Quantum computation and spectroscopy of artificial spins

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Civilization has advanced as people discovered new ways of exploiting various physical resources such as materials, *forces* and *energies*. In the twentieth century *information* was added to the list when the invention of computers allowed complex information processing to be performed outside human brains. The history of computer technology has involved a sequence of changes from one type of physical realization to another — from gears to relays, from valves to transistors and then to integrated circuits, and so on. Today's advanced lithographic techniques can squeeze fraction of micron wide logic gates and wires onto the surface of silicon chips. Soon they will yield even smaller parts and inevitably reach a point where logic gates are so small that they are made out of only a handful of atoms. On the atomic scale matter obeys the rules of *quantum mechanics*, which are quite different from the classical rules that determine the properties of conventional logic gates. So if computers are to become smaller in the future, new, quantum technology must replace or supplement what we have now.

The point is, however, that quantum technology can offer much more than cramming more and more bits to silicon and multiplying the clock-speed of microprocessors. It can support entirely new kind of computation with qualitatively new algorithms based on quantum principles.

Let us have a closer look at a basic chunk of information namely *one bit*. From a physical point of view, a bit is a physical system which can be prepared in *one of the two* different states representing two logical values — no or yes, false or true, or simply 0 or 1. For example, in digital computers, the voltage between the plates in a capacitor represents a bit of information: a charged capacitor denotes bit value 1 and an uncharged capacitor bit value 0.

One bit of information can be also encoded using two different polarizations of light or two different electronic states of an atom. However, if we choose an atom as a physical bit then quantum mechanics tells us that apart from the two distinct electronic states the atom can be also prepared in a *coherent superposition* of the two states. This means that the atom is *both* in state 0 and state 1.

To illustrate the idea of a quantum object let us look at Fig. 1.

Let us try to reflect a single photon off a half-silvered mirror i.e. a mirror which

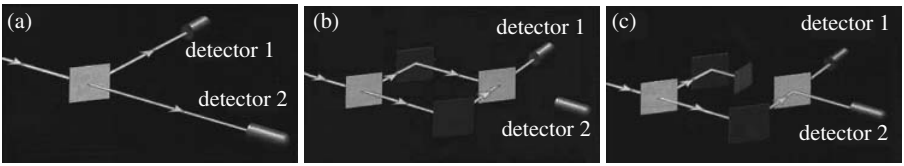

Figure 1. Generic setup to demonstrate quantum interference

reflects exactly half of the light which impinges upon it, while the remaining half is transmitted directly through it (panel A). It seems that it would be sensible to say that the photon is *either in the transmitted or in the reflected beam* with the same probability. That is one might expect the photon to take one of the two paths choosing randomly which way to go. Indeed, if we place two photodetectors behind the half-silvered mirror in direct lines of the two beams, the photon will be registered with the same probability either in the detector 1 or in the detector 2.

Does it really mean that after the half-silvered mirror the photon travels in either reflected or transmitted beam with the same probability 50%? No, it does not! In fact the photon takes "two paths at once". This can be demonstrated by recombining the two beams with the help of two fully silvered mirrors and placing another half-silvered mirror at their meeting point, with two photodectors in direct lines of the two beams (panel B). With this set up we can observe a truly amazing quantum interference phenomenon.

If it were merely the case that there were a 50% chance that the photon followed one path and a 50% chance that it followed the other, then we should find a 50% probability that one of the detectors registers the photon and a 50% probability that the other one does. However, that is not what happens. If the two possible paths are exactly equal in length, then it turns out that there is a 100% probability that the photon reaches the detector 1 and 0% probability that it reaches the other detector 2. Thus the photon is certain to strike the detector 1! It seems inescapable that the photon must, in some sense, have actually traveled both routes at once for if an absorbing screen is placed in the way of either of the two routes, then it becomes equally probable that detector 1 or 2 is reached (panel C). Blocking off one of the paths actually allows detector 2 to be reached; with both routes open, the photon somehow knows that it is not permitted to reach detector 2, so it must have actually felt out both routes. It is therefore perfectly legitimate to say that between the two half-silvered mirrors the photon took both the transmitted and the reflected paths or, using more technical language, we can say that the photon is in a *coherent superposition* of being in the transmitted beam and in the reflected beam. By the same token an atom can be prepared in a superposition of two different electronic states, and in general a quantum two

state system, called a *quantum bit* or a *qubit*, can be prepared in a superposition of its two logical states 0 and 1. Thus one qubit can encode at a given moment of time both 0 and 1. In this connection qubit behaves as an artificial spin 1/2 placed in an external tunable "magnetic field" and thus described by the Hamiltonian

$$\mathscr{H} = -\mathbf{B}(t) \cdot \mathbf{S} = -\frac{1}{2} B_x(t) \hat{\sigma}_x - \frac{1}{2} B_z(t) \hat{\sigma}_z \,, \tag{1}$$

where $\hat{\sigma}_i$ are Pauli matrices, while $\mathbf{B}$ is the generalized magnetic field. The qubit can be addressed by manipulating generalized fields B_x and B_z, and this is the way to implement quantum algorithms.

The story of quantum computation started as early as 1982, when the physicist Richard Feynman considered simulation of quantum-mechanical objects by other quantum systems [1]. However, the unusual power of quantum computation was not really anticipated until the 1985 when David Deutsch of the University of Oxford published a crucial theoretical paper [2] in which he described a universal quantum computer. After the Deutsch paper, the hunt was on for something interesting for quantum computers to do. At the time all that could be found were a few rather contrived mathematical problems and the whole issue of quantum computation seemed little more than an academic curiosity. It all changed rather suddenly in 1994 when Peter Shor from AT&T's Bell Laboratories in New Jersey devised the first quantum algorithm that, in principle, can perform efficient factorization [3].This became a "killer application" — something very useful that only a quantum computer could do. Difficulty of factorization underpins security of many common methods of encryption; for example, RSA — the most popular public key cryptosystem which is often used to protect electronic bank accounts gets its security from the difficulty of factoring large numbers. Potential use of quantum computation for code-breaking purposes has raised an obvious question — what about building a quantum computer.

In principle we know how to build a quantum computer; we can start with simple quantum logic gates and try to integrate them together into quantum circuits. A quantum logic gate, like a classical gate, is a very simple computing device that performs one elementary quantum operation, usually on two qubits, in a given period of time. Of course, quantum logic gates are different from their classical counterparts because they can create and perform operations on quantum superpositions. The gates can be described by two spins 1/2 with *controllable* interaction,

$$\mathscr{H} = -\frac{1}{2} \sum_{i=1,2} \mathbf{B}^{(i)} \cdot \hat{\sigma}^{(i)} + \sum_{i \neq j, \alpha, \beta} J^{ij}_{\alpha\beta} \hat{\sigma}^{(i)}_{\alpha} \hat{\sigma}^{(j)}_{\beta} \,, \tag{2}$$

where $\alpha, \beta = x, y, z$. However if we keep on putting quantum gates together into circuits we will quickly run into some serious practical problems. The more interacting qubits are involved the harder it tends to be to engineer the interaction that would display the quantum interference. Apart from the technical difficulties of working at single-atom and single-photon scales, one of the most important problems is that of preventing the *surrounding environment* from being affected by the interactions that generate quantum superpositions. The more components the more likely it is that quantum computation will spread outside the computational unit and will irreversibly dissipate useful information to the environment. This process is called *decoherence*. Thus the race is to engineer sub-microscopic systems in which qubits interact only with themselves but not not with the environment.

At present time there exist several ideas and model devices implementing quantum algorithms. Among them are atomic systems, photon devices based on sets of specifically designed cavities, etc. Very important role is played by solid-state implementations which allow scaling to large number of qubits. However, solid state devices relatively strongly interact with environment.

There are several ideas of solid state devices implementing quantum algorithms. They are based on orbital degrees of freedom in quantum dots, spins of electrons occupying impurity atoms, and devices based on macroscopic quantum tunneling.

In this talk, the devices belonging to the last group will be considered. Special emphasis will be maid on the devices combining Josephson effect in superconductors with Coulomb blockade effects specific for small electronic devices. After an introduction to the Josephson and Coulomb blockade effects and describing main ideas behind quantum devices we will focus on mechanisms of interaction with environment leading to decoherence. In this connection, after introduction of basic methods of spectroscopy of qubits (artificial spins), several recent experiments [4] on spectroscopic studies of various qubits will be discussed in connection with our theoretical models [5] developed in close collaboration with Princeton University and Argonne National Laboratory, USA, and NEC Research Institute, Japan.

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