Novel Scheme for Universal Quantum Computation
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Abstract
A scenario for realization of a quantum computer is proposed consisting of spatially distributed q-bits fabricated in a host structure where nuclear spin-spin coupling is mediated by laser pulse controlled electron-nuclear transferred hyperfine (superhyperfine) Fermi contact interaction. Operations illustrating entanglement, nonlocality, and quantum control logic operations are presented and discussed. The notion of universality of quantum computation is introduced and the irreducible conditions are presented. It is demonstrated that the proposed generic scenario for realization of a quantum computer fulfills these conditions.

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1 I. Introduction

The Nobel Laureate Richard Feynman first suggested that a new type of computer, running on the principles of quantum rather than classical mechanics, might have an exponential speed-up in computation time over a classical device for some tasks[1]. This observation engendered the development of a theory of a digital quantum computer by David Deutsch of Cambridge University[2], in which he demonstrated the intrinsic massive parallelism of quantum computation by operating on a coherent superposition of a large number of states. In particular, a single computation acting on N quantum bits can achieve the same effect as 2N simultaneous computations acting on classical bits. For N=300, this is a number greater than the number of atoms in the visible universe. Obviously, no classical computer could ever be built to compete with this kind of processing power. Exact methods and applications that harness this enormous potential are currently the subject of intense research. In 1994 Peter Shor of Bell Labs announced the discovery of an algorithm which, if running on a quantum computer, could find prime factors of large numbers in polynomial time[3]. There is currently no known classical counterpart that can accomplish the same task in less than exponential time. Shor’s factoring algorithm was the impetus for an explosion of research aimed toward the theory and experimental implementation of a working digital quantum computer[4]. In a subsequent development, Lov Grover discovered an algorithm that shows a square-root speed-up over a classical machine for the task of searching a large unordered database[5]. Even
though Grover’s algorithm is only polynomially faster than a classical algorithm, the wide range of its applicability to data search makes it very enticing. Another extremely important class of problems is represented by the so-called "intractable" NP-complete set. These problems are at the core of a wide range of practical routing, layout, and other logistics issues. A prototypical example here is the traveling salesman problem (TSP). It is widely believed that no classical algorithm that can solve this problem, or any other member of this class, exactly in less than exponential time. Such problems are now a challenge for quantum computers and algorithm developers.

Various approaches are currently in process for laboratory realization of essential elements to perform quantum computing, namely, the construction of qubits and demonstration of quantum logic operations. The work of Jeff Kimble and his colleagues at the California Institute of Technology (Cal Tech) emphasizes the use of entangled photon states using microcavities to construct quantum logic gates [6]. Correspondingly, David Wineland and his group at NIST, following the theoretical predictions of Peter Zoller and coworkers [7], achieved what amounts to a two bit quantum register using laser excitation control of atoms in cold ion traps [8]. These methods require large scale, state-of-the-art laboratory facilities and defy scalability beyond a few qubits. Aside from the requirements of extremely sophisticated laboratory facilities and procedures, quantum decoherence occurs in these schemes at a time scale of nanoseconds at best, and is a major obstacle. Recently, Neil Gershenfeld and Isaac Chuang introduced a revolutionary scheme for quantum computing using nuclear spins and the methods of nuclear magnetic resonance (NMR) to construct and manipulate quantum logic [9]. Free temporal evolution takes place virtually without decoherence due to the robust isolation of nuclear spins caused by screening by the atoms electrons. This version of quantum computation can be controlled and processed with current state-of-the-art technology. More recently, Chuang, Gershenfeld, and Kubinec (CGK) reported, using this scheme, the first ever laboratory demonstration of a genuine quantum computation [10] by execution of Grover’s quantum search algorithm [5]. This included loading of the registers, unitary execution of the quantum calculation, and read-out of the results. Their results, though it utilized only four input registers, constitute a significant step forward toward the practical realization of a useful quantum computer. One of the problems in scaling, in this regard, to a practical device is that the nuclear spins within a molecule that form the computational basis must rely on chemical shifts to be distinguished from one another. These shifts are usually very small and consequently the rf pulses that must control the computation are required to be sufficiently long so as not to couple distinct spins by resonance overlap. This is usually of the order of microseconds. Thus, computation is required to be exceedingly slow. A second, and more severe problem in scaling is that the read-out signal necessarily diminishes exponentially with the size of the quantum bit register. The current state-of-the-art limits this size to no more than 15 bits. We recognized early on [11] that these difficulties could be mitigated by selectively coupling the nuclear and electronic intrinsic spin angular momenta via hyperfine or transferred hyperfine interactions [12,13]. Further emphasis has
been recently enunciated in the use of electron-nuclear spin coupling and control for quantum computation by David DiVincenzo[14]. These comments were stimulated by the specific seminal suggestions by Kane[15] for nanostructures in Si. The scheme proposed by Kane surmounts the problems of scalability and individual nuclear spin addressability that is inherent in the liquid state NMR methods [9,10]. However, it suffers in principle from the requirement of electron charge transfer, and the measurement of single electronic charge by nanostructured gates for signal read-in and read-out. Otherwise, electronic charge migration is required for mediation of nuclear spin coupling as well as the shift of individual nuclear spins in and out of resonance with a constant rf field. Electronic charge and spin migration is controlled by nanofabricated gates. The requirements of the procedure are beyond current fabrication technology, but this is likely to change in the reasonably near future. However, there remain problems connected with charge transfer control for nuclear spin identification, and single charge measurements for read-in and read-out.

Our purpose here is to present a scheme for quantum computation that is universal and that does not suffer from the limiting conditions of liquid state NMR and that may offer a more viable alternative to the proposed scheme of Kane. We draw upon the favorable decoherence properties of nuclear spin systems utilized in NMR quantum computing, and the solid state distributed implanted nuclear spin elements system coupled via electron hyperfine and transferred hyperfine interactions proposed by Kane. Our scheme involves a distributed individually addressable system of electron spin/nuclear spin qubits and state-of-the-art microwave single electron spin resonance for signal read-in and sensitive optical fluorescence for read-out. Our treatment here is generic. Specific materials and optimizations are relegated to a future publication.

In the next section we present and discuss the irreducible requirements for a universal quantum computer. Our generic scheme is presented in Section III. Quantum logic, entanglement, nonlocality and quantum information memory are discussed in Section IV where it is shown that all the conditions of Section II are met. The last section is used for discussion and comparison with other proposed methods and schemes, and for concluding remarks.

2 II. Requirements for Universal Quantum Computer

Quantum computational (QC) algorithms are of only esoteric significance apart from the hardware capability to execute them. The resource and technological investiture necessary to develop such a device would necessitate design requirements that fulfill the capability to perform any given quantum computation and accommodate the execution of any algorithm, including initial state preparation, read-in and read-out. A quantum computer design meeting these requirements will be termed universal. The design must meet, therefore, certain irreducible
requirements that are both necessary and sufficient for the execution of any given QC algorithm. Establishing these requirements necessitates the identification of the set of elemental operations common to the execution of all quantum computational algorithms that, in a particular operational sequence, are sufficient for the execution of any given algorithm. A universal quantum computer must be capable of execution of the elemental operations.

It is conjectured that the identification of universal elemental operations common to all QC algorithms and sufficient in specific combination are simple Hadamard transforms, together with a generalized quantum phase shift operation [16]. The work of Cleve, et.al. [16] is the basis for this conjecture. A simple Hadamard transform, $H$, on a qubit $|q\rangle$, $q = 0, 1$ is given by [16]

$$
|0\rangle \xrightarrow{H} \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \tag{1}
$$

$$
|1\rangle \xrightarrow{H} \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle) \tag{2}
$$

This operation is exactly equivalent to a uniform single particle beam splitter[17], and is a special case of the more general Quantum Fourier Transform (QFT),

$$
|a\rangle \xrightarrow{F_{2^m}} \sum_{y=0}^{2^m-1} e^{2\pi iy/2^m} |y\rangle \tag{3}
$$

In terms of a two-bit operation a subsequent phase shift operation can impart a conditional phase shift to one component of the transformed wave function,

$$
|0\rangle |1\rangle \xrightarrow{H} \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) |u\rangle \xrightarrow{\phi} \frac{1}{\sqrt{2}}(|0\rangle + e^{i\varphi} |1\rangle) |u\rangle \tag{4}
$$

Or a conditional transition of the auxiliary qubit as well,

$$
\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) |u\rangle \xrightarrow{\text{C-NOT}} \frac{1}{\sqrt{2}}(|0\rangle |u\rangle + e^{i\varphi} |1\rangle |v\rangle) \tag{5}
$$

thus forming an entangled state and constituting a controlled NOT-gate (C-NOT). Ultimately, quantum trajectories are brought together as in a Mach-Zehnder interferometer to produce quantum interference[17]. The intermediate conditional operation, phase shift and/or entanglement, requires auxiliary qubits and a unitary operation[16]. The corresponding network representation is given in fig. 1.

Fig. 1. Network representation of quantum Mach-Zender interferometer with generalized phase shifter.

Thus, the elemental operations are conjectured to be constituted by a simple QFT, a conditional phase shift and/or entanglement, and ultimately a QFT.
that brings together quantum trajectories to produce quantum interference. The later constitutes the results of a computation, i.e. collapse of the wave function. These operations are entirely equivalent to the unique characterization of quantum computation: a) quantum superposition, b) quantum entanglement, and c) quantum interference.

In addition to the ability to facilitate the operational requirements discussed above, a universal digital quantum computer must satisfy the following criteria:

i) A distinct set of distributed qubits must be defined that are individually addressable.

ii) The qubits must be linkable via a binary interaction.

iii) Must be capable of performing two-bit logic operations, i.e. C-NOT gate.

iv) The speed of operation must satisfy the Preskill criterion, i.e. the capability must exist for the execution of at least 104 distinct operations within the quantum decoherence time.

v) Arbitrary initial state preparation must be clearly executable.

We present our generic scheme for realization of a quantum computer in the next section. In section IV we discuss the fulfillment of the above criteria in our proposed scheme.

3 III. Realization of a Universal Quantum Computer

Our proposed scheme is similar to the seminal proposal of Kane[15], but does not depend upon electronic charge migration for read-in and read-out, nor wave function displacement to distinguish nuclear spin qubits. Our scheme, that we feel offers a viable alternative, is represented in fig.2.

Fig. 2. Schematic representation of distributed qubit array as discussed in the text. Atoms C and A are embedded in the Si wave guide as shown. The Stark gates are depicted above atoms C external to the guide, and the bias gates, located on the top and edge of the guide are also shown.

As depicted in fig. 2 the two-qubit system is constituted by the unpaired single electron spin of atom C, and the nuclear spin of atom A. The specification of the atomic constituents is that atom C be composed of a single loosely bound unpaired electron and isotope of nuclear spin $I_C = 0$, whereas, atom A is composed of isotope with $I_A = 1/2$ and no unpaired electrons. The configuration of atoms A and C, shown in fig. 2, is embedded in an optical waveguide composed of pure Si of isotope $I_{SI} = 0$. The substrate also consists of Si with $I_{SI} = 0$ to avoid background interference. The electron spin of atom C is coupled to the nuclear spin of atom A by electronic wavefunction overlap as shown in fig 2. The coupling is via Fermi contact interaction[18] given generically for isotropic
transferred hyperfine interaction by

$$A_x = \frac{8\pi\beta\beta_n}{3S} \left[ a_{1s}^2 |\psi_{1s}(0)|^2 + a_{2s}^2 |\psi_{2s}(0)|^2 + 2a_{1s}a_{2s} |\psi_{1s}(0)||\psi_{2s}(0)| \right]$$  \hspace{1cm} (6)

where $\beta$ is the Bohr magneton, $\beta_n$ the nuclear magneton, and the wave functions $\psi_{ks}(0)$, $k = 1, 2$, are the 1s and 2s orbitals of atom A evaluated at its nucleus, and the $a_{ks}$ are overlap integrals coupling the electron wave function of atom C with the 1s and 2s inner shell wave functions of atom A. Thus, the unpaired electron spin of atom C is coupled with the nuclear spin of atom A by contact interaction mediated by the inner shell s-state orbitals of atom A.

The interaction is controlled by laser field induced electronic excitation of atom C from its ground s-state (no overlap interaction with atom A) to an electronic excited state with a p-, or d-, orbital, with strong overlap and superhyperfine interaction with one or both of its nearest neighbor atoms A. Enhanced, as well as suppressed, interaction is controlled by gates mounted external to the waveguide, that produce a positive or negative bias. Outer shell, loosely bound, electronic wave functions may be as extensive as 20nm in a solid of sufficiently high dielectric constant, so nearest neighbor C-A atom configurations must be within this range. Selective excitation is provided by a gate that sandwiches atom C used to Stark shift atom C into and out of resonance with the cw laser field in the waveguide, thus enabling $\pi$-excitation/deexcitation. The nuclear spin flips are controlled by microwave induced simultaneous electron-nuclear spin flips mediated by the transferred hyperfine interaction.

The elementary, time independent, spin Hamiltonian for this system is,

$$H = g\beta H_0 S_z + S.A.I. - g_n\beta_n H_0 I_z$$  \hspace{1cm} (7)

where $g$ and $g_n$ are the electron and nuclear gyromagnetic ratios. Here, we have omitted the weak transverse time dependent part of the Hamiltonian for simplicity. The first and third terms are the Zeeman terms for the electronic and nuclear spins, respectively, coupling to the constant magnetic field, $H_0$. The second term expresses the transferred hyperfine coupling between the electron spin $S$ of atom C and the nuclear spin $I$ of atom A. These are coupled via the superhyperfine tensor A, that for isotropic homogeneous interaction is diagonal in the representation where $S_z$ and $I_z$ are aligned with $H_0$, and is given in magnitude by (6). For simplicity we assume isotropy in what follows unless stated otherwise. To first order, and with the condition

$$g\beta >> A_x >> g_n\beta_n$$  \hspace{1cm} (8)

the eigen energies of (7) with associated quantum numbers, $m_s$ and $m_I$ for electron spin and nuclear spin in the representation in which the Zeeman terms are diagonal are given by,

$$E(m_s, m_I) = g\beta H_0 m_s + A_x m_s m_I$$  \hspace{1cm} (9)

Fig. 3. Zeeman and superhyperfine energy level splitting and microwave frequency transition for simultaneous electron-nuclear spin flips.
The corresponding Zeeman energy level diagram is shown in fig. 3. It is seen that simultaneous electron-nuclear spin flips can be induced by an applied microwave field of frequency $\omega$, according to the selection rule $\Delta m_F = 0$, where $F = S + I$ is the total spin angular momentum. Thus the $E_4 \rightarrow E_2$ transition, corresponding to simultaneous electron - nuclear spin flips, is allowed under the proper selection rules, $\Delta m_F = \pm 1, 0$, but the $E_3 \rightarrow E_1$ transition is forbidden. Explicitly, for an isotropic tensor $A$, i.e. diagonal in this representation, transitions are induced according to the second term in (7) by the operators $S^+ I^-$, consistent with the selection rule for simultaneous electron - nuclear spin transitions indicated in fig. 3. However, provided the symmetry is such that $A$ is not diagonal in this representation, or if there is an element of symmetry breaking, then the superhyperfine interaction described by the second term in (7) can contain contributions from mixed terms $S_x S_y, S_y S_x$ that can cause the transition $E_3 \rightarrow E_4$. Such conditions can, in principle, be regulated by local impurities or the natural local symmetry environment.

With these conditions, simultaneous electron - nuclear spin flips can be controlled by externally applied microwave pulses mediated by transferred hyperfine interactions. The interaction can be regulated, i.e. turned on - off, by laser pulse electronic excitation / deexcitation between the ground s - state of atom C (no electronic wave function overlap with the nuclear spin of atom A) and an electronic excited state of nonzero orbital angular momentum (strong overlap with the nucleus of atom A) as indicated in fig. 4. This introduces also the option of storing information in the nuclear spin system. Most important, however, is the single qubit selectivity facilitated by selective laser pulse excitation using the Stark shift gates discussed earlier. In the next Section we discuss some useful specific performance aspects of the model.

With reference to figs. 3-4 we identify the calculational basis,

$$|\downarrow\rangle_e \downarrow\rangle_n, |\uparrow\rangle_e \downarrow\rangle_n, |\downarrow\rangle_e \uparrow\rangle_n, |\uparrow\rangle_e \uparrow\rangle_n$$

(10)

where $|\rangle_e$ and $|\rangle_n$ represent electron, and nuclear spin states, respectively. The Zeeman split electron spin manifold depicted in fig. 3 can be driven by a microwave pulse of frequency $\omega$ into a coherent superposition described by a single spin rotation unitary transformation, $U(t)$,

$$U(t) |\downarrow\rangle_e \uparrow\rangle_n = \alpha(t) |\downarrow\rangle_e \uparrow\rangle_n + \beta |\uparrow\rangle_e \downarrow\rangle_n$$

(11)

where $|\alpha|^2 + |\beta|^2 = 1$. The operation (10a), together with

$$U(t) |\downarrow\rangle_e \downarrow\rangle_n = \alpha(t) |\downarrow\rangle_e \downarrow\rangle_n + \beta |\uparrow\rangle_e \downarrow\rangle_n$$

(12)
form a quantum controlled NOT-gate (C-NOT-gate). The target bit \( |n\rangle \) is flipped contingent upon the state of the control bit \( |e\rangle \). The externally applied coherent microwave pulse induced unitary transformation drives the electron-nuclear spin system ground and excited states into an entangled pair via the transferred hyperfine interaction, and the entanglement is manifestly nonlocal. Since two-bit gates are universal in quantum computing [19], the identification of the set of qubits and the calculational basis, together with the demonstrated C-NOT gate, (12), fulfills the requirement for universal quantum computation, i.e., any algorithm is executable in the system provided the system is scalable.

Worth noting here is that if the target state is initially \(|\uparrow\rangle_n\), then the unitary transformation is to the two-bit sub-manifold, \({|\downarrow\rangle_e |\uparrow\rangle_n, |\uparrow\rangle_e |\downarrow\rangle_n}\}, (11); whereas, given the target state \(|\downarrow\rangle_n\), the same transformation results in the transformation to the submanifold, \({|\downarrow\rangle_e |\downarrow\rangle_n, |\uparrow\rangle_e |\uparrow\rangle_n}\}. These alternatives are isomorphic to the oracle of the Deutsch-Jozsa Promise Algorithm [20], and the initial nuclear spin target state can be determined by application of that algorithm in a single unitary operation.

A different calculational basis can be identified, independently, with respect to the nuclear spins. Selective rf field induced nuclear spin flips can be induced by laser pulse controlled transferred hyperfine interaction. The selective transferred hyperfine interaction can be used to induce significant nuclear spin level shifts. This interesting alternative and option will not be pursued further here, but will be treated elsewhere. We feel that we have presented here the simplest approach to quantum computation with respect to this particular scheme.

So far, we have discussed results for selective coupling between an atom C, with respect to its electronic component, and a single atom A, with its nuclear component. Now we focus attention on electronic wave function mediated coupling of two adjacent nuclear spins, fig. 2. For this case, instead of (7) we have the Hamiltonian

\[
H = g\beta H_0 S_z + A_k S I_k + A_{k+1} S I_{k+1} - g_{nk}\beta H_0 I_z^{(k)} - g_{nk+1}\beta H_0 I_z^{(k+1)} \tag{13}
\]

and to first order and within the approximation (8), the associated energy levels are given by

\[
E(m_s, m_{I_k}, m_{I_{k+1}}) = g\beta H_0 m_s + A_s m_s (m_I + m_{I_{k+1}}) \tag{14}
\]

Here, \( k \) labels the location of atom \( A_k \), and \( m_{I_k} \), and \( m_{I_{k+1}} \) are the spin quantum numbers for nuclei of atoms \( A_k \) and \( A_{k+1} \) respectively. The corresponding energy level diagram and transitions are displayed in fig. 5. Fig.5 Zeeman and superhyperfine energy level splittings and microwave field induced transitions for electron spin mediated nuclear spin flips (see fig. 2). Here, the left-hand arrow corresponds to the nuclear spin of the kth atom of type A whereas the right-hand arrow corresponds to the nuclear spin of the \( k+1 \) atom of type A.

As an example, consider the \( \Delta m_I = -1 \) microwave excitation from the
ground initial state

\[ |\psi(t)\rangle = |\downarrow\rangle_e |\uparrow\uparrow\rangle_n \]  \hspace{1cm} (15)

to the state

\[ U_1(t) |\downarrow\rangle_e |\uparrow\uparrow\rangle_n = |\downarrow\rangle_e |\uparrow\downarrow + \downarrow\uparrow\rangle_n \]  \hspace{1cm} (16)

Corresponding to the transition \( E_6 \rightarrow E_2 \), fig.5. Here, the left arrow in \( |\rangle_n \) always refers to atom \( A_k \), and the right arrow refers to atom \( A_{k+1} \) nuclear spin. This is followed by the \( \Delta m_I = 0 \) microwave pulse deexcitation,

\[ U_1(t) |\uparrow\rangle_e |\uparrow\downarrow + \downarrow\uparrow\rangle_n = |\downarrow\rangle_e |\uparrow\downarrow + \downarrow\uparrow\rangle_n \]  \hspace{1cm} (17)

Corresponding to the transformation \( E_2 \rightarrow E_5 \). Subsequently, this is followed by laser pulse induced adiabatic electron spin-nuclear spin decoupling

\[ |\downarrow\rangle_e |\uparrow\downarrow + \downarrow\uparrow\rangle_n \rightarrow |\uparrow\downarrow + \downarrow\uparrow\rangle_n \]  \hspace{1cm} (18)

\[ A_s \rightarrow 0 \]  \hspace{1cm} (19)

thus storing entangled state information in the nuclear spin system,

\[ |\psi_f\rangle_n = |\uparrow\downarrow + \downarrow\uparrow\rangle_n \]  \hspace{1cm} (20)

Now, suppose the superhyperfine coupling is again induced adiabatically via laserpulse electronic excitation, except that the overlap is enhanced with respect to the left-hand atom \( A_n \), and at the same time suppressed with regard to the right hand atom, \( A_{n+1} \) by means of the outer gate elements, fig. 3. The electron spin of atom C is now coupled to the nuclear spin of atom \( A_n \) only. This is represented by

\[ |\uparrow\downarrow + \downarrow\uparrow\rangle_n \rightarrow |\downarrow\rangle_e |\uparrow\downarrow + \downarrow\uparrow\rangle_n \]  \hspace{1cm} (21)

\[ A_s \neq 0 \]  \hspace{1cm} (22)

Then, microwave excitation from the initial state (18) gives

\[ U_1(t) |\downarrow\rangle_e |\uparrow\downarrow + \downarrow\uparrow\rangle_n = |\uparrow\rangle_e |\uparrow\downarrow + \downarrow\uparrow\rangle_n \]  \hspace{1cm} (23)

Then, adiabatic laser pulse induced electron-spin, nuclear-spin decoupling yields the entangled nuclear spin state,

\[ |\psi_f\rangle_n = |\uparrow\downarrow + \downarrow\uparrow\rangle_n \]  \hspace{1cm} (24)

Thus, we have manipulated the system to induce two distinct entangled pairs of spin states, (20) and (24), and this information can be stored in the nuclear spin system. In a similar manner we can produce a uniform superposition of (20) and (24).
5 V. Universality

We are now in position to discuss the universality of our scheme in relation to the criteria of Section II.: i) We have identified a distinct set of qubits and a computational basis, (10), fig. 2; ii) The qubits are distinct, distributed, and individually addressable, fig. 3; iii) The coupling of electron and nuclear spins is via transferred hyperfine interaction, (5-6), fig. 3; iv) We have demonstrated a C-NOT gate, (11,12); v) The speed of operation is governed by the rate at which an externally applied microwave field can cause simultaneous electron-nuclear spin flips. This rate is limited by the strength of the transferred hyperfine interaction, as 10KHz - 100MHz. The nuclear spin flip relaxation times in Si:31P are measured to be within the 1-10 hour range at low temperatures [21], whereas the direct electron spin relaxation is found to be on the order of one hour. The electron spin resonance (ESR) line width for 106 Phosphorus ions / cm3 in Si was observed to be 1kHz using spin-echo techniques [22], much narrower than the ESR frequency on the order 10 GHz. Thus, Preskill’s criterion [23] is well satisfied for the configuration of our QC scheme; vi) We demonstrated selective single qubit addressability in Section IV. Initial state preparation can be established either globally by the usual techniques of electron-nuclear spin resonance, NMR, and ESR, or by selective single bit preparation using laser pulse selective electronic excitation and subsequent microwave pulse initial state preparation. There are a variety of combinations of techniques that can be used; however, the selective single qubit preparation is sufficient to guarantee arbitrary initial state preparation capability; vii) Input information can be imparted selectively to either the nuclear or electronic spin systems, or both, by microwave pulse excitation following selective laser pulse electronic excitation. Output information can be rendered efficiently via optical fluorescence from electronic excited states. Output information is therefore imparted to the excited state electronic spin system. The fluorescence yield conveys all information involving the electron-spin nuclear-spin system. The specifics of optical fluorescence and detection for this system will be the subject of another publication [24]; viii) Scalability was clearly identified in the previous Section, (15-24).

6 VI. Summary and Conclusions

We have demonstrated a scheme for quantum computing and shown that it satisfies the irreducible set of criteria for universality. Our scheme has definitive advantages over other schemes involving solid state systems, notably that of Kane [15], and Yablonovitch [25]. These schemes, each, involve electron charge transfer and readin / readout requiring single electron charge measurements. Our method is more robust, depending upon microwave pulse excitation control for reading and sensitive optical fluorescence and single photon detection for readout.
Fabrication technology requirements for the scheme proposed here is currently beyond the state-of-the-art, but this current impasse is expected to be alleviated within a few years due to the rapid progress in Nanoscience of materials and fabrication, especially in regard to silicone fabrication technology. Another concern involves the specific choice of atomic species to satisfy the conditions required for the qubit design. This requires simultaneous materials study and optimization analysis. The spectroscopy techniques required in this scheme provide a particular challenge. The NMR, ESR, and double resonance requirements correspond to well developed techniques; however, this combined with integrated laser pulse excitation adds a third component to constitute a triple resonance spectroscopy. This may lead to the cultivation of an interesting and useful spin-off as a novel method in spectroscopy.

It is felt that the proposed scheme combines several novel ideas to provide a realistic multi-purpose method of exploiting quantum parallelism, entanglement, and interference. We anticipate that the scheme and analysis expressed here can serve as a template for advancement toward realization of a practical universal quantum computer.

7 References

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