QUANTUM NANOSCIENCE

Everything discussed in the separate document on Classical Nanoscience is really just an extension of existing ideas to a much smaller scale. If this was all that was involved in nanoscience, it would be a little hard to see why people were so excited. However it is almost a truism that moving into a new realm opens up entirely new possibilities, requiring a new theoretical framework, and new experimental ideas and techniques. This is where theoretical physics comes into its own- indeed, theorists have been suggesting some very exotic scenarios in the last 2 decades, and the prospect of these has been driving a lot of the research in nanoscience during this time.

The most crucial new element that enters at the very small scale is of course quantum mechanics. In all of the ideas and developments discussed above, quantum mechanics enters in a 'passive' way- it is necessary for a proper explanation of the physical systems involved (just as it is for any physical system), but does not enter in any crucially new way in their actual behaviour. The results to be expected when the quantum properties move to centre stage are very dramatic indeed. To see why this is, we first need a brief explanation of what is different about quantum behaviour. Readers may find it useful to read the separate document on classical nanoscience first- the present document is an extension of it (NB: Figure numbering also begins in the document on Classical Nanoscience)

1: QUANTUM BEHAVIOUR

Quantum mechanics confronts us with a remarkable situation. On the one hand, quantum mechanics is by far the most successful scientific theory ever created. Indeed, it still has no known limits, and its application to physical systems ranging over 47 decades of length scale, from 10^{-21}m (a million times smaller than a proton) up to 10^{26}m (or 10^{11} light years, the size of the visible universe) has completely transformed our understanding of the physical world. On the other hand, this incredibly powerful theory is, in a quite profound way, incomprehensible to us, because of what it says about the nature of physical reality. In what follows a sketch is given of some of the key ideas in quantum mechanics, and in section 2 we will see how these should lead in practice to some very startling new technologies in the next few decades.

1 (a) *The "Superposition Principle"*: **We are so used to the idea that a physical system is in some definite state, that it is hard to imagine things otherwise. Statements like "there is a ball on the chair", or "the book is open", assume that physical objects are in a definite state (otherwise it is hard to imagine what "is" in these phrases means, or what the verb "to be" would signify). In a very deep way, we feel that 'physical reality' involves definite objects which are in definite physical states. Thus, we can put a coin flat on the table, and not only is the coin itself assumed to be 'real', but it also definitely has either 'heads' or 'tails' facing up (ie., it is in a definite physical state of either 'heads' or 'tails').**

However quantum mechanics says something very different, and apparently nonsensical- that a physical system like a coin can *simultaneously* be in a state of both “heads” and “tails”! This is called a ‘*superposition of states*’ in quantum mechanics. According to quantum theory, if a physical system can exist in any one of a set of different physical states, then it can also exist in any superposition of these. For example, suppose we have a system that can exist in ordinary ‘classical physics’ in one of 2 different states- a coin is a good candidate, existing in a state of ‘heads’ or ‘tails’. In quantum mechanics we can form a superposition of both heads and tails- as though the coin was simultaneously in both states! Physicists write such superpositions in a simple way. Suppose we label a state ‘heads’ by the symbol “|+>” (here the “+” means ‘heads’, and the “| >” indicates we are talking about a quantum state). In the same way, the state ‘tails’ is labeled by |--> . Then a superposition of equal parts heads and tails is written as (|+> + |-->). Note this superposition is a single definite quantum state- the bizarre feature is that this state can be a superposition of several different ‘classical’ states (where by ‘classical’ states we mean the states we are used to in ordinary common sense life).

|+> + |--> =

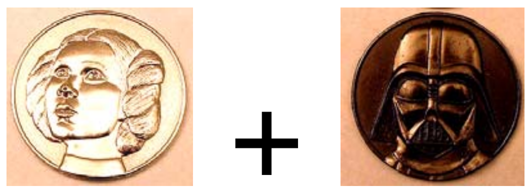


Fig. 12: ***A superposition of* ‘heads’ *and* ‘tails’**

The difficulties attending such superpositions were highlighted in 1935, when Schrodinger described how according to quantum mechanics one might put a cat (now called “*Schrodinger’s Cat*”) simultaneously into a superposition of “live” and “dead” states. Schrodinger’s argument was intended to show that bizarre superpositions of radically different classical physical states were logically possible in quantum mechanics. For many years most physicists took Schrodinger’s Cat to be a *reductio ad absurdum* (as did Schrodinger), and assumed that macroscopic quantum states must in some way be absolutely forbidden. However, starting in 1979 with theoretical work of Leggett and collaborators, it was shown that macroscopic quantum superpositions could indeed exist under special circumstances (although a superposition of live and dead cats is probably a fantasy), and they were first prepared experimentally, in superconductors at low temperature, in 2003. They are expected to be crucial to any future ‘quantum technology’ (see below).

1(b) *Quantum “Entanglement”*: The idea of superposition is bad enough for our common sense views, but it is certainly not the most bizarre feature of quantum mechanics. This honour falls to what is called ‘entanglement’. Consider TWO coins- let’s call them coin A and coin B- and suppose we correlate their behaviour so that, eg., they must always have opposite states (NB: to physically correlate them can be done in various ways- in fact any interaction between them will, in quantum mechanics, lead to some kind of correlation). Now there are 2 possible ways for the coin states to be oppositely oriented. One is to have coin A as heads, and coin B as tails- this state would be written as |+ -->. However we could also have coin A as tails, and coin B as heads- this state would be written as | -- +>. Common sense tells us that we must have one situation or the other. However in

quantum mechanics, again, we can have a superposition of the two possibilities- giving a state which is written as (|+ --> + |-- +>); see figure below:

|+ --> + |-- +> =


Fig. 13: ***An entangled pair of coin states, as described in text.***

Now the startling thing is that in such a superposition, *we can attribute no physical state to either of the coins separately* - only the PAIR of coins is in a definite state. Thus when 2 physical systems are in an entangled state, the physical state of one of the systems on its own *does not exist*- only the 'pair state' is physical real. We see that entanglement demands a radical revision of our notion of 'reality'. The conflict between quantum notions of reality, and very deeply-entrenched common sense intuitions, is certainly the most difficult philosophical problem raised by modern physics. Many have simply refused to accept such strange ideas. The most notable objections came from Einstein: starting from the famous 'Einstein-Podolsky-Rosen' paradox (1935), he argued that quantum mechanics must be incomplete, by showing that entanglement led to apparently nonsensical experimental consequences. To the end of their lives, Einstein and Schrodinger never accepted that physical reality could be this way. However, experiments in the last 25 years have not only confirmed entanglement in the lab, but shown it can be used as a tool to do incredible things - discussed in section 2 below. Nowadays one talks of entanglement as a new 'resource' (meaning, amongst other things, that it can be used to develop new technologies- see below).

Fig. 14***: Two of Walt Disney's images of the power of modern quantum physics, embodied (LEFT) in a malevolent genie towering over the fisherman, or (RIGHT) in a benevolent genie, whose power is harnessed for the good of all (from* 'Our Friend the Atom'** ***(1964)).***

Walt Disney summed up, in his remarkable film "Our Friend the Atom", the 2-sided face of quantum mechanics that we now perceive, by the analogy of an Arabian genie. On the one hand, a theory of

apparently limitless scope and power, quite unprecedented in previous human history, and on the other hand, an interpretation and an associated ontology that seem mysterious & paradoxical. Nobody can truly claim to understand quantum theory, and some of its greatest practitioners feel instinctively that it must somehow be flawed or incomplete, despite its unparalleled success. Others argue that it is here to stay, and the flaw is in our own intuitions of reality. Whatever one may think about these essentially philosophical issues, they can no longer be ignored- in the next few decades, macroscopic devices will be built which depend essentially on entanglement and superposition for their operation, bringing uniquely quantum-mechanical phenomena into our everyday world.

1 (c) *Key Features of Quantum Mechanics*: **As indicated above, quantum mechanics has been applied to virtually every physical system we know, with extraordinarily revealing consequences. This has happened not just in physics but also in chemistry and biology- the stunning changes in chemistry and biology, with the unraveling of the genetic code and our now essentially complete understanding of chemistry, stem entirely from the development of quantum mechanics. With some hindsight we can see that the 1st stage of what is often called the 'quantum revolution' is now more or less complete- this consisted in the unraveling of already known physical phenomena, and the exploration of new phenomena revealed by quantum mechanics, in a mostly passive navigation of the natural world on all length scales. The seeds of the 2nd stage were sown many years ago, with the use of quantum mechanics to develop fundamentally new physical systems, not present in Nature. Well-known examples of this are in devices such as transistors and lasers, now at the heart of a large part of the modern electronics industry. But such devices hardly use the full potential of quantum mechanics, embodied in the ideas of superposition and entanglement. Only now are we on the threshold of huge changes, as we begin to learn how to do this. Most of the coming developments are labeled under the heading of 'Quantum Nanoscience', with applications coming under the umbrella of 'Quantum NanoTechnology'. In the rest of this section I describe some of the relevant quantum ideas underlying these new developments; the next section (section 2) describes some of the applications being envisaged for a future quantum nanotechnology.**

(i) DISCRETE QUANTUM STATES: In classical physics we are accustomed to a continuum of possible states for a physical system- we imagine, eg., a particle passing continuously from one position to another along some classical trajectory, and such continuous change now seems quite a natural idea, notwithstanding the old objections and paradoxes of Zeno of Elea. However, as already hinted above, a quantum system can often only exist in one or more of a discrete set of states. This key feature of quantum systems arises whenever they are confined in some finite region of space. Such confinement happens when the system in question is subject to some force attracting it towards that region. Physicists represent this pictorially by defining a 'potential' which represents the energy of the system coming from its interaction with the force- an attractive force creates a 'potential well'. Thus, eg., in a Hydrogen atom, a negatively charged electron is attracted towards the positively charged proton nucleus, and classically it would simply orbit the proton (until it radiated energy away, and it would then 'fall down' the potential well to the centre, ie., collapse into the proton!).

However the quantum electron can only go into certain discrete states - each state has a different energy, and so we talk about 'energy levels'. Each level refers to a different possible quantum state. There is always a lowest state of all, which is called the '*ground state*'; if the electron settles

into this state, it can lose no more energy. States of higher energy than the ground state are called '*excited states*'. This is a perfectly general feature of a quantum system localized in a potential well- the example in the figure not only shows the energy levels, but also how a particle in any of these states spreads out in space inside the potential well:

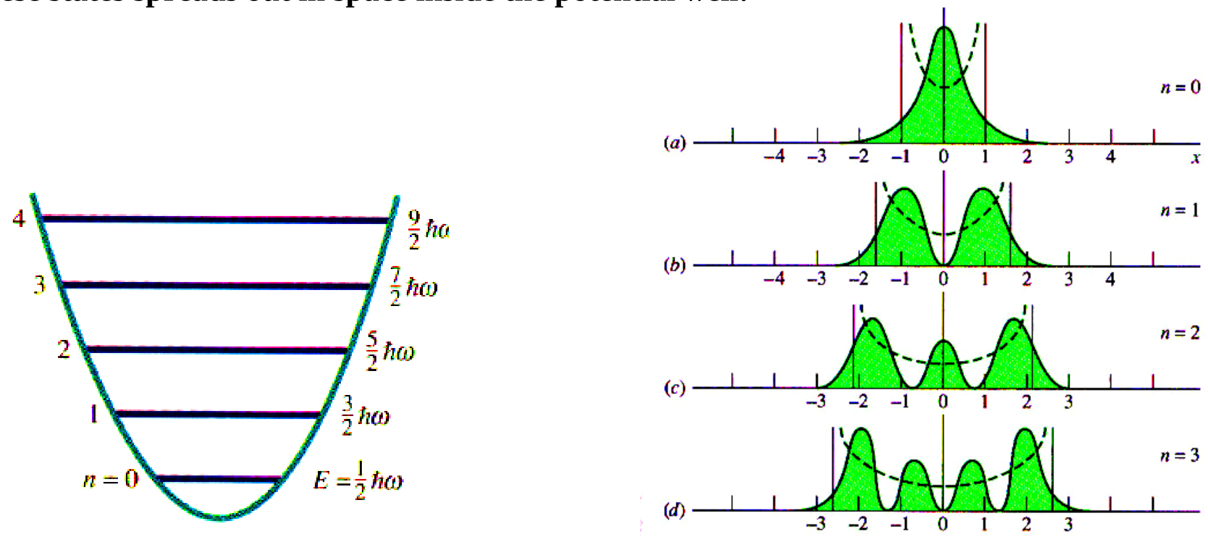


Fig 15: ***Bound states in a potential well.* LEFT: *the well, with energy levels shown as horizontal lines.* RIGHT: *the probability to find the particle at some position relative to the bottom of the well (the lowest energy position), for the lowest ground state (n=0) and the first few excited states.***

The electron in an atom can make transitions between the different states, but to do so it must absorb or emit the energy difference- which it does by absorbing or emitting a photon. Since only certain values of this energy difference are possible, only certain energies of the photon are possible. It is this result which is responsible for the colours of objects- photons of different energies are associated with different colours, and atoms or molecules from which some specific material is made will only emit light at specific energies, which correspond to the colour of the material. In fluorescent materials, the atoms absorb radiation at some time (putting the electrons into excited states), and then much later they radiate photons (so that the electrons decay back down to lower states), so that the material seems to glow with no apparent external stimulus acting.

One can now, with the tools of nanofabrication, make very small artificial potential wells for electrons in semiconducting materials- small regions where the electrons have lower energy- and confine one or a few electrons in these wells. These 'quantum wells' (also called 'quantum dots' when the region is really small) trap electrons like artificial atoms, but they can be made in a wide variety of shapes and sizes (we saw some in Fig. 4 of the document on classical nanoscience). One can also connect these wells or dots with 'quantum wires' (ie., extremely small potential wells in the shape of a channel), and in the wires one can put 'quantum gates' (ie., potential barriers which can be raised or lowered, using external electric fields). In other words, one can make electric components like transistors, or even complete circuits, at the nanoscale, with only a few electrons involved. We thus already have in place one of the ingredients required to make electronic devices at the molecular scale.

One other thing is useful to understand. As one makes the confining region smaller, both the energies of the confined states, and the energy differences between the different states (one talks of the here of the 'energy level splittings'), increase rather quickly. At the length scale of atoms, the energies involved are those associated with chemical reactions (which are just transitions between energy levels inside one or several atoms). But if we look at the much smaller atomic nucleus (which is a collections of protons and neutrons bound together by the so-called 'strong' force), the energies are huge- transitions between nuclear levels are associated with thermonuclear processes (which drive the stars, as well as thermonuclear weapons). On the other hand particles inside a large volume hardly show quantum properties at all- the energy levels are so closely packed together that the system behaves as though there is a continuum of possible states.

(ii) BOSONS & FERMIONS: One can still talk about particles in quantum mechanics, although they aren't in general localised at a particular point in space (indeed, if left free to move, they more naturally spread out into a wave-like state, propagating though space). However it turns out that all particles in Nature must be one of 2 kinds. One kind is called a 'boson' (after the Indian physicist S Bose); these particles have a natural tendency to all go into the *same* quantum-mechanical state, preferably the ground state (a process called 'Bose-Einstein condensation', or BEC- see (v) below). Bosons are responsible for the forces between the particles of matter, ie., between fermions- the best-known example is the photon, which is exchanged between charged particles and causes attraction between unlike charges and repulsion between like charges.

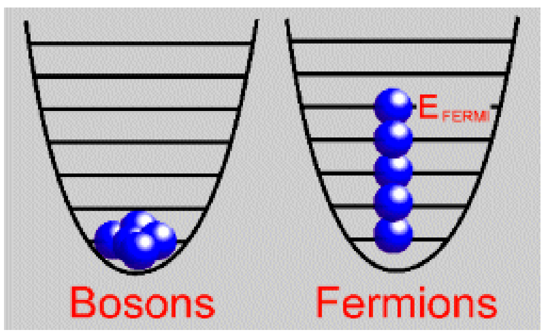


Fig 16: ***How bosons and fermions will fill up quantum states differently (see text)***

On the other hand one has 'fermions', which can never go into the same quantum state- so that a collection of fermions must all go into *different* states. All particles from which ordinary matter is made- electrons, protons, neutrons, etc.- are fermions. This fact is crucial to the structure of matter. In an atom containing several electrons, each electron will go into a different state, filling up higher and higher energy levels. Since each one of these states is different, and the electrons in each one are distributed differently in space, atoms having different numbers of electrons have different shapes and behave differently. Thus we get the chemical elements, corresponding to different atoms. If instead matter were made from bosons, it would immediately collapse, as all the electrons in all the atoms dropped into the same lowest-energy state close to the atomic nuclei- and all atoms would end up looking all the same.

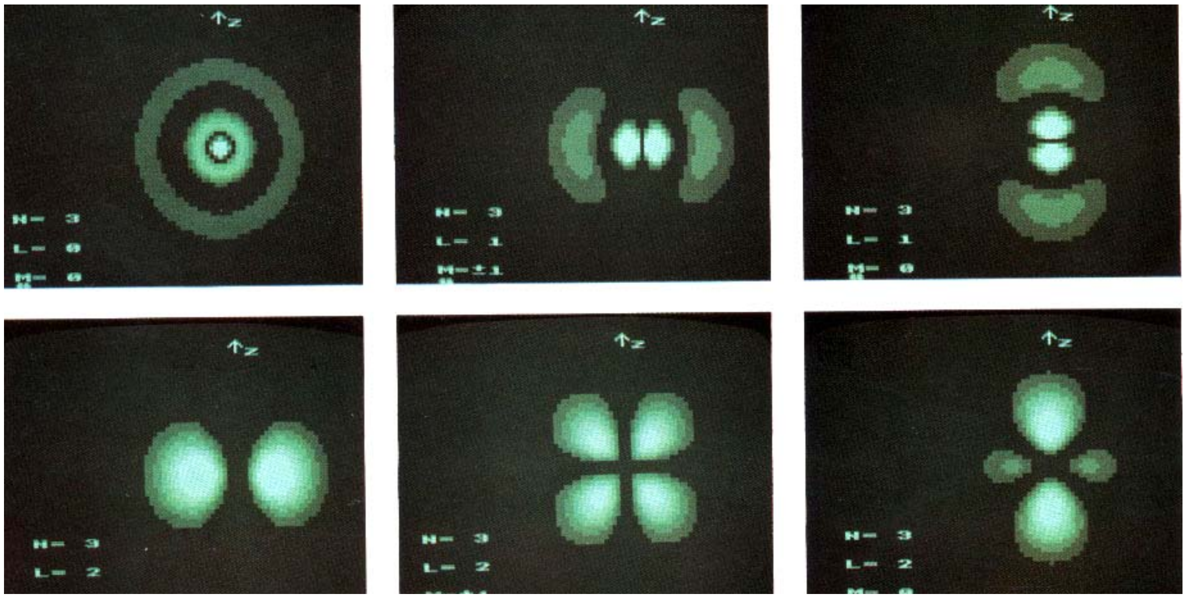


Fig 17: ***Different electronic states in an atom- the pictures show how the electron is distributed around the nucleus in the different states. The lowest energy state (sometimes called the 'ground state' is the one shown at top left.***

It is interesting to look at the shapes of the different electronic states in an atom (figure above). The electron distribution projects out from the atom in different lobe-shaped clouds, depending on which state we are looking at. It is this that is responsible for the existence of directed bonds between atoms. If 2 atoms approach each other, the electrons can arrange themselves amongst the different states in such a way that the 2 atoms attract, with electrons on the 2 atoms overlapping to some extent between the different electron lobes. Some of the lobes then orient themselves into a line between the 2 atoms- these are the bonds (we shall see a little later that this happens because of something called 'quantum tunneling'). It is remarkable that the original ideas of Democritus, concerning the shapes of different '*atomoi*', which then link together in various ways, should find their final justification in quantum theory.

(iii)SPIN: In the same way as a spinning ball or the spinning earth, even elementary particles like electrons or protons can have 'spin'. In the same way as we have seen above, a given particle has a finite number of discrete spin states- the simplest systems, like an electron, only have 2 spins states. These spin states are associated with circulating currents, and the circulating currents generate a magnetic field- in this way all atoms having a non-zero spin or angular momentum generate a magnetic field. This field is small, unless one is very close to the atom; however, if all the atoms in a solid align their spins in the same direction, the combined fields from all of them can be quite large- this is how we get a magnetic material. This kind of spin ordering can also be done at the nanoscale, most conveniently in nanoscale magnetic molecules- many thousands of different molecules of this kind have been produced.

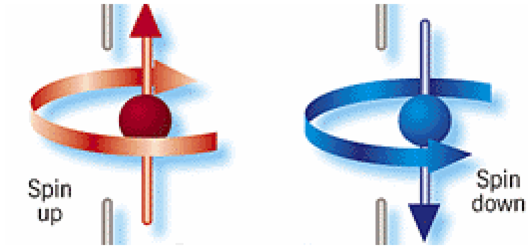


Fig 18: ***A 2-state spin system- the 2 states behave as though the have circulating currents (in opposite directions), which generate small magnetic fields (which are either up or down)***

Note that spins are also very sensitive to any external magnetic field, which strongly affects their dynamics, causing the spin axis to turn in various ways. This means that by using magnetic fields, or applied electromagnetic waves, we can manipulate spins in many ways. Because of their sensitivity to fields, spins are also very useful probes of any ambient fields. The use of spin and of magnetism is of course ubiquitous in modern technology, from hard discs and CD's to MRI scanners (in the former, information is stored in the orientation of very small magnets; and in the latter, nuclear spins in the body sense the weak fields from the local chemical environment, allowing a detailed map of the body to be produced).

One other useful thing about spin to note is that it is a kind of angular momentum, and so its total value in a physical process normally cannot change (we say that it is a '*conserved*' quantity, in the same way as total energy is conserved). This allows us to very easily prepare entangled pairs of spins. Recall that when we produced an entangled pair of coins, we asked that they have opposite states. For spins this is easy- we can produce a pair of spins whose total angular momentum is zero, and then they must be opposite. Then the analogy with the coins is quite precise, if we imagine that 'spin up' corresponds to 'heads', and 'spin down' to 'tails' (cf, section 1(b) above). The entangled state (|+ --> + | -- +>) then corresponds to an equal superposition of "up, down" and "down, up" states.

(iv)PHOTONS & FIELDS: We are all familiar with electromagnetic waves- depending on their wavelength, these can be radio waves, microwaves, light waves, UV, X-rays, or gamma rays. These are all wavelike excitations of the electromagnetic (EM) field, predicted in Maxwell's 19th century classical theory (which itself unified our understanding of electric and magnetic phenomena, and led to the first technological revolution of the early 20th century where machines began to replaced by electromagnetic devices for lighting, heating and power, communication, etc.). In classical physics this EM field is a continuous field, extending throughout space. In quantum mechanics the excitations of the EM field are bosonic particles, the so-called light quanta called photons. We have seen already that these can be emitted or absorbed by atoms, when the electrons make transitions between different states; and that they are responsible for the forces between charges. A typical EM wave is made from huge numbers of photons in different states, so many that the wave appears continuous rather than particulate.

Waves themselves have fascinating behaviour- one of the most striking is interference, when waves from 2 different sources meet, and we see them either adding (constructive interference) or canceling (destructive interference) depending on where one is in space. A simple way to show this

is via the famous '2-slit interference' experiment (Fig. 19 below, centre & right), in which light is passed through 2 slits A and B, which each act as a source for the transmitted light, which then arrives on a screen C.

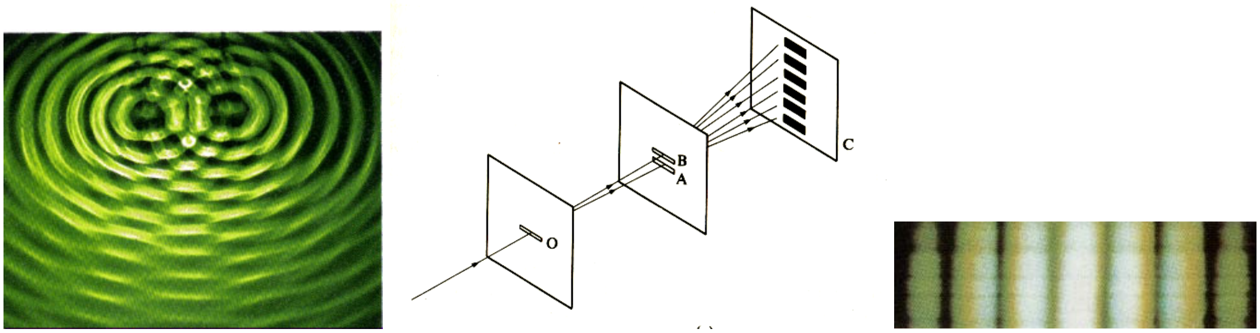


Fig 19: ***Wave properties of light.*** LEFT: ***interference between waves from 2 sources.*** CENTRE: ***the 2-slit interference experiment.*** RIGHT: ***Experimental 2-slit interference from a green light source.***

The quantum nature of light reveals itself if we lower the light intensity, until only a few photons are passing through the slits each second- no longer do we see a continuous wave, but instead, the light arrives in distinct 'packages' on the screen- these are the photons. Amazingly, as one lets the photons accumulate on the screen, the wave interference pattern reappears- the photons only arrive on the screen in regions of constructive wave interference! This is sometimes called 'wave-particle duality'.

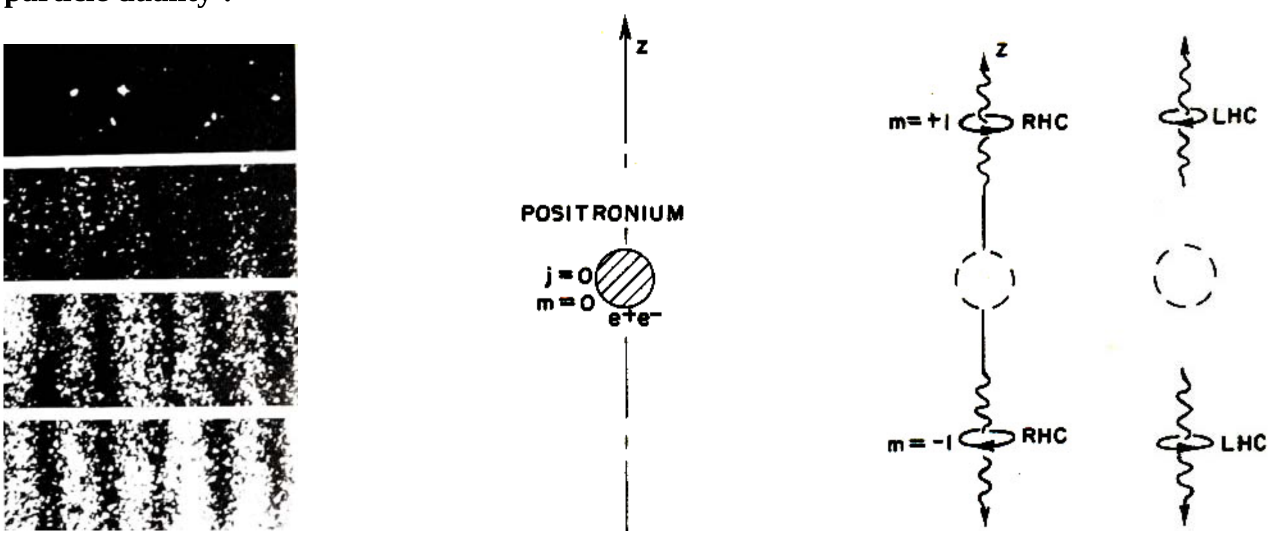


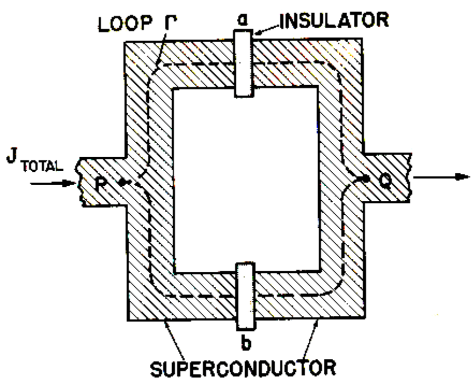
Fig. 20: ***Quantum properties of light/photons.*** LEFT: ***How the 2-slit interference pattern develops in time, as more and more photons arrive.*** RIGHT: ***Decay of zero-spin positronium into 2 photons moving in opposite directions. 2 final states are possible- one with helicities*** m= +1, -1 ***for photons moving up/down, and the other with the opposite helicities, ie.,*** m = -1, +1 ***respectively.***

Much more dramatic quantum effects are seen when we correlate *pairs* of photons. The example shown in Fig. 20 at right is very much the same as the example of 2 entangled spins just discussed above, in that photons also have a kind of 'spin' (called 'helicity' in the case of photons). One can produce a pair of photons with opposite helicity by annihilating an electron-positron pair (when bound together these are called 'positronium'). If the initial angular momentum of the positronium is zero, then the total helicity of the photons must also be zero. Fig. 20 shows the 2

possible outcomes. One is a state which we will call |+ --> (referring to the positive and negative helicities respectively); but by now the reader will realize that a legitimate quantum state can be formed by superposing this state with the other possible decay product of the annihilation, ie., with the state | -- +> (in which it is now the *negative* helicity state that is moving upward). Thus, we can now form the entangled photon state (|+ --> + | -- +>). Interestingly, it was with such states that the experimental proof of entanglement was first given.

In the last 4 decades we have learnt to manipulate photon states with exquisite control. By putting a large number of photons in exactly the same quantum state (where they are happy to go, being bosons), we get what is called coherent light- this is what is produced by a laser. Photons in this Bose-Einstein (BEC) condensed state are remarkably stable, making laser light extremely useful. With combinations of lasers, entangled photon states, and atoms, quite extraordinary things have been done in recent years, which will be central to future nanoscience- we will see this in section 2 below.

(v) BOSE-EINSTEIN CONDENSATION (BEC): We have already seen how bosons like photons can all be put into the same state, a ‘coherent’ or ‘BEC’ state. Since ordinary matter is made from particles that are all fermions, it would seem at first glance impossible to have a ‘coherent state’ of, say, electrons, in which they all go into the same state. However, if one combines 2 fermions into a pair, then they will for many purposes behave like a boson. In metallic systems this can happen- there is a rather weak attraction between electrons which is mediated by the quanta of sound waves (called ‘phonons’), which at low temperatures allows pairs to form- these can then form a coherent or ‘BEC’ state in which all pairs are in exactly the same state. Thus in a certain sense we can make the analogue of a coherent photon state, but now with electrons in a metallic conductor. The result, when the metal goes into this state, is a quite dramatic change in its properties - it becomes a *superconductor*. Superconductors show remarkable behaviour- for example, because the electrons are constrained to all do the same thing, they can flow with no resistance (so we can set a current flowing in a superconducting circuit, and it will continue to circulate forever). Properties like this make superconductors extremely useful in certain technological applications. One of the most remarkable of these is called the ‘SQUID’ (from “Superconducting Quantum Interference Device”); it is essentially an analogue of the 2-slit interference system for photons that we just described above. Electrons passing via 2 different paths recombine (see Fig. 21, below left), and the resulting current flow is shown at right. One gets the same interference as with photons passing through 2 slits, except here the interference pattern can be manipulated with a magnetic field- this is because the electrons, being charged, feel the magnetic field. Because all the electrons are behaving in the same way, their response to the magnetic field is a coherent response from all of them, making the SQUID fantastically sensitive to small changes in external magnetic field:



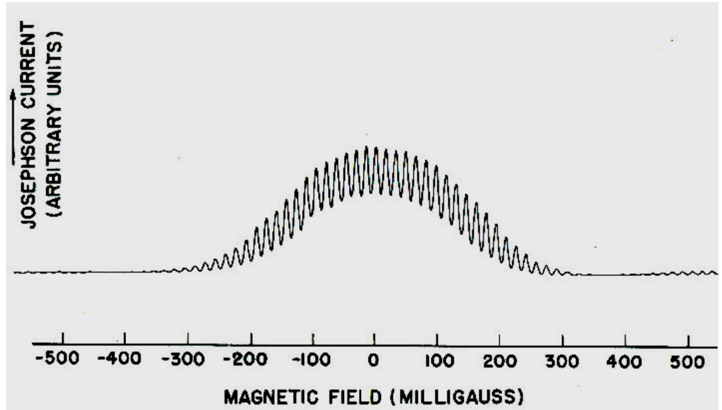


Fig 21: ***The 'SQUID'.*** **LEFT:** ***schematic SQUID- electrons come in at left, travel through the 2 arms, via the insulating 'Josephson junctions' a and b, and out to the right.*** **RIGHT:** ***The current coming out of the SQUID as a function of the magnetic field through the SQUID.***

We shall see a lot more of the SQUID below, in our discussions of future quantum nanotechnology. Note that one can do the same tricks with *neutral* fermions (ie., not possessing a charge, like electrons), and one then gets *superfluid* behaviour. An example is provided by Helium; this is a gas until very low temperatures, when it becomes liquid, and then superfluid- at which point it flows through the tiniest of holes (down almost to atomic scales) with no viscosity- leading to quite spectacular behaviour at times!

(vi) QUANTUM TUNNELING: Suppose we have a quantum system which is attracted towards some point is space- so there is a potential well around this point- but that if it moves farther away, it is repelled.

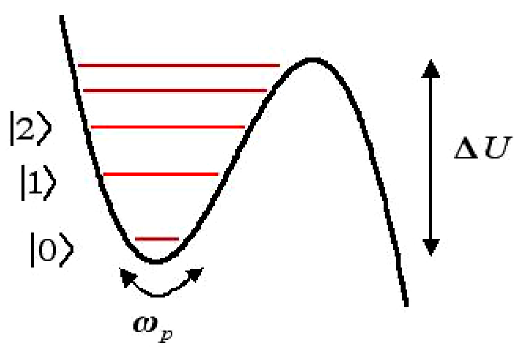


Fig. 22(a)

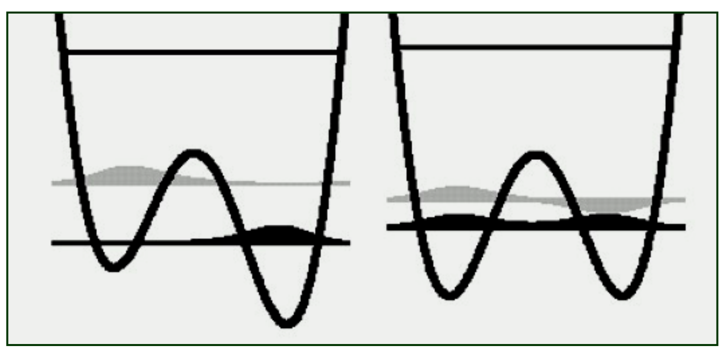


Fig. 22(b)

Fig 22(a)**:** ***A 'metastable well' potential, in which a particle is prevented by an energy barrier (of height ΔU) from moving off to the right- but in the right region its energy will be still lower.***

Fig 22(b)**:** ***The '2-well' potential. In the left picture we see the 2 states localized in the left and right wells, which have different energies (the left well state has higher energy). In the right picture they have equal energy, but now tunneling allows them to form 'superpositions' of the left and right well state- the ground state is shown in black, and the excited state is shown in light grey.***

This is precisely what happens in, eg., an atomic nucleus- nuclear particles like protons are attracted very strongly to each other by the 'strong force', but this force is very short-ranged, and if they move apart, there is a residual repulsive electric force between them, because they have like positive electric charges. In this way one ends up with the kind of 'metastable well' potential shown above left (Fig 22(a)).

Now in classical physics, a particle trapped in the well cannot escape unless it is given enough energy to go over the barrier, by 'kicking it' with some external force- otherwise it will just oscillate with some frequency ω_P inside the potential well. Quantum mechanically, there will be energy levels corresponding to states trapped in the well- however, quantum mechanics also tells us that these states can 'quantum tunnel' through the barrier, and escape to the right, even without being kicked. This is why heavy nuclei are unstable, and subject to radioactive decay- particles can slowly tunnel out, and once they do, they are rapidly accelerated away by the strong repulsive force outside the nucleus (ie., they 'roll down' the potential slope on the right). The fast outcoming particles from a nucleus can cause a lot of 'radiation damage', blasting molecules and atoms apart when they collide with them- this is why radioactive materials are dangerous. Another interesting example of quantum tunneling is in the STM discussed at the beginning of this document (intro to section 1), in which electrons tunnel from the very fine tip, across a small gap (of width only a few atom diameters in size) into whatever the STM is looking at. The tunneling current (ie., the number of electrons tunneling across per second) is exquisitely sensitive to how far the electrons have to tunnel, so that by moving the tip just above the surface one is looking at, a very detailed topographic map can be made- as we saw in the document on Classical Nanoscience.

A remarkable consequence of tunneling arises if we allow a particle to tunnel between 2 potential wells (Fig. 22(b)). In the absence of tunneling between these wells, each well would have a lowest energy state, and a particle in one of these states would spread out at the bottom of its well- this is what is seen in the left picture in Fig 21(b), where the 2 wells have different energies. However, if we bring the left well down in energy, so that it has the same energy as the right one, then something very interesting happens. The 2 states, which we will now call $|L\rangle$ and $|R\rangle$ (for 'left' and 'right' wells) now have the same energy- and this means that the particle can actually tunnel between the 2 states. Thus a particle put into state $|L\rangle$ will quickly tunnel to $|R\rangle$, and then back again- in fact it will end up oscillating between the 2 wells, at some frequency Δ_o (the tunneling frequency). This has a remarkable effect, because it turns out that a superposition of the 2 states, given by $|0\rangle = (|L\rangle + |R\rangle)$, actually has a lower energy than either $|L\rangle$ or $|R\rangle$; in fact it is the lowest energy 'ground state' of the system. In this state, the particle is not in one well or the other- it is in BOTH of them! There is also a higher energy excited state $|1\rangle$, given by the superposition $|1\rangle = (|L\rangle - |R\rangle)$; and in fact the energy splitting E between the 2 states is given by the formula $E = h\Delta_o$, where *h* is a number called Planck's constant.

The existence of this tunneling is terribly important for the structure of our everyday world. It was mentioned previously that chemical bonds form when the electron states in different atoms start to overlap, forming tube-like connections between the atoms. We now see how this can happen- tunneling allows the states on different atoms to combine into lower energy superpositions, in which the electrons are no longer localized on one or other atom, but extend across both of them. Thus tunneling allows atoms to bond together into complex molecular structures, with stick-like bonds between them. Actually one can go farther- in many molecules,

whole atoms can tunnel between 2 or more different positions in the molecule. A simple example of this is the Ammonia molecule NH_3, shown below, where the Nitrogen atom tunnels back and forth through a barrier formed by the triangular 'cage' of Hydrogen atoms (in doing so it must push its way through the centre of the triangle, elbowing the 3 H atoms aside). The actual ground state of the molecule is a superposition of the 2 states in which the N atom is above/below the H_3 triangle, in an exact analogue of the SQUID ground state discussed above.

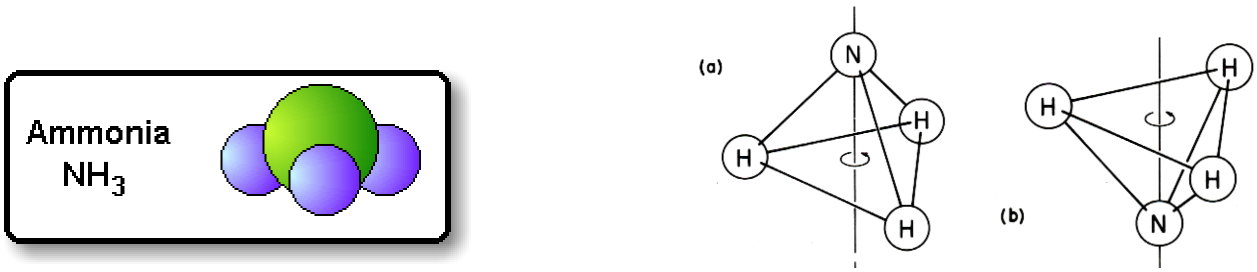


Fig 23: ***The Ammonia molecule.*** **LEFT:** ***basic structure, with a Nitrogen atom above a triangle of Hydrogen atoms.*** **RIGHT:** ***The N atom can also lie below the H_3 triangle, and tunnels between the 2 configurations (a) and (b).***

(vii) DECOHERENCE, PROBABILITIES, & MEASUREMENTS: Our last item on the quantum shopping list looks at something more fundamental and thought-provoking. Let's first ask- why do we not see quantum behaviour at our own human scale? There are 2 reasons for this, and both come from the basic structure of quantum mechanics. The 1st reason is that quantum mechanics itself makes a distinction between large and small, in that the magnitude of things- of energies, lengths, time intervals, etc.- are all related to a fundamental constant *h*, called 'Planck's constant of action'. That such a distinction should exist is quite unprecedented in classical physics, where no scale or interval is more fundamental than any other- units of time (seconds) or length (metres) are fixed purely as matters of convention, to make them appropriate to the human scale in their magnitudes But in quantum mechanics, all physical processes are associated with a quantity called 'action' (usually labeled by the symbol $\mathcal{S}$), and the amount of action in any process can be counted in units of *h*, ie., the action can be written as a pure number $n = \mathcal{S}/h$. Now the crucial point is that any processes that we ourselves are aware of usually involve astronomically large values of *n*. When *n* is large compared to unity, it becomes very hard to distinguish quantum behaviour from classical – large numbers of quantum states start to behave in very similar ways, energy level splittings become extremely small, etc. From this point of view our everyday world seems to be classical simply because it is intrinsically BIG.

However there is a much more interesting and subtle 2nd reason why quantum phenomena are hard to see except at microscopic scales. This is because no physical system in Nature is isolated- even if for some very special reason it may not be interacting significantly right now with the surrounding universe, it most certainly has in the past. Now, as we have already seen above, this inevitably means that the quantum system becomes *entangled* with its surroundings. Suppose, for example, that an entangled pair of spins, or photons, in a state given by (|+ --> + | -- +>), has interacted with its background environment in such a way that the background is influenced differently by the 2 components of the pair state (these 2 components being |+ --> and | -- +> respectively). Then the environment will be correlated differently with the 2 components- moreover, it will be *entangled* with the pair (which for definiteness we will henceforth assume to be a pair of spins). But this means that we can no longer separate the environment from the pair, or even talk any more about the pair as a single quantum state. Only the combined state of ‘spin pair + environment’ can be considered to really exist.

This is of course a bizarre situation- in the real world it is hopeless for us to try to track the state of the environment (which will quickly involve very large regions, since photons will interact with the spins and then move rapidly away from earth). So we can ask instead- how will the spin pair on its own appear to behave, if we ignore the environment with which it is entangled? The interesting answer is that what we will see will be *one or other* of the 2 components, with a certain *probability* of each happening. In the present case, since each component has equal weight on the original pair state, the probability of each outcome will be the same, ie., 50%. Note the fundamental change here- the behaviour is exactly what we would expect if instead of a quantum entangled superposition of 2 pair states, we instead had just *one or the other*. But this is just *classical* behaviour- the system behaves as if it is *EITHER* in state |+ --> *OR* in state | -- +>, but we just don’t know which (hence the probabilities!). Physicists say that instead of a superposition of the 2 states, we now just have a ‘*mixture*’ (sometimes called an ‘incoherent mixture’), meaning one or the other state, instead of both. This process of destruction by the environment, of coherence between the 2 components of the state superposition, is called ‘*decoherence*’.

To see how fundamental is the role of decoherence and of probabilities in quantum physics, now suppose that we have a simple superposition of 2 states and we try to *measure* which of the 2 states the system is ‘really’ in. As an example consider now a *single* spin, in an equal superposition of states of ‘spin up’ and ‘spin down’ (written as (|+> + | -->), using our previous notation). To make a measurement, we must have an interaction of the spin with some ‘measuring apparatus’; this is typically some large physical system which can ‘distinguish’ between the 2 states, and from which we can then ‘read off’ the result. Physically this means there must be some physical degree of freedom of the apparatus (sometimes called the ‘pointer’ degree of freedom), which interacts with the spin in such a way that it goes into quite different pointer states depending on which state the spin is in. But consider what this implies- the pointer states are also quantum mechanical, and they must now be *entangled* with the 2 different spin states. Let’s call the relevant pointer states |U> and |D> (referring to ‘up’ and ‘down’). If now the apparatus is a ‘perfect’ measuring system (meaning that the final state of the pointer after measurement is perfectly correlated with the initial state of the spin system before it is measured), then if we do not disturb the spin state, the final state of the combined ‘spin+pointer’ system is nothing but (|+ U> + | -- D>) ie., just the same sort of entangled state we dealt with previously when discussing a pair of entangled spins! Note, incidentally, that we have not *copied* the spin state to the measuring system (actually this is not possible- one cannot ‘clone’ states in quantum mechanics). We have instead entangled the two together into a single superposition, ie., into a single quantum state.

On reflection, this seems nonsensical- how can a macroscopic system (the combined ‘spin + measuring apparatus’) be in a quantum state? After all, the whole point of the measuring system is that it is supposed to tell us *which* state the spin is in- implying that it must itself be in one or the other state, ie., it must behave *classically*, not quantum-mechanically! The orthodox answer to this question, offered by decoherence theory, is that even though the pointer states may initially be entangled with the spin states alone, they will very quickly entangle with their surrounding environment after this. As soon as this happens, and given we cannot track the environment, the

combined 'spin+pointer' will then behave as a *mixture* of the states |+ U> and | -- D>; ie., in one or the other of the two. In other words, *either* we will find the pointer and the spin to be both 'up', *or* both to be 'down'. However, we cannot say which- only that there is a 50% probability of one OR the other. We see that the probabilistic element of quantum mechanics must inevitably enter our own classical macroscopic world (a result first recognized by M Born in 1927).

If the reader feels a little suspicious of the 'orthodox' discussion just given, or finds it just too strange for comfort, I should immediately emphasize that this is a normal healthy reaction to quantum mechanics- it means you have properly followed the discussion! One way of coming to terms with it all is to probe the ideas with questions. Obvious questions are

(a) How does decoherence really work physically? And can it be 'unravelled', or reversed?

(b) suppose we consider the environment as part of the entire quantum system (ie., 'spin+apparatus+environment'); then this is still in a superposition, ie., the superposition and entanglement are still 'out there'. Since this environment ultimately involves the whole universe, does this mean that the universe can be in a superposition?

(c) What about us- can we be in superpositions (for example, of 2 mental states)?

Interestingly these questions, and others, are raised in acute form by recent developments in physics, and quantum nanoscience will at some point make them of practical importance. Let us now move to these modern developments, and the emerging field of 'quantum devices'.

2: QUANTUM DEVICES

Armed with the qualitative ideas given above, we can now properly appreciate what is involved in the future field of 'quantum technology'. Let us first reiterate the distinction made above between 'classical systems', whose underlying physics may depend completely on quantum mechanics, but whose operation does not involve intrinsically quantum phenomena such as interference, superposition, or entanglement. These were already dealt with in the first section of this document, in the discussion of 'classical nanoscience'. We now come to engineered systems whose behaviour is fundamentally quantum mechanical, and in particular, to the 'quantum devices' which are expected to be the building blocks of a future quantum technology. First, however, a brief note on how far we are in pushing quantum mechanics up to the macroscopic scale.

MACROSCOPIC QUANTUM STATES: Most of the quantum phenomena discussed in the previous section occur at the microscopic scale, at the atomic or molecular level. For several decades after the discovery of quantum mechanics in 1925 it was assumed that quantum phenomena only took place at this microscopic scale. The paradoxes of Schrodinger and Einstein-Podolsky-Rosen seemed to make the whole idea of *macroscopic* quantum states quite nonsensical- how could strange things like coherence or entanglement happen at the scale of tables, chairs, and humans?

Two things have gradually altered the opinions of physicists on this point. The first was the realisation that quantum mechanics really does work at every length scale to which it has been applied. A key

step here was the application of quantum mechanics in the 1940's and 50's to the hitherto mysterious phenomena of superfluidity and superconductivity, leading to the demonstration that were large-scale Bose-Einstein condensation (BEC) effects (see (v) above). Although this involved the BEC of only microscopic objects into a single quantum state, it yielded dramatic macroscopic consequences, now known to apply equally to superconducting wires or neutron stars.

The second development began with the realisation by Leggett et al. (theoretical work from 1979-87) that in a proper quantum treatment of superconductors, one could also get quantum tunneling, quantum superpositions and even entangled states- in *macroscopic* superconducting SQUIDs! That quantum mechanics could give this result struck Leggett as so counter-intuitive, that he proposed that quantum mechanics be tested at the macroscopic scale using such experiments. The experiments have been a long time in coming, and a proper test of quantum theory at the macroscopic scale with SQUIDs has yet to be done. However in the last 5 years some very striking results have been found in the lab- the most remarkable being the preparation of superpositions between 2 states where current is circulating clockwise or anti-clockwise in a superconducting ring (recall that in superconductors, current flows with no resistance). The ring itself is several μm in size, and the number of electrons that are involved in the current is roughly 10^{10}, a very large number. While not yet macroscopic, this is certainly full-blooded quantum mechanics at the mesoscopic scale. Now all of this is very important for what follows, because it shows that we can imagine making devices on quite large scales that behave in a fundamentally quantum-mechanical way. As we will see, this opens some extraordinary possibilities (as well as a philosophical can of worms!). In what follows I will go through some of these possibilities.

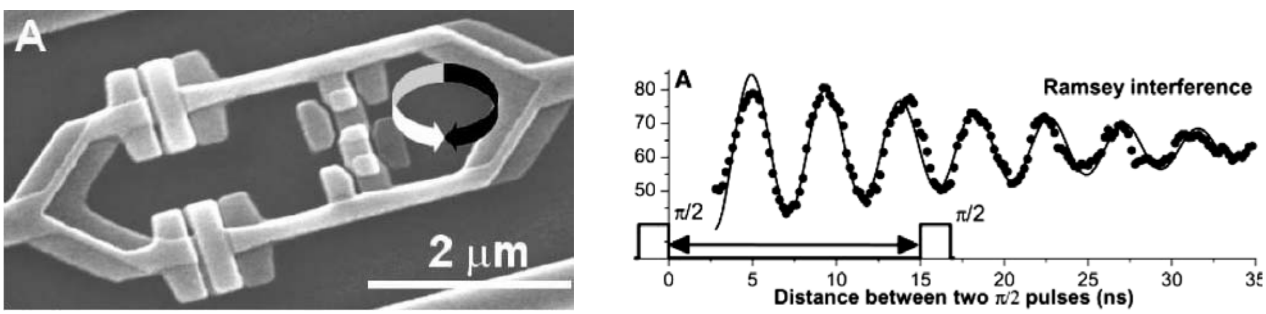


Fig. 24: ***A superconding 'qubit' (Delft lab).*** **LEFT*: the qubit- the 2 states have currents circulating in opposite directions.*** **RIGHT*: interference between current states at different times, as the system oscillates from one current state to another.***

(1) QUANTUM INFORMATION PROCESSING: In the last 20 years a remarkable new development has matured, which is based on quantum entanglement. This is the idea of "quantum information processing". In an ordinary computer, information is encoded in a collection of classical "2-state" systems (ie., systems which can exist in one of 2 states, like + or --, or heads and tails). Although the total number of possible states of *N* classical 2-state systems is very large if *N* is large (it is 2^N), the system, being classical, can only exist in ONE of these states at any one time- a classical computation consists in a sequence of changes in which one state goes to another. In a modern computer, a sequence of very many such changes (or 'logical/computational operations') may be involved- this takes time, even if the changes are occurring quickly, and energy is dissipated while it is being done. This is why your laptop heats up- it may be doing over 10^9

operations per second. Your own body is also a very complex computer- each cell is a small factory, operating according to a sophisticated plan, and although each cell works fairly slowly, the total number of operations per second in the human body is of order 10^{20}, a colossal number. Luckily the heat generated per logical operation in our bodies is much smaller, by a factor of about 1 billion, than in a laptop (our cells operate much more slowly, but also more efficiently, than integrated circuits). Otherwise each of us would radiate more intensely than the sun!

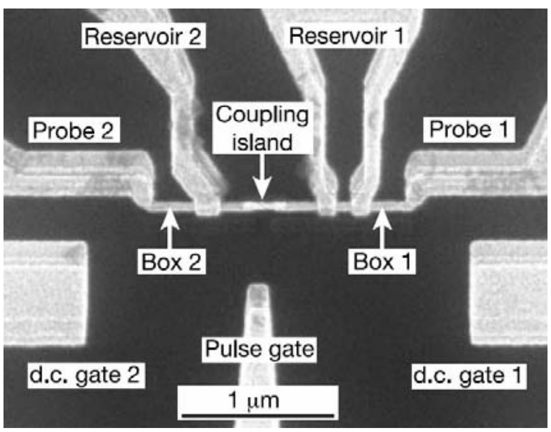
As we have seen, a quantum system is quite different- instead of existing in one state at any time, it can exist in a *"superposition"* of states, ie., simultaneously in several states at once. Consider again a quantum 2-state system, which as we saw can be simultaneously in each state. Now in general the superposition will have weights w_+ and w_- assigned to components |+> and |--> respectively (typically these weights are different, ie., one component will dominate over the other).

If we now assemble a set of *N* quantum 2-state systems (these being known as 'qubits'), and connect them together in a 'quantum circuit' of some kind, we can in principle put this single quantum circuit into a colossal superposition of 2^N different states, each with their own weighting and their 2^N different phases. Thus in principle a single quantum state of this kind can contain a huge amount of information. In what is called '*quantum parallelism*', this quantum information processing system can do massive parallel computation- or a single computation going roughly 2^N times faster than a classical computer. This is not just a huge quantitative change in computation speed- the very nature of computation is being changed here, because quantum information processing involves entanglement between the many qubits in an essential way. Much has been written about how this would compromise all existing security, banking, and information storage systems, etc; but the truth is that we can hardly imagine the changes that would be wrought by such a qualitative change in computation and information processing. So far only a few quantum computing algorithms have been worked out properly- in fact one of these, the Shor algorithm (P. Shor, 1994) launched the large present day interest in quantum computing. The Shor algorithm factorizes a large number exponentially faster than a classical computer- since most security and information systems are protected by encryption codes requiring factorization of numbers, this is of great practical interest. Another quantum algorithm, the Grover algorithm, searches any large data base much faster than a classical algorithm (although not exponentially faster). It is proving rather hard to find other algorithms, but more will certainly be found. There has been intense interest in quantum computation from the security community (including military organizations around the world), with the realization that a quantum computer would be able to decode any classically encrypted message involving a public 'key distribution system' (ie., not involving a private encryption like a one-time pad). This includes all those messages written before the first quantum computer is built!

Curiously, another invention involving entanglement provides a partial solution to this. Called 'quantum crytography', this works by having a shared entangled state between the sender and receiver of a message- this is the quantum version of a 1-time pad, because if anyone tries to read the entanglement, they will interfere with it and this will be detected by the 2 parties, even if the entanglement is not destroyed. Quantum cryptography then works by exchanging information in classical form, using public channels, but it can only be decoded if one has access to the entangled quantum state.

(2) MAKING PHYSICAL QUBITS: It is of course all very well to talk about quantum computers, but for all of this talk to be meaningful, one has to *make* one! There are 2 main problems here, to which we will come presently, but first let us look at what has been done so far- the progress is actually very impressive. To make a quantum computer, most designs assume a collection of 2-state systems that can interact together in controllable ways, so as to perform a computation (or some other kind of information processing operation). In conventional jargon, these 2-state system are called 'qubits' (in contrast with the ordinary bits used in classical computation, now called 'C-bits'). I quickly outline here the 3 main designs presently being developed- one should stress that things are changing fast in this field, and what is discussed here will certainly be completely out of date 10 years from now.

,(i) SUPERCONDUCTING QUBITS: These are all related to the devices used to test quantum mechanics at the macroscopic scale (see Fig 24 above). One design, the 'flux qubit', uses 2 different current states in a superconductor- this current can be detected by the magnetic field it generates. Another design, the 'charge qubit', also uses a very small superconductor (the so-called 'Cooper pair box'), but now allows electric charges to move on and off the superconductor- the 2-level system is now the box with and without an extra electric charge. Both designs have worked, in that they have been successfully operated as qubits- those sequences of changes in their quantum states which are relevant to quantum computation have been carried out in the lab (indeed now in 8 labs, notably those in Delft, Tokyo, Paris, and Yale). Experimenters have also succeeded in entangling 2 such qubits, as we see below.



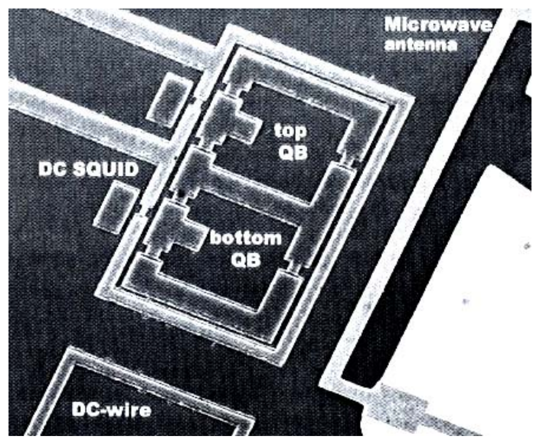


Fig. 25: ***Operating designs for entangled pair of superconducting qubits.*** **LEFT:** ***pair of Cooper pair boxes (Nakamura, Tokyo, 2003); note scale at bottom.*** **RIGHT:** ***Pair of SQUIDs (Delft, 2002)***

The advantage of using superconducting qubits is that the technology of fabrication and operation is well understood. The disadvantage is that they are rather big, contain a lot of unavoidable junk (impurities, imperfections, crystal defects, nuclear spins, etc), and it is hard to make them to exact specifications. The problem of junk is very important- junk causes decoherence, which as we shall see below is the MAJOR stumbling block to any kind of quantum technology.

(ii) SPIN QUBITS: Many are pinning their hopes on much smaller qubits built from spins. These are similar to superconducting qubits in that they both generate magnetic fields, but the spin

qubis have 2 key advantages- first, no moving electrons (ie., electric currents) are involved; and second, they can be made much smaller, and at least in some case with absolute purity.
The hopes of many are being pinned on qubits built from magnetic molecules, which are precisely reproducible- they can also be easily built into interacting networks, which communicate without moving electrons around (it is this movement of electrons which generates all the heat in contemporary computers). These are genuinely nanoscale objects (see fig. 26):

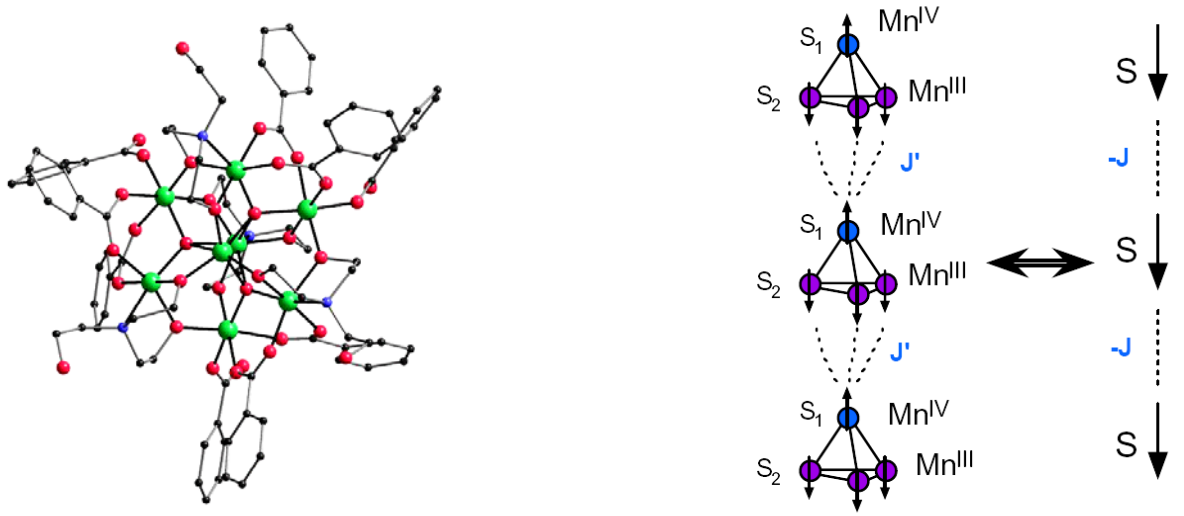


Fig. 26: ***Qubits from magnetic molecules.*** **LEFT:** ***The 'Fe-8' molecule, widely studied as a possible magnetic qubit (Morello, UBC).*** **RIGHT:** ***A quantum 'spin net' of 'Mn$_4$' molecules- this is a set of molecular magnets behaving as qubits, which couple together magnetically in a chain structure (Christou et al., Florida)***

The advantages of purity and reproducibility mean that one can also eliminate most sources of decoherence in such molecules apart from nuclear spins, and there are ways of either removing these or at least suppressing their effects (Stamp & Tupitsyn, 2004). The main disadvantage at present is that the molecules are so small that it is impossible to see what individual molecular spins are doing- thus there is no real demonstration yet of qubit behaviour for any of these molecules. However once probes have been developed which can observe and manipulate them, tremendous computing power will become available in a very small volume. In the more distant future, schemes have been imagined in which the computing is done entirely by nuclear spins, inside magnetic molecules, with the read-in or read-out of information accomplished by coupling these to electronic spins. The great advantage here is that nuclear spins can be isolated extraordinarily well from their surroundings-so well that the time required for decoherence to destroy entanglement or superposition can be days (or even months at very low temperatures!).

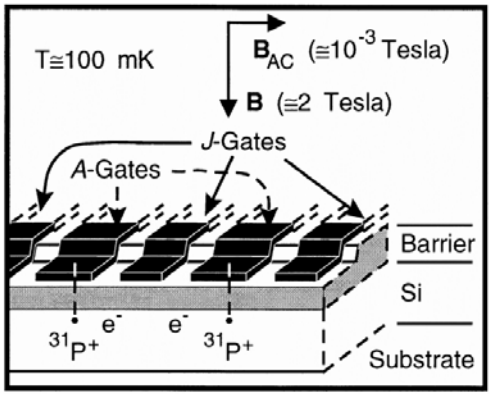


Fig 27: ***The Sydney/Maryland design for a spin qubit computer (the P ions) in a semiconductor***

Other spin qubit designs involve putting either single electronic spins or nuclear spins into very pure semiconductors- one is at the scale of single atoms or single nuclear spins. There are quite a few designs under discussion here, including electronic spins in quantum dots, or in various electronic heterostructures. No experiments have yet demonstrated qubit behaviour here, and there is a real problem with decoherence in many of them- again, because of unavoidable junk.

(iii) ION TRAP/CAVITY QUBITS: These are rather different from the first two, in that they are not solid-state based. Instead one traps a small number of single atoms in an 'ion trap', which is basically an evacuated container, usually of long cylindrical shape. In this tube the atoms are typically ionized (ie., they have lost an electron, giving them a net electric charge), and strung out in a line, so that one can address them individually (ie., manipulate or measure the quantum state of any one of them, independently of the others).

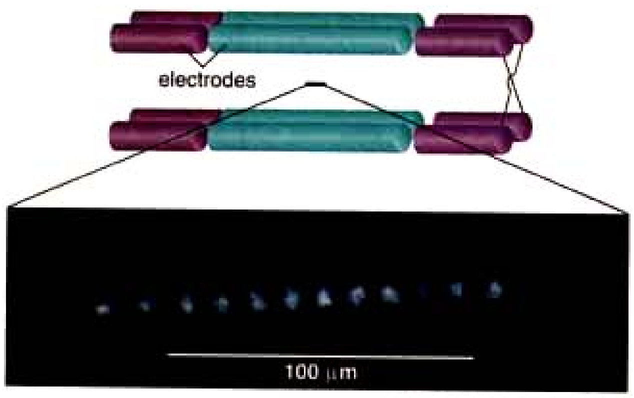


Fig 28**: *the interior of a linear ion trap: we see 11 ions held in position by the electric fields from the surrounding electrodes (and imaged optically).***

In the most common designs, each of the ions can be in one of 2 states (eg., 2 different atomic states, or 2 different spin states). In a related design, atoms pass in and out of a carefully designed cavity- while they are in this cavity the electronic state of the atom can be made to interact strongly with the cavity, in such a way that we can manipulate and/or observe the ion state. By

passing several atoms through it is possible to entangle their states together, and to entangle them with the photons passing through the cavity.

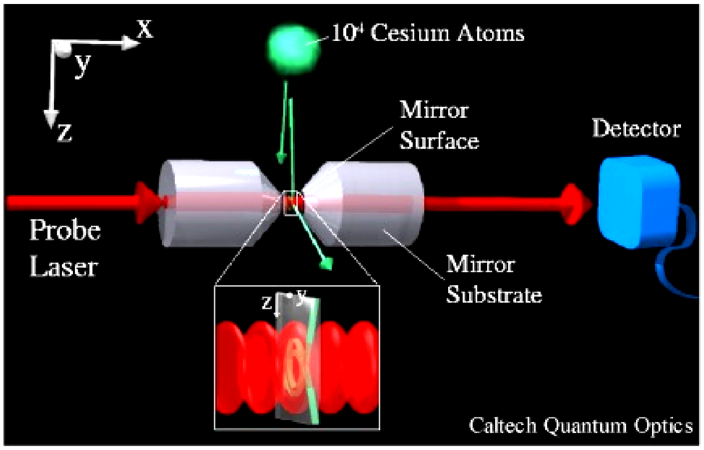


Fig 29: ***An example of a cavity QED set-up, from Caltech. The atoms fall into the cavity, are held there for some time by focused high-intensity laser light before falling out.***

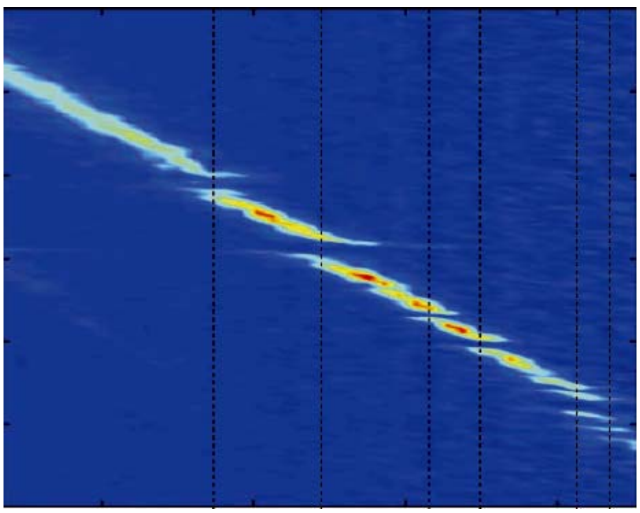
The great advantages of the ion trap and cavity designs are (i) that decoherence can be made extremely small, and (ii) that the ions or atoms are very easily manipulated, and one can look at the state of each one individually, by allowing them to interact with photons. This latter result is quite remarkable given that we are dealing with single atoms, and is possible because one can artificially enhance the interaction between photons and atoms in various ways. In many respects the techniques of atomic physics are many years ahead of those in solid-state physics- the atomic physics of single atoms, and of atom-photon interactions, is remarkably clean. Curiously however, many atomic physicists still feel that in the end quantum computers will be built from solid-state components. This is because it is hard at present to see how one can scale up the design of ion traps or cavity systems, to the very large number of qubits required for a really useful quantum computer. It is, on the other hand, easy to imagine a portable (indeed very small) quantum computer made from thousands, or even millions, of solid-state qubits.

So far so good- we have seen how some of the more popular designs for quantum computation are supposed to work. Let us now turn to some of the problems. Quantum computation will not be easy to attain- quantum superpositions are extremely fragile, and their preparation and preservation imposes extraordinary technical requirements on nanofabrication, including purity, reproducibility, low temperatures, etc. In many ways one can think of the global effort to make quantum devices like this as a kind of 'moon shot', in which the effort is worthwhile because even if it fails, the spin-off into ordinary technology will be enormous. In the same way that the USA spearheaded the development of microelectronics by supporting the space programme, some countries now support quantum device research so as to put themselves in the nanotechnology vanguard.

From the scientific point of view the 2 big problems facing quantum information processing are (i) decoherence, and (ii) communication between qubits. The problem of decoherence is particularly severe- many still feel that quantum computation will never happen because decoherence will

increase uncontrollably as we entangle more and more qubits. However it is almost a truism in science that problems breed both solutions and further interesting ideas- so I finish off with 3 of these:

Decoherence Suppression: **As noted above, in solid-state qubits at low temperatures, decoherence comes mostly from 'junk' effects. What this means physically is that in the environment, there are many unwanted 2-state systems that can entangle with the qubits in a quantum computer, or some other quantum information processing system. Since we cannot track these environmental 2-state systems, they cause decoherence. In a real solid, they can be anything from nuclear spins to spin impurities, or 'defects' in the solid (no solid, no matter how well prepared, is free of these). Since all of these environmental 2-level systems behave like spins, this environment is usually called the 'spin bath'. In the figure below we see the effects of this spin bath on the dynamics of a superconducting qubit (left); and on the right we see the effect on the spin bath itself, of a magnetic qubit. Both the qubit and the spin bath environment have their behaviour radically altered.**



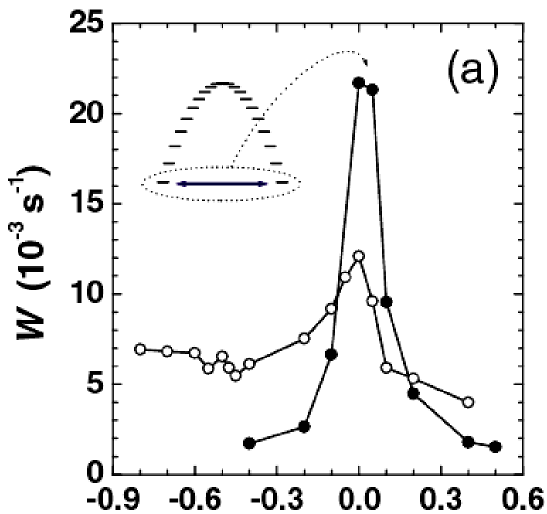


Fig 30**:** ***The effects of decoherence.*** LEFT**:** ***A superconducting SQUID scans through different tunneling splittings, & 'resonates' with different environmental 2-state systems- disrupting its behaviour (Martinis et al, Santa Barbara).*** RIGHT**:** ***The nuclear spin environment entangles with a magnetic molecular spin, & its relaxation rate W is radically increased (Morello et al, Leiden)***

Can the environmental degrees of freedom be controlled? A number of ways have been imagined. One is to apply strong magnetic fields to freeze their dynamics- more ambitious ideas involve manipulating the bath spins themselves using time-varying fields. These ideas may well work- physicists have a great deal of experience in manipulating spins (particularly nuclear spins). A more amusing idea comes from the '*monogamy*' theorems of quantum information, according to which if a system A is entangled with a system B, it cannot also entangle with another system C. The idea is then to deliberately entangle the spin bath environment with something else, thereby preventing it from entangling with the qubits. Yet another option is to simply make the system very pure, in an effort to get rid of all the 'junk' 2-level systems- these efforts even extend to 'isotopically purifying' the system of all nuclear isotopes possessing a nuclear spin. Note that this

can be done with certain molecules (which themselves have the advantage of being exactly reproducible). There are currently many ideas floating around in the literature , for how to control decoherence; which ones will work best remains to be seen.

***Error Correction*: It was again P Shor who realised that one way of dealing with decoherence was to do the quantum analogue of what is done every day in a classical laptop- by having systematic error correction techniques embodied in the software. Classical error correction of information is in principle very simple- one simply makes redundant copies of the information. However it turns out, as noted previously, that one cannot copy or 'clone' a quantum state without destroying the original. Instead what is done, if one wants to protect quantum information (embodied in the quantum state of some system A) is to entangle this quantum state with the state of another system B. The larger system A+B then contains all the original information, and one is at liberty to involve many other systems in this entanglement (these now being the 'error correction' part of the computer). It is then found that even if the original quantum system A suffers decoherence by interacting with some environment, then provided B is not affected by the source of decoherence, it is still possible to recover the quantum state of A by performing operations on system B. In principle error correction is then very important, since it offers a cure to the decoherence problem. In fact things are not so easy, because it turns out that the state of the system B must be considerably more complex than that of A if this is to work- moreover, decoherence can also act on the system B! Thus one can get into a situation where the error correction system creates more errors than it cures. However some primitive error correction systems have already been devised and tested.**

***Quantum Communication and 'Teleportation':* In connection with quantum cryptography, it was mentioned above that one required the sharing of an entangled state between a sender and a receiver. If one can do this, another interesting possibility is also opened up, called 'quantum teleportation'. The name is somewhat of an exaggeration – what is done is to transmit information from a source A to a receiver B about a quantum state (which we will call $|\psi>$), held at A, so that it can be reconstructed at B. Note that one could never do this by just measuring the state at A, and then sending the result of the measurement to B – if our original state was some superposition of several states, all the measurement would do is tell us that the system was in one of these states. The key is that A and B also share another state, which is entangled between A and B, and which we will call $|\Phi>$. What is done is then is to allow the state $|\psi>$ to entangle with the state $|\Phi>$, and then a measurement is made at A on the combined states. This measurement has then destroyed the delicate entanglement- however, it can be shown that if A then lets B know the result of this measurement, B can use it and the 'other half' of the entangled state it originally shared with A, to reconstruct the state $|\psi>$. Note that the observer at A doesn't actually know what the state $|\psi>$ was, nor does the observer at B; all that has been done is to reconstruct or 'teleport' it from A to B. This kind of 'quantun information communication' has been done in several labs, notably in Caltech and Vienna.**

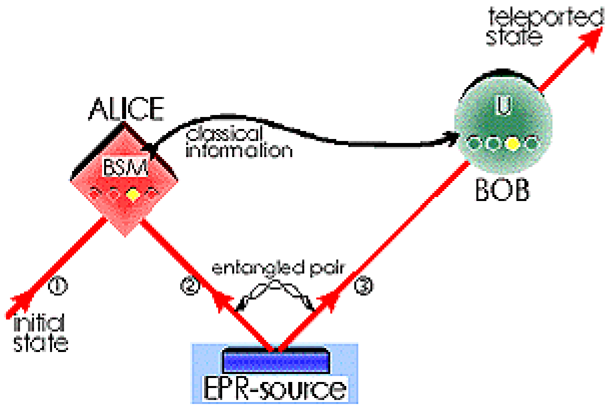


Fig 31: ***The basic design for quantum teleportation, in which Alice at A teleports to Bob at B a quantum state (the initial state shown) by entangling it with an 'entangled pair state' which is shared by Alice and Bob (see text).***

More generally one can ask about the communication of quantum information, and about how one can set up long-distance entangled states, in which 2 quantum systems, one at A and the other at B, can be successfully entangled and held in an entangled state for some period of time. The best answer to this so far has been using again the workhorse of atom-photon interactions, discussed above for cavities. A quantum state of several atoms in one cavity system at A is entangled with those in another cavity by entangling both with the state of photons which pass between the cavities. The key here is that photon states can be transmitted with very high fidelity between cavities, over large distances- this has now been done over nearly 100 km. Because they travel at the velocity of light this means almost instantaneous entanglement between states at different locations. The big challenge is to do this, not between a few atoms in different cavities, but between solid-state qubit circuits– this has not yet been done and is a hard problem. However for the foreseeable future the best bet for quantum communication seems to be lasers- this means that whatever the heart of a quantum information processing may look like (and it will be invisible to the naked eye!), the external part of it will look something like what is shown below.

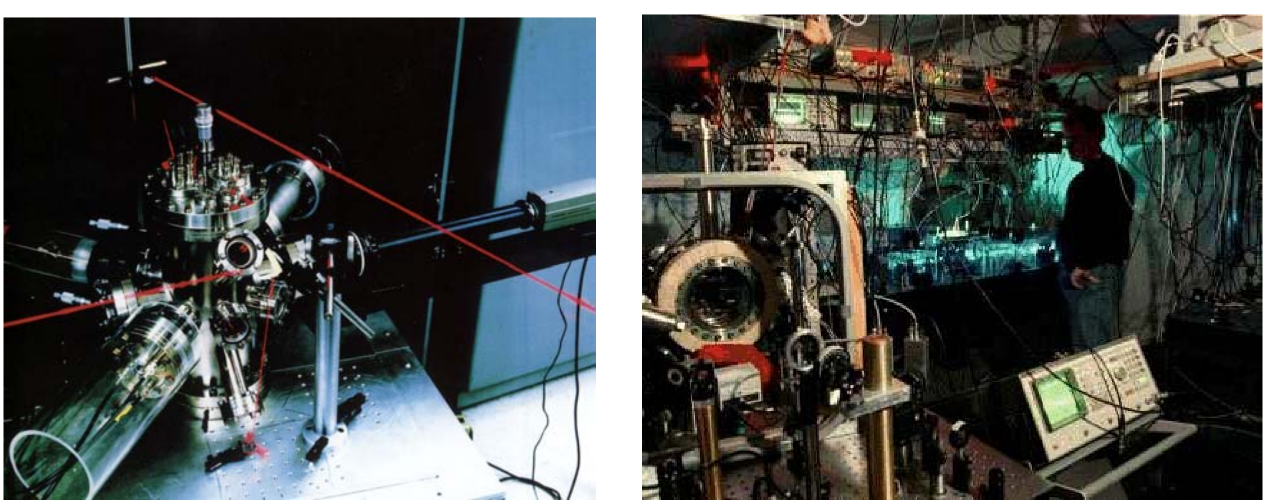


Fig 32: ***scenes from a quantum optics lab:*** **LEFT:** ***a set-up in which 2 qubits are being remotely entangled by lasers.*** **RIGHT:** ***The lab of E Polzik (Copenhagen).***

SUMMARY

The survey of quantum nanoscience given above is only meant to give a flavor of what is going on, and of where it is going. This document is mainly intended to introduce key concepts, and most of the really novel ideas are quantum-mechanical. Deep theoretical challenges are posed by the new areas being opened up here- we have only begun to imagine some of the possibilities. Long-term developments will be decisively influenced by these new ideas. The most radical and unpredictable ideas in nanoscience are likely to come from 'quantum nanoscience' ie., the development of devices & technology based on interference, entanglement, and quantum coherence. If even a fraction of the predictions made for this new field pan out, the revolution in technology will be as important as the industrial revolution.

P.C.E. Stamp (Dec 2005)