Journal of Magnetism and Magnetic Materials 453 (2018) 1–9

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Research articles

Quantum information generation, storage and transmission based on nuclear spins ☆

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ARTICLE INFO

Article history:
Received 7 April 2017
Received in revised form 5 October 2017
Accepted 20 December 2017
Available online 4 January 2018

Keywords:
Quantum information processing
Quantum communications
Zeeman effect
spin-Hamiltonian
EPR spectrum
Quantum ion-radical system

ABSTRACT

A new approach to quantum information generation, storage and transmission is proposed. It is shown that quantum information generation and storage using an ensemble of N electron spins encounter unresolvable implementation problems (at least at the present time). As an alternative implementation we discuss two promising radical systems, one with N equivalent nuclear spins and another with N nonequivalent nuclear spins. Detailed analysis shows that only the radical system containing N nonequivalent nuclei is perfectly matched for quantum information generation, storage and transmission. We develop a procedure based on pulsed electron paramagnetic resonance (EPR) and we apply it to the radical system with the set of nonequivalent nuclei. The resulting EPR spectrum contains 2^N transition lines, where N is the number of the atoms with the nuclear spin $\frac{1}{2}$, and each of these lines may be encoded with a determined qudit sequence. For encoding the EPR lines we propose to submit the radical system to two magnetic pulses in the direction perpendicular to the z axis of the reference frame. As a result, the radical system impulse response may be measured, stored and transmitted through the communications channel. Confirming our development, the *ab initio* analysis of the system with three anion radicals was done showing matching between the simulations and the theoretical predictions. The developed method may be easily adapted for quantum information generation, storage, processing and transmission in quantum computing and quantum communications applications.

1. Introduction

Quantum mechanics predicts many novel effects resulting from the Heisenberg particle dualism and superposition principles. The fusion of classical information theory and quantum mechanics had created the interdisciplinary quantum information field in recent decades. In quantum information the smallest information unit is a qubit, which is usually encoded in the quantum state of a physical system, and the transfer of the quantum state corresponds to transfer of quantum information.

The main idea of quantum computation was proposed by Gershenfeld and Chuang [6] and based on the electron spin quantization. Thus, an electron spin angular momentum is $s = \frac{1}{2}$, and the state of the electron is determined by two electron spin projections, $\alpha_e = |\frac{1}{2}, +\frac{1}{2}\rangle$ and $\beta_e = |\frac{1}{2}, -\frac{1}{2}\rangle$, on the z axis in the space-fixed reference frame. Unfortunately, in the isotropic space the electron spin states degenerate and, as a result, are undefined; however, in the presence of an external magnetic field with the intensity $B_{\parallel}$, which is applied along the z axis of the reference frame, the spin-polarized states are split by energy due to the Zeeman effect [25]. In this case both states are defined and a binary code can be assigned to each of them as for example $\alpha_e \to |1\rangle$ and $\beta_e \to |0\rangle$. Actually, the information is stored in the eigenvectors form; however, physically this information can be decoded only using the system response on external perturbation to detect the eigenvector with well determined eigenvalues. The measurement of corresponding eigenvalues gives us the information about eigenvector. Nevertheless, storage and transmission of these two states are still a big challenge.

There are many publications analyzing quantum information storage and transmission. In 1993, Bennett et al. [1] demonstrated that quantum state can be teleported. The quantum teleportation is a process of quantum information transmission from one location to another. The idea of a quantum state teleportation has further been developed in [4,21,27,12]. However, the electron spin-polarized state transmission and storage encounters a large

☆ Vladimir Makarov acknowledges the financial support received from PR NASA EPSCoR, NASA Cooperative Agreement NNX13AB22A. Authors also grateful to Dr. Igor Khmelinskii who greatly improved the manuscript.
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https://doi.org/10.1016/j.jmmm.2017.12.074
0304-8853/

inconvenience due to its fast depolarization. As was shown earlier [17,19,20,18], the lifetime of a spin-polarized state in solid materials is in the range of pico- to microseconds. Because extending the lifetime of a spin-polarized state is a quite a challenging problem, no solutions acceptable for practical applications yet exist. However, as an approach alternative to quantum information transmission, the counterfactual quantum-information transfer was proposed, without transmitting any physical particles. Using the Mach-Zehnder type interferometer, such method was tested in [5,13,14,22,7]. The counterfactual idea was further extensively studied theoretically and experimentally [24,30,31,16,2]. It is shown that information could be transported in a secure way between two remote participants without particles traveling through the quantum channel.

In this paper we developed and analyzed a new concept of quantum information generation, storage and transmission using the counterfactual transport idea. Applying pulsed electron paramagnetic resonance (EPR) to a radical system with N nonequivalent nuclear spins, we induce EPR spectral transitions [29]. As will be shown, the EPR spectrum of the radical system contains 2^N spectral lines with the same intensity and a unique qudit code may be assigned to each line. Further, all operations over qudits like storage, transmission and computation may be executed by operating on the spectral line frequencies instead of operating on the electron spins.

In Section 2 we discuss uncorrelated, weakly correlated and strongly correlated interactions of the electron spins within the ensemble of N electron spins. We show that using EPR for an ensemble of N electron spins the quantum information encoding encounters serious problems even in the more favorable case, when the ensemble of electrons is strongly correlated. In Section 3 we analyze the radical system spin-Hamiltonian, find the nuclear spin state energies and determine the basis state functions. In Section 4 we analyze two radical systems, namely one with N equivalent nuclei, and another with N nonequivalent nuclei. We show that the radical system containing N nonequivalent nuclei may be successfully used for generation, storage, encoding without unambiguity, and transmission of quantum information. Section 5 presents the proposed new approach to quantum information generation, storage and transmission. We present possible quantum radical system implementations and the *ab initio* analysis of the EPR spectra of $^{12}\mathbf{C}^{1}_{24}\mathbf{H}_{12}$ and $^{12}\mathbf{C}^{1}_{24}\mathbf{H}_{3}(\mathbf{C}(\mathbf{CH}_3)_3)_9$ cylindrical structures anion-radicals in Section 6. Section 7 shortly discusses some computing issues in the field of multi-valued logics. Finally, we resume our work in Conclusions.

2. The role of electron spins correlation

Theoretically, an ensemble of N electrons may generate up to 2^N binary digital words. However, depending on the electron spin interactions within the ensemble of N electrons, the total number of combinations may vary. We consider three different levels of mutual correlations between N electrons: (a) uncorrelated, (b) weakly correlated, and (c) strongly correlated [10].

In the case (a) the N spins are completely independent, i.e. for each value of the spin angular momentum the energy of the Zeeman splitting is the same and equals to $g\mu_B B_\parallel$, where g is the electron spin g-factor and μ_B is the Bohr magneton. The total energy of the spin-up state is $+\frac{N}{2} g\mu_B B_\parallel$ and the total energy of the spin-down state is $-\frac{N}{2} g\mu_B B_\parallel$. However, this system has only two states with different energies that can be physically identified, separated by the energy gap of $g\mu_B B_\parallel$. Any other state combinations are spectroscopically equivalent. Therefore, an ensemble of N uncorrelated spins cannot be used for quantum information generation.

In the case (b) spin states with different total spin angular momenta in zero magnetic field are split by weak exchange, V_{exch}, interaction, where $V_{exch} \ll \gamma$, and γ is the Zeeman state natural width. Hence, the spin states can be considered as degenerated or quasi-degenerated in zero magnetic field. In the presence of an external magnetic field, when the energy of Zeeman state splitting is much larger than V_{exch}, the Zeeman components with the same total spin projection on the magnetic field direction possess practically the same energy, i.e. all states $|S, M_S\rangle$ with different S and the same M_S are quasi-degenerated. As a result, the unambiguous encoding of spectral lines is impossible; therefore, systems with a weakly correlated ensemble of N electrons cannot be used for encoding quantum information.

In the case (c) the spin states with different total angular momenta S are split by an exchange interaction V_{exch} into states with different energy [9], where the exchange interaction for N unpaired electrons is defined as:

$$V_{exch} = -2 \sum_{i,j,i \neq j} J_{ij} (\hat{s}_i \cdot \hat{s}_j), \tag{1}$$

where J_{ij} is the exchange integral that involves interaction between ith and jth electrons [10].

When providing $V_{exch} \gg k_B T$, then the ground electronic state of system with N unpaired electrons, coupled by exchange interaction (1), will be split into a multiplet, where state with maximum multiplicity has minimum energy; it is because this state has the most correlated electron motion [15,10]. This lowest electronic state has maximum multiplicity and this state is mostly populated.

In the presence of an external magnetic field the state with the maximum spin angular momentum splits into $N+1$ Zeeman states (the total spin angular momentum of this state is $N/2$), where N is the number of electrons [29]. The maximum projection state may be found as [29,4]

$$|S = N/2; M_S = S\rangle = \prod_i^N \alpha_{ei}. \tag{2}$$

The other spin projection states, $M_S = -S, \ldots, +S$, may be obtained by successive application of the annihilation operator [9,10] on (2)

$$|S; M_S = S - n\rangle = \hat{S}_-^n \prod_i^N \alpha_{ei}, \tag{3}$$

where $\hat{S}_- = \sum_i^N \hat{s}_{-,i}$ and $\hat{s}_{-,i}$ is an annihilation operator for a single electron, and $n = 1, 2, \ldots, 2S+1$.

As an example, Fig. 1 shows the Zeeman states for 10 strongly correlated electrons. As follows from the selection rules for magnetic-dipole transitions between different Zeeman energy levels, $\Delta M_S = \pm 1$, [15], such transitions are only possible between

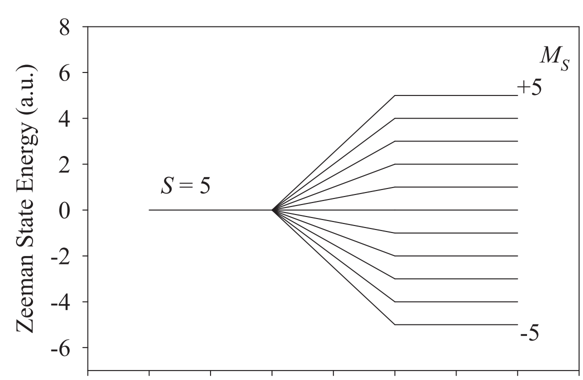

Fig. 1. The Zeeman state levels for the electronic ground state of ten strongly correlated electrons.