23. Applications of quantum mechanics – life, pleasure and their tools

Now that we can look at quantum effects without ideological baggage, let us have some serious fun in the world of quantum theory. The quantum of action has large number of important consequences for biology, chemistry, technology and science fiction. We will only explore a cross section of these vast topics, but it will be worth it.

Biology

Typeset in November 2002

A special form of electromagnetic motion is of importance to humans: life. We mentioned at the start of quantum theory that life cannot be described by classical physics. Life is a quantum effect. Let us show this.

Living beings can be described as matter objects showing metabolism, information processing, information exchange, reproduction and motion. Obviously, all these properties follow from a single one, to which the others are enabling means:

▷ *Living beings are objects able to reproduce.**

This definition implies several consequences. In order to reproduce, living beings must be able to move in self-directed ways. An object able to perform self-directed motion is called a *machine*. All self-reproducing beings are machines.

Since reproduction is simpler the smaller the system, most living beings are extremely small machines for the tasks they perform, especially when compared to human made machines. Astonishingly, this is the case even though the design of human machines has considerably fewer requirements: human-built machines do not need to be able to reproduce; as a result, they do not need to be made of a single piece of matter, as all living beings have to. Despite the restrictions nature has to live with, living beings hold many miniaturization world records:

▪ The brain has the highest processing power per volume of any calculating device so far. Just look at the size of chess champion Gary Kasparov and the size of the computer against which he played.

▪ The brain has the densest and fastest memory of any device so far. The set of compact disks (CDs) or digital versatile disks (DVDs) that compare with the brain is many thousand times larger.

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▪ Motors in living beings are many orders of magnitude smaller than human-built ones. Just think about the muscles in the legs of an ant.

▪ The motion of living beings beats the acceleration of any human-built machine by orders of magnitude. No machine moves like a grasshopper.

▪ Living being's sensor performance, such as that of the eye or the ear, has been surpassed by human machines only recently. For the nose this feat is still extremely far away. Also the sensor sizes developed by evolution – think about the ears or eyes of a common fly – is still unbeaten.

* However, there are examples of objects which reproduce and which nobody would call living. Can you find some examples, together with an clearer definition?

Challenge 993 n

- Flying living beings – such as a fruit fly – are still thousands of times smaller than anything built by humans.
- Can you spot more examples? Challenge 994 n

The superior miniaturization of living beings is due to their continuous strife for efficient construction. In their structure, everything is connected to everything: each part influences many others. Indeed, the four basic processes in life, namely metabolic, mechanical, hormonal and electrical, are intertwined in space and time. For example, breathing helps digestion; head movements pump liquid through the spine; a single hormone influences many chemical processes. Furthermore, all parts in living systems have more than one function. For example, bones provide structure and produce blood; nails are tools and shed chemical waste.

The miniaturization, the reproduction, the construction and the functioning of living beings all rely on the quantum of action. Let us see how.

Reproduction

All the astonishing complexity of life is geared towards reproduction. *Reproduction* is the ability of an object to build other objects similar to itself.*

Since reproduction requires mass increase, reproducing objects show both metabolism and growth. In order that growth leads to a similar object as the original one, a construction plan is necessary. This plan must be similar to the plan used by the previous generation. Organizing growth with a construction plan is only possible if nature is made of smallest entities which can be assembled following that plan.

We can thus deduce that reproduction implies that matter is made of smallest entities. If matter was not made of smallest entities, there would be no way to realize reproduction. Reproduction thus requires quantum theory. Indeed, without the quantum of action there would be no DNA molecules and there would be no way to inherit our own properties – our own construction plan – to children.

Passing on a plan implies that living beings must have ways to store information. Living beings must have some built-in memory. We know already that a system with memory must be made of many particles. There is no other way to store information. The large number of particles is mainly necessary to protect the information from the influences of the outside world.

Our own construction plan, made of what biologist call genes, is stored in DNA molecules. Reproduction is thus first of all a transfer of parent's genes to the next generation. We will come back to the details below. We first have a look on how our body moves itself and its genes around.

Quantum machines

Living beings are machines. How do these machines work? From a physical point of view, we need only a few sections of our walk so far to describe them: universal gravity and

See page 549 * Only a similar object is possible, as an exact copy would contradict the properties of nature, in particular those of quantum theory itself, as we found out above.

QED. Simply stated, life is an electromagnetic process taking place in weak gravity.* But the details of this statement are tricky and interesting. Table 491 gives an overview of motion processes in living beings. Interestingly, all motion in living beings can be summarized in a few classes by asking for the motor driving it.

Nature has developed a few small but powerful devices to realize all motion types used by living beings. Given the long time that living systems have been around, these devices are extremely efficient. In fact, both the ion pumps and chemical pumps found in cell membranes are specialized molecular motors. Even though there is still a lot to be learned about them, what is known is already spectacular enough.

How do we move? – Molecular motors

How do our muscles work? What is the underlying motor? One of the beautiful results of modern biology, helped by chemistry and physics, is the elucidation of this issue. It turns out that muscles work because they contain molecules which change shape when supplied with energy. This shape change is repeatable. A clever combination and repetition of these molecular shape changes is then used to generate macroscopic motion. There are three basic classes of molecular motors: linear motors, rotational motors, and pumps.

Linear motors are at the basis of muscle motion; other linear motors separate genes during cell division. They also move organelles inside cells and displace cells through the body during embryo growth, when wounds heal, or in other examples of cell motility.

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We encountered rotational motors already above. Nature uses them to rotate the cilia of many bacteria as well as sperm tails. Researchers have also discovered that evolution also produced molecular motors which turn around DNA helices like a motorized bolt would turn around a screw. Such motors are attached at the end of some viruses and insert the DNA into virus bodies when they are being built by infected cells, or extract the DNA from the virus after it has infected a cell. Another rotational motor, the smallest known so far – 10 nm across and 8 nm high – is ATP synthase, a protein that synthesizes most ATP in cells. (Ref. 617, Ref. 614)

The ways molecules produce movement in linear motors was uncovered during the 1990s. This started a wave of research on all other molecular motors. There are no temperature gradients involved, as in car engines, no electrical currents, as in electrical motors, and no concentration gradients as in chemically induced motion. The central part of linear molecular motors is a combination of two protein molecules, namely myosin and actin. Myosin changes between two shapes and literally *walks* along actin. It moves in regular small steps. The motion step size has been measured with beautiful experiments to be some multiple of 5.5 nm. A step, usually forward, but sometimes backwards, results whenever an ATP (adenosine triphosphate) molecule, the standard biological fuel, hydrolyses to ADP (adeno- (Ref. 615, Ref. 615)

* In fact, also the nuclear interactions play some role for life: cosmic radiation is one source for random mutations, which are so important in evolution. Plant growers often use radioactive sources to increase mutation rates. But obviously, radioactivity can also terminate life. (Ref. 613)

The nuclear interactions are also implicitly involved in several other ways. They were necessary to form the materials – carbon, oxygen, etc. – required for life. Nuclear interactions are behind the main mechanism for the burning of the sun, which provides the energy for plants, for humans and for all other living beings (except a few bacteria in inaccessible places).

Motion type	examples	main involved devices
Growth	collective molecular processes in cell growth	ion pumps
	gene turn-on and turn-off	linear molecular motors
	aging	linear molecular motors
Construction	material types and properties (polysaccharides, lipids, proteins, nucleic acids, others)	material transport through muscles
	forces and interactions between biomolecules	membrane pumps
Functioning		
	details of metabolism (respiration, digestion)	muscles, ion pumps
	energy flow in biomolecules	
	thermodynamics of whole living system and of its parts	muscles
	muscle working	molecular motors
	nerve signalling	ion motion, ion pumps
	brain working	ion pumps
	illnesses	cell motility, chemical pumps
	viral infection of a cell	rotational molecular motors for RNA transport
Defence		
	the immune system	cell motility
Reproduction		
	information storage and retrieval	linear molecular motors inside cells
	cell division	linear molecular motors inside cells
	sperm motion	rotational molecular motors
	courting	muscles, brain
	evolution	muscles, linear molecular motors

Table 47 Motion and motors in living beings

sine diphosphate), releasing its energy. The force generated is about 3 to 4 pN; the steps can be repeated several times a second. Muscle motion is the result of millions of such elementary steps taking place in concert.

How do molecular motors work? Such motors are are so small that the noise due to the molecules of the liquid around them is not negligible. But nature is smart: with two tricks it takes advantage of Brownian motion and transforms it into molecular motion. Molecular

Summing up, the nuclear interactions play a role in the appearance and in the in destruction of life; but they play no (known) role for the actions of particular living beings.

Figure missing

Figure 220 Myosin and actin: the building bricks of a molecular motor

motors are therefore also called *Brownian motors*. The first trick is the use of an asymmetric, but periodic potential, a so-called *ratchet*. Secondly, a temporal variation of the potential is used, together with an energy input to make it happen. The most important realizations are
Ref. 616 shown in Figure 221.

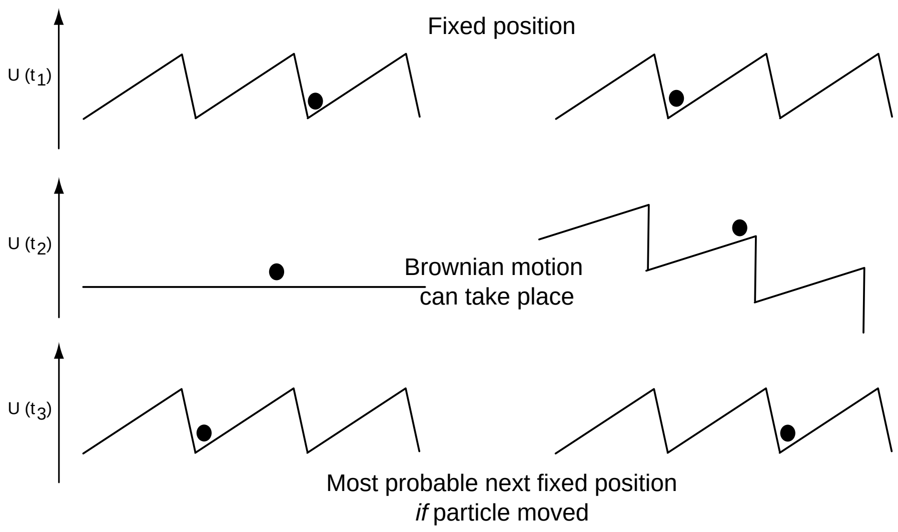

Figure 221 Two types of Brownian motors: switching potential (left) and tilting potential (right)

The periodic potential variation allows that for a short time the Brownian motion of the moving molecule – typically 1 μm/s – affects its position. Then the molecule is fixed again. Most of the time, the position will not change. But if the position changes, the intrinsic asymmetry of the ratchet shape ensures that most of the time the molecule advances in the preferred direction. Then the molecule is fixed again, waiting for the next potential change. On average, the myosin molecule will move in one direction. Nowadays the motion of single molecules can be followed in special set-ups. The cited experiments confirm that muscles use such ratchet mechanisms. The ATP molecule adds energy to the system and triggers the potential variation through the shape change it induces in the myosin molecule. That is how our muscles work.

Another well-studied linear molecular motor is the kinesin-microtubule system which carries organelles from one place to the other within a cell. As in the previous example, also here chemical energy is converted into unidirectional motion. Researchers are able to attach small silica beads to single molecules and can thus follow their motion and apply forces. Kinesin moves with around 800 nm/s, in steps lengths which are multiples of 8 nm, using one ATP molecule at a time, and exerting a force of about 6 pN.

Quantum ratchets also exist as human built systems, such as electrical ratchets for electron motion or optical ratchets that drive small particles. Much experimental research is going on in the field.

Curiosities and challenges of biology

The physics of life is still not fully explored.

▪ Many molecules found in living beings, such as sugar, have mirror molecules. However, in all living beings only one of the two sorts is found. Life is intrinsically asymmetric. How can this be? Challenge 995

▪ How can it be that the genetic difference between man and chimpanzee is given as about 1%, whereas the difference between man and woman is one chromosome in 46, in other words, about 2.2%? Challenge 996 n

▪ How would you determine which of two identical twins is the father of a baby? Challenge 997 n

▪ Can you give at least five arguments to show that a human clone, if there will ever be one, is a completely different person that the original? Challenge 998

▪ Could life come to earth from space? Challenge 999

▪ How did life start? Challenge 1000

▪ Life is not a clearly defined concept. The definition used above, as beings which can reporduce, has its limits when applied to old animals not able to reproduce any more, to a hand cut off by mistake, or to sperm or ovules. It also gives problems when trying to apply it to single cells. Is the definition of life as ‘self-determined motion in the service of reproduction’ more appropriate? Is the definition of life as ‘what is made of cells’ more appropiate? Challenge 1001

The physics of pleasure

Pleasure is a quantum effect. The reason is simple. Pleasure comes from the senses. All senses measure. And all measures rely on quantum theory. Indeed, the human body, like an expensive car, is full of sensors. Evolution has build these sensors in such a way that they trigger pleasure sensations whenever we do with our body what we are made for.

Among the most astonishing aspects is the sensitivity of our body sensors. The *ear* is so sensitive and at the same time so robust against large signals that the experts are still studying how it works. No known sensor can cover an energy range of 10^{13}; the detected intensity ranges from 1 pW/m^2 to 10 W/m^2, the corresponding air pressure variations from 20 μPa to 60 Pa.

In addition, the ear can distinguish at least 1500 pitches with its 16 to 20000 hair cells. The ear can distinguish 400 from 401 Hz using a pitch sharpening mechanism in the ear. Audible sound wavelengths span from 17 m (20 Hz) to 17 mm (20 kHz).

The *eye* is a position dependent photon detector. Each eye contains around 126 million separate detectors on the retina. Their spatial density is the highest possible that makes sense, given the diameter of the lens of the eye. There are about 6 million less sensitive colour detectors, the cones, and 120 million highly sensitive general light intensity detectors, the rods. That is the reason that at night all cats are grey. Until recently, human built light sensors with the same sensitivity as rods had to be helium cooled, because technology was not able to build sensors at room temperature as sensitive as the human eye.

The *touch sensors* are distributed over the skin, with a surface density which varies from one region to the other. It is lowest on the back, and highest in the face and on the tongue. There are separarte sensors for pressure, for deformation, for vibration and for tickling. Some react proportionally to the stimulus intensity, some differentially.

The taste mechanisms of *tongue* are only partially known. The tongue produces five taste signals* – sweet, salty, bitter, sour, proteic – and the mechanisms are just being unravelled. No sensors with a distinguishing ability of the same degree have been built by humans so far.

The *nose* can distinguish numerous smells. Together with the five signals that the sense of taste can produce (sweet, salty, bitter, sour, proteic) the nose produces a vast range of sensations. It protects against chemical poisons, such as smoke, or biological poisons, such as faecal matter. In contrast, artificial gas sensors exist only for a small range of gases. Artificial taste and smell sensors would allow to check wine or cheese during their production, thus making its inventor extremely rich.

The body also contains orientation sensors, extension sensors in each muscle, pain sensors, heat sensors and coldness sensors. Other animals feature additional types. Sharks can feel electrical fields, snakes have sensors for infrared, and pigeons can feel magnetic fields. Many birds can see UV light. Bats are able to hear ultrasound up to 100 kHz and more. Whales can detect and localize infrasound signals.

We can conclude that the sensors nature provides us with are state of the art; their sensitivity and ease of use is the highest possible. Since all sensors trigger pleasure or help to
Ref. 618 avoid pain, nature obviously wants us to enjoy life with the most intense pleasure possible. Studying physics is one way to do this.

There are two things that make life worth living:
Mozart and quantum mechanics.

* Taste is *not* distributed on the tongue in distinct regions; this is an incorrect idea that has been copied from
Challenge 1002 n book to book for over a hundred years. You can perform a falsification by yourself, using sugar or salt grains.

Victor Weisskopf*

– CS – more to be added – CS –

Why can we observe motion?

Studying physics can be one of the most intense pleasures of life. Our human condition is central to this ability. In our adventure so far we found that we experience motion only because we are of finite size, only because we are made of a large but finite number of atoms, only because we have a finite but moderate temperature, only because we are a mixture of liquids and solids, only because we are electrically neutral, only because we are large compared to a black hole of our same mass, only because we are large compared to our quantum mechanical wavelength, only because we have a limited memory, only because our brain forces us to approximate space and time by continuous entities, and only because our brain cannot avoid describing nature as made of different parts. If any of these conditions were not fulfilled we would not observe motion; we would have no fun studying physics.

In addition, we saw that we have these abilities only because our forefathers lived on earth, only because life evolved here, only because we live in a relatively quiet region of our galaxy, and only because the human species evolved long after than the big bang.

If any of these conditions were not fulfilled, or if we were not humans (or animals), motion would not exist. Motion is in many ways an illusion, as Zeno of Elea claimed. To say the least, the observation of motion is due to the limitations of the human condition. A final description of motion and nature therefore must take this connection into account. Before we do that, we explore a few details of this connection.

Material science

Did you know that one cannot use a boiled egg as toothpick?
Karl Valentin

We mentioned several times that the quantum of action would explain all properties of matter. In our walk we can only touch this vast and interesting topic. Let us explore the most interesting selection.

Why does the floor not fall?

We do not fall through the mountain. Some interaction keeps us from falling through. In turn, the continents keep the mountains from falling through them. Also the liquid magma in the earth's interior keeps the continents from sinking. Atoms, despite being mostly empty clouds, do not penetrate each other. All this is due to the Pauli principle between electrons. See page 554
It avoids that atoms interpenetrate each other.

* Victor Weisskopf (Vienna, 1908 – 2002), acclaimed theoretical physicist who worked with Einstein, Born, Bohr, Schrödinger and Pauli. He worked on the Manhattan project but later in life intensely campained against the use of nuclear weapons. He was professor at MIT and for many years director of CERN, in Geneva. He wrote several successful physics textbooks.

But not all floors keep up due to the fermion character of electrons. Atoms are not impenetrable at all pressures. Some floors are so exciting to study that people have spent their whole life to understand why they do not fall, or when they do, how it happens: the surfaces of stars.

In most stars, the radiation pressure of the light plays only a minor role. But the light pressure plays a role in determining the size of red giants, such as Betelgeuse.

In many stars, such as in the sun, the gas pressure takes the role which the incompressibility of solids and liquids has for planets. The pressure is due to the heat produced by the nuclear reactions.

The next star type appears whenever light pressure, gas pressure, and the electronic Pauli pressure cannot keep atoms from interpenetrating. In that case, atoms are compressed until all electrons are pushed into the protons. Protons then become neutrons, and the whole star has the same mass density of atomic nuclei, namely about $\ldots \cdot 10^{\cdot\cdot}\ \mathrm{kg/m^3}$. A spoonful weighs about ...tons. In neutron stars, the size is also determined by Pauli pressure; however, it is the Pauli pressure between neutrons, triggered by the nuclear interactions. These *neutron stars* are all around 10 km in radius.

See page 644

If the pressure increases still further the star becomes a black hole, and never stops collapsing. Black holes have no floor; they still have a constant size, though, determined by the horizon curvature.

See page 326

The question whether there other star types exist in nature, with other floor forming mechanisms – such as quark stars – is still a topic of research.

How can one look through matter?

Quantum theory discovered that all obstacles have only finite potential heights. That leads o the question: Is it possible to look through matter? For example, can we see what is hidden inside a mountain? To be able to do this, we need a signal which fulfils two conditions: it must be able to *penetrate* the mountain, and it must be scattered in a *material-dependent* way. Table 48 gives an overview of the possibilities.

Table 48 Signals penetrating mountains and other matter

Signal	penetration depth in stone	achieved resolution	material dependence	use
matter				
diffusion of water or liquid chemicals	ca. 5 km	ca. 100 m	medium	mapping hydrosystems
diffusion of gases	ca. 5 km	ca. 100 m	medium	studying vacuum systems
electromagnetism				
sound, explosions	0.1 – 10 m	ca. $l/100$	high	oil and ore search
ultrasound		1 mm	high	medicine: imaging
infrasound and earthquakes	100 000 km	100 km	high	mapping of earth crust and mantle
static magnetic fields			medium	cable search, cable fault localisation

Signal	penetration depth in stone	achieved resolution	material dependence	use
static electric fields				
electrical currents				soil investigations, search for tooth decay
X rays	a few metre	5 μm	high	medicine, material analysis, airports
visible light	ca. 1 cm	0.1 μm	medium	imaging of many sorts
IR	ca. 1 cm	0.1 μm	medium	mammography of the future
mm and THz waves	below 1 mm	1 mm		see through clothes Ref. 626
radio waves	10 m	1 m to 1 mm	small	soil radar, magnetic imaging, research into solar interior
weak interactions				
neutrino beams	light years	zero	very weak	studies of sun
strong interactions				
cosmic radiation	1 m to 1 km			
radioactivity	1 mm to 1 m			airports
gravitation				
change of gravitational acceleration		50 m	low	oil & ore search

Many signals are able to penetrate a mountain. However, only sound or radio waves provide the possibility to distinguish different materials, or to distinguish solids from liquids and from air. In addition, any good method requires a large number of signal sources and of signal receptors, and thus a large amount of cash.

Will there ever be a simple method allowing to look into mountains as well as X-rays allow to study human bodies? For example, will it ever be possible to map the interior of the pyramids? A motion expert like the reader should be able to give a definite answer. Challenge 1003 n

One of the high points of twentieth century physics was the development of the best method so far to look into matter with dimensions of about a meter or less: magnetic resonance imaging. We will discuss it later on. See page 632

The other modern imaging technique, ultrasound imaging, is getting more and more criticized. It is much used for prenatal diagnostics of embryos. However, studies have found that ultrasound produces extremely high levels of audible sound to the baby, especially when the ultrasound is switched on or off, and that babies react negatively to this loud noise.

What is necessary to make matter invisible

Everybody has already imagined what adventures would be possible if we could be invisible for a while. Some years ago, a team of Dutch scientists found a material than can be switched from mirror mode to transparent mode using an electrical signal. This seems a first Ref. 625

step to realize the dream to become invisible at will.

Nature shows us how to be invisible. An object is invisible if it has no surface, no absorption and small size. In short, invisible objects are either small clouds or composed of them. Most atoms and molecules are examples. Homogeneous non-absorbing gases also realize these conditions. That is the reason that air is (usually) invisible. When air is not homogeneous, it can be visible, e.g. above hot surfaces.

In contrast to gases, solids or liquids do have surfaces. Surfaces are usually visible, even if the body is transparent, because the refractive index changes there. For example, quartz can be made so transparent that one can look through 1 000 km of it; pure quartz is thus more transparent than usual air. Still, objects made of pure quartz are visible to the eye due to the index change at the surface. Quartz can be invisible only when submerged in liquids with the same refractive index.

In other words, to become invisible, we must transform ourselves into a diffuse cloud of non-absorbing atoms. On the way to become invisible, we would loose all memory and all genes, in short, we would loose all our individuality. But an individuum cannot be made of gas. An individuum is defined through its boundary. There is no way that we can be invisible; a reversible way to perform the feat is even more unrealistic. In fact, we can say that physics shows that only the dead can be invisible.

Curiosities and challenges of material science

Material science is not a central part of this walk. But a few curiosities can give a taste of it.

▪ What is the maximum height of a mountain? This question is of course of interest to all climbers. Many effects limit the height. The most important is the fact that under heavy pressure, solids become liquid. For example, on earth this happens at about 27 km.This is quite a bit more than the highest mountain known, which is the volcano Mauna Kea in Hawaii, whose top is about 9.45 km above the base. On Mars gravity is weaker, so that mountains can be higher. Indeed the highest mountain on Mars, Olympus mons, is 80 km high. Can you find a few other effects limiting mountain height?

Ref. 627 Challenge 1004 Challenge 1005 n

▪ Do you want to become rich? Just invent something that can be produced in the factory, is cheap, and can substitute duck feathers in bed covers and sleeping bags.Another industrial challenge is to find an artificial substitute for latex. Challenge 1006

▪ What is the difference between solids, liquids, and gases? Challenge 1007

▪ At low temperatures of about 2 mK, helium-3 becomes a *superfluid*. It is even able, after an initial kick, to flow over obstacles, such as glass walls.

▪ Dislocations in crystals are a pet topic of many physicists. For example, their motion is described by the same formulas as special relativity, with the speed of sound being limit speed.

– CS – to be continued – CS –

▪ Quantum theory shows that tight walls do not exist. Ever material is penetrable. Why? Challenge 1008 n

▪ Quantum theory shows that even if tight walls would exist, the lid of such a box can never be tightly shut. Can you provide the argument? Challenge 1009 n

▪ Quantum theory predicts that heat transport at a given temperature is quantized. Can you guess the unit of thermal conductance? Challenge 1010

▪ Robert Full has shown that van der Waals forces are responsible for the way that geckos walk on walls and ceilings. The gekko, a small reptile with a mass of about 100 g, uses an elaborate structure on its feet to perform the trick. Each foot has 500 000 hairs each split in up to 1000 small spatulae, and each spatula uses the van-der-Waals force to stick to the surface. As a result, the gekko can walk on vertical glass walls or even glass ceilings; the sticking force can be as high as 100 N per foot. Ref. 628

▪ Millimetre waves and terahertz waves are emitted by all bodies at room temperature. Modern cameras allow to image them. This allows to see through clothes and thus to detect hidden weapons in airports. But the development of practical and affordable detectors which can be handled as easily as a binocular is still an topic of research.

Quantum technology

Quantum effects do not appear only in microscopic systems. Several quantum effects are important in modern life; transistors, lasers, superconductivity and a few other effects and systems are worth knowing.

Quantized conductivity

In 1996, the Spanish physicist J.L. Costa-Krämer and his colleagues performed a simple experiment. They put two metal wires on top of each other on a kitchen table and attached a battery, a 10 kΩ resistor and a storage oscilloscope to them. They then measured the electrical current while knocking on the table. In the last millisecond before the wires detach, the conductivity and thus the electrical current diminished in regular steps of a few 7 μA, as can easily be seen on the oscilloscope. This simple experiment could have beaten, if it had been performed a few years earlier, a number of enormously expensive experiments which discovered this quantization at costs of several million euros, using complex set-ups and low temperatures. Ref. 631

In fact, quantization of conductivity appears in any electrical contact with a small cross section. In such situations the quantum of action implies that conductivity can only be a multiple of $2e^2/\hbar \approx 1/12\,906\,1/\Omega$. Can you confirm this result? Challenge 1011

Note that electrical conductivity can be as small as required; only *quantized* electrical conductivity has the minimum value of $2e^2/\hbar$.

The fractional quantum Hall effect

The fractional quantum hall effect is one of the most intriguing discoveries of material science. In 1982, Robert Laughlin predicted that in this system one should be able to observe objects with electrical charge $e/3$. This strange prediction was indeed verified in 1997. Ref. 632

The story begins with the discovery of Klaus von Klitzing of the quantum Hall effect. In 1980 he found that in two-dimensional systems at low temperatures – about 1 K – the electrical conductance is quantized in multiples of the quantum of conductance

$$S = n\,\frac{e^2}{\hbar} \quad . \qquad (447)$$

This is a section of the freely downloadable e-textbook

MOTION MOUNTAIN

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along the concepts of modern physics

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To the kind reader

In exchange for getting this section for free, I ask you for a short email on the following:

- What was hard to understand?
- Did you find any mistakes?
- What figure or explanation were you expecting?
- Which page was boring?

Of course, any other suggestion is welcome. This section is part of a physics text written over many years. The text lives and grows through the feedback from its readers, who help to improve and to complete it. For a particularly useful contribution (send it in english, italian, dutch, german, spanish, portuguese, or french) you will be mentioned in the foreword of the text, or receive a small reward, or both.

Enjoy!

Christoph Schiller
mm@motionmountain.net

The explanation is straightforward and is the quantum analogue of the classical Hall effect, which describes how conductance varies with applied magnetic field. Von Klitzing received the Nobel prize in physics for the discovery, as it was completely unexpected, allows a highly precise measurement of the fine structure constant and allows to detect the smallest voltage variations measureable.

Two years later, it was found that in extremely strong magnetic fields the conductance could vary in steps one third that size. Other, even stranger fractions were also found. Robert Laughlin explained all these results by assuming that the electron gas could form collective state showing quasiparticle excitations with a charge $e/3$. This was confirmed 15 years later, and earned him a Nobel price as well. We have seen in several occasions that quantization is best discovered through noise measurements; also in this case, the clearest confirmation came from electrical current noise measurements.

How can we imagine these excitations?

– CS – explanation to be inserted – CS –

What do we learn from this result? Systems in two dimensions have states which follow different rules than systems in three dimensions. The first question one asks is whether we can infer something about quarks from this result. Quarks are the constituents of protons and neutrons, and have charges $e/3$ and $2e/3$. At this point we need to stand the suspense; we come back to this issue later on.

Can two photons interfere?

In 1930, Dirac made the famous statement already mentioned above:*

> Each photon interferes only with itself. Interference between two different photons never occurs.

Often this statement is misinterpreted as implying that two separate photon *sources* cannot interfere. It is almost unbelievable how this false interpretation has spread through the literature. Everybody can check that this statement is incorrect with a radio: two distant radio stations transmitting on the same frequency lead to beats in amplitude, i.e. to *wave interference*. (This should not to be confused with the more common *radio interference*, with usually is simply a superposition of intensities.) Radio transmitters are coherent sources of photons, and any radio receiver shows that two such sources can indeed interfere. Ref. 644

In 1949, interference of two different sources has been demonstrated with microwave beams. Numerous experiments with two lasers and even with two thermal light sources have shown light interference from the fifties onwards. Most cited is the 1963 experiment by Magyar and Mandel; they used two ruby lasers emitting light pulses and a rapid shutter camera to produce spatial interference fringes. Ref. 644

However, all these experimental results do not contradict the statement by Dirac. Indeed, two photons cannot interfere for several reasons.

* See the famous, beautiful but difficult textbook P.A.M. Dirac, *The Principles of Quantum Mechanics*, Clarendon Press, Oxford, 1930, page 9.

▪ Interference is a result of space-time propagation of waves; photons appear only when the energy-momentum picture is used, mainly when interaction with matter takes place. The description of space-time propagation and the particle picture are mutually exclusive – this is one aspect of the complementary principle. Why does Dirac seem to mix the two in his statement? Dirac employs the term 'photon' in a very general sense, as quantized state of the electromagnetic field. When two coherent beams are superposed, the quantized entities, the photons, cannot be ascribed to either of the sources. Interference results from superposition of two coherent states, not of two particles.

▪ Interference is only possible if one cannot know where the detected photon comes from. The quantum mechanical description of the field in a situation of interference never allows to ascribe photons of the superposed field to one of the sources. In other words, if you can say from which source a detected photon comes from, you *cannot* observe interference.

▪ Interference between two beams requires a fixed phase between them, i.e. an uncertain particle number; in other words, interference is only possible if the photon number for each of the two beams is unknown.

A better choice of words is to say that interference is always between two (indistinguishable) states, or if one prefers, between two possible (indistinguishable) histories, but never between two particles. In summary, two different electromagnetic beams can interfere, but not two different photons.

Can two electron beams interfere?

Figure yet to be included

Figure 222 An electron hologram

Do coherent electron sources exist? Yes, as it is possible to make holograms with electron beams. However, electron coherence is only transversal, not longitudinal. Transversal coherence is given by the possible size of wavefronts with fixed phase. The limit of this size is given by the interactions such a state has with its environment; if the interactions are weak, matter wave packets of several metres of size can be produced, e.g. in particle colliders, where energies are high and interaction with matter is low.

Actually, the term transversal coherence is a fake. The ability to interfere with oneself is not the definition of coherence. Transversal coherence only expresses that the source size is small. Both small lamps (and lasers) can show interference when the beam is split and recombined; this is not a proof of coherence. Similarly, monochromaticity is not a proof for coherence either.

A state is called *coherent* if it possesses a well-defined phase throughout a given domain of space or time. The size of that region or of that time interval defines the degree of coherence. This definition yields coherence lengths of the order of the source size for small 'incoherent' sources. Nevertheless, the size of an interference pattern, or the distance d between its maxima, can be much larger than the coherence length l or the source size s.

In summary, even though an electron can interfere with itself, it cannot interfere with a second one. One needs uncertain electron numbers to see a macroscopic interference pattern. That is impossible, as electrons (at usual energies) carry a conserved charge.

– CS – several sections to be added – CS –

Challenges and dreams of quantum technology

Many challenges in applied quantum physics remain, as quantum effects seem to promise to change old technological dreams into reality.

- Are ghost images in TV sets, often due to spurious reflections, examples of interference? Challenge 1013 n
- Is it possible to make A4-size, thin, and flexible colour displays for an affordable price? Challenge 1014 d
- What happens when two monochromatic electrons overlap? Challenge 1015 h
- Will there ever be desktop laser engravers for 2000 Euro? Challenge 1016 h
- Will there ever be room-temperature superconductivity? Challenge 1017 h
- Will there ever be teleportation of everyday objects? Challenge 1018 n
- Will there ever be applied quantum cryptology? Challenge 1019 d
- Will there ever be printable polymer electronic circuits, instead of lithographically patterned silicon electronics as it is now? Challenge 1020 d
- Can you show in great lines that consciousness is a quantum process?And that it is electromagnetic? Challenge 1021 n