Lattice Vibrations in Semiconductor

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University of Central Florida researchers have developed a way to control the speed of light. Not only can they speed up a pulse of light and slow it down, they can also make it travel backward. [22]

X-ray free-electron lasers (XFELs) produce incredibly powerful beams of light that enable unprecedented studies of the ultrafast motions of atoms in matter. [21]

Using ultrashort laser pulses lasting a few picoseconds (trillionths of a second), Lawrence Livermore National Laboratory (LLNL) researchers have discovered an efficient mechanism for laser ablation (material removal) that could help pave the way to the use of lower-energy, less costly lasers in many industrial laser processing applications. [20]

Engineers at Ruhr-Universität Bochum have developed a novel concept for rapid data transfer via optical fibre cables. [19]

Particles can exchange their spin, and in this way spin currents can be formed in a material. [18]

Researchers have shown that certain superconductors—materials that carry electrical current with zero resistance at very low temperatures—can also carry currents of 'spin'. [17]

The first known superconductor in which spin-3/2 quasiparticles form Cooper pairs has been created by physicists in the US and New Zealand. [16]

Now a team of researchers from the University of Maryland (UMD) Department of Physics together with collaborators has seen exotic superconductivity that relies on highly unusual electron interactions. [15]

A group of researchers from institutions in Korea and the United States has determined how to employ a type of electron microscopy to cause regions within an iron-based superconductor to flip between superconducting and non-superconducting states. [14]

In new research, scientists at the University of Minnesota used a first-of-its-kind device to demonstrate a way to control the direction of the photocurrent without deploying an electric voltage. [13]

Brown University researchers have demonstrated for the first time a method of substantially changing the spatial coherence of light. [12]

Researchers at the University of Central Florida have generated what is being deemed the fastest light pulse ever developed. [11]

Physicists at Chalmers University of Technology and Free University of Brussels have now found a method to significantly enhance optical force. [10]

Nature Communications today published research by a team comprising Scottish and South African researchers, demonstrating entanglement swapping and teleportation of orbital angular momentum 'patterns' of light. [9]

While physicists are continually looking for ways to unify the theory of relativity, which describes large-scale phenomena, with quantum theory, which describes small-scale phenomena, computer scientists are searching for technologies to build the quantum computer using Quantum Information.

In August 2013, the achievement of "fully deterministic" quantum teleportation, using a hybrid technique, was reported. On 29 May 2014, scientists announced a reliable way of transferring data by quantum teleportation. Quantum teleportation of data had been done before but with highly unreliable methods.

The accelerating electrons explain not only the Maxwell Equations and the Special Relativity, but the Heisenberg Uncertainty Relation, the Wave-Particle Duality and the electron's spin also, building the Bridge between the Classical and Quantum Theories.

The Planck Distribution Law of the electromagnetic oscillators explains the electron/proton mass rate and the Weak and Strong Interactions by the diffraction patterns. The Weak Interaction changes the diffraction patterns by moving the electric charge from one side to the other side of the diffraction pattern, which violates the CP and Time reversal symmetry.

The diffraction patterns and the locality of the self-maintaining electromagnetic potential explains also the Quantum Entanglement, giving it as a natural part of the Relativistic Quantum Theory and making possible to build the Quantum Computer with the help of Quantum Information.

Contents

Author: George Rajna

Preface

While physicists are continually looking for ways to unify the theory of relativity, which describes large-scale phenomena, with quantum theory, which describes small-scale phenomena, computer scientists are searching for technologies to build the quantum computer.

Australian engineers detect in real-time the quantum spin properties of a pair of atoms inside a silicon chip, and disclose new method to perform quantum logic operations between two atoms. [5]

Quantum entanglement is a physical phenomenon that occurs when pairs or groups of particles are generated or interact in ways such that the quantum state of each particle cannot be described independently – instead, a quantum state may be given for the system as a whole. [4]

I think that we have a simple bridge between the classical and quantum mechanics by understanding the Heisenberg Uncertainty Relations. It makes clear that the particles are not point like but have a dx and dp uncertainty.

Amplifier for terahertz lattice vibrations in a semiconductor crystal

In analogy to the amplification of light in a laser, vibrations of a semiconductor crystal, so-called phonons, were enhanced by interaction with an electron current. Excitation of a metal-semiconductor nanostructure by intense terahertz (THz) pulses results in a 10-fold amplification of longitudinal optical (LO) phonons at a frequency of 9 THz. Coupling such lattice motions to propagating sound waves holds potential for ultrasound imaging with a sub-nanometer spatial resolution.

The fundamental principle of laser light can be adopted for phonons via the vibrational quantum in a crystal. Phonons can be absorbed or emitted by electrons in the crystal lattice. A net amplification of phonons requires that their number emitted per second via stimulated emission is larger than that absorbed per second. In other words, there must be more electrons emitting than absorbing a phonon. This condition is illustrated schematically in Fig. 1, in which the electron energy is plotted as a function of the electron momentum k, following roughly a parabolic dependence.

For a thermal equilibrium distribution of electrons at room temperature [sketched by filled blue circles of different size in Fig. 1(a)], electron states at higher energies have a smaller population than those at lower energies, resulting in a net phonon absorption. Stimulated emission of a phonon can only prevail if a so-called population inversion exists between two electronic states separated by both the energy and the momentum of the corresponding phonon in the crystal [Fig. 1(b)]. For optical phonons, this condition is very difficult to fulfill because of their comparatively high energy.

Researchers from the Max-Born-Institute in Berlin, Germany, the Sandia National Laboratories, Albuquerque, New Mexico, and the State University of New York at Buffalo, New York, have now demonstrated the amplification of optical phonons in a specially designed metal-semiconductor nanostructure [Fig. 1(c)]. The system consists of a metallic dog-bone antenna on top of a layered semiconductor structure consisting of GaAs and AlAs. This structure is irradiated with an ultrashort pulse at THz frequencies.

On the one hand, the THz pulse excites longitudinal optical (LO) phonons; on the other hand, it drives an electron current in the thick GaAs layer. The LO phonons oscillating with a frequency of 9 THz (9 000 000 000 000 Hertz, about 450 million times the highest frequency humans can hear) are amplified by interaction with the electrons. The strength or amplitude of the phonon oscillations is monitored via the concomitant change of the refractive index of the sample. The latter is measured with the help of a second ultrashort pulse at higher frequency. In Fig. 1(d), the time evolution of the phonon excitation is shown. During the peaks of the curve, there is a net phonon amplification with the yellow area under the peaks being a measure of the phonon oscillation amplitude. The movie attached shows the spatiotemporal evolution of the coherent phonon amplitude which displays both periods of phonon attenuation [situation Fig. 1(a)] and phonon amplification [situation Fig. 1(b)] depending on the phase of the THz pulse.

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Play

Left: Amplitude of GaAs optical phonons at the interface between the thin AlAs layer and the thick GaAs layer [Fig. 1(c)]. Red curve: LO phonon oscillations with a THz-driven electronic current in the thick GaAs layer. Blue curve: phonon oscillations without the amplifying mechanism. Right: Spatiotemporal evolution [cf. moving circles in the left panel] of the LO phonon amplitude as a function of the penetration depth from the AlAs/GaAs interface into the thick GaAs layer [Fig. 1(c)]. The movie clearly shows alternating periods of phonon attenuation [situation Fig. 1(a)] and phonon amplification [situation Fig. 1(b)] depending on the phase of the driving THz pulse. Credit: Forschungsverbund Berlin e.V. (FVB)

The present work is a proof of principle. For a usable source of high-frequency sound waves, it is necessary to further increase the amplification. Once such a source is available, it can be used for extending the range of sonography towards the length scale of individual biological cells. While the non-propagating optical phonons cannot be directly used for imaging, one can transform them into acoustic phonons with the same frequency in another material and apply the latter for sonographic imaging. [23]

Researchers develop way to control speed of light, send it backward

University of Central Florida researchers have developed a way to control the speed of light. Not only can they speed up a pulse of light and slow it down, they can also make it travel backward.

The results were published recently in the journal *Nature Communications*.

This achievement is a major step in research that could one day lead to more efficient optical communication, as the technique could be used to alleviate data congestion and prevent information loss. And with more and more devices coming online and data transfer rates becoming higher, this sort of control will be necessary.

Previous attempts at controlling the speed of light have included passing light through various materials to adjust its speed. The new technique, however, allows the speed to be adjusted for the first time in the open, without using any pass-through material to speed it up or slow it down.

"This is the first clear demonstration of controlling the speed of a pulse light in free space," said study co-author Ayman Abouraddy, a professor in UCF's College of Optics and Photonics. "And it opens up doors for many applications, an optical buffer being just one of them, but most importantly it's done in a simple way, that's repeatable and reliable."

Abouraddy and study co-author Esat Kondakci demonstrated they could speed a pulse of light up to 30 times the speed of light, slow it down to half the speed of light, and also make the pulse travel backward.

The researchers were able to develop the technique by using a special device known as a spatial light modulator to mix the space and time properties of light, thereby allowing them to control the velocity of the pulse of light. The mixing of the two properties was key to the technique's success.

"We're able to control the speed of the pulse by going into the pulse itself and reorganizing its energy such that its space and time degrees of freedom are mixed in with each other," Abouraddy said.

"We're very happy with these results, and we're very hopeful it's just the starting point of future research," he said. [22]

Ghostly X-ray images could provide key info for analyzing X-ray laser experiments

X-ray free-electron lasers (XFELs) produce incredibly powerful beams of light that enable unprecedented studies of the ultrafast motions of atoms in matter. To interpret data taken with these extraordinary light sources, researchers need a solid understanding of how the X-ray pulses interact with matter and how those interactions affect measurements.

Now, computer simulations by scientists from the Department of Energy's SLAC National Accelerator Laboratory suggest that a new method could turn random fluctuations in the intensity of laser pulses from a nuisance into an advantage, facilitating studies of these fundamental interactions. The secret is applying a method known as "ghost imaging," which reconstructs what objects look like without ever directly recording their images.

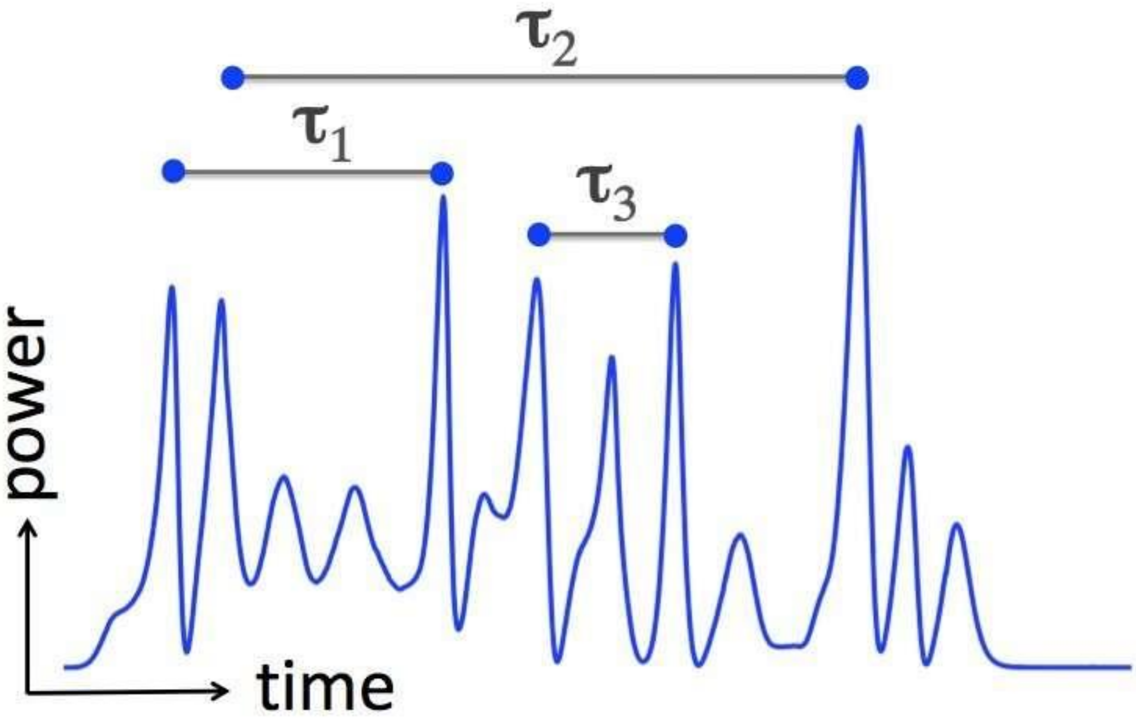
"Instead of trying to make XFEL pulses less random, which is the approach we most often pursue for our experiments, we actually want to use randomness in this case," said James Cryan from the

Stanford PULSE Institute, a joint institute of Stanford University and SLAC. "Our results show that by doing so, we can get around some of the technical challenges associated with the current method for studying X-ray interactions with matter."

The research team published their results in *Physical Review X*.

Taking advantage of X-ray spikes

Scientists commonly look at these interactions through pump-probe experiments, in which they send pairs of X-ray pulses through a sample. The first pulse, called the pump pulse, rearranges how electrons are distributed in the sample. The second pulse, called the probe pulse, investigates the effects these rearrangements have on the motions of the sample's electrons and atomic nuclei. By repeating the experiment with varying time delays between the pulses, researchers can make a stop-motion movie of the tiny, fast motions.



Simulated profile of an X-ray pulse from an X-ray free-electron laser. It consists of a train of narrow spikes whose intensity (power) fluctuates randomly. SLAC researchers suggest using pairs of these spikes for pump-probe experiments that trigger and measure structural changes in a sample, turning a former nuisance into an advantage. This example highlights three pairs of spikes with different time delays between them. Credit: SLAC National Accelerator Laboratory

One of the challenges is that X-ray lasers generate light pulses in a random process, so that each pulse is actually a train of narrow X-ray spikes whose intensities vary randomly between pulses.

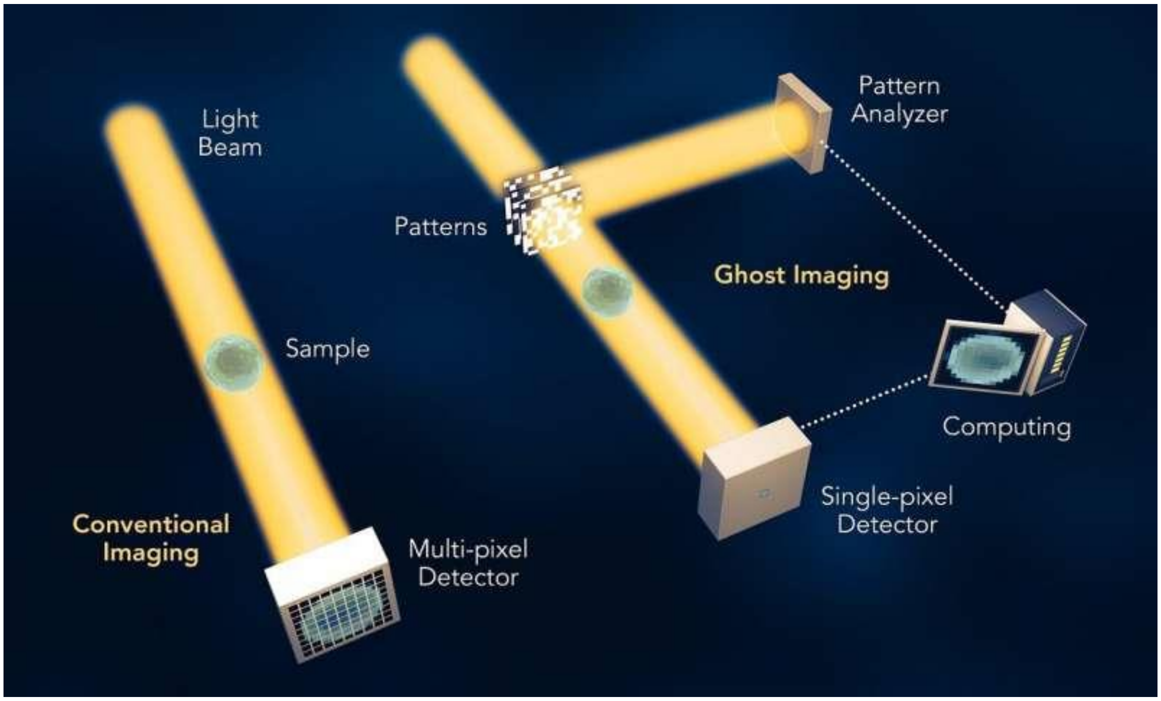
"Pump-probe experiments therefore typically require that we first prepare well-defined, short pulses that are less random," said SLAC's Daniel Ratner, the study's lead author. "In addition we need to control the time delay between them very well."

In the new approach, he said, "We wouldn't have to worry about any of that. We would use X-ray pulses as they come out of the XFEL without further modifications."

In fact, in this new way of thinking each pair of spikes within a single X-ray pulse can be considered a pair of pump and probe pulses, so researchers could do many pump-probe measurements with a single shot of the XFEL.

Taking ghostly snapshots

To produce snapshots of a sample's molecular motions with this method, Ratner and his coworkers want to apply the technique of ghost imaging.



In conventional imaging (left), light falling on an object produces a two-dimensional image on a detector. Ghost imaging (right) constructs an image by analyzing how random patterns of light shining onto the object affect the total amount of light coming off the object. Credit: Greg Stewart/SLAC National Accelerator Laboratory

In conventional imaging, light falling on an object produces a two-dimensional image on a detector – whether the back of your eye, the megapixel sensor in your cell phone or an advanced X-ray detector. Ghost imaging, on the other hand, constructs an image by analyzing how random patterns of light shining onto the object affect the total amount of light coming off the object.

"In our method, the random patterns are the fluctuating spike structures of individual XFEL pulses," said co-author Siqi Li, a graduate student at SLAC and Stanford and lead author of a previous study that demonstrated ghost imaging using electrons. "To do the image reconstruction, we need to repeat the experiment many times – about 100,000 times in our simulations. Each time, we measure the pulse profile with a diagnostic tool and analyze the signal emitted by the sample."

In a computational process that borrows ideas from machine learning, researchers can then turn these data into a visualization of the X-ray pulse's effects on the sample.

A complementary tool

So far, the new idea has been tested only in simulations and awaits experimental validation, for instance at SLAC's Linac Coherent Light Source (LCLS) X-ray laser, a DOE Office of Science user facility. Yet, the researchers are already convinced their method could complement conventional pump-probe experiments.

"If future tests are successful, the method could strengthen our ability to look at very fundamental processes in XFEL experiments," Ratner said. "It would also offer a few advantages that we would like to explore." These include more stability, faster image reconstruction, less sample damage and the prospect of doing experiments at faster and faster timescales. [21]

New method for better laser-material interaction

Using ultrashort laser pulses lasting a few picoseconds (trillionths of a second), Lawrence Livermore National Laboratory (LLNL) researchers have discovered an efficient mechanism for laser ablation (material removal) that could help pave the way to the use of lower-energy, less costly lasers in many industrial laser processing applications.

The new method, reported in a *Journal of Applied Physics* paper published online, uses short-wavelength, high-fluence (energy per unit area) laser pulses to drive shock waves that melt the target material. After the passage of the shock wave, the melt layer is placed under tension during a process known as relaxation, ultimately leading to the ejection of material through cavitation (unstable bubble growth).

The researchers used a combination of experiments and enhanced computer simulations in a previously unexplored range of laser energies and wavelengths to study picosecond laser pulse ablation of aluminum, stainless steel and silicon. Their findings show that ultraviolet (UV) picosecond pulses at fluences above 10 joules per square centimeter (J/cm2) can remove more material with less energy than longer-wavelength pulses.

"We discovered that this range above 10 joules per square centimeter, particularly for UV laser pulses, was behaving very differently than lower fluences and longer wavelengths," said Jeff Bude, NIF & Photon Science deputy principal associate director for Science & Technology.

"The removal rate jumps when you go beyond 10 joules per square centimeter, and especially for the UV light," Bude said. "At the same time the jump in the removal is accompanied by an increase in the removal efficiency—a reduction in the amount of energy required to remove a given volume of material.

"That was really intriguing to us; it suggested that maybe there's a different mechanism going on here. So we decided picosecond laser ablation would provide a good test case to probe ablation physics in a regime that was not well understood."

The study is thought to be the first comprehensive look at the picosecond-pulse laser ablation process. Selected as an "Editor's Pick" by the *Journal of Applied Physics* editors, the research was part of an ongoing Laboratory Directed Research and Development (LDRD) study of pulsed-laser material modification led by Bude.

The researchers compared the results from laser wavelengths of 355 nanometers (UV) and 1,064 nm (near-infrared) over a fluence range of 0.1 to 40 J/cm2 and found that the shorter wavelengths enhanced removal by nearly an order of magnitude over the measured removal at 1,064 nm. Laser ablation was many times more efficient at the UV wavelength compared to the near-infrared in all three materials.

Simulations using the radiation hydrodynamic code HYDRA showed that the increase in ablation efficiency was due to the UV laser pulses penetrating deeper into the ablative plume and depositing energy closer to the target surface, which resulted in higher-pressure shocks, deeper melt penetration and more extensive removal due to cavitation.

"The removal mechanism—shock heating creating a melt and then removing that with cavitation—requires less energy to remove material than vaporization of the material," Bude said. "That's the explanation for why it's more efficient."

"This discovery was really facilitated by our unique modeling and simulation capability here at the Lab," said LLNL analyst Wes Keller, lead author of the paper. "This was a particularly challenging problem to model because the laser energy deposition process was closely coupled with the material hydrodynamic response, requiring a unique code like HYDRA that has this integrated capability."

Complicated response

In some ways the research was a case of turning a challenge into an opportunity. Shortly after the study began, the researchers realized that material response to picosecond lasers was a good deal more complicated than if the more common femtosecond (quadrillionths of a second) lasers had been used.

"When you're trying to understand picosecond laser processing, some of the simplifying assumptions of the physics that you get with very short (femtosecond) pulses are no longer reliable," Bude said. Rather than simply absorbing the laser energy and vaporizing, "the material was moving, it was evolving in the laser plume," he said. This meant that the models had to be tweaked to account for both the hydrodynamics of the melting material and the interactions between the laser pulse and the plasma (ionized gas) in the ablative plume.

"We really needed to model laser-plasma interaction correctly," Bude said, "so we had to do a lot of creative experiments to fix some inadequacies in the model. Ultimately, we were able to identify the essential physics of this regime, and we discovered that you have to have shock heating to create micron-deep melt. And then after you create this deep melt with shock heating you need a mechanism to remove it, and we discovered that that mechanism was cavitation."

Once they realized that temporally shaped, or timed, pulses could exploit the instabilities in the melted material, the researchers were able to use shaped pulses to create a more efficient way to remove material. "We were able to leverage this understanding to do laser processing a different way," Bude said, "so it actually had a lot of spinoff benefits," some of which will be detailed in additional papers now in preparation.

The results also suggest that picosecond-pulse lasers offer several advantages over the more commonly used femtosecond lasers in terms of cost, efficiency and damage control. In addition, they offer options for efficient frequency conversion for wavelength flexibility.

"There is some indication," Bude said, "that in the regime of picosecond to tens of picoseconds (pulses) you can get the same sort of quality and behavior in your laser cutting, drilling and shaving functions that you could with more expensive lasers operating at less than a picosecond." The findings thus could lead to new or more efficient laser applications in industry, national defense, medicine and many other fields. [20]

Spin lasers facilitate rapid data transfer

Engineers at Ruhr-Universität Bochum have developed a novel concept for rapid data transfer via optical fibre cables. In current systems, a laser transmits light signals through the cables and information is coded in the modulation of light intensity. The new system, a semiconductor spin laser, is based on a modulation of light polarisation instead. Published on 3 April 2019 in the journal *Nature*, the study demonstrates that spin lasers have the capacity of working at least five times as fast as the best traditional systems, while consuming only a fraction of energy. Unlike other spin-based semiconductor systems, the technology potentially works at room temperature and doesn't require any external magnetic fields. The Bochum team at the Chair of Photonics and Terahertz Technology implemented the system in collaboration with colleagues from Ulm University and the University at Buffalo.

Rapid data transfer is currently an energy guzzler

Due to physical limitations, data transfer that is based on a modulation of light intensity without utilizing complex modulation formats can only reach frequencies of around 40 to 50 gigahertz. In order to achieve this speed, high electrical currents are necessary. "It's a bit like a Porsche where fuel consumption dramatically increases if the car is driven fast," compares Professor Martin Hofmann, one of the engineers from Bochum. "Unless we upgrade the technology soon, data transfer and the Internet are going to consume more energy than we are currently producing on Earth." Together with Dr. Nils Gerhardt and Ph.D. student Markus Lindemann, Martin Hofmann is therefore researching into alternative technologies.

Provided by Ulm University, the lasers, which are just a few micrometres in size, were used by the researchers to generate a light wave whose oscillation direction changes periodically in a specific way. The result is circularly polarised light that is formed when two linear perpendicularly polarised light waves overlap.

In linear polarisation, the vector describing the light wave's electric field oscillates in a fixed plane. In circular polarisation, the vector rotates around the direction of propagation. The trick: when two linearly polarised light waves have different frequencies, the process results in oscillating circular polarisation where the oscillation direction reverses periodically – at a user-defined frequency of over 200 gigahertz.

Speed limit as yet undetermined

"We have experimentally demonstrated that oscillation at 200 gigahertz is possible," describes Hofmann. "But we don't know how much faster it can become, as we haven't found a theoretical limit yet."

The oscillation alone does not transport any information; for this purpose, the polarisation has to be modulated, for example by eliminating individual peaks. Hofmann, Gerhardt and Lindemann have verified in experiments that this can be done in principle. In collaboration with the team of Professor Igor Žutić and Ph.D. student Gaofeng Xu from the University at Buffalo, they used numerical simulations to demonstrate that it is theoretically possible to modulate the polarisation and, consequently, the data transfer at a frequency of more than 200 gigahertz.

The generation of a modulated circular polarisation

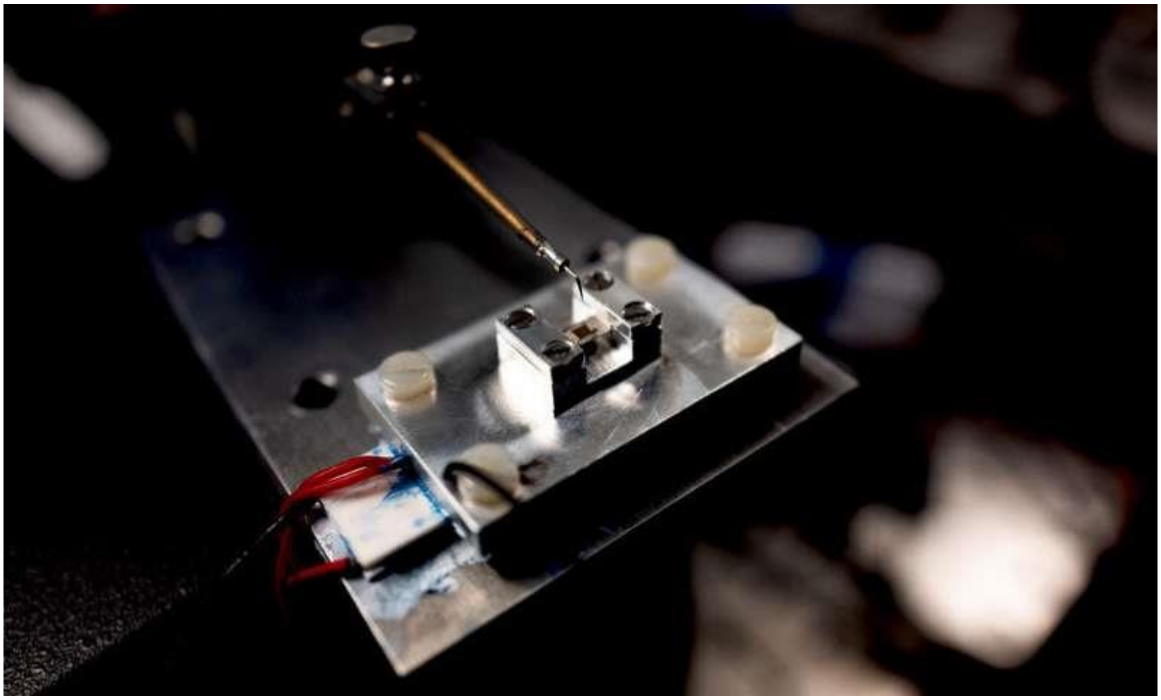
Two factors are decisive in order to generate a modulated circular polarisation degree: the laser has to be operated in a way that it emits two perpendicular linearly polarised light waves simultaneously, the overlap of which results in circular polarisation. Moreover, the frequencies of the two emitted light waves have to differ enough to facilitate high-speed oscillation.

The laser light is generated in a semiconductor crystal, which is injected with electrons and electron holes. When they meet, light particles are released. The spin – an intrinsic form of angular momentum – of the injected electrons is indispensable in order to ensure the correct polarisation of light. Only if the electron spin is aligned in a certain way, the emitted light has the required polarisation – a challenge for the researchers, as spin alignment changes rapidly. This is why the researchers have to inject the electrons as closely as possible to the spot within the laser where the light particle is to be emitted. Hofmann's team has already applied for a patent with their idea of how this can be accomplished using a ferromagnetic material.

Frequency difference through double refraction

The frequency difference in the two emitted light waves that is required for oscillation is generated using a technology provided by the Ulm-based team headed by Professor Rainer Michalzik. The semiconductor crystal used for this purpose is birefringent. Accordingly, the refractive indices in the two perpendicularly polarised light waves emitted by the crystal differ slightly. As a result, the waves have different frequencies. By bending the semiconductor crystal, the researchers are able to adjust the difference between the refractive indices and, consequently, the frequency difference. That difference determines the oscillation speed, which may eventually become the foundation of accelerated data transfer.

"The system is not ready for application yet," concludes Martin Hofmann. "The technology has still to be optimised. By demonstrating the potential of spin lasers, we wish to open up a new area of research."



Spin lasers whose oscillation frequency can be mechanically controlled via the mount. Electrical contact can be made via an adjustable needle. Credit: RUB, Kramer

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One-way roads for spin currents

Spin is a type of angular momentum intrinsic to particles, roughly speaking as if they were spinning on themselves. Particles can exchange their spin, and in this way spin currents can be formed in a material. Through years of research, scientists have learned how to control such spin currents in an analogous way such that they can control the flow of electrons, the basis of a field of physics known as spintronics.

The study of the effect of strong interactions in quantum systems is particularly challenging. However, it is well known that strong interaction between quantum particles can completely change the properties of a system, making it, for instance, ferromagnetic, superconducting, etc. Strong interactions in spin systems can also allow for the generation of interesting transport properties in a material.

Researchers from Singapore University of Technology and Design (SUTD), University Insubria and Universidade Federal de Minas Gerais report a new approach to controlling spin currents based on strong spin-spin interactions, which results in diodes for spin current with a giant rectification. In this work, the researchers demonstrated analytically and via advanced numerical simulations that if the interactions are stronger than a certain magnitude, the system can drastically change and becomes an insulator, preventing currents from flowing. Interestingly, this drastic change to insulating behaviour only occurs when trying to impose the current in one direction. When trying to drive a spin current in the opposite direction, the flow is possible and the system is not an insulator.

These predictions could lead to substantial progress in material science, and new devices could be built based on this principle. The researchers propose experiments with atoms near absolute zero or with structures made of a few atoms deposited carefully on surfaces.

SUTD Assistant Professor D. Poletti, who led the research effort, says, "This is a very interesting effect we have stumbled upon. Much more interesting physics are yet to be uncovered in strongly interacting spintronic systems, and this can lead to the creation of new technologies." This research work was recently published in renowned American journal *Physical Review Letters*. [18]

Some superconductors can also carry currents of 'spin'

Researchers have shown that certain superconductors—materials that carry electrical current with zero resistance at very low temperatures—can also carry currents of 'spin'. The successful combination of superconductivity and spin could lead to a revolution in high-performance computing, by dramatically reducing energy consumption.

Spin is a particle's intrinsic angular momentum, and is normally carried in non-superconducting, non-magnetic materials by individual electrons. Spin can be 'up' or 'down', and for any given material, there is a maximum length that spin can be carried. In a conventional superconductor electrons with opposite spins are paired together so that a flow of electrons carries zero spin.

A few years ago, researchers from the University of Cambridge showed that it was possible to create electron pairs in which the spins are aligned: up-up or down-down. The spin current can be carried by up-up and down-down pairs moving in opposite directions with a net charge current of zero. The ability to create such a pure spin supercurrent is an important step towards the team's vision of creating a superconducting computing technology which could use massively less energy than the present silicon-based electronics.

Now, the same researchers have found a set of materials which encourage the pairing of spin-aligned electrons, so that a spin current flows more effectively in the superconducting state than in the non-superconducting (normal) state. Their results are reported in the journal *Nature Materials*.

"Although some aspects of normal state spin electronics, or spintronics, are more efficient than standard semiconductor electronics, the large-scale application has been prevented because the large charge currents required to generate spin currents waste too much energy," said Professor Mark Blamire of Cambridge's Department of Materials Science and Metallurgy, who led the research. "A fully-superconducting method of generating and controlling spin currents offers a way to improve on this."

In the current work, Blamire and his collaborators used a multi-layered stack of metal films in which each layer was only a few nanometres thick. They observed that when a microwave field was applied to the films, it caused the central magnetic layer to emit a spin current into the superconductor next to it.

"If we used only a superconductor, the spin current is blocked once the system is cooled below the temperature when it becomes a superconductor," said Blamire. "The surprising result was that when we added a platinum layer to the superconductor, the spin current in the superconducting state was greater than in the normal state."

Although the researchers have shown that certain superconductors can carry spin currents, so far these only occur over short distances. The next step for the research team is to understand how to increase the distance and how to control the spin currents. [17]

Spin-3/2 superconductor is a first, say physicists

The first known superconductor in which spin-3/2 quasiparticles form Cooper pairs has been created by physicists in the US and New Zealand. The unconventional superconductor is an alloy of yttrium, platinum and bismuth, which is normally a topological semimetal.

The research was done by Johnpierre Paglione and colleagues at the University of Maryland, Iowa State's Ames Laboratory, the Lawrence Berkeley National Laboratory and the Universities of Otago and Wisconsin.

Conventional superconductivity arises in a material when spin-1/2 electrons form “Cooper pairs” because of interactions between the electrons and vibrations of the material’s crystalline lattice. These pairs are bosons with integer (usually zero) spin, which means that at very low temperatures they can condense to form a state that conducts electrical current with no resistance.

Spin-orbit interaction

In the alloy studied by Paglione and colleagues, charge is carried by particle-like quasiparticles with spin-3/2. These quasiparticles arise from interactions between the spins of electrons and the positive charges of the atoms that make up the alloy. This effect is called spin-orbit coupling and is particularly strong in this material. The result is that the spin-3/2 state – which combines spin and orbital angular momentum – is the lowest energy state.

When the team cooled the material, they found that it is a superconductor at temperatures below about 800 mK. This came as a surprise because this temperature is nearly 1000 times higher than expected if the superconductivity involved conventional Cooper pairs.

Paglione and colleagues also studied how magnetic fields penetrate the material. Superconductors can expel magnetic fields but the process is not perfect, with some magnetic field lines penetrating the surface of the material and persisting to small depths. Measuring this penetration effect gives important details about the nature of the pairing responsible for superconductivity.

Mind the gap

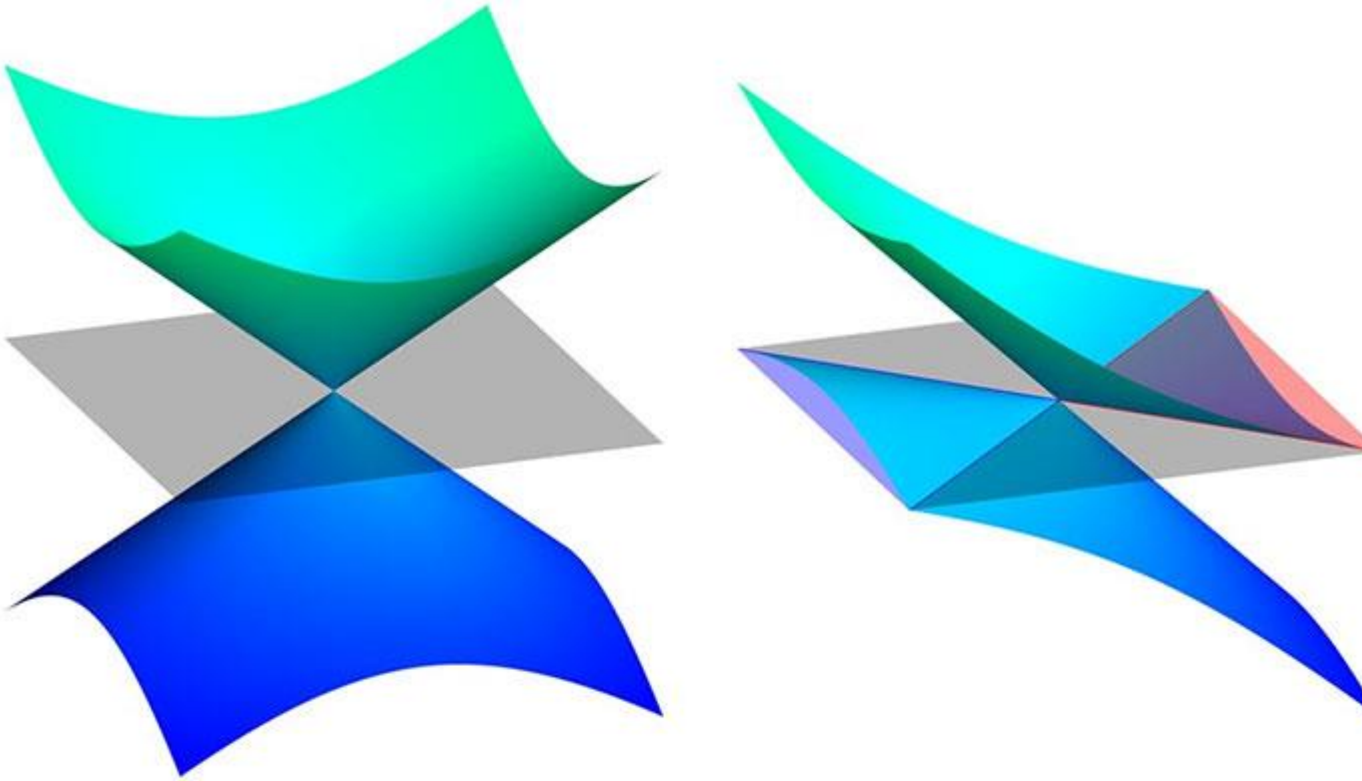
When the team measured the penetration depth as a function of temperature, they found that it increased linearly rather than exponentially – the latter being a characteristic of a conventional superconductor. This suggests that the energy gap between the superconducting and normal states of the material is not isotropic in space, as is the case in conventional superconductors.

This rule out spin-1/2 Cooper pairs so the team investigated other possibilities. They found that all possible pairings of spin-1/2 and spin-3/2 s in the alloy resulted in isotropic gaps except the case where two spin-3/2 quasiparticles join to make a pair with a combined spin of 3.

“No one had really thought that this was possible in solid materials,” says Paglione, adding it “was quite a surprise given the simplicity of the electronic structure in this system”.

Non-trivial topology

What is particularly exciting about the material, say the researchers, is the topological nature of how the superconductivity arises. The spin-3/2 quasiparticles are a result of topology related to the strong spin-orbit coupling. Paglione also says, “the superconductivity that forms may itself have a non-trivial topology”. “This is a more subtle thing and harder to prove,” he adds, “but essentially the phase of the superconducting wave function may have a ‘twist’ in it that gives a non-trivial (chiral) topology. This has profound implications, such as possibility of Majorana fermion excitations from the superconducting condensate.”



Type-II Dirac fermions spotted in two different materials

Paglione says that spin-3/2 superconductivity could exist in other materials and the phenomenon could have technological and fundamental applications. If such superconductors are indeed topological, he believes that they could form the basis for fault-tolerant quantum computers. On a fundamental level, he says that spin-3/2 fermions provide a very rich spectrum of possible pairing configurations for physicists to study – adding that their work has already garnered significant interest from other physicists.

Indeed, an important fundamental question, says Paglione, is how the spin-3/2 fermions pair up in the first place. “What’s the glue that holds these pairs together?” he asks. “There are some ideas of what might be happening, but fundamental questions remain – which makes it even more fascinating.”

The research is described in *Science Advances*. [16]

A different spin on superconductivity—Unusual particle interactions open up new possibilities in exotic materials

Now a team of researchers from the University of Maryland (UMD) Department of Physics together with collaborators has seen exotic superconductivity that relies on highly unusual electron interactions. While predicted to occur in other non-material systems, this type of behavior has remained elusive. The team's research, published in the April 6 issue of *Science Advances*, reveals effects that are profoundly different from anything that has been seen before with superconductivity.

Electron interactions in superconductors are dictated by a quantum property called spin. In an ordinary superconductor, electrons, which carry a spin of ½, pair up and flow uninhibited with the help of vibrations in the atomic structure. This theory is well-tested and can describe the behavior of most superconductors. In this new research, the team uncovers evidence for a new type of superconductivity in the material YPtBi, one that seems to arise from spin-3/2 particles.

"No one had really thought that this was possible in solid materials," explains Johnpierre Paglione, a UMD physics professor and senior author on the study. "High-spin states in individual atoms are possible but once you put the atoms together in a solid, these states usually break apart and you end up with spin one-half. "

Finding that YPtBi was a superconductor surprised the researchers in the first place. Most superconductors start out as reasonably good conductors, with a lot of mobile electrons—an ingredient that YPtBi is lacking. According to the conventional theory, YPtBi would need about a thousand times more mobile electrons in order to become superconducting at temperatures below 0.8 Kelvin. And yet, upon cooling the material to this temperature, the team saw superconductivity happen anyway. This was a first sign that something exotic was going on inside this material.

After discovering the anomalous superconducting transition, researchers made measurements that gave them insight into the underlying electron pairing. They studied a telling feature of superconductors—their interaction with magnetic fields. As the material undergoes the transition to a superconductor, it will try to expel any added magnetic field from its interior. But the expulsion is not completely perfect. Near the surface, the magnetic field can still enter the material but then quickly decays away. How far it goes in depends on the nature of the electron pairing, and changes as the material is cooled down further and further.

To probe this effect, the researchers varied the temperature in a small sample of the material while exposing it to a magnetic field more than ten times weaker than the Earth's. A copper coil surrounding the sample detected changes to the superconductor's magnetic properties and allowed the team to sensitively measure tiny variations in how deep the magnetic field reached inside the superconductor.

The measurement revealed an unusual magnetic intrusion. As the material warmed from absolute zero, the field penetration depth for YPtBi increased linearly instead of exponentially as it would for a conventional superconductor. This effect, combined with other measurements and theory calculations, constrained the possible ways that electrons could pair up. The researchers concluded that the best explanation for the superconductivity was electrons disguised as particles with a higher spin—a possibility that hadn't even been considered before in the framework of conventional superconductivity.

The discovery of this high-spin superconductor has given a new direction for this research field. "We used to be confined to pairing with spin one-half particles," says Hyunsoo Kim, lead author and a UMD assistant research scientist. "But if we start considering higher spin, then the landscape of this superconducting research expands and just gets more interesting."

For now, many open questions remain, including how such pairing could occur in the first place. "When you have this high-spin pairing, what's the glue that holds these pairs together?" says Paglione. "There are some ideas of what might be happening, but fundamental questions remain-which makes it even more fascinating." [15]

Scientists control superconductivity using spin currents

A group of researchers from institutions in Korea and the United States has determined how to employ a type of electron microscopy to cause regions within an iron-based superconductor to flip between superconducting and non-superconducting states. This study, published in the December 1 edition of *Physical Review Letters*, is the first of its kind, and it opens a door to a new way of manipulating and learning about superconductors.

The iron-based superconductors, one of which was studied in this work, are one of several classes of these fascinating materials, which have the ability to conduct electricity with virtually zero resistance below a certain temperature. Scientists are still working out the complex atomic-level details that underlie these materials' electronic and magnetic behaviors. The iron-based materials, in particular, are known to display intriguing phenomena related to co-existing superconducting and magnetic states.

Here, researchers studied a compound composed of strontium (Sr), vanadium (V), oxygen (O), iron (Fe), and arsenic (As), with a structure consisting of alternating FeAs and Sr_2VO_3 layers. They probed its magnetic and electronic properties with a spin-polarized scanning tunneling microscope (SPSTM), a device that passes an atomically sharp metal tip – just a few atoms wide – over the surface of a sample. The tip and the sample do not touch but are brought in quantum-scale proximity to each other so that a bias voltage applied between them causes a current to flow between the tip and the sample. In this case, the current is spin-polarized, meaning its electrons tend to have the same spin – the tiny magnetic field carried by an electron that points either "up" or "down," like a bar magnet.

Typically, this material's FeAs layer is strongly superconducting and prefers a certain magnetic order, dubbed C_2 order, that refers to how the magnetic fields of its atoms (which are due, in turn, to electron spins) are arranged. Results of the SPSTM scan show that the injected spin-polarized current, when sufficiently high, induces a different magnetic order, C_4 order, in the FeAs layer. In that same local area, superconductivity somehow magically disappears.

"To our knowledge, our study is the first report of a direct real-space observation of this type of control by a local probe, as well as the first atomic-scale demonstration of the correlation between magnetism and superconductivity," said the paper's corresponding author, Jhinhwan Lee, a physicist at the Korea Advanced Institute of Science and Technology, to *Phys.org*.

Lee and his group introduced new ways to perform SPSTM using an antiferromagnetic chromium (Cr) tip. An antiferromagnet is a material in which the magnetic fields of its atoms are ordered in an alternating up-down pattern such that it has a minimal stray magnetic field that can inadvertently kill local superconductivity (which can happen with ferromagnetic tips, such as Fe tips, that other SPSTM researchers use). They compared these Cr tip scans with those taken with an unpolarized tungsten (W) tip. At low bias voltages, the surface scans were qualitatively identical. But as the voltage was increased using the Cr tip, the surface started to change, revealing the C_4 magnetic symmetry. The C_4 order held even when the voltage was lowered again, although was erased when thermally annealed (heat-treated) beyond a specific temperature above which any magnetic order in the FeAs layer disappears.

To study the connection between the C_4 magnetic order and the suppression of superconductivity, Lee and his group performed high-resolution SPSTM scans of the C_4 state with Cr tips and compared them with simulations. The results led them to suggest one possible explanation: that the low-energy spin fluctuations in the C_4 state cannot mediate pairing between electrons. This is critical because this pairing of electrons, defying their natural urge to repel each other, leads to superconductivity.

Spin-fluctuation-based pairing is one theory of electron pairing in iron-based superconductors; another set of theories assume that fluctuations in the electron orbitals are the key. Lee and his group believe that their results seem to support the former, at least in this superconductor.

"Our findings may be extended to future studies where magnetism and superconductivity are manipulated using spin-polarized and unpolarized currents, leading to novel antiferromagnetic memory devices and transistors controlling superconductivity," said Lee. [14]

Researchers steer the flow of electrical current with spinning light

Light can generate an electrical current in semiconductor materials. This is how solar cells generate electricity from sunlight and how smart phone cameras can take photographs. To collect the generated electrical current, called photocurrent, an electric voltage is needed to force the current to flow in only one direction.

In new research, scientists at the University of Minnesota used a first-of-its-kind device to demonstrate a way to control the direction of the photocurrent without deploying an electric voltage. The new study was recently published in the scientific journal *Nature Communications*.

The study reveals that control is effected by the direction in which the particles of light, called photons, are spinning—clockwise or counterclockwise. The photocurrent generated by the spinning light is also spin-polarized, which means there are more electrons with spin in one direction than in the other. This new device holds significant potential for use in the next generation of microelectronics using electron spin as the fundamental unit of information. It could also be used for energy efficient optical communication in data centers.

"The observed effect is very strong and robust in our devices, even at room temperature and in open air," said Mo Li, a University of Minnesota electrical and computer engineering associate professor and a lead author of the study. "Therefore, the device we demonstrate has great potential for being implemented in next-generation computation and communication systems."

Optical spin and topological insulators

Light is a form of electromagnetic wave. The way the electric field oscillates, either in a straight line or rotating, is called polarization. (Your polarized sunglasses block part of the unpleasant reflected light that is polarized along a straight line.) In circularly polarized light, the electric field can spin in the clockwise or counterclockwise direction. In such a state, the particle of light (photon) is said to have positive or negative optical spin angular momentum. This optical spin is analogous to the spin of electrons, and endows magnetic properties to materials.

Recently, a new category of materials, called topological insulators (TI), was discovered to have an intriguing property not found in common semiconductor materials. Imagine a road on which red cars only drive on the left lane, and blue cars only in the right lane. Similarly, on the surface of a TI, the electrons with their spins pointing one way always flow in one direction. This effect is called spin-momentum locking—the spin of the electrons is locked in the direction they travel.

Interestingly, shining a circularly polarized light on a TI can free electrons from its inside to flow on its surface in a selective way, for example, clockwise light for spin-up electrons and counterclockwise for spin-down electrons. Because of this effect, the generated photocurrent on the surface of the TI material spontaneously flows in one direction, requiring no electric voltage. This particular feature is significant for controlling the direction of a photocurrent. Because most of the electrons in this current have their spins pointing in a single direction, this current is spin-polarized.

Controlling direction and polarization

To fabricate their unique device that can change the direction of a photocurrent without the use of an electric voltage, the University's research team integrated a thin film of a TI material, bismuth selenide, on an optical waveguide made of silicon. Light flows through the waveguide (a tiny wire measuring 1.5 microns wide and 0.22 micron high) just like electrical current flows through a copper wire. Because light is tightly squeezed in the waveguide, it tends to be circularly polarized along a direction normal to the direction in which it flows. This is akin to the spin-momentum locking effect of the electrons in a TI material.

The scientists supposed that integrating a TI material with the optical waveguide will induce strong coupling between the light in the waveguide and the electrons in the TI material, both having the same, intriguing spin-momentum locking effect. The coupling will result in a unique optoelectronic effect—light flowing along one direction in the waveguide generates an electrical current flowing in the same direction with electron spin polarized.

Reversing the light direction reverses both the direction of the current and its spin polarization. And this is exactly what the team observed in their devices. Other possible causes of the observed effect, such as heat generated by the light, have been ruled out through careful experiments.

Future prospects

The outcome of the research is exciting for the researchers. It bears enormous potential for possible applications.

"Our devices generate a spin-polarized current flowing on the surface of a topological insulator. They can be used as a current source for spintronic devices, which use electron spin to transmit and process information with very low energy cost," said Li He, a University of Minnesota physics graduate student and an author of the paper.

"Our research bridges two important fields of nanotechnology: spintronics and nanophotonics. It is fully integrated with a silicon photonic circuit that can be manufactured on a large scale and has already been widely used in optical communication in data centers," He added. [13]

Research demonstrates method to alter coherence of light

Brown University researchers have demonstrated for the first time a method of substantially changing the spatial coherence of light.

In a paper published in the journal Science Advances, the researchers show that they can use surface plasmon polaritons—propagating electromagnetic waves confined at a metal-dielectric interface—to transform light from completely incoherent to almost fully coherent and vice versa. The ability to modulate coherence could be useful in a wide variety of applications from structural coloration and optical communication to beam shaping and microscopic imaging.

"There had been some theoretical work suggesting that coherence modulation was possible, and some experimental results showing small amounts of modulation," said Dongfang Li, a postdoctoral researcher in Brown's School of Engineering and the study's lead author. "But this is the first time very strong modulation of coherence has been realized experimentally."

Coherence deals with the extent to which propagating electromagnetic waves are correlated with each other. Lasers, for example, emit light that's highly coherent, meaning the waves are strongly correlated. The sun and incandescent light bulbs emit weakly correlated waves, which are generally said to be "incoherent", although, more precisely, they are characterized by low yet measurable degrees of coherence.

"Coherence, like color and polarization, is a fundamental property of light," said Domenico Pacifici, an associate professor of engineering and physics at Brown and coauthor of the research. "We have filters that can manipulate the color of light and we have things like polarizing sunglasses that can manipulate polarization. The goal with this work was to find a way to manipulate coherence like we can these other properties."

To do that, Li and Pacifici took a classic experiment used to measure coherence, Young's double slit, and turned it into a device that can modulate coherence of light by controlling and finely tuning the interactions between light and electrons in metal films.

In the classic double-slit experiment, an opaque barrier is placed between a light source and a detector. The light passes through two parallel slits in the barrier to reach the detector on the other side. If the light shown on the barrier is coherent, the rays emanating from the slits will interfere with each other, creating an interference pattern on the detector—a series of bright and dark bands called interference fringes. The extent to which the light is coherent can be measured by the intensity of bands. If the light is incoherent, no bands will be visible.

"As this is normally done, the double-slit experiment simply measures the coherence of light rather than changing it," Pacifici said. "But by introducing surface plasmon polaritons, Young's double slits become a tool not just for measurement but also modulation."

To do that, the researchers used a thin metal film as the barrier in the double slit experiment. When the light strikes the film, surface plasmon polaritons—ripples of electron density created when the electrons are excited by light—are generated at each slit and propagate toward the opposite slit.

"The surface plasmon polaritons open up a channel for the light at each slit to talk to each other," Li said. "By connecting the two, we're able to change the mutual correlations between them and therefore change the coherence of light."

In essence, surface plasmon polaritons are able to create correlation where there was none, or to cancel any existing correlation that was there, depending on the nature of the light coming in and the distance between the slits.

One of the study's key results is the strength of the modulation they achieved. The technique is able to modulate coherence across a range from 0 percent (totally incoherent) to 80 percent (nearly full coherent). Modulation of such strength has never been achieved before, the researchers say, and it was made possible by using nanofabrication methods that allowed to maximize the generation efficiencies of surface plasmon polaritons existing on both surfaces of the slitted screen.

This initial proof-of-concept work was done at the micrometer scale, but Pacifici and Li say there's no reason why this couldn't be scaled up for use in a variety of settings.

"We've broken a barrier in showing that it's possible to do this," Pacifici said. "This clears the way for new two-dimensional beam shapers, filters and lenses that can manipulate entire optical beams by using the coherence of light as a powerful tuning knob." [12]

53 attoseconds: Research produces shortest light pulse ever developed

Researchers at the University of Central Florida have generated what is being deemed the fastest light pulse ever developed.

The 53-attosecond pulse, obtained by Professor Zenhgu Chang, UCF trustee chair and professor in the Center for Research and Education in Optics and Lasers, College of Optics and Photonics, and Department of Physics, and his group at the university, was funded by the U.S. Army Research Laboratory's Army Research Office.

Specifically, it was funded by ARO's Multidisciplinary University Research Initiative titled "Post-BornOppenheimer Dynamics Using Isolated Attosecond Pulses," headed by ARO's Jim Parker and Rich Hammond.

This beats the team's record of a 67-attosecond extreme ultraviolet light pulse set in 2012.

Attosecond light pulses allow scientists to capture images of fast-moving electrons in atoms and molecules with unprecedented sharpness, enabling advancements in solar panel technology, logic and memory chips for mobile phones and computers, and in the military in terms of increasing the speed of electronics and sensors, as well as threat identification.

"This is the shortest laser pulse ever produced," Hammond said. "It opens new doors in spectroscopy, allowing the identification of pernicious substances and explosive residue."

Hammond noted that this achievement is also a new and very effective tool to understand the dynamics of atoms and molecules, allowing observations of how molecules form and how electrons in atoms and molecules behave.

"This can also be extended to condensed matter systems, allowing unprecedented accuracy and detail of atomic, molecular, and even phase, changes," Hammond said. "This sets the stage for many new kinds of experiments, and pushes physics forward with the ability to understand matter better than ever before."

Chang echoed Hammond's sentiments about this achievement being a game-changer for continued research in this field.

"The photon energy of the attosecond X-ray pulses is two times higher than previous attosecond light sources and reached the carbon K-edge (284 eV), which makes it possible to probe and control core electron dynamics such as Auger processes," Chang said. "In condensed matter physics, the ultrafast electronic process in carbon containing materials, such as graphene and diamond, can be studied via core to valence transitions. In chemistry, electron dynamics in carbon containing molecules, such as carbon dioxide, Acetylene, Methane, etc., may now be studied by attosecond transient absorption, taking advantage of the element specificity."

This development is the culmination of years of ARO funding of attosecond science.

It all started with an ARO MURI about eight years ago titled "Attosecond Optical Technology Based on Recollision and Gating" from the Physics Division. This was followed by single investigator awards, Defense University Research Instrumentation Programs and finally an ARO MURI titled "Attosecond Electron Dynamics" from the Chemistry Division.

From the ARL/ARO perspective, Hammond said that this achievement, which included researchers from around the globe, shows how continued funding into fundamental research using several instruments, such as MURIs, DURIPS, and single investigator awards, can be used in a coherent and meaningful way to push the forward the frontiers of science.

Chang's team includes Jie Li, Xiaoming Ren, Yanchun Yin, Andrew Chew, Yan Cheng, Eric Cunningham, Yang Wang, Shuyuan Hu, and Yi Wu, who are all affiliated with the Institute for the

Frontier of Attosecond Science and Technology, or iFAST; Kun Zhao, who is also affiliated with the Chinese Academy of Sciences, and Michael Chini with the UCF Department of Physics. [11]

Method to significantly enhance optical force

Light consists of a flow of photons. If two waveguides – cables for light – are side by side, they attract or repel each other. The interaction is due to the optical force, but the effect is usually extremely small. Physicists at Chalmers University of Technology and Free University of Brussels have now found a method to significantly enhance optical force. The method opens new possibilities within sensor technology and nanoscience. The results were recently published in Physical Review Letters.

To make light behave in a completely new way, the scientists have studied waveguides made of an artificial material to trick the photons. The specially designed material makes all the photons move to one side of the waveguide. When the photons in a nearby waveguide do the same, a collection of photons suddenly gather very closely. This enhances the force between the waveguides up to 10 times.

"We have found a way to trick the photons so that they cluster together at the inner sides of the waveguides. Photons normally don't prefer left or right, but our metamaterial creates exactly that effect," says Philippe Tassin, Associate Professor at the Department of Physics at Chalmers University of Technology.

Philippe Tassin and Sophie Viaene at Chalmers and Lana Descheemaeker and Vincent Ginis at Free University of Brussels have developed a method to use the optical force in a completely new way. It can, for example, be used in sensors or to drive nanomotors. In the future, such motors might be used to sort cells or separate particles in medical technology.

"Our method opens up new opportunities for the use of waveguides in a range of technical applications. It is really exciting that man-made materials can change the basic characteristics of light propagation so dramatically," says Vincent Ginis, assistant professor at the Department of Physics at Free University of Brussels. [10]

Researchers demonstrate quantum teleportation of patterns of light

Nature Communications today published research by a team comprising Scottish and South African researchers, demonstrating entanglement swapping and teleportation of orbital angular momentum 'patterns' of light. This is a crucial step towards realizing a quantum repeater for high-dimensional entangled states.

Quantum communication over long distances is integral to information security and has been demonstrated in free space and fibre with two-dimensional states, recently over distances exceeding 1200 km between satellites. But using only two states reduces the information capacity of the photons, so the link is secure but slow. To make it secure and fast requires a higher-dimensional alphabet, for example, using patterns of light, of which there are an infinite number. One such pattern set is the orbital angular momentum (OAM) of light. Increased bit rates can be achieved by using OAM as the carrier of information. However, such photon states decay when transmitted over long distances, for example, due to mode coupling in fibre or turbulence in free space, thus requiring a way to amplify the signal. Unfortunately such "amplification" is not allowed in the quantum world, but it is possible to create an analogy, called a quantum repeater, akin to optical fibre repeaters in classical optical networks.

An integral part of a quantum repeater is the ability to entangle two photons that have never interacted - a process referred to as "entanglement swapping". This is accomplished by interfering two photons from independent entangled pairs, resulting in the remaining two photons becoming entangled. This allows the establishment of entanglement between two distant points without requiring one photon to travel the entire distance, thus reducing the effects of decay and loss. It also means that you don't have to have a line of sight between the two places.

An outcome of this is that the information of one photon can be transferred to the other, a process called teleportation. Like in the science fiction series, Star Trek, where people are "beamed" from one place to another, information is "teleported" from one place to another. If two photons are entangled and you change a value on one of them, then other one automatically changes too. This happens even though the two photons are never connected and, in fact, are in two completely different places.

In this latest work, the team performed the first experimental demonstration of entanglement swapping and teleportation for orbital angular momentum (OAM) states of light. They showed that quantum correlations could be established between previously independent photons, and that this could be used to send information across a virtual link. Importantly, the scheme is scalable to higher dimensions, paving the way for long-distance quantum communication with high information capacity.

Background

Present communication systems are very fast, but not fundamentally secure. To make them secure researchers use the laws of Nature for the encoding by exploiting the quirky properties of the quantum world. One such property is entanglement. When two particles are entangled they are connected in a spooky sense: a measurement on one immediately changes the state of the other no matter how far apart they are. Entanglement is one of the core resources needed to realise a quantum network.

Yet a secure quantum communication link over long distance is very challenging: Quantum links using patterns of light languish at short distances precisely because there is no way to protect the link against noise without detecting the photons, yet once they are detected their usefulness is destroyed. To overcome this one can have a repeating station at intermediate distances - this allows one to share information across a much longer distance without the need for the information to physically flow over that link. The core ingredient is to get independent photons to become entangled. While this has been demonstrated previously with two-dimensional states, in this work the team showed the first demonstration with OAM and in high-dimensional spaces. [9]

How to Win at Bridge Using Quantum Physics

Contract bridge is the chess of card games. You might know it as some stuffy old game your grandparents play, but it requires major brainpower, and preferably an obsession with rules and strategy. So how to make it even geekier? Throw in some quantum mechanics to try to gain a competitive advantage. The idea here is to use the quantum magic of entangled photons–which are essentially twins, sharing every property–to transmit two bits of information to your bridge partner for the price of one. Understanding how to do this is not an easy task, but it will help elucidate some basic building blocks of quantum information theory. It’s also kind of fun to consider whether or not such tactics could ever be allowed in professional sports. [6]

Quantum Information

In quantum mechanics, quantum information is physical information that is held in the "state" of a quantum system. The most popular unit of quantum information is the qubit, a two-level quantum system. However, unlike classical digital states (which are discrete), a two-state quantum system can actually be in a superposition of the two states at any given time.

Quantum information differs from classical information in several respects, among which we note the following:

However, despite this, the amount of information that can be retrieved in a single qubit is equal to one bit. It is in the processing of information (quantum computation) that a difference occurs.

The ability to manipulate quantum information enables us to perform tasks that would be unachievable in a classical context, such as unconditionally secure transmission of information. Quantum information processing is the most general field that is concerned with quantum information. There are certain tasks which classical computers cannot perform "efficiently" (that is, in polynomial time) according to any known algorithm. However, a quantum computer can compute the answer to some of these problems in polynomial time; one well-known example of this is Shor's factoring algorithm. Other algorithms can speed up a task less dramatically - for example, Grover's search algorithm which gives a quadratic speed-up over the best possible classical algorithm.

Quantum information, and changes in quantum information, can be quantitatively measured by using an analogue of Shannon entropy. Given a statistical ensemble of quantum mechanical systems with the density matrix S, it is given by.

Many of the same entropy measures in classical information theory can also be generalized to the quantum case, such as the conditional quantum entropy. [7]

Quantum Teleportation

Quantum teleportation is a process by which quantum information (e.g. the exact state of an atom or photon) can be transmitted (exactly, in principle) from one location to another, with the help of classical communication and previously shared quantum entanglement between the sending and receiving location. Because it depends on classical communication, which can proceed no faster than the speed of light, it cannot be used for superluminal transport or communication of classical bits. It also cannot be used to make copies of a system, as this violates the no-cloning theorem. Although the name is inspired by the teleportation commonly used in fiction, current technology provides no possibility of anything resembling the fictional form of teleportation. While it is possible to teleport one or more qubits of information between two (entangled) atoms, this has not yet been achieved between molecules or anything larger. One may think of teleportation either as a kind of transportation, or as a kind of communication; it provides a way of transporting a qubit from one location to another, without having to move a physical particle along with it.

The seminal paper first expounding the idea was published by C. H. Bennett, G. Brassard, C. Crépeau, R. Jozsa, A. Peres and W. K. Wootters in 1993. Since then, quantum teleportation has been realized in various physical systems. Presently, the record distance for quantum teleportation is 143 km (89 mi) with photons, and 21 m with material systems. In August 2013, the achievement of "fully deterministic" quantum teleportation, using a hybrid technique, was reported. On 29 May 2014, scientists announced a reliable way of transferring data by quantum teleportation. Quantum teleportation of data had been done before but with highly unreliable methods. [8]

Quantum Computing

A team of electrical engineers at UNSW Australia has observed the unique quantum behavior of a pair of spins in silicon and designed a new method to use them for "2-bit" quantum logic operations.

These milestones bring researchers a step closer to building a quantum computer, which promises dramatic data processing improvements.

Quantum bits, or qubits, are the building blocks of quantum computers. While many ways to create a qubits exist, the Australian team has focused on the use of single atoms of phosphorus, embedded inside a silicon chip similar to those used in normal computers.

The first author on the experimental work, PhD student Juan Pablo Dehollain, recalls the first time he realized what he was looking at.

"We clearly saw these two distinct quantum states, but they behaved very differently from what we were used to with a single atom. We had a real 'Eureka!' moment when we realized what was happening – we were seeing in real time the `entangled' quantum states of a pair of atoms." [5]

Quantum Entanglement

Measurements of physical properties such as position, momentum, spin, polarization, etc. performed on entangled particles are found to be appropriately correlated. For example, if a pair of particles is generated in such a way that their total spin is known to be zero, and one particle is found to have clockwise spin on a certain axis, then the spin of the other particle, measured on the same axis, will be found to be counterclockwise. Because of the nature of quantum measurement, however, this behavior gives rise to effects that can appear paradoxical: any measurement of a property of a particle can be seen as acting on that particle (e.g. by collapsing a number of superimposed states); and in the case of entangled particles, such action must be on the entangled system as a whole. It thus appears that one particle of an entangled pair "knows" what measurement has been performed on the other, and with what outcome, even though there is no known means for such information to be communicated between the particles, which at the time of measurement may be separated by arbitrarily large distances. [4]

The Bridge

The accelerating electrons explain not only the Maxwell Equations and the Special Relativity, but the Heisenberg Uncertainty Relation, the wave particle duality and the electron's spin also, building the bridge between the Classical and Quantum Theories. [1]

Accelerating charges

The moving charges are self maintain the electromagnetic field locally, causing their movement and this is the result of their acceleration under the force of this field. In the classical physics the charges will distributed along the electric current so that the electric potential lowering along the current, by linearly increasing the way they take every next time period because this accelerated motion. The same thing happens on the atomic scale giving a dp impulse difference and a dx way difference between the different part of the not point like particles.

Relativistic effect

Another bridge between the classical and quantum mechanics in the realm of relativity is that the charge distribution is lowering in the reference frame of the accelerating charges linearly: $ds/dt = at$ (time coordinate), but in the reference frame of the current it is parabolic: $s = a/2\ t^2$ (geometric coordinate).

Heisenberg Uncertainty Relation

In the atomic scale the Heisenberg uncertainty relation gives the same result, since the moving electron in the atom accelerating in the electric field of the proton, causing a charge distribution on delta x position difference and with a delta p momentum difference such a way that they product is about the half Planck reduced constant. For the proton this delta x much less in the nucleon, than in the orbit of the electron in the atom, the delta p is much higher because of the greater proton mass.

This means that the electron and proton are not point like particles, but has a real charge distribution.

Wave – Particle Duality

The accelerating electrons explains the wave – particle duality of the electrons and photons, since the elementary charges are distributed on delta x position with delta p impulse and creating a wave packet of the electron. The photon gives the electromagnetic particle of the mediating force of the electrons electromagnetic field with the same distribution of wavelengths.

Atomic model

The constantly accelerating electron in the Hydrogen atom is moving on the equipotential line of the proton and it's kinetic and potential energy will be constant. Its energy will change only when it is changing its way to another equipotential line with another value of potential energy or getting free with enough kinetic energy. This means that the Rutherford-Bohr atomic model is right and only that changing acceleration of the electric charge causes radiation, not the steady acceleration. The steady acceleration of the charges only creates a centric parabolic steady electric field around the charge, the magnetic field. This gives the magnetic moment of the atoms, summing up the proton and electron magnetic moments caused by their circular motions and spins.

The Relativistic Bridge

Commonly accepted idea that the relativistic effect on the particle physics it is the fermions' spin - another unresolved problem in the classical concepts. If the electric charges can move only with accelerated motions in the self maintaining electromagnetic field, once upon a time they would reach the velocity of the electromagnetic field. The resolution of this problem is the spinning particle, constantly accelerating and not reaching the velocity of light because the acceleration is radial. One origin of the Quantum Physics is the Planck Distribution Law of the electromagnetic oscillators, giving equal intensity for 2 different wavelengths on any temperature. Any of these two wavelengths will give equal intensity diffraction patterns, building different asymmetric constructions, for example proton - electron structures (atoms), molecules, etc. Since the particles are centers of diffraction patterns they also have particle – wave duality as the electromagnetic waves have. [2]

The weak interaction

The weak interaction transforms an electric charge in the diffraction pattern from one side to the other side, causing an electric dipole momentum change, which violates the CP and time reversal symmetry. The Electroweak Interaction shows that the Weak Interaction is basically electromagnetic in nature. The arrow of time shows the entropy grows by changing the temperature dependent diffraction patterns of the electromagnetic oscillators.

Another important issue of the quark model is when one quark changes its flavor such that a linear oscillation transforms into plane oscillation or vice versa, changing the charge value with 1 or -1. This kind of change in the oscillation mode requires not only parity change, but also charge and time changes (CPT symmetry) resulting a right handed anti-neutrino or a left handed neutrino.

The right handed anti-neutrino and the left handed neutrino exist only because changing back the quark flavor could happen only in reverse, because they are different geometrical constructions, the u is 2 dimensional and positively charged and the d is 1 dimensional and negatively charged. It needs also a time reversal, because anti particle (anti neutrino) is involved.

The neutrino is a 1/2spin creator particle to make equal the spins of the weak interaction, for example neutron decay to 2 fermions, every particle is fermions with ½ spin. The weak interaction changes the entropy since more or less particles will give more or less freedom of movement. The entropy change is a result of temperature change and breaks the equality of oscillator diffraction intensity of the Maxwell–Boltzmann statistics. This way it changes the time coordinate measure and makes possible a different time dilation as of the special relativity.

The limit of the velocity of particles as the speed of light appropriate only for electrical charged particles, since the accelerated charges are self maintaining locally the accelerating electric force. The neutrinos are CP symmetry breaking particles compensated by time in the CPT symmetry, that is the time coordinate not works as in the electromagnetic interactions, consequently the speed of neutrinos is not limited by the speed of light.

The weak interaction T-asymmetry is in conjunction with the T-asymmetry of the second law of thermodynamics, meaning that locally lowering entropy (on extremely high temperature) causes the weak interaction, for example the Hydrogen fusion.

Probably because it is a spin creating movement changing linear oscillation to 2 dimensional oscillation by changing d to u quark and creating anti neutrino going back in time relative to the proton and electron created from the neutron, it seems that the anti neutrino fastest then the velocity of the photons created also in this weak interaction?

A quark flavor changing shows that it is a reflection changes movement and the CP- and T-symmetry breaking!!! This flavor changing oscillation could prove that it could be also on higher level such as atoms, molecules, probably big biological significant molecules and responsible on the aging of the life.
Important to mention that the weak interaction is always contains particles and antiparticles, where the neutrinos (antineutrinos) present the opposite side. It means by Feynman's interpretation that these particles present the backward time and probably because this they seem to move faster than the speed of light in the reference frame of the other side.

Finally since the weak interaction is an electric dipole change with ½ spin creating; it is limited by the velocity of the electromagnetic wave, so the neutrino's velocity cannot exceed the velocity of light.

The General Weak Interaction

The Weak Interactions T-asymmetry is in conjunction with the T-asymmetry of the Second Law of Thermodynamics, meaning that locally lowering entropy (on extremely high temperature) causes for example the Hydrogen fusion. The arrow of time by the Second Law of Thermodynamics shows the increasing entropy and decreasing information by the Weak Interaction, changing the temperature dependent diffraction patterns. A good example of this is the neutron decay, creating more particles with less known information about them.

The neutrino oscillation of the Weak Interaction shows that it is a general electric dipole change and it is possible to any other temperature dependent entropy and information changing diffraction pattern of atoms, molecules and even complicated biological living structures.

We can generalize the weak interaction on all of the decaying matter constructions, even on the biological too. This gives the limited lifetime for the biological constructions also by the arrow of time. There should be a new research space of the Quantum Information Science the 'general neutrino oscillation' for the greater then subatomic matter structures as an electric dipole change. There is also connection between statistical physics and evolutionary biology, since the arrow of time is working in the biological evolution also.
The Fluctuation Theorem says that there is a probability that entropy will flow in a direction opposite to that dictated by the Second Law of Thermodynamics. In this case the Information is growing that is the matter formulas are emerging from the chaos. So the Weak Interaction has two directions, samples for one direction is the Neutron decay, and Hydrogen fusion is the opposite direction.

Fermions and Bosons

The fermions are the diffraction patterns of the bosons such a way that they are both sides of the same thing.

Van Der Waals force

Named after the Dutch scientist Johannes Diderik van der Waals – who first proposed it in 1873 to explain the behaviour of gases – it is a very weak force that only becomes relevant when atoms and molecules are very close together. Fluctuations in the electronic cloud of an atom mean that it will have an instantaneous dipole moment. This can induce a dipole moment in a nearby atom, the result being an attractive dipole–dipole interaction.

Electromagnetic inertia and mass

Electromagnetic Induction

Since the magnetic induction creates a negative electric field as a result of the changing acceleration, it works as an electromagnetic inertia, causing an electromagnetic mass. [1]

Relativistic change of mass

The increasing mass of the electric charges the result of the increasing inductive electric force acting against the accelerating force. The decreasing mass of the decreasing acceleration is the result of the inductive electric force acting against the decreasing force. This is the relativistic mass change explanation, especially importantly explaining the mass reduction in case of velocity decrease.

The frequency dependence of mass

Since $\boldsymbol{E = h\nu}$ and $\boldsymbol{E = mc^2}$, $\boldsymbol{m = h\nu / c^2}$ that is the $\boldsymbol{m}$ depends only on the $\boldsymbol{\nu}$ frequency. It means that the mass of the proton and electron are electromagnetic and the result of the electromagnetic induction, caused by the changing acceleration of the spinning and moving charge! It could be that the $\boldsymbol{m_o}$ inertial mass is the result of the spin, since this is the only accelerating motion of the electric charge. Since the accelerating motion has different frequency for the electron in the atom and the proton, they masses are different, also as the wavelengths on both sides of the diffraction pattern, giving equal intensity of radiation.

Electron – Proton mass rate

The Planck distribution law explains the different frequencies of the proton and electron, giving equal intensity to different lambda wavelengths! Also since the particles are diffraction patterns they have some closeness to each other – can be seen as a gravitational force. [2]

There is an asymmetry between the mass of the electric charges, for example proton and electron, can understood by the asymmetrical Planck Distribution Law. This temperature dependent energy distribution is asymmetric around the maximum intensity, where the annihilation of matter and antimatter is a high probability event. The asymmetric sides are creating different frequencies of electromagnetic radiations being in the same intensity level and compensating each other. One of these compensating ratios is the electron – proton mass ratio. The lower energy side has no compensating intensity level, it is the dark energy and the corresponding matter is the dark matter.

Gravity from the point of view of quantum physics

The Gravitational force

The gravitational attractive force is basically a magnetic force.

The same electric charges can attract one another by the magnetic force if they are moving parallel in the same direction. Since the electrically neutral matter is composed of negative and positive charges they need 2 photons to mediate this attractive force, one per charges. The Bing Bang caused parallel moving of the matter gives this magnetic force, experienced as gravitational force.

Since graviton is a tensor field, it has spin = 2, could be 2 photons with spin = 1 together.

You can think about photons as virtual electron – positron pairs, obtaining the necessary virtual mass for gravity.

The mass as seen before a result of the diffraction, for example the proton – electron mass rate Mp=1840 Me. In order to move one of these diffraction maximum (electron or proton) we need to intervene into the diffraction pattern with a force appropriate to the intensity of this diffraction maximum, means its intensity or mass.

The Big Bang caused acceleration created radial currents of the matter, and since the matter is composed of negative and positive charges, these currents are creating magnetic field and attracting forces between the parallel moving electric currents. This is the gravitational force experienced by the matter, and also the mass is result of the electromagnetic forces between the charged particles. The positive and negative charged currents attracts each other or by the magnetic forces or by the much stronger electrostatic forces!?

The gravitational force attracting the matter, causing concentration of the matter in a small space and leaving much space with low matter concentration: dark matter and energy.
There is an asymmetry between the mass of the electric charges, for example proton and electron, can understood by the asymmetrical Planck Distribution Law. This temperature dependent energy distribution is asymmetric around the maximum intensity, where the annihilation of matter and antimatter is a high probability event. The asymmetric sides are creating different frequencies of electromagnetic radiations being in the same intensity level and compensating each other. One of these compensating ratios is the electron – proton mass ratio. The lower energy side has no compensating intensity level, it is the dark energy and the corresponding matter is the dark matter.

The Higgs boson

By March 2013, the particle had been proven to behave, interact and decay in many of the expected ways predicted by the Standard Model, and was also tentatively confirmed to have + parity and zero spin, two fundamental criteria of a Higgs boson, making it also the first known scalar particle to be discovered in nature, although a number of other properties were not fully proven and some partial results do not yet precisely match those expected; in some cases data is also still awaited or being analyzed.

Since the Higgs boson is necessary to the W and Z bosons, the dipole change of the Weak interaction and the change in the magnetic effect caused gravitation must be conducted. The Wien law is also important to explain the Weak interaction, since it describes the T_{max} change and the diffraction patterns change. [2]

Higgs mechanism and Quantum Gravity

The magnetic induction creates a negative electric field, causing an electromagnetic inertia. Probably it is the mysterious Higgs field giving mass to the charged particles? We can think about the photon as an electron-positron pair, they have mass. The neutral particles are built from negative and positive charges, for example the neutron, decaying to proton and electron. The wave – particle duality makes sure that the particles are oscillating and creating magnetic induction as an inertial mass, explaining also the relativistic mass change. Higher frequency creates stronger magnetic induction, smaller frequency results lesser magnetic induction. It seems to me that the magnetic induction is the secret of the Higgs field.

In particle physics, the Higgs mechanism is a kind of mass generation mechanism, a process that gives mass to elementary particles. According to this theory, particles gain mass by interacting with the Higgs field that permeates all space. More precisely, the Higgs mechanism endows gauge bosons in a gauge theory with mass through absorption of Nambu–Goldstone bosons arising in spontaneous symmetry breaking.

The simplest implementation of the mechanism adds an extra Higgs field to the gauge theory. The spontaneous symmetry breaking of the underlying local symmetry triggers conversion of components of this Higgs field to Goldstone bosons which interact with (at least some of) the other fields in the theory, so as to produce mass terms for (at least some of) the gauge bosons. This mechanism may also leave behind elementary scalar (spin-0) particles, known as Higgs bosons.

In the Standard Model, the phrase "Higgs mechanism" refers specifically to the generation of masses for the $W^{\pm}$, and Z weak gauge bosons through electroweak symmetry breaking. The Large Hadron Collider at CERN announced results consistent with the Higgs particle on July 4, 2012 but stressed that further testing is needed to confirm the Standard Model.

What is the Spin?

So we know already that the new particle has spin zero or spin two and we could tell which one if we could detect the polarizations of the photons produced. Unfortunately this is difficult and neither ATLAS nor CMS are able to measure polarizations. The only direct and sure way to confirm that the particle is indeed a scalar is to plot the angular distribution of the photons in the rest frame of the centre of mass. A spin zero particles like the Higgs carries no directional information away from the original collision so the distribution will be even in all directions. This test will be possible when a much larger number of events have been observed. In the mean time we can settle for less certain indirect indicators.

The Graviton

In physics, the graviton is a hypothetical elementary particle that mediates the force of gravitation in the framework of quantum field theory. If it exists, the graviton is expected to be massless (because the gravitational force appears to have unlimited range) and must be a spin-2 boson. The spin follows from the fact that the source of gravitation is the stress-energy tensor, a second-rank tensor (compared to electromagnetism's spin-1 photon, the source of which is the four-current, a first-rank tensor). Additionally, it can be shown that any massless spin-2 field would give rise to a force indistinguishable from gravitation, because a massless spin-2 field must couple to (interact with) the stress-energy tensor in the same way that the gravitational field does. This result suggests that, if a massless spin-2 particle is discovered, it must be the graviton, so that the only experimental verification needed for the graviton may simply be the discovery of a massless spin-2 particle. [3]

Conclusions

In August 2013, the achievement of "fully deterministic" quantum teleportation, using a hybrid technique, was reported. On 29 May 2014, scientists announced a reliable way of transferring data by quantum teleportation. Quantum teleportation of data had been done before but with highly unreliable methods. [8]

One of the most important conclusions is that the electric charges are moving in an accelerated way and even if their velocity is constant, they have an intrinsic acceleration anyway, the so called spin, since they need at least an intrinsic acceleration to make possible they movement .

The accelerated charges self-maintaining potential shows the locality of the relativity, working on the quantum level also. [1]

The bridge between the classical and quantum theory is based on this intrinsic acceleration of the spin, explaining also the Heisenberg Uncertainty Principle. The particle – wave duality of the electric charges and the photon makes certain that they are both sides of the same thing. The Secret of Quantum Entanglement that the particles are diffraction patterns of the electromagnetic waves and this way their quantum states every time is the result of the quantum state of the intermediate electromagnetic waves. [2]

The key breakthrough to arrive at this new idea to build qubits was to exploit the ability to control the nuclear spin of each atom. With that insight, the team has now conceived a unique way to use the nuclei as facilitators for the quantum logic operation between the electrons. [5]

Basing the gravitational force on the accelerating Universe caused magnetic force and the Planck Distribution Law of the electromagnetic waves caused diffraction gives us the basis to build a Unified Theory of the physical interactions also.

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