

# Light Spectrum Identify Molecules

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*By hitting electrons with an ultra-intense laser, researchers have revealed dynamics that go beyond 'classical' physics and hint at quantum effects. [18]*

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*Researchers at the Harvard John A. Paulson School of Engineering and Applied Sciences, together with collaborators from the Fu Foundation School of Engineering and Applied Science at Columbia University, have developed a system to convert one wavelength of light into another without the need to phase match. [15]*

*Light, which travels at a speed of 300,000 km/sec in a vacuum, can be slowed down and even stopped completely by methods that involve trapping the light inside crystals or ultracold clouds of atoms. [14]*

*A research team led by physicists at LMU Munich reports a significant advance in laser-driven particle acceleration. [13]*

*And now, physicists at the Department of Energy's Lawrence Berkeley National Laboratory (Berkeley Lab) and their collaborators have demonstrated that computers are ready to tackle the universe's greatest mysteries. [12]*

*The Nuclear Physics with Lattice Quantum Chromodynamics Collaboration (NPLQCD), under the umbrella of the U.S. Quantum Chromodynamics Collaboration, performed the first model-independent calculation of the rate for proton-proton fusion directly from the dynamics of quarks and gluons using numerical techniques. [11]*

*Nuclear physicists are now poised to embark on a new journey of discovery into the fundamental building blocks of the nucleus of the atom. [10]*

*The drop of plasma was created in the Large Hadron Collider (LHC). It is made up of two types of subatomic particles: quarks and gluons. Quarks are the building blocks of particles like protons and neutrons, while gluons are in charge of the strong interaction force between quarks. The new quark-gluon plasma is the hottest liquid that has ever been created in a laboratory at 4 trillion C (7 trillion F). Fitting for a plasma like the one at the birth of the universe. [9]*

*Taking into account the Planck Distribution Law of the electromagnetic oscillators, we can explain the electron/proton mass ratio and the Weak and Strong Interactions. Lattice QCD gives the same results as the diffraction patterns of the electromagnetic oscillators, explaining the color confinement and the asymptotic freedom of the Strong Interactions.*

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## Preface

The diffraction patterns of the electromagnetic oscillators give the explanation of the Electroweak and Electro-Strong interactions. [2] Lattice QCD gives the same results as the diffraction patterns which explain the color confinement and the asymptotic freedom.

The hadronization is the diffraction pattern of the baryons giving the jet of the color – neutral particles!

## A laser, a crystal and molecular structures: New tool uses wider light spectrum to identify molecules

Researchers have built a new tool to study molecules using a laser, a crystal and light detectors. This new technology will reveal the structures of molecules with increased detail and specificity.

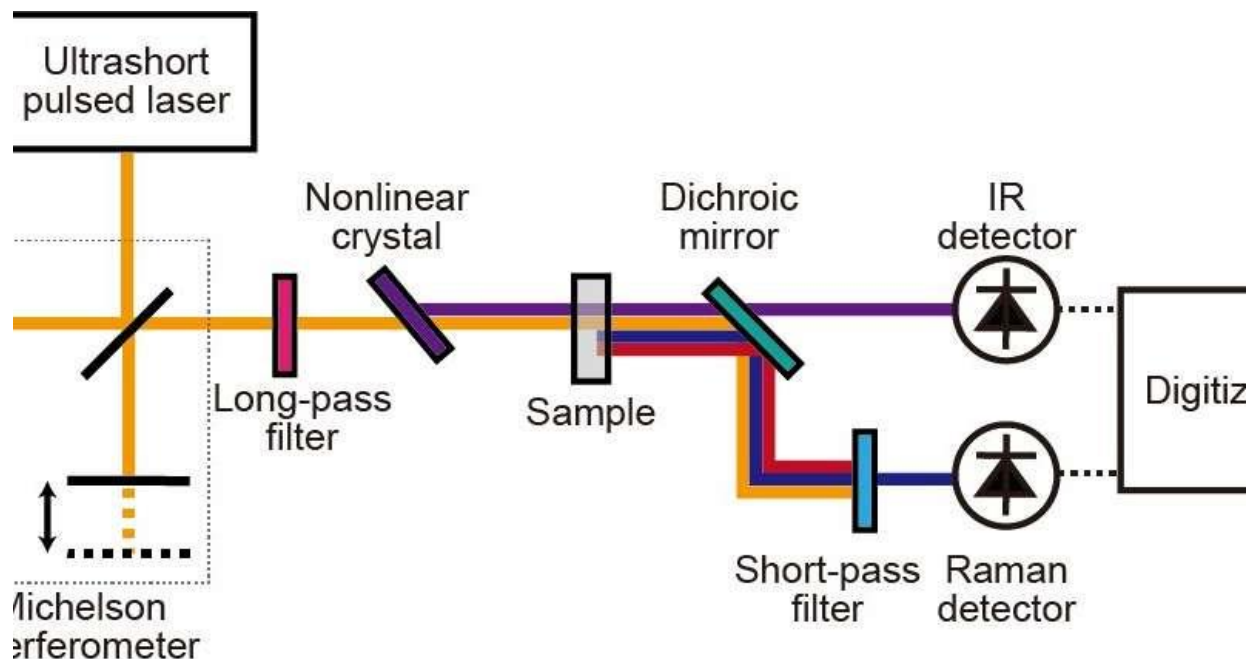
"We live in the molecular world where most things around us are made of molecules: air, foods, drinks, clothes, cells and more. Studying molecules with our new technique could be used in medicine, pharmacy, chemistry, or other fields," said Associate Professor Takuro Ideguchi from the University of Tokyo Institute for Photon Science and Technology.

The new technique combines two current technologies into a unique system called complementary vibrational [spectroscopy](#). All molecules have very small, distinctive vibrations caused by the movement of the atoms' nuclei. Tools called spectrometers detect how those vibrations cause molecules to absorb or scatter light waves. Current spectroscopy techniques are limited by the type of light that they can measure.

The new complementary vibrational spectrometer designed by researchers in Japan can measure a wider spectrum of light, combining the more limited spectra of two other tools, called infrared absorption and

Raman scattering spectrometers. Combining the two spectroscopy techniques gives researchers different and complementary information about molecular vibrations.

"We questioned the 'common sense' of this field and developed something new. Raman and infrared spectra can now be measured simultaneously," said Ideguchi.



Complementary vibrational spectroscopy is based on a dual-modal Fourier-transform spectrometer with an ultrashort pulsed laser. The Raman measurement is made by Fourier-transform coherent Raman scattering spectroscopy. The infrared measurement is made by Fourier-transform infrared absorption spectroscopy with infrared light generated at a nonlinear crystal. Credit: Takuro Ideguchi

Previous spectrometers could only detect light waves with lengths from 0.4 to 1 micrometer (Raman spectroscopy) or from 2.5 to 25 micrometers (infrared spectroscopy). The gap between them meant that Raman and [infrared spectroscopy](#) had to be performed separately. The limitation is like trying to enjoy a duet, but being forced to listen to the two parts separately.

Complementary vibrational spectroscopy can detect light waves around the visible to near-infrared and mid-infrared spectra. Advancements in ultrashort pulsed laser technology have made complementary vibrational spectroscopy possible.

Inside the complementary vibrational spectrometer, a titanium-sapphire laser sends pulses of near-infrared light with the width of 10 femtoseconds (10 quadrillionths of a second) towards the chemical sample. Before hitting the sample, the light is focused onto a crystal of gallium selenide. The crystal generates mid-infrared light pulses. The near- and mid-infrared light pulses are then focused onto the sample, and the absorbed and scattered [light](#) waves are detected by photodetectors and converted simultaneously into Raman and infrared spectra.

So far, researchers have tested their new technique on samples of pure chemicals commonly found in science labs. They hope that the technique will one day be used to understand how molecules change shape in real time.

"Especially for biology, we use the term 'label-free' for molecular vibrational spectroscopy because it is noninvasive and we can identify [molecules](#) without attaching artificial fluorescent tags. We believe that complementary vibrational spectroscopy can be a unique and useful technique for molecular measurements," said Ideguchi. [19]

## **Intense laser experiments provide first evidence that light can stop electrons**

By hitting electrons with an ultra-intense laser, researchers have revealed dynamics that go beyond 'classical' physics and hint at quantum effects.

Whenever light hits an object, some of the light scatters back from the surface of the object. However, if the object is moving extremely fast, and if the light is incredibly intense, strange things can happen.

Electrons, for example, can be shaken so violently that they actually slow down because they radiate so much energy. Physicists call this process 'radiation reaction'.

This radiation reaction is thought to occur around objects such as black holes and quasars ([supermassive black holes](#) surrounded by a disc of gas). Being able to measure radiation reaction in the lab will therefore provide insights into processes that occur in some of the most extreme environments in the universe.

Radiation reaction is also interesting to physicists studying effects beyond 'classical' physics, as the equations (known as Maxwell's equations) that traditionally define the forces acting on objects fall short in these [extreme environments](#).

Now, a team of researchers led by Imperial College London have demonstrated radiation reaction in the lab for the first time. Their results are published today in the journal *Physical Review X*.

They were able to observe this radiation reaction by colliding a laser beam one quadrillion (a billion million) times brighter than light at the surface of the Sun with a high-energy beam of electrons. The experiment, which required extreme precision and exquisite timing, was achieved using the Gemini laser at the Science and Technology Facilities Council's Central Laser Facility in the UK.

Photons of light that reflect from an object moving close to the speed of light have their energy increased. In the extreme conditions of this experiment, this shifts the reflected light from the visible part of the spectrum all the way up to high energy gamma rays. This effect let the researchers know when they had successfully collided the beams.

Senior author of the study, Dr. Stuart Mangles from the Department of Physics at Imperial, said: "We knew we had been successful in colliding the two beams when we detected very bright high energy gamma-ray radiation.

"The real result then came when we compared this detection with the energy in the electron beam after the collision. We found that these successful collisions had a lower than expected electron energy, which is clear evidence of radiation reaction."

Study co-author Professor Alec Thomas, from Lancaster University and the University of Michigan, added: "One thing I always find so fascinating about this is that the electrons are stopped as effectively by this sheet of light, a fraction of a hair's breadth thick, as by something like a millimetre of lead. That is extraordinary."

The data from the experiment also agrees better with a theoretical model based on the principles of quantum electrodynamics, rather than Maxwell's equations, potentially providing some of the first evidence of previously untested quantum models.

Study co-author Professor Mattias Marklund of Chalmers University of Technology, Sweden whose group were involved in the study, said: "Testing our theoretical predictions is of central importance for us at Chalmers, especially in new regimes where there is much to learn. Paired with theory, these experiments are a foundation for high-intensity laser research in the quantum domain."

However more experiments at even higher intensity or with even higher energy electron beams will be needed to confirm if this is true. The team will be carrying out these experiments in the coming year.

The team were able to make the [light](#) so intense in the current experiment by focussing it to a very small spot (just a few micrometres—millionths of a metre—across) and delivering all the [energy](#) in a very short duration (just 40 femtoseconds long: 40 quadrillionths of a second).

To make the electron beam small enough to interact with the focussed laser, the team used a technique called 'laser wakefield acceleration'.

The laser wakefield technique fires another intense laser pulse into a gas. The [laser](#) turns the gas into a plasma and drives a wave, called the wakefield, behind it as it travels through the plasma. Electrons in the plasma can surf on this wake and reach very high energies in a very short distance. [18]

## What causes ionic wind?

The phenomenon of ionic wind has been known about for centuries: by applying a voltage to a pair of electrodes, electrons are stripped off nearby air molecules, and the ionized air collides with neutral air molecules as it moves from one electrode to the other. The effect is easy enough to produce that it often appears at science fairs, and may even have a future in spacecraft propulsion. However, exactly what causes ionic wind is still an open question.

In a new paper published in *Nature Communications*, a team of researchers from South Korea and Slovenia has experimentally investigated how ionic wind is caused when [charged particles](#) collide with [neutral particles](#). One of their main findings is that electrons—and not only ions—play an important role in generating ionic wind, prompting them to call the effect "electric wind."

"In general, the electric wind has been called an 'ionic wind' because only the positive and negative ions have been considered as key players," coauthor Wonho Choe, Professor at the Korea Advanced Institute of Science and Technology, told *Phys.org*. "In our study, however, both electrons and ions participate in the generation of electric wind, depending on the polarity of the biased electrode. So the use of nomenclature for the 'ionic wind' requires a new consensus. We use the term 'electric wind' instead of 'ionic wind,' as our key finding indicates that electrons are the main player rather than negative ions such as  $O^{2-}$  and  $O^-$  during the negative voltage period."

In their experiments, the researchers generated a neutral helium flow and a pulsed plasma jet at various voltages. Then they used a technique called Schlieren photography (which is often used to photograph airplanes in flight) to take pictures of the flows of these particles. By controlling the pulse width and height of the plasma jet, the researchers monitored how these changes affect the particles' movement and the resulting wind.

As this is the first experiment to clearly show the coupling between neutral and charged particles in a plasma, the results provide direct evidence of what happens as the electrons and ions push the neutral particles away. The resulting momentum transfer causes a charged particle drag, which generates an electrohydrodynamic force (one caused by charged particles), giving rise to a clearly observable wind of charged particles.

"The electric wind was previously considered to be a result of collisional momentum transfer from accelerated charged particles and neutral particles, based on heuristic observations and experiments," Choe said. "However, as mentioned in our paper, there was no convincing evidence regarding the major mechanism (the correlation between plasma and momentum transfer) for the generation of electric wind, which is created during either the 'streamer propagation (ionization wave)' or the 'space charge drift.' Our model experiments clearly show that the contribution of the moving plasma streamer to electric wind generation is negligible, and the electric wind is mainly caused by the residual space charges after the plasma streamer propagates and collapses."

The results should lead to a better understanding of the interactions between charged and neutral particles in various situations, and has potential applications in areas such as flow control engineering.

"Our findings may have applications for reducing the drag force on a vehicle, resulting in the reduction of fuel consumption and nitrogen oxides, which are an environmental pollutant and one of the major sources of micro dusts," Choe said. "It may also reduce flow separation on wind turbine blades."

The researchers also plan to investigate potential applications with plasmas.

"One of the recent interesting topics in the plasma community is the selective control of chemical production by low-temperature air plasmas," Choe said. "We have planned research to study a correlation between plasma chemicals and electric wind. We may also investigate the possible correlation between the electric wind and the plasma ball, a phenomenon that can occur when lightning strikes." [17]

## Physicists Just Found a New Way to Bend a Fundamental Rule of Light Waves

One of the more well-known rules in physics is that light can only ever go one speed, so long as nothing stands in its way.

But new research has found there could be an interesting exception to this rule, where the mixing of light waves could bring them to a complete standstill.

The discovery hints at new ways of wrangling not just photons but nearly any kind of wave, which could be useful in technology that relies on information sent and stored using light.

Delaying light's journey isn't itself all that hard. Put a bunch of atoms in their way, and photons will take their time slipping in and out of the forest of particles.

Chill those particles right down so they lose their individual identities, and [light can be set into slow motion](#) and [even stopped completely](#) as it passes through the cloud.

[More recently](#), it's been shown that light's pathway can be affected by changing its angular momentum, effectively twisting it so it takes longer than its usual 299,792,458 metres per second to get from A to B.

A small group of physicists from the Israel Institute of Technology and the Institute for Pure and Applied Mathematics (IMPA) in Brazil have now come up with another method, showing it's theoretically possible to weave waves of light together in such a way that they stop dead in their tracks.

The trick relies on tuning the light waves so they meet at what's called an exceptional point – mathematical jargon that describes how the features of different waves match one another at a given coordinate.

Exceptional points were little more than mathematical concepts until fairly recently, when [researchers demonstrated experimentally](#) that they could be created by confining microwaves within a narrow grid.

When we talk about light waves, most of us imagine ripples of varying heights and length.

Light is of course defined by qualities such as wavelength and frequency, but it also has numerous other properties that form repeating patterns as photons traverse space.

These patterns can be tweaked by constraining their properties using things called [waveguides](#), so two light waves can coalesce within the same space. This combination of properties described as an exceptional point gives rise to some interesting behaviours.

Last year researchers [applied these points to the development of sensors](#) that could respond to the smallest disruptions.

Now physicists have shown using mathematical models that it's possible to use a kind of waveguide that balances the wave's energy to produce an exceptional point where light stands still.



By toggling the set-up in such a way that the waves can gain or lose energy, the light waves can be made to coalesce and freeze, or speed up and resume their journey out the other side.

If we're to be particularly pedantic, we shouldn't imagine it as photons standing still waiting for the go signal. No fundamental laws are being broken.

Just as light passing through a medium or being twisted is still technically moving at light speed, the photons in these waves are caught in a figurative electromagnetic whirlwind based on their interactions at the exceptional point.

For now, this achievement is still just by the numbers – a light-stopping device based on exceptional points hasn't been built.

But if it does, we'd have another way to manipulate waves of light. The researchers also speculate that the same concepts technically apply to any kind of wave, including sound.

Given photons are quickly becoming the new electrons [in information technology](#), we need all the tools we can find to get a firm grip on these speedy little particles.

This research was published in [Physical Review Letters](#). [16]

## **Integrated metasurface converts colors of light over broadband inside a waveguide**

One of the biggest challenges in developing integrated photonic circuits—which use light rather than electrons to transport information—is to control the momentum of light. Colors of light travel at different speeds through a material but in order for light to be converted between colors, it needs to have the same momentum or phase.

Many devices have been designed to [momentum](#)-match or phase-match [light](#) at various points throughout an integrated circuit but what if the phase-matching process could be circumvented all together in certain cases?

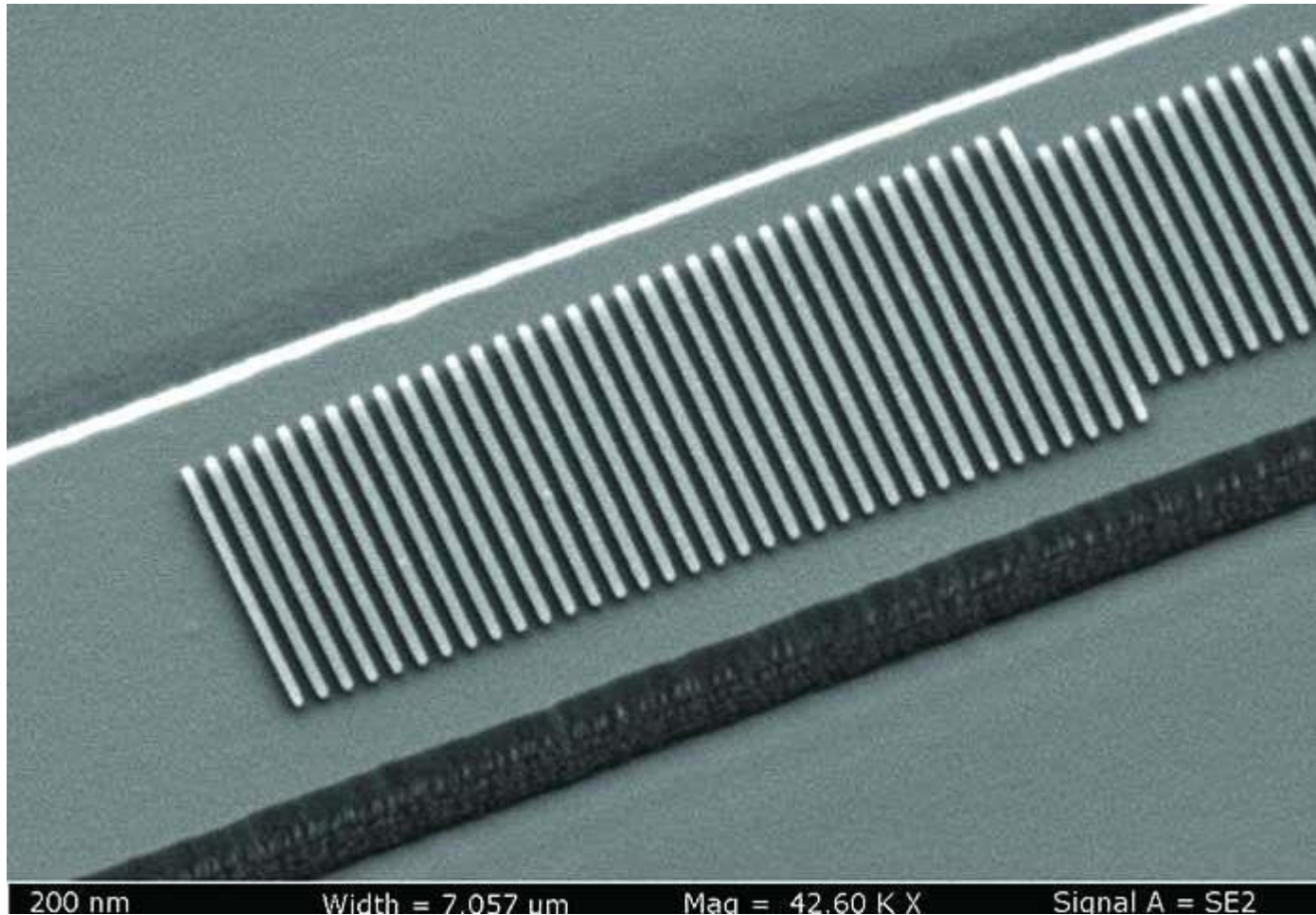
Researchers at the Harvard John A. Paulson School of Engineering and Applied Sciences, together with collaborators from the Fu Foundation School of Engineering and Applied Science at Columbia University, have developed a system to convert one wavelength of light into another without the need to phase match.

The research was published in *Nature Communications*.

"For any wavelength conversion process to be efficient, it has to be carefully designed to phase match, and it only works at a single wavelength," said Marko Loncar, the Tiansai Lin Professor of Electrical Engineering at SEAS and senior author of the paper. "The devices shown in this work, in contrast, do not need to satisfy the phase-matching requirement, and can convert light in a broad [color](#) range."

The converter relies on a metasurface, consisting of an array of [silicon nanostructures](#), integrated into a lithium niobate waveguide. The light passes through waveguide, interacting with the nanostructures along

the way. The array of nanostructures act like a TV antenna—receiving the optical signal, manipulating its momentum and re-emitting it back into the waveguide.



Scanning electron microscope (SEM) image of the fabricated device. Credit: Loncar Lab/Harvard SEAS

"Unlike most metasurfaces, where light travels perpendicularly to the metasurface, here light interacts with the metasurface while being confined inside a waveguide," said Cheng Wang, co-first author of the paper and postdoctoral fellow at SEAS. "In this way, we take advantage of both the momentum control from the metasurface and a long interaction distance."

The researchers demonstrated that they could double the frequency of a wavelength, converting near infrared colors to red, with high efficiency over a broad bandwidth. In previous research, the team demonstrated that they could also control and convert the polarization and mode of a guided wave using a similar structure.

"The integrated [metasurface](#) is distinct from other phase-matching mechanisms in that it provides a unidirectional optical momentum to couple optical energy from one to another color components—while inhibiting the inverse process—which is critical for realizing broadband nonlinear conversion," said Nanfang Yu, assistant professor of applied physics at Columbia and a co-senior author of the paper. "Future work will demonstrate broadband integrated photonic devices based on metasurfaces for realizing other functions such as optical modulation." [15]

## Speed of light drops to zero at 'exceptional points'

Light, which travels at a speed of 300,000 km/sec in a vacuum, can be slowed down and even stopped completely by methods that involve trapping the light inside crystals or ultracold clouds of atoms. Now in a new study, researchers have theoretically demonstrated a new way to bring light to a standstill: they show that light stops at "exceptional points," which are points at which two light modes come together and coalesce, in waveguides that have a certain kind of symmetry.

Unlike most other methods that are used to stop light, the new method can be tuned to work with a wide range of frequencies and bandwidths, which may offer an important advantage for future slow-light applications.

The researchers, Tamar Goldzak and Nimrod Moiseyev at the Technion – Israel Institute of Technology, along with Alexei A. Mailybaev at the Instituto de Matemática Pura e Aplicada (IMPA) in Rio de Janeiro, have published a paper on stopping light at exceptional points in a recent issue of *Physical Review Letters*.

As the researchers explain, exceptional points can be created in waveguides in a straightforward way, by varying the gain/loss parameters so that two light modes coalesce (combine into one mode). Although light stops at these exceptional points, in most systems much of the light is lost at these points. The researchers showed that this problem can be fixed by using waveguides with parity-time (PT) symmetry, since this symmetry ensures that the gain and loss are always balanced. As a result, the [light intensity](#) remains constant when the light approaches the exceptional point, eliminating losses.

To release the stopped light and accelerate it back up to normal speed, the scientists showed that the gain/loss parameters can simply be reversed. The most important feature of the new method, however, is that the exceptional points can be adjusted to work with any frequency of light, again simply by tuning the gain/loss parameters. The researchers also expect that this [method](#) can be used for other types of waves besides [light](#), such as acoustic waves. They plan to further investigate these possibilities in the future. [14]

## Playing billiards with a laser beam

A research team led by physicists at LMU Munich reports a significant advance in laser-driven particle acceleration. Using tiny plastic beads as targets, they have produced proton bunches that possess unique features, opening up new opportunities for future studies.

In their experiments, a team led by [physicists](#) at LMU Munich fired a powerful laser pulse at a micrometer-sized plastic sphere, blasting a bunch of protons from the target and accelerating them to velocities approaching the speed of light. The resulting velocity distribution is much narrower than that obtained when thin metal foils are used as targets. The physicist now present their research results in the scientific journal *Nature Communications*

Recent years have seen remarkable advances in the development of a new approach to the acceleration of [subatomic particles](#). This strategy makes use of the intense electric fields associated with pulsed, high-energy laser beams to accelerate electrons and protons to 'relativistic' velocities (i.e. speeds approaching that of light). Hitherto, the laser shot has generally been directed at a thin metal foil, generating and accelerating a plasma of [free electrons](#) and positively charged ions. Physicists at LMU have now replaced the foil target by a plastic microsphere with a diameter of one-millionth of a meter. These beads are so tiny that they cannot be stably positioned by mechanical means. Instead, the researchers use an electric field to levitate the target particle. Using a feedback circuit, the levitated bead can be trapped with sufficient precision to ensure that it does not drift off the beam axis. The electromagnetic trap was designed and built in the Department of Medical Physics at LMU.

"The basic approach is analogous to collisions between billiard balls. In our experiment, one of the balls is made of light and the other is our tiny levitated target," explains Peter Hilz, who led the experiments. This novel approach to the generation of [proton](#) beams will make experiments feasible which have hitherto been out of reach. [13]

## Applying machine learning to the universe's mysteries

Computers can beat chess champions, simulate star explosions, and forecast global climate. We are even teaching them to be infallible problem-solvers and fast learners.

And now, physicists at the Department of Energy's Lawrence Berkeley National Laboratory (Berkeley Lab) and their collaborators have demonstrated that computers are ready to tackle the universe's greatest mysteries. The team fed thousands of images from simulated high-energy particle collisions to train computer networks to identify important features.

The researchers programmed powerful arrays known as neural networks to serve as a sort of hivelike digital brain in analyzing and interpreting the images of the simulated particle debris left over from the collisions. During this test run the researchers found that the neural networks had up to a 95 percent success rate in recognizing important features in a sampling of about 18,000 images.

The study was published Jan. 15 in the journal *Nature Communications*.

The next step will be to apply the same machine learning process to actual experimental data.

Powerful machine learning algorithms allow these networks to improve in their analysis as they process more images. The underlying technology is used in facial recognition and other types of image-based object recognition applications.

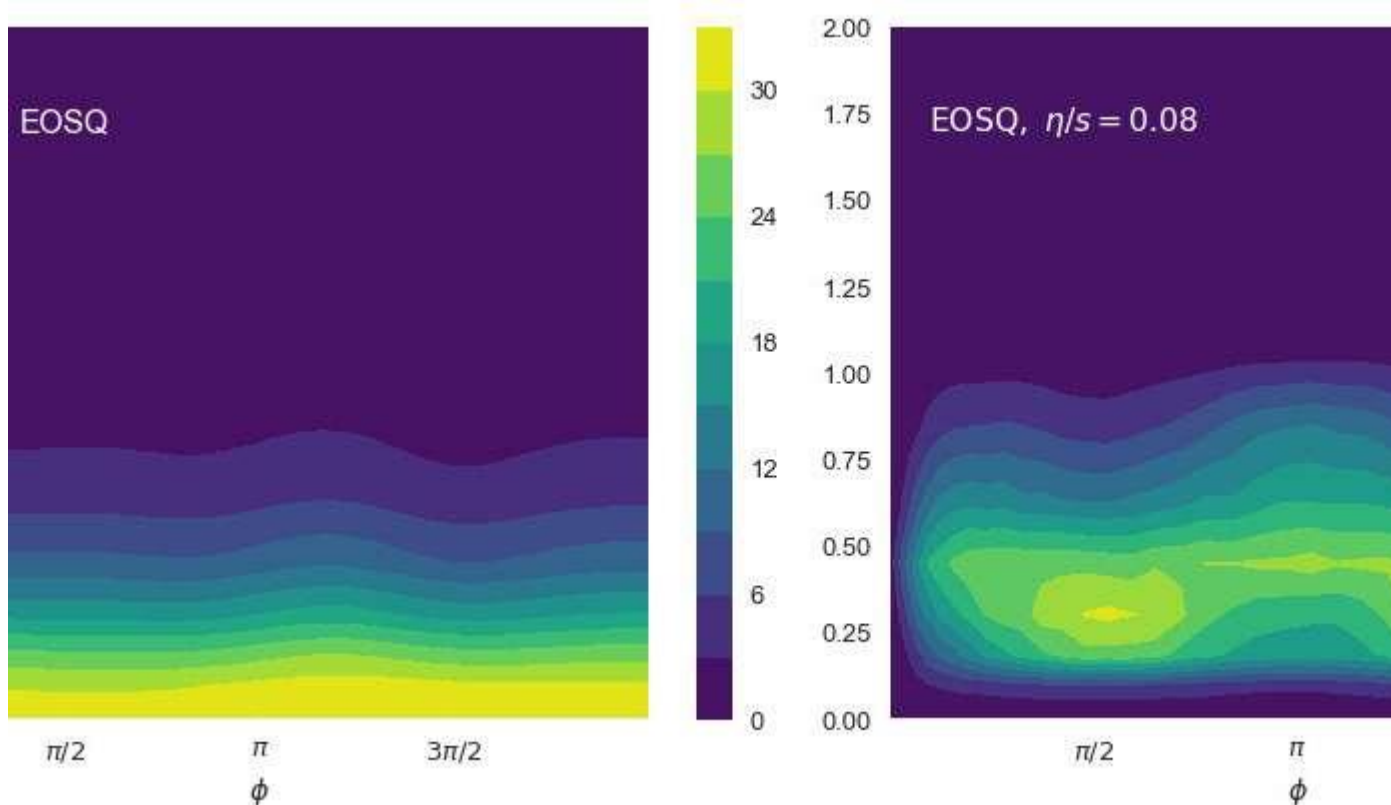
The images used in this study - relevant to particle-collider nuclear physics experiments at Brookhaven National Laboratory's Relativistic Heavy Ion Collider and CERN's Large Hadron Collider - recreate the conditions of a subatomic particle "soup," which is a superhot fluid state known as the quark-gluon plasma believed to exist just millionths of a second after the birth of the universe. Berkeley Lab physicists participate in experiments at both of these sites.

"We are trying to learn about the most important properties of the quark-gluon plasma," said Xin-Nian Wang, a nuclear physicist in the Nuclear Science Division at Berkeley Lab who is a member of the team. Some of these properties are so short-lived and occur at such tiny scales that they remain shrouded in mystery.

In experiments, nuclear physicists use particle colliders to smash together heavy nuclei, like gold or lead atoms that are stripped of electrons. These collisions are believed to liberate particles inside the atoms' nuclei, forming a fleeting, subatomic-scale fireball that breaks down even protons and neutrons into a free-floating form of their typically bound-up building blocks: quarks and gluons.

Researchers hope that by learning the precise conditions under which this quark-gluon plasma forms, such as how much energy is packed in, and its temperature and pressure as it transitions into a fluid state, they will gain new insights about its component particles of matter and their properties, and about the universe's formative stages.

But exacting measurements of these properties - the so-called "equation of state" involved as matter changes from one phase to another in these collisions - have proven challenging. The initial conditions in the experiments can influence the outcome, so it's challenging to extract equation-of-state measurements that are independent of these conditions.



The diagram at left, which maps out particle distribution in a simulated high-energy heavy-ion collision, includes details on particle momentum and angles. Thousands of these images were used to train and test a neural network to identify [...more](#)

"In the nuclear physics community, the holy grail is to see phase transitions in these high-energy interactions, and then determine the equation of state from the experimental data," Wang said. "This is the most important property of the [quark-gluon plasma](#) we have yet to learn from experiments."

Researchers also seek insight about the fundamental forces that govern the interactions between quarks and gluons, what physicists refer to as quantum chromodynamics.

Long-Gang Pang, the lead author of the latest study and a Berkeley Lab-affiliated postdoctoral researcher at UC Berkeley, said that in 2016, while he was a postdoctoral fellow at the Frankfurt Institute for Advanced Studies, he became interested in the potential for artificial intelligence (AI) to help solve challenging science problems.

He saw that one form of AI, known as a deep convolutional neural network - with architecture inspired by the image-handling processes in animal brains - appeared to be a good fit for analyzing science-related images.

"These networks can recognize patterns and evaluate board positions and selected movements in the game of Go," Pang said. "We thought, 'If we have some visual scientific data, maybe we can get an abstract concept or valuable physical information from this.'"

Wang added, "With this type of machine learning, we are trying to identify a certain pattern or correlation of patterns that is a unique signature of the equation of state." So after training, the network can pinpoint on its own the portions of and correlations in an image, if any exist, that are most relevant to the problem scientists are trying to solve.

Accumulation of data needed for the analysis can be very computationally intensive, Pang said, and in some cases it took about a full day of computing time to create just one image. When researchers employed an array of GPUs that work in parallel - GPUs are graphics processing units that were first created to enhance video game effects and have since exploded into a variety of uses - they cut that time down to about 20 minutes per image.

They used computing resources at Berkeley Lab's National Energy Research Scientific Computing Center (NERSC) in their study, with most of the computing work focused at GPU clusters at GSI in Germany and Central China Normal University in China.

A benefit of using sophisticated neural networks, the researchers noted, is that they can identify features that weren't even sought in the initial experiment, like finding a needle in a haystack when you weren't even looking for it. And they can extract useful details even from fuzzy images.

"Even if you have low resolution, you can still get some important information," Pang said.

Discussions are already underway to apply the machine learning tools to data from actual heavy-ion collision experiments, and the simulated results should be helpful in training [neural networks](#) to interpret the real data.

"There will be many applications for this in high-energy particle physics," Wang said, beyond particle-collider experiments. [12]

## Large-scale simulations of quarks promise precise view of reactions of astrophysical importance

The fusion of two protons initiates the primary nuclear cycle that powers the Sun. The rate of this low-energy, weak-interaction fusion is too small to be measured in the laboratory. While nuclear model predictions for this reaction are impressive, calculations without models would reduce uncertainties and offer a more accurate view of proton-proton fusion and related processes. Using a technique called lattice quantum chromodynamics, scientists performed the first successful model-independent calculation of the proton-proton fusion rate directly from the fundamental dynamics of quarks and gluons (the building blocks of protons and nuclei).

This work paves the way to calculate the rate of proton-proton [fusion](#), and similar nuclear reactions of astrophysical importance, with new levels of precision.

The Nuclear Physics with Lattice Quantum Chromodynamics Collaboration (NPLQCD), under the umbrella of the U.S. Quantum Chromodynamics Collaboration, performed the first model-independent [calculation](#) of the rate for proton-proton fusion directly from the dynamics of quarks and gluons using numerical techniques. The rate of this process is too small to be measured in the laboratory today for two reasons: the electrostatic repulsion between the low-energy protons and the small weak interaction rates. The team achieved the theoretical prediction for this process through calculations in which [electrostatic repulsion](#) was removed and the weak interaction rates were increased to provide access to the critical elements of the process.

These were then restored using systematic approximations to the underlying physical theory (effective field theory techniques) in making the prediction for the reaction rate. The first lattice [quantum](#) chromodynamics calculation of the strength of the weak transition between the triton and helium-3 (which carry significant information of spin interactions in nuclear medium) was also performed in this work and found to be consistent with experimental measurements. These calculations used lattice quantum chromodynamics, a technique in which space-time is represented by a finite grid of points, and the quantum fields describing the quarks and gluons are defined on these points and the links between them, respectively. This method provides an evaluation of the quantum chromodynamics path integral, through Monte Carlo sampling of the quantum mechanical motion of the quarks and gluons (the subatomic particles that bind the quarks together).

This method is completely controlled and can be systematically improved and refined by reducing the physical distance between the grid points, by increasing the volume of space-time, and by increasing the sampling of the path integral. This work used configurations ("snapshots" of the quantum-mechanical vacuum) generated using the Chroma software suite developed within DOE's Scientific Discovery through Advanced Computing funded U.S. Quantum Chromodynamics Collaboration. Existing algorithms and code for forming nuclear correlation functions in lattice quantum chromodynamics calculations and new algorithms including the interactions of quarks with external probes, developed within NPLQCD, were used to calculate the key quantities that determine the rate for proton-proton fusion.

The results of these calculations were connected to nature using effective field theory techniques. Understanding gained in NPLQCD's calculations of the thermal neutron capture process  $n+p \rightarrow d+\gamma$  was used in making this connection. With increased computational resources, these calculations can be systematically refined to provide an uncertainty in the rate for proton-proton fusion, and similar nuclear reactions, which is significantly smaller than is possible with other techniques. This breakthrough was made possible by algorithmic developments and high-performance supercomputing resources. [11]

## **Jefferson Lab completes 12 GeV upgrade of the Continuous Electron Beam Accelerator Facility**

Nuclear physicists are now poised to embark on a new journey of discovery into the fundamental building blocks of the nucleus of the atom. The completion of the 12 GeV Upgrade Project of the Continuous Electron Beam Accelerator Facility (CEBAF) at the Department of Energy's Thomas Jefferson National Accelerator Facility (Jefferson Lab) heralds this new era to image nuclei at their deepest level.

The unique capabilities of the newly upgraded CEBAF pushes the boundaries of the precision frontier ever deeper into the heart of matter and enables a full range of research opportunities. Completed on time and on budget, the \$338 million upgrade has tripled CEBAF's original operating energy and commissioned a new experimental area dedicated to providing insight into one of the universe's great mysteries: why the fundamental constituents of matter, quarks, may never be found in isolation. The three existing experimental areas were also upgraded to allow the 3D imaging of the quarks in nuclei and to facilitate unique searches for new physics.

Project completion follows on the successful commissioning of the last two experimental areas in the spring. Jefferson Lab staff then worked diligently to install and commission the last, individual pieces of equipment needed for full operations in each of its four experimental halls. With that work completed, the laboratory received official notification from DOE on Wednesday, Sept. 27, of the formal approval of Critical Decision 4 (CD-4), Approve Project Completion and Start of Operations.

"The advanced capabilities of the upgraded CEBAF accelerator and detectors to search for exotic new particles, departures from nature's symmetries, and details of quark behavior inside nuclei at a scale previously inaccessible promise a truly exciting watershed of scientific discovery," said Dr. Tim Hallman, Associate Director for Nuclear Physics in DOE's Office of Science.

"The 12 GeV CEBAF Upgrade Project team is thrilled to reach the successful conclusion of this complex project," said Allison Lung, Jefferson Lab's Chief Planning Officer and Director of the 12 GeV CEBAF Upgrade Project. "This moment is a culmination of the dedication and the hard work of hundreds of Jefferson Lab staff members, Users, and subcontractors."

CEBAF, an Office of Science User Facility, is the world's most advanced particle accelerator for investigating the quark structure of the atom's nucleus. Based on superconducting radiofrequency (SRF) technology, the accelerator produces a stream of charged electrons that scientists use to probe the nucleus of the atom, its protons and neutrons, and their quarks and gluons. Its higher energy electron beams provide the cleanest probes of nuclear matter at the highest intensities



ever achieved, enabling precision experiments that were once thought beyond our reach for deepening our understanding of nuclear matter.

The CEBAF accelerator was originally designed to provide electrons at energies of 4 billion electronvolts, or 4 GeV, although efficiencies in its design and extensive experience in running the facility allowed Jefferson Lab operators to eventually achieve 6 GeV electron beams in its original configuration. The \$338 million, multi-year 12 GeV CEBAF Upgrade Project tripled CEBAF's original operating energy.

The project entailed the addition of 10 new accelerating units to CEBAF to increase its energy, the construction of a fourth experimental hall, as well as an additional arc of magnets and an extension of the accelerator tunnel to deliver beam to the hall. In addition, other utility and equipment upgrades were made, including an addition to the refrigeration plant that enables CEBAF's SRF technology and new and upgraded equipment to the existing experimental halls to capitalize on the more energetic electron beams for experiments.

CEBAF can now deliver its full-energy electron beams, up to 12 GeV, to the Hall D complex, and up to 11 GeV electron beams into its original experimental areas, Halls A, B and C.

"The kind of research that we pursue explores the most fundamental mysteries," said Lung. "And completing the upgrade paves the way for the resumption of Jefferson Lab's scientific program in earnest, with expanded capabilities that will allow an unprecedented glimpse into the heart of matter."

The newly upgraded CEBAF enables a diverse and compelling program of experiments proposed by the lab's 1,500-member community of scientists who come to Jefferson Lab from around the world to conduct their research.

"The scientists who rely on our facilities to provide the capabilities they need to carry out groundbreaking research are the reason we are here," said Stuart Henderson, Jefferson Lab Director.

"Jefferson Lab is entering an exciting new era of scientific discovery, powered by the 12 GeV Upgrade and the research it will enable, on behalf of our Users and the DOE."

"This is a momentous occasion met with great excitement following extensive preparations by our entire community of scientists, postdocs and Ph.D. students," said Krishna Kumar, a professor at Stonybrook University and chairperson of the Jefferson Lab Users Group Board of Directors, which represents scientists who conduct their research at Jefferson Lab. "We can now deploy the entire arsenal of unique capabilities of the upgraded CEBAF to carry out measurements with precision and accuracy that would not be possible elsewhere in the world and thus make new discoveries about the forces among the fundamental building blocks of matter."

With the upgraded machine, scientists will probe how quarks interact, how they spin, and how they are distributed inside protons and neutrons. CEBAF's energetic probes and precision beams will enable the first three-dimensional views of the structure of protons and neutrons. And researchers have already initiated groundbreaking studies of the strong force, the force that glues matter together, in the laboratory's newest experimental hall.

Scientists will also use CEBAF to push the limits of our understanding of the Standard Model of Particle Physics, a theory that describes fundamental particles and their interactions in terms of the strong, weak and electromagnetic forces. CEBAF probes the Standard Model in two ways: by testing its predictions for the structure of protons and neutrons, and also by testing its completeness with high-precision measurements at low energies, where discrepancies could reveal signatures of new forms of matter.

The extension of CEBAF's experimental reach into the heart of matter has drawn the interest and kindled excitement of researchers worldwide. The laboratory's User community has grown from 1,200 in the pre-12 GeV Upgrade era to more than 1,500 today. Thus far, 78 experiments have been approved for running with the 12 GeV upgraded CEBAF. Of those, four experiments were already completed during the initial facility commissioning and ramp up. CEBAF is currently scheduled to begin full operations in December.

The 12 GeV CEBAF Upgrade Project began in 2004, when the DOE recognized that it filled a "mission need" in the field of nuclear physics with the approval of Critical Decision Zero (CD-0). This critical decision process approval allowed the laboratory to proceed with conceptual design, and planning of project acquisition and execution. Project engineering and design efforts began in 2006, followed by finalization of project definition in 2007, start of construction in 2008 and approval of initial operations in 2014.

CEBAF is the world's most powerful microscope for studying the nucleus of the atom. The CEBAF accelerator is cooled to within a few degrees of absolute zero to enable its superconducting components. If it weren't superconducting, it would require three times as much power to operate, and performance would be greatly reduced. The mass of an object increases as its speed increases, so at 12 billion electron-Volts (12 GeV), the electrons in the CEBAF beam increase in mass 23,500 times. [10]

## **Physicists Recreate Substance Similar To The Plasma Believed To Have Existed At The Very Beginning Of The Universe**

The first seconds of the universe were filled with a boiling, chaotic inferno. It was packed with a dense plasma: a soup-like fire, made up of some of the tiniest particles in the universe.

Unbelievably, physicists have recreated a substance that they think is very similar to this early universe plasma. Albeit, just the tiniest drop.

The drop of plasma was created in the Large Hadron Collider (LHC). It is made up of two types of subatomic particles: quarks and gluons. Quarks are the building blocks of particles like protons and neutrons, while gluons are in charge of the strong interaction force between quarks. The new quarkgluon plasma is the hottest liquid that has ever been created in a laboratory at 4 trillion°C (7 trillion°F). Fitting for a plasma like the one at the birth of the universe.

The plasma was created after a collision between a proton and a lead nucleus. The physicists had always thought that this collision wouldn't produce enough particles (around 1,000) to create a plasma. A collision between two lead nuclei, for comparison, is known to produce plasma but creates twenty times more particles (around 25,000) following collision. However, the results defied their expectations.

“Before the CMS experimental results, it had been thought the medium created in a proton on lead collisions would be too small to create a quark-gluon plasma,” said Quan Wang, a physicist from Kansas University (KU), in a statement. “The analysis presented in this paper indicates, contrary to expectations, a quark-gluon plasma can be created in very asymmetric proton on lead collisions.”

“This is the first paper that clearly shows multiple particles are correlated to each other in protonlead collisions, similar to what is observed in lead-lead collisions where quark-gluon plasma is produced,” added Yen-Jie Lee, from the Michigan Institute of Technology (MIT). “This is probably the first evidence that the smallest droplet of quark-gluon plasma is produced in proton-lead collisions.”

This new research looks at particle physics with a fresh perspective. Instead of counting individual numbers of particles, the plasma forces physicists to look at the behavior of a volume of particles.

There is also speculation that this plasma replicates the conditions of the early universe. “It’s believed to correspond to the state of the universe shortly after the Big Bang,” Wang continued. This plasma is different to other quark-gluon plasma that have been made before now. The interactions in this plasma are extremely strong, which distinguishes it from other plasmas which interact infrequently (like gas particles). This is what makes the researchers think it might be similar to an early universe plasma.

“While we believe the state of the universe about a microsecond after the Big Bang consisted of a quark-gluon plasma, there is still much that we don’t fully understand about the properties of quarkgluon plasma.” [9]

## Asymmetry in the interference occurrences of oscillators

The asymmetrical configurations are stable objects of the real physical world, because they cannot annihilate. One of the most obvious asymmetry is the proton – electron mass rate  $M_p = 1840 M_e$  while they have equal charge. We explain this fact by the strong interaction of the proton, but how remember it his strong interaction ability for example in the H – atom where are only electromagnetic interactions among proton and electron.

This gives us the idea to origin the mass of proton from the electromagnetic interactions by the way interference occurrences of oscillators. The uncertainty relation of Heisenberg makes sure that the particles are oscillating.

The resultant intensity due to n equally spaced oscillators, all of equal amplitude but different from one another in phase, either because they are driven differently in phase or because we are looking at them an angle such that there is a difference in time delay:

$$(1) \quad I = I_0 \sin^2 n \varphi/2 / \sin^2 \varphi/2$$

If  $\varphi$  is infinitesimal so that  $\sin\varphi = \varphi$  than

$$(2) \quad I = n^2 I_0$$

This gives us the idea of

$$(3) \quad M_p = n^2 M_e$$

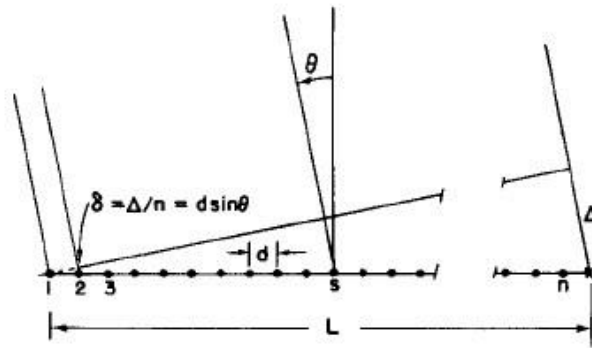


Fig. 30-3. A linear array of  $n$  equal oscillators, driven with phases  $\alpha_s = s\alpha$ .

Figure 1.) A linear array of  $n$  equal oscillators

There is an important feature about formula (1) which is that if the angle  $\varphi$  is increased by the multiple of  $2\pi$  it makes no difference to the formula.

So

$$(4) \quad d \sin \theta = m \lambda \text{ and we get } m\text{-order beam if } \lambda \text{ less than } d. [6]$$

If  $d$  less than  $\lambda$  we get only zero-order one centered at  $\theta = 0$ . Of course, there is also a beam in the opposite direction. The right chooses of  $d$  and  $\lambda$  we can ensure the conservation of charge.

For example

$$(5) \quad 2(m+1) = n$$

Where  $2(m+1) = N_p$  number of protons and  $n = N_e$  number of electrons.

In this way we can see the  $H_2$  molecules so that  $2n$  electrons of  $n$  radiate to  $4(m+1)$  protons, because  $d_e > \lambda_e$  for electrons, while the two protons of one  $H_2$  molecule radiate to two electrons of them, because of  $d_e < \lambda_e$  for this two protons.

To support this idea we can turn to the Planck distribution law, that is equal with the Bose – Einstein statistics.

## Spontaneously broken symmetry in the Planck distribution law

The Planck distribution law is temperature dependent and it should be true locally and globally. I think that Einstein's energy-matter equivalence means some kind of existence of electromagnetic oscillations enabled by the temperature, creating the different matter formulas, atoms molecules, crystals, dark matter and energy.

Max Planck found for the black body radiation

As a function of wavelength ( $\lambda$ ), Planck's law is written as:

$$B_{\lambda}(T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}.$$

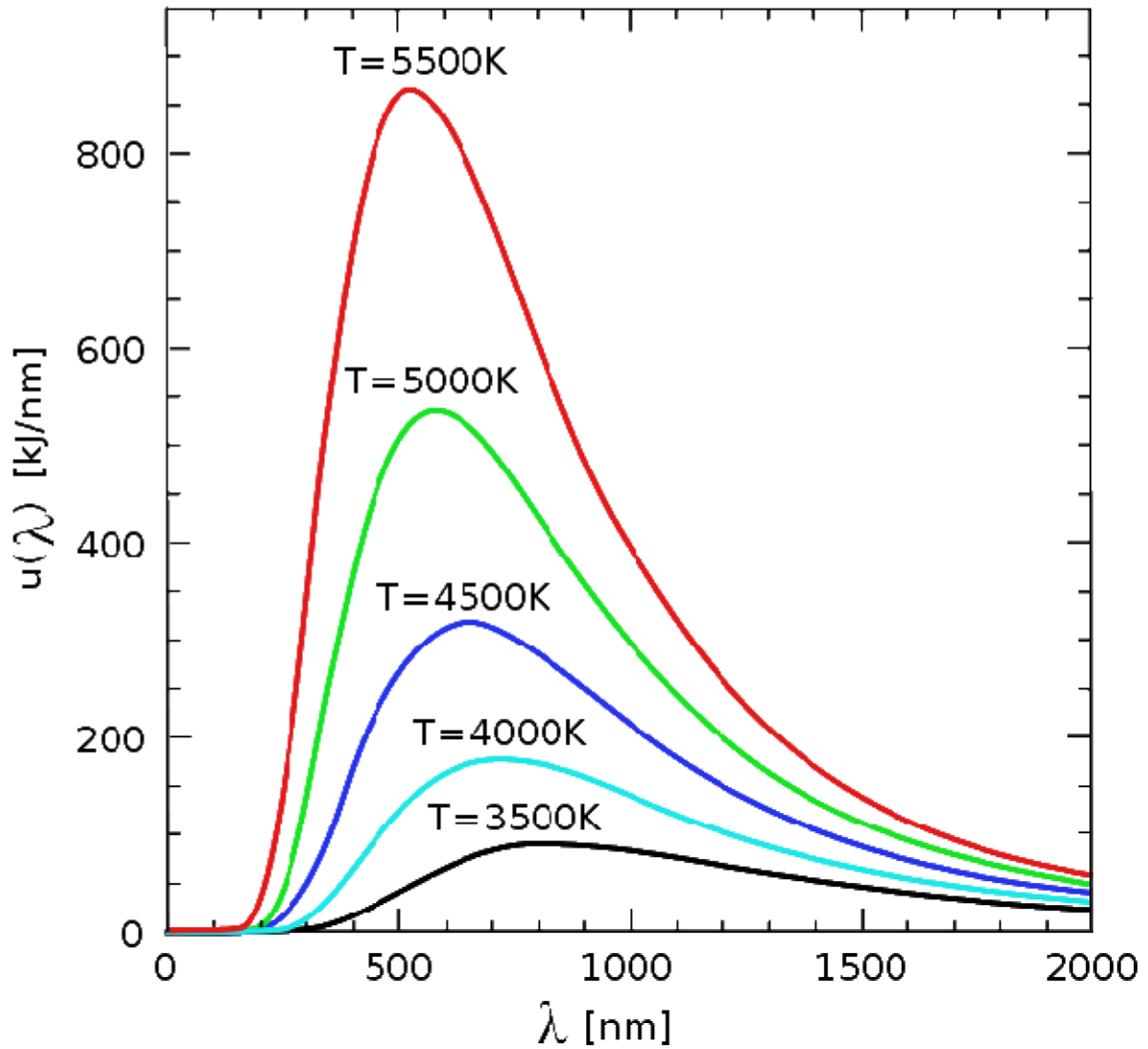


Figure 2. The distribution law for different T temperatures

We see there are two different  $\lambda_1$  and  $\lambda_2$  for each T and intensity, so we can find between them a d so that  $\lambda_1 < d < \lambda_2$ .

We have many possibilities for such asymmetrical reflections, so we have many stable oscillator configurations for any T temperature with equal exchange of intensity by radiation. All of these configurations can exist together. At the  $\lambda_{\max}$  is the annihilation point where the configurations are symmetrical. The  $\lambda_{\max}$  is changing by the Wien's displacement law in many textbooks.

$$(7) \quad \lambda_{\max} = \frac{b}{T}$$

where  $\lambda_{\max}$  is the peak wavelength, T is the absolute temperature of the black body, and b is a constant of proportionality called *Wien's displacement constant*, equal to  $2.8977685(51) \times 10^{-3} \text{ m} \cdot \text{K}$  (2002 CODATA recommended value).

By the changing of T the asymmetrical configurations are changing too.

## The structure of the proton

We must move to the higher T temperature if we want look into the nucleus or nucleon arrive to  $d < 10^{-13}$  cm. [2] If an electron with  $\lambda_e < d$  move across the proton then by (5)  $2(m+1) = n$  with  $m = 0$  we get  $n = 2$  so we need two particles with negative and two particles with positive charges. If the proton can fraction to three parts, two with positive and one with negative charges, then the reflection of oscillators are right. Because this very strange reflection where one part of the proton with the electron together on the same side of the reflection, the all parts of the proton must be quasi lepton so  $d > \lambda_q$ . One way dividing the proton to three parts is, dividing his oscillation by the three direction of the space. We can order  $1/3$  e charge to each coordinates and  $2/3$  e charge to one plane oscillation, because the charge is scalar. In this way the proton has two  $+2/3$  e plane oscillation and one linear oscillation with  $-1/3$  e charge. The colors of quarks are coming from the three directions of coordinates and the proton is colorless. The flavors of quarks are the possible oscillations differently by energy and if they are plane or linear oscillations. We know there is no possible reflecting two oscillations to each other which are completely orthogonal, so the quarks never can be free, however there is asymptotic freedom while their energy are increasing to turn them to orthogonal. If they will be completely orthogonal then they lose this reflection and take new partners from the vacuum. Keeping the symmetry of the vacuum the new oscillations are keeping all the conservation laws, like charge, number of baryons and leptons. The all features of gluons are coming from this model. The mathematics of reflecting oscillators show Fermi statistics.

Important to mention that in the Deuteron there are 3 quarks of  $+2/3$  and  $-1/3$  charge, that is three u and d quarks making the complete symmetry and because this its high stability.

## 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.

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  $1/2$  spin creator particle to make equal the spins of the weak interaction, for example neutron decay to 2 fermions, every particle is fermions with  $1/2$  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  $\frac{1}{2}$  spin creating; it is limited by the velocity of the electromagnetic wave, so the neutrino's velocity cannot exceed the velocity of light.

## **The Strong Interaction - QCD**

### **Confinement and Asymptotic Freedom**

For any theory to provide a successful description of strong interactions it should simultaneously exhibit the phenomena of confinement at large distances and asymptotic freedom at short distances. Lattice calculations support the hypothesis that for non-abelian gauge theories the two domains are analytically connected, and confinement and asymptotic freedom coexist.



Similarly, one way to show that QCD is the correct theory of strong interactions is that the coupling extracted at various scales (using experimental data or lattice simulations) is unique in the sense that its variation with scale is given by the renormalization group. The data for  $\alpha_s$  is reviewed in Section

19. In this section I will discuss what these statements mean and imply. [4]

## Lattice QCD

**Lattice QCD** is a well-established non-perturbative approach to solving the quantum chromodynamics (QCD) theory of quarks and gluons. It is a lattice gauge theory formulated on a grid or lattice of points in space and time. When the size of the lattice is taken infinitely large and its sites infinitesimally close to each other, the continuum QCD is recovered. [6]

Analytic or perturbative solutions in low-energy QCD are hard or impossible due to the highly nonlinear nature of the strong force. This formulation of QCD in discrete rather than continuous space-time naturally introduces a momentum cut-off at the order  $1/a$ , where  $a$  is the lattice spacing, which regularizes the theory. As a result, lattice QCD is mathematically well-defined. Most importantly, lattice QCD provides a framework for investigation of nonperturbative phenomena such as confinement and quark-gluon plasma formation, which are intractable by means of analytic field theories.

In lattice QCD, fields representing quarks are defined at lattice sites (which leads to fermion doubling), while the gluon fields are defined on the links connecting neighboring sites.

## QCD

QCD enjoys two peculiar properties:

- **Confinement**, which means that the force between quarks does not diminish as they are separated. Because of this, it would take an infinite amount of energy to separate two quarks; they are forever bound into hadrons such as the proton and the neutron. Although analytically unproven, confinement is widely believed to be true because it explains the consistent failure of free quark searches, and it is easy to demonstrate in lattice QCD.
- **Asymptotic freedom**, which means that in very high-energy reactions, quarks and gluons interact very weakly. This prediction of QCD was first discovered in the early 1970s by David Politzer and by Frank Wilczek and David Gross. For this work they were awarded the 2004 Nobel Prize in Physics.

There is no known phase-transition line separating these two properties; confinement is dominant in low-energy scales but, as energy increases, asymptotic freedom becomes dominant. [5]

## Color Confinement

When two quarks become separated, as happens in particle accelerator collisions, at some point it is more energetically favorable for a new quark-antiquark pair to spontaneously appear, than to allow the tube to extend further. As a result of this, when quarks are produced in particle accelerators, instead of seeing the individual quarks in detectors, scientists see "jets" of many color-neutral particles (mesons and baryons), clustered together. This process is called hadronization, fragmentation, or string breaking, and is one of the least understood processes in particle physics.

[3]

## 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]

### The frequency dependence of mass

Since  $E = h\nu$  and  $E = mc^2$ ,  $m = h\nu/c^2$  that is the  $m$  depends only on the  $\nu$  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  $m_0$  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. [2]

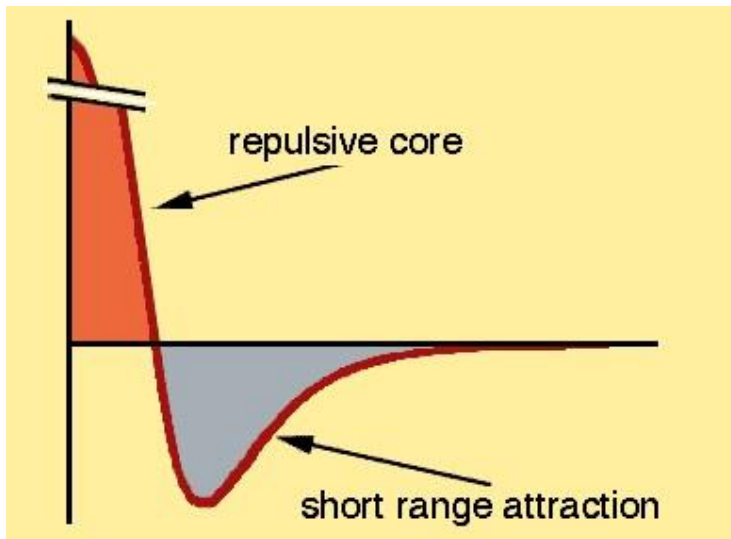
There is an asymmetry between the mass of the electric charges, for example proton and electron, can understood by the asymmetrical Planck Distribution Law. This temperature dependent energy distribution is asymmetric around the maximum intensity, where the annihilation of matter and antimatter is a 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.

### The potential of the diffraction pattern

The force that holds protons and neutrons together is extremely strong. It has to be strong to overcome the electric repulsion between the positively charged protons. It is also of very short range, acting only when two particles are within 1 or 2 fm of each other.

1 fm (femto meter) =  $10^{-15}$  m =  $10^{-15}$  m = 0.000000000000001 meters.

The qualitative features of the nucleon-nucleon force are shown below.



There is an extremely **strong short-range repulsion** that pushes protons and neutrons apart before they can get close enough to touch. (This is shown in orange.) This repulsion can be understood to arise because the quarks in individual nucleons are forbidden to be in the same area by the Pauli Exclusion Principle.

There is a **medium-range attraction** (pulling the neutrons and protons together) that is strongest for separations of about 1 fm. (This is shown in gray.) This attraction can be understood to arise from the exchange of quarks between the nucleons, something that looks a lot like the exchange of a pion when the separation is large.

The density of nuclei is limited by the short range repulsion. The maximum size of nuclei is limited by the fact that the attractive force dies away extremely quickly (exponentially) when nucleons are more than a few fm apart.

Elements beyond uranium (which has 92 protons), particularly the trans-fermium elements (with more than 100 protons), tend to be unstable to fission or alpha decay because the Coulomb repulsion between protons falls off much more slowly than the nuclear attraction. This means that each proton sees repulsion from every other proton but only feels an attractive force from the few neutrons and protons that are nearby -- even if there is a large excess of neutrons.

Some "super heavy nuclei" (new elements with about 114 protons) might turn out to be stable as a result of the same kind of quantum mechanical shell-closure that makes noble gases very stable chemically. [7]

## Conclusions

Lattice QCD gives the same results as the diffraction theory of the electromagnetic oscillators, which is the explanation of the strong force and the quark confinement. [8]

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