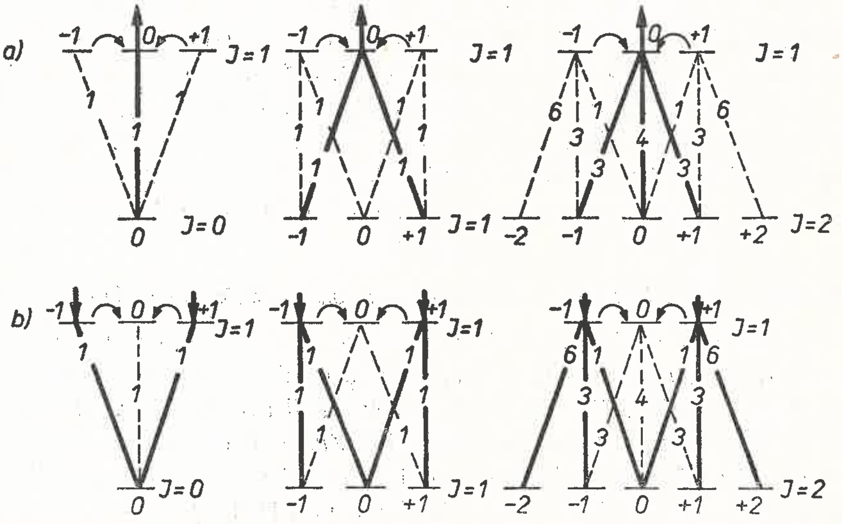

Fig. 3. Diagram of magnetic sublevels of level with $J = 1$ and possible π and σ transitions to levels with $J = 0, 1$ and 2. Arrows show the main flow population due to the π laser transition; continuous lines — components of which the intensities are changed directly by laser oscillations; dashed lines — components of which the intensities are changed due tocollision effects. a) laser oscillations depopulate sublevel with $m = 0$; b) laser oscillations populate sublevels with $m = \pm 1$

TABLE II

	Polarization components (respective to the laser tube)	Components of transitions (π or σ)	Observations parallel to E vector		Components of transitions (π or σ)	Observations perpendicular to E vector	
			Measurements	Values calculated from measurements*		Measurements	Values calculated from measurements*
635.2 $\Delta J = -1$	⊥	σ	40*		σ	36	
	∥	π	14		π	16*	
543.3 $\Delta J = 0$	⊥	σ	28−~0.5	28	σ	26	28
	∥	π	40	40	π	37	40
593.9 $\Delta J = +1$	⊥	σ	33	33	σ	29	33
	∥	π	29	30	π	29	30

The results in Table II were obtained with a magnetic field of about 50 Gauss. In this case, there is a new axis of quantization, so emission on π and σ transitions get a new orientation in space. Now, linearly polarized σ laser oscillations (now laser oscillations do not gain from π transitions) depopulate sublevels with $m = \pm 1$, and the spectral line at 635 nm — for polarization perpendicular to the laser tube, or magnetic field — reaches maximal changes in intensity. So, the laser action can be assumed to induce a decrease in the population of sublevels $m = \pm 1$ by 40%, and for $m = 0$ — by 16%. These data were used in formulas (3), (4) for calculating in changes of the remaining lines (see Table II); and this time a good fit of calculated values to measured results is evident.

A theory of the effects which occur when laser radiation interacts resonantly with excited atoms in a magnetic field has been developed by Decomps et al. [7].

5. *Anisotropy induced by laser oscillations on transition* $(J = 1) \rightarrow (J = 1)$

The transition $(J = 1) \rightarrow (J = 1)$ may be a very interesting one because one of its components $(J = 1,\ m = 0) \rightarrow (J = 1, m = 0)$ is forbidden by the selection rules for magnetic quanta number. For this transition we shall additionally verify our previous assumptions. In this case the π laser transition $\Delta m_J = 0$ depopulate mainly sublevels with $m = \pm 1$. The effect should be similar to that on the laser transition $(J = 1) \rightarrow (J = 0)$ when the magnetic field is directed along the laser tube. Next, the anisotropy seems to be identical for upper and lower laser levels.

In order to make sure, that the above considerations are true, measurements on laser transition $5s'[1/2]_1^0 \rightarrow 3p'[1/2]_1$ $\Delta J = 0$ at 640 nm have been performed. Because the experiment shows, that lines from the $5s'[1/2]_1^0$ level are emitted isotropically in space,

TABLE III

	Polarization components (respective to the laser tube)	Components of transitions (π or σ)	Observations perpendicular to E vector	
			Measurements	Values calculated from measurements*
616.4 $\Delta J = -1$	$\perp$	π	2.4*	
	$\parallel$	σ	18*	
603.0 $\Delta J = 0$	$\perp$	π	18	18
	$\parallel$	σ	10	10
588.2 $\Delta J = +1$	$\perp$	π	12	12
	$\parallel$	σ	13	13

the results of measurements and calculations for the $3p'[1/2]_1$ level are presented only, see Table III. All components of polarization for spectral lines starting from the $5s'[1/2]_1^0$ level change their intensities by the same value 18%. It seems that this difference in the behaviour of the $5s'[1/2]_1^0$ and $3p'[1/2]_1$ level may be caused by a collision transfer of the population within sublevels m_J, which for the upper level is more efficient than for the lower one.

6. Conclusions

Let us recapitulate the topics of this article. The appearance of anisotropy of spontaneously emitted lines, observed without any magnetic field, requires the following condition to be fulfilled: laser action pumps only some of the sublevels of the splitting caused by the laser field of optical the E vector, see work [1]. The results of the experiment show that the transfer of population by collision within sublevels of the $5s'[1/2]_1^0$ and $3p'[1/2]_1$ levels occurs. Rates of those population flows may be calculated by means of equations giving the balance of level population in the stationary state [2, 5].

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