I. INTRODUCTION

It is well appreciated by physicists and laymen alike that light moves extremely fast in a vacuum. The speed of light demands incredible respect, as it enjoys unique privilege in modern physics' most fundamental theories. So it was perhaps extremely surprising to the scientific community to find that, not only can light be slowed to the speed of a moving vehicle, but that it can be done rather easily, only by exciting a three-level sodium gas in a systematic way.

We first review how EIT arises from a three-level system being excited by two lasers. We then recall how this directly affects the group velocity of the laser pulse, and briefly mention the ability to trap the light by varying the intensities of the lasers. We then go through two experiments that demonstrate this phenomenon, and conclude with various applications of slowed and stopped light.

II. THEORY

A. Derivation for Electromagnetically-Induced Transparency

1. Interaction Picture

It is much simpler to perform this derivation in Dirac’s interaction picture. We reproduce the crucial results here. For a Hamiltonian given by:

\[ H(t) = H_0 + H_I(t) \]

and a wave function \( |\psi_S(t)\rangle \), the Schrödinger’s equation gives us:

\[ i\hbar \frac{\partial}{\partial t} |\psi_S(t)\rangle = H(t) |\psi_S(t)\rangle \]

We can transform the wave function into the "interaction" picture by using:

\[ |\psi_I(t)\rangle = e^{iH_0t/\hbar} |\psi_S(t)\rangle \]

and the new Schrödinger’s equation in this picture becomes:

\[ i\hbar \frac{\partial}{\partial t} |\psi_I(t)\rangle = H_I(t) |\psi_I(t)\rangle \]

So the interaction picture allows us to focus on only the time-dependent part of the Hamiltonian.

2. EIT in a three-level system

Consider an atomic system with three levels \( |1\rangle, |2\rangle, |3\rangle \) with energies \( E_1 < E_2 < E_3 \). Electric dipole transitions are permitted between \( |1\rangle \leftrightarrow |3\rangle \) and \( |2\rangle \leftrightarrow |3\rangle \) but are forbidden between \( |1\rangle \leftrightarrow |2\rangle \) directly.

At time \( t = 0 \) we excite the atom with two lasers. One laser (the "probe" laser) oscillates at \( \omega_p = (E_3 - E_1)/\hbar \), and serves to measure the absorption of the medium. The other laser (the "coupling" laser) oscillates at \( \omega_c = (E_3 - E_2)/\hbar \) and (as we will see) serves to induce the transparency.

Our Hamiltonian is given by:

\[ H(t) = H_0 + H_I(t) \]

with

\[ H_0 = \sum_k E_k e^{-i\omega_k t} |k\rangle \langle k| \]

\[ H_I(t) = \hbar \Omega_p e^{-i\omega_p t} |1\rangle \langle 3| + \hbar \Omega_c e^{-i\omega_c t} |2\rangle \langle 3| + \text{h.c.} \]

In the interaction picture we find:

\[ i\hbar \frac{\partial}{\partial t} |\psi_I(t)\rangle = H_I(t) |\psi_I(t)\rangle \]

\[ \Rightarrow i\hbar \sum_k c_k(t) |k\rangle = \sum_k c_k(t) H_I(t) |k\rangle \]

\[ \Rightarrow \begin{pmatrix} \dot{c}_1(t) \\ \dot{c}_2(t) \\ \dot{c}_3(t) \end{pmatrix} = \frac{i}{\hbar} \begin{pmatrix} 0 & 0 & \Omega_p \\ 0 & 0 & \Omega_c \\ \Omega_p & \Omega_c & 0 \end{pmatrix} \begin{pmatrix} c_1(t) \\ c_2(t) \\ c_3(t) \end{pmatrix} \]

The transparency comes from the existence of a \( \tilde{c}(0) \) where \( c_3(t) = 0 \) for all \( t \). Namely, if \( \tilde{c}(0) \) is the dark state \( |D\rangle \):

\[ |D\rangle = \frac{1}{\sqrt{\Omega_c^2 + \Omega_p^2}} (\Omega_c, -\Omega_p, 0) \]

then \( \dot{c}(t) = 0 \) and \( c_3(t) = 0 \). The dark state is stationary, and a collection of atoms will tend to decay into it. Hence, the existence of the coupling laser staves the \( |3\rangle \) state, preventing the atom from absorbing the \( |1\rangle \leftrightarrow |3\rangle \) resonance and causing a gap in the absorption spectrum.

B. EIT \(\Rightarrow\) Slowed light

In optics, it is common to describe the behavior of absorption as a complex component of the refractive index.
n. Adopting this formalism, the Kramers-Kronig relations show [1] that the absorption and refraction spectrums are not independent; in particular, the absorption fixes the refractive behavior as:

$$n(\omega) = 1 + \frac{c}{\pi \omega} \int_0^\infty \frac{\alpha(\omega')}{\omega^2 - \omega'^2} \, d\omega' \tag{13}$$

where $\alpha$ is the absorption coefficient as a function of frequency.

Figure 2(ab) of [2] illustrates sample graphs of transmission and refraction as a function of detuning. The sharp change in the absorption coefficient close to resonance manifests itself in a similarly large derivative in the refractive index.

The group velocity of light propagating through a medium can be described by [2]:

$$v_g = \frac{c}{n(\omega_p) + \omega_p \frac{dn}{d\omega_p}} \tag{14}$$

Hence, we see that a large $dn/d\omega_p$ manifests itself in a slow group velocity at high frequencies.

C. Stopped light theory

When the coupling laser is abruptly turned off while the probe pulse is acting on the atom, we see from Eq. (11) that the interaction Hamiltonian yields a simple Rabi oscillation between the $|1\rangle$ and $|3\rangle$ states. Hence, when the coupling laser turns on again, we expect the laser pulse to remain qualitatively unchanged. A recent paper predicts that the pulse information is effectively stored in the gas when the coupling laser is turned off.

[3]

III. EXPERIMENTS

A. Slowed light

We investigate an experiment that demonstrates the slowdown of the group velocity of light to 17 m/s, approximately 10^7 times slower. [2] A gas of 10^10 sodium atoms is prepared in a magneto-optical trap. They are cooled to 1 mK through a Zeeman slower, and then further cooled to 50 µK through a polarization gradient. They are then optically pumped into the $F = 1$ ground state. The lasers are turned off, the atoms are magnetically confined in a "4 Dee" trap, and an asymmetric harmonic potential is applied to filter out all states besides $M_F = -1$ (aligned with the probe pulse, along the $z$ axis of the trap). They are further cooled to below the Bose-Einstein condensate temperature $T_c = 435nK$, leaving a cloud of ~ 1 million atoms.

We treat the sodium atoms as a three-level system where:

$$|1\rangle = |F = 1, M_F = -1\rangle$$
$$|2\rangle = |F = 2, M_F = -2\rangle$$
$$|3\rangle = |F = 2, M_F = -2\rangle$$

The probe laser is tuned to the $|1\rangle \leftrightarrow |3\rangle$ transition linearly-polarized along the $z$-axis, while the coupling laser is tuned to the $|2\rangle \leftrightarrow |3\rangle$ transition, left-circularly polarized. A separate imaging beam is tuned to the $|3\rangle \leftrightarrow |4\rangle = |F = 3, M_F = -2\rangle$ transition, which goes through the sodium trap and is focused onto a CCD, to determine the dimensions of the sodium cloud (this beam is never on while the other lasers are, and hence does not significantly affect the experiment). All three lasers are perpendicular to each other.

At the opposite end of the probe pulse are a pinhole and a flipper mirror, which can be rotated to direct the beam to a photomultiplier tube or a CCD. The photomultiplier tube is used to measure pulse delay, and the CCD is used for imaging the cloud (similar to the use of the imaging beam but in the transverse direction). Recall that the sodium atoms are initialized in the $|1\rangle$ state. The coupling beam is turned on, and the probe pulse is swept through various detunings from $\omega_p$. The transmission spectrum is provided in Figure 2a of [2]. We note that a sharp increase in transmission is seen just slightly off of resonance, as predicted by our model for electromagnetically-induced transparency. The index of refraction over detuning is given in Figure 2b of the same reference. At resonance, the slope is very large, which indicates (by Eq. (14)) a very low group velocity. Figure 3 of [2] shows the delay as detected by the photomultiplier tube of the probe signal. The light pulse takes $\tau_{\text{delay}} = 7.05 \, \mu$s to travel the distance of the sodium cloud (with $L = 229 \, \mu$m), with the group velocity $v_g = 32.5 \, m/s$, just under 7 orders of magnitude the speed of light in a vacuum.

B. Stopped light

A similar experiment was performed, where researchers were able to trap pulses of light from the probe in the sodium gas by modifying the intensity of the coupling laser. [4] The experimental setup was exactly the same as in [2], with some minor changes. The relevant three-level states are now:

$$|1\rangle = |F = 1, M_F = -1\rangle$$
$$|2\rangle = |F = 2, M_F = 1\rangle$$
$$|3\rangle = |F = 2, M_F = 0\rangle$$

It is also now necessary to measure the coupling laser as well as the pulse laser. The two lasers are merged with a
beam splitter at different polarizations (the probe laser $z$-polarized and the coupling laser $x$-polarized). They are circularly polarized with a quarter-wave plate before they enter the sodium cloud. They are sent through another quarter-wave plate (so that they are both linearly polarized, orthogonal to each other), through a pinhole, and then a polarizing beam splitting cube which separates the probe and coupling lasers. The coupling laser is sent to a photomultiplier tube, and the probe laser is sent to a flipper mirror, which can be selected to direct the beam to a CCD (for imaging) or a photomultiplier. The sodium atoms are initialized in the $|1\rangle$ state. Two different experiments are then conducted. The first one serves to measure the group velocity of the light pulse. The coupling laser is turned on $\approx 7 - 8 \mu s$ before the probe laser is. A reference pulse is first measured, by pulsing the probe laser in the absence of atoms. The photomultiplier collects this pulse almost instantly (where the collection time is defined to be time $t = 0$). Then, the magnetic trap is populated with sodium atoms and the same experiment is performed. The pulse is now seen at $t = 11.8 \mu s$. With a cloud of 339 $\mu m$ this corresponds to a group velocity of $v_g \approx 28.7$ m/s. This agrees with the experiment in [4].

The second experiment attempts to freeze the probe pulse inside of the sodium trap. It is determined from the first experiment that the pulse is completely encapsulated in the medium $6.3 \mu s$ after the reference pulse. The coupling laser is again turned on $\approx 7 - 8 \mu s$ before the probe pulse, but it is turned off at $6.3 \mu s$, when the pulse is contained in the trap. The pulse can then be regenerated nearly on-demand by turning on the coupling laser at a future time. For instance, turning on the coupling laser at $t = 46 \mu s$ leads to almost full regeneration (compared to the first experiment, where the coupling laser was not turned off), whereas turning on the coupling at $t = 840 \mu s$ leads to a regeneration about half the intensity, with further dropoff being somewhat exponential. This data, including a graph of transmission vs. storage time, is provided in Figure 2 of [4].

IV. CONCLUSIONS

The experiments demonstrate that information from light pulses can be stored in an atomic medium. The ability to stop light in particular has been considered for use in quantum information processing, since the storage technique suggests storage times as high as 1 ms. Controlled atom-atom interactions can be used to implement quantum gates, and it is known that the exchange operation is universal. [5]

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