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Realization of Quantum Computers for Experimental Purposes

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ABSTRACT
Quantum theory is one of the most successful theories that have influenced the course of scientific progress during the twentieth century. It has presented a new line of scientific thought, predicted entirely inconceivable situations and influenced several domains of modern technologies. There are many different ways for expressing laws of science in general and laws of physics in particular. Similar to physical laws of nature, information can also be expressed in different ways. The fact that information can be expressed in different ways without losing its essential nature, leads for the possibility of the automatic manipulation of information. All ways of expressing information use physical system, spoken words are conveyed by air pressure fluctuations: "No information without physical representation". The fact that information is insensitive to exactly how it is expressed and can be freely translated from one form to another, makes it an obvious candidate for fundamentally important role in physics, like interaction, energy, momentum and other such abstractors. This is a project report on the general attributes of Quantum Computing and Information Processing from a layman's point of view.
Keywords — *quantum computation, EPR, quantum mechanics, superposition, unitary transformation, decoherence.*

I. INTRODUCTION

The number of atoms needed to represent a bit of memory has been decreasing exponentially since 1950. An observation by Gordon Moore in 1965 laid the foundations for what came to be known as "Moore's Law" – that computer processing power doubles every eighteen months. If Moore's Law is extrapolated naively to the future, it is learnt that sooner or later, each bit of information should be encoded by a physical system of subatomic size. As a matter of fact this point is substantiated by the survey made by Keyes in 1988 [1]. This plot shows the number of electrons required to store a single bit of information. An extrapolation of the plot suggests that we might be within the reach of atomic scale computations with in a decade or so at the atomic scale however.

With the size of components in classical computers shrinking to where the behaviour of the components, is practically dominated by quantum theory than classical theory, researchers have begun investigating the potential of these quantum behaviours for computation. Surprisingly it seems that a computer whose components are all to function in a quantum way are more powerful than any classical computer can be [2]. It is the physical limitations of the classical computer and the possibilities for the quantum computer to perform certain useful tasks more rapidly than any classical computer, which drive the study of quantum computing.

A computer whose memory is exponentially larger than its apparent physical size, a computer that can manipulate an exponential set of inputs simultaneously – a whole new concept in parallelism; a computer that computes in the twilight (space like) zone of Hilbert Space (or possibly a higher space – Grassman Space & so on), is a quantum computer. Relatively few and simple concepts from quantum mechanics are needed to make quantum computers a possibility [3]. The subtlety has been in learning to manipulate these concepts. If such a computer is inevitability or will it be too difficult to build on, is a million dollars question.

II. EXPERIMENTAL REALISATION OF QUANTUM COMPUTERS

A. Materials of Low Dimensionality – Quantum Dot

In 1959 physicist Richard Feynman gave an after-dinner talk exploring the limits of miniaturization. The scientist wrote about the potential for nanoscience in an influential 1959 talk "There's Plenty of Room at the Bottom." thus ushering a new era of the field of low dimensional materials [4]. One thing common about all the conducting nanomaterials is that, in spite of the contraction in the size of the material, the basic characteristics of the material remains the same- the energy levels remain the same. This fact remains true as long as the size of the material undergoes noticeable change. The number of energy levels increases and they start shifting towards 'blue' region [5]. By this, it is meant that the wavelength is smaller than green, yellow, orange and red. But with the decrease in wavelength, the frequency increases.

Now we know that the energy level E is given by the equation [6]:

$E = h\nu$ where h: Planck's constant and ν is frequency.

As the frequency increases by shifting towards blue, the energy increases [7]. Therefore, these materials are capable of storing more energy and are said to exhibit nanoproperty. The cause of the above said phenomena is stated below:

There is a wavelength called Compton Wavelength, which decides at which energy levels of the materials change.

$\lambda_c = h/(m_0 * c)$
h: Planck's constant
m_0: rest mass
c: velocity of light

If the size of any material is comparable with its Compton's wavelength, it exhibits nanoproperty and the materials are called Nanomaterial [8]. This is found to be the order 10^{-9} m. This is the reason why these materials exhibit nanoproperty. Thus, we come to the conclusion that as we move from macro to nano dimensions, we observe the following:

1. There is an additional constraint in the movement of electrons and protons.
2. There is reduction in the degree of freedom.

Therefore, these materials are also called as materials of low dimensionality, in which the charge density increases by decreasing the degree of freedom. The uses of nanomaterials in the manufacturing of computers justify Moore's Law, which states that [9]:

"In every eighteen months, the capacity of processing and carrying information of the computers is doubled."

This is possible by decreasing the number of electrons required to carry one bit of information. Most of the nanomaterials are characterised by the decrease of the degrees of freedom. Effective reduction of geometry to two or fewer dimensional systems is possible by a strong spatial localisation to a plane, line or point(i.e. confinement of an electron in at least one direction at the de-Broglie wavelength) occurs only in the case of atoms and electrons localised on crystal imperfections(e.g. on impurities) [10].

Quantum Wells are one of the three basic components of quantum devices, which are ultra thin, quasi 3-D planes. A narrow strip sliced from one of the planes is a 1-D quantum wire. Dicing up a 1-D wire yields a 0-D quantum dot. Reducing the number of dimensions in this manner forces electron to behave in a more atom like manner. All the three devices mentioned are the quantum devices i.e. they have nanostructures. Thus, we can say that with the evolution of nanotechnology comes the era of Diminishing dimensions from 3-dimensions, which was commonly found, to 2-dimensions in the form of Quantum Wells. Quantum wells were followed by quantum wires at 1-dimensional level. And now the level 0-dimension can be attained by the concept of quantum dots [11].

Quantum Dots are major contenders for being used as a building blocks of future Quantum Computers as compared to others like Nuclear Magnetic Resonance technique, Trapped Ion technique etc because of the fundamental fact that decoherence of these systems is very less hence even if they are prepared to act as quantum bits they degenerate very fast and interact with the environment thus loosing their coherence behaviour [12]. Quantum Dots being 0-Dimensional entities have practically no degree of freedom hence their interaction with the environment is also ideally zero thus they can act as qubits to a larger extent. Further analysis and stability criterion are analysed in the subsequent sections.

III. NEED FOR MODIFIED COULOMB POTENTIAL AND ITS ANALYSIS

The highly successful theory of electricity and magnetism amalgamated with the laws of classical mechanics, leading to classical electrodynamics is plagued with a serious problem right from its inception [13]. The problem lies in the interaction of charge particles when the distances tend to zero. The energy of the particle becomes infinite, its field momentum becomes infinite and its equation of motion leads to solutions like run-away solutions and pre-acceleration phenomenon, which are non-physical. This has been termed as "Problem of Divergences" in the classical electrodynamics.

It was envisaged that the advent of Quantum Theory would resolve all these difficulties. However, this did not prove true. All these problems are still present in the quantum version of the theory and appear in an even more complicated manner [14]. In the last ten decades, even since Lorentz identified the problem in 1903, a number of attempts have been made to circumvent divergence problem of Classical Electrodynamics. Out of all the prescriptions, the renormalization technique and Rohrlich procedure of invoking boundary conditions have drawn special attention. During the course of present investigation, I am bringing to the forefront an attempt which has been made to reformulate the theory of electricity and magnetism. In the process, a simple but an elegant prescription proposed by Prof. Y M Gupta has been used [15]. For the development of proposed formalism a stand has been taken that the problem as enunciated above must be solved initially at the classical level and only then the reformulation be carried forward to the quantum level. This procedural development automatically ensures the basic stringent requirement that the future theory must be a covering theory of the present one: invoking Bohr Correspondence Principle- "*In the limit when the proposed modification is withdrawn, the proposed theory reduces to the existing one.*"
The proposed formalism is based on the observation that in the realm of known formalism of Classical Electrodynamics potential function, field intensity, field momentum and interaction force, all, are singular at the origin(R=0) i.e. all these physical quantities become infinite in the limit of zero distance. It is this singularity, which is the crux of the problem. In the present formalism we choose a potential

function such that it is suitably and correctly chosen such that it is regular at the origin as well as all other space points, we automatically get physical quantities free from singularity. This is a logical way to obtain a whole set of dependent quantities which are regular ab initio. But at the same time it is also clear that all attempts at changing the basic equations of Electrodynamics (Maxwell equations) have proved unsuccessful. As a matter of fact, it is required to keep the basic equations of electrodynamics intact and yet look for a suitable potential function (solution of basic equations) that provides divergence-free solutions to the problems of Classical Electrodynamics (field energy, field intensity, field momentum etc.) [16]. To achieve this objective, prescriptions proposed by Prof. Y M Gupta have been followed. The important features of the prescriptions are-

1. The basic equations of Electrodynamics (Maxwell equations) remain intact.
2. The form of potential function, as obtained, is such that it is regular at all space points including origin. Notwithstanding this, it also gives rise to field intensities, field energies and interaction forces that are regular at all space points ab initio.
3. No free parameter is introduced into the theory- it is basically a parameter free theory.
4. The prescription very gently obeys Bohr Correspondence Principle. In other words, in the limit of large distances the proposed potential function reduces to usual Coulomb potential function.
5. The prescription is quite general in nature and not restricted to electrodynamics alone. Indeed, it can be applied to any inverse square force law. (E.g. Newtonian gravitational force and Yukawa Nuclear force.)

When the whole problem is analysed very closely, it is observed that the crux of the problem in hidden in the fact that in the realm of known formalism of classical electrodynamics potential function, field intensity, field momentum and interaction force is infinite at the origin (R=0). It is this singularity in the behaviour of these physical quantities that must be removed systematically for the fundamental development of the theory of electrodynamics. If the potential function is suitably and correctly selected, we shall automatically get physical quantities that are regular at the origin as well as other space points. This is a logical way to remove singularities in a systematic way [17]. Once we are able to obtain the suitable potential function, we can then attempt to carry forward the reformulation to the quantum level. This procedural development will ensure that, the basic stringent requirement, that the future theory must be a covering theory of the previous one, is automatically fulfilled.

IV. CONCLUSIONS

Though decoherence can be described as an effective process, its dynamics is not understood but an attempt has been made in the present project work in the form of Symmetry breaking argument or need for an entropy like parameter or function to account for irreversibility in the system. To be able to control decoherence, one should be able to figure out the eigenstates favored by the environment in a given setup. The dynamics of measurement process in not understood fully, though the attempt is also made in this regard in this project. Measurement is just described as a non-unitary projection operator in an otherwise unitary quantum theory. Ultimately both the system and the observer are made up of quantum building blocks, and a unified quantum description of both measurement and decoherence must be developed. Apart from theoretical gain, it would help in improving the detectors that operate close to the quantum limit of observation. For the physicist, it is of great interest to study the transition from classical to quantum regime. Enlargement of the system from microscopic to mesoscopic levels, and reduction of the environment from macroscopic to mesoscopic levels, can take us there. If there is something beyond quantum theory lurking, there it would be noticed in the struggle for making quantum devices. We may discover new limitations of quantum theory in trying to conquer decoherence. Theoretical developments alone will be no good without a matching technology. Nowadays, the race for miniaturization of electronic circuits in not too far away from the quantum reality of nature. To devise new types of instruments, we must change our view-points from scientific to technological-quantum effects which are not for only observation; we should learn how to control them for practical use. The future is not foreseen yet, but it is definitely promising.

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