Evidence for Electron Spin Entanglement between Two Coupled Quantum Dots

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Nanotechnology offers much promise for developing new electronic devices that utilize the quantum properties of electrons or atoms for increased functionality. One powerful aspect of this field is the ability to create new quantum states that are in an entangled coherent superposition of two or more quantum objects that contain more information than the sum of the objects. We are attempting to use the spin of an electron to form a coherent multi-spin entangled state whose main feature is its non-locality. This type of non-locality has been shown for photons but not for electrons. Our experiment is modeled after the theoretical suggestion that a coupled quantum dot system together with a beam splitter can be used to demonstrate the entanglement of spin singlet states via a shot noise cross-correlation measurement. Two electron spins can be deterministically entangled by weakly coupling two nearby quantum dots (see Fig. 2). The resulting entangled state can be in either an S=0 singlet or S=1 triplet state. Measuring and cross-correlating the shot noise in each of the two output channels after a 50/50 beam splitter should provide evidence that the electrons have been entangled. Theoretically, entangled spin singlets will give a negative cross-spectrum of -4eIT(1-T), where T is the transmission probability through the beam splitter. All other incoherent correlations should give less than -0.5 eI. A large negative cross-spectrum is shown in Fig. 1 in the vicinity of a 50/50 beam split providing evidence for entangled electrons.

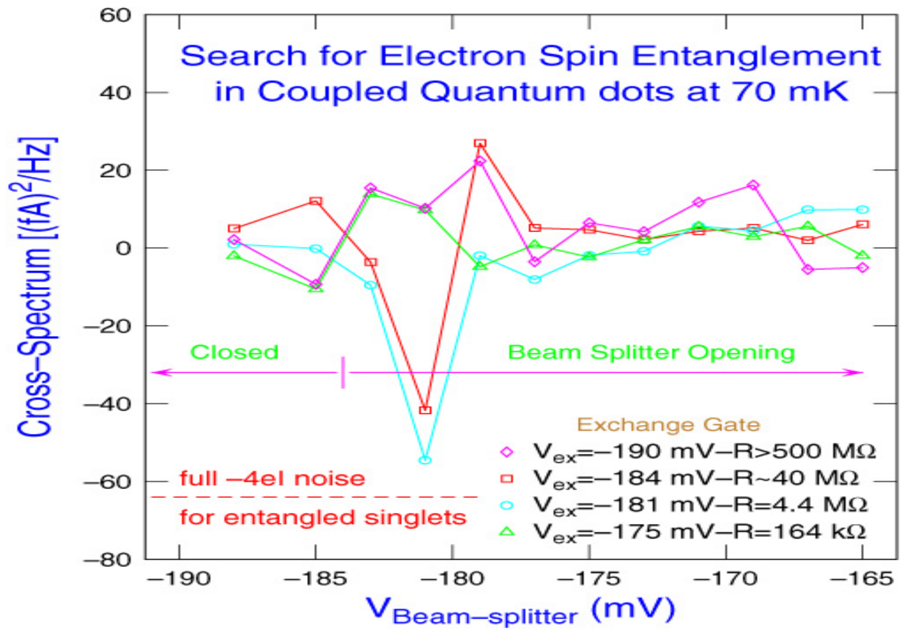

Fig 1. Cross correlation of the shot noise from two coupled quantum dots at zero applied magnetic field as a function of voltage on the beam splitter for 4 different barrier heights separating the dots. 100 pA of dc current is passing through each dot. A 50/50 beam split is achieved near –181 mV. As theoretically predicted, for very large or very small barrier heights (large or small exchange gate voltages) the cross spectrum should be zero at all beam splitter voltages. A negative cross-spectrum should appear in the vicinity of a 50/50 beam split if spin singlet electrons are entangled.

Electronic circuits function by controlling the flow of electrons from one location to another. These electrons have a mass and contain electrical charge and can be thought of as particles moving from one place to another. As we shrink the size of electrical circuits down to the nano-scale, under certain conditions these electrons behave as waves and can exhibit a wide variety of purely quantum phenomena normally not observable at much larger size scales. As an example, electron waves can exhibit interference patterns just as light waves do. The electron also has another non-classical property called spin that classically would arise from the circulation or rotation of charge, but just as the case of a proton, the electrons spin is a quantum property that can only be in one of two different quantum states; spin pointing up or spin pointing down. In addition, research over the last 13 years has shown that we can create regions called quantum dots in an electrical circuit that contain only a few electrons. The electrons in these quantum dots only can leave or enter the dot one at a time and the rate of entering or leaving can be controlled by a gate electrode in much the same way the gate on a conventional transistor works. By placing two quantum dots within 20-50 nanometers from one another, the spin of an electron in one quantum dot can interact with the spin of the electron in the second dot. Under certain conditions, these two separate quantum objects (the spin of each electron) can form a single new coherent quantum object similar to a two electron molecule even though the electrons are spatially separate. The lifetime of this new quantum state in most electrical circuits is very short and is controlled by interactions with the environment but it is generally believed to be in the range of 0.1 to 10 nanoseconds. We say that this new state is an entangled state because it retains information about both electron spins as well as the possibility of storing additional information. This entangled state can be one of zero net spin if a spin up electron in one dot is combined with a spin down electron in the other. This entangled state exhibits the strange quantum property of non-locality. For example, if we allow one of the two entangled electrons to exit the quantum dot and move far away from the second one, both of the original electrons remain in the entangled quantum state. This non-locality has been shown for two photons and they are frequently referred to as EPR (Einstein-Podolsky-Rosen) pairs but entanglement of this type has yet to be proven to exist for electrons in tiny electrical circuits. The most well accepted measurement for proving the existence of entangled electron spins is by a shot noise correlation technique. Shot noise arises from time dependent fluctuations of the magnitude of the current arriving at a detector. In a vacuum tube, for example, the shot noise represents the change in the current arriving at the cathode over a certain period of time and it's magnitude is 2eI per unit bandwidth where e is the charge of the electron and I is the average dc current in the circuit. In the coupled quantum dot circuit shown in Fig. 2, after entangling two electron spins we allow the two electrons to exit the quantum dot and give them a chance to interact again with a finite probability for interchange at the beam splitter. This interaction will force both electrons into one of the two exit channels. If we measure the noise correlation between the two cryogenic current detectors (one on each outgoing channel), we should observe a negative cross-spectrum correlation of magnitude –4eIT(1-T), where T is the probability of transmission through the beam splitter. The 4eI appears because we are dealing with 2 entangled electrons instead of an one electron transmission process. We control the probability T by adjusting the voltage on the gate below the opening marked BS in Fig. 2. T(1-T) is a maximum when T=½ and the negative cross spectrum signal should go to zero very fast as we change T. Shown in Fig. 1 is the measured cross spectrum as a function of the voltage on the beam splitter at 4 different coupling strengths between the two quantum dots. The very large negative dip at a beam splitter gate voltage of –181 mV occurs for two of the traces shown; very close to where we have independently determined that T~½. For the case of –190 mV exchange gate voltage where the barrier height is very high (weak coupling between dots), we do not expect any entanglement. For the opposite case of –175 mV exchange gate voltage where the electrons can easily tunnel back and forth between the two quantum dots we also cannot have entanglement because the electrons become indistinguishable. The two data traces at -181 and -184 mV exchange gate voltages seem to provide strong evidence that we have succeeded in entangling two electron spins. In the future we will need to entangle many electron spins and manipulate and readout the wealth of information that is potentially stored in the multi-spin entangled state. This is required for many quantum electronics applications but is absolutely essential for all quantum computer applications.

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Educational:

Graduate students: Samir Garzon, and Yuanzhen Chen.

These students receive training in areas such as e-beam and optical lithography, sample design, evaporation, sputtering, ion milling, sample characterization, cryogenics, and low noise measurements. All these skills are needed by the microelectronics industry.

Societal Impact:

One of the most important aspects of replacing conventional electronic devices with those fabricated at the nano-scale is that new quantum phenomena arise. Manipulation of electron spins is already providing the basis for new classes of electronic and magnetic devices and entangling electron spins offers the possibility of storing and manipulating much more complex information than modern day devices can achieve.

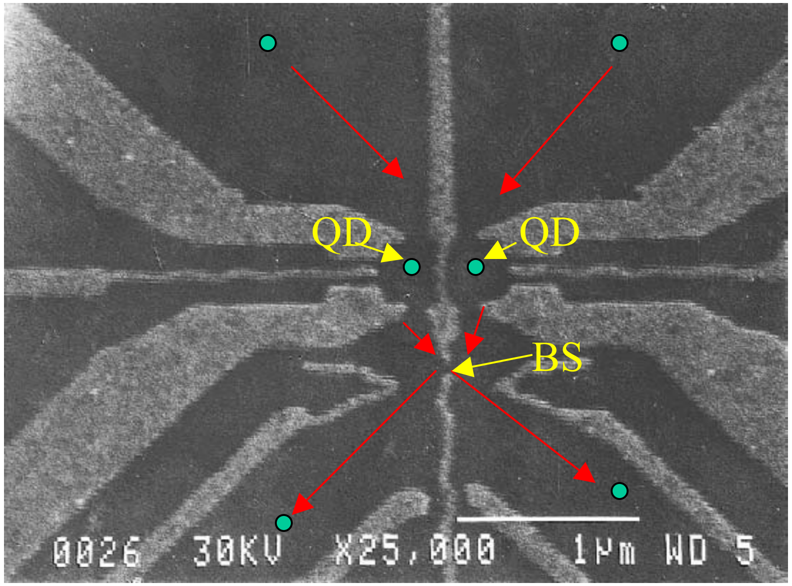

Fig. 2. Photograph of the coupled quantum dot sample used in the electron spin entanglement experiment. Electrons (green dots) enter from the top one at a time into each quantum dot (QD) where their spins can interact with one another, possibly forming an entangled spin singlet state (a two electron molecule that is spatially separate). The two entangled electrons are ejected from the quantum dots and allowed to interact at the 50/50 beam splitter (BS) and then exit the sample via the two lower channels. The cross correlation of the current noise in each channel is performed with the aid of low noise cryogenic amplifiers.