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Schrödinger's Cat in Nanoscopolis

Schrödinger's cat

Schrödinger's cat is a provocative thought experiment that illustrates the novelty of quantum physics. Published in 1935, Erwin Schrödinger described the cat paradox shortly after co-fostering the invention of quantum mechanics [Schrödinger, 1935]:

> "One can even set up quite ridiculous cases. A cat is penned in a steel chamber, along with the following diabolical device (which must be secured against direct interference by the cat); In a Geiger counter there is a tiny bit of radioactive substance, so small that perhaps in the course of one hour one of the atoms decays, but also, with equal probability, perhaps none, if it happens, the counter tube discharges and through a relay releases a hammer which shatters a small flask of hydrocyanic acid. If one has left this entire system to itself for an hour, one would say that the cat still lives, if meanwhile, no atom has decayed. The first atomic decay would have poisoned it. The Psi function for the entire system would express this by having in it the living and the dead cat (pardon the expression) mixed or smeared out in equal parts."

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Quantum physics, through the wave function Psi, describes the quantitative behaviour of microscopic particles and their interactions. According to quantum physics, a system is allowed to be in a simultaneous superposition of two or more states. This appears to be at odds with the nature we observe in our daily life. Schrödinger's cat illustrates what happens if a macroscopic object would behave as a single microscopic particle. Our naïve intuition tells us that the cat cannot be dead and alive at the same time, yet, for simple and small enough entities, the analogue of this is exactly what occurs.

The macroscopic world is also determined by quantum physics, although its quantum nature is seldom directly encountered. A macroscopic object consists of a very large number of microscopic particles, and in order for the macroscopic object to exhibit measurable quantum features, all microscopic particles must be in coherently related states. For a huge number of microscopic particles that are the building blocks of a macroscopic object, macroscopic quantum behaviour is often extremely unlikely. Usually, macroscopic quantum behaviour is so rare that for all practical purposes, even by waiting as long as the age of the universe, it is impossible to observe it. Besides, macroscopic objects are also coupled to other macroscopic objects that further decrease quantum coherence.

In contrast, in the classical world, the world as it was understood before the invention of quantum physics, the universe is intuitive and predestined, and there is clarity over where a particle or wave moves and resides. This picture agrees more with our daily intuition. For these reasons, quantum physics might appear for many as philosophical, controversial, complicated and not well understood. However, most researchers in the field of quantum physics have a more pragmatic point of view: quantum physics is a mathematical, precise, and universal tool for describing various natural phenomena.

Technology

In 1965, the co-founder of Intel, Gordon Moore, observed that the number of transistors on an integrated circuit roughly doubles every two years [Moore, 1965]. Four decades later, we still benefit from this continued technological progress. The resulting exponential growth is known as Moore's Law and is followed by an exponential miniaturizing of nanoelectronics components. Today (2007), the minimum feature size of a transistor in an Intel Pentium processor is around 50nm. This is a very small length scale that should be compared to the distance between the atoms in silicon which is around 0.5 nm. If the exponential reduction in transistor size continues, a transistor will be as small as an atom around the year 2020! It is therefore unlikely that the same growth can continue in the same way for the next two decades. This technological growth will come to an end, or completely new concepts will have to be introduced.

Moore's Law, and the rapid miniaturization towards atomic size, pose technological challenges: First, envisage a computer with one atom per bit, and an efficient transfer of information with one photon (the smallest light quanta) per bit. Second, consider an even more exotic scenario: Develop a quantum computer with less than one atom per bit, and less than one photon per bit quantum information transfer.

Classically, information is stored as '1' and '0'. This is typically represented in a computer by a high or low electric voltage. These high or low electric voltage signals are induced by millions of charged electrons. The resulting '1' and '0' information bits are classic since they result from the average properties of a huge number of microscopic particles that are unlikely to be in one unique macroscopic quantum state. A quantum bit can store '1' and '0' in the same way that the cat is dead and alive in Schrödinger's thought experiment. Even more important, two or more quantum bits can be in *entangled states* in which the quantum bits must be described with reference to each other and not individually. Some important computer algorithms are much faster on a hypothetical quantum computer. For example, Shor's quantum algorithm factorizes a number much faster than known classical algorithms [Shor, 1997]. This might appear as an academic problem, but is in practice significant because it implies that public key cryptography can be broken. Many cryptography schemes use a public key number which is the product of two large prime numbers. These codes can be opened by factoring the public key, which is impossible on a conventional computer because it takes too much time, but feasible on a large enough quantum computer. Similarly, a quantum computer can also solve other problems that are impossible to handle on conventional computers. However, Dell and HP do not sell quantum computers. So far, prototype experimental work has only realized less than 10 quantum bits that work coherently together.

Nanoscopolis

The subject of quantum physics was invented in response to the observed behaviour of atoms. Atomic physics is therefore the prime example of applied quantum mechanics. It is microscopic since the elementary particles, the nucleus and the electron, set the natural length unit at 0.05 nanometres, which is the radius of a hydrogen atom. With atoms as building blocks, we have explored the properties of condensed matter surrounding us and what is often termed the macroscopic world. Quantum physics dictates the behaviour of materials, e.g. the common metals Al and Cu, semiconductors Si, and ferromagnets Fe. The macroscopic features are results of intricate quantum mechanical behaviour at the level of the inter-atomic distance between atoms in a solid, typically on the order of 0.5 nm. For instance, semiconductors and magnets cannot be understood without invoking quantum physics. However, although quantum physics dictates material properties, phenomena such as quantum entanglement and quantum interference are usually not seen in macroscopic materials like Al, Cu, Si and Fe. The properties of most material compounds in nature are already determined by nature in the sense that they depend on the exact arrangement of the atoms.

The existence of an interesting intermediate world of phenomena where the bizarre rules of quantum theory are measurable with techniques normally applied to macroscopic matter, is the key issue in an exciting new field: physics on the nano-scale, or physics in nanoscopolis. For instance, electrical resistance can become quantized for sufficiently small semiconductor devices [van Wees, 1988].

Allow me to illustrate how small a nanometre is. The road from Trondheim to Oslo in Norway is about 500 kilometres long. Let us imagine that we put coffee cups in a row along the road from Trondheim to Oslo. We can then take a satellite picture of the road with the cups and print it out on a normal sheet of paper in front of us. In nanoscopolis, the objects are as small as the coffee cups in this picture. They are much larger than the interatomic distances, yet very much smaller than objects that we can observe with our eyes.

In 1989, Don Eigler wrote nano-history. The IBM scientist used 35 xenon atoms to spell the IBM logo [Eigler, 1990]. This signalled a new trend in which technology can change the arrangement of atoms down to the atomic level. The quantum features that occur in nanoscopolis are fundamentally interesting and could possibly also be used in modern technology. State-of-the-art technology enables material growth atom by atom. This unprecedented precision allows the construction of new materials with desired electrical, magnetic and mechanical behaviour.

In nanoscopolis, researchers are able to use precise tools to construct *artificial atoms*. These *quantum dots* are areas where electrons are confined in materials. By manipulating these materials, *artificial atoms* can be constructed with desired properties. A major part of the motivation for research on materials in nanoscopolis has less ambitious aims. The goal is to design devices with new degrees of freedom arising from their quantum nature, less energy loss, and reduced size. One such 'new' degree of freedom is the electron spin. The electron was discovered by J. J. Thomson in 1897, making it the first sub-atomic particle ever detected. It has an electrical charge. Two types of experimental evidence which arose in the 1920s suggested an additional property of the electron and an intrinsic angular momentum as if the electron were spinning around its own axis. This quantum property was called electron spin.

An electron has a spin as well as a charge. The recognition of spin as binary variable analogues to electrons and holes in semiconductors has opened new fields of science and technology that have already led to commercial devices and hold great promise for nanoscale science and information technology. The giant magneto resistance (GMR) in magnetic metallic multi-layers discovered only fifteen years ago was applied to magneto-resistive read heads for hard disks in high-end desktop computers five years ago and is the dominant technology in this field [IBM, 1997].

Conclusions

The quantum world is very different from our intuitive understanding of the classical world. Technological needs and scientific curiosity are going to drive the miniaturization of magnetic structures into the mesoscopic and nanoscopic regimes in which the basic physics has still to be explored. In the not too far distance, the technology might take into account the bizarre nature of quantum physics. It is far from clear whether quantum computers will ever actually be made, but on the way to such a paradigm, we will get a better understanding of quantum physics on a larger scale and with a higher degree of precision than ever before.

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