Using a 'box model' of the global carbon and sulphur cycles, Gill *et al.*[1] also estimate that the ocean sulphate reservoir was then a small fraction of its current size. That perhaps explains why, compared with today, the sulphur-isotope system during the Cambrian seems to have been exceptionally sensitive to perturbations. However, there are inconsistencies here that require further attention. Despite the estimate of a small sulphate reservoir, the authors found puzzlingly high concentrations of sulphate in many of their rock samples, which remain to be explained. As Gill *et al.* point out, the sulphur-isotope trends and values also seem to differ between localities, suggesting that not all of the sulphur-isotope values are representative of the global ocean. Although spatial heterogeneity of $\delta^{34}S$ is a key prediction of a low-sulphate ocean, such variability makes the authors' size estimates for the marine sulphate reservoir uncertain.

Nevertheless, these new geochemical data[1] are remarkable, in that they pass all geochemical tests of Palmer's anoxia–extinction hypothesis. The distribution of ocean anoxia, and in particular the periodic expansion of toxic sulphide-rich waters, was possibly one key factor that determined how animals evolved on Earth. ■

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QUANTUM PHOTONICS

Entangled photons on a chip

Using photonic chips to control single photons in waveguides is a promising route to technologies based on the photons' quantum properties. The ability to measure entanglement on such chips is a key step in that direction.

MIRKO LOBINO & JEREMY L. O'BRIEN

The counterintuitive properties of quantum entanglement have been a topic of intense (meta)physical debate since the idea's inception at the start of the last century. Einstein famously thought that the "spooky action at a distance" arising from entanglement meant that the theory of quantum mechanics was incomplete; it has subsequently proved to be the most successful theory ever developed in terms of its predictive power. However, entanglement and other weird properties of quantum mechanics are not just a scientific curiosity. Researchers around the world are trying to harness them to gain unprecedented power and functionality in information processing, secure communication and precision measurement. Writing in *Physical Review Letters*, Sansoni *et al.*[1] demonstrate a particularly attractive type of measurement of quantum entanglement between photons that brings these quantum technologies a step closer.

Among the physical systems being used to develop quantum technologies, photons are particularly appealing because of their low noise (information preserving), high-speed transmission and ease of manipulation at the single-photon level[2]. They are indispensable for quantum communication[3] and quantum metrology[4], and of the various approaches to the longer-term goal of quantum computing[5], photonics is a leading candidate[6].

The remarkable properties of quantum entanglement are beautifully exhibited by two 'polarization entangled' photons. Polarization is the direction in which light's electric field oscillates. When the polarization of one of the photons is measured, the outcome is completely uncertain — half of the time it will be horizontal and the other half vertical, or half at +45° and half at −45°, depending on the direction in which it is measured. However, the outcome of the same measurement on the second photon is precisely known: it will either give the same result as for the first photon, in which case the measurements are perfectly correlated; or it will always be the opposite (that is, horizontal for vertical, +45° for −45°, and so on), in which case they are perfectly anti-correlated. (Whether they are perfectly correlated or perfectly anti-correlated depends on the exact way in which the photons are entangled.)

By itself, that's not so surprising. Such correlations are common in our everyday experience. For example, the presence of your keys in your pocket is perfectly correlated with them not being on the hook at home. But when these measurements are repeated on many pairs of such identically prepared entangled photons, no matter at what angles the polarization is measured (horizontal, vertical, diagonal, and so on), the same perfect correlations are seen — and this is clearly at odds with our intuitive understanding of how the world works.

Sansoni and colleagues[1] now demonstrate the measurement of such polarization entanglement of two photons using an integrated waveguide device that incorporates waveguide channels on a chip. The channels guide light in the same way as the optical fibres used in telecommunications (by means of total internal

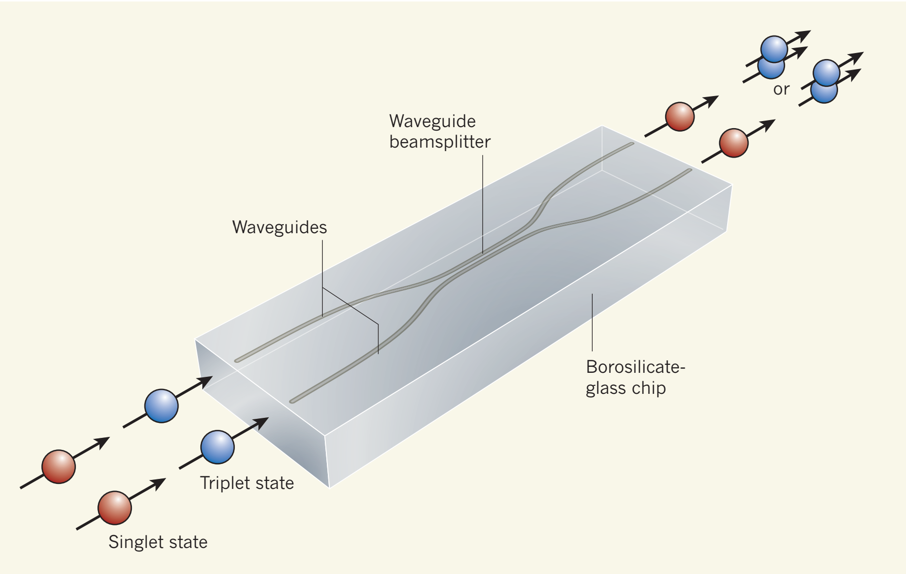

Figure 1 | Measuring entanglement on a chip[1]. A pair of photons is launched into a waveguide beamsplitter on a borosilicate-glass chip. By measuring whether the photons exit in separate waveguides or together in the same waveguide, the nature of the photons' entangled input state — singlet or triplet — can be determined.

reflection in the waveguides), and the device allows the authors to identify the type of polarization entanglement carried by the pair of photons (Fig. 1).

A major obstacle to quantum technologies based on photons, and indeed to the pursuit of fundamental quantum science with photons, has been the construction of photonic quantum circuits from bulk optical elements (such as centimetre-sized mirrors and beamsplitters) that are bolted to large, vibration-stabilized optical tables, with the photons propagating in free space. This approach is unwieldy, unscalable and limited in performance. Recently, quantum circuits that incorporate silica-glass waveguides on silicon chips have been used to overcome these problems[7], following in the footsteps of devices developed for optical telecommunications. This alternative technique has been used to demonstrate small-scale quantum information processing algorithms[8], quantum metrology with up to four entangled photons[9], and a quantum 'walk' of two correlated photons[10].

However, in all of these demonstrations, the quantum information carried by the photons has been path encoded — that is, a photon in one waveguide is used to encode a logical bit 0, with a photon in a second waveguide encoding a logical bit 1. This path encoding is incompatible with the commonly used and very convenient polarization encoding — for example, horizontal photon polarization for a 0 and vertical polarization for a 1. Using polarization encoding in waveguides is not straightforward because the speed with which these two polarizations of light propagate is typically slightly different owing to an effect called birefringence, which is caused by the geometry and/or the materials from which the waveguides are made. This birefringence changes the polarization state of photons propagating in the waveguide, from diagonal to circular for example, and can ultimately depolarize the photons, limiting their capacity to interfere and leading to a loss of information.

An alternative approach to constructing waveguides, used by Sansoni *et al.*[1], involves tightly focusing a powerful pulsed laser beam onto a material such as glass and so permanently changing the material's properties to create a waveguide. By scanning the position of the focused spot around the sample, waveguides can be directly written in all three dimensions of the sample. Quantum photonic circuits with circular waveguides[11] have been made in this way — suggesting that the waveguides would exhibit low birefringence and be able to support polarization encoding. In their study, Sansoni *et al.*[1] demonstrate that the approach can indeed lead to waveguides that support polarization encoding.

They used the technique to fabricate two waveguides on a glass chip and bring them into close proximity, so making a device — termed a directional coupler — that acts like a beamsplitter: it reflects half of the incident light and transmits the other half. When an entangled pair of photons was launched into the two waveguides, the symmetry of the entanglement injected into the device — technically called 'singlet' or 'triplet' states — could be determined. This is because the singlet state 'anti-bunches' at the coupler such that the photons come out of each output waveguide separately, whereas the triplet states 'bunch' such that both photons come out in the same waveguide (Fig. 1).

This polarization-compatible approach to on-chip integrated quantum photonics holds great potential for being combined with the standard methods for generating and measuring photonic entanglement. As the authors[1] point out, it should make the implementation of sophisticated multi-photon quantum circuits such as entanglement filters[12], and even more advanced circuits, much more straightforward. However, integrated devices that can perform polarization rotations in analogy with their bulk optical counterparts — 'integrated waveplates' — will ultimately be crucial, as will a path to miniaturizing these circuits further to make large quantum photonic circuits possible. As with all approaches to quantum photonic technologies, single-photon sources and detectors remain an important requirement, together with their integration with quantum circuits[2]. ■

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ALZHEIMER'S DISEASE

Recollection of lost memories

With age comes wisdom, or so they say. The reality is that, with age, the ability to store memories declines. One way of tackling this problem might be to raise neuronal levels of the signalling molecule EphB2. SEE ARTICLE P.47

ROBERT C. MALENKA & ROBERTO MALINOW

Where did I put those keys? What did I have for dinner last night? Cognition — most notably, the ability to store memories — inevitably declines with age. What's more, for an increasing proportion of individuals, this decline progresses aggressively to the point that they cannot care for themselves. Alzheimer's disease is the leading cause of such dementia in the elderly, affecting almost 50% of people over the age of 85. But despite considerable progress in understanding the biology of this disease, an effective treatment remains elusive. On page 47 of this issue, Cissé *et al.*[1] provide compelling evidence that manipulation of a specific membrane protein — the receptor tyrosine kinase EphB2 — in a mouse model of Alzheimer's disease can reverse the characteristic memory deficits and so may make for a promising therapeutic strategy.

The leading hypothesis for the cause of Alzheimer's disease — based initially on human genetic findings, and supported by many cell-biological, animal-model and human studies — is chronically high brain levels of a peptide fragment termed Aβ. Indeed, mutations in the enzymes that generate Aβ or in the Aβ precursor protein, which lead to increased Aβ levels, are associated with early-onset Alzheimer's[2,3].

Mice genetically engineered to express these same mutations develop cognitive deficits as they age[2,3]. In normal mice, meanwhile, raising neuronal Aβ levels causes a loss of synaptic junctions between these cells that correlates well with the degree of dementia in humans. Furthermore, Aβ can now be imaged non-invasively in the human brain, and brain images of patients with Alzheimer's disease show Aβ accumulation, the extent of which correlates with memory decline[4]. Thus, there is great motivation to determine how Aβ accumulation leads to memory impairment.

Learning and memory are thought to require