Low uncertainty for an intriguing future

Quantum optics has come a long way since its birth at the beginning of the 1900s. *Nature Photonics* spoke to Anton Zeilinger to gain some perspective on its progress.

What are the origins of quantum optics?

In 1905, Einstein explained the photoelectric effect by proposing that light consists of particles. He was building on Planck's theory of black-body radiation, which explains that light can only be emitted in discrete packets of energy — quanta. By 1909, Einstein had already realized that these ideas led to some conceptual problems that are extremely interesting. The quantum nature of light is important when dealing with individual photons or with special quantum states such as 'squeezed states', where the uncertainty relation becomes crucial. Quantum optics is important in many fields of research; a complete understanding of atomic transitions, and hence of lasers, cannot be achieved without it.

What were the important events after Einstein proposed the quantization of light?

There were many important studies, but the entanglement experiments, starting with those of Freedman and Clauser in 1972 at Berkeley, were particularly important. They achieved the first experimental proof that correlations between two entangled photons can be stronger than in classical models, which are local. The correlations violated Bell's inequality, which was derived for such classical correlations. This was followed by many beautiful experiments, most notably those performed by Aspect. Another important development was high-precision optical experiments and the optical frequency-comb, for which Hänsch and Hall received half of the Nobel Prize for Physics in 2005.

A long time passed between Einstein's first proposal of the quantization of light and the experiments performed in the 1970s, and it is important to consider the reason for this. First, several important developments coincided in the 1970s — particularly the invention of the laser, which made it possible to achieve new sources of light at unprecedented levels of intensity and spectral purity. This is crucial for producing single photons, which are now very useful for quantum optics experiments. A second factor was the proposal that quantum mechanics can experimentally violate Bell's inequality, thanks to non-local correlations. There is perhaps a third factor — that of academic culture. Before the early 1970s it was quite unpopular to be working on fundamental quantum mechanics; your colleagues looked at you as if you were a little strange.

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Currently, what are people working on?

At the moment there are so many different approaches, which makes it difficult to single out one study in particular. Of course, an interesting field is quantum cryptography for the secure transmission of information, meaning that a secret key doesn't have to be transported from A to B anymore, but is created simultaneously at A and B by the quantum measurement process in a non-local way. I believe that cryptography is mature enough to be commercialized, but has not really been adopted yet. Quantum random-number generation, however, is quite advanced and ready to be implemented. Quantum computation promises to provide computers with unprecedented speed, but that is some way off.

Personally, I'm still — as always — mostly interested in the fundamental questions. We are currently working on entanglement-based quantum cryptography and long-distance quantum communication at distances of 144 km. We are also doing new tests of quantum reality beyond Bell's inequality to understand quantum optics better. We are also interested in scalable quantum optics and computation in integrated circuits. Work in integrated quantum optics, such as that of Jeremy O'Brien and others, is very exciting. The scalability to larger and more complex systems is the challenge there.

What are the limitations that must be overcome?

The current limitations are the sources and detectors. The ideal source would allow you to 'dial your quantum state'; you would specify the number of photons desired and their particular states, push a button, and then photons in that state would be produced. Such a source would be very important for quantum computation. We are far from having such a source, but it is not completely impossible. We have already achieved this for two-photon sources, and we are nearly there for three- and four-photon sources. For detectors we have a similar problem; we require an extremely reliable detector that is able to distinguish between individual photons. Actually these detectors exist now, but they are superconducting and therefore very expensive and difficult to handle. There are only about three groups in the world that are able to build them.

Solving both the source and detector problems would be a big step forward for quantum computation. For sources there are many possible research areas such as the nitrogen vacancies in diamond and parametric down-conversion, which functions as a probabilistic source but may be almost deterministic by using short-pulsed lasers and quantum dots. Building quantum repeaters to cover larger distances for communicating quantum information remains a major challenge too.

INTERVIEW BY DAVID PILE