Prepulses as a distinctive characteristic of resonant pulse propagation in degenerate atomic media

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Prepulses are associated with resonant pulse propagation in degenerate media. We show numerically that the appealing explanation of prepulses in terms of separate pulse propagation dynamics for strong and weak dipole channels in a $Q(2)$ degenerate atomic medium is incorrect, although prepulses remain a characteristic of degenerate media.

Prepulses in coherent resonant pulse propagation (CRPP) have been considered a fingerprint of degenerate gaseous systems. They are small-area pulses, with the linear dynamics of truly small-area pulses, at the leading edge of a large-area output pulse. They have been observed experimentally in complex degenerate systems such as gaseous SF_6 (Ref. 1) and iodine atomic vapor.[2,3] Xu *et al.*[3] have given an appealing explanation for their existence, based on a linear interaction of the input pulse with the weaker dipole of the degenerate system. This explanation implies an attractive separation of the atomic dynamics: linear for the prepulse with the weaker dipole and nonlinear for the remaining large-area pulse with the stronger atomic dipole. Here we test this explanation through numerical simulations.

We study these prepulses by modeling the CRPP in degenerate media and comparing the corresponding pulses with similar small-area pulses, produced by the input pulse reshaping toward a soliton, on the π–2π branch of the area theorem in a two-level atom (TLA) medium.[4] Here there is no separation of the interaction into linear and nonlinear dynamics unless the two pulse terms are well isolated. Now, if the prepulses are indeed characteristic of degenerate systems, they should be quite different from this TLA analog. We show here that there is no such separation of the prepulse dynamics from the composite pulse dynamics.

Under equivalent conditions, we compare the results of numerical simulations of CRPP in nondegenerate (a TLA), $Q(2)$ degenerate, and accidental degeneracy (AD) media. The $Q(2)$ degenerate system exists in iodine atomic vapor[3] and can be described by two independent TLA models[5]; we refer to it as a 2-TLA model. The model for AD[6] corresponds to a three-level atom with a V structure where the two excited levels coincide. The AD model does not have independent dipoles[6]; thus the formation of prepulses is inhibited. When the input pulse is weak, absorption will occur, and none of these differences plays a relevant role.

We solve the coupled Bloch–Maxwell differential equations numerically. The Bloch equations for the ith TLA are

$$\dot{p}_i = i\Delta p_i + i\lambda_i \Omega w_i - p_i/T_{2i},$$
$$\dot{w}_i = -\mathrm{Im}(p_i{}^* \lambda_i \Omega), \qquad (1)$$

where $i = 1, 2$, $\lambda_1 = 1$, and $\lambda_2 = \lambda$. Maxwell's equation of interest is[7]

$$\partial\Omega/\partial z' = -iB(\langle p_1\rangle + \lambda\langle p_2\rangle)/(1 + \lambda^2). \qquad (2)$$

The Rabi frequency Ω and the absorption coefficient α are defined in terms of the stronger dipole moment. λ is the ratio of the second dipole to the first and stronger one. The remaining variables are defined as follows: p_i is the microscopic polarizations; w_i is the population inversion; Δ is the atomic detuning; T_{2i} is the incoherent decay time. Im is the imaginary part, and the dots over the variables denote differentiation with respect to local time t. In Eq. (2), z' is the propagation distance in units of the absorption coefficient ($z' = \alpha z$), $B = 1/2\pi g(0)$, where $g(\Delta)$ is the inhomogeneous atomic line and $\langle\ \rangle$ denotes its average.

We propagate a Gaussian-profile pulse with a 1.2π input area through enough Beer's lengths to include any reasonable experimental propagation as well as to reach the limits of ideal steady-state propagation in an absorber. In an inhomogeneously broadened TLA medium the small-splitting pulse, which is the linear interaction response, is part of the reshaping process of the input pulse; the trailing edge, which is the nonlinear response, lengthens, is delayed, and evolves into a 2π optical soliton. Figure 1 shows that at 12 Beer's lengths the small-splitting pulse separates and suffers anomalous absorption.[4] Numerical simulations show that if the input area pulse is almost 2π the small-splitting pulse is gently absorbed; if it is slightly larger than π a separation between the linear and the nonlinear parts occurs at shorter propagation distances. In either case the nonlinear part produces a soliton, which will be shorter in the larger-area input case.

The prepulse can be observed by numerically solving Eqs. (1) and (2) with $\lambda = 0.5$. A prepulse is shown in Fig. 2. Comparing Figs. 1 and 2, we observe that for the 2-TLA model the small pulse on the leading edge does not quite split, and neither component becomes independent. If dynamic breaking occurs, the large-

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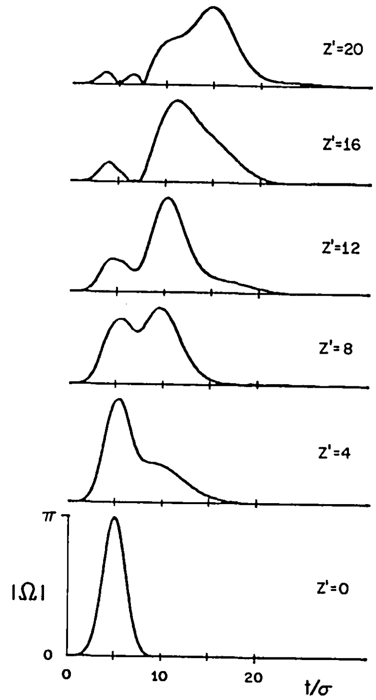

Fig. 1. Numerical solution to Eqs. (1) and (2) for a TLA medium ($\lambda = 0$). The input pulse is Gaussian with width (FWHM) $\tau = 1.2$ and area $A(0) = 1.2\pi$. The inhomogeneous decay time is $1/T_2^* = 1.5$, the homogeneous decay time is $T_2 = \infty$, and $\sigma = \tau/2(\ln 4)^{1/2}$.

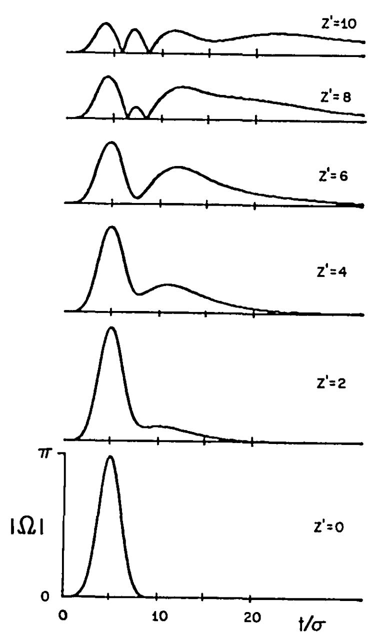

Fig. 2. Numerical solution to Eqs. (1) and (2) for a $Q(2)$ medium ($\lambda = 1/2$). The input pulse is the same as in Fig. 1, and each dipole group has an inhomogeneous line with $1/T_2^* = 1.5$ width. The homogeneous decay time was assumed to be infinite, as in Fig. 1.

area pulse should lead to a steady-state pulse. We clarify this point by looking at the pulse-area and energy propagation equations[5]:

$$\partial A/\partial z' = -(1/2)(\sin A + \lambda \sin \lambda A)/(1 + \lambda^2), \qquad (3)$$

$$\partial e/\partial z' = (\cos A + \cos \lambda A - 2), \qquad (4)$$

where A and e are the area and the energy, respectively. For $\lambda = 0.5$ in Eq. (3), A has a steady-state value of 2π, but in Eq. (4) e does not. Thus the large-area pulse observed in Fig. 2 cannot be a steady-state pulse. This result brings into question the argument of separability of the dynamics into channels.[3]

This apparent contradiction with the experimental results reported in Ref. 3 can be understood with the aid of the corresponding area theorem for each model, whose solutions are plotted in Fig. 3. The TLA and

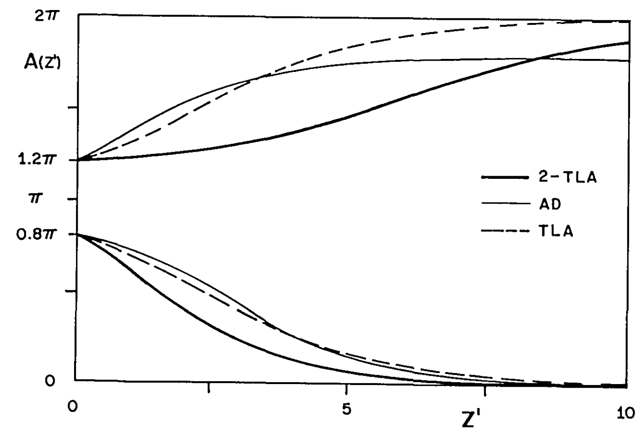

Fig. 3. Branch of the area theorem for the degenerate [Eq. (3) with $\lambda = 1/2$], nondegenerate [Eq. (3) with $\lambda = 0$], and AD cases.

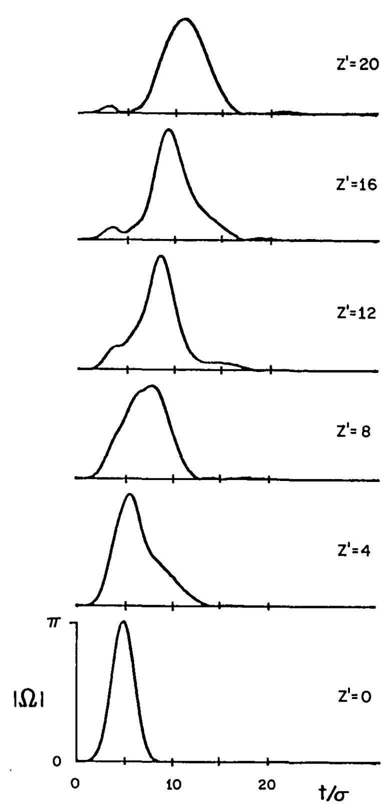

Fig. 4. Numerical simulation of pulse propagation for the same input pulse as in Figs. 1 and 2 in the AD medium. The inhomogeneous atomic line of the two upper levels was identical with $1/T_2^* = 1.5$ width.

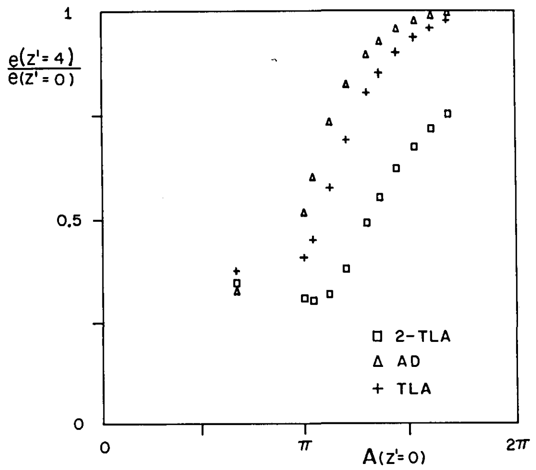

Fig. 5. Relative pulse energy versus input pulse area (saturation curve) for the TLA model, the 2-TLA model, and AD. The pulse energy has been assumed to be proportional to $\int|\Omega|^2 dt$, and the output pulse is given at $z' = 4$.

the Q-degenerate media both reach steady-state values for an area of 2π, and the AD medium for an area of 1.789π.[6] But the 2-TLA medium does not have stable energy at those values [Eq. (4)]. The pulse in the 2-TLA medium broadens without acquiring independent nonlinear characteristics (Fig. 2), and a prepulse is part of a nonsteady pulse as a consequence of its nonseparability in different dipole dynamics.

The rate of splitting is related to the slope of the corresponding area's upper branch. In the TLA model, when the slope for the input pulse area is small the pulse splits gently in a short penetration distance. The 2-TLA model behaves similarly, but its corresponding area branch is flatter (Fig. 3). Then under similar conditions the small-splitting pulse will separate faster in the degenerate model (see Figs. 1 and 2) and so is recognized as a prepulse. Inhomogeneous broadening is important in the observation of both effects. Our numerical experiments show that if $\tau/T_2^* < 10$, the prepulse or the small-splitting pulse can be observed. This result agrees with the detection[1,3] and nondetection[4] of these effects in previous experimental work. On the other hand, CRPP in a medium with AD is closer to a TLA than to a 2-TLA model since its atomic equations (Bloch-like) can be reduced to equations similar to those for the TLA.[6] Thus the pulse approaches an optical soliton in the steady state. In Fig. 4 it is easy to identify the forming soliton (compare it with Fig. 1).

The failure to create a stable pulse in a 2-TLA system, and therefore a separation of dynamics among the channels, is manifested as low transmitted output time-integrated energy. Figure 5 shows the behavior of the relative time-integrated pulse energy at a fixed penetration distance, $z' = 4.0$. Several input pulse-area values were changed in the π–2π region (saturation curve). It is evident that energy transmission is much greater in the TLA than in 2-TLA because of the more intense output pulse coming from the optical soliton. The AD stable pulse is closer to the TLA soliton and therefore also shows good transmission.

In conclusion, we have numerically compared CRPP in two different but simple degenerate atomic models and in a nondegenerate atomic model in an effort to test the characteristics that define a prepulse. Numerical results show that a prepulse is associated with degenerate dipole transitions that are not coupled through atomic levels. However, there is no separation in the dynamics of the prepulse, as was earlier suggested. A prepulse is part of an unstable large-area pulse that broadens under conditions of fixed area.

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7. The authors thank the referee for his or her suggestion for the final form of the equations, which preserves the characteristics of the linear propagation.