allows McGuyer and co-workers to probe inherent molecular phenomena that increase the linewidth of subradiant transitions to finite values. The authors relate these perturbations to two effects: radiative decay via the higher-order magnetic dipole and electric quadrupole transitions, and non-radiative decay via non-adiabatic Coriolis mixing towards the $^1S_0 + {}^3P_0$ lower-lying continuum. They theoretically account for the respective contributions of these two effects and find satisfying agreement with experiment. Interestingly, they also demonstrate coherent manipulation of subradiant states by inducing Rabi oscillations.

All in all, the demonstration of the tremendous precision achievable by spectroscopy of ultracold molecules promises a wealth of future measurements exploiting the complex structure of these systems. Foreseeable applications range from benchmarking of *ab initio* quantum chemistry calculations, to testing for variation of fundamental constants[8]. ❐

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TEN YEARS OF NATURE PHYSICS

Slowly but surely

In 2006, *Nature Physics* published a paper reporting a Stern–Gerlach effect for dark polaritons and one revealing the existence of slow-light solitons. Both of these papers have significantly advanced the field of slow-light research.

Ebrahim Karimi and Robert W. Boyd

Slow-light research[1] explores ways of dramatically slowing down the speed of light pulses travelling through an optical medium. Two papers published in *Nature Physics* in 2006 significantly advanced this field, revealing unexpected effects. Leon Karpa and Martin Weizt reported the observation of a Stern–Gerlach effect for dark polaritons propagating through a rubidium vapour under slow-light conditions created by electromagnetically induced transparency[2]. And Joe Mok and colleagues observed a slow-light optical soliton propagating in a shape-invariant manner through a nonlinear dispersive material[3].

The concept of velocity is well-defined for particles, but it is much murkier for waves. In fact, as a consequence of dispersion, a pulsed beam spreads and is distorted during propagation. Therefore, a unique value of the velocity cannot be assigned to a pulse propagating inside a material medium. This is due to the fact that a pulse comprises a superposition of an infinite number of monochromatic waves. These waves interfere either constructively or destructively in such a way that the beam is both spatially and temporally well localized.

When such a pulse traverses a dispersive medium, the relative phases among the various spectral components of the pulse change during propagation. Thus, it causes a change to the effects of destructive and constructive interference, consequently modifying the position (and shape) of the pulse compared with propagation in vacuum. The velocity with which a pulse moves though such a medium is often well described by the group velocity, which is dependent on a dispersive term that can be manipulated to slow the light pulse down to everyday human velocities. There are two ways to achieve this control[4]: by using the dispersive term in the group index of the material medium, or by exploiting structural resonances. The two *Nature Physics* publications[2,3] each report a different approach.

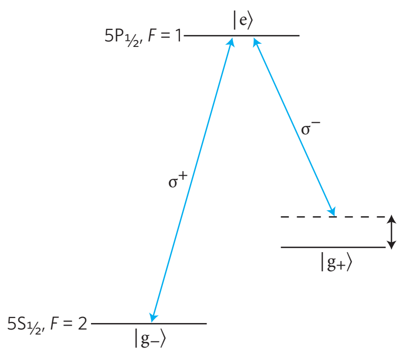

Figure 1 | Simplified rubidium energy-level diagram showing the conditions for establishing electromagnetically induced transparency and producing a strong slow-light effect. The destructive interference between the two pathways (defined by the polarization of the light; either σ^+ or σ^-) leading to the excitation of the upper level creates a dark polariton — a quasiparticle in which the photon and atomic excitation are strongly coupled. Because of the strong coupling, a photon acquires atomic-like properties, making a Stern–Gerlach effect possible. Reproduced from ref. 2.

In the original experiment by Stern and Gerlach, a beam of silver atoms passed through a region of non-uniform magnetic field. Each atom then experienced a force and, as the silver atoms had zero orbital angular momentum, the only contribution to the total angular momentum came from electron spin. This resulted in the beam of silver atoms splitting into two components, separated along the direction of the magnetic field gradient. In fact, the Stern–Gerlach experiment was later recognized as the first experimental demonstration of electron spin.

One would not expect photons to exhibit such an effect, because the photon does not possess a magnetic moment — as is the case for all particles with zero rest mass. However, under slow-light conditions, the photon is strongly coupled to the material medium. The experiment by Karpa and Weizt made use of the strong dispersion of atomic rubidium vapour under conditions of slow-light based on electromagnetically induced transparency[5,6] (Fig. 1).

Under these conditions, it helps to think of photons and atoms not as separate entities but rather as a coupled system in the form of a quasiparticle known as a dark polariton[7]. Such a quasiparticle can possess a magnetic moment through the properties of the rubidium atom. Karpa and Weizt[2] showed that in the slow-light regime the dark polariton acquired a magnetic moment with a value that depended on the hyperfine *g*-factor. The laser beam underwent a transverse deflection that could be understood as a Stern–Gerlach effect. They also showed that the transverse deflection increased with the inverse of the group velocity of the light — that is, the deflection increased with the amount of time an individual polariton spends within the slow-light medium.

The work by Karpa and Weizt[2] was significant for several reasons. Whereas much of the previous slow-light work was aimed at exploring propagation effects and maximizing the group index, Karpa and Weizt studied the subtle physics that can occur as a result of strong light–matter coupling under slow-light conditions. It served to confirm the theoretical predictions[7] regarding the properties of dark polaritons. And it foreshadowed more recent work demonstrating that exotic physics[8] can occur as a result of the strong interaction under slow-light conditions.

Later that same year, Mok *et al.*[3] showed that by introducing a third-order nonlinearity into a structured medium such as a fibre Bragg grating, one can suppress all dispersion terms[9,10]. A fibre Bragg grating is a modified optical fibre in which the refractive index of the core, *n*, varies periodically with position. This structure produces a cascade of Fabry–Pérot resonators that possesses a photonic bandgap, centred on the Bragg wavelength. In this situation, the forward and backward propagating waves are strongly coupled to one another. The transmission of a fibre Bragg grating is shown in Fig. 2. Wavelengths that fall inside and outside the bandgap region are reflected and transmitted, respectively, by the grating. In the case of transmitted wavelengths, however, the group velocity is modified such that it varies from zero at the edge of the photonic bandgap to c/n for wavelengths far from the bandgap, where c is the speed of light. The group velocity is strongly frequency dependent,

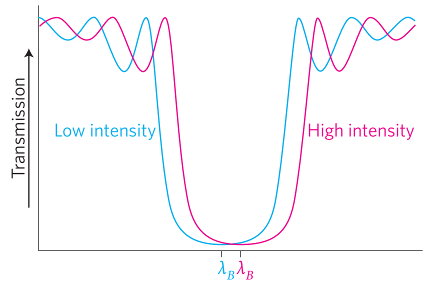

Figure 2 | Transmission spectrum of a fibre Bragg grating. The transmission drops to zero over a stop-band centred on the Bragg wavelength λ_B. Near the edge of the stop band, there is a strong slow-light effect related to the repeated back-and-forth scattering of light from the Bragg structure. However, the group velocity describing this effect is highly dispersive, which leads to a broadening and distortion of the transmitted light pulse. At high laser intensities, the spectrum shifts to longer wavelengths because of the nonlinear change in the refractive index of the material. This nonlinear change in the structure can compensate for the broadening and distortion of the pulse through the formation of an optical soliton. Reproduced from ref. 3.

and thus leads to significant distortion of the optical pulse. Therefore, the useful delay that a short pulse can experience is highly limited.

Mok *et al.*[3] were able to overcome the problem of pulse distortion by making use of pulses in the form of optical solitons. In an optical soliton, the tendency of a pulse to become distorted by the dispersion of the refractive index is exactly balanced by the nonlinear response of the medium. The nonlinear response leads to the refractive index of the material being intensity dependent — a dependency controlled by a coefficient describing its nonlinear response. As a result of this modification, both the Bragg wavelength and the bandgap shift to longer wavelengths for positive values of this coefficient and for high-intensity pulses. In other words, the light pulse adjusts the bandgap, and thus the previously reflected low-intensity pulses can be transmitted if their intensity is high enough.

A straightforward calculation shows that because the material dispersion of the fibre is much smaller than the structural dispersion of the grating, it does not play a significant role for relatively short propagation distances. Therefore, one can exclude the dispersion effect completely by the formation of a soliton. Mok *et al.*[3] were able to reduce the velocity of a sub-nanosecond intense laser pulse to 16% of the vacuum speed of light without introducing a significant change in the pulse shape. They also showed that the optical properties of the fibre Bragg grating could be adjusted by varying the mechanical strain on the grating. Thus, the desired control on both mechanical strain and pulse intensity enabled a tunable delay in pulse propagation, with important implications for pulse storage and communication with short pulses. ❒

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