Coherent Exciton Waves

David Snoke

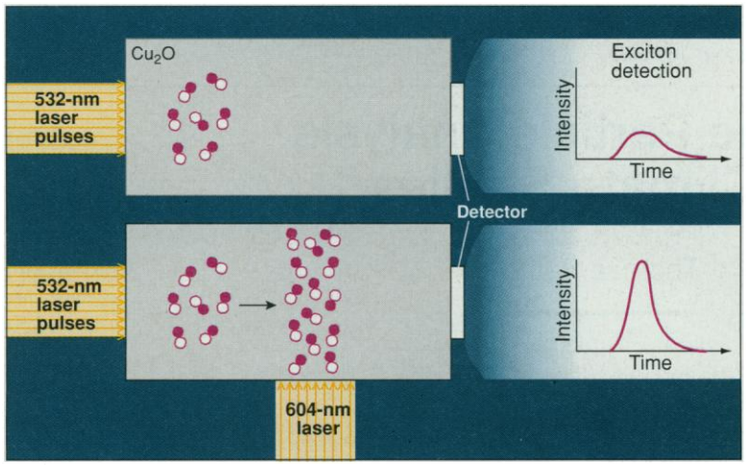
How do you get a beam of light with a wavelength of 600 nm to pass through an aperture only 10 Å in radius without loss to diffraction? Can 600-nm light travel down a fiber only 50 Å wide? These feats might seem impossible, but the physics of excitons allows such possibilities. An exciton is the fundamental quantum of electrical excitation in a solid, consisting of an excited electron and hole bound together in a neutral pair, analogous to a neutral hydrogen atom. Recent work has shown that it is possible to create coherent amplified beams of excitons, just as a laser generates coherent beams of photons (*1*).

In certain materials, photons of visible light can be converted into excitons, each of which has a radius of 10 to 50 Å in typical semiconductors. An exciton can move freely through the material, and its constituent parts eventually recombine, emitting a second photon. Unlike free electrons or holes, excitons do not carry charge or mass across the material; they carry energy. During their brief lifetime, however, they act like massive particles. There is therefore no contradiction if photon energy passes through an aperture of size much less than the photon wavelength without diffraction. The photon can be converted into an exciton, which stores the energy in the electronic states with short wavelength while passing through the aperture, and the exciton can then convert back into a photon on the other side.

This property of excitons has long been known and has been used to get light to the end of the tiny tips in scanning microscopes (*2*). Plants use excitons to collect light from a wide area and concentrate it into a small spot. The problem has been that excitons, acting as free particles, normally move incoherently. While moving through an aperture or any other structure, they normally propagate diffusively—that is, they spread out spatially and lose monochromaticity because of random scattering processes in the material. Because excitons are bosons like photons, however, there has been great interest in whether they can be made to propagate coherently. In that case, pulses or beams of excitons could carry energy through an aperture with very little diffraction loss. Because the excitons have mass, the coherent exciton pulse would essentially be a "superfluid" while it existed.

The work (*1*) by Mysyrowicz of Ecolé Polytechnique in Palaiseau, France, and Benson and Fortin of the University of Ottawa, Canada, has shown that excitons can indeed propagate coherently. As far back as 1990, exciton pulses in the semiconductor Cu_2O were observed in time-resolved optical imaging experiments to propagate ballistically through the material following intense laser pulses (*3*). Link and Baym (*4*) suggested that these results were consistent with coherence and superfluidity. Optical spectra indicated that the excitons were highly coherent, but at that time, it was not clear whether the ballistic propagation could not be attributed to a much more mundane effect, namely, a "phonon wind" created from the heat deposited by the laser, which blows the excitons across the crystal medium as the heat flows out of the excitation region. Such an effect had been seen previously for electron-hole droplets in semiconductors (*5*), and models of phonon wind have reproduced some of the effects in Cu_2O (*6*).

In 1993, the Palaiseau–Ottawa collaboration examined the same effect with a very different kind of detection (*7*). In these experiments, excitons were detected electronically on the back surface of the crystal, before they recombined into photons. Because excitons in Cu_2O have lifetimes well over 10 μs, the researchers found that the excitons could travel ballistically for distances of centimeters, at speeds around 5×10^5 cm/s. Because they used intense, heat-generating laser pulses for these experiments also, there was still debate about whether the ballistic travel was truly related to the coherence of the excitons. In Wolfe's laboratory at Urbana, however, spectral evidence (*8*) was accumulating that the excitons in Cu_2O are truly coherent at high density. Researchers at the Walter Schottky Institute in Garching, Germany, also reported measurements that suggested superfluid transport of excitons in two-dimensional GaAs structures (*9*).



Exciton amplifier. (**Top**) A beam of coherently propagating excitons is created by pulses of laser light at 532 nm. The excitons are collected and measured at the other side. (**Bottom**) When laser light at 604 nm is added, a second group of excitons is created. These join the propagating pulse and increase the number of excitons collected at the far surface.

In the past year, the Palaiseau–Ottawa researchers have added innovations to their experiments that seem to demonstrate the coherent nature of the ballistic exciton pulses (*1*). First, they showed that cold excitons also participate in the ballistic transport, which would argue against the phonon wind explanation. Second, they have shown stimulated amplification (see figure) of the exciton pulse. Because excitons are bosons, they have an enhancement factor of $(1 + n_f)$ for all scattering processes, where n_f is the number of particles in the final state, just the opposite of the $(1 - n_f)$ factor for transitions to occupied final states of fermions, which leads to Pauli exclusion. The $(1 + n_f)$ factor for bosons causes them to "attract" each other, leading to amplification. For photons, this $(1 + n_f)$ stimulated emission factor is the basis of the laser; because excitons act analogously, Mysyrowicz, Benson, and Fortin have suggested the name "excitoner" for the coherent exciton pulse. Precursors of this effect had been seen before in the semiconductor CuCl (*10*), but the strong "polariton" effect in CuCl, which mixes exciton and photon states, made it difficult to distinguish whether the coherence lay in the excitons or the photons. By using excitons in Cu_2O with very weak coupling to photons, the Palaiseau–Ottawa researchers showed that the coherence lay en-

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tirely in the excitons.

Because excitons have mass, the spontaneous appearance of coherence of the excitons at high density is closely related to the phenomenon of Bose-Einstein condensation (*11*). In essence, all of the particles are attracted to a single quantum state. Unlike atomic gases, however, an exciton gas can undergo Bose condensation at relatively high temperature. Although the experiments at the Ottawa were done at 2 K, all of the coherent effects can in principle be observed at much higher temperatures. Excitons in Cu_2O, like many tightly bound excitons, are stable and a strong source of luminescence at room temperature (*12*).

Five years ago, the only laboratory examples of spontaneous coherence of massive particles were liquid helium and superconductors, both of which are strongly interacting systems. In the past 2 years, however, two new systems of massive particles have been demonstrated to have spontaneous attraction to a single coherent state, each of which is weakly interacting: alkali gases and excitons. For this reason, much of the theory for alkali gases and excitons has been applied equally to both disciplines. The exciton gas, unlike the atomic gas, has a transient lifetime of only microseconds, but on the time scales of modern optical communication devices, which exceed gigahertz switching rates, that is a very long time.

The work on coherent propagation of excitons has provided a new kind of light source, namely, a beam that propagates as a wave with a wavelength of angstroms but carries photons with energy in the visible range. Only time and imagination can tell what new applications may arise from this novel effect.

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Airborne Particle Analysis for Climate Studies

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Particulates in Earth's troposphere and stratosphere are important in many scientific, medical, and technological respects: They control climate change to a high degree, strongly influence atmospheric chemistry, affect our health, and disturb technological processes like chip manufacturing. Despite the pressing need for detailed information, the properties of aerosols are still hard to measure and classify owing to their tremendous diversity in particle number density, size, shape, physical state, and chemical composition. Moreover, measurement of these properties is often complicated because certain components are highly volatile and cannot be collected and analyzed by ex situ methods. Here, the recent blossoming of mass spectrometric (MS) methods (see figure) for contact-free real-time analysis of individual aerosol particles opens a new large field of applications with as yet unexplored possibilities. The work by Noble and Prather reported in a recent issue of *Environmental Science and Technology* (*1*) is an impressive realization of such an approach, providing an accurate measurement of the particle's size before it is ionized for subsequent chemical analysis.

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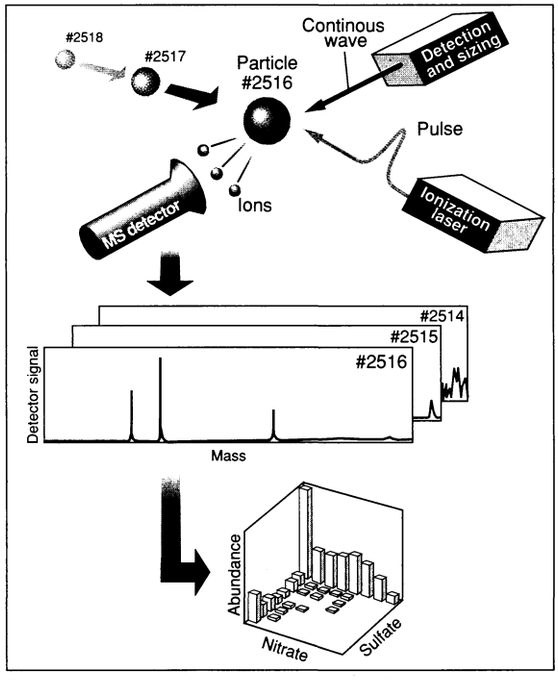

Resolved complexity and data reduction. An individual particle is detected by a continuous-wave laser and then ionized by a strong pulse from a second laser. The ions are mass analyzed, and information from hundreds or thousands of particles is grouped together to obtain the physical information. Spectra and abundance chart adapted from (*8*).

A glance at the mass spectra obtained from such methods reveals the wealth of information sometimes hidden in an individual micrometer-sized particle—indeed, too much to be easily digested when 10 such spectra come in every second. Some of them are easily classifiable, but many are different from all others. One might almost wonder what this flood of information is good for if it cannot be divided easily into broad categories.

It must be clear that in situ chemical analysis of individual airborne particles combined with accurate measurements of their physical properties will be indispensable in many fields of aerosol-related research if progress is to be made. We can perceive this with help of the following two examples. First, there is reason to believe that the anthropogenic component of tropospheric aerosols exerts a large negative driving force on Earth's climate that partly masks the positive forcing by anthropogenic greenhouse gases (*2*). However, in contrast to gaseous species, the radiative effects of aerosols up to now are modeled only very crudely because of the complex regional and temporal behavior of aerosol distributions, sizes, and chemical compositions, all of which govern the radiative interaction. This situation calls for closure experiments in which all the relevant parameters—radiation,