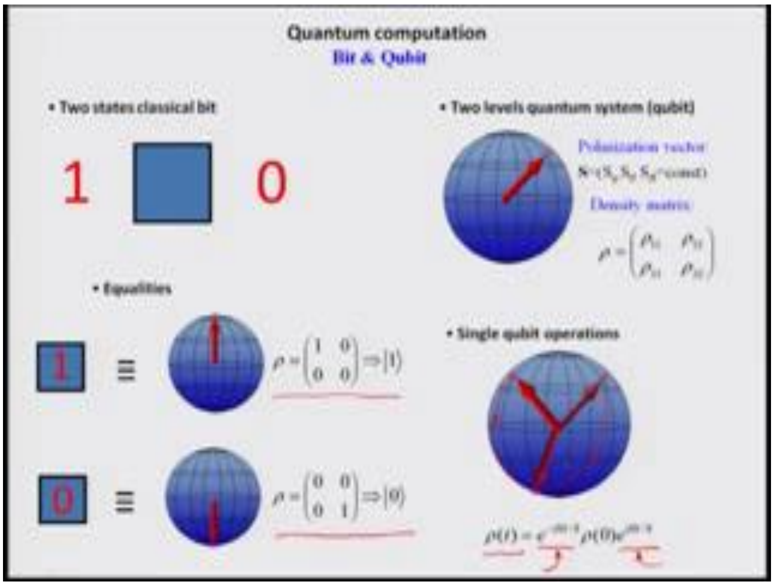
Implementation Aspects of Quantum Computing
Prof. Debabrata Goswami
Department of Chemistry
Indian Institute of Technology, Kanpur

Lecture - 32
Understanding Implementation Issues from the basics-II

We have been discussing Implementation Of Quantum Computing, but in this particular week we are focusing more on the basics in relation to the implementations that we have discussed over the last several weeks, the reason for making this revision is to make an understanding of all the connects that exists between the basics as well as the implementation angels.

(Refer Slide Time: 00:39)

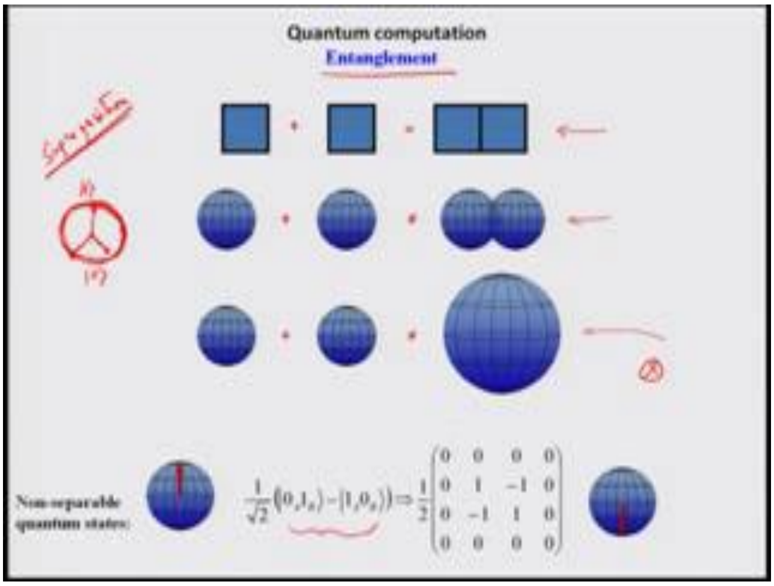


In this regard, let us once more revisit the concept of the bit and the qubit has to how we can look at it in some sense classical bit has exactly two possibilities as we all know, on the other hand the quantum bits as we call about are shown in terms of spheres that is because, there is a polarization vector which keeps on taking any particular position around the entire sphere and this is represented in terms of the coefficients of each of these different directions that it leads to in terms of possibilities of the directions and that is known as the Density Matrix.

The equalities which exist in some sense are defined in regard to the bits to the qubits and when the density matrix is pointing toward upward direction then it is say one particular state of the qubit, which is equal to a particular measurement in terms of the bit. So, the 0's and 1 in some sense represent the two opposite cases of the sphere points that we are looking in terms of quantum. So, the density matrix essentially represents the probability of the state that we are finally, measuring. So, when it is 0 at state, then it has a particular diagonal element only populated whereas, when it is the excise state then it is the other diagonal element which is unity.

So, for single qubit operations, there is a continuous sets of values, for a single qubit operation therefore, there are many sets of values that the state the density matrix can take as a function of time for instance as it is evolved with the help of the schrodinger equation. So, this is the integral integrated part of the Schrodinger equation, where the Hamiltonian is thought to be constant over the short period of time that this integration that this time evolution is occurring. So, the time evolution essentially occurs as a result of the unitary transforms provided by the Hamiltonian. So, this is the unitary operation we are looking at as the state is changing with time.

(Refer Slide Time: 03:23)



Now, the curious aspect of the quantum computing lies in the fact that, in terms of bits the additions or the putting together of bits puts them in sense as it is shown, here pictorially and it can be always put together such that it can also be taken apart in the same way. So, that the left and side and the right hand side for the classical case always remains the same, on the other hand that is not quite true when we are looking at the putting together quantum bits, because there the simple additive properties of these kinds are not going to work and the cases where these connectivitys of this kind work and you can always look at them in together is the case where the qubit is assuming and taking all other possible states as we discussed in the last line, where the final measure of a particular value of the qubit is a representation of the probability of one particular state with respect to the other in terms of the classical sense.

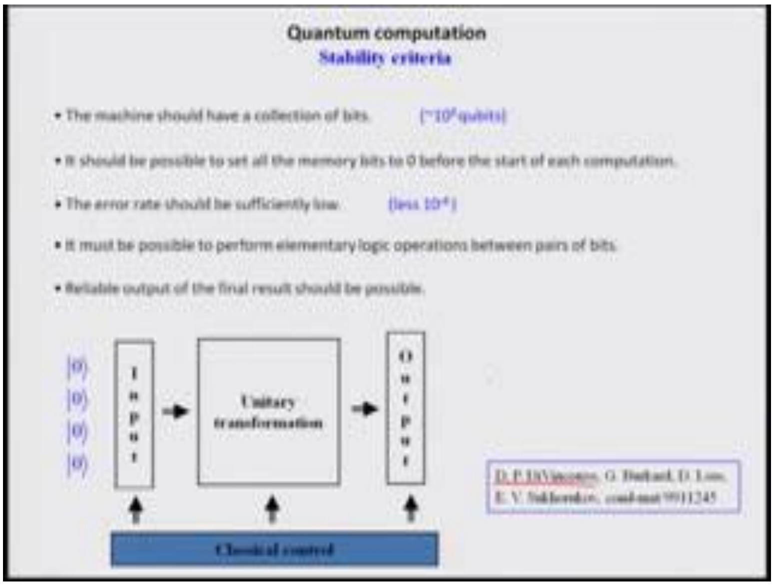
So, in some sense the collapse of the wave function into one or the other is possible, because of the spherical principle that we have developed where we are saying that the all possible values can then be looked at as a function of the wave at any point of time the measurement is looked at, and as a result what is happening is at any point of time collapse leads to the values that are connected to this particular measure at that time. So, this is a probability or the principle of super position of the particular aspect of being in one versus the other state.

This is the principle of super position, whenever we talk about for the single qubit which can exists in this kind of a form; however, when 2 cube itself come together the picture is not the same, because this does not give rise to a new set which can be broken down into this. So this overall idea, that the quantum states can always be separable. So the separable part is always known as proposition condition. So, there can be cases where the qubit come together, but they will only be behave as additive properties then they are going to remain as preposition state; however, if they cannot follow that principle and they are of the kind where we end up producing results where they cannot be looked at simple additive properties then this the idea of entanglement and that is happening only because of the process of dense a products that occur over point of systems in between the matrices.

So, these non separable quantum states essentially give rise to conditions where they are not possible to be taken down to the original starting points of the qubits that these individuals can be related to and therefore, their behavior is very different and not the kind of things you are used to and that is the idea about entanglement. In some sense it also gives rise to this unique nature where the measurement of one of the parts of the entangled set gives rise to the measurement of the other entangled set that is, because they can only exists in a particular state and they cannot be separated out. So, even if they are physically separated their behavior can be measured in a moment one of them is measured in this sense.

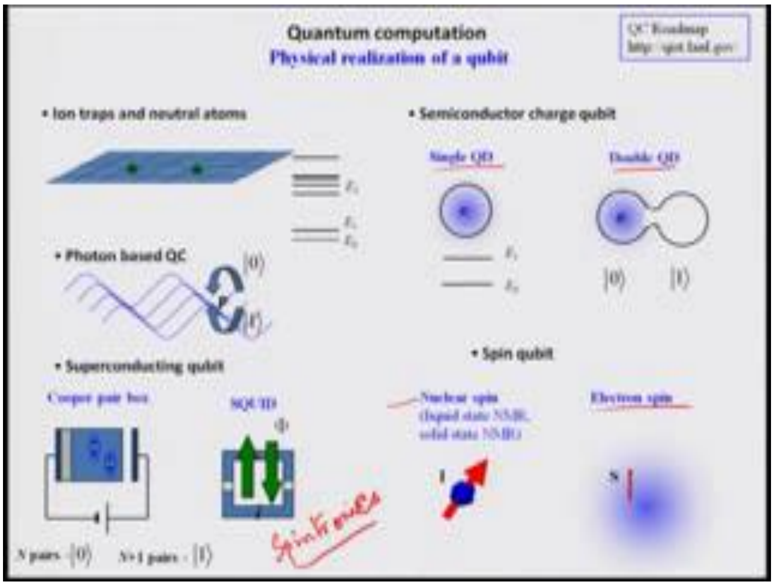
So, entangled states behave in a very different way as compared to the regular bits in some sense and that particular idea of entanglement is at the herd of quantum and this is been a statement, which has been made several times by me in this entire course to ensure that we realize the main aspect where the quantumness plays a very important role.

(Refer Slide Time: 08:19)



Let us see how we go ahead with this. So, the stability criteria which is often used for the number of qubits this is at the time: when we were making sure that the implementations aspects are looked at properly. So, the machine should have a collection of bits and these bits would generally be of numbers, which make some levels say 1000 qubits and it should be possible to set all the memory bits to 0 before, the start of each competition the error rates should be sufficiently small may be less than 10 to the power of minus 4 or so must be possible to perform elementary logic operations between (Refer Time: 09:02) of bits and reliable output of the final result should be possible. And this is basically the criteria which was initially taken from the principles, which was developed earlier by (Refer Time: 09:19) as we discussed and most of the aspects of the work is done in terms of the unitary transforms, which occurred in the quantum level, but they can be controlled in terms of the unitary transfers or the data input output, because those are the points which relate to the outside world and that is one thing, which I think was also obvious when we were talking about the de wave technology of implementation.

(Refer Slide Time: 09:47)

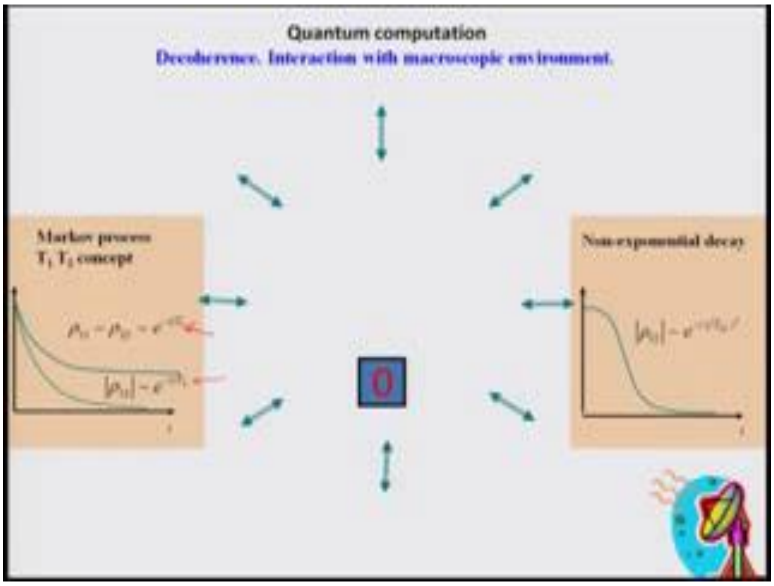


So, here in real term of the physical realization of the qubit here goes some of the ideas, which have been discussed in detail the ion trap and neutral atoms for instance have the different states, where these are under the different trapped conditions and they correlate and that is the ones, which have been addressed there have been other areas which are the photon based quantum computing where the spins of the systems have been addressed by using the photon.

The photon current going clockwise versus counter clockwise its produced the different results, which have been utilized in terms of photon based quantum computing, it is also utilized many other ways of looking at this problem and the other very important implementation qubit has been the superconducting qubit and that was partly one of the ones which was used in the d wave computing, where the qubits are superconducting loops, which were addressed by using either the current loop going one way or the magnetic loop going other way and in case of de wave it was the current loop going clockwise versus counter clockwise and the magnetic field created being of the two offset kinds, which were utilized for developing the computer.

The other important aspect is the cooper pair box where the spins of the system are being utilized and there are number of pairs, which are being used the number of pairs essentially ensure, whether it is of one state versus the other, similarly they can be addressed by using the giant magnetic field principles of the squid and we have discussed a little bit of it in terms of applying the current, and I am seeing the magnetic field aspects as a result of these applications. So, that is the place where spintronics was talked about as we discussed in the last week, semiconductor charged qubit was also the case where we used a single quantum dot where the energy states of the quantum dots played a role, if double quantum dots where used in they gave rise to qubit conditions the spin qubit has been very very effective in terms of being either nucleus spin, which has been addressed in terms of liquid state n m r as well as solid state n m r or the electron spin, which has been utilized in many applications also.

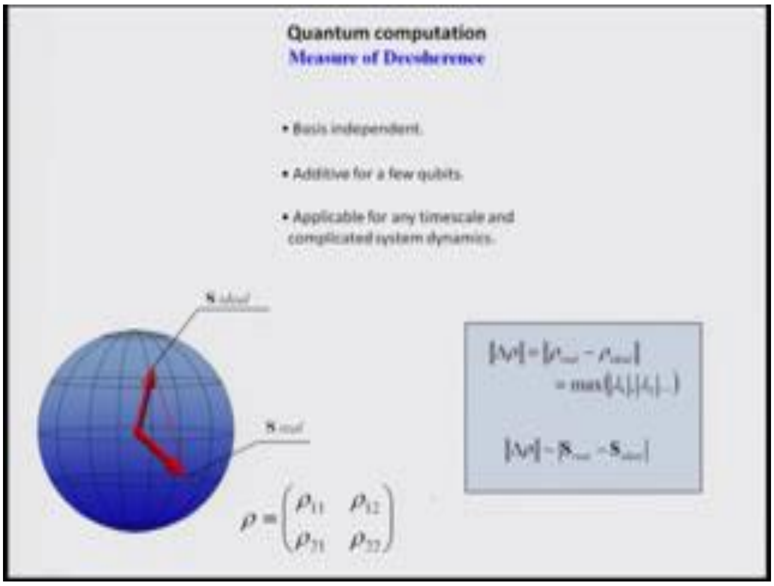
(Refer Slide Time: 12:40)



The major aspects of the quantum computing also lies in terms of de coherence and the interaction with the microscopic environment, because the essential quantum nature of the system diminishes after a because there is a life time, which the quantum system will be able to preserve this information and that is the part which is important. So, if it is the mark of kind of process, which is typical of the n m r spin cases these are the t 1 t 2, these follow typical exponential decays and there the excised state time scales versus the phase of the system time scales, which have different time scales; obviously, the phase across a different spins have a faster rate of decay compared to the electronic state decay.

So, this corresponds to the electronic state or the particular nuclear state that is been looked at spin state whereas, this one corresponds to the relative phase of the states that are been looked at and that has a faster rate compared to the other one by exceptive the both of them correspond to the de coherence of the system and there also cases where the de coherence of the state could be non exponential and that is more to do with this neutrons and other conditions and depending on whether we are going to be having any of these particular state, where we have created a super position of the of the quantum information state as we showed in the actual case. So, this is the quantum state which is the having all the information it actually goes down to the classical state, which is then has lost all the coherent aspects in it and these are the major reasons why has to be careful in terms of making sure that we are able to measure before the interaction takes it down to the classical limit.

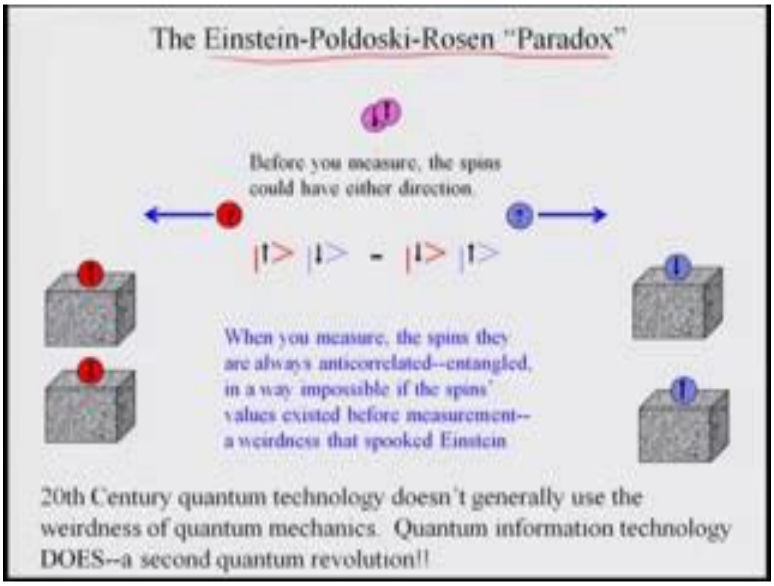
(Refer Slide Time: 15:05)



So, the microscopic environmental effects have to be reduced as much as possible. So, the one aspect which has been important in that sense has been the measure of de coherence, which is basis dependent and is additive for a few qubits, but is applicable for any time scales and complicated system dynamics. So, this is the kind of principle where the coherence of the system sort of diminishes and that is one of the parts, which is important to make sure there is not too small at any point of time because, interactions or carrying out gates would require the coherence to be available.

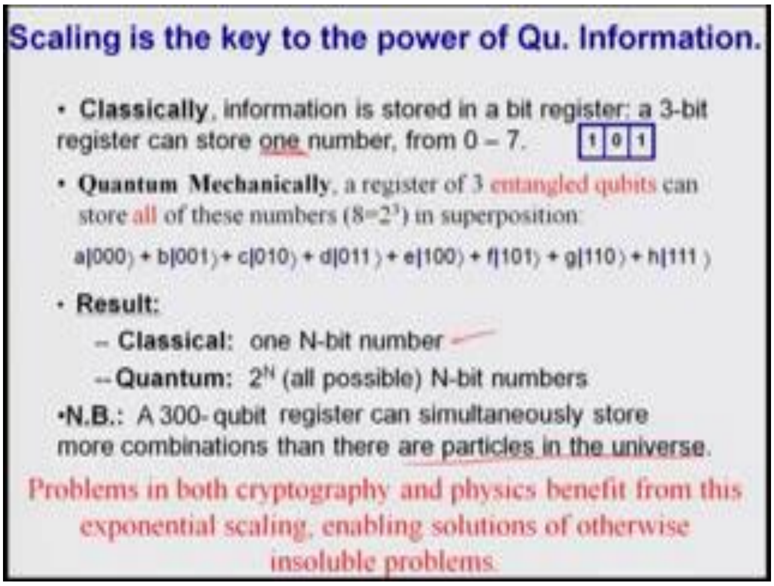
So, in the case where the system essentially goes between being completely coherent to the state where it essentially is being possible to be seen after certain period of time is the sort of like the ideal versus the real cases and many a times these are therefore, measured in terms of density matrices, because the advantage of looking at density matrix is that the property of the system can be captured very well. So, this is one of the areas where a lot of efforts have been put especially in terms of ensemble systems like n m r or in many coupled in spin systems where these studies have to be done very coupled studies manner.

(Refer Slide Time: 16:40)



One of the important aspects which we have been always talking about is the idea of entangle, which gave rise to the age old aspect of The Einstein Poldoski Rosen Paradox. Which simply deals with the fact that measurement of one essentially leads to the measurement of the other in terms entangle pair essentially it means that before you measure the spin could have been in either direction or, whenever you measure the spins they are always articulated entangled in a way that is impossible if the spin value is existed before the measure, and this is weirdness that, this was not liked by Einstein and that is why he made this statement and was of the impression quantum mechanics is essentially having some clause, because this kind of a action at a distance should not be possible to figured out (Refer Time: 17:39) because if the pair is created at some point of time and they are been separated out in spite of how so; however, far they are separate out any measurement of one of the possible states would give rise to the automatic measure or knowledge of the other state and that is one of the issues, which became a problem. We know that part of that was utilized and sufficiently correctly addressed by bells in equality proof leaded to the fact that, it is indeed possible to do these measurements and that has led to the entire idea of important measurement concepts in quantum information theory.

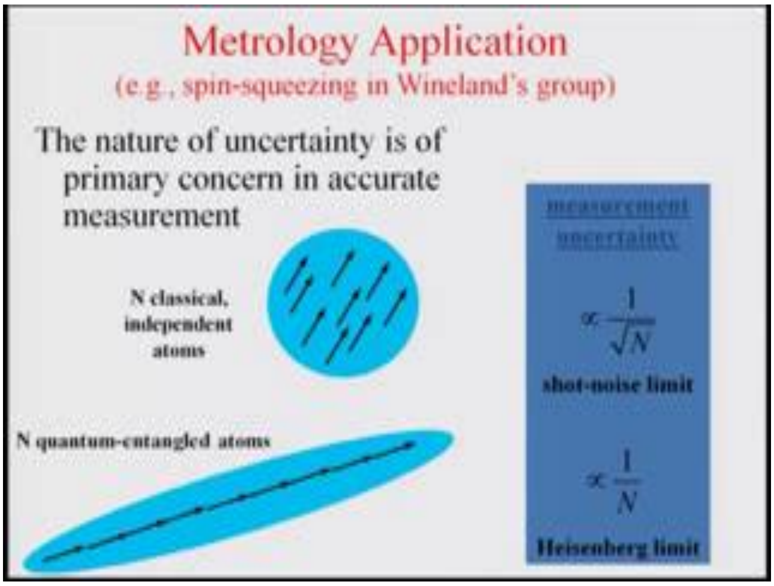
(Refer Slide Time: 18:26)



So, one of the other important parts of the quantum information is the scaling, and in terms of the scaling aspects it is important to realize that classical information is told in a bit register for example, the 3 bit register can store 1 number from 0 to 7; however, quantum mechanically are register of 3 entangled qubit it can store all these numbers, which all the numbers simultaneously in a super position, which is 8 numbers because it is 2 to the power 3 and. So, register of 3 numbers can essentially in quantum mechanics have all the numbers stood at the same time whereas, in classical sense it was only 1 number which could have been stored. So, that is the extreme benefit of the scaling that is available to due to quantum information.

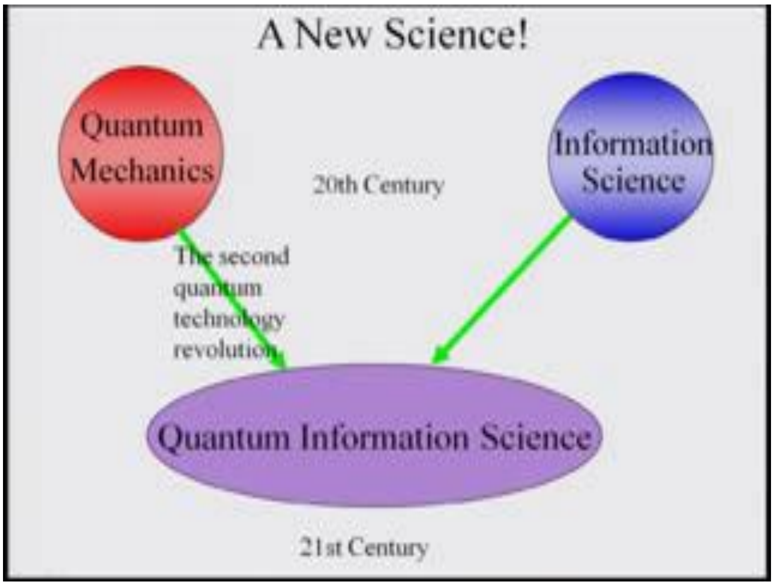
As a result a classical computer therefore, is a n bit number crunching machine whereas, a quantum computer is 2 to the power n all possible and bit number crunching machine. So, as a result 300 cubit register can simultaneously store more combinations and there are particles in the universe, and that is a very important aspect of the quantum computing. So, problems in both cryptography and physics benefit from these exponential scaling enabling solutions of otherwise insoluble problems, so one of the biggest advantages of the quantum problem.

(Refer Slide Time: 20:01)



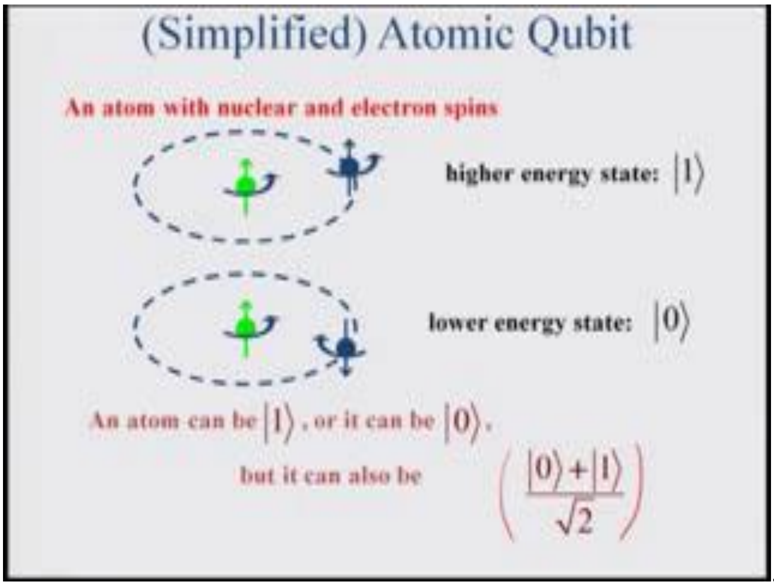
Weinberg, who got the Nobel Prize for cold atoms also shown, Wineland, (Refer Time: 20:10) who also got the Nobel prize for cold atom discovery has shown meteorology applications of cold atom based ion trap quantum computing, and that he was able to show, because of the usage of the entangled atoms which gave the benefit of producing large array of states together simultaneously and the nature of uncertainty of prime concern in accurate measurements typically and so far n classical independent atoms they are randomly or they can be oriented in a certain way in a particular set; however, for entangled atoms it can be shown that the short noise limit is possible with a larger accuracy and these are of heavy applications in meteorology. So, this was one of the additional benefits, which are shown by wineland group.

(Refer Slide Time: 21:16)



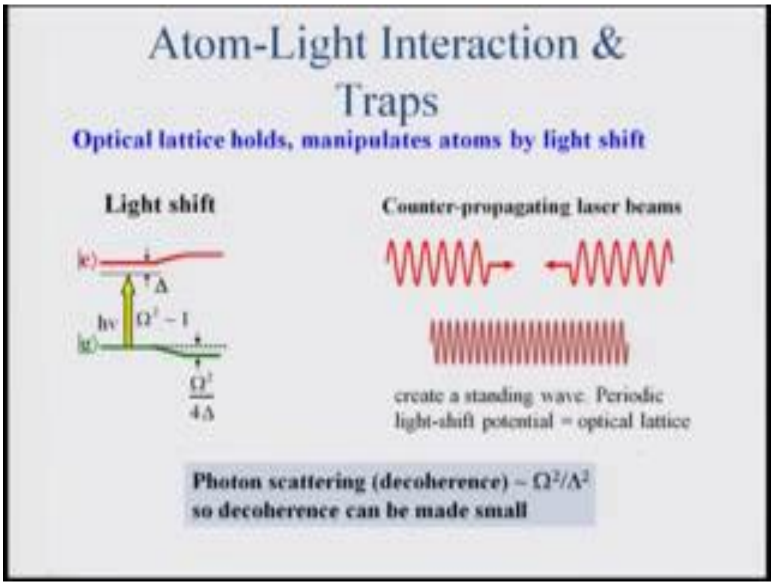
So, the idea of quantum mechanics merging with information science has led to the revolution of quantum information science, which is a big advantage.

(Refer Slide Time: 21:27)



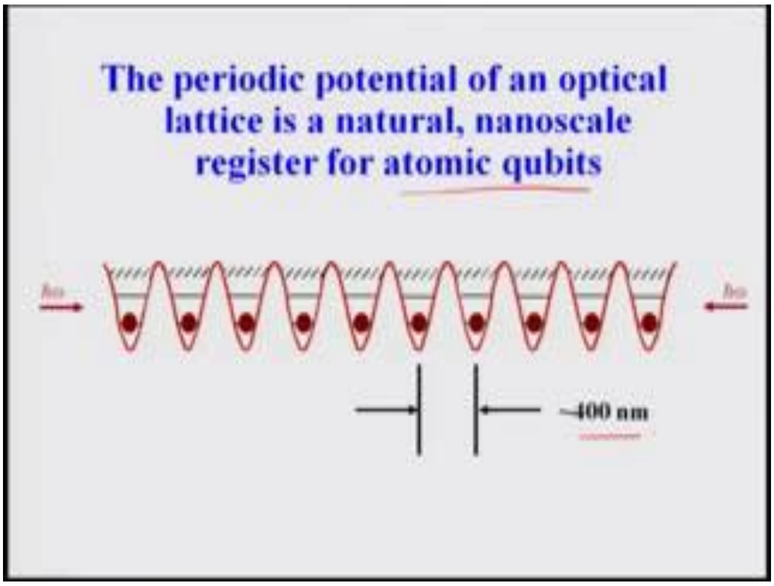
In the simplest possible state of the atomic qubit the idea of the use of spin states of the electron can be simply understood from the fact that it is, its rotation one way versus the other can be correlated to the way the overall spin of the electron is going to affect, because of its connectivity with the nucleus spin which is of when we are the other. So, the low energy state would have a condition when they spin out the electron is opposite to that of the nucleus, which is there of a same kind then it will have a higher energy state. So, any particular state atom can be either in 1 or 0, but it can also be in the same position possible state of the two cases.

(Refer Slide Time: 22:22)



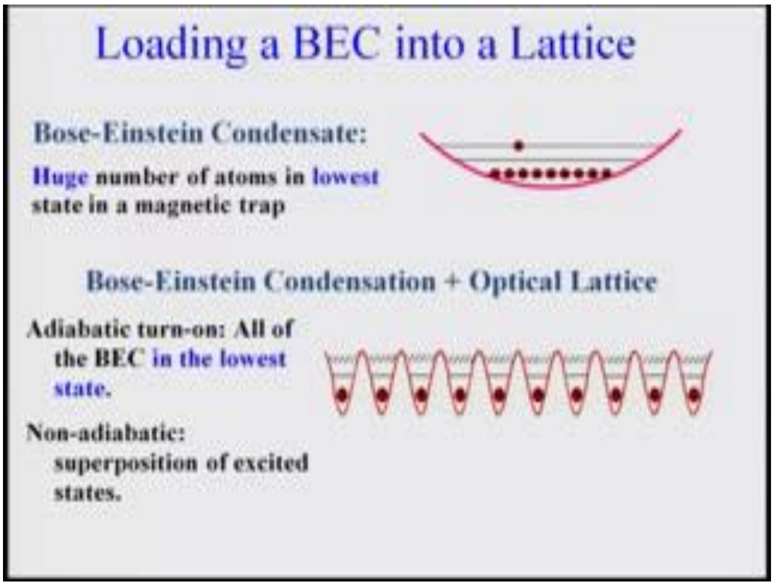
So, atom light interaction in the trap can be utilized to use atoms for quantum computing or quantum information processing. The counter parting laser beams can create a standing wave where the periodic light shift potential is equivalent to the optical lattice, and the light shift can be utilized to make sure the photons scattering or the de coherence is so small that it can be utilized for getting very long lived trapped atoms which can be used for quantum information process. So, this optical lattice holds manipulates atoms by light shifting and these are going to be very useful to create the standing wave periodically light shift potential where the particles can the atoms can essentially lie.

(Refer Slide Time: 23:16)



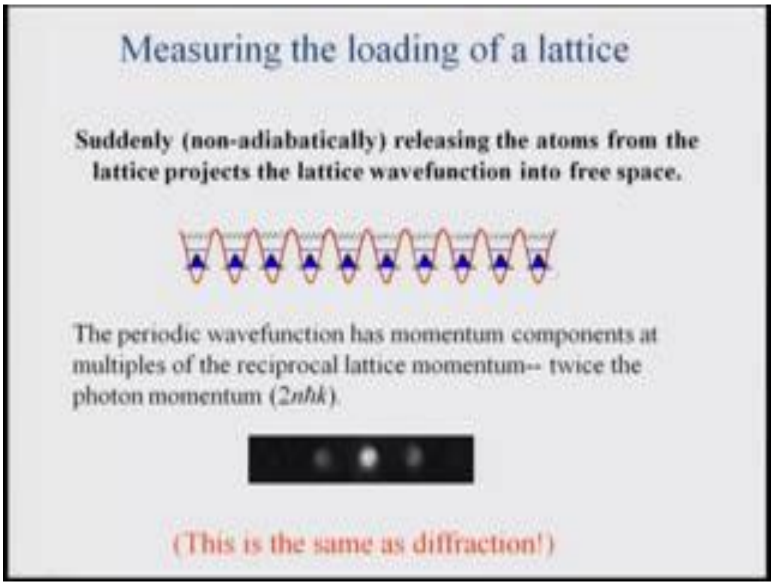
So, the periodic of an optical lattice is a natural nanoscale register for atomic qubit typically speaking, when we talk about ion traps and ions magnetic field and others can be utilized because of the charge nature of the system or the atomic case its only the spin which is being utilized in this case and the idea of light producing an optical lattice for which the interactions can be set up with the atoms is very effective.

(Refer Slide Time: 24:00)



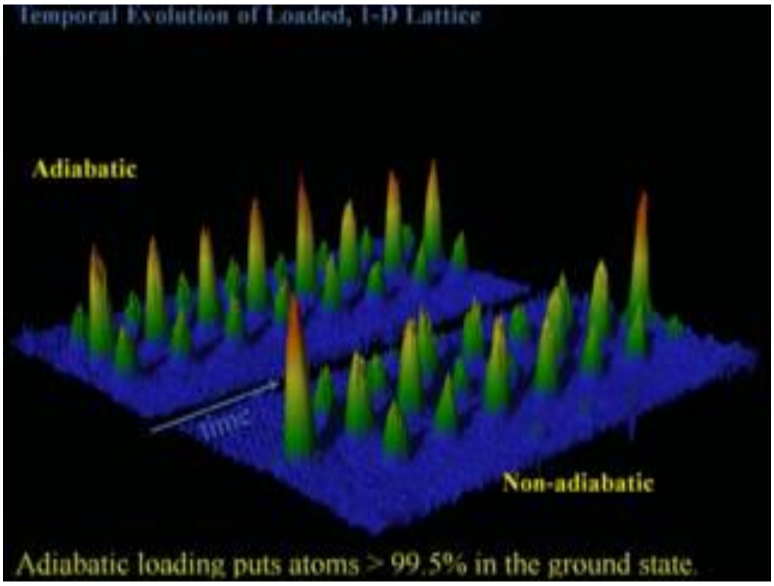
So, in such case lattice can be set up as small as say 400 nano meter spacing. and that can be addressed with light and Bose Einstein condensate, can thus be loaded into a lattice of this sort a huge number of atoms in the lowest state in a magnetic trap it can easily generated in a Bose Einstein condensate, and such a Bose Einstein condensate can then be put into an optical lattice as which has been produced by standing wave created by counter propagating light, and the way to then address these atomic states have a way to the lattice states of these atoms is been addressed by either using the adiabatic process where all the Bose Einstein condensate is in the lowest state. So, it is an adiabatically cooled condition it is adiabatic turn on condition it could be non adiabatic, where the superposition of excited states are also involved and that is how the states could be put together.

(Refer Slide Time: 25:00)



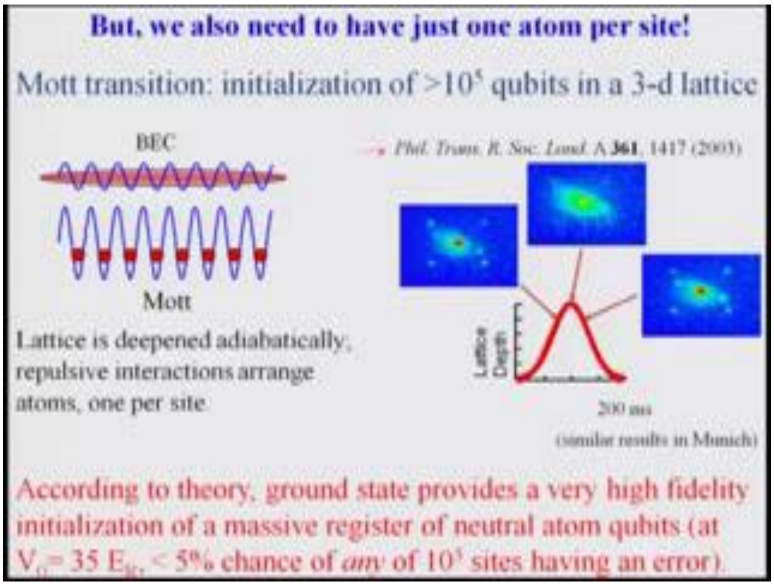
And those loaded states can then be looked at by certainly none adiabatically releasing the atoms from the lattice projects the lattice wave function into the free space. The periodic wave function has momentum components at multiples of the reciprocal lattice momentum, which is twice the photon momentum and this is same as diffraction and as a result this can be measuring how the system behaves and as a result this can end up helping in terms of working with the atoms as if it is in a crystal lattice.

(Refer Slide Time: 25:44)



So, here is a way how the system can essentially be looked at in time. So, in temporal revolution of the loaded 1 d lattice can be seen that under adiabatic condition everything is lowest possible state whereas, when adiabatic conditions are applied. That it suddenly provided the impulse it can undergo or have excited states coupled with it and can give rise to, whether aspects adiabatic loading can put the atoms in about 99.5 percent of the ground states and this is the kind of work, which wineland was able to show and was highly appreciated in terms of the work that he done with this case.

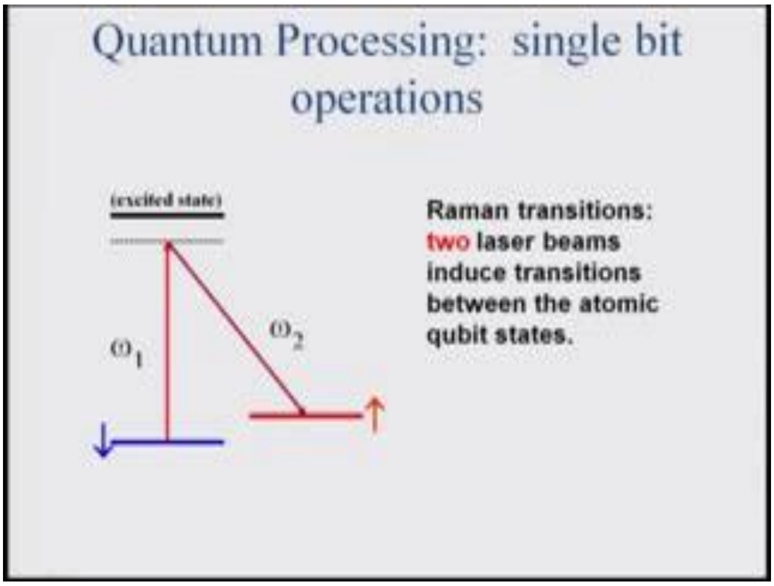
(Refer Slide Time: 26:32)



It also needs to be understood that, in this case each site needs to be just 1 atom. So, the initialization of say ten to the power of 5 qubits in a 3 d lattice greater than that is necessary. These Bose Einstein condensate is then which is been addressed by light would have to be looked at in a slightly different way and this is the kind of a which has been reported in this ah work by weinland 2003, wherein it was possible to make the lattice have a adiabatically deep end criteria by making the field change in the frequency going from change the property has made it deeper versus shallower and the lattice is depend adiabatically, adiabatically means it is done slowly the ramping is done.

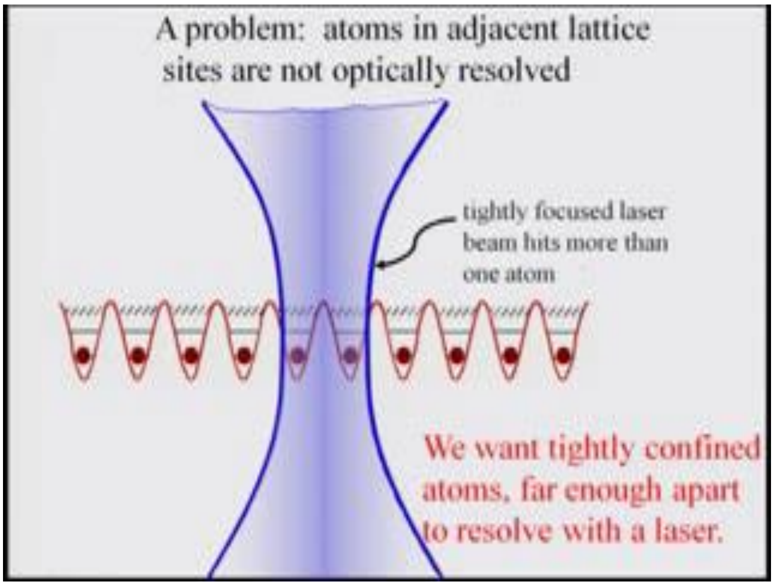
So, that the depend adiabatically repulsive interactions arrange the atoms one per site, and that is how it was possible to set it up in such a way and this was shown to work not only from his lab this bolder, but also it was shown from the results in nudnik (Refer Time: 27:54) and according to theory ground state provides a very high fidelity of initialization of a massive register of neutral atoms qubits at certain voltage values with an error rate less than 5 percent chance of any of the 10 to the power 5 sites having an error. So, that is the level of fidelity which is possible achieved by using this adiabatic principle of making sure that the atoms are loaded in the in the sites of interest.

(Refer Slide Time: 28:25)



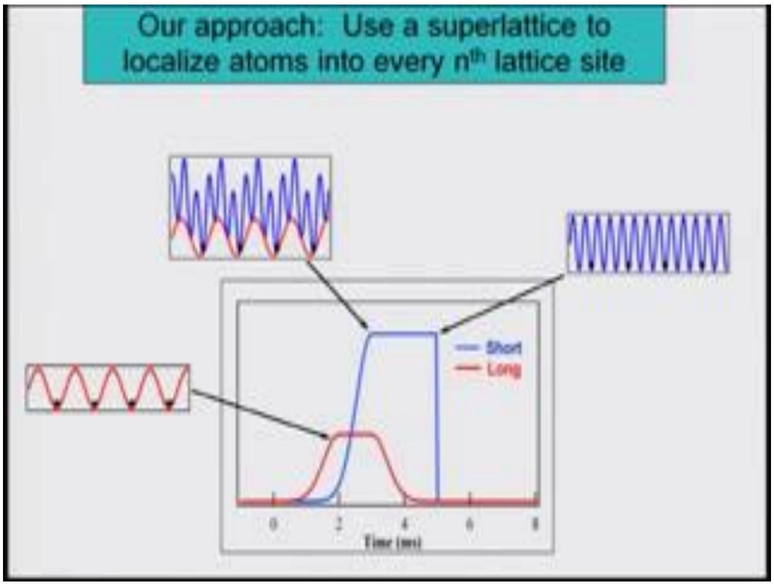
The next process essentially require the application of quantum processing in a single bit operation, which could be simply done by using Raman transitions between, because there are 2 laser beams anyway which are there to provide the lattice. So, the 2 laser beams induce transitions between the atomic qubit states and that could be utilized for the quantum processing.

(Refer Slide Time: 28:52)



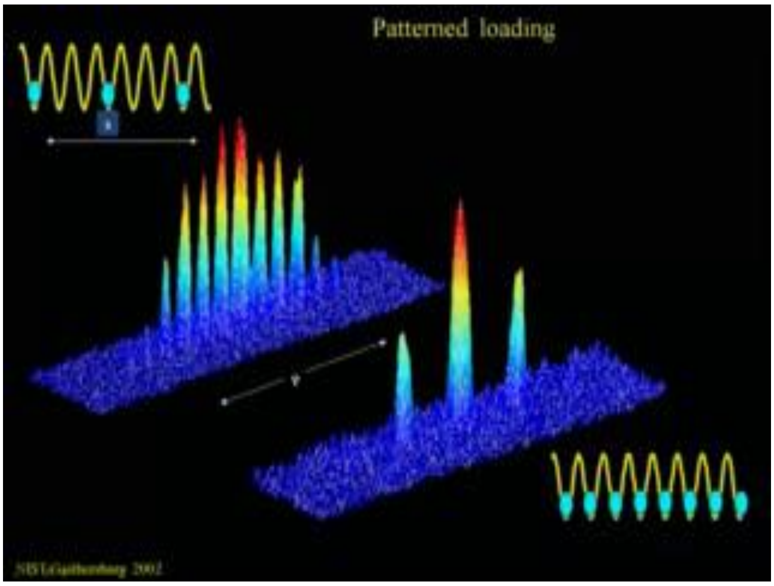
And; however, the problem in this particular case lies in the fact that the atoms in the adjacent lattice sides are not optically resolved, because the laser beam even though it is tightly focused, it would heat more than 1 atom because the diffraction limit its pot size of the laser cannot be better than the wave length of light in that range and whereas, these lattice size are going to be much better could be smaller in terms of their arrangements. So, what their demand was that they wanted to have tightly confined atoms far enough apart to resolve with a laser, otherwise tightly focused lasers would still hit more than 1 atom.

(Refer Slide Time: 29:41)



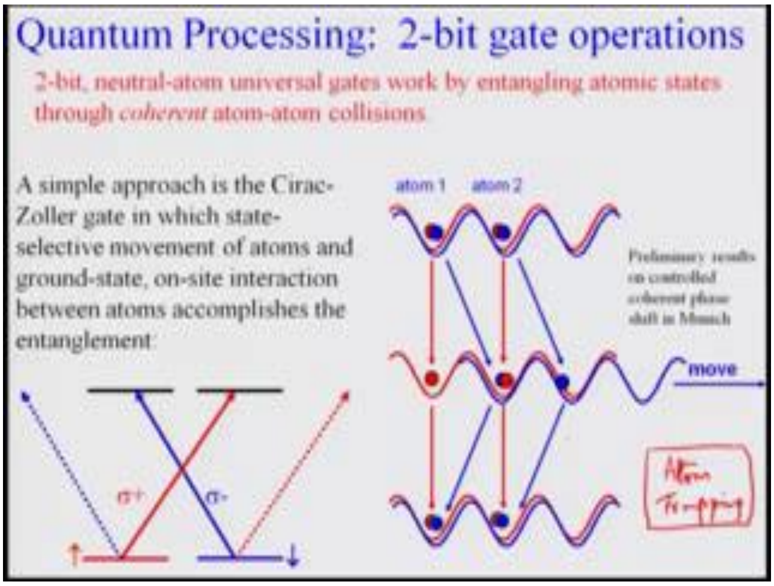
And this one, one of the approaches that Weinberg group made was to use a super lattice of local atoms with every n th lattice atom, where the property of the light was used in such a way that they were able to utilize this. These are more details of the exact experimental parts, but it is important to realize that they were able to use these atoms for doing quantum processing and area which we have always eluted to, but we did not really go into the details.

(Refer Slide Time: 30:15)



So, I thought, so, you certain details of this problem they were able to do a pattern loading of the system in (Refer Time: 30:21) 2002 experiment of theirs and these spatially patterned loaded atoms where being addressed and studied by using light as a means to do the computational aspects in this case the quantum processing.

(Refer Slide Time: 30:39)



So, they were able to show 2 qubit operations by using 2 bit neutral atom universal gates by entangling atomic states through coherent atom collisions. And this particular simpler approach, they used the Circa-Zoller gate in which state selective movement of atoms in down state on site interactions between atoms that were utilized for accomplishing entanglement. So, the preliminary results on the control coherent shift in these kinds of experiments enabled the motion of the atoms, in this sense they are sort of similar to what was shown in terms of ion tarp studies that I had discussed in detail earlier; however, here it is important to realize these are atoms. So, that they are not charts species. So, it is not the magnetite field which is used in these cases these are all optical fields which have being implied in very controlled fashion, so that these kinds of motions can be available.

This was one of the aspects of the atom trapping principle which was used for showing quantum computing. So, this is similar to the idea in terms of ion traps; however, here and optical lattice is been used to load the atoms and individually addressed by use of principle of coherent atom, atom collision between the states by using laser beams or appropriate wavelengths and energy, so that they can essentially do this kind of an activity. In some sense this kind of work was quite unique in relation to the ion trap also although it followed similar principles, and with that I am going to end the aspects of looking at the ion trap and related aspects of the quantum processing, which in this case we specifically focused a little bit more on the atom traps to also include this idea as has quite been obvious in our previous discussions, and we will be carrying forward the discussions into the other some aspects of solid state quantum computing that we looked at earlier into the next lectures. So, see you next time.