Probing complex materials with quantum spectroscopy

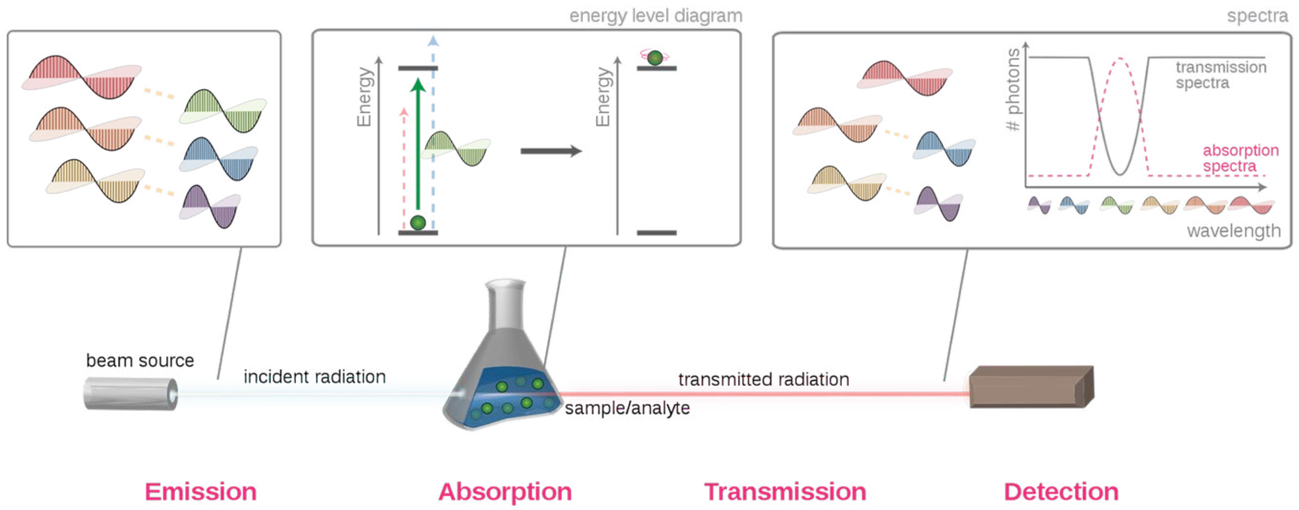
Entanglement is one of the most well-known and mysterious properties of quantum mechanics. In some materials, it can create complex webs of interactions between molecules, which are notoriously difficult to study. Through his research, Professor Eric Bittner at the University of Houston has designed and demonstrated a new technique for probing these interactions, named 'quantum spectroscopy.' His team's approach could soon offer researchers an effective way to study and engineer these exotic materials, potentially leading to new advances in quantum technologies.

The technique of 'absorption spectroscopy' is widely used by researchers to probe the compositions of material samples. Depending on the material's composition, certain wavelengths of light will be absorbed by its constituent atoms and molecules as it passes through, leaving characteristic gaps in the spectra of the light that emerges. By analysing the positions and widths of these gaps, researchers can precisely determine the molecular makeup of their samples.

Through the latest advances in technology, spectroscopic techniques are now being adapted to study more exotic materials. Perhaps most intriguingly, researchers are starting to probe materials whose behaviours can only be described through the more mysterious rules of quantum mechanics. However, getting to this point has been a monumental challenge; requiring methods far more advanced than those used in traditional absorption spectroscopy. In their research, Professor Bittner and his colleagues have used cutting-edge theories and experiments to realise these techniques for the first time, using photons which are coupled together by an effect named 'quantum entanglement'.

ACTION AT A DISTANCE

On the very smallest of scales, the classical rules of physics which govern how particles behave can no longer apply. Instead, their dynamics are governed by quantum mechanics, which introduces an entirely new set of mathematical rules. In particular, the principle states that individual particles can exist in multiple quantum 'states' at the same time. When the particle is observed, this set of 'superimposed' states will collapse, so that observers



Absorption spectroscopy is widely used to analyse the compositions of materials, allowing researchers to precisely determine their molecular makeup.

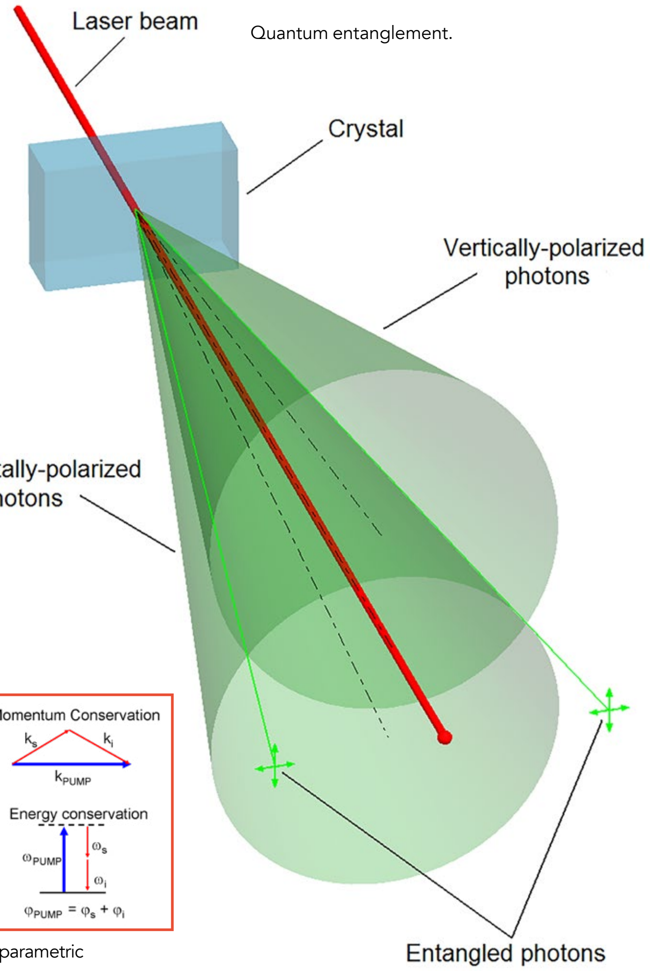
will observe just one state – with each state having a certain probability of being observed.

Even more strangely, the laws of quantum mechanics mean that the outcome of a measurement of one particle can entirely depend on that of another. 'Quantum entanglement occurs when two or more particles interact in such a way that the quantum state of each particle cannot be determined independently of the state of the others—even though the particles may become separated from each other,' Prof Bittner explains. 'This gave rise to Einstein's comment of "spooky action at a distance".' Although the underlying causes of quantum entanglement are not yet understood, the effect can still be incredibly useful to researchers.

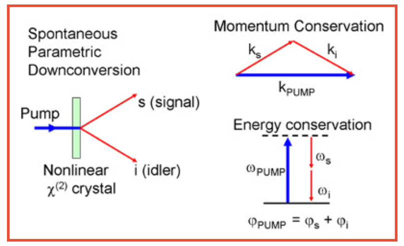
Through specialised optical arrangements, researchers are now able to generate entangled pairs of photons by themselves, giving them access to exciting new capabilities. In recent years, entanglement has been exploited to develop a wide variety of cutting-edge technologies, which promise to transform the ways in which we communicate in the future. 'Entanglement between identical quantum particles, such as photons, is the foundational heart and soul of quantum theory and enables modern quantum technologies such as quantum computing and quantum communication,' Prof Bittner continues. For his research team, the effect provides a unique opportunity to explore a further mysterious consequence of quantum mechanics – which until recently, appeared far too complex to study using more traditional techniques.

ENTANGLED WEBS OF INTERACTIONS

Within the classical materials we are familiar with, atoms and molecules interact as they exchange mechanical forces with each other, which propagate through the material over time. However, for materials with behaviours governed by quantum properties, the case can be entirely different. In these 'complex' materials, the quantum states of some molecules can become



Quantum entanglement.



Schematic of spontaneous parametric down-conversion.

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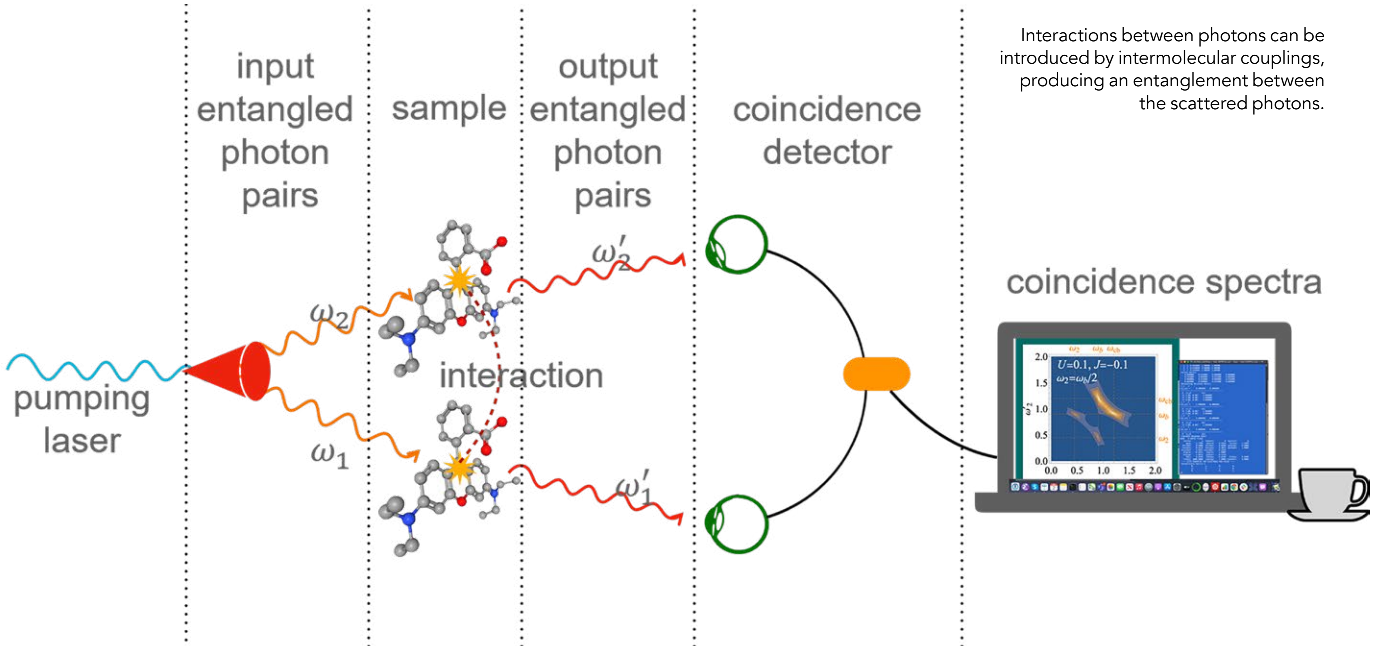
entangled with those of others. With so many quantum particles in the system, this can result in deeply complex webs interactions, which have become notoriously difficult to study.

Clearly, there is no way for researchers to explore these behaviours using conventional absorption spectroscopy. Yet through the research of Prof Bittner's team, this situation is now changing. In his research, he is studying how pairs of photons can become entangled as they pass through samples of complex materials, before measuring the nature of this entanglement after the photons have passed through. Then, in the same way as the positions and widths of gaps in light spectra can be used to identify the compositions of material samples, this photon entanglement can be used as a probe of correlated interactions within complex materials.

USING ENTANGLEMENT AS A PROBE

To explore how the entanglement between photons can be changed in this way, Prof Bitner's team exploited a process named 'double-resonance scattering.' Here, neighbouring molecules in the sample behave like a single 'virtual' particle. As they absorb the photon pair, both molecules will collectively be excited to a higher quantum state. Eventually, the virtual particle will move back to its ground state by re-emitting the photon pair; but crucially, the nature of entanglement between the photons will carry information about the correlations between both molecules in the pair.



Interactions between photons can be introduced by intermolecular couplings, producing an entanglement between the scattered photons.

If the two molecules are independent and don't interact with each other, the outgoing photons will behave like individual, uncorrelated particles. However, if the molecules are correlated with each other, the re-emitted photons will be entangled, and cannot be separated into their own single product states. Therefore, the information carried by the outgoing photons can be used to measure intermolecular interactions within the sample. To obtain this information, Dr Bitner's team reconstructed the quantum states of the virtual particles through a series of two-photon counting experiments. They also showed how the intermolecular correlations within these virtual particles can be used to map changes in a value named the 'entanglement entropy' of the two re-emitted photons.

If the photons have become entangled, the measurement of one detector will correspond with that of the other, enabling the team to compare their entanglement entropy before and after their interaction with the molecules. 'By measuring the change in entanglement entropy on the final state, you can quantify and measure the interaction between photons and molecules,' explains Prof Bittner. 'We also show how correlated motions between molecules can increase or decrease entanglement, even though the molecular pair are not directly coupled and only "interact" via a common noisy environment.' This technique presents a significant step forward in researchers' ability to determine how the molecular constituents of complex materials will interact with each other. Furthermore, these advances could already have promising real-world applications.

NEW EXPLORATIONS OF COMPLEX MATERIALS

Through recent studies, researchers have now shown how complex materials could be exploited in a wide variety of situations, both in nature and in man-made technologies. By probing the nature of their entangled webs using quantum spectroscopy, these materials could be studied far more easily. 'The goal of our work is to develop suitable experimental methods using quantum entanglement as sensitive spectroscopic probes of complex material systems, such as photosynthetic centres in light-harvesting bacteria, topological insulators, and low-dimensional electronic semiconductors,' Prof Bittner concludes.

By measuring the change in entanglement entropy on the final state, you can quantify and measure the interaction between photons and molecules.

Currently, it is not fully understood how some single-celled organisms can gain their energy directly from sunlight. Therefore, quantum spectroscopy could offer biologists new insights into how these bacteria rely on the principles of quantum mechanics for their survival. Elsewhere, the technique could allow researchers to better exploit materials like topological insulators – whose quantum properties give them conductive surfaces, but insulating interiors. In addition, it could lead to new insights into atom-thick semiconductors, including graphene-based materials.

The vast improvements in measurement afforded by quantum spectroscopy could enable researchers to engineer materials which are ideally suited for technologies including quantum computing and communications. Through further work to scale up the technique, suitable for probing larger, more complex material samples, the potential for quantum spectroscopy could soon extend even further; and may enable researchers to gain a greater understanding of the mysterious nature of quantum mechanics as a whole.

Behind the Research

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Research Objectives

Professor Bittner's main research interest lies with the dynamics of molecules in their excited electronic states.

Detail

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Bio

Dr Eric Bittner is Moores Professor of Chemical Physics at the University of Houston. He received his PhD from the University of Chicago in 1994 and after an NSF postdoctoral fellowship at UT-Austin and Stanford joined the UH faculty. Dr Bittner is a Fellow of the Royal Society of Chemistry and the American Physical Society. He was a Guggenheim Fellow and a Fulbright Fellow and most recently was the Leverhulme Trust Visiting Professor in Physics at Durham University.

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Collaborators

- Carlos Silva (Ga Tech)
- Andrei Piryatinski (LANL)
- Hao Li (UH)

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Personal Response

How could your technique be scaled up to study larger systems of interacting molecules?

"Quantum spectroscopy really acts at the single quantum level and would probe the quantum dynamics of single molecules or perhaps a handful or molecules in close proximity. The crucial issue we're trying to study is how pairs of excitons interact and how this interaction is transcribed onto the outgoing photon state. We are currently applying the theory to study biexcitons in thin-film organic semiconductors."