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Single-Spin Devices and the Foundations of Quantum Mechanics

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Abstract:
It is well known that electron spin is quantized, and is measured to be either spin up or spin down in a magnetic field, as was first demonstrated in the classic Stern-Gerlach experiment almost 100 years ago. However, it is also believed that a quantum spin may be indeterminate until it is measured, being in a quantum superposition of the two quantum states. On the contrary, I propose (based on a locally realistic spin-quantized picture of quantum waves) that an electron quantum state is always either spin up or spin down, but is never in a superposition of the two. This concept should be directly testable using a two-stage Stern-Gerlach experiment, similar to that presented in standard quantum textbooks, but apparently never carried out experimentally. This experiment should be straightforward using modern atomic beam laboratory equipment. If successful, this could lead to a serious review of quantum foundations, as well as a new set of practical applications. In particular, a binary storage or logic element based on quantum spin should continue to work down to the atomic scale. This should enable computer memories with orders of magnitude greater density than those based on conventional magnetic memories.

I. What is Spin?

As generally understood in quantum mechanics, spin is an intrinsic parameter associated with fundamental point particles such as an electron or a photon. On the contrary, in the spin-quantized wave picture [1,2], a "particle" of mass m is a coherent localized domain in a real vector field rotating at angular frequency $\omega = mc^2/\hbar$, whereby the rotating field carries angular momentum, and the total angular momentum of an electron is quantized to $\hbar/2$. The fundamental relations $E = \hbar\omega$ and $\mathbf{p} = \hbar\mathbf{k}$ follow from spin quantization, which transforms a world of microscopic continuous fields into one of discrete particles. As shown in Fig. 1, the quantum phase is a real phase angle associated with the rotating vector field. The phase may be uniform in a particle at rest, but a phase gradient develops from the Lorentz transformation of this field for a moving particle, as required for a de Broglie wave.

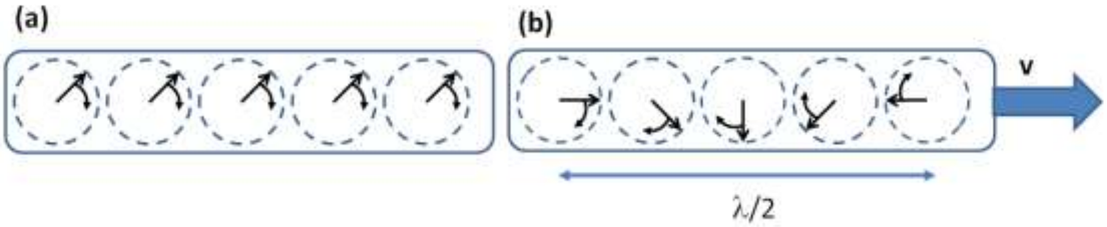

Fig. 1. Rotating coherent vector field constituting matter wave such as an electron, with distributed angular momentum and quantized spin. (a) Electron at rest, with fields rotating in phase at $\omega = mc^2/\hbar$. (b) Moving electron, with phase gradient corresponding to de Broglie wavelength.

Now consider an electron in a magnetic field **B**. The magnetic moment $\boldsymbol{\mu}$ of the charged electron will align either parallel or antiparallel with **B**. These two states differ in energy (and hence rotational frequency) by $\Delta E = 2\mu B$. A quantum change from one state to the other is accompanied by emission or absorption of a single photon with energy $2\mu B$ and spin $\pm\hbar$. One may have a two-electron state that consists of two electrons of opposite spins, but no other configurations are possible consistent with the Pauli principle. In particular, a single-electron state cannot be a superposition of two opposite spins, contrary to the orthodox theory.

What happens to an electron in the ground (parallel) state if **B** changes direction? The electron sees a time-varying electromagnetic field, but if the change is sufficiently slow, the electron spin axis will rotate to track the change in direction, remaining in the parallel ground state. In doing so, its total energy and frequency remain constant, while the torque needed to change the angular momentum comes from the source of **B**. This represents a consistent picture that makes sharply different predictions from orthodox quantum theory, as shown below.

II. Stern-Gerlach Experiments

In the original Stern-Gerlach (SG) experiment in 1922 [3,4,5], a beam of neutral univalent atoms (Ag) was directed into a non-uniform magnetic field. This performed magnetic separation on the atomic beam, with transverse motion in proportion to the magnetic moment of the atom (and hence that of the single valence electron). The beam was found to split into two discrete sub-beams, as opposed to the continuous distribution that would be expected from classical physics. This provided the earliest experimental evidence of quantization of spin. The SG experiment may be easily understood if one assumes that the atoms are in a *mixture* of spin-up and spin-down states, as shown in Fig. 2a. The gradient in magnetic field simply provides magnetic separation of these two populations. This explanation contrasts with the explanation in the orthodox quantum theory, in which the initial state of all the atoms is an undefined *linear superposition* of spin-up and spin-down states. The experiment constitutes a quantum measurement that forces a given electron into one or the other of these states, which are then separated in the gradient. This yields the same split beam result as the argument above.

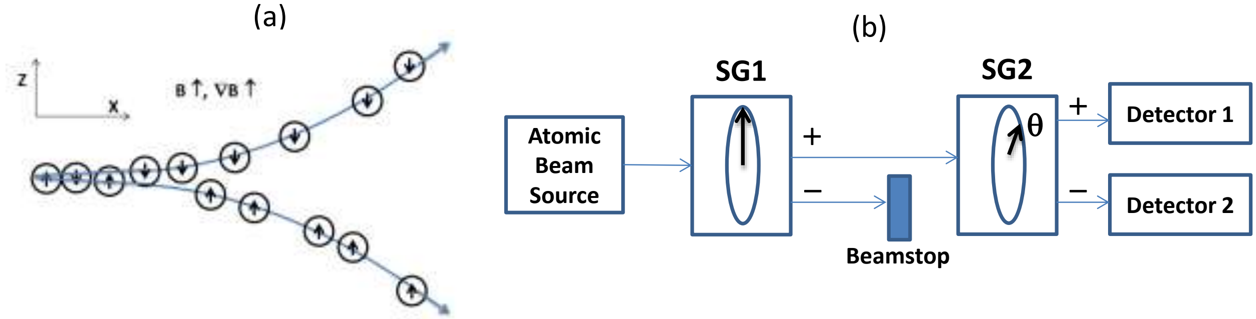

Fig. 2. Concepts of Stern-Gerlach experiments: One-Stage (a) and Two-Stage (b). A beam of spin-½ atoms move in the +x-direction in a magnetic field **B** *pointing in the +z-direction, with an additional field gradient* ∇B_z *in the +z-direction. In (b), the first stage polarizes an initially unpolarized atomic beam into an excited state (+) and a ground state (–), and the second stage rotates the magnetic field by an angle* θ*.*

However, these two approaches predict quite different results for the two-stage SG experiment shown in Fig. 2b. This two-stage SG experiment is a standard paradigm for quantum measurement, and is widely used in quantum mechanics texts (including the Feynman Lectures [4]), but this has apparently never been tested (as Feynman admitted). The second stage is the same as the first, but rotated by an angle θ. Because of fringe fields **B** remains nonzero outside the apparatus, and in the spin-quantized picture, the spins in the excited (+ state) will all rotate smoothly into the rotated excited state, yielding 100% in Detector 1 and 0% in Detector 2. In contrast, the orthodox quantum theory states that the excited-state spins will project onto a rotated spin basis in the 2nd polarizer, yielding $\cos^2\theta$ in Detector 1 and $\sin^2\theta$ in Detector 2. This latter prediction is so well established that there is an online Flash Demo that incorporates it [5]. This experiment should be straightforward to do using modern atomic-beam equipment [6], which would provide a definitive test of these two alternative approaches.

III. Application to Spin Memory Devices

All practical digital logic and memory device technologies are based on solid-state bistable elements, with each of the two states stable for an appropriate length of time. Consider a single spin in a static magnetic field ~1T. The energy-level splitting of ~0.1 meV corresponds to a temperature ~ 1K and a frequency ~ 30 GHz. For very low temperatures and large fields, thermal excitation due to phonons would be unlikely, as would spontaneous emission from the excited state, so that both states should be relatively long-lived. A single isolated spin might be located on an impurity atom near the surface of what is otherwise a spin-compensated crystal with no other electronic magnetic moments. It is well known that such spin states form very narrow resonant transitions, which form the basis for the phenomenon of electron spin resonance (ESR), also known as electron paramagnetic resonance (EPR). A properly shaped narrowband inversion pulse will cause the spin to be excited from the ground state to the excited state, or relax from the excited state down to the ground state via stimulated emission. These pulses are directly analogous to those in nuclear magnetic resonance (NMR), although the frequency for ESR is ~10^4 larger.

Consider, then, a single spin closely coupled to a nanocoil as in Fig. 3a. This coil could serve to transmit a resonant inversion signal to the spin, and could also send a weak resonant emission signal to a sensitive narrowband receiver. While the signal from a single spin is quite small, recent experiments have shown that it can be detected [7]. Such spins could be placed in a two-dimensional array as shown in Fig. 3b, where the distance between spins might be as small as 10 nm. This may be far enough apart to prevent coupling between spins, but would also permit an enormous memory density of 1 $Tbit/cm^2$. One can also envision a set of address and readout lines. For example, the static magnetic field could exhibit a gradient along the address lines, so that each column would have a unique resonant frequency, which could be read out using a sensitive narrowband receiver at the end of the column.

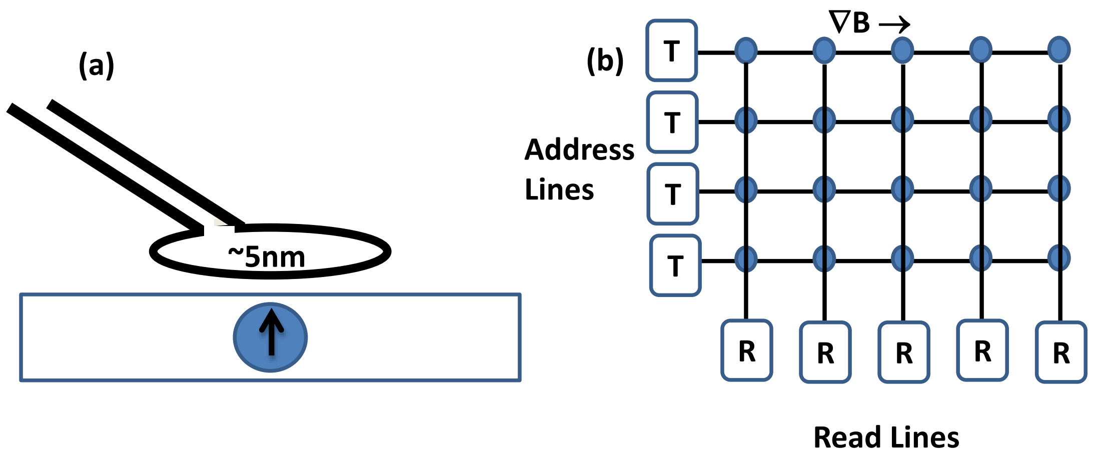

Fig. 3. Proposed spin-based memory cell and array. (a) Single spin near surface of crystal coupled to nanocoil. (b) Spin memory array in magnetic field gradient with horizontal address lines connected to transmitters T and vertical read lines connected to receivers R.

IV. Implications for Quantum Information Theory

The two-dimensional Hilbert-space model for electron spin provides the paradigm for quantum measurement and quantum information theory. This assumes a qubit with superposition of quantum states for a single spin, and quantum entanglement between N such superposition states. Indeed, it is the expansion of this Hilbert space by 2^N with N coupled qubits that forms the basis for the exponential parallel speedup promised by quantum computing. But if spins are real localized waves as envisioned by the spin-quantized wave picture, then such entanglement should not exist, and the entire foundation of quantum computing would become questionable. The proposed two-stage Stern-Gerlach experiment should provide a critical test for both theory and applications of quantum mechanics.

References

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About the Author

Dr. Alan M. Kadin (amkadin@alumni.princeteon.edu) has maintained an interest in the foundations of quantum theory for 40 years, since his undergraduate thesis at Princeton on hidden variables. He received his PhD in experimental physics from Harvard on superconductivity, and went on to a career in the science and technology of superconducting devices in academia and industry, including a position as Associate Professor of Electrical Engineering at the University of Rochester, and as Senior Scientist at Hypres, Inc. He is now an independent consultant based in Princeton Junction, NJ.