The SORCERER'S APPRENTICE: a QUANTUM PARABLE

The Fisherman & the Genie (Disney, from the Arabian Nights)

Quantum Mechanics is unique in the intellectual history of the world, because

(i) It has no known limits to its validity
(ii) Fundamentally, we do not understand it at all!

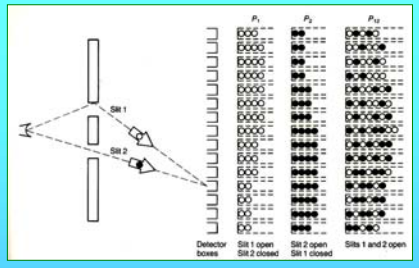
Walt Disney saw it as a Djinni ("genie"), for Good or Bad.

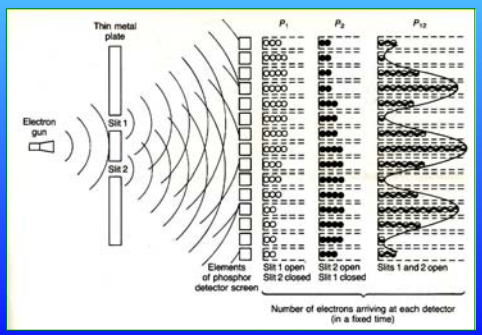
The Genie of Power (Disney)

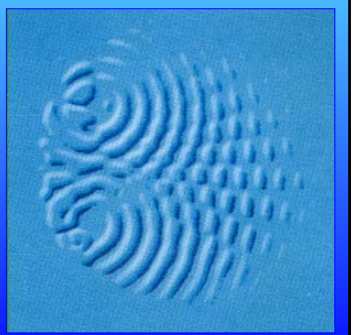
Particle – Wave DUALITY

There is NO WAY that one can understand the propagation of quantum particles through 2 slits as 'particles'; they show wavelike interference.

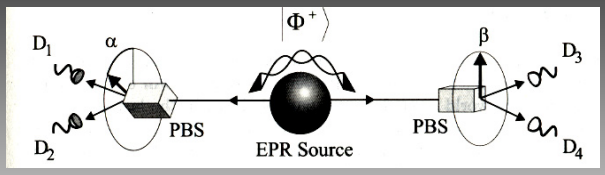
On the other hand there is no way that one can understand their propagation as mere waves either- they arrive in "lumps".







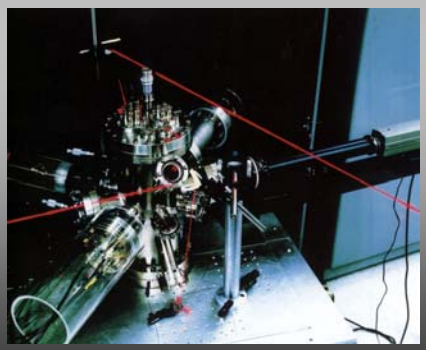
Quantum Entanglement



Just as bizarre is the phenomenon of NON-LOCAL ENTANGLEMENT"

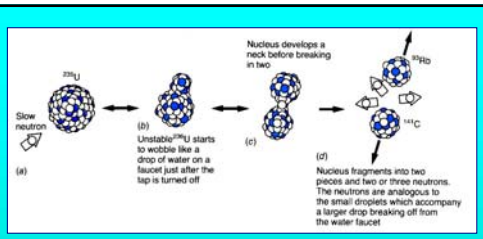
The result here is that the observed behaviour of one of the systems depends on what happens to the other- no matter how far apart they are (such that no signal can propagate between them).

Such experiments are now done in the lab (usually with photons). A major challenge is to achieve this on a larger scale.



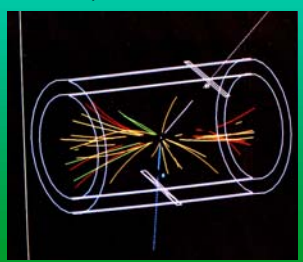
A set-up for experiments on EPR-entangled photons

Q.M. on the Small Scale



At the atomic and sub-atomic scales, interference and superposition are everywhere. The physics of the nucleus was unravelled once the existence of the "weak" & "strong" forces was realised- this explained radioactive decay and led to nuclear weapons. In the following years investigations at ever higher energies probed subnuclear processes, culminating in the period 1967-73 with the formulation of the "standard model", which unifies the strong, weak, and EM interactions in a single quantum theory. This allows an explanation of the high-energy processes in astrophysics.

Nuclear fission

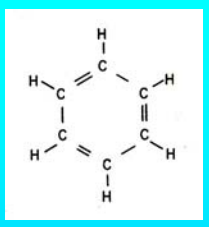


We still have no clear idea how to unify the standard model with gravitation- this is the main goal of modern string theory.

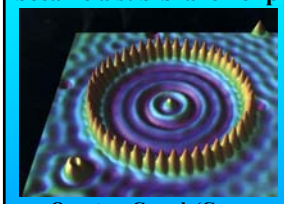
Q.M. on the SMALL SCALE

The structure of atoms and molecules is essentially quantum- mechanical- the electrons live in probability amplitude clouds around the central nuclei. As Dirac put it, with the advent of QM, chemistry became a sub-branch of physics- although it is a long way from the QM equations to the structure of, eg., the DNA molecule. Nevertheless QM led to the 20th century revolution in chemistry and biology

Wave-function for H atom.



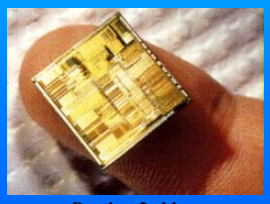
Benzene molecule



Quantum Corral (Co on metallic Cu surface)

C-60 molecule

DNA molecule



Pentiun 2 chip

In the same way QM allowed us to understand the electronic structure of solids, including metals, semiconductors, magnets, polymers, etc., and of liquids from water to liquid crystals. Beginning in the 1960's, this has triggered a massive and continuing techno- revolution

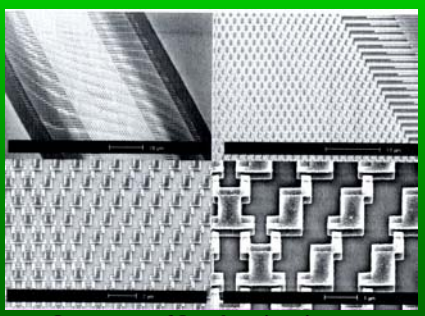
Effect of Q.M. on the Large Scale

Although quantum effects like interference and entanglement were not expected at the macroscopic scale by the founders of Q.M., the indirect effect of Q.M. is clear, at scales from the nanoscopic up to our size. In fact, one can't understand physical processes and structure at the large scale without Q.M.

Superconducting levitation effect

However there ARE a few direct effects of QM on the large scale, which are very dramatic (for some, the most dramatic effects of QM anywhere in Nature). These are superfluiditiy and superconductivity, involving the coherent quantum behaviour of huge numbers of particles . These systems can show very strange behaviour.

Superfluid fountain



Large array of Josephson junctions

Quantum Mechanics on the Large Scale

Until QM, almost all astrophysical processes were beyond our comprehension. We now have an incredibly detailed understanding of how stars function, from birth to death, and of the physics of objects ranging from comets & planets to nebulae and galaxies. Relativistic quantum field theory has opened up the structure of supernovae, neutron stars & black holes, and exposed the story of the universe back to its beginning.

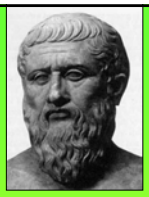
Zeldovich distribution

M16 (Eagle nebula)

Supernova (bottom left) in NGC 5426

Cross-section inside a neutron star (mass ~1.4 suns, diameter ~10 km)

Section of the Hubble deep space probe.



Plato (428-348 BC)

The Philosophical Problem

Some have thrown up their hands and said that Plato got it right all along- that when it comes to understanding physical reality we are all in the cave...

Some new philosophical approaches have evolved

'One may ..limit the use of the word PHENOMENON to refer to Observations obtained under specified circumstances, including an account of the whole experiment' (N. Bohr)

There is no quantum world, only an abstract quantum description. It is wrong to think that the task of physics is to find out how Nature is. Physics concerns what we can say about Nature.

'We are suspended in Language' (attributed to N. Bohr)

N.Bohr (1885-1962)

This rather positivist approach was evolved because

(i) It was believed that the macroscopic world must be classical, ie., REAL

(ii) The belief that the QM state or "wave-function" was NOT real

So long as the wave-packet reduction is an essential component of QM, and so long as we do not know exactly how and when it takes over from the Schrodinger equation, we do not have an exact and unambiguous formulation of our most fundamental physical theory.

J.S. Bell (1964)

Some attempts to Resolve the Quantum Paradoxes

(1) The MANY WORLDS Interpretation

(1) Statistical Interpretation

(2) QUANTUM GRAVITY Interpretation

(3) "Consciousness" interpretation.

The SORCERER'S APPRENTICE

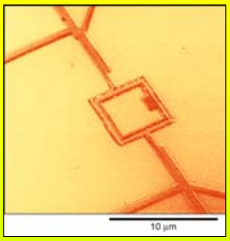
Another Approach to the Quantum Problems

WE are going to take the following point of view- which sounds orthodox but is not.

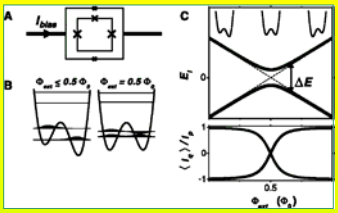
(1) Let us suppose that QM really does work up to the macroscopic scale- that there is never a breakdown. This means no classical measuring apparatus, no prohibition of large scale quantum states or superpositions, etc. We should therefore be ready to look at some very counter-intuitive stuff.

(2) We also assume no special role for Mind. This means that mental states can be quantum-mechanical, at least in principle. However any Godel-like self-referential processes will also have nothing special to do with mind or conscious entities. Mind will be viewed as an attribute of physical objects, nothing more.

(3) Now- we go out and look for large-scale quantum processes- this is a voyage of discovery, of the kind that physicists do best at!



Experiments on SQUIDs



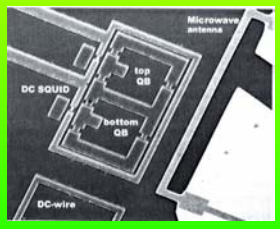
MACROSCOPIC QUANTUM INTERFERENCE involves interference between The single SQUID flux states states

$$\Psi_+ \sim \psi_1+\psi_2 \quad \text{and} \quad \Psi_- \sim \psi_1-\psi_2$$

where ψ_1 and ψ_2 are the 2 flux states. Recently "Rabi oscillations" have been observed between these states.

MACROSCOPIC QUANTUM ENTANGLEMENT involves harnessing many of these SQUIDs together. If each is in some superposition, then we get an incredibly complex system.

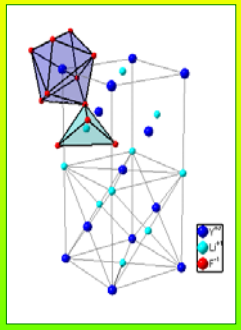
The nanoengineering of such structures, and the suppression of decoherence in them, is one of the most exciting challenges today in physics.



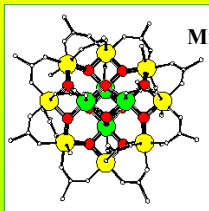
Coupled pair of SQUID qubits

The Quest for Magnetic Qubits

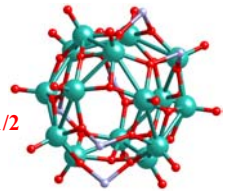
Another way of trying to set up complex entangled states is to use Nanomagnetic systems- here is some of the cast of characters.



Ho ions in $LiYF_4$ host

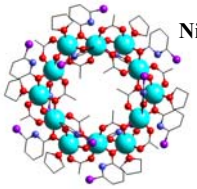


Mn_{12} S = 10

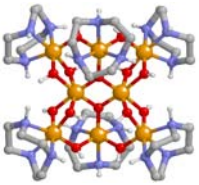


V_{15} S = 1/2

Single-molecule magnets (SMM)
Giant spins



Ni_{12} S = 12



Fe_8 S = 10

Decoherence Puzzles

Many aspects of decoherence are poorly understood- and are also central problems in physics. Some examples:

(i) Can very high energy processes (up to even the Planck length and beyond) cause decoherence at low energies? Are these essential to an eventual theory of Q Gravity?

(ii) Why are decoherence rates at low energies in solids so anomalously high?

(iii) Is decoherence the reason for classical behaviour at macroscopic scales?

(iv) What mechanisms are responsible for decoherence in systems like magnets & superconductors- and how can we SUPPRESS them?

(v) How can we characterize decoherence mathematically, specially in systems with a large number of entangled subsystems (eg., in a QUIP system)

and so on…..

Decoherence in SQUIDs

A.J. Leggett et al., Rev. Mod Phys. 59, 1 (1987)
AND
PCE Stamp, PRL 61, 2905 (1988)
Prokof'ev and Stamp Rep Prog Phys 63, 669 (2000)

A very detailed analysis of couplings to the oscillator bath modes (these being mainly electrons, phonons, photons) shows, as one might expect, that their effects are worse at higher energy (ie., if either Δ_o or kT is large). In fact the decoherence rate goes like

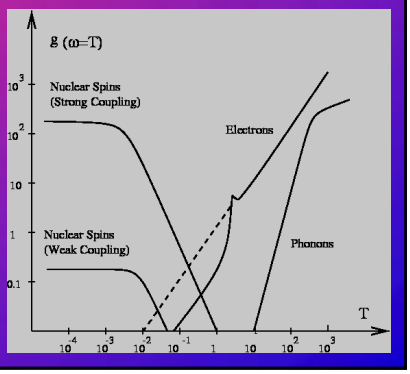
$$\tau_\phi^{-1} \sim \Delta_o \; g(\Delta,T) \coth(\Delta/2kT)$$

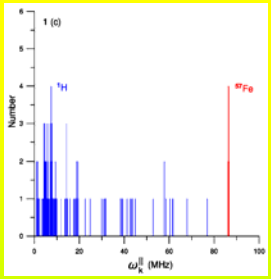
With the spectral function $g(\omega,T)$ as shown.

On the other hand paramagnetic spin impurities (particularly in the Josephson junctions), and nuclear spins have a Zeeman coupling to the SQUID flux which peaks at low energies- at energies below E_o, this typically causes complete incoherence. In the more interesting regime when $\Delta_o >> E_o$, the decoherence rate turns out to be:

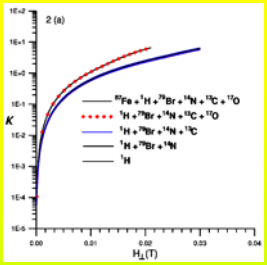
$$1/\tau_\phi = \Delta_o \; (E_o/8\Delta_0)^2$$

(we will see later where this comes from).

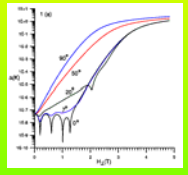




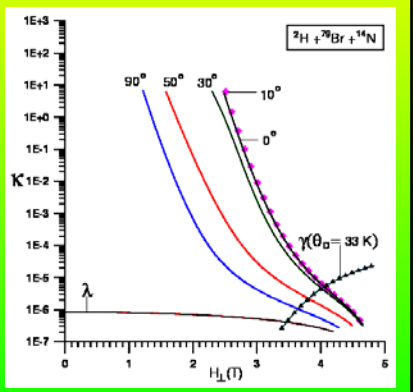
DECOHERENCE in the Fe-8 Molecule



This remarkable molecule can not only be well-characterised in experiments, it also can be given a very accurate theoretical analysis. All nuclear spin interactions can be determined theoretically.



The prediction of the analytic theory is actually very clear. at a high transverse field, where the tunneling splitting rockets up, the precessional decoherence falls very fast.



Only 2 things limit the lower bound on decoherence- a weak topological decoherence, and phonon decoherence.

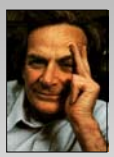
The highest coherence Q-factor predicted is about 10^7 !!

EXPERIMENTS are maybe 3-4 yrs away

QUANTUM INFORMATION PROCESSING

So much has been written on this recently that there seems little point in repeating it here!

The basic ideas of quantum information processing were developed by Feynman, Benioff, Deutsch, etc., in the period 1980-1990, but without specific examples of quantum computations. Common to all of this work was the idea that one could use a superposition of N entangled qubit states to do information processing/computation- ie., states of the form



FEYNMAN

$$\Psi = \Sigma\, \alpha(\sigma_1^z, \sigma_2^z, \ldots \sigma_N^z)\, [\, \chi(\sigma_1^z)\, \chi(\sigma_2^z) \ldots\ldots \chi(\sigma_N^z)]$$

where the $\chi(\sigma_j^z)$ are spin-1/2 wave functions. An example is

$$\Psi = \alpha_{++}|+ +> \; + \; \alpha_{+-}|+ ->\; + \; \alpha_{-+}|- +> \; + \; \alpha_{--}|- ->$$

and the crucial thing is that we can play with the phases of each of these coefficients (ie., $\alpha_{++} = |\alpha_{++}|\, \exp(i\phi_{++})$).

2 crucial things have happened since- the development of algorithms using such wave-functions, to do computations exponentially powerful in N (by Shor); and "error correction" routines allowing one to correct errors arising from, eg., decoherence. The big problem is still- how to suppress decoherence!

Back to the Sorcerer's Apprentice…….

If we are to adopt a reasonable attitude to Quantum Mechanics, we have to stop constantly pretending to be the Sorcerer. In fact the basic structure of QM is still not properly understood, and it is the job of an apprentice to learn!

Wild speculations about, eg., the role of mind in the collapse of the wave-function, or consciousness in everything from the solution to the quantum paradoxes, to the general structure of the universe (eg., the "anthropic principle, or the mentalist theory of Q measurements), are a throwback to pre-Renaissance ideas. The idea that all of these things can be solved by some theory of quantum gravity also strains credulity. These paradoxes are ones about ordinary condensed systems- this is where the solution lies.