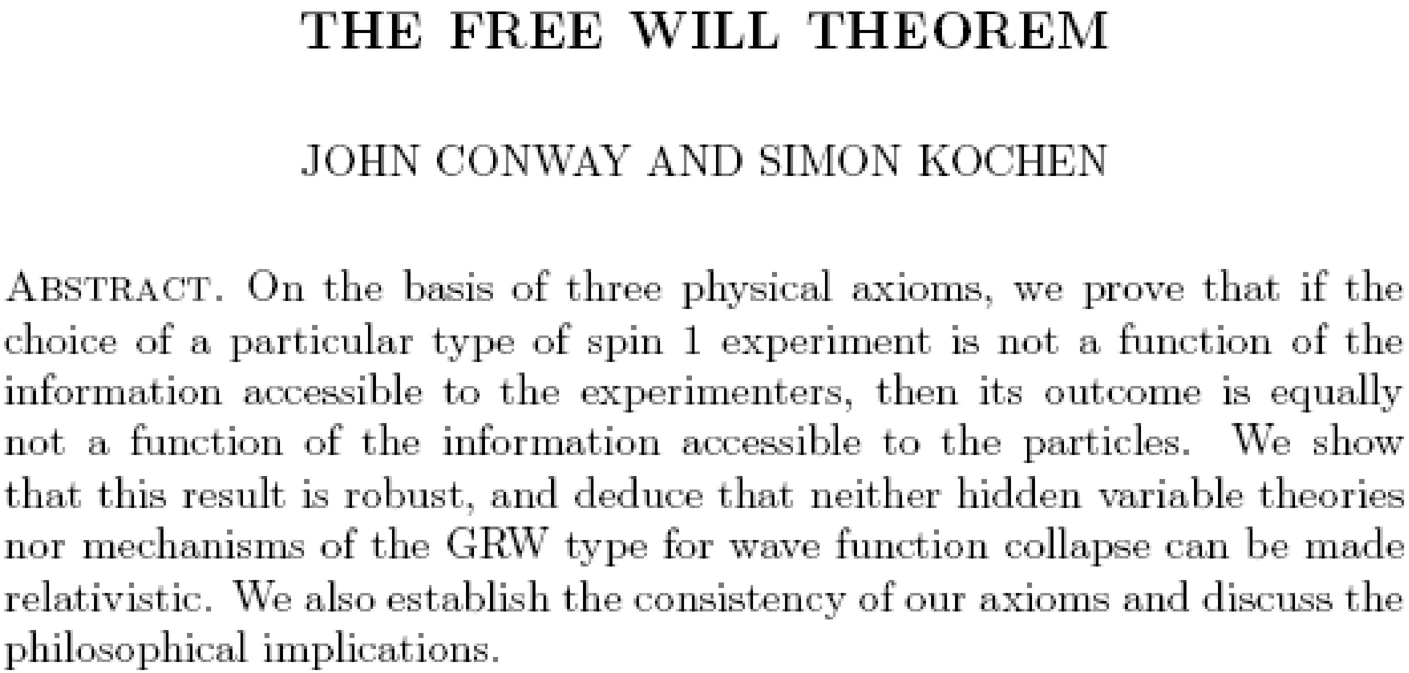
Non-dispersive optics using storage of light

Greg Dmochowski

~~March 24, 2010~~

March 31, 2010

My first choice



THE FREE WILL THEOREM

JOHN CONWAY AND SIMON KOCHEN

ABSTRACT. On the basis of three physical axioms, we prove that if the choice of a particular type of spin 1 experiment is not a function of the information accessible to the experimenters, then its outcome is equally not a function of the information accessible to the particles. We show that this result is robust, and deduce that neither hidden variable theories nor mechanisms of the GRW type for wave function collapse can be made relativistic. We also establish the consistency of our axioms and discuss the philosophical implications.

Non-dispersive optics using storage of light

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Abstract

We demonstrate the non-dispersive deflection of an optical beam in a Stern-Gerlach magnetic field. An optical pulse is initially stored as a spin-wave coherence in thermal rubidium vapour. An inhomogeneous magnetic field imprints a phase gradient onto the spin wave, which upon reacceleration of the optical pulse leads to an angular deflection of the retrieved beam. We show that the obtained beam deflection is non-dispersive, i.e. its magnitude is independent of the incident optical frequency. Compared to a Stern-Gerlach experiment carried out with propagating light under the conditions of electromagnetically induced transparency, the estimated suppression of the chromatic aberration reaches 10 orders of magnitude.

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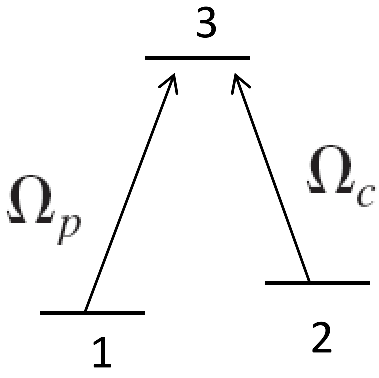
Ingredients

- (quick) EIT review
  - Slow light and stored light
- Theory behind experiment
  - Magnetic moment of slow light
- Experimental results
- Griping?

Electromagnetically-induced transparency

- A quantum interference effect:
  - Destructive interference of transition amplitudes suppresses absorption
  - i.e. an otherwise opaque medium is rendered transparent
- Brings with it a significant reduction of group velocity (*via* Kramers Kronig relations), which has allowed for ‘slow light’ and ‘stored light’.



$$\tan\theta = \frac{\Omega_p}{\Omega_c},$$

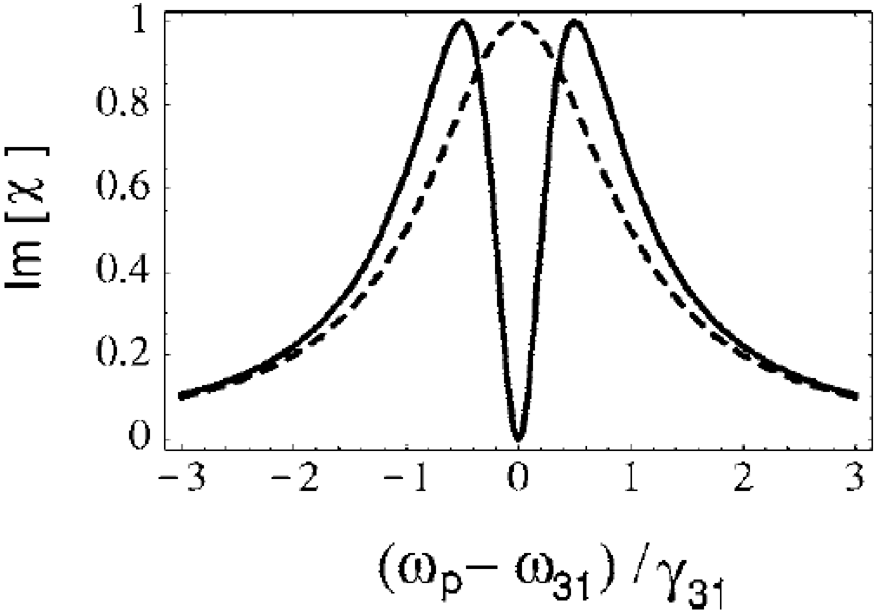
$$\tan 2\phi = \frac{\sqrt{\Omega_p^2 + \Omega_c^2}}{\Delta}.$$

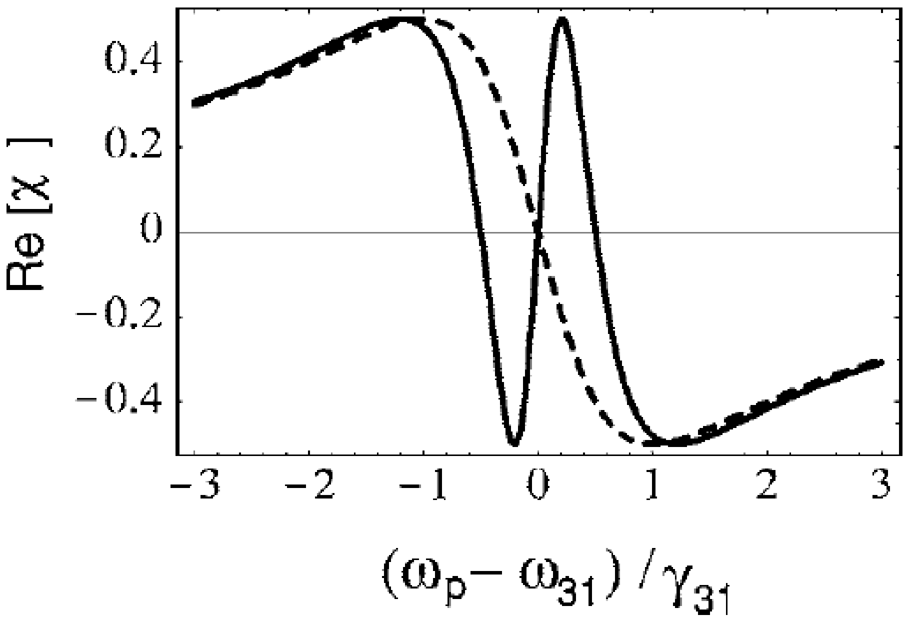
$$|a^+\rangle = \sin\theta\sin\phi|1\rangle + \cos\phi|3\rangle + \cos\theta\sin\phi|2\rangle,$$

$$|a^0\rangle = \cos\theta|1\rangle - \sin\theta|2\rangle,$$

$$|a^-\rangle = \sin\theta\cos\phi|1\rangle - \sin\phi|3\rangle + \cos\theta\cos\phi|2\rangle.$$

Kramer and his Kronies

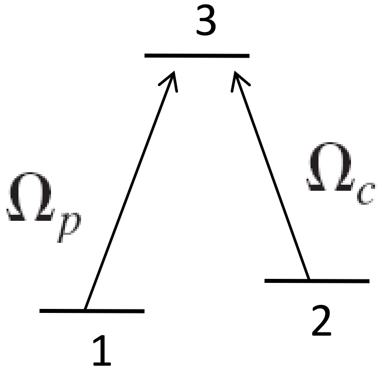


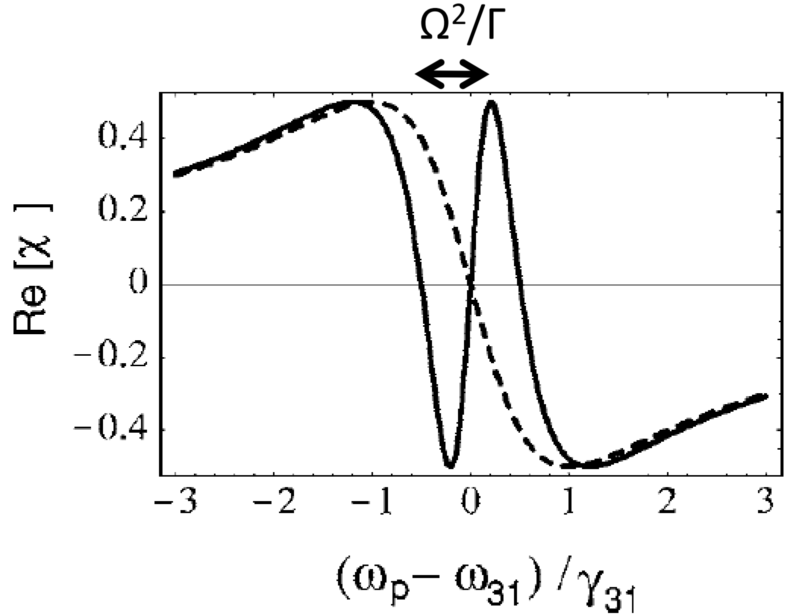


$$\begin{aligned} v_g &= \frac{\partial \omega}{\partial k} \\ &= \frac{c}{n + \omega \frac{\partial n}{\partial \omega}} \end{aligned}$$

Storing light

- 'Standard' way to store light:
  - Adiabatically reduce control beam power to zero
  - This first slows down signal beam and then coherently stores it as 'spin-wave' coherence in the atomic medium





$$|a^0\rangle = \cos\,\theta|1\rangle - \sin\,\theta|2\rangle$$

Magnetic moment of slow light

LETTERS

A Stern–Gerlach experiment for slow light

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Slow light has been spatially deflected by Stern-Gerlach (SG) magnetic field

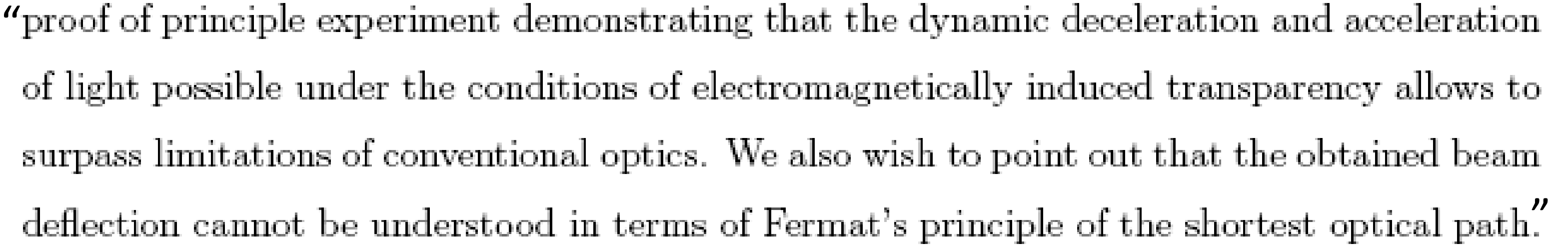
- i.e. Slow light (“dark polariton”) has some effective magnetic moment!
- This, however, is very dispersive

L. Karpa and M. Weitz, Nature Physics Letters **2**, 332 (2006).

Non-dispersive deflection of slow light

Here, they ‘demonstrate non-dispersive’ deflection of optical beam traveling in EIT medium:

1. Store light pulse as a ‘spin-wave’ in thermal Rb vapour
2. Impose phase gradient by SG field
3. Reaccelerate pulse and (part of) its deflection is found to be non-dispersive



“proof of principle experiment demonstrating that the dynamic deceleration and acceleration of light possible under the conditions of electromagnetically induced transparency allows to surpass limitations of conventional optics. We also wish to point out that the obtained beam deflection cannot be understood in terms of Fermat’s principle of the shortest optical path.”

Deflection angles

$$\boxed{\alpha_{tot} = \alpha_{store} + \alpha_{move}}$$

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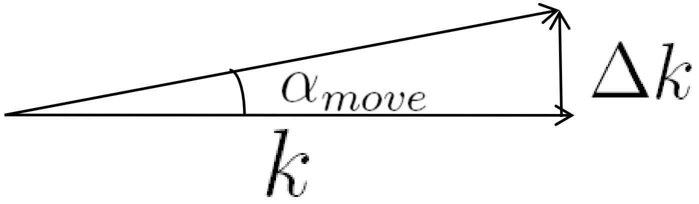
1. α$_{move}$

$$\alpha_{move} \cong \frac{\Delta k}{k}$$



$$\Delta k = \frac{1}{\hbar} \int_0^{L/v_g} F_{SG} dt \quad \left\{ \begin{array}{l} F_{SG} = \mu_{pol} \left(\frac{dB_z}{dx} \right) \\ \mu_{pol} \cong 2 g_F \mu_B \quad v_g \ll c \end{array} \right.$$

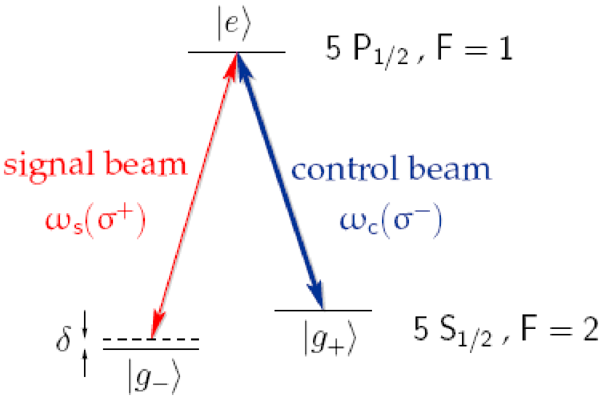
Therefore:

$$\boxed{\alpha_{move} \cong \left(\frac{dB_z}{dx} \right) \frac{2 g_F \mu_B \lambda L}{h v_g}}$$

Dispersive!

Spatially varying magnetic field

$|g_-\rangle$ and $|g_+\rangle$ correspond to $m_F = -2$ and $m_F = 0$



Zeeman splitting:

$$\Delta E(x) = 2 g_F \mu_B B_z(x)$$

Accumulated phase:

$$\Delta\varphi(x) = \frac{1}{\hbar}\int_0^{\tau} \Delta E(x)\,dt$$

Optical path length variation:

$$\Delta s(x) = \lambda \Delta\varphi(x)$$

Deflection angles

$$\boxed{\alpha_{tot} = \alpha_{store} + \alpha_{move}}$$

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2. α_{store}

- For constant field gradient:

$$\Delta\varphi(x) = 2g_F\mu_B\left(\frac{dB_z}{dx}\right)x\tau/\hbar \cong \alpha_{store}kx$$

- Therefore, angle deflection 'accumulated' over storage time, τ:

$$\boxed{\alpha_{store} = \left(\frac{dB_z}{dx}\right)\frac{2g_F\mu_B\lambda\tau}{h}}$$

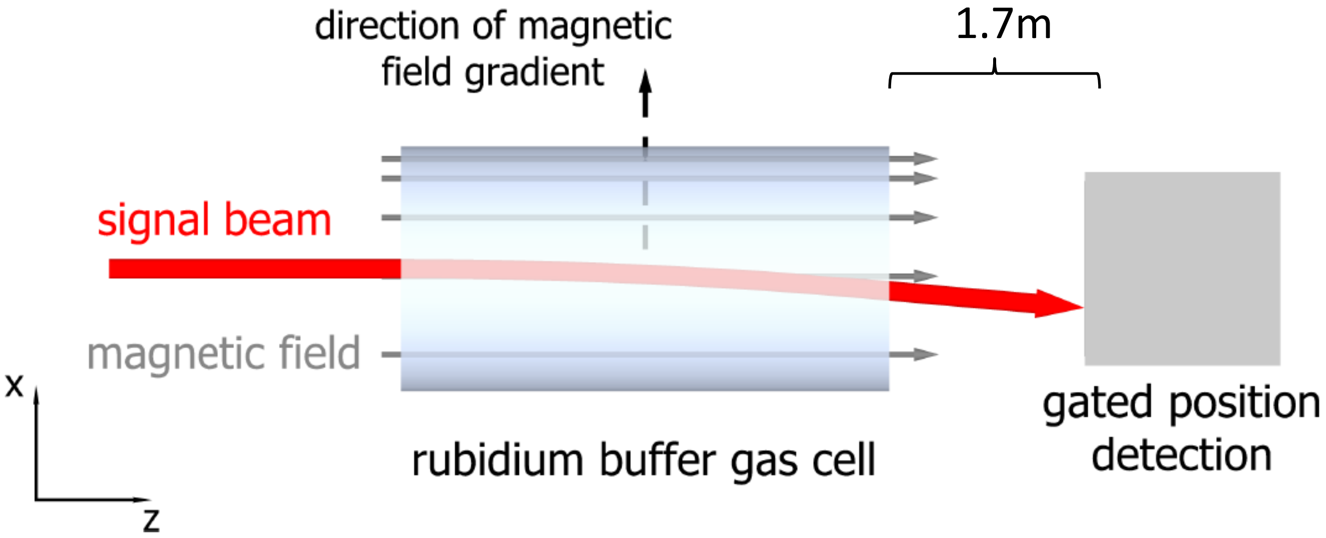
Comparison of deflection angles

> “It is instructive to compare the variations of the deflection angle in the incident optical frequency. Whereas the variation of the deflection angle acquired during the stored light phase resembles that of an optical grating and is as low as $\frac{\Delta\nu}{\nu} \cong 10^{-10}$ in the spectrally narrow transmission width of an EIT resonance, e.g. $\Delta\nu \cong 20$ kHz in our experiment. In contrast, the optical group velocity varies by a factor of order unity over the spectral width of the dark resonance, so that the chromatic aberration of the Stern-Gerlach deflection of stored light is suppressed with respect to that acquired in the propagating light phase by an expected factor $\frac{\Delta\nu}{\nu}$, i.e. ten orders of magnitude!”

$$\alpha_{store} = \left(\frac{dB_z}{dx}\right)\frac{2g_F\mu_B\lambda\tau}{h}$$

$$\alpha_{move} \cong \left(\frac{dB_z}{dx}\right)\frac{2g_F\mu_B\lambda L}{hv_g}$$

Experiment



direction of magnetic field gradient

1.7m

signal beam

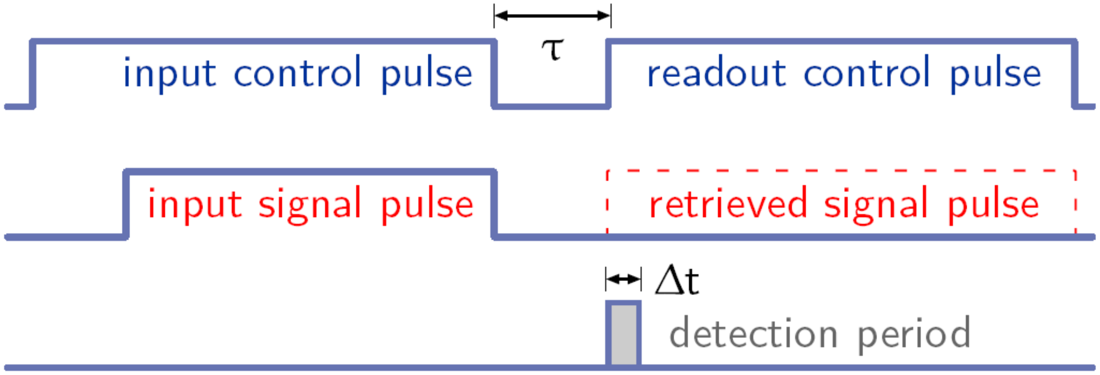
magnetic field

x

z

rubidium buffer gas cell

gated position detection



τ

input control pulse

readout control pulse

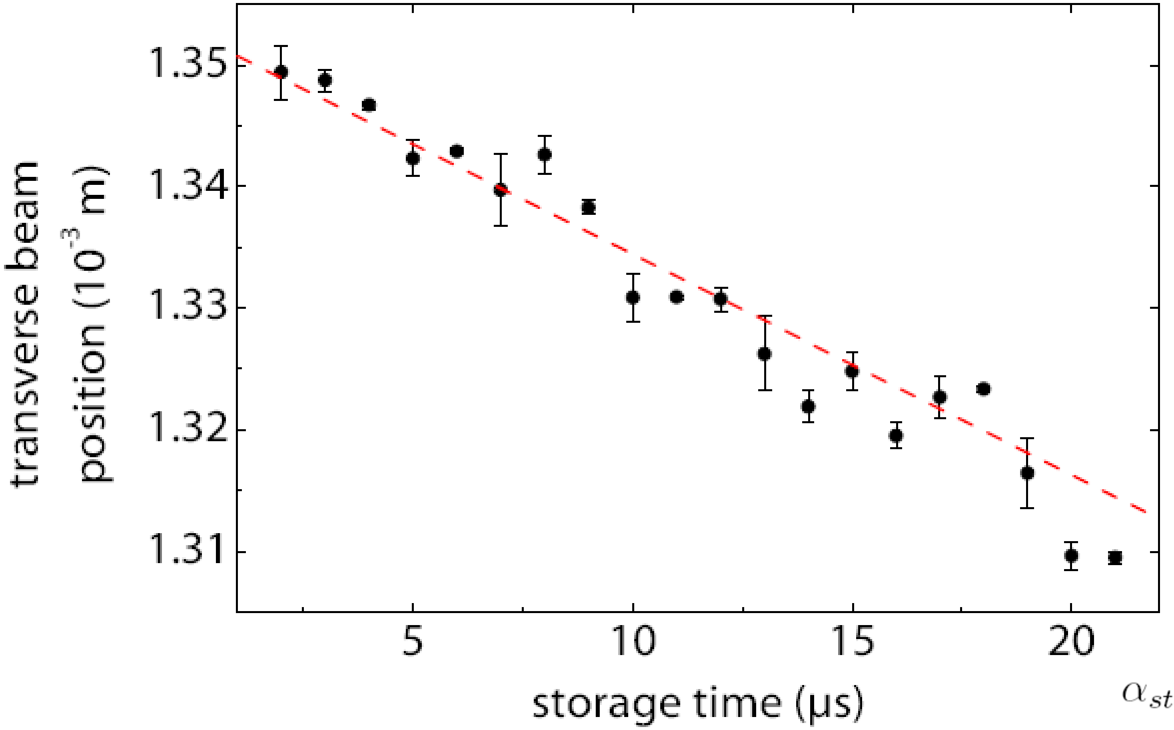
input signal pulse

retrieved signal pulse

Δt

detection period

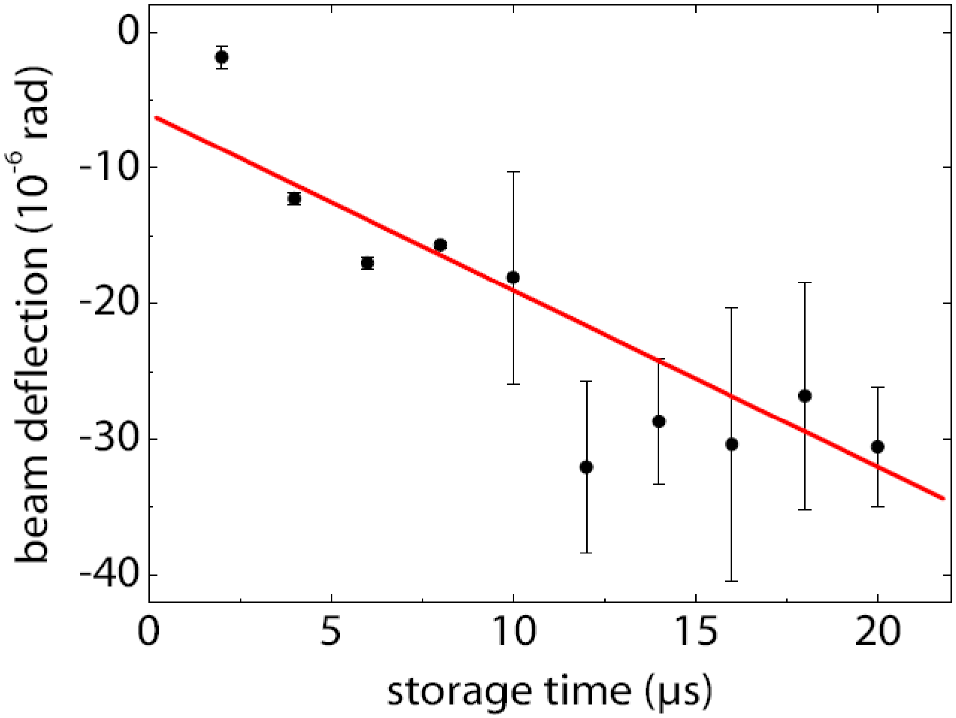
Transverse position versus storage time



$$\alpha_{store} = \left(\frac{dB_z}{dx}\right)\frac{2g_F\mu_B\lambda\tau}{h}$$

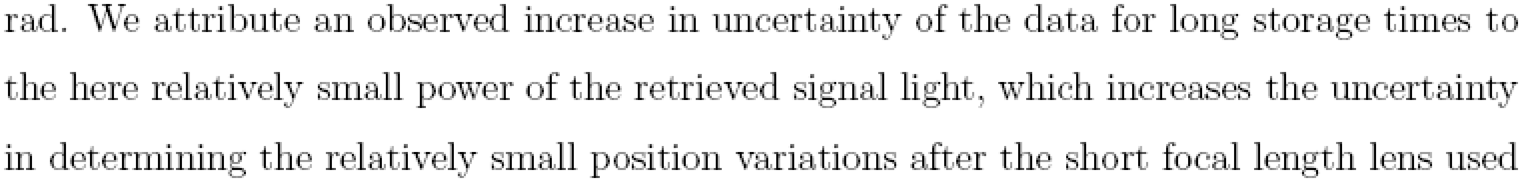
FIG. 3: Measured signal beam position after retrieval as a function of the storage time. The data points were recorded with a two-photon detuning of $\delta \cong 0$ in the beam center. The points give the average position values determined in four measurement sessions, each acquiring the average of the results of 100 subsequent position measurements. The shown error bars were determined from the standard deviation of the results of the independent sessions. The data points have been fitted with a linear function, as shown by the dashed red line.

Beam deflection angle vs. storage time

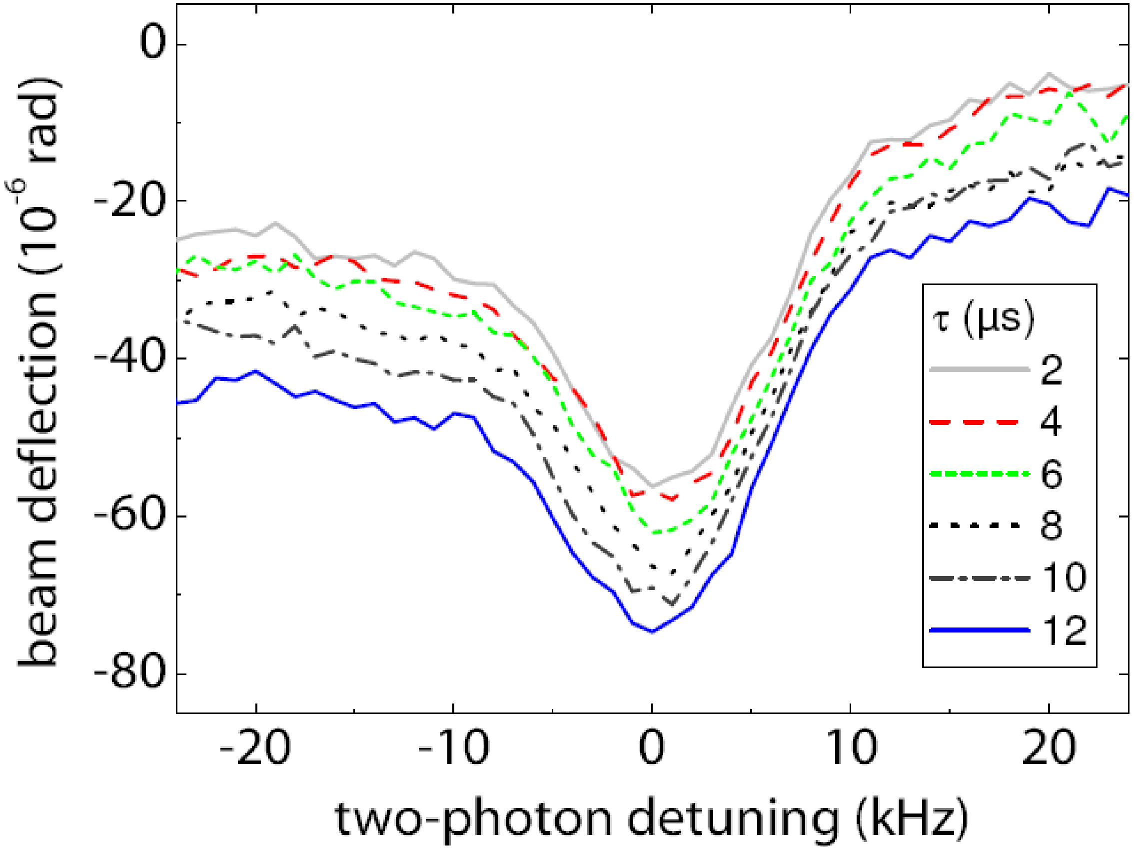


Experimental: (1.30 ± 0.09) rad/s

Theoretical: (1.35 ± 0.08) rad/s


rad. We attribute an observed increase in uncertainty of the data for long storage times to the here relatively small power of the retrieved signal light, which increases the uncertainty in determining the relatively small position variations after the short focal length lens used

“Principal experimental result”



Conclusions

- Slow light ‘dark polariton’ has an effective magnetic moment
  - i.e. Slow light can be deflected stern-gerlach style
- There are two contributions to this deflection:
  - The deflection attributed to propagation is highly dispersive
  - Deflection attributed to ‘stored’ light appears non-dispersive
- But can you have the latter without the former?!

“Principle experimental result”

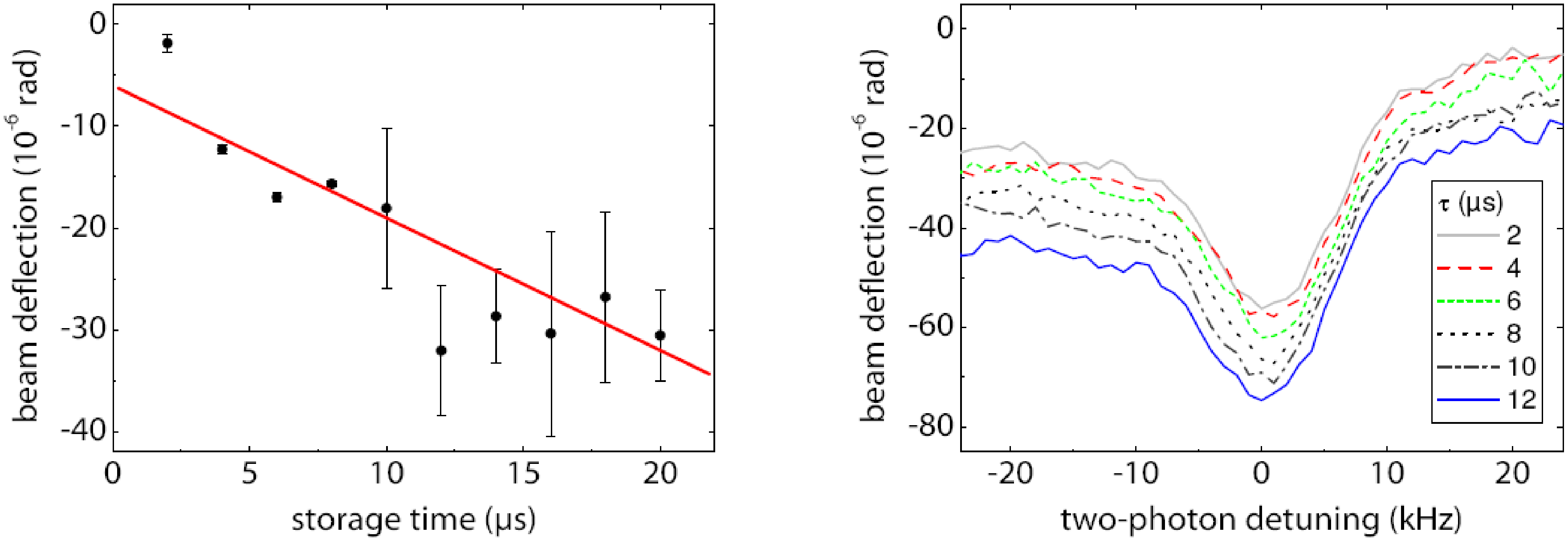


FIG. 4: **(a)** Relative signal beam angle deflection for different values of the light storage duration for the case of a two-photon detuning $\delta \cong 0$. The data has been shifted by the offset deflection acquired during the (non-stationary) phases of slow propagation to account solely for the deflection during the storage period. **(b)** Deflection of the retrieved signal beam versus the two-photon detuning for different values of the storage duration.