Effects of Degeneracy on Self-Induced Transparency

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The effects of degeneracy on self-induced transparency (SIT) have been studied using optical pulses gated from a cw dye laser and four different degenerate systems in Na. Delays, nonlinear transmission, peaking, and breakup were altered only slightly by degeneracy. This unexpected insensitivity to degeneracy of SIT features is in agreement with the McCall-Hahn pulse-area, pulse-energy description, computer simulations, and a simple physical explanation of general applicability.

Degeneracy has been assumed to prevent the observation of such characteristic features of self-induced transparency (SIT) as peak amplification and breakup of an optical pulse.[1-3] We report an experiment which clearly demonstrates that degenerate transitions do not prevent the observation of all of the characteristic features of SIT.

SIT was first demonstrated in ruby[4] and immediately afterwards in SF_6.[5] The complicated energy-level structure of SF_6 led to interest in the effects of degeneracy, but it was assumed that degeneracy prevented peaking and pulse breakup.[1-3] The effects of degeneracy on SIT phenomena are clarified here in sodium vapor using a dye laser. There are three advantages of this system over the CO_2 laser-SF_6 system. First, sodium (Na) is a simpler system with clearly defined degenerate transitions with known dipole moments. Second, for weak magnetic fields there are at least two sets of clearly defined combinations of moments which can be studied independently. Third, in high magnetic fields the Na system becomes nondegenerate. Therefore, the same system can be used to study both nondegenerate and degenerate SIT.

The basic apparatus consisted of a cw dye laser[6] and Na absorption cell. The spectral profile of the dye laser was reduced from about 0.5 Å to 20 MHz in a single longitudinal mode by the use of three etalons. The output of the dye laser was then gated through a Glan prism by a Pockels cell at the rate of 100 pulses per second.[7] This resulted in 5-nsec pulses which were focused by a 38-cm lens into a 2-mm sodium cell. The sodium cell was housed in an oven and placed in a magnetic field which could be varied from 0 to 8 kG. A 15-cm lens was used to image the excited region in the cell onto a 100-μm aperture in order to select only the uniform-plane-wave region for observation.[7] The output from the aperture was then focused by a third lens onto a fast detector and then displayed on a 7904 Tektronix oscilloscope.[7]

A quantitative study of peak amplification and breakup was carried out by Gibbs and Slusher, using a Hg laser and Rb atoms.[7] Because they found such good agreement between theory and experiment, it is desirable to start with a similar nondegenerate system and then observe what happens when degeneracy is added. In large magnetic fields Na transitions of different M_J are well resolved, but several M_I transitions are excited as a result of a large Doppler width. However, the system is effectively nondegenerate since the moments are all equal. As shown in Fig. 1, the dye-laser–Na data taken in a large magnetic field are in good agreement with computer simulations of the experiment using Bloch's and Maxwell's equations for a nondegenerate transition.[8] Figure 1 illustrates the potential use of SIT phenomena to measure relative, or even absolute, transition dipole strengths. The output pulse shape depends on the area of the input pulse, $A=(2p/\hbar)\int \mathcal{E}(t)\,dt$, which is proportional to the time integral of the slowly varying electric field envelope $\mathcal{E}(t)$ and the dipole moment p.

The near-ideal Na–dye-laser system was then used to study the degeneracies that occur in weak magnetic fields. The good quantum numbers are then F and M_F, and several different transitions can be excited simultaneously. For example, for the D_1 ($^2S_{1/2}\rightarrow{}^2P_{1/2}$) transition in fields of 0 to 60 G, dye laser pulses tuned to the $F=2$ to $F'=1,2,$

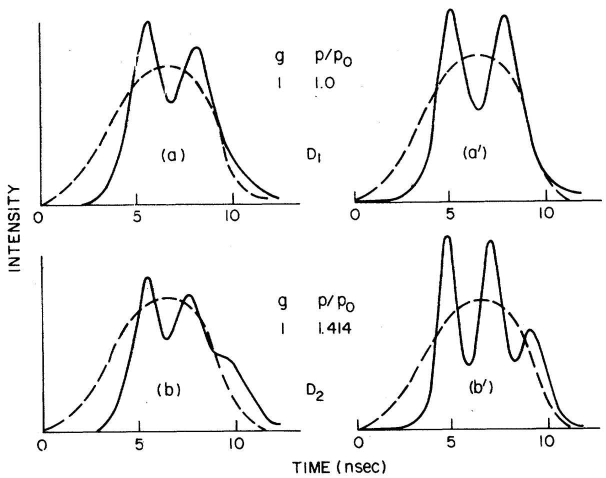

FIG. 1. Experimental output pulse shapes for linearly polarized ($\Delta M_J = 0$) nondegenerate transitions: (a) D_1 and (b) D_2. The corresponding computer simulations are (a′) D_1, $A=16$, $T_1=24$, $T_2=32$, and (b′) D_2, $A=15$, $T_1=19.2$, $T_2=32$. Note the different output shapes for the same input, demonstrating the use of SIT to measure relative dipole strengths. The dipole moments are theoretically in the ratio $1:\sqrt{2}$; the g's are statistical weights. Moment-dependent output pulse shapes were also seen for circularly polarized transitions where the relative moments are $\sqrt{2}:1:\sqrt{3}$.

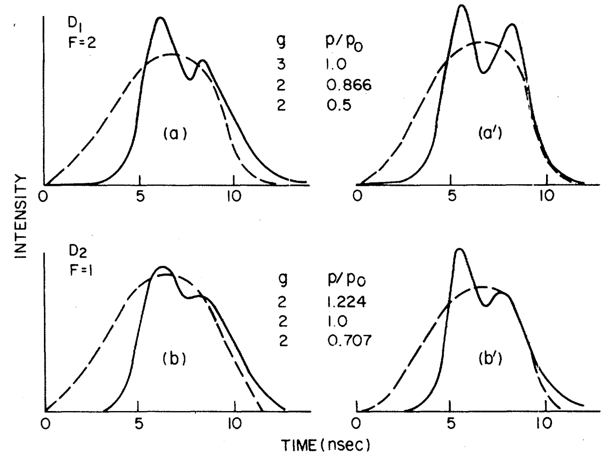

FIG. 2. Experimental output pulse shapes for the degenerate cases: (a) $D_1(F=2)$ and (b) $D_2(F=1)$. (a′), (b′) The corresponding computer simulations with input areas A_0 of 16 and 15, respectively, and $T_1=24$, $T_2=32$.

$\Delta M_F = 0$, transitions excited moments with ratios 1.0:0.87:0.5. Figure 2(a) shows that the characteristic features of peaking and breakup were clearly present in this case. The computer simulation in Fig. 2(a) is in good agreement with experimental results. Nonlinear transmission and delays did not differ much from the nondegenerate case. Similar results were found for $D_1(F=1)$ transitions. Surprisingly, all of the characteristics of SIT were similar to those in the nondegenerate case.

For the D_2 (${}^2S_{1/2} \rightarrow {}^2P_{3/2}$) transitions from $F=1$ in fields of 60 to 120 G, several moments were excited with ratios 1.2:1.0:0.707; see Fig. 2(b). Peaking and pulse breakup were diminished while the nonlinear transmission and delays remained relatively unchanged. In Fig. 2(b′) the computer simulation is shown to be in good agreement with experiment. Similar results were found for $D_2(F=2)$ transitions.

These experimental results can be understood in a qualitative way with a pulse-area, pulse-energy analysis.[9] The advantage of this approach is its simplicity and low cost as compared to computer solutions of the Bloch and Maxwell equations.[10] The area theorem describes the evolution and predicts the stable values of the pulse area: $dA_0/dz \equiv -\alpha S/2$, where $S/A_0 = [\sum g_i p_i \times \sin(A_0 p_i)]/A_0 \sum g_i p_i^2$ is the nonlinear correction to the small-area peak absorption coefficient $\alpha/2$, g_i is the statistical weight of the ith dipole moment whose value is p_i relative to the high-field $\Delta M_J = 0$ D_1 moment $p_0 = 2.6\times10^{-18}$ esu cm, and $A_0 \equiv (2p_0/\hbar)\int \mathcal{E}(z,t)\,dt$ is the area for a moment of value p_0. The pulse energy per unit area τ varies as $d\tau/dz = -\alpha\tau F(A_0)$, where $\tau = (c/4\pi) \times \int [\mathcal{E}(z,t)]^2\,dt$. A good approximation[9] to F for smooth pulse shapes is related to the energy $W(A_0)$ of N atoms at exact resonance after the passage of a pulse of area A_0:

$$W(A_0) + \frac{N\hbar\omega}{2} = \frac{N\hbar\omega}{2}\,\frac{\sum g_i[1-\cos(p_i A_0)]}{\sum g_i} = A_0^2 F(A_0)\,\frac{\sum g_i p_i^2}{\sum g_i}.$$

The high-area oscillations are more apparent on a plot of W than F.

S and W curves are shown in Fig. 3. The positively sloped zero in the D_1 $S(A_0)$ curve (a) at about 4.2π predicts a stable area for which the atoms are returned as efficiently as possible to the ground state. The D_1 W curve (a) indicates that the modulation in the energy stored in the atoms is not very different from the nondegenerate case (c). Thus, breakup and peaking are predicted to be similar to the nondegenerate case in agreement with experimental results. The dipoles 1.00 and 0.87 are nearly equal and there-

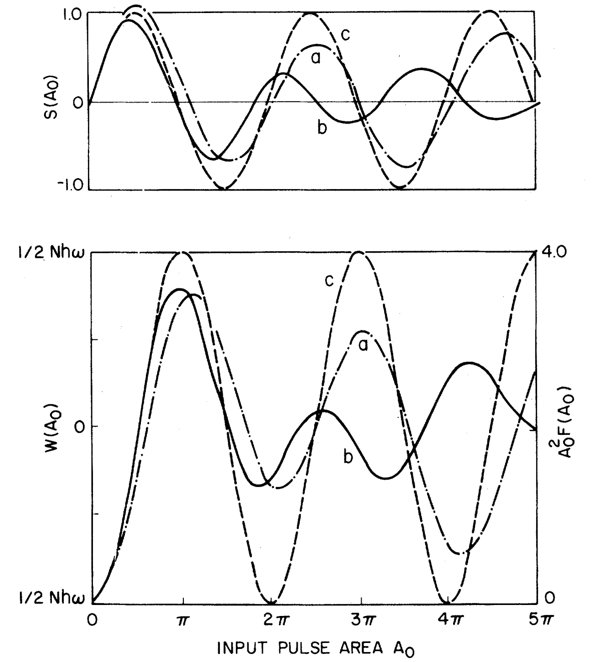

FIG. 3. S and W for (curves a) degenerate $D_1(F=2)$ transitions, (curves b) degenerate $D_2(F=1)$ transitions, and (curves c) nondegenerate transition. The modulation of the output pulse for the same number of atoms should be ideal, good, and poor in the nondegenerate, degenerate D_1, and degenerate D_2 cases, respectively. Experimental results agree with these predictions.

fore act together and effectively modulate the pulse. The 0.5 dipole has little effect on pulse modulation and peaking because its oscillations are slower and absorption much weaker.

The D_2 S curve (b) indicates that a stable area exists at 3.3π. The W curve (b) indicates that the modulation of energy stored in the atoms is reduced from the D_1 case and therefore, in agreement with experimental results, peaking and breakup are expected to be diminished. The difference between two of the transition dipole moments (1.22 and 1.00) prevents them from absorbing and reradiating energy simultaneously. More energy is lost than in the D_1 case since a 4π-area pulse for one dipole will be about 3π in area for the second dipole and therefore leave atoms excited as the pulse propagates through the medium. However, it is important to note that propagation losses and delay times are affected similarly by degeneracy and relaxation losses and that in practice relaxation effects often dominate.[3]

Previously the effects of degeneracy on nonlinear transmission, delays, and low-loss propagation rather than on reshaping have been stressed.[1,3] It was expected, as a rule, that degeneracy would prevent breakup and peaking. The remarkable point of this Letter is that pulse breakup and peaking are seen in degenerate systems and are found to be more sensitive indicators of degeneracy effects. Degeneracy prevents breakup only when there are several moments of comparable absorption that differ by enough to compete but not enough that one oscillates much more slowly than the other. If all transitions have the same weight, moments less than one-half the maximum value will have too little absorption to have much effect. Therefore, it is the exception rather than the rule that degeneracy prevents breakup.

It is interesting that D_2 SIT was observed to be near ideal again in zero field. The spectral width of the 5-nsec pulse is greater than the hyperfine splitting of the $^2P_{3/2}$ excited state so that each ground state is excited into a linear combination of two excited states. Each excited transition now has the same transition dipole moment predicting that nondegenerate SIT should be observed.[11] Experimental results were in excellent agreement with this prediction. This observation emphasizes that the effect of degeneracy on SIT depends not solely on the atom but also on the spectral width of the exciting laser.

In summary, the Na-dye system is ideal for testing the effects of degeneracy on SIT. The experiment demonstrated the usefulness of dye lasers in studying coherent optical effects[12] and measuring the relative magnitudes of transition dipole moments. It was clearly demonstrated that degeneracy does not necessarily prevent the observation of peaking and pulse breakup. A pulse-area, pulse-energy analysis is a good, qualitative, inexpensive indicator of the relative peaking and modulation to be expected. A general rule for good 4π breakup may be followed. If several of the degenerate moments are nearly equal and dominate the absorption, good breakup will be observed. On the other hand, if the difference between the moments dominating the absorption prevents them from absorbing and reradiating cooperatively, breakup will be diminished. For example, for P or R linearly polarized transitions in molecules, the moments cluster close to their largest value. Therefore, breakup and peaking are predicted in SF_6 as reported.[2]

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[1]C. K. Rhodes, A. Szoke, and A. Javan, Phys. Rev. Lett. 21, 1151 (1968); C. K. Rhodes and A. Szoke, Phys. Rev. 184, 25 (1969).

[2]A. Zembrod and Th. Gruhl, Phys. Rev. Lett. 27, 287 (1971).

[3]F. A. Hopf and C. K. Rhodes, Opt. Commun. 8, 88 (1973); F. A. Hopf, C. K. Rhodes, and A. Szoke, Phys. Rev. B 1, 2833 (1970).

[4]S. L. McCall and E. L. Hahn, Phys. Rev. Lett. 18, 908 (1967), and Phys. Rev. 183, 457 (1969).

[5]C. K. N. Patel and R. E. Slusher, Phys. Rev. Lett. 19, 1019 (1967).

[6]A. Dienes, E. P. Ippen, and C. V. Shank, IEEE J. Quantum Electron. 8, 388 (1972).

[7]H. M. Gibbs and R. E. Slusher, Phys. Rev. Lett. 24, 638 (1970); R. E. Slusher and H. M. Gibbs, Phys. Rev. A 5, 1634, and 6, 1255 (1972).

[8]Degeneracy was added to the program of Ref. 7. For the degenerate transitions the approximate values $T_1 = 24$ nsec and $T_2 = 32$ nsec were used. Because of the short input pulse, output shapes depend only weakly on the relaxation times. Relaxation was assumed not to couple the degenerate transitions; experimentally, this was not always the case. A careful study of relaxation details would have to include coupling.

[9]S. L. McCall and E. L. Hahn, in *The Physics of Quantum Electronics*, edited by S. F. Jacobs and J. B. Mandelbaum (Optical Sciences Center, The University of Arizona, Tucson, Ariz., 1968), pp. 65–99; Rhodes, Szoke, and Javan, Ref. 1; S. L. McCall and E. L. Hahn, Phys. Rev. A 2, 861 (1970).

[10]The $S(A)$ and $W(A)$ curves were run on a PDP-8 computer and could be done on many calculators.

[11]See p. 864 of McCall and Hahn, third citation of Ref. Ref. 9.

[12]For example, we have observed large Faraday rotations of SIT pulses on the D_2 transition in sodium.