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Shifts of the $n = 4$ hydrogen and 3^3D helium levels induced by TEA CO_2 laser radiation

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Résumé. — Les déplacements des niveaux $n = 4$ de l'hydrogène et 3^3D de l'hélium ont été mesurés lorsque le faisceau d'un laser CO_2 TEA est focalisé (100 MW/cm^2) dans une décharge luminescente d'hydrogène ou d'hélium. Des déplacements de quelques dixièmes d'angström ont été observés pour les raies d'émission H_β ($n=4 \rightarrow n'=2$) de l'hydrogène atomique et $5\ 876 \text{ Å}$ ($3^3\text{D} \rightarrow 2^3\text{P}$) de l'hélium atomique.

Abstract. — The shifts of $n = 4$ hydrogen and 3^3D helium levels have been measured when the atoms of a hydrogen or helium glow discharge are irradiated by a focused (100 MW/cm^2) TEA CO_2 laser beam. Shifts of some tenths of an angström have been detected for the ($n = 4 \rightarrow n' = 2$) H_β hydrogen and ($3^3\text{D} \rightarrow 2^3\text{P}$) $5\ 876 \text{ Å}$ helium emission lines.

1. Introduction. — The non resonant perturbation of an atomic system by an E.M. radiation has been the subject of theoretical and experimental studies. A recent review has been given in a paper by Delone *et al.* [1].

In addition to much theoretical work, only a few experiments have been devoted to the so-called non resonant « Dynamic Stark Effect » (D.S.E.) or light-shift. These studies fall into two groups :

The first and predominant one, concerns the multiphotonic interaction processes where near-resonant D.S.E. largely intervenes. These experiments provide indirect evidence of the perturbation caused by laser radiation on an atomic structure [2].

The other corresponds to direct experimental single level perturbation diagnostics by emission and absorption line shift measurements. They are not numerous and actually insufficient for any extensive comparison between theory and experiment to be made.

In our laboratory, theoretical and experimental works have already been devoted to hydrogen and helium level shifts induced by c.w. CO_2 laser radiation ($P_L < 500 \text{ W}$). In these experiments at low laser flux levels ($I_L < 5 \text{ MW/cm}^2$), only the most important expected perturbation, that is shifts of the $n = 6$ hydrogen [3] and 4^3S helium levels [4] have been measured and compared with theoretical predictions.

In this paper we relate preliminary results on non resonant D.S.E. obtained with TEA CO_2 laser inten-

sity in the 100 MW/cm^2 range. The main purpose of this study is to perform a systematic investigation of D.S.E. in hydrogen and helium atoms, particularly high order effects [5] and satellites [6].

2. Experimental arrangement. — The experimental set-up schematically shown in figure 1 is described in the following.

2.1 DISCHARGE TUBE. — The atomic excited states are populated in a low pressure glow discharge. The essential part of this discharge tube consists of a capillary (inner diameter $\simeq 0.5 \text{ mm}$) interrupted by an adjustable distance of approximately 0.2 cm . The mean visible plasma diameter in the interaction region is 0.2 cm for a typical pressure of 10 torr . This plasma ($n_e < 10^{13} \text{ cm}^{-3}$, $T_e \simeq 4 \text{ eV}$) is created by large current pulses (intensity = 5 A , width = $80 \mu\text{s}$) superimposed on a weak D.C. current adjustable between 5 mA and 20 mA .

2.2 TEA CO_2 LASER. — The TEA CO_2 laser of Burnett type [7] built in our laboratory gives an energy of 2 joules limited in a main peak of 150 ns F.W.H.M. ($\lambda = 10.59 \mu\text{m}$, repetition rate = $5 \times 10^{-2} \text{ Hz}$). Energy, shape and time position of the laser pulse are respectively measured for each shot with a power-

Fig. 1. — Experimental set-up : (1) Discharge power supply, (2) TEA CO₂ laser, (3) Monochromator, (4) ISIT, (5) O.M.A., (6) Pulse generator, (7) Monitoring system, (8) Recorder, (9) Minicomputer, (10) Video system.

meter and a photondrag connected to high-pass frequency oscilloscopes.

The laser beam of 3 cm initial diameter is focused into the plasma in the interspace between the two orifices of the capillary with a 15 cm focal length NaCl lens (diameter 4.0 cm). The obtained spot diameter is 0.2 cm and covers the whole interspace between the orifices of the capillary.

2.3 SPECTRUM DETECTION AND ANALYSIS. — The discharge light emission with and without laser radiation is observed perpendicular to the laser beam and focused on the slit of a 1.15 cm SOPRA grating spectrometer and then onto the Intensified Silicon Intensifier Target detector (1205 ISIT) of an Optical Multichannel Analyser (O.M.A. P.A.R. 1205 A). This detector consists of 500 channels covering a spectral range of 35 Å. The ISIT is gated by a 1.3 kV negative pulse delivered, by a H.V. pulse generator (P.A.R.C. 1211) containing integral pulse width and pulse delay controls. This generator can be triggered by a synchronization pulse, limiting gating of ISIT to the laser pulse event.

2.4. MONITORING SYSTEM. — Figure 2 shows the timing diagram of the monitoring system. At first the electronic lights on the discharge tube and triggers the laser. Then, the laser preionization light is used to make coincident gating of ISIT with laser shot. Fluorescent light emitted by the discharge is detected by the target of ISIT which is read several times (7-15), then the spectral information is transferred to the A memory of O.M.A.; multiple readout scans improve the signal to noise ratio [8]. Between two laser shots, the background noise of the system is memorized by the same procedure into the B memory. Finally,

the difference between A and B is transferred onto an oscilloscope, a recorder and a minicomputer.

Fig. 2. — Timing diagram : (a) Monitoring signal, (b) Current pulse, (c) Laser triggering signal, (d) Preionization light intensity, (e) laser pulse, (f) Gating of ISIT.

2.5 DATA PROCESSING. — A minicomputer NOVA 3 DATA GENERAL stores all the laser shots validated by the monitoring processor (threshold of

Fig. 3. — Experimental recorded signals of the 5 876 Å helium line for $I_L = 100 \text{ MW/cm}^2$.

energy, time accuracy). A smoothing method partially reduces the effect of ISIT dark current noise when the detected light is weak.

3. Results. — The shifts of the most intense lines have been observed with this experimental set-up working with laser intensities of $I_L = 100 \pm 30 \text{ MW/cm}^2$. Shifts of 5 876 Å line of helium ($3^3D \rightarrow 2^3P$) and H_β line of hydrogen ($n = 4 \rightarrow n' = 2$) are respec-

tively shown in figures 3 and 4. Since the photon number emitted by the discharge during 150 ns in these transitions remains rather weak, the monochromator slit had to be opened to 500 μm in order to perform a single spectrum analysis, and the observed line profiles correspond to the apparatus function. The measured shifts of the line centres give direct information on the upper level perturbations since the lower *detection* levels are practically not affected by the laser

Fig. 4. — Experimental recorded signals of the H_β hydrogen line for $I_L = 100 \text{ MW/cm}^2$.

perturbation as predicted from theoretical calculations

$$(\Delta E(n=4)/\Delta E(n=2) \approx 40,$$

$$\Delta E(3^3D)/\Delta E(2^3P) \approx 130) \quad [4], [9].$$

These calculations were performed in first order perturbation frame work both for hydrogen and helium atoms :

$$\Delta E_n = -1.425 \times 10^{-11} I_L \times$$

$$\times \sum_{n' \neq n} |\langle n' | \mathbf{e} \cdot \mathbf{r} | n \rangle|^2 \frac{E_{n'} - E_n}{(E_{n'} - E_n)^2 - \hbar^2 \omega_L^2}. \quad (1)$$

In this expression, all the quantities are in atomic units except for I_L which is expressed in MW/cm². $E_n, E_{n'}$ are respectively the energies of the n and n' levels, $\hbar\omega_L$ is the energy of a laser photon and $\langle n' | \mathbf{e} \cdot \mathbf{r} | n \rangle$ is the electric dipole matrix element. In this matrix element, $\mathbf{e}$ is the polarization vector of the laser field.

This approximation holds provided

$$\Delta E_n \ll |E_{n'} - E_n \pm \hbar\omega_L|,$$

which is the case for the two investigated levels.

Light-shift values for hydrogen have been calculated through eq. (1) by a direct summation method [9]. Accuracy for the $n=4$ state can be estimated to be $\approx 0.2\%$ from sum rule comparisons.

In the case of helium, use was made of quantum defect theory to approximate the dipole matrix elements. Two different numerical methods — direct

Table I. — *Theoretical and experimental values of H_β hydrogen and 5 876 Å helium line shifts induced by TEA CO₂ laser radiation for $I_L = 100$ MW/cm².*

Lines	Theoretical values (Å) [4], [9]	Experimental values (Å)
Helium (3 ³ D → 2 ³ P)	0.393 ± 0.048	0.21 ± 0.14
Hydrogen (n = 4 → n' = 2)	0.288 ± 0.012	0.28 ± 0.163

summation and Green function techniques — have been compared [4]. The corresponding values are accurate to within 15 %.

Experimental and theoretical values are compared in table I for $I_L = 100$ MW/cm². Within the experimental errors bar (determination of the effective laser intensity and limited spectral resolution) these preliminary results are in agreement with the theoretical results. An investigation made in the same conditions on the H_α line of hydrogen ($n=3 \rightarrow n'=2$) showed no significant shift, in agreement with theoretical calculations.

Investigation of more excited states is important in order to point out high order effects particularly on the $n=5$ hydrogen and the 4 ³S helium levels with laser intensities > 100 MW/cm² and production of satellites on the H_β line of hydrogen ($n=6 \rightarrow n'=2$).

Consequently experimental improvements are being made in two directions : namely laser characteristics (useful repetition-rate, wider laser pulse) and enhanced high excited state populations.

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