Strong-Field Effects in Saturation Spectroscopy of Atomic Beams

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New surprising features have been observed in the shape of the saturation signal in a Ca atomic beam as the laser intensity is increased: the usual saturation dip is turned into a peak and then evolves into a triplet. The atomic transitions of interest for optical frequency standards, such as the intercombination $^1S_0$-$^3P_1$ line of Ca, correspond to long-lived atomic systems. In such a case the interaction physics, whose geometry is illustrated on Figure 1, is dominated by transit physics and by the atomic recoil. The observed features are directly associated with these two aspects.

When atoms, initially in the ground state $| a >$ with momentum $\vec{p}_0$, interact with laser beams having opposite wavevectors $\pm\vec{k}$, they are scattered into a superposition of narrow and well-resolved wave packets centered around $\vec{p}_0 + m\hbar\vec{k}$ where m is an integer number. The Schrödinger equation for the wave packet amplitudes $\ldots b_{-1}, a_0, b_1 \ldots$ is written as [1]:

$$\frac{d}{dt}\begin{pmatrix} \cdot \\ a_2 \\ b_1 \\ a_0 \\ b_{-1} \\ a_{-2} \\ \cdot \end{pmatrix} = -i \begin{pmatrix} \ldots & R_2 & V^- & 0 & 0 & 0 & \ldots \\ \ldots & V^{-*} & R_1 & V^{+*} & 0 & 0 & \ldots \\ \ldots & 0 & V^+ & R_0 & V^- & 0 & \ldots \\ \ldots & 0 & 0 & V^{-*} & R_{-1} & V^{+*} & \ldots \\ \ldots & 0 & 0 & 0 & V^+ & R_{-2} & \ldots \end{pmatrix} \begin{pmatrix} \cdot \\ a_2 \\ b_1 \\ a_0 \\ b_{-1} \\ a_{-2} \\ \cdot \end{pmatrix}$$

where the matrix elements are given by: $V^{\pm}(t) = -\Omega F_{pro}(v_x t) \exp\, i\,(\Delta \mp k v_z)\, t$ for the interaction with the $(\pm)$ wave, and $R_m = m^2\hbar k^2/2M_{Ca}$ for the recoil shift corrections. $\Omega = \mu E_0/2\hbar$ is the Rabi pulsation and $\Delta = \omega - \omega_0$ is the detuning. We emphasize that the usual Gaussian dependence has to be replaced by the exact actual profile $F_{pro}(x)$ delivered by the single-mode optical fiber in order to get good agreement. These equations are solved numerically and integrated over the velocity distribution. The calculated lineshapes displayed on Figure 3 can be compared with the experimental results of Figure 2.

We conclude that:
1-the strong field non-linear response of a two-level system is very sensitive to the Fourier content of the field seen by the atoms.
2-even when the transit linewidth is large compared to the recoil shift, multiple momentum exchanges bringing the atomic system out of resonance, can alter significantly the transition probability with a frequency signature which corresponds exactly to the observed signal.

References:

[1] Ch. J. Bordé et al., Phys. Rev. **A30** (1984) 1836

Figure 1 Experimental setup

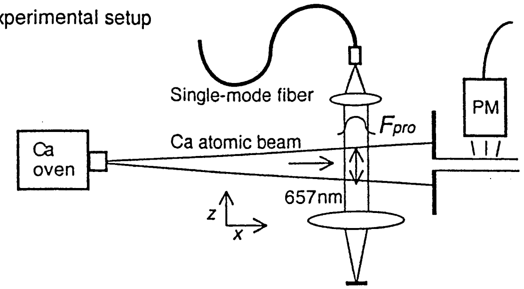

Figure 2 Experimental results

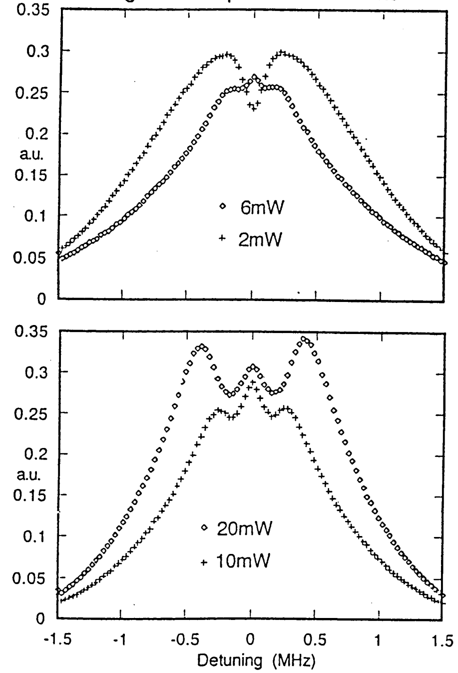

Figure 3 Calculated lineshapes