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# Saturation of the 0-0 hyperfine-transition linewidth enhancement factor in optically pumped alkali-metal vapors

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In a previous publication [Phys. Rev. A 31, 1440 (1985)], we determined the linewidth enhancement factor (LEF) of the microwave-power-broadened linewidth of the 0-0 hyperfine transition in optically pumped alkali-metal vapors. This factor is essentially a measure of the ratio of the transition linewidth to the microwave Rabi frequency. In the previous study, optical pumping out of only one hyperfine multiplet was considered. In the present study, the expressions are generalized to include optical pumping out of both hyperfine multiplets simultaneously. Dramatic changes in the behavior of the LEF as a function of the optical-pumping rate are predicted.

In a previous publication[1] we presented a theory of the 0-0 hyperfine transition in optically pumped alkali-metal vapors. Included in that analysis were the effects of the Zeeman degeneracy of the hyperfine levels. Often, though, when discussing this problem analogies are drawn with NMR analyses; the Zeeman degeneracies are neglected and the alkali atoms are treated as two-level systems. In this two-level approximation optical pumping is taken both as a longitudinal relaxation process, creating a population imbalance between the two spin orientations, and a transverse relaxation process contributing to the spins' dephasing. With the application of a magnetic field rotating in a plane perpendicular to the orientation axis, whose strength is characterized by the Rabi frequency $\omega_1$, the normalized population difference between the two orientations decreases and a Lorentzian line shape is observed. The half-width $\Delta_{1/2}$ of this Lorentzian is given by the standard NMR linewidth formula,

$$\Delta_{1/2}=\sqrt{\Gamma_2^2+(\Gamma_2/\Gamma_1)\omega_1^2}\ , \tag{1}$$

with $\Gamma_1$ and $\Gamma_2$ the longitudinal and transverse relaxation rates, respectively.

With the inclusion of the hyperfine-level Zeeman degeneracy, the alkali atom is no longer a two-level system. The optically detected line shape remains a Lorentzian; however, our analysis showed that while the half width could be put in the same form as that resulting from the two-level approach,

$$\Delta_{1/2}=\sqrt{\Gamma_2^2+(\Gamma_2/\Gamma_{1\beta})\omega_1^2}\ , \tag{2}$$

it displayed very different physical behavior. $\Gamma_{1\beta}$, which can be *thought* of as a longitudinal relaxation rate, was actually a complicated function of the photon-absorption rate $B$, the "dark" longitudinal relaxation rate $\gamma_1$, and the nuclear spin $I$. The significance of $\Gamma_{1\beta}$ is particularly clear in the limit of microwave-power broadening, where the linewidth is dependent on both the linewidth enhancement factor (LEF) $\Gamma_2/\Gamma_{1\beta}$ and the Rabi frequency:

$$\Delta_{1/2}(\text{power broadened})\simeq\omega_1\sqrt{\Gamma_2/\Gamma_{1\beta}}\ . \tag{3}$$

In order to highlight the relevant physics, our theory was specific to the case of optical pumping out of only one hyperfine level, and predicted that the LEF would increase without limit as the photon-absorption rate increased. This behavior was then verified by the results of a laser optical-pumping experiment. However, in many optical-pumping experiments, specifically those employing lamps, both hyperfine sublevels are optically excited.[2] In the present paper the results of our previous theory are generalized so as to include this "dual" optical pumping, and its effect on the LEF is considered.

It is a straightforward matter to include the effects of optical pumping out of both hyperfine multiplets into the equations of Ref. 1 (see, for example, Ref. 3). This modification was performed, and the $\Lambda$ matrix of Ref. 1 was inverted symbolically using MACSYMA[4,5] in order to obtain the appropriate ground-state density matrix elements and an expression for the fractional population in the $F=b=I-1/2$ hyperfine multiplet $\eta_b$. In the following expressions all of the symbols are as defined in Ref. 1, except that the photon-absorption rate $B$ now explicitly refers to absorption out of the $F=b$ multiplet and $A$ refers to the photon-absorption rate for the $F=a=I+1/2$ multiplet. Summarizing the results:

$$\eta_b=\left[\frac{g_b(A+\gamma_1)}{g_a(B+\gamma_1)+g_b(A+\gamma_1)}\right]\left[\frac{\Gamma_2^2+\Delta^2+(\Gamma_2/\Gamma_{1\alpha})\omega_1^2}{\Gamma_2^2+\Delta^2+(\Gamma_2/\Gamma_{1\beta})\omega_1^2}\right]\ , \tag{4}$$

$$\Gamma_2=\tfrac{1}{2}(A+B)+\gamma_2\ , \tag{5}$$

$$\Gamma_{1\alpha}=(B+\gamma_1)\left[1+\left(\frac{g}{4g_b}\right)\left(\frac{B-A}{A+\gamma_1}\right)\right]^{-1}\ , \tag{6}$$

and

$$\Gamma_{1\beta}=\frac{(A+\gamma_1)(B+\gamma_1)(g_aB+g_bA+g\gamma_1)}{g[(A+B)/2]^2+A(B-A)+\gamma_1\langle g[(A+B)/2+\gamma_1]+g_aB+g_bA\rangle}\ , \tag{7}$$

where $g_a$, $g_b$, and $g$ refer to the $F=a$ multiplet degeneracy, $F=b$ multiplet degeneracy, and total ground-state degeneracy, respectively. Again, in the limit of microwave-power broadening the linewidth is magnified by the square root of the LEF $\Gamma_2/\Gamma_{1\beta}$; however, these rates are now given by Eqs. (5) and (7).

 

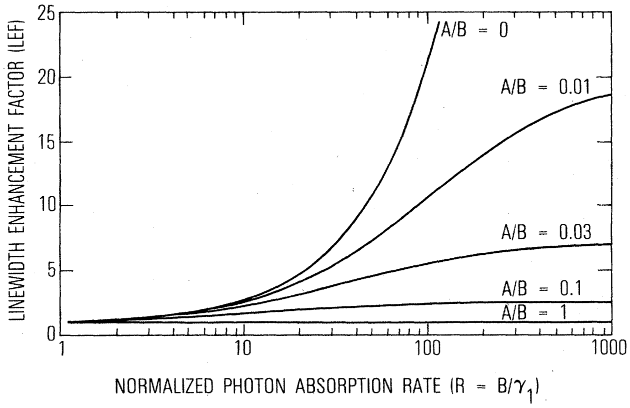


FIG. 1. Linewidth enhancement factor (LEF) as a function of the normalized photon-absorption rate $R=B/\gamma_1$. $A$ is the photon-absorption rate from the $F=a=I+1/2$ multiplet and $B$ is the photon-absorption rate from the $F=b=I=1/2$ hyperfine multiplet; $\gamma_1$ is the "dark" longitudinal relaxation rate. When optical pumping out of both hyperfine sublevels occurs, the LEF is dramatically altered. For example, with only 1% optical pumping out of the $F=a$ multiplet, the microwave-power-broadened linewidth can be orders of magnitude narrower than the linewidth in the case where there is no optical pumping out of the $F=a$ multiplet.

In Fig. 1 we show the effect of the dual optical pumping on the LEF for $I=3/2$. Specifically, we have considered the LEF as a function of the $F=b$ normalized photon-absorption rate $R$ (i.e., $R=B/\gamma_1$) for various values of the ratio $A/B$. The striking feature of the figure is that for even very small relative values of $A$, the effect of the dual optical pumping on the LEF is dramatic: rather than exhibiting the unbounded increase when $A=0$, when $A\neq 0$ the LEF saturates at sufficiently high intensities. Qualitatively, one can understand this behavior by considering Eq. (24) of Ref. 1, which shows that $\Gamma_2/\Gamma_{1\beta}\sim R$. When $A \ll B$, one can consider $A$ as an additional relaxation mechanism so that $R\rightarrow R'\sim B/(A+\gamma_1)$. If $A$ is some fixed fraction $f$ of $B$, then $R'\sim B/(fB+\gamma_1)$. Thus, when $(B/\gamma_1)>f^{-1}$, $R'$ saturates, which in turn implies the saturation of the LEF.

In conclusion, we note that as a result of excitation in the wings of the absorption line, the photon-absorption rate $A$ can never rigorously be set equal to zero; thus, an unbounded increase in the LEF is impossible. In the case of lithium, sodium, and potassium, where the ground-state hyperfine splitting is not much greater than the Doppler broadening, the significance of the absorption-line wings on the saturation of the LEF may be non-negligable.

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[1]J. C. Camparo and R. P. Frueholz, Phys. Rev. A **31**, 1440 (1985).
[2]P. L. Bender, E. C. Beaty, and A. R. Chi, Phys. Rev. Lett. **1**, 311 (1958).
[3]G. Missout and J. Vanier, Can J. Phys. **53**, 1030 (1975).
[4]R. Pavelle, M. Rothstein, and J. Fitch, Sci. Am. **245**, 136 (1981).
[5]MACSYMA is a large symbolic manipulation program developed at the Massachusettes Institute of Technology Laboratory for Computer Science and supported from 1975 to 1983 by the U.S. National Aeronautics and Space Administration under Grant No. NSG-1323, by the U.S. Office of Naval Research under Grant No. N00014-77-C-0641, by the U.S. Department of Energy under Grant No. ET-78-C-02-4687, and by the U.S. Air Force under Grant No. F49620-79-C-020, and since 1982 by Symbolics, Inc., of Cambridge, Massachusettes. MACSYMA is a trademark of Symbolics, Inc.