Using Ultra-Slow Light Physics to Improve LIDAR

Yuri Rostovtsev

Zoe Sariyanni

Marlan Scully

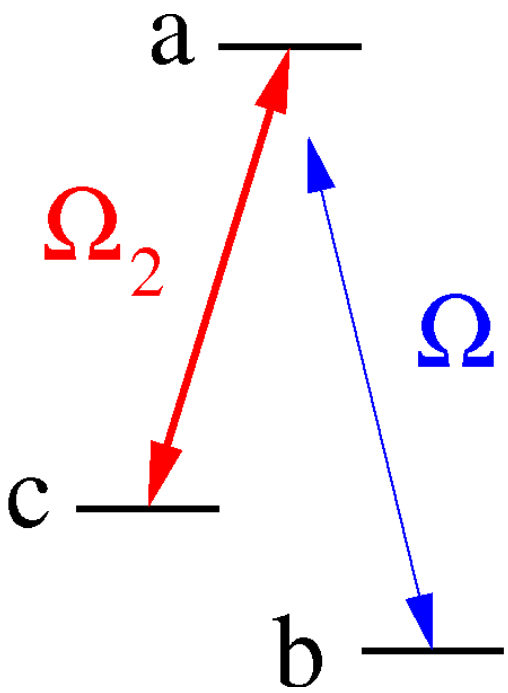
Texas A&M and Princeton

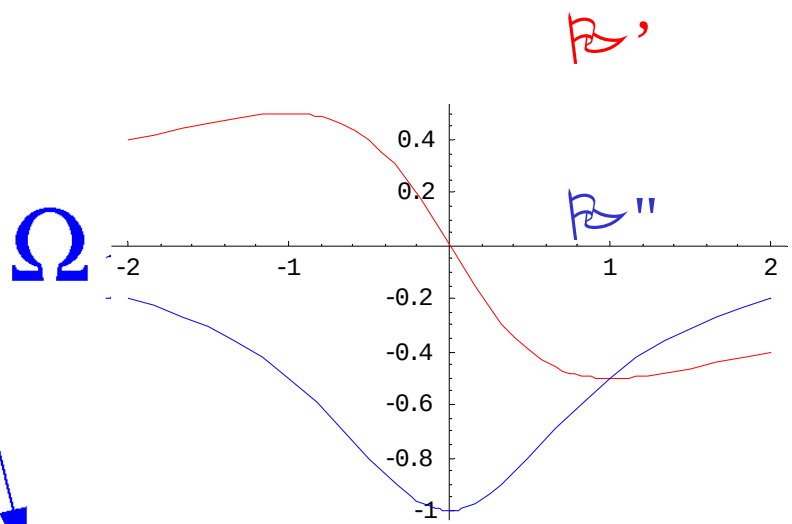
VOLUME 66, NUMBER 20 PHYSICAL REVIEW LETTERS 20 MAY 1991

Observation of Electromagnetically Induced Transparency

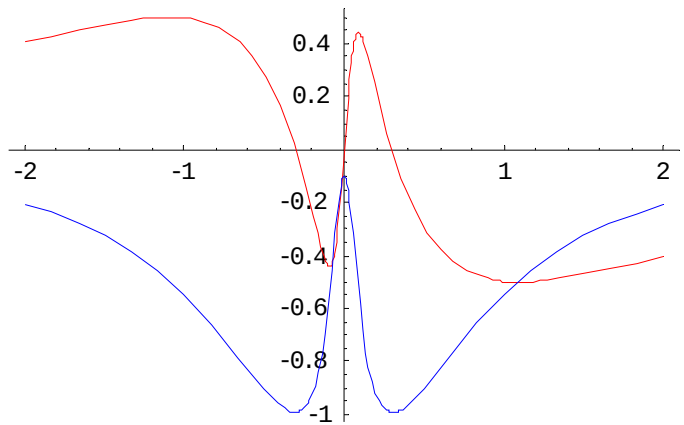
K.-J. Boller, A. Imamoğlu, and S. E. Harris
Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305
(Received 12 December 1990)

We report the first demonstration of a technique by which an optically thick medium may be rendered transparent. The transparency results from a destructive interference of two dressed states which are created by applying a temporally smooth coupling laser between a bound state of an atom and the upper state of the transition which is to be made transparent. The transmittance of an autoionizing (ultraviolet) transition in Sr is changed from $\exp(-20)$ without a coupling laser present to $\exp(-1)$ in the presence of a coupling laser.





Probe frequency



Probe frequency

Ultra-slow light via EIT

Light speed reduction to 17 metres per second in an ultracold atomic gas

Lene Vestergaard Hau*†, S. E. Harris‡, Zachary Dutton*† & Cyrus H. Behroozi*§

* *Rowland Institute for Science, 100 Edwin H. Land Boulevard, Cambridge, Massachusetts 02142, USA*
† *Department of Physics, § Division of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, USA*
‡ *Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305, USA*

Techniques that use quantum interference effects are being actively investigated to manipulate the optical properties of quantum systems[1]. One such example is electromagnetically induced transparency, a quantum effect that permits the propagation of light pulses through an otherwise opaque medium[2–5]. Here we report an experimental demonstration of electromagnetically induced transparency in an ultracold gas of sodium atoms, in which the optical pulses propagate at twenty million times slower than the speed of light in a vacuum. The gas is cooled to nanokelvin temperatures by laser and evaporative cooling[6–10]. The quantum interference controlling the optical properties of the medium is set up by a 'coupling' laser beam propagating at a right angle to the pulsed 'probe' beam. At nanokelvin temperatures, the variation of refractive index with probe frequency can be made very steep. In conjunction with the high atomic density,

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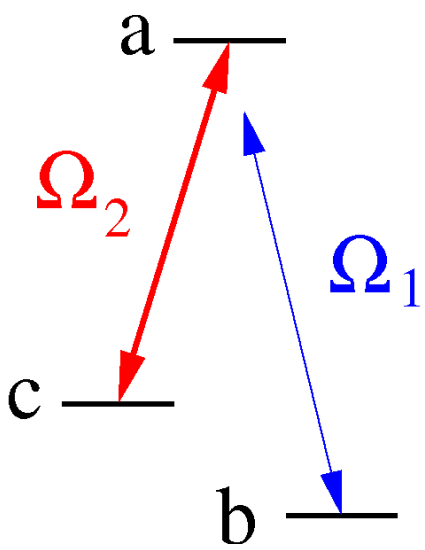
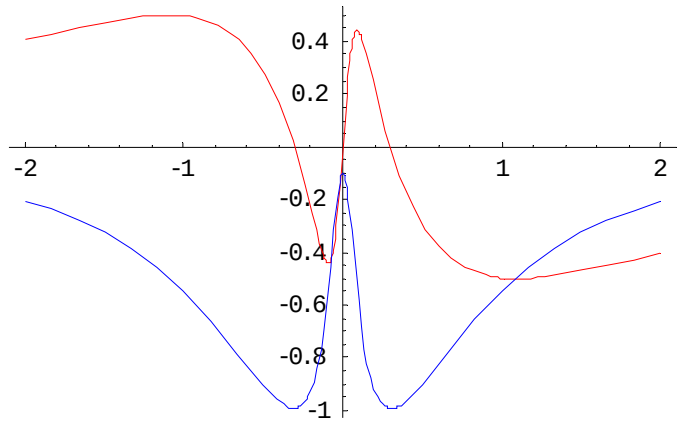




Probe frequency

VOLUME 82, NUMBER 26 PHYSICAL REVIEW LETTERS 28 JUNE 1999

Ultraslow Group Velocity and Enhanced Nonlinear Optical Effects in a Coherently Driven Hot Atomic Gas

Michael M. Kash,[1,5] Vladimir A. Sautenkov,[1] Alexander S. Zibrov,[1,3] L. Hollberg,[3] George R. Welch,[1] Mikhail D. Lukin,[4] Yuri Rostovtsev,[1] Edward S. Fry,[1,2] and Marlan O. Scully[1,2]
[1]*Department of Physics, Texas A&M University, College Station, Texas 77843-4242*
[2]*Max-Planck-Institut für Quantenoptik, D-85748 Garching, Germany*
[3]*National Institute for Standards and Technology, Boulder, Colorado 80303*
[4]*ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138*
[5]*Department of Physics, Lake Forest College, Lake Forest, Illinois 60045*
(Received 7 April 1999)

We report the observation of small group velocities of order 90 m/s and large group delays of greater than 0.26 ms, in an optically dense hot rubidium gas (≈360 K). Media of this kind yield strong nonlinear interactions between very weak optical fields and very sharp spectral features. The result is in agreement with previous studies on nonlinear spectroscopy of dense coherent media. [S0031-9007(99)09488-0]

PACS numbers: 42.50.Gy, 42.55.–f, 42.65.Wi

Electromagnetically Induced Coherent Backscattering

Yuri V. Rostovtsev,[1] Zoe-Elizabeth Sariyanni,[1] and Marlan O. Scully[1,2,3]

[1]*Department of Physics and Institute for Quantum Studies, Texas A & M University, Texas 77843, USA*

[2]*Princeton Institute for the Science and Technology of Materials and Department of Mechanical & Aerospace Engineering, Princeton University, New Jersey 08544, USA*

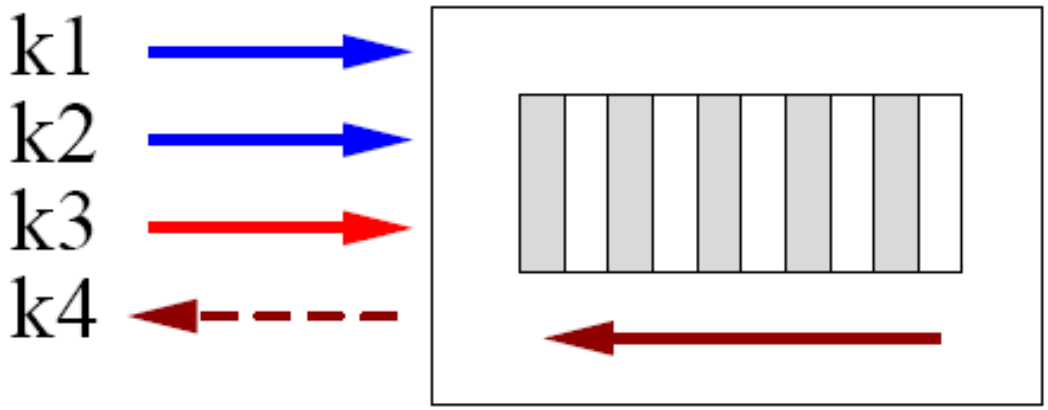
[3]*Max-Planck-Institute für Quantenoptik, D-85748 Garching, Germany*

(Received 17 November 2005; published 14 September 2006)

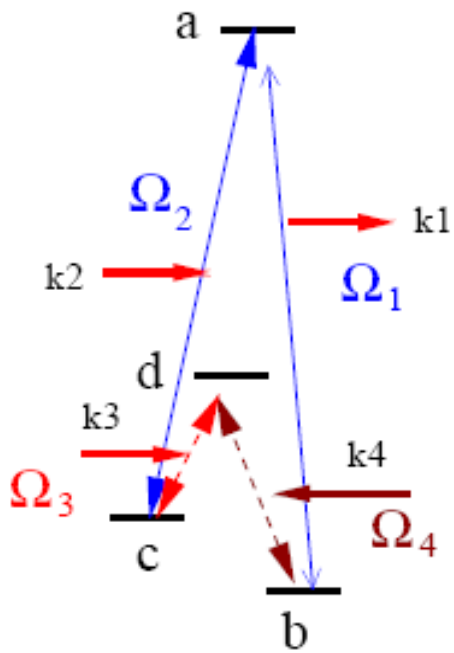
We demonstrate a strong coherent backward wave oscillation using forward propagating fields only. This is achieved by applying laser fields to an ultradispersive medium with proper chosen detunings to excite a molecular vibrational coherence that corresponds to a backward propagating wave. The physics then has much in common with the propagation of ultraslow light. Applications to coherent scattering and remote sensing are discussed.

DOI: 10.1103/PhysRevLett.97.113001 PACS numbers: 32.80.Qk, 42.50.Hz, 42.65.Dr

Coherent scattering



$$k_1 - k_2 + k_3 = k_4$$



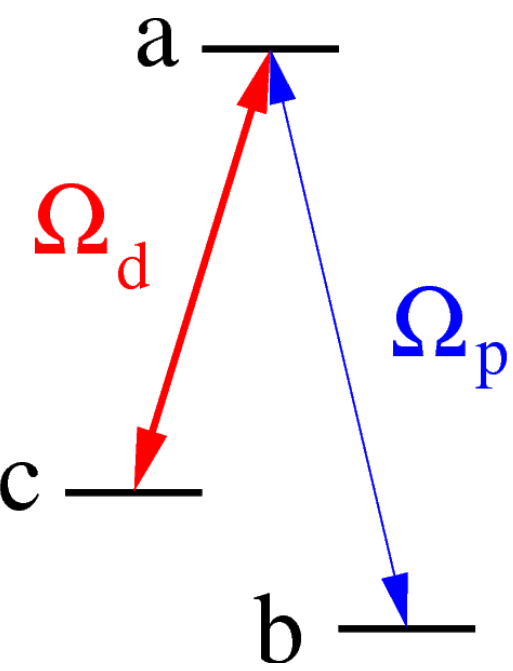
The coherent space grating is determined by

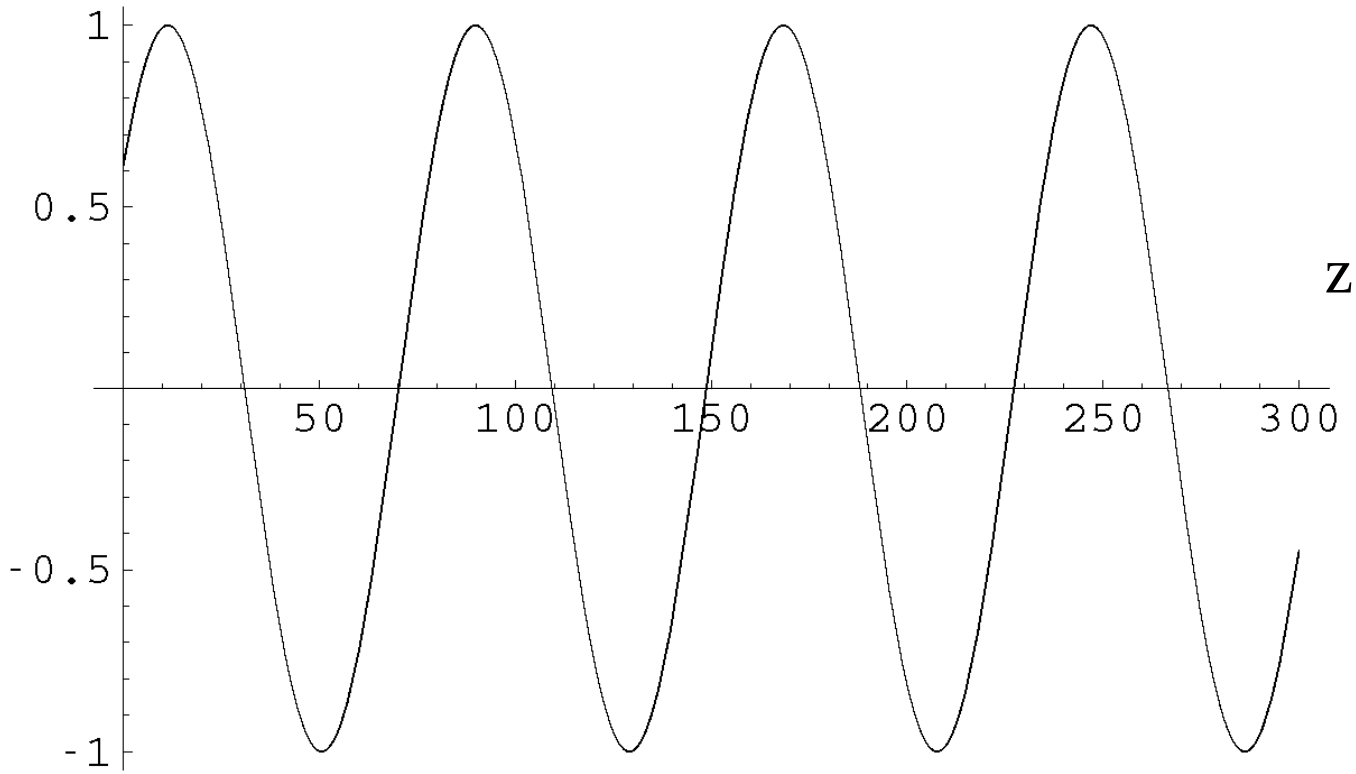
$$\rho_{cb} = -\frac{\Omega_1 \Omega_2^*}{|\Omega_1|^2 + |\Omega_2|^2} e^{i\Delta k z}$$

where

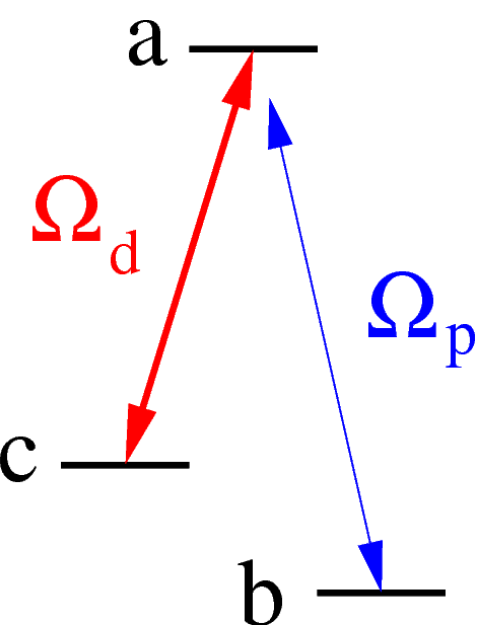
$$\Delta k = k_1 - k_2 = \frac{\omega_{cb}}{c} + \frac{\nu_1 - \omega_{ab}}{V_g}$$

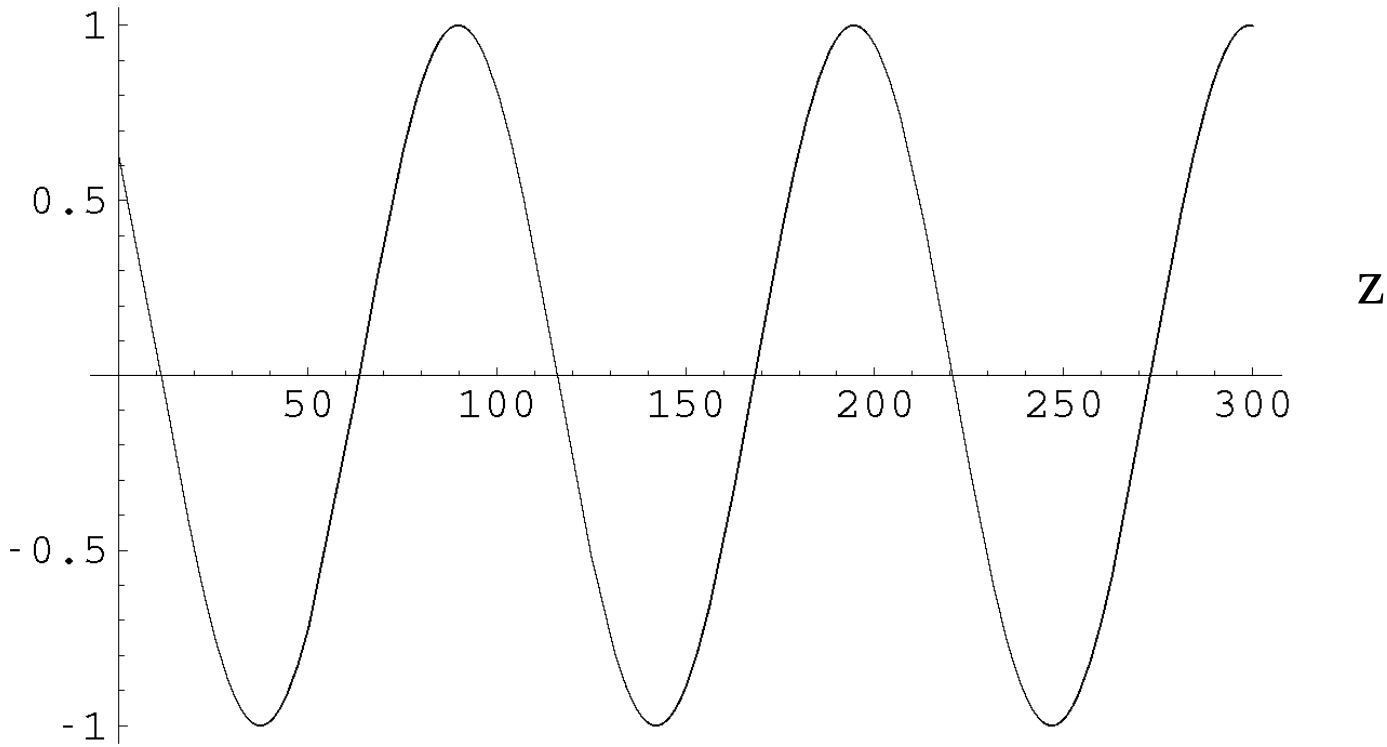
Polarization of b-c transition at the two-photon resonance

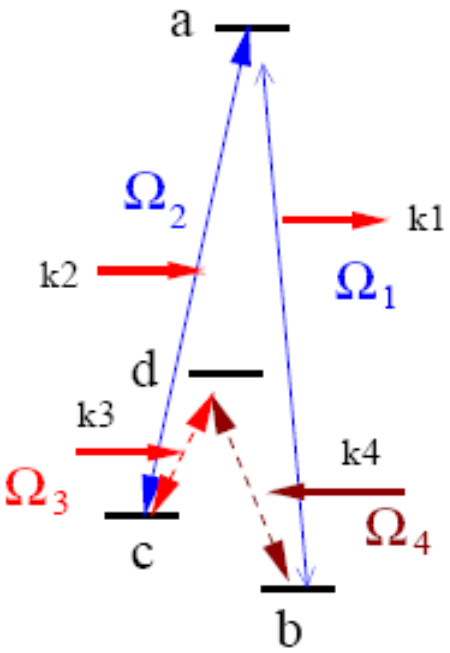




Polarization of b-c transition off the two-photon resonance







Estimation

Density is given by

$$N = \frac{16k_4}{3\lambda^2}\left(\frac{|\Omega_2|^2}{\gamma_r|\delta\nu|}\right) \simeq \frac{16k_4}{3\lambda^2}$$

NO (a resonant transition at 236 nm, $A^2\Sigma^+ - X^2\Pi$), vibration frequency of 1900 cm^{-1}, 5.26 μm

$$N_{NO} = 8 \cdot 10^{15}\ \mathrm{cm}^{-3}$$

NO_2 (a resonant transition at wavelength 337 nm, vibrational frequency of 750 cm^{-1}, 13.3 μm)

$$N_{NO2} = 1.4 \cdot 10^{15}\ \mathrm{cm}^{-3}$$

For transition between rotational levels $\simeq 10\ \mathrm{cm}^{-1}$,
the required molecular density of NO and NO_2 molecules is $N \simeq 1.2 \cdot 10^{13}\ \mathrm{cm}^{-3}$

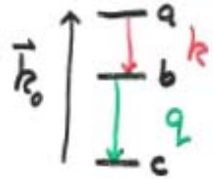
Directed Spontaneous Emission from an Extended Ensemble of N Atoms

Edward Fry
Anil Patnaik
Anatoly Svidzinsky
Suhail Zubairy

Texas A&M and Princeton

Phase Matched Down Conver.

@ One Photon → Two Photons



$$|\Psi\rangle = \sum_{\vec{k}\vec{q}} C_{\vec{k}\vec{q}} |\vec{k}\vec{q}\rangle$$

$$C_{\vec{k}\vec{q}} = \sum_j \frac{\gamma_{ab}^{(k)} \gamma_{bc}^{(q)} \; e^{-i(\vec{k}+\vec{q}-\vec{k}_0)\cdot\vec{r}_j}}{(\nu_k + \nu_q - \omega_{ac} + i\gamma)(\nu_q - \omega_{bc} + i\Gamma)}$$

$$\Rightarrow \delta(\vec{k} + \vec{q} - \vec{k}_0)$$

Dir. of $\vec{k}$ and $\vec{q}$ Photons

Automatically Phase Matched

(PRL Jan '06)

Directed Spontaneous Emission from an Extended Ensemble of N Atoms: Timing Is Everything

Marlan O. Scully,[1,2,3] Edward S. Fry,[1,2] C. H. Raymond Ooi,[1,2,3] and Krzysztof Wódkiewicz[4]

[1]*Max-Planck-Institut für Quantenoptik, D-85748, Garching, Germany*

[2]*Institute for Quantum Studies, Texas A&M University, College Station, Texas 77843-4242, USA*

[3]*Princeton Institute for the Science and Technology of Materials, Princeton University, New Jersey 08544-1009, USA*

[4]*Uniwersytet Warszawski, Hoża 69, PL-00-681 Warszawa, Poland*

(Received 12 September 2005; published 3 January 2006)

A collection of N static atoms is fixed in a crystal at a low temperature and prepared by a pulse of incident radiation of wave vector $\vec{k}_0$. The N atoms are well described by an entangled Dicke-like state, in which each atom carries a characteristic phase factor $\exp(i\vec{k}_0 \cdot \vec{r}_j)$, where $\vec{r}_j$ is the atomic position in the crystal. It is shown that a single photon absorbed by the N atoms will be followed by spontaneous emission in the same direction. Furthermore, phase matched emission is found when one photon is absorbed by N atoms followed by two-photon down-conversion.

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FIRST:

The Essence of the Problem

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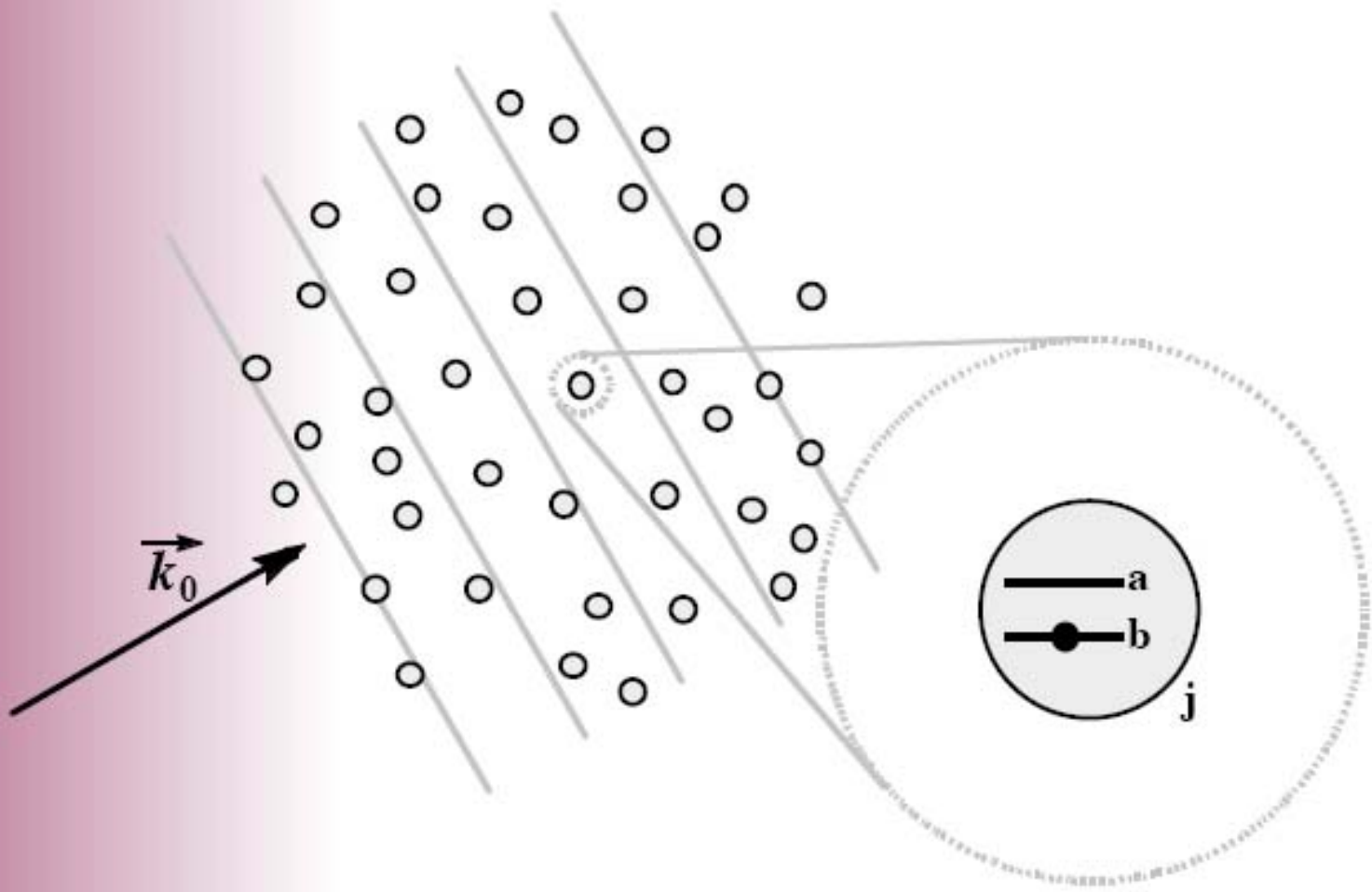
Consider an ensemble of two-level atoms,



and incident photons of wave vector $\vec{k}_0$.

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We prepare the state in which one photon of wavevector $\vec{k}_0$ is absorbed in the ensemble of two-level atoms.

The state is such that there is one and only one excited atom; we just do not know which one.

It is NOT a coherent superposition of atomic levels!

It is an ENTANGLED STATE.

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An important point, our entangled state,

$$\Psi_{\vec{k}_0 N} = \frac{1}{\sqrt{N}} \sum_j e^{i\vec{k}_0 \cdot \vec{r}_j} \left| b_1, b_2, \ldots, a_j, \ldots, b_N \right\rangle |0\rangle$$

is quite different from the state produced by a beam of photons passing through (and interacting weakly) with an ensemble of atoms:

$$\Psi_{\vec{k}_0 A} = \alpha \left| b_1, b_2, \ldots, b_N \right\rangle |0\rangle + \sum_j \beta_j \left| b_1, b_2, \ldots, a_j, \ldots, b_N \right\rangle |0\rangle + \ \ldots$$

This state involves a superposition of levels with contributions of a small dipole moment from each atom. It will lead to directional emission.

The excited atom will then spontaneously decay, emitting a photon.

Will the emitted photon go into 4π sr?

Or, will it be directionally correlated with $\vec{k}_0$?

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In their classic paper, Eberly and Rehler say:

"We emphasize that all our results have been derived by assuming that the plane-wave excitation pulse leaves each atom with a finite dipole moment. It is the relative phases of these dipole moments which fixes the direction of the single prominent "spike" of the far-field radiation pattern. If all the dipole moments are zero . . . , there is no preferred direction which is imposed by the excitation pulse."

In our entangled case, the dipole moments are ZERO, and the emission is directional, $\vec{k}_0$.

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How does one produce this special entangled state?

$$\Psi_{\vec{k}_0 N} = \frac{1}{\sqrt{N}} \sum_j e^{i\vec{k}_0 \cdot \vec{r}_j} \left| b_1, b_2, \ldots, a_j, \ldots, b_N \right\rangle$$

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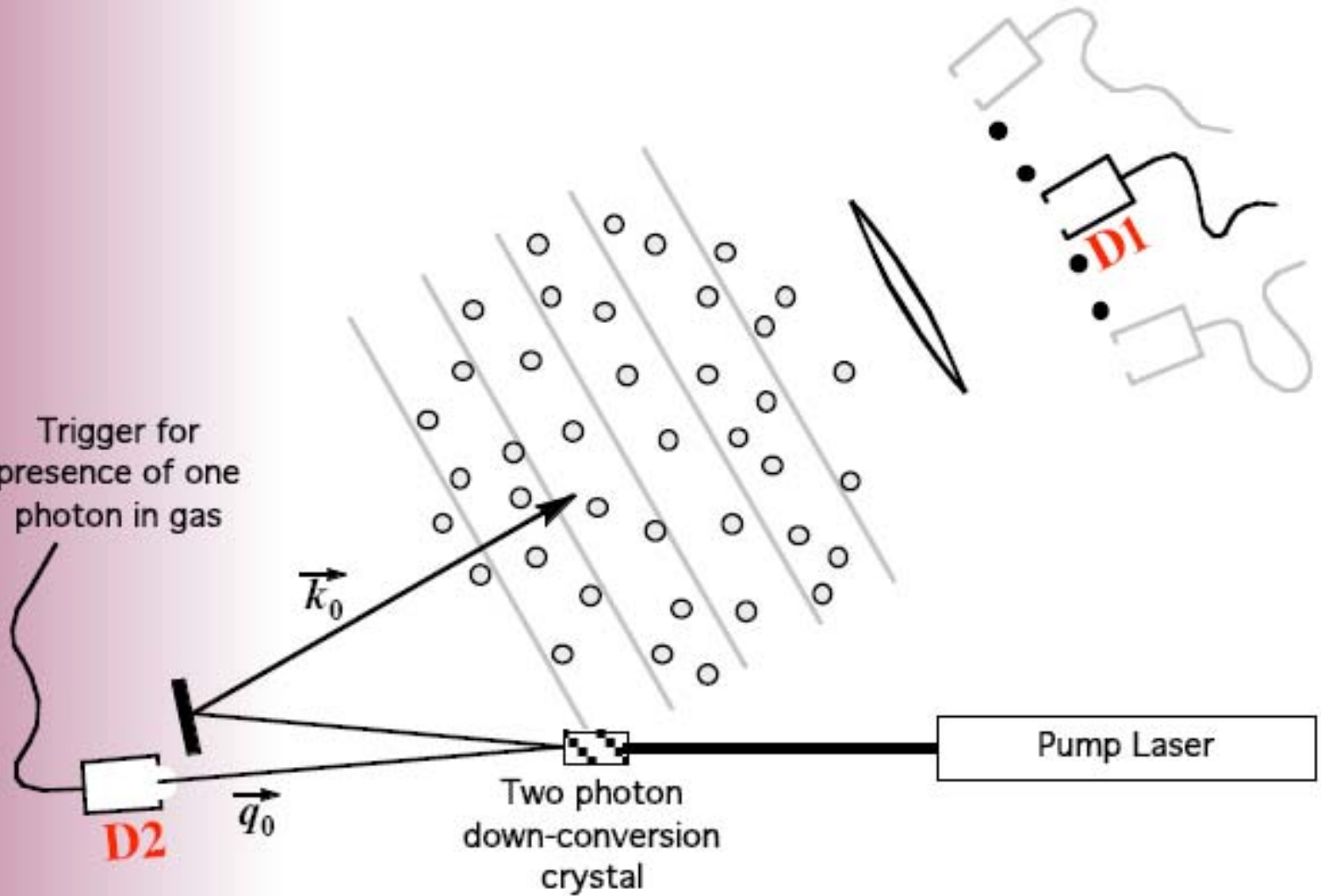

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Given a count in D2, the absence of an immediate count in D1 ensures that one photon has been absorbed and that this special entangled state has been created.

Directional emission is observed via the appearance of a delayed count in D1 that is correlated with the count in D2.

It is a correlation measurement.

This is very different from the simple intensity measurement with a weakly interacting photon beam.

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Finally, let's explicitly consider the spontaneous decay of the normalized N-atom entangled state,

$$\Psi_{\vec{k}_0 N}=\frac{1}{\sqrt{N}}\sum_j e^{i\vec{k}_0\cdot\vec{r}_j}\left|b_1,\ldots,a_j,\ldots,b_N\right\rangle|0\rangle$$

The interaction Hamiltonian for spontaneous emission is

$$W(t)=\hbar\sum_{j,\vec{k}} g_{\vec{k}}\left|b_j\right\rangle\left\langle a_j\right|\hat{a}^{\dagger}_{\vec{k}}\, e^{-i\vec{k}\cdot\vec{r}_j}\, e^{-i(\nu_{\vec{k}}-\omega)t}+\text{adj.}$$

Take $\nu_{\vec{k}}\approx\omega$, then the final state is of the form

$$C\left|b_1,\ldots,b_N\right\rangle\sum_{\vec{k}} g_{\vec{k}}\left|1_{\vec{k}}\right\rangle\sum_j e^{i(\vec{k}_0-\vec{k})\cdot\vec{r}_j}$$

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The last factor provides the directionality information

$$\sum_j e^{i(\vec{k}_0-\vec{k})\cdot\vec{r}_j} \approx \frac{N}{V}\iiint_V d^3r\, e^{i(\vec{k}_0-\vec{k})\cdot\vec{r}}$$

$$= \frac{8\pi^3 N}{V}\,\delta^3(\vec{k}_0-\vec{k})$$

The spontaneously emitted photon ($\vec{k}$) has the same direction as the absorbed photon ($\vec{k}_0$)

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THE INITIAL END!

Dear Marlan,

I think that your letter on directional spontaneous emission from an entangled initial state is really great. When I first saw the paper, my first reaction was that this had to be wrong, but I redid the calculation and sure enough, ... you are right. I then tried to see if Doppler broadening will destroy the effect, but unless I made a mistake in the calculation, it doesn't - anyway, I love it.

Best regards

Pierre

Dear Olga and Vitaly,

I have received a call from Munich TU group. They asked me with the proper remarks to have a look on a paper of Marlan in PRL 96,010501 (2006). I was really shocked. The main result of this paper: " a single photon absorbed by the N atoms [in a crystal] will be followed by spontaneous emission in the same direction" was published by me many years ago (see Soviet Phys. JETP 23,178 (1966). Moreover, this result is reproduced in my late review-paper " Theory of coherent phenomena and fundamentals in nuclear resonant scattering " (see Hyperfine Interaction 123/124, 83 (1999)) that I am sure you have seen. The important conclusion that follows this result in our papers was the prediction of the disappearance (suppression) of the resonance level width (gamma) in a crystal. In this connection the formal expressions in Marlan paper are simply not correct.

All the best,

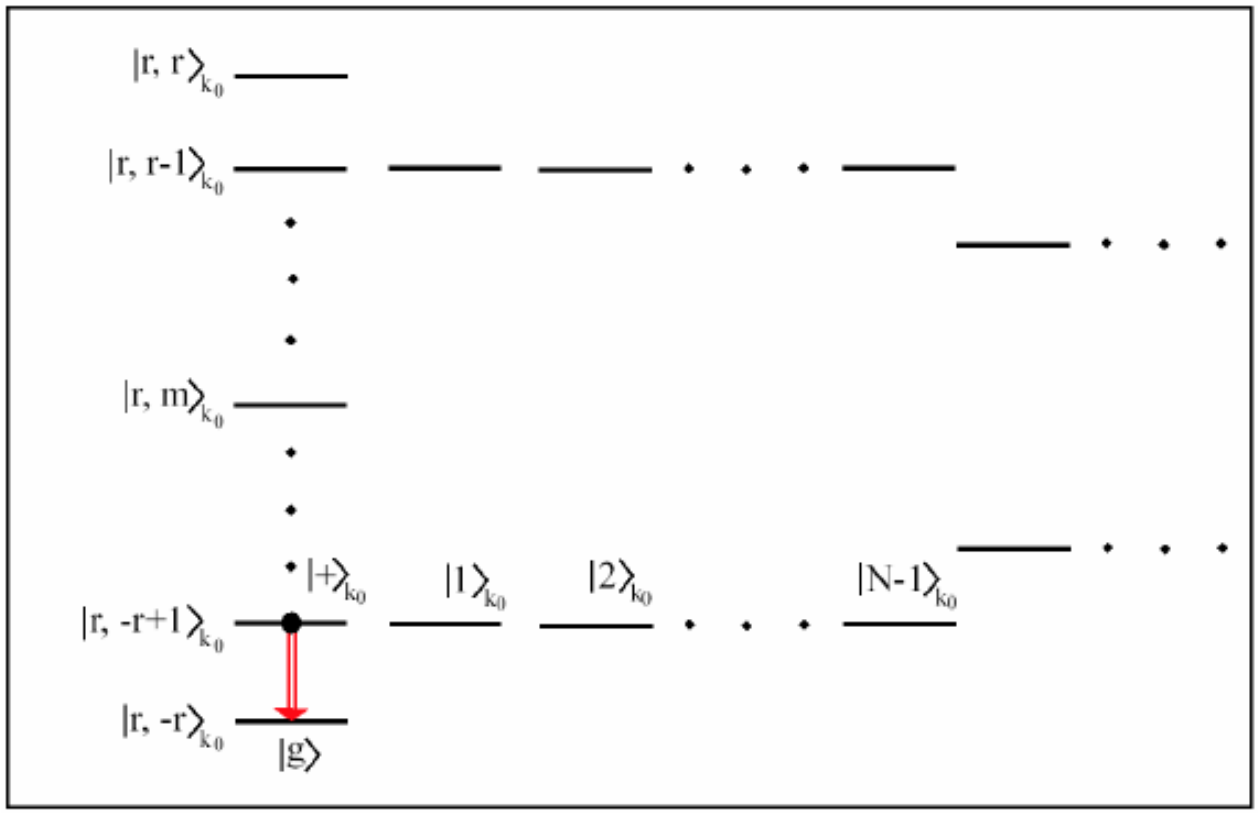
Yuri

Correlated Spontaneous Emission

Marlan O. Scully
Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, D-85748 Garching, Germany
Institute for Quantum Studies and Dept. of Physics, Texas A&M Univ., Texas 77843 and
Applied Physics and Materials Science Group, Eng. Quad., Princeton Univ., Princeton 08544
(Dated: September 14, 2006)

In a recent paper [1], it is shown that a single photon absorbed by N atoms will be followed by spontaneous emission in the same direction. This paper stimulated vigorous debate. For example, Y. Kagan states that in his analysis of this problem: "The important conclusion that follows this result in our papers was the prediction of the disappearance (suppression) of the resonance level width (gamma) in crystal. In this connection the formal expression in [1] are simply not correct." In the present paper, it is shown that the results of [1] are correct.

[1] *Phys. Rev. Lett.* **96**, 010501 (2006).



$$|g\rangle_{k_0} = |\downarrow\downarrow \ldots \downarrow\rangle$$

$$|+\rangle_{k_0} = \frac{1}{\sqrt{N}}\left[\sum_j |\downarrow\downarrow \ldots \uparrow_j \ldots \downarrow\rangle e^{i\vec{k}_0\cdot\vec{r}_j}\right]$$

$$|N-1\rangle_{k_0} = \frac{1}{\sqrt{N(N-1)}}\left[|\uparrow\downarrow \ldots \downarrow\rangle e^{i\vec{k}_0\cdot\vec{r}_1} + |\downarrow\uparrow \ldots \downarrow\rangle e^{i\vec{k}_0\cdot\vec{r}_2} + \cdots - (N-1)|\downarrow\downarrow \ldots \uparrow_N\rangle e^{i\vec{k}_0\cdot\vec{r}_N}\right]$$