Changing Concepts of Light and Matter

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Introduction

Light and matter, just as space and time, play a central role in our life. Evolution has given our brain a compelling intuition for these concepts. This intuition has been essential for survival of our species, but it can hinder our progress towards a deeper understanding.

Light

Light was long considered as something given by God. Artists learned to use of colours to express beauty and emotions. Leonardo da Vinci observed in his *Tratto della Pittura* that it is possible to arrange colours in a circle so that the most pleasing combinations are opposites.

Already around 300 BCE, Euclid recognized that light travels along straight lines. There were many unsuccessful early attempts to find out the speed of light, including experiments by Galileo Galilei. The first quantitative estimate was made in 1676 by Olaf Roemer from astronomical observations of the moons of Jupiter. He estimated a speed of light which was about 26% smaller than the value of 299,792,458 meters per second, as it is now determined for light in vacuum.

Isaac Newton was perhaps the first to investigate systematically what happens when a ray of white sunlight is sent through a glass prism, so that the light is dispersed into a rainbow of colours. Newton argued that these different colors must correspond to different kinds of light particles.

Light waves

Around the beginning of the 19th century, Thomas Young demonstrated that light behaves like a wave. He observed interference fringes by diffracting light from fine lines ruled on a glass plate. Just like water waves passing through a double slit, light waves reinforce each other if they oscillate in phase, and they cancel each other if they oscillate with opposite phases. Augustin-Jean Fresnel formulated a mathematical theory of light waves that is still used today to describe phenomena of interference and diffraction in optics.

From interference patterns, one could determine the wavelength of light. Visible light spans the range from 400 nm in the blue to 800 nm in the red. The oscillation frequency can be calculated by dividing the speed of light by the wavelength. Blue light oscillates about a million billion times per second. The nature of these waves remained unknown until James Clerk Maxwell's theory of electromagnetic fields. Today, we know that visible light represents a small part of a spectrum of electromagnetic waves that ranges from radio waves to gamma rays.

In the late 19th century, Albert Abraham Michelson studied the interference of light waves with an instrument now called Michelson interferometer. By rotating this instrument in his laboratory, he demonstrated the unexpected result that the speed of light does not change with the direction relative to the motion of earth. This finding stimulated some revolutionary insights, which Albert Einstein formulated in his special and general theory of relativity, and which have profoundly changed our concepts of space and time.

The quest for a deeper understanding continues, as the question has been raised whether space and time are perhaps emergent phenomena that do not exist outside a universe.

Light particles

The quest for more efficient electric lighting in the late 19th century motivated researchers at the Physikalisch Technische Reichsanstalt in Berlin to study carefully the spectrum of light emitted by hot bodies, so-called blackbody radiation. The spectra were in stark disagreement with theoretical predictions based on a thermal equilibrium between radiation and the hot walls. Max Planck found in 1909 that he could model the observed spectra accurately, if he made the revolutionary assumption that light is emitted and absorbed in quanta of energy $E=h f$, where h is Planck's constant and f the frequency of light.

Today we have verified in countless experiments that light can be made to appear as if it were a wave or as if it were made of particles or photons, dependent on the chosen apparatus. With an imaging detector that is

sensitive to individual photons, one can even observe the gradual build-up of interference fringes in the patterns of observed clicks. A similar duality between wave nature and particle nature was later found for electrons, atoms and other matter.

John Clauser and Alain Aspect attracted much attention in the 1970s and early 1980s, when they demonstrated [1, 2] that observed pairs of photons exhibit correlations in their polarizations predicted by quantum physics and known as entanglement. Even though such entanglement remains counter-intuitive, it has since become a resource for quantum engineers to realize new concepts for quantum cryptography, quantum information processing, and quantum computing.

Lasers

An even more momentous revolution was ignited in 1958, when Arthur L. Schawlow and Charles H. Townes published their seminal paper on Infrared and Optical Masers [3]. They pointed out how it should be possible to construct amplifiers and oscillators for light waves, similar to what was possible for radio waves. Their proposal triggered a race [4] to build the first laser which Theodor Maiman won in 1960 with his pulsed ruby laser. The far reaching impact of lasers on science and technology is illustrated by the fact that 26 Nobel Prizes have now been awarded for work around the laser, if we include the most recent Nobel Prize in Chemistry for super-resolution microscopy.

Matter

The nature of matter had remained obscure for a long time. Philosophers such as Democritus or Aristotle had speculated that matter may be made up of small indivisible building blocks or atoms, but these thoughts were soon forgotten. They were revived by chemists in the 17th and 18th century, culminating in the “New System of Chemical Philosophy” which was published by John Dalton in 1808. By measuring the proportions in which elements react to form chemical compounds, Dalton presented experimental evidence for the existence of atoms, and he even could give relative atomic weights of different elements. However, the nature of these atoms remained unknown.

The size of molecules in air was first estimated in 1865 by Austrian scientist Johann Joseph Lohschmidt from the dynamical theory of gases. He arrived at a size of about 1 nm, twice as large as now determined by modern methods.

Spectroscopy

Further insights came from the spectra of light emitted or absorbed by atomic vapors. Joseph v. Fraunhofer was the first to study the absorption lines that appear in the spectrum of sunlight when observed with a prism or grating spectrograph. The later work of Kirchhoff and Bunsen in the 19th century established spectral analysis of the light emitted by atoms in flames as a useful method of identifying different elements by their spectral fingerprints.

The simplest visible spectrum is emitted by the lightest of the elements, atomic hydrogen. The visible Balmer lines were first observed in the light of stars. The Swiss school teacher Johann Jakob Balmer succeeded in finding a mathematical formula that described the wavelengths of these lines. His formula was later generalized by Johannes Robert Rydberg, who introduced the Rydberg constant as an empirical constant.

Atom models

A deeper understanding of the inner workings of atoms was not possible before the discovery of radioactivity by Henri Becquerel in 1896 and the subsequent discovery of the atomic nucleus by Ernest Rutherford in 1909. By scattering alpha rays from a gold foil, Rutherford showed that almost all the mass of an atom must be concentrated in a tiny positively charged nucleus. Before, some physicists had assumed that negatively charged light electrons were embedded like raisins in a positively charged dough.

After this discovery, Niels Bohr tried to explain the Balmer spectrum of hydrogen with a planetary atom model. He assumed that the single electron of a hydrogen atom orbits the nucleus like a planet orbits the sun. However, he soon realized that a classical model would not work. He then made the revolutionary assumptions that there exist certain stable orbits with quantized angular momentum where the electron does not radiate. Light is emitted or absorbed during transitions between these quantized orbits. This old Bohr model had many shortcomings, but it was able to calculate the Rydberg constant in terms of the mass and charge of the electron, Planck’s constant, and the speed of light.

From wave mechanics to quantum electrodynamics

In his 1924 PhD thesis, Louis de Broglie introduced the concept of matter waves. He argued that electrons can behave like waves, and that the stable orbits in a hydrogen atom are those where an integer number of

wavelengths fits around the circumference. In late 1925, Erwin Schrödinger formulated a mathematical wave equation for matter waves, his famous Schrödinger equation. This equation could be solved in closed form for the electron in hydrogen, and it has since stood countless confrontations between experimental observations and theoretical predictions.

What does the Schrödinger equation and its solution, the Schrödinger wavefunction, describe? This question remains hotly disputed among philosophers of science even today, as the ever growing number of interpretations of quantum mechanics indicates. Most working physicists seem to accept the pragmatic Copenhagen interpretation: the Schrödinger equation describes our information about the probability of meter readings and detector clicks. Quantum mechanics is a phenomenological theory that deals with our observable world [5]. This interpretation is sharpened and made more consistent by the emerging interpretation of QBism, which defines probability in the sense of Bayesian statistics as a personal belief [6]. Most other interpretations introduce speculative additions to the theory which have no observable consequences. They are motivated by the desire to eliminate the „observer" from the description of the world by positing some imagined underlying inner workings beneath the observable phenomena. However, unlike previously in science, such speculative additions have so far inevitably led to conceptual puzzles, contradictions, misunderstandings, and pseudo-problems. The rules of quantum mechanics, as we know them today, are very general, like the laws of thermodynamics, and they can be applied without a deeper knowledge of the underlying “reality”.

In 1928, Paul Dirac succeeded in generalizing the Schrödinger equation so that it includes Einsteins's relativistic effects. Miraculously, his Dirac equation could account for the observed spin of the electron, and it even described the existence of anti-electrons or positrons. Some felt at the time that this equation is so beautiful that it must describe the ultimate truth. The Dirac equation made detailed predictions about the fine structure of hydrogen spectral lines. In the 1930s, tests of these predictions became a hot topic in atomic physics, with contradicting experimental results.

The discovery, that the Dirac equation does not describe the energy levels of hydrogen correctly came only after the Second World War. Willis Lamb demonstrated by radiofrequency spectroscopy of an atomic beam of excited metastable hydrogen, that two states, which should have precisely the same energy according to Dirac, are in fact split by a Lamb shift of about 1 GHz. An intuitive explanation was given by Hans Bethe, who considered quantum fluctuations of the electromagnetic field in vacuum, which are always present, even at absolute zero temperature. These fluctuations smear out the position of the electron, so that it appears less tightly bound in the 2S orbital where it comes close to the nucleus than in the 2P orbital. A smaller effect of the opposite sign is due to vacuum polarization, the fact that virtual electron-positron pairs in a strong electric field make the vacuum polarizable.

The discovery of the Lamb shift and the concurrent discovery by Polykarp Kusch that the magnetic moment of the spinning electron does not agree with the predictions of the Dirac theory lead to the development of the theory of quantum electrodynamics. In 1965, the Nobel Prize in Physics was awarded to Shin'ichiro Tomonaga, Julian Schwinger, and Richard Feynman for their fundamental work in quantum electrodynamics, with deep-ploughing consequences for the physics of elementary particles. Their theory has become a model for modern quantum field theories, including string theory, which attempts to reconcile quantum physics and general relativity.

Complex quantum matter

Next to studying the properties of ever-smaller building blocks in our world, the understanding of their collective interplay is equally important. Early on, studies of condensed matter at low temperature revealed unexpected phenomena. In 1911, Heike Kamerlingh Onnes discovered that the electrical resistance of mercury disappears when it is cooled by liquid helium. In the same experiment he also observed that liquid helium becomes superfluid below 2.2 Kelvin. In 1924, Satyendra Nath Bose and Albert Einstein pointed out, that a dilute gas of atoms close to absolute zero temperature should reach a state where a large fraction of the atoms occupies the lowest quantum state of motion. People suspected that superconductivity and superfluidity might be manifestations of such Bose-Einstein condensation. However, a microscopic theory for the former was only given in 1957 by John Bardeen, Leon Cooper, and John Robert Schrieffer. The quantum theory of complex condensed matter remains one of the most challenging fields of modern physics today.

In 1974, it was pointed out that laser radiation pressure can cool atomic gases quickly close to absolute zero temperature [7]. Even lower temperatures can be reached by subsequent evaporation cooling in a magnetic or optical trap. At very low temperatures, the atoms can no longer be described as particles, but they have to be considered as wave packets. Bose-Einstein condensation occurs below a critical temperature, as first observed in 1995 by Eric Cornell and Carl Wieman for ultracold rubidium atoms [8] and by Wolfgang Ketterle for sodium [9]. Such condensates can be described as coherent matter waves, in analogy to coherent laser light waves.

The experimental realization of quantum degenerate gases marked a scientific revolution [10]. It is now possible to prepare highly controllable aggregates of millions of bosonic or fermionic particles at microkelvin temperatures. Although such ultracold gas clouds are extremely dilute (a hundred thousand times thinner than the air around us), they nevertheless allow to simulate the behaviour of strongly interacting materials and help to better understand intriguing many-body phenomena such as superconductivity, superfluidity and quantum magnetism. By using interfering laser beams, a crystalline light pattern formed by hundreds of thousands of microscopic light traps may be formed, in which the atoms have to move. In such a crystal of light the normal roles of matter and light are completely reversed: rather than using light to probe an atomic crystal, light is used to form an optical crystal in which matter is trapped. Such novel settings have enabled to create conditions, which are impossible to find in real materials, thereby realizing a more than 30 year old dream of Richard Feynman of a ‘quantum simulator’. Such quantum simulators are today used in many laboratories around the world with applications in condensed matter physics, high-energy physics and cosmology, statistical physics and quantum information.

Elementary particles

Experiments with large particle accelerators soon discovered a bewildering number of new particles. The 1969 Nobel Prize in Physics was awarded to Murray Gell-Mann for his discoveries concerning the classification of elementary particles and their interactions. Today, all known particles can be described by the Standard Model in terms of six different quarks and six leptons, all Fermions. The forces between these particles are mediated by four different Bosons. The additional recently discovered Higgs Boson explains within the Standard Model why some particles have mass.

Proton size puzzle

In the context of the hydrogen atom, the proton nucleus appears as a composite system, made up of three quarks held together by gluons. To accurately predict the energy levels and spectral lines of hydrogen, one needs to know the size of this proton, or, more accurately, its mean quadratic charge radius.

Very precise spectroscopy of hydrogen became possible starting in the early 1970s by the advent of tunable highly monochromatic lasers and powerful techniques of spectroscopy without Doppler broadening. In the first experiments of this kind [11], our group at Stanford observed a hydrogen gas discharge by laser saturation spectroscopy, so that the predicted fine structure components of the red Balmer alpha lines could be directly resolved in the optical spectrum, including the line splitting due to the Lamb shift. This was the beginning of a long quest for ever-higher spectral resolution and measurement accuracy. The slightest discrepancy between experiment and theoretical predictions could have momentous consequences for our fundamental understanding of the quantum world. During this pursuit, the fractional frequency uncertainty has been reduced from a part in 107 [12] to a few parts in 1015 [13]. The absolute frequency of the sharp 1S-2S two-photon resonance has recently been measured to 15 significant decimal digits. Such accurate measurements have become possible since the laser frequency comb technique invented around 1997 has made it easy to count the oscillations of a light waves [14].

Thanks to accurate spectroscopy of different transitions in hydrogen, it has been possible to determine the size of the proton, provided the theory of quantum electrodynamics is correct. To test this theory, one needs an independent measurement of the size of the proton. One very good, if challenging, approach is laser spectroscopy of man-made muonic hydrogen, where the electron is replaced by the 200 times heavier muon. Since the muon orbitals are 200 times closer to the proton than those of the electron, their energies are affected much more strongly by the nuclear size.

In 2010, an international collaboration lead by Randolf Pohl reported on the successful observation of the 2S-2P Lamb shift in muonic hydrogen at the Paul Scherrer Insitute PSI. Including more recently published results, the proton charge radius could be determined to better than on part per thousand by these experiments [15]. However, the size turned out to be about 4% smaller than the accepted value from hydrogen spectroscopy and from electron scattering experiments at large accelerators. This proton size puzzle remains unresolved. It may be due to some mistake, or it may hint at a dent in the armour of quantum electrodynamics.

Outlook

Several research teams at CERN are working towards laser spectroscopy of anti-hydrogen, made up of a positron orbiting around an anti-proton [16]. We can perhaps expect first results during the coming year. The slightest difference between hydrogen and anti-hydrogen would shake our long-held belief in the symmetry between matter and anti-matter.

The frequency comb technique, invented for precise spectroscopy of hydrogen, is finding new applications much beyond its original purpose. As calibration tools for large astronomical spectrographs, frequency combs

will permit new questions in precision astronomy. Aside from the search for earth-like exoplanets, they will enable new tests for general relativity. They might also provide new answers to the question whether fundamental constants are truly constant. By observing the change of cosmic red shifts with time, they might provide direct evidence for the accelerated expansion of space in our universe.

Cosmologists tell us that known matter constitutes only 5% of our universe. Dark matter of unknown composition accounts for 26.8% and even more mysterious dark energy for 68.3%. As we begin to better understand these mysteries, our concepts of light and matter are likely to undergo further dramatic changes in the future.

To cope with such unknowns, we need some ingenious scientists who are free to explore nature out of sheer curiosity.

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