Pressure Broadening of the 1.3 \( \mu m \) Iodine Laser Line

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The storabale energy of a high-power laser is inversely proportional to its stimulated emission cross-section \( \sigma \). By adding a foreign gas, the emission line is broadened and is thereby lowered. We have measured \( \sigma \) of the iodine laser as a function of the pressure of several gases (Ar, \( \text{N}_2 \), CO, \( \text{CO}_2 \), \( \text{SF}_6 \), \( \text{CF}_2\text{Br}_2 \), \( \text{CF}_2\text{F}_2 \), \( \text{CF}_2\text{Cl}_2 \), \( \text{CF}_2\text{F}_2\text{Cl}_2 \), \( \text{CF}_2\text{F}_2\text{CO} \)) by an absolute and a relative method. \( 1/\sigma \) is a linear function of the pressure in spite of the fact that overlapping of the hyperfine structure components varies considerably in the range investigated. For optimum energy storage, \( \text{CO}_2 \) is a good compromise between pressure broadening and chemical deactivation of the excited I-atoms. At one atmosphere of \( \text{CO}_2 \), 5 to 7 J/cm\(^2\) can be stored, the hyperfine structure is largely blurred, and the amplification of pulses shorter than 100 psec should be possible.

I. Introduction

In high-power lasers energy is normally accumulated and stored in a laser amplifier until a pulse from a laser oscillator induces the amplifier to emit. A parameter of crucial importance for energy storage is the stimulated emission cross-section \( \sigma \) of the active medium. The inversion storable per unit cross-section is inversely proportional to \( \sigma \):

\[
\Delta n_{st} = \ln \frac{V_{th}}{\sigma}
\]

(1)

\( \Delta n_{st} \) = storable inversion density, \( l \) = length of the active medium, \( V_{th} \) = threshold amplification, \( \sigma \) = maximum cross-section of the gain profile.

In the photochemical iodine laser \( \sigma \) can be varied over a large range by pressure broadening. We determined the effect of various gases (Ar, \( \text{N}_2 \), CO, \( \text{CO}_2 \), \( \text{SF}_6 \), \( \text{CF}_2\text{Br}_2 \), \( \text{CF}_2\text{F}_2 \), \( \text{CF}_2\text{Cl}_2 \), \( \text{CF}_2\text{F}_2\text{Cl}_2 \), \( \text{CF}_2\text{F}_2\text{CO} \)) on \( \sigma \) of the iodine laser transition (1.3 \( \mu m \)) by combining small and large-signal gain measurements of single nanosecond pulses. In addition, some conclusions could be drawn concerning the homogeneity of the spectrum, which is of importance in the saturation behaviour of the iodine laser.

Previous workers have measured pressure broadening by He, Ar \(^{1,2}\) and \( \text{CF}_2\text{I}^{3}\). But in \(^3\) the hyperfine structure has not been considered; and for the measurements of \(^1\) and \(^2\) long pulses were used, in which case the influence of the recombination of ground state iodine atoms with the radicals is not well known. Further work has been done on the ratios of pressure broadening coefficients due to He and Ar \(^{4,5}\) the other noble gases, and \( \text{CO}_2 \). A recent paper \(^5\) reports pressure broadening by \( \text{CF}_2\text{I} \).

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Fig. 1. Hyperfine structure of the iodine laser transition; $F$ = quantum number of electronic plus nuclear angular momentum, $g$ = degeneracies, $q$ = normalized relative intensities.

The F-numbers and the degeneracies $g$ are written on the left and right sides of the levels, respectively. In the lower part of Fig. 1 the relative intensities $q$ of the six lines are shown according to Sobel’man.

Usually, $\sigma$ is defined in such a way that $\Delta n$ in the product $\sigma \Delta n$ [e.g. in (1)] means the total inversion, summed over the hfs levels. This definition implies that $\sigma$ is smaller by a factor $a = \Delta n_i/\Delta n$ ($\Delta n_i$ being the inversion density between the sublevels $i$ and $j$) than a cross-section based on an individual transition from sublevel $i$ to sublevel $j$. (Of course, a cross-section based on an individual transition can only be defined if this transition is well resolved in the spectrum.) Similarly, $A$ is defined such that $n$ in the product $A \cdot n$ means the total population density in the upper levels. $A$ has to be multiplied by a factor $a = n_i/n$, if it is related to the upper sublevel $i$. Because the upper levels are initially populated in the ratio of their degeneracies, whereas the number of the ground state iodine atoms produced in the photolysis of the usual iodides is negligible, $a$ is equal to $a^\prime$.

In the iodine laser, $a$ is calculated from the ratio of the statistical weights (Fig. 1) to be 5/12 or 7/12, depending on whether the initial level is the $F = 2$ or $F = 3$ sublevel of the $^2P_{3/2}$ state.

In any formulae where $\sigma$ or $A$ occurs without being multiplied by $\Delta n$ or $n$ [e.g. in (2) and (4)] a correction for the factor $a$ is necessary. Thus, the half-width of the strongest iodine laser line $F = 3 \rightarrow F = 4$ (being equal to the half-width of the other hfs lines) is calculated from

$$\sigma_{34}/a = \frac{I^2}{4 \pi^2} \frac{A_{34}}{A \nu} \frac{1}{\Delta \nu}.$$  

Here $\sigma_{34}$ is the cross-section at the frequency of the $F = 3 \rightarrow F = 4$ transition, again based on the total inversion $\Delta n$, $q_{34}$ is the normalized intensity (see Fig. 1) of this hfs transition. $A$ is again the total transition probability based on the population of both the upper levels, which is calculated from the maximum of the 3 $\rightarrow$ 4 line and is calculated from the total spectrum as long as the lines are narrow. In the same way, Eq. (5) has to be replaced provided that $\beta_i$ refers to the $3 \rightarrow 4$ transition and provided that this lines is well resolved:

$$a_i = 1.3 \cdot 10^{-9} \text{ cm}^2 \text{ Hz} \cdot \beta_i.$$  

**c) Broadening and Internal Relaxation**

With increasing pressure broadening the lines begin to overlap. The gain profiles corresponding to the individual lines with the relative intensities of Fig. 1 must be added (Figure 2). The maximum of the resulting gain curve corresponds to a $\sigma$ value ($\sigma_{\text{total}}$) which may again be used in (1). But this $\sigma$ cannot be expected to fulfill a linear relation like (4) for, with increasing overlap of the lines, $\sigma_{\text{total}}$ does not decrease as much with pressure as the $\sigma$ of a single line. Figure 3 shows $\sigma_{\text{total}}$ (called simply $\sigma$ henceforth) calculated from spectra like those of Fig. 2 as a function of the width $\Delta \nu$ of a single line.

If $\Delta \nu$ is a linear function of pressure, this type of curve is also expected for $1/\sigma$ as a function of pressure. Figure 3 can be used to determine the linewidth of the single lines from measured $\sigma$ values, if the assumption of Lorentzian line profiles is correct.

In an intermediate broadening case like in Fig. 2b the emission can be considered as consisting of two homogeneous lines resulting from two independent upper levels with degeneracies 5 and 7 and one
lower level of statistical weight 24. A similar situation can arise for smaller line-widths, if the pulses are long enough: Yukov et al.\textsuperscript{16,17} have shown that collisions efficiently induce internal relaxation among the sublevels of the ground state, whereas the \( ^2P_{1/2} \) sublevels relax very much more slowly. So, for a sufficiently long pulse even an only slightly broadened spectrum can appear as consisting of two homogeneous parts.

**III. Measuring Method**

a) \textit{Absolute Measurement of } \( \sigma \)

The starting point for the measurement of \( \sigma \) is the formula for the small-signal amplification \( V_{ss} \):

\[
V_{ss} = \exp(\sigma AN I) .
\]  

(7)

If both \( V_{ss} \) and \( AN \) can be measured, \( \sigma \) can easily be calculated.

Again, \( \sigma \) denotes the maximum cross-section of the gain profile. Therefore, it has to be checked if the input frequency (to be amplified) is close to this maximum.

Previous workers have deduced \( AN \) from the oscillator energy:

\[
E_{osc} = (h/\nu)(AN - AN_{th})IQ ,
\]

(8)

\[
b = 1 + g_u/g_l\]

(9)

(\( Q \) is the geometric cross-section of the active medium, and \( g_u \) and \( g_l \) are the degeneracies of the upper and lower levels, respectively.) The threshold inversion \( AN_{th} \) can be eliminated by varying the threshold amplification \( V_{th} \), i.e. by varying the cavity losses, and extrapolating to \( V_{th} = 0 \). Unfortunately, the degeneracy factor \( b \) is uncertain. On the one hand, all hfs sublevels can relax among each other within the long time involved in oscillator emission, so that the statistical weights should be taken as 12 and 24 and \( b \) should be equal to 1.5. On the other hand, some experiments indicate that the \( \text{i-C}_3\text{F}_7 \) radicals produced in the photolysis of \( \text{i-C}_3\text{F}_7\text{I} \) rapidly recombine with ground state iodine atoms, so that \( b \) has to be set equal to 1 as in other four level lasers. So it is desirable to determine \( AN \) and \( \sigma \) by short pulses.

Therefore, we measured the amplification \( V \) for small and large input energy densities \( e_{in} \) using...
single one-nanosecond pulses. The saturation energy
density \(e_s\) was then determined from
\[
V = (e_s/e_{in})\ln[1 + (\exp(e_{in}/e_s) - 1)V_{ss}] \quad (10)
\]
by a graphical method. In the case of a homoge-
nous line, \(\sigma\) can then be calculated from
\[
e_s = h\nu/b\sigma. \quad (11)
\]
Two questions now arise: 1) Has the cross-section
\(\sigma\) in (11) to be corrected in the same way as dis-
cussed in paragraph II b), i.e. has \(\sigma\) to be divided
by \(a\) in order to convert it to a cross-section based
on the inversion for an individual transition?
2) What happens to Eq. (11) if, as in the iodine
laser, only part of the inversion can respond to a
given input frequency, i.e. if the spectrum is not
completely homogeneous?

Large-signal amplification by a single well re-
solved homogeneous line can obviously be treated
as if the other lines did not exist, i.e. \(\sigma\) has in fact to.
be converted to a cross-section based on the corre-
sponding individual inversion by dividing it by \(a\).
Equation (11) becomes
\[
e_s = a(h\nu/b\sigma). \quad (12)
\]
Depending on which of the levels emit, \(a\) is equal to
the fractional population of either the \(F = 3\) level
\((a = 7/12)\) or the \(F = 2\) level \((a = 5/12)\). For line
widths similar to those of Fig. 2 b the spectrum con-
ists of two homogeneous parts. Equation (12) is
again valid, \(a = 7/12\), if the emission is in the high-
frequency part of the spectrum, and \(a = 5/12\) for
the low-frequency part. If the line widths are much
larger than the line distances, the whole spectrum is
homogeneous; in this case (11) has to be used or,
alternatively, one has to set \(a = 1\) in (12).

So, \(a\) can be looked at as a parameter character-
izing homogeneity. It is just the fraction of the in-
version which can respond to the input frequency.
But it has to be remembered that in intermediate
broadening cases, where the spectrum cannot be
divided into homogeneous parts, Eq. (10) cannot
be applied and therefore \(e_s\) and \(a\) are not defined.

The degeneracy factor \(b\) in Eq. (12), which is
considering from (9), again depends on the input
frequency, the degree of overlap, and the ratios of
the relaxation times to the pulse duration. \(g_a\) und \(g_l\)
in Eq. (9) are the effective statistical weights of the
upper and lower levels respectively, i.e. the sum of
the degeneracies of the levels involved in the emis-

### IV. Experiments

#### a) Set-up for Absolute \(\sigma\) Measurements

The absolute measurements of \(\sigma\) (large and small-
signal gains) were made with the set-up in Figure 4.
The oscillator and pulsescutting system are described
in 18. The oscillator is operated in TEM\(_{00}\) mode and
is acousto-optically mode-locked. Filled with 100
torr \(i\)-C\(_3\)F\(_7\)I, it emits a pulse train of 1 ns pulses.
The cutting system (Glan prism, Pockels cell, Glan
prism) extracts from this train a single pulse of
about 0.5 mJ energy. By means of Fabry-Perot mea-
surements of the frequency-doubled pulses, we
found 19 that these pulses, cut out of the beginning
of the train, only contain the frequency corresponding
to the high-frequency part of the spectrum. This
is an indication 19 that Zeeman splitting of the lines
by the magnetic field of the flash lamps can be dis-
regarded in our configuration of pairs of parallel
flashlamps. It was also disregarded in the amplifiers.
The preamplifier was only used for the one high-
pressure measurement, at 50 torr C\(_3\)F\(_7\)I + 700 torr
CO\(_2\), in order to reach the saturation energy at this
pressure. When the preamplifier was flashed with
1 kJ of electrical energy, with a filling pressure of
200 torr of C\(_3\)F\(_7\)I, the pulse at the entrance of the
main amplifier had an energy of 30 to 40 mJ. The
beam diameter at this point was around 4 mm.

This beam passes through the centre of the main
amplifier tube. Its inner diameter was 25 mm; 80 cm of
its length was flashed with two pairs of parallel
flashlamps, supplied with an electrical energy of
600 J in the low-pressure measurements,
and 3 kJ otherwise. At the exit of the amplifier, a
diaphragm cut out the central 5 mm\(^2\) of the beam
in order to fulfill the requirement of equal energy den-
sity over the beam cross-section for the large-signal gain measurements.

Portions of the input and output pulses arrived with a time delay at the same detector, a Valvo XA 1003 vacuum photodiode. The time resolution of the set-up (diode, cable, and Tektronix 7704 oscilloscope) was just somewhat poorer than the pulse length (∼1 nsec); thus it was the energy amplification that was measured. For small-signal amplification measurements, the preamplifier was not operated, and the input pulse was attenuated by a factor of 500 to 5000. The input energy density was calculated from the output energy, the beam cross-section after the diaphragm, and the amplification. The output energy was measured with a Quantronix 504 calorimeter with head 500, which was compared with a Cilas CG 64 calorimeter. Since both instruments agreed within 5 per cent, they were taken to be sufficiently exact.

b) Set-up for Relative σ Measurements

Most of the relative measurements of σ (small-signal gain ratios) were done with the simpler set-up of Figure 5. The flashlamps of the oscillator were fed with 2 kJ of electrical energy lasting about 2.5 ms. With a filling of 2 torr C\textsubscript{3}F\textsubscript{7}I + 20 torr SF\textsubscript{6}, the oscillator emission was about 2 ms long and fairly smooth. At this low pressure, the oscillator line widths can be expected to be not much more than the Doppler width. Since the pressure used in the amplifier were higher (20 torr C\textsubscript{3}F\textsubscript{7}I + foreign gas) it is the σ value of the amplifier line centre which was measured. The spectral output of the oscillator was unknown. But relative measurements done with the set-up in Fig. 4 for Ar and CO\textsubscript{2} it was shown that the results agreed within 5 per cent. The amplifier was pumped by a pair of flashlamps supplied with 900 J of electrical energy for about 3 µs. For every gas a series of measurements was done: 20 torr of pure C\textsubscript{3}F\textsubscript{7}I resulted in an amplification of about 1000; then mixtures of 20 torr of C\textsubscript{3}F\textsubscript{7}I with increasing contents of foreign gas (almost to one atmosphere) were taken until the amplification was of the order of 2. This corresponds to a lowering of σ by a factor of 10.

Deactivation of the iodine atoms by the foreign gas reduces the amplification, too. If only the small-signal amplification is measured, as in the relative measurements, care has to be taken to distinguish this effect from pressure broadening. The long oscillator signal allowed deactivation constants to be determined separately, simply by looking at the decay of the amplification. At higher pressures, these measurements are perturbed by sound waves deflecting the beam. The first one arrives about 50 µs after the flash at the centre of the amplifier tube (24 mm diameter). Their effect is essentially neutralized by the lens of short focal length in front of the photomultiplier tube (RCA 7102).

V. Results and Discussion

a) The Right Choice of a and b

Our absolute σ values, obtained from the saturation energies, are based on the assumption \( a = 7/12, \ b = 1.78 \) at low pressures and \( a = 1, \ b = 1.5 \) at 50 torr C\textsubscript{3}F\textsubscript{7}I + 700 torr CO\textsubscript{2}. This choice of parameters can be justified in two ways:

1) At low pressure (up to about 250 torr of argon), the relaxation time of the lower levels can be estimated to be greater than the measuring time of 1 ns\textsuperscript{16,17}. Furthermore, down to \( \sigma = 7 \cdot 10^{-10} \text{cm}^2 \), the overlapping of the 3→4 line with adjacent lines is calculated to be negligible. Thus, only the levels \( \text{2P}_1/2 \ (F=3) \) and \( \text{2P}_3/2 \ (F=4) \) are involved in the amplification of our single-frequency input pulse. In the high-pressure measurement, however, overlapping of the hfs lines was already substantial (intermediate between Fig. 2 b and 2 c) so that at the high input energy density all levels could respond to the input frequency. But the limit \( \sigma = 1 \) was probably not quite attained.

2) If different \( a \) and \( b \) parameters are chosen, different absolute σ values are obtained. The relative σ values based on them change in the same ratio, according to (13):

\[
\sigma_{\text{rel}} = \frac{\lg V_{ss}(p_M)}{\lg V_{ss}(p_0)} \sigma_{\text{abs}}(p_0)
\]

(13)

where \( a/b \) also depends on the pressure \( p_0 \). When the data for \( V_{ss} \) and \( e_s \) at either low or high pressure \( p_0 \) of CO\textsubscript{2} were inserted into (13), varying of \( a/b \) as a parameter resulted in the set of straight lines of Figure 6.

The three pairs of \( a \) and \( b \) values given in Fig. 6 correspond to the three cases

a) \( a = 7/12, \ b = 1 + 7/9, \ a/b = 0.33 \): no relaxation, no spectral overlap (Fig. 2 a),

b) \( a = 7/12, \ b = 1 + 7/24, \ a/b = 0.45 \): fast relaxation among the lower levels only or spectral overlapping of the lines with a common upper level, but vanishing overlapping of lines with different upper levels (Fig. 2 b),
Fig. 4. Set-up for determination of $\sigma$ by ns pulses, ml acoustooptical mode-locker.

Fig. 5. Set-up for determination of $\sigma$ and of deactivation rates by ms pulses. $B$ diaphragm, $F$ filter, $D$ photomultiplier, $V$ vacuum line.

Fig. 6. $1/\sigma$ as a function of CO$_2$ pressure, assuming different $a$ and $b$ parameters. ◦ according to absolute measurements, assuming different $a/b$ values, + according to relative measurements and based on low pressure ◦, × according to relative measurements and based on high pressure ◦.

Fig. 7. $1/\sigma$ as a function of pressure of 1. pure C$_3$F$_3$I, 2. Ar + 50 torr C$_3$F$_3$I, 3. CO$_2$ + 50 torr C$_3$F$_3$I. ◦ absolute measurement; × relative measurement, both done with ns pulses. For comparison the absolute measurements of Aldridge$^1$ (---) and Zujev et al.$^2$ (---), both for Ar at a very small iodide pressure, have been included.
c) $a = 1, b = 1 + 12/24, a/b = 0.67$: fast relaxation among the lower levels and among the upper levels or complete blurring of the hyperfine structure (not quite attained in Figure 2c).

Figure 6 shows that only one set of $a$ and $b$ parameters exists that makes the relative $\sigma$ values consistent (i.e. brings $+$ and $\times$ crosses to coincidence) irrespective of whether they are based on the low or high-pressure absolute $\sigma$. This set corresponds to case a) at low pressure and case c) at high pressure.

$b) \sigma$ as a Function of Pressure

Figure 7 shows the data obtained from the nanosecond pulse set-up. In this figure, $\sigma$ is plotted versus the pressure $p_M$ of the broadening gas C$_3$F$_7$, CO$_2$ and Ar. The slopes of the straight lines are the $\beta_M$ coefficients defined by Equation (4). The accuracy of the absolute values of $\sigma$ is mainly limited by the accuracy in the measurement of the energy density which we estimate to be $\pm 20$ per cent. The measurements were reproducible within about $\pm 5$ per cent. Included in the figure are literature data$^{1,2}$ for argon at low iodide pressure, which have been measured using long pulses. The agreement of the slopes is remarkable.

The quoted authors$^{1,2}$ took an $a/b$ value of 0.67 because for longer emission times case c) is expected to be valid. The agreement of their $\sigma$ values with our ns pulse measurements confirms their assumption. However, in our measurements with long pulses we found quite another value of $a/b$, namely $a/b = 1$. This difference may be due to the much higher photolysis density we achieved in our apparatus (10 torr of iodine atoms, typically; flash duration $\sim 5 \mu$s). Our explanation is that in our case essentially all excited iodine atoms can emit because of the fast recombination of ground state iodine atoms with the C$_3$F$_7$ radicals$^{29}$. This infers that $a/b = 1$.

While behaviour like that in Fig. 3 was expected for $1/\sigma$ as a function of pressure, we have connected our data points in Fig. 7 by straight lines, because over our limited range of these two types of functions could not clearly be distinguished. Therefore, our data can be extrapolated to higher pressures only with due caution. On the other hand, the data of Aldridge in Fig. 7 indicate that a linear relation between $1/\sigma$ and pressure holds up to 2000 torr Argon. If the proportionality (6) of $1/\sigma$ and the half-width $\Delta \nu$ of a single line is assumed to hold at least approximately, a linear relation between $1/\sigma$ and pressure implies that $\Delta \nu$ temporarily grows faster than linearly with foreign gas pressure. Such behaviour was observed$^{9}$ at much higher pressures when the collision partners pass a potential minimum during the collision. But then deviations from the Lorentzian line profile are also observed$^{9}$.

c) The Extraction Efficiency $a/b$

The parameter $a$ reflects the degree of homogeneity of the gain spectrum and $a/b$ is directly equal to the maximum extraction efficiency. The result $a/b = 0.67$ at high pressure therefore demonstrates that already at a pressure resulting in $\sigma = 1.8 \times 10^{-19}$ cm$^2$, which is close to the optimum of $\sigma$ for energy storage (see Sect. VI), the stored inversion can be extracted up to 67 per cent by a single frequency pulse. This efficiency is twice the low pressure value. The result $a = 1$ at high pressure implies that the gain spectrum is homogeneous; this means that saturation at one frequency reduces the gain homogeneously at all frequencies.

d) Broadening and Deactivation by Various Gases

Broadening by the other gases was only followed down to $\sigma = 3$ to $4 \times 10^{-19}$ cm$^2$. In this range again, a linear dependence of $1/\sigma$ on the gas pressure $p_M$ was found. The "broadening coefficients" $\beta_M$ defined by Eq. (4) are listed in the table for all gases investigated by us and by previous workers. The relative measurements of Aldridge$^4$ and Padrick and Palmer$^5$ are based on Hohla's value for C$_3$I$_3$.$^3$

Whereas the agreement of the $\beta_M$ values of $^{1,2,4}$ with ours is quite good, we cannot explain the deviations from the experimental results of $^5$. At low pressure, the broadening coefficients $\alpha_M$ defined by Eq. (3) can be calculated from $\beta_M$ and Equation (5a). The result for argon, for example, is $4.6$ MHz/torr; this compares favourably with a value of $4.3$ MHz/torr, which was theoretically estimated by assuming a Lennard-Jones potential for the collision.$^5$ The table shows that the $\beta_M$ coefficients vary considerably with the nature of the gas. However, the most effective gases also strongly quench the excited iodine atoms. Deactivation constants are also given in the table. These were used to calculate the foreign gas pressure $P_{10}$, which deactivates 10 per cent of the inversion in 10 $\mu$s. (One cannot
use much longer pumping times because of pressure waves penetrating the medium from the wall with approximately sound velocity.)

VI. Conclusion

Present-day optical technology limits the maximum load of optical components such as mirrors and windows to about 5 GW/cm². If the total energy of a laser amplifier is to be extracted in a one-nanosecond pulse, there is no use in storing much more than 5 J/cm² in the amplifier. Assuming a threshold amplification 1000, which is easily attained experimentally, a stored energy density of 5 J/cm² would be possible in the iodine laser according to Eq. (1) if \( \sigma \approx 2 \cdot 10^{-19} \text{cm}^2 \). Obviously, this desired \( \sigma \) value can be attained with several gases, especially with Ar, \( \text{N}_2 \), and \( \text{CO}_2 \), in the case of \( \text{CO}_2 \) even at atmospheric pressure. Unfortunately, our measurement of the deactivation constant indicates that the pressure of \( \text{CO}_2 \) should not exceed 700 torrs. If lower \( \sigma \) values are desired, Ar should be preferred.

At a \( \sigma \) value of \( 2 \cdot 10^{-19} \text{cm}^2 \) the hyperfine structure is already extensively blurred (Figure 2). The total half-width is then more than 35 GHz, which should allow pulses shorter than 100 ps to be produced and amplified.

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R. H. Garstang, J. Res. Nat. Bur. Stand. A 68, 61 [1964]; G. H. Shortley, Phys. Rev. 57, 225 [1940]; the calculated spontaneous transition rate $A_{\text{total}} = 7.96 \text{ sec}^{-1}$ is to be preferred to the experimental ones $^{14a}$ which are all smaller; since the calculation of the magnetic dipole part of the transition rate does not involve any approximation, the actual value should be greater than $A_{\text{magnetic}} = 7.904 \text{ sec}^{-1}$.

A survey of experimental values can be found in $^{15}$; a further value in $^2$.


R. Volk, to be published.
