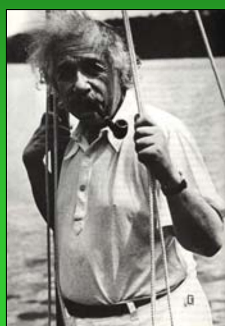
FRONTIERS in QUANTUM THEORY

The EPR paradox depends on having entanglement between 2 widely separated quantum systems- and having the entangled state be a sum (a 'superposition') of 2 or more other states. It is bizarre- but most can live with it if it only involves microscopic systems.

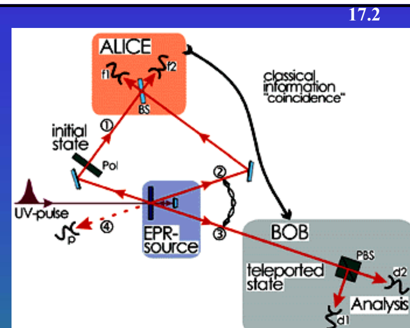
The Cat

But what if one of the 2 systems that is entangled is BIG (macroscopic)? This is the question asked by Schrodinger in the same year (1935). The large system could be a measuring system, entangled with a microscopic system. But Schrodinger imagined a CAT.



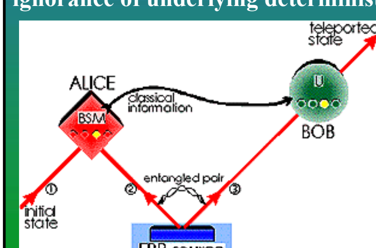
In Schrodinger's setup, the decay of a radioactive atom is detected, & fed via an amplifier to poison a cat. But the decay is probabilistic (it happens by quantum tunneling), so the nucleus will usually be in a superposition of a decayed state |d> and an un-decayed state |u>. But this means that the joint nucleus-Cat state is a sum of 2 states, viz., |d>|D> & |u>|L>, where |D> & |L> refer to DEAD & LIVE cat states. The cat is apparently in a superposition of live and dead states!

ENTANGLEMENT EXPTs.



Entanglement experiments have advanced greatly in recent years. We can now do experiments in which the quantities being measured on 2 entangled systems, are varied randomly- so quickly that no signal or interaction can pass between the 2 systems fast enough to create entanglement correlations.

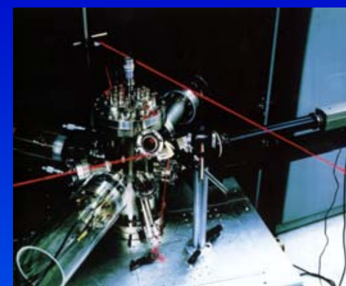
We can compare QM with "local hidden variable theories" (ie., ones where the probabilistic results of QM arise from ignorance of underlying deterministic variables, which are 'local', ie,, which describe individual systems). The famous result of JS Bell was that certain entanglement experiments can rule out ANY such theory in favour of QM- and they have now done so.

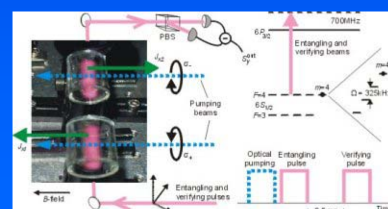


Recently 'Q Teleportation' of information has been discussed.

ENTANGLEMENT EXPERIMENTS with PHOTONS

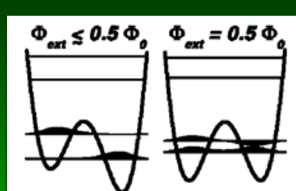
17.3





Macroscopic Quantum Tunneling & Coherence

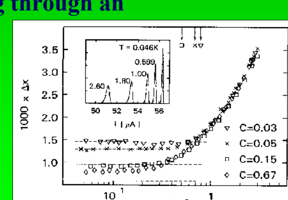
17.4



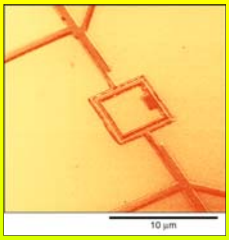
So far all quantum phenomena we've seen involve microscopic systems. We now come to a crucial development.

Consider again the SQUID system (pp 16.14, 12.6). Different flux states are separated by an energy barrier. Can one quantum tunnel between 2 different flux states, given the v. large difference in circulating current between 2 flux states? Actually yes,because we can make the energy barrier v. small- roughly 10^5 times less than the energy splitting in the H atom!

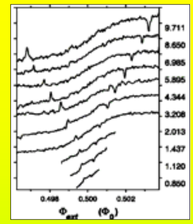
It was predicted by A.J. Leggett (1978) that one could get "Macroscopic Quantum Tunneling" in such a situation- this means tunneling through an energy barrier between 2 states that differ in the motion of a macroscopic number of particles (in this case, 2 different current states in the SQUID ring).



Experiments in the 1980's found this tunneling at very low temperatures- the theory worked! But this left the 2nd prediction of Leggett- that one could have superpositions of 2 different flux states (see above). This is like a Schrodinger's Cat superposition- but can it be made? This has now been answered…



Experiments on SQUIDs



LEFT: The SQUID Ring in which the superpositions were seen

ABOVE: The the energy levels of A SQUID vary as we change the external field. These levels are superpositions of flux states.
Expts. cause transitions between these (ABOVE).

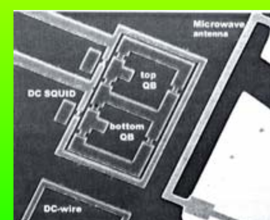
MACROSCOPIC QUANTUM SUPERPOSITION involves the single SQUID flux state superpositions

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

where ψ_1 and ψ_2 are the 2 flux states. Recently "Rabi oscillations" have been observed between these states, in DELFT (Holland). These states involve perhaps 10^{12} electrons- although not as big as a Cat, this is an impressively large superposition.

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

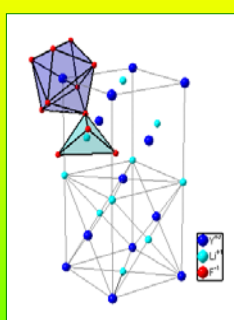
The nanoengineering of such structures, & the suppression of decoherence in them, is one of the most exciting challenges today. So far we are at the stage of coupling 2 SQUIDs and demonstrating entanglement.



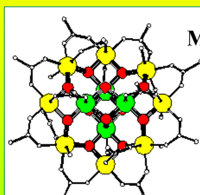
Coupled pair of SQUID qubits

The Quest for Magnetic Qubits

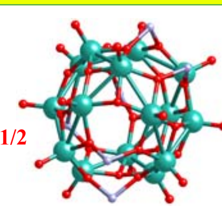
Another way of trying to set up complex entangled states is to use magnetic systems. For example, v. large magnetic domain walls (cf. p. 16.7) have shown macroscopic tunneling, just like SQUID flux. Right now interest is focussed on magnetic molecules and atoms which behave as 2-level systems- as 'Qubits".



Ho ions in $LiYF_4$ host



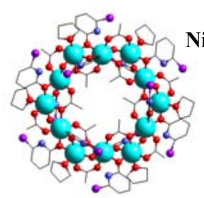
Mn_{12} S = 10



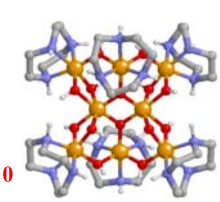
V_{15} S = 1/2

Single-molecule magnets (SMM)

Giant spins



Ni_{12} S = 12



Fe_8 S = 10

QUANTUM INFORMATION PROCESSING

The basic ideas of quantum information processing were developed by Feynman, Benioff, Deutsch, etc., in the period 1980-1990. The idea was that one could use a superposition of N entangled qubit states to do information processing/ computation- ie., states of the form

FEYNMAN

$$\Psi = \alpha_{++}|++\rangle + \alpha_{+-}|+-\rangle + \alpha_{-+}|-+\rangle + \alpha_{--}|--\rangle$$

(this is an entangled state of 2 Qubits)

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

Since then algorithms have been developed 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. Decoherence is the crucial problem- a problem involving nanoscience and theoretical condensed matter physics.