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## Hyperfine structure and isotope shift of the 640.2 and 626.6 nm lines of neon

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**Résumé.** — Nous avons utilisé un laser accordable monomode pour exciter les raies  $\lambda = 640,2$  et  $626,6$  nm de  $^{20}\text{Ne}$ ,  $^{21}\text{Ne}$  et  $^{22}\text{Ne}$ . Par une méthode de pompage optique sélectif en vitesse, nous avons mesuré les structures hyperfines et les déplacements isotopiques des deux raies. Les valeurs obtenues pour les constantes de structure hyperfine du niveau  $2p_9$  du  $^{21}\text{Ne}$  sont les suivantes :

$$A(2p_9) = -142,5 \pm 1,5 \text{ MHz}$$

$$B(2p_9) = -113 \pm 8 \text{ MHz}.$$

Les valeurs que nous avons obtenues d'autre part pour les déplacements isotopiques sont en accord avec la formule valable pour un effet de masse pur.

**Abstract.** — A tunable single mode laser has been used to excite the  $\lambda = 640.2$  and  $626.6$  nm lines of  $^{20}\text{Ne}$ ,  $^{21}\text{Ne}$  and  $^{22}\text{Ne}$ . Using the velocity selective optical pumping method, we have measured the hyperfine structures and isotopic shifts of these two lines. We obtain the following values for the  $^{21}\text{Ne}$  hyperfine structure constants of the  $2p_9$  level :

$$A(2p_9) = -142.5 \pm 1.5 \text{ MHz}$$

$$B(2p_9) = -113 \pm 8 \text{ MHz}.$$

We have also measured isotope shifts and obtained values in good agreement with the mass-shift formula.

The hyperfine structure constants  $A$  and  $B$  of the levels belonging to the  $2p^53p$  electronic configuration of  $^{21}\text{Ne}$  ( $I = 3/2$ ) have been measured by various experimental techniques. Giacobino [1] used the level-crossing method to obtain  $A$  and  $B$  for the  $2p_2$ ,  $2p_4$ ,  $2p_5$ ,  $2p_6$ ,  $2p_7$  and  $2p_8$  levels, and Husson and Grandin [2] for the  $2p_{10}$  level. An *absorption line narrowing method* was used by Delsart and Keller [3] to measure the  $2p_4$  hyperfine constants. Nevertheless, the hyperfine structure of the  $2p_9$  level has not yet been experimentally measured, presumably because this level has a  $J = 3$  value and is radiatively connected only to one lower level, the  $1s_5$  ( $^3P_2$ ) level. This situation can raise experimental problems in level-crossing experiments, since it is often convenient to detect the atomic fluorescence at a wavelength which differs from that used for excitation. These difficulties do not occur with absorption techniques, such as the Doppler-free *velocity selective optical pumping* spectroscopic method [4]. We thus decided to use this method in order to measure hyperfine structure constants of  $^{21}\text{Ne}$ .

**1. Experimental set-up.** — The experimental set-up is very similar to the description given in reference [4]. The neon gas was contained in sealed pyrex cells, 6 cm in diameter, with some helium buffer gas ( $p = 50$  mtorr); the metastable levels of Ne were populated by an electrodeless discharge ( $v \simeq 12$  MHz). Two different cells were used : one containing a partial pressure  $p = 12$  mtorr of  $^{21}\text{Ne}$ , the other 5 mtorr of natural neon (90 % of  $^{20}\text{Ne}$ , 10 % of  $^{22}\text{Ne}$ ). The pumping beam was provided by a single mode cw dye laser, operating with a *double Michelson* mode selector, and placed inside an air-tight box for pressure scanning of the frequency [5]. The frequency of the laser was locked on an external plane Perot-Fabry cavity (5 cm quartz spacers), inside a second box, which was independently pressure scanned. The low frequency part of the error signal was used to drive the pressure of the laser box, the high frequency part to act on a PZT ceramics and to change the dye laser cavity length (this operation reduced the frequency jitter to about 4 MHz). A mixture of two dyes, R6G and R640, was used to obtain both wavelengths,

$\lambda = 6\,266$  and  $6\,402$  Å. The pumping beam was expanded to about  $1\text{ cm}^2$  in order to avoid any saturation of the optical transition. Large velocity selective optical pumping signals were obtained with hyperfine pumping inside the lower electronic level (this pumping occurs with any pump polarization). This is why the linear polarization of the dye laser was directly used in most experiments. Nevertheless, in a few cases ( $^{20}\text{Ne}$ - $^{22}\text{Ne}$  isotope shift for example), better signals were obtained, like in [4], with a circular pump polarization which allows one to create an atomic orientation. The counterpropagating beam was provided by the same laser; the use of a beam splitter made unnecessary any angle between the pump and beam. The pump beam intensity was modulated at 40 kHz; this frequency is high enough to correspond to a low laser intensity noise, and to reduce considerably the collision-induced background of the spectra [6] (this background arises mainly from Ne-He collisions which transfer hyperfine population differences between distinct velocity classes). Then, only atoms that are simultaneously in resonance with both laser beams contribute to the signal.

**2. Structure of the spectra.** — When the laser frequency is swept over an atomic resonance line, different kinds of narrow (Doppler-free) resonances are observed. Let us for example discuss the line structure which occurs when the  $\lambda = 6\,402$  Å line ( $J=2 \leftrightarrow J=3$ ) of  $^{21}\text{Ne}$  is used. The pumping process does not affect the total population of the  $^3\text{P}_2$  state (as far as collisional transfer does not reduce the excited state population). In other words, the sum of the four hyperfine populations  $F = 1/2, 3/2, 5/2$  and  $7/2$  of the  $^3\text{P}_2$  metastable state is constant, and the optical pumping regime ensures that the hyperfine populations  $F' = 3/2, 5/2, 7/2$  and  $9/2$  of the excited state are negligible.

So, the signals observed are mainly due to hyperfine pumping inside the  $^3\text{P}_2$  state (with a linear laser polarization, the alignment of each  $F$  level can also contribute to the signal). Two kinds of resonances appear : *direct resonances* corresponding to atoms with a zero velocity component along the beam, and *cross-over resonances* corresponding to non-zero velocities. The positions of the former give directly atomic transition frequencies, while the positions of the latter correspond to the half sum of two atomic frequencies. More specifically, we can expect the following resonances :

(a) 9 direct resonances associated with optical transitions between  $F$  and  $F'$  sublevels. Their sign corresponds to a decrease of the absorption of the gas. Actually, the  $F = 7/2 \leftrightarrow F' = 9/2$  transition would not produce any hyperfine pumping in the absence of collisions changing  $F'$  in the excited level (the number of resonances would then be 8).

(b) 7 cross-over resonances associated with two atomic transitions sharing the same upper  $F'$  level. They correspond to an increase of the gas absorption.

(c) 7 cross-over resonances associated with two atomic transitions sharing the same lower  $F$  level. They correspond to a decrease of the gas absorption.

(d) 14 *fluorescence-induced* cross-over resonances between two atomic transitions having no common sublevel. They correspond to an increase of the gas absorption.

Figure 1 shows the experimental curve obtained when the laser frequency is scanned through the  $\lambda = 6\,402$  Å resonance line. The two gas cells mentioned above were set in line on the pumping and probe beams in order to use them simultaneously and observe the lines of the three isotopes. The direct resonances (a) are identified by the  $F$  and  $F'$  values.

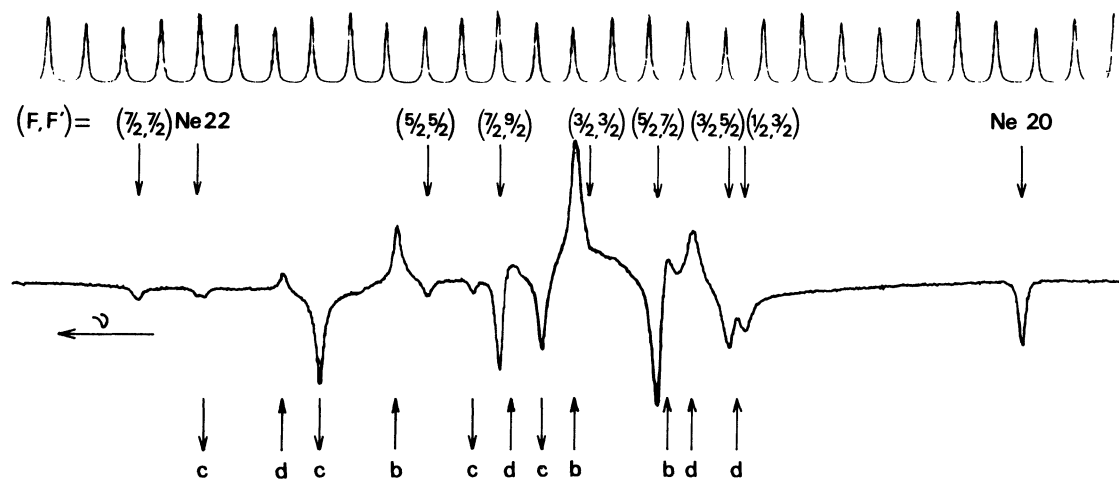


Fig. 1. — Experimental velocity selective optical pumping spectrum obtained when the laser is scanned through the  $1s_3(^3\text{P}_2)$ - $2p_3$  atomic resonances ( $\lambda = 6\,402$  Å). The second trace was obtained from a reference planfocal Perot-Fabry interferometer (50 cm). Direct resonances (a) are identified by the  $F$  and  $F'$  values (lower and upper hyperfine levels of the transition). As explained in the text, the presence of the  $F = 7/2 \leftrightarrow F' = 9/2$  line is due to inelastic collisions changing  $F'$  in the excited level. The cross-over resonances are denoted (b), (c), (d), according to their nature (see text). The  $^{20}\text{Ne}$  and  $^{22}\text{Ne}$  lines are also visible.

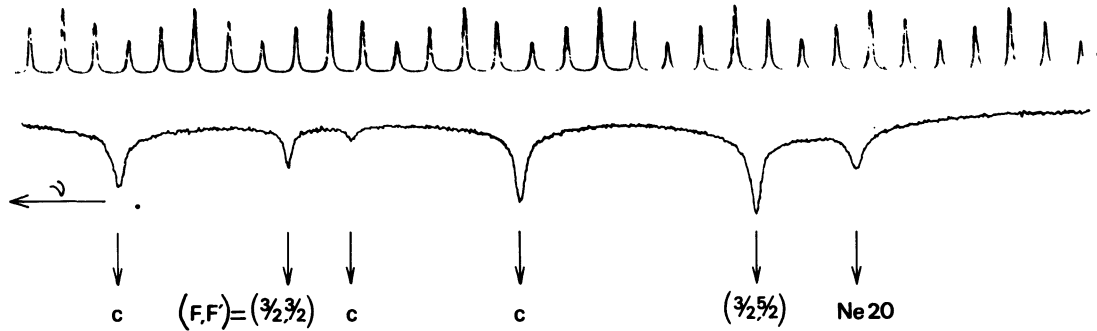


Fig. 2. — Spectrum obtained with the 6266 Å line ( $1s_3(^1P_0)-2p_5$ ). The lower state is the  $^3P_0$  metastable state and, for  $^{21}\text{Ne}$ , the observed structure arises from the hyperfine coupling inside the  $J = 1$  excited level.

The width of the resonances is about 18 MHz, which arises from the natural linewidth (8 MHz), the laser jitter, and presumably the non-zero divergence of the probe beam.

Figure 2 shows the experimental curve obtained under the same experimental conditions, with the wavelength  $\lambda = 6266$  Å. The lower state of the corresponding transition is the  $^3P_0$  metastable state, where orientation (or alignment) optical pumping is possible in principle only when the nuclear spin  $I$  is non-zero (i.e. for  $^{21}\text{Ne}$ ). Nevertheless, since the upper level  $J = 1$  is connected to other lower levels by spontaneous emission, population optical pumping is possible (velocity selective decrease of the population of the  $^3P_0$  state), and signals were obtained for all isotopes. For  $^{21}\text{Ne}$ , the observed structure is due to the hyperfine coupling inside the excited level.

**3. Results.** — From the observed spectra, one can deduce independently the hyperfine structure constants in both metastable  $1s_5$  ( $^3P_2$ ) and excited  $2p_9$  levels. Actually, the former has already been measured with a very high accuracy [7] and the only new results we have obtained concern the  $2p_9$  level (see table I). Using the data of [7] and our results, one can calculate the position of all the lines visible in figure 1; we have checked that the positions coincide with a good accuracy.

In a similar way, the hyperfine structure constants of the  $2p_5$  level have been deduced from the spectra shown in figure 2. All results are summarized and compared to other data in table I. For the  $1s_5$  and  $2p_5$  levels, our results are in good agreement with previous experimental data. To our knowledge, no previous measurement is available for the  $2p_9$  level, but  $A$  and  $B$  can be compared to recent semi-empirical theoretical calculations ([8] and [9]).

The data obtained were also used to measure the isotope shift  $\delta\sigma(20-21)$  for the two 6402 and 6266 Å lines. We also measured the even-even isotope shift  $\delta\sigma(20-22)$ , which had already been measured before [10]. The results are given in table II and a good agreement with [10] is found for  $\delta\sigma(20-22)$ . For both lines, the relationship

$$\frac{\delta\sigma(20-21)}{22} = \frac{\delta\sigma(20-22)}{42}$$

Table II. — Values (in MHz) of the isotope shifts for the two 6402 Å and 6266 Å lines.

	This work	Other measurements [10]
6402 Å	$\delta\sigma(20-22) = 1630 \pm 3$ $\delta\sigma(20-21) = 856 \pm 7$	$\delta\sigma(20-22) = 1629 \pm 3$
6266 Å	$\delta\sigma(20-22) = 1651 \pm 3$ $\delta\sigma(20-21) = 866.5 \pm 6.5$	$\delta\sigma(20-22) = 1647 \pm 3$

Table I. — Values (in MHz) of the hyperfine constants of the  $1s_5$ ,  $2p_9$  and  $2p_5$  levels.

	This work	Other experiments	Theoretical calculations
$1s_5$	$A = -267.5 \pm 0.8$ $B = -113.3 \pm 3.2$	$A = -267.68 \pm 0.03$ $B = -111.55 \pm 0.10$ [7]	$A = -267.9$ $B = -111.6$ [8]
$2p_9$	$A = -142.5 \pm 1.5$ $B = -113 \pm 8$		$A = -138.3$ $B = -111.6$ [8] $A = -143 \pm 3$ [9]
$2p_5$	$A = -436.5 \pm 1.2$ $B = +43.3 \pm 2.2$	$A = -436.6 \pm 0.6$ $B = +41.8 \pm 1.2$ [1]	$A = -433.2$ $B = +43.2$ [8] $A = -439 \pm 3$ [2]

is well fulfilled within our error bars (this relationship expresses the fact that the isotope shift is a pure mass effect). Similar results have been obtained by Champeau and Keller [11] for different lines of neon.

In conclusion, these experiments show that the Doppler-free velocity selective optical pumping method

can easily be used to perform atomic-structure measurements.

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