A FOCUS Research Sampler - 2004

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• Slides 24,25 Self-similar parabolic beam generation
A nugget from FOCUS:

Title: Bell Inequality Violation between Single Atom and Single Photon


We have measured correlations between the hyperfine state of a single trapped atomic ion and the polarization state of a single emitted photon, and have directly shown a violation of a Bell inequality\(^1\). This is the first measurement of a violation between different kinds of particles, and represents a strict characterization of quantum entanglement in the atom/photon system. While the entangled pair is generated probabilistically, it may seed the large-scale entanglement throughout a quantum network for applications in distributed quantum computing and quantum communication.

Bell Inequality Violation between Single Atom and Single Photon


Bell inequality test prerequisites:
- entanglement between two particles
- independent quantum control (rotations) of particles
- independent measurement of particles

\[ |\psi\rangle = |\downarrow\rangle |V\rangle + |\uparrow\rangle |H\rangle \]

**Experiment schematic**

**Measured Correlations**

\[
\left| C\left(0, \frac{\pi}{4}\right) - C\left(\frac{\pi}{2}, \frac{\pi}{4}\right) \right| - C\left(0, \frac{3\pi}{4}\right) - C\left(\frac{\pi}{2}, \frac{3\pi}{4}\right) = 2.203(28) > 2
\]

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The University of Michigan and the University of Texas at Austin
NSF Award 0114336
FOCUS is a collaborator in the Subpicosecond Pulse Source (SPPS) experiment at the Stanford Linear Accelerator Center (SLAC). SPPS is the world’s only accelerator-based source of femtosecond hard x-ray pulses. SPPS will continue to be the brightest source of laboratory x-rays until it is supplanted for construction of the first x-ray free-electron laser, the Linac Coherent Light Source (LCLS).

We use these pulses to study how matter moves on the fastest time scales, typically following intense laser excitation. In order to achieve the highest possible resolution it is imperative that the laser excitation and the x-ray pulses are exquisitely timed to each other. However, current technology does not permit a good enough level of synchronization. Therefore, it becomes necessary to measure the relative arrival time on each individual laser and x-ray pulses. The timing is performed by measuring the extremely large electric fields associated with the ultrarelativistic electron pulses in the accelerator, using a non-destructive technique known as electrooptic sampling (EOS), see figure below. These electron pulses then go on to produce the x-rays as they pass through a device made of permanent magnets, known as an undulator. Ideally the electron beam arrival time measurement corresponds to the x-ray arrival time. An independent direct (but destructive) measurement of the x-ray timing shows that the two measurements can be correlated to approximately 60 fs. These measurements will allow us to use the SPPS and later LCLS beams with significantly improved temporal resolution.
Femtosecond x-ray stopwatch

A. Cavalieri, D. Fritz, S. Lee, P. Bucksbaum, D. Reis and SPPS Collaboration

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A nugget from FOCUS:

**Sub-Doppler Cooling in a Raman Optical Lattice Geometry**

R. Zhang, N. V. Morrow, P. R. Berman, G. Raithel

The reduction of the basic periodicity of optical lattices is of significant interest due to potential applications of optical lattices in atom lithography. In this project, we create a 1D lattice on the $5S_{1/2} F=1 \rightarrow 5P_{3/2} F'=1$ transition of $^{87}$Rb using four lattice beams with different frequencies (Fig.1a and Fig.1b). The geometry of the lattice leads to a “standing-wave” Raman field that drives the transition between the two magnetic sublevels $m=1$ and $m=-1$. This leads to spatial modulation of the atomic density with period of $\lambda/4$, a reduction of factor of 2 from conventional optical lattices and Raman cooling schemes.

Though it is by no means obvious that the Raman Optical Lattice (ROL) supports any laser cooling, theoretical work shows the presence of a sub-Doppler cooling mechanism. An experimental demonstration of the cooling is achieved with the standard time-of-flight technique. In Fig.1c we present a comparison between the typical momentum distributions of atoms after molasses and ROL cooling stages. The typical molasses temperatures are around 50 mK, whereas the ROL temperature is 8 mK. We further characterize the cooling process and study the dependence of the temperatures on time, intensity, Raman detuning $\delta$, and the average atom-field detuning $\Delta$. The results for the latter are represented in Figs. 1d and 1e (experimental data and Quantum Monte Carlo Wave function simulations, respectively). Overall, we have shown that there is a robust sub-Doppler cooling present in the ROL, and we have identified the conditions for optimal cooling.
Sub-Doppler Cooling in a Raman Optical Lattice (ROL) Geometry

R. Zhang, N.V. Morrow, P.R. Berman, G. Raithel, University of Michigan

Lattice geometry

$5S_{1/2} F=1 \rightarrow 5P_{3/2} F'=1 \quad(^{87}\text{Rb})$

Comparison of momentum distributions for molasses and ROL

Temperature dependence on atom-field detuning $\Delta$

Periodicity of the lattice produced by these fields is $\lambda/4$ rather than $\lambda/2$, where $\lambda$ is the field’s wavelength

Results:

• Robust Sub-Doppler cooling found to be present
• Identification of conditions for optimal cooling

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A nugget from FOCUS:

**Relativistic attosecond optoelectronics**

Natalia Naumova, John Nees, Anatoly Maksimchuk, Victor Yanovsky, and Gerard Mourou

Particle-in-cell simulations indicate that attosecond electron bunches are efficiently generated when relativistic, strong and tightly focused p-polarized laser pulses interact with sharp boundaries of overdense plasmas. This effect is demonstrated in a simulation in which a 15 fs laser pulse with intensity 2x10^{20}W/cm^2 is incident obliquely at 70° on a plasma layer (see Figures). Under the action of the incident and reflected wave the electron concentration is abruptly peaked. A group of counterstreaming electrons is pushed away from the plasma through nulls in the electromagnetic field. These electrons inherit a peaked density distribution and form relativistic ultrashort bunches in vacuum. Escaping the target with relativistic velocities, electrons in their turn compress the reflected radiation, generating a train of attosecond electromagnetic pulses. The synchronism of attosecond electromagnetic pulses and attosecond electron bunches increases their applicability, opening the path to *relativistic attosecond optoelectronics*.


http://www.eecs.umich.edu/CUOS/attosecond

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NSF Award 0114336
Relativistic attosecond optoelectronics

Natalia Naumova, John Nees, Anatoly Maksimchuk, Victor Yanovsky, and Gerard Mourou, University of Michigan

Simulation results for 15fs laser pulses with intensity $2 \times 10^{20} \text{W/cm}^2$.

http://www.eecs.umich.edu/CUOS/attosecond

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NSF Award 0114336
A nugget from FOCUS:

**Title**: Scaling Ion Trap Quantum Computation through Fast Quantum Gates

**Investigators**: Luming Duan

We have proposed a method to achieve scalable quantum computation based on fast quantum gates using an array of trapped ions, without the requirement of ion shuttling. Conditional quantum gates are obtained for any neighboring ions through spin-dependent acceleration of the ions from periodic photon kicks. The gates are shown to be robust to influence of all the other ions in the array and insensitive to the ions' temperature.

Trapped ions constitute one of the most promising systems for implementation of quantum computation. Quantum gates have been demonstrated at the level of a few ions in this system. One of the central problems in this direction is to find methods to scale up this system for larger-scale quantum computation.

The proposed scaling method provides an attractive alternative to the conventional scaling method based on the ion shuttling, avoiding a series of challenges associated with the ion separation in a complicated structure and the near-ground-state ion cooling. The mutual strong influence between the ions from the long-range Coulomb interaction normally sets a significant obstacle to scalable quantum computation. However, we show that as long as the gate speed is faster than the local ion oscillation frequency, this unwanted influence can be arbitrarily reduced with a remarkable method for noise cancellation. Besides the proposal of an efficient scaling method, we also extend the previous fast gate scheme from two ions to a lattice of ions, and give a different design of the fast quantum gates with the use of periodic laser pulses only. Such periodic pulses are significantly easier for experimental realization. (We acknowledge helpful discussion with Chris Monroe on this work).
Scaling Ion Trap Quantum Computation through Fast Quantum Gates

Luming Duan, University of Michigan

Fast laser pulses induce state-dependent forces on each target ion in an ion crystal

State-dependent trajectory of the ion in phase space, which, combined with the Coulomb interaction, yields conditional quantum gates

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Thin film ferroelectric materials show promise as memory devices and transducers. A microscopic understanding of the role of coherent interfaces is currently lacking. We have imaged the interface structure of ultrathin PbTiO$_3$ films grown epitaxially on SrTiO$_3$ (001) using x-ray Coherent Bragg Rod Analysis (COBRA), which is sensitive to sub-Ångstrom displacements of the constituent atoms.

COBRA reveals several interesting and unexpected details of the interface structure, including a hitherto unobserved displacement of one of the oxygen sub-lattices on the substrate side of the interface. The results provide an atomistic basis for understanding the polarization of ferroelectric thin films [Physical Review B (in press)].
A Bose-Einstein Condensate in a Box
Todd Meyrath, Chih-Sung Chuu, Jay Hanssen, Gabriel Price, Florian Schreck, Mark Raizen
FOCUS Center, Center for Nonlinear Dynamics, and Department of Physics,
The University of Texas at Austin
We report experimental progress towards the quantum control of individual atoms from a Bose-Einstein condensate. Our system consists of a single one-dimensional BEC in $^{87}$Rb that is optically trapped in a crossed pair of Hermite-Gaussian TEM$_{01}$ mode beams. Each beam is tightly focused in one direction and elongated in the other, so that the overlap of the two beams creates a narrow dark tube. We measure the two transverse oscillation frequencies in the tube to be 16 and 50 KHz, comparable to what is reached with optical lattices, but with a single condensate instead of many identical replicas. Axial confinement in our trap is provided by Gaussian beam end-caps producing a "particle-in-a-box" type geometry. At the smallest measured numbers of 300 atoms, we observe fragmentation of the condensate and have determined that it is due to slight variations in the optical potential along the axial direction. We have successfully implemented an optical compensation scheme to flatten the axial potential. We have also demonstrated single atom detection with nearly unit quantum efficiency and this set-up is fully integrated with the new trap, paving the way for direct measurements of quantum atom statistics.
Bose Einstein Condensate in a Box

Mark G. Raizen, University of Texas

An “optical box” is used to trap a BEC

The inset shows a single-atom image on a camera

Absorption image of the 1-D condensate

Single atom detection in an avalanche photodiode showing quantized fluorescence

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A nugget from FOCUS:
Coherent Population Transfer of $^{85}$Rb Atoms into Rydberg States
Tara Cubel, Kevin Teo, Vladimir Malinovsky, Jeff Guest, Aaron Reinhard, Brenton Knuffman, Paul Berman, and Georg Raithel
Recently, quantum information processing methods have been proposed that involve the efficient transfer of atoms from ground states into high-lying Rydberg states. Stimulated Raman Adiabatic Passage (STIRAP) is a robust method for achieving this transfer. We have performed STIRAP on $^{85}$Rb atoms using two laser pulses resonant with the 5S->5P and the 5P->44D transitions. The data in figure (a) show that, as expected, the excitation probability is greatest when the upper transition (5P->44D) STIRAP pulse precedes the lower transition (5S->5P) STIRAP pulse. To determine the excitation efficiency, two identical STIRAP sequences have been applied to the same atoms. The second STIRAP sequence excites the atoms left over after the first STIRAP sequence. A detailed analysis of the signal reduction of the second sequence relative to the signal of the first sequence, shown in Figure (a), has shown that the excitation efficiency reaches a maximum of 70%. This is seen in Figure (b), where we show values of the Rydberg excitation efficiency vs. the central Rabi frequency of the upper transition, $\Phi_0/(2\pi)$, and position r. This work is the first quantitative demonstration of STIRAP into Rydberg states using narrow-bandwidth laser pulses. Using state-selective field ionization, we could identify a high sensitivity of the excited Rydberg atoms to population transfer into neighboring n-levels. These collisions occur within just a few hundred nanoseconds after excitation, and are thought to be responsible for disagreements between theory and experiment in the range $\Delta T>0$ of Figure (a).
Coherent Population Transfer of Atoms into Rydberg States

Tara Cubel, Kevin Teo, Vladimir Malinovsky, Jeff Guest, Aaron Reinhard, Brenton Knuffman, Paul Berman, and Georg Raithel, University of Michigan

Stimulated Raman Adiabatic Passage (STIRAP) is a robust method for efficient transfer of atoms from ground states into high-lying Rydberg states. We have quantitatively studied the excitation efficiency of such a scheme using cold Rb atoms. An influence of collisions on the excitation has been observed.

(a) Rydberg excitation vs STIRAP pulse delay for a pair of STIRAP sequences applied to the same atoms. The efficiency is greatest when the upper-transition (5P→44D) STIRAP pulse precedes the lower-transition one (5S→5P). The signal difference between 1st and 2nd sequence is used to calculate the absolute efficiency, which is found to be ~70%.

(b) Calculated efficiency of the Rydberg-state excitation vs. the central Rabi frequency of the upper transition, ω_b/(2π), and radial position r in the laser beam. The Rabi frequency of the lower transition is ~10MHz. The detailed calculations confirm that the excitation efficiency in our experiment is ~70%.

(c) Evidence of collisions. Within a few 100ns after STIRAP excitation, the atoms undergo state-changing collisions. This is seen is state-selective field ionization spectra. The collisions are thought to explain the experiment-theory disagreement in the range ΔT>0 seen in Fig (a).

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A nugget from FOCUS:

Title: Precision Atomic Lifetime Measurement with Fast Laser Pulses


We report precision measurements of the excited state lifetime of the 2P_{1/2} and 2P_{3/2} levels of a single trapped Cd+ ion. This method involves selective excitation of a single trapped ion to an excited state (lifetime of order nanoseconds) by a fast optical pulse derived from a mode-locked laser (length of order picoseconds). Arrival of the spontaneously-emitted photon from the ion is correlated in time with the excitation pulse, and the exponential distribution of time delays from many such events provides the excited state lifetime. By using this technique, we are able to eliminate prevalent systematic errors such as pulse pileup, radiation trapping, flight from view, sub/superradiance, non-selective excitation and/or detection, and potential effects from applied light during the measurement interval. The lifetimes are measured to be 3.262(6) nsec for the 2P_{1/2} state and 2.771(6) nsec for the 2P_{3/2} state. With uncertainties of less than 0.2%, these results are among the most precise measurements of atomic state lifetimes to date.
Precision Atomic Lifetime Measurement with Fast Laser Pulses


- Measure distribution of delay times between applied laser pulse and collected spontaneous emission
- Low systematic errors: precision of measurement better than 0.2%

\[ \tau = 3.262(6) \text{ nsec} \]

\[ 10^6 \text{ events} \text{ (~1 hour)} \]

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A nugget from FOCUS:

**Controlling atomic vibrations to isolate anharmonicity**
D. Fritz, E. Murray, J. Wahlstrand, S. Fahy and D. A. Reis

Researchers at FOCUS in collaboration with visiting scientist Stephen Fahy and his student Eamonn Murray from University College Cork are studying the effect of anharmonicity on extremely high amplitude vibrations (phonons) using the semimetal bismuth as a model system. When an ultrafast laser pulse interacts with the material exciting a large fraction of the valence electrons, the atoms suddenly find themselves far from equilibrium. This results in high amplitude coherent oscillations of the atoms about a new equilibrium position with a natural frequency dependent on the strength of the interatomic forces. At high enough amplitudes, we expect that the motion will become distorted (anharmonic) leading to an amplitude dependent frequency. Past experiments have been unable to unravel this effect from softening of the inter-atomic forces, which also affects the oscillation frequency.

In order to separate these effects, we use two laser pulses to excite the sample at different times. In analogy with pushing a child on a swing, if the second pulse comes at the right time, the vibration is enhanced. If the second pulse is purposely mistimed, the vibration is diminished. In this manner, we could study the effects of vibration amplitude on the frequency independent of all other dynamics of the system. The results were also compared with first principles theoretical calculations. In both instances, we show that weakening of the atomic bonds plays a much more important role than anharmonicity in the dynamics of the system. This is an important step in understanding the much more complex coupled dynamics of ultrafast laser excited materials.

Center for the Advancement of Frontiers in Optical Coherent and Ultrafast Science
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NSF Award 0114336
Controlling atomic vibrations to isolate anharmonicity

D. Fritz\textsuperscript{1}, E. Murray\textsuperscript{2}, J. Wahlstrand\textsuperscript{1}, S. Fahy\textsuperscript{1,2}, D. Reis\textsuperscript{1}

\textsuperscript{1}University of Michigan, \textsuperscript{2}University College Cork

Potential Energy vs. Carrier Concentration

optical probe of coherent motion: two pump pulses control amplitude at fixed $n(t)$

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The University of Michigan and the University of Texas at Austin
NSF Award 0114336
A nugget from FOCUS:

**Coherent Acoustic Phonons: Propagation Studies and Imaging Applications**

Theodore B. Norris and Brian C. Daly

We use ultrashort optical pulses to generate and detect coherent acoustic phonons (ultrasound with frequency > 100 GHz) in thin films grown on crystalline substrates. Our work with these phonon pulses has followed two paths over the past year: nanostructure acoustic imaging and studies of phonon propagation in silicon. Our experimental arrangement (Fig. 1a) allows detection of the coherent phonon pulses in the far field of the acoustic source. As a result, for the first time, the combined effects of acoustic diffraction, dispersion, and nonlinearity on these phonon pulses can be quantifiably measured. Results on a 0.5 mm sample of [111] oriented Si are shown in (Fig. 1b). We have also extended our capabilities with phonon pulses to include the imaging of lithographically defined patterns grown on the surface of a Si wafer. An acoustic image of 1 micron sized lines is shown in Fig. 2 along with a corresponding SEM of the same structure. The estimated resolution of the image is roughly 700 nm. Next year’s work will include efforts at improving the image resolution and imaging buried nanostructures.
Coherent Acoustic Phonons: Propagation Studies and Imaging Applications

Theodore B. Norris and Brian C. Daly, University of Michigan

Ultrashort pulses from a Ti:Sapphire laser are used to generate and detect coherent acoustic phonons.

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Second-Harmonic Generation (SHG) using spatially inhomogeneous fs pulses to probe light-emitting nano-interfaces of Silicon nanocrystals

M, Downer, FOCUS Center and Physics Department, University of Texas at Austin

Si nanocrystals emit light from unusual, poorly understood electronic states at their interfaces

Conventional single-beam SHG

New two-beam SHG: a robust, nano-interface-sensitive probe

TEM$_{00}$ mode of incident fs laser

experiment theory

TEM$_{01}$ mode of single-beam SHG generated at buried Si nano-interfaces: very weak, but it revealed the nonlocal dipole mechanism of nano-interface SHG, prompting authors to invent 2-beam SHG

Greatly enhanced SHG with 2 intersecting orthogonally-polarized fs pulses opens the door to noninvasive spectroscopy of buried nano-interfaces

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NSF Award 0114336
A nugget from FOCUS:

Title: Self-similar parabolic beam generation
Investigators Guoqing Chang, Herbert G. Winful, Almantas Galvanauskas, and Theodore B. Norris

The self-similar evolution of parabolic pulses in nonlinear dispersive amplifying media, e.g. in an Yb-doped fiber amplifier, has recently attracted much interest. To date, all the work on parabolic propagation has focused on temporal pulse evolution: the temporal evolution shaped by dispersion and nonlinearity. On the other hand it is well known that diffraction of paraxial optical beams is strongly analogous to dispersive propagation of quasi-monochromatic pulses in dielectric media. Given the space-time duality, a question that naturally arises is this: does there exist a self-similar spatial parabolic beam, i.e. a spatial analog to the temporal parabolic pulse? In contrast to the dispersion that is a 1-dimensional effect, diffraction of a beam can be either 1-dimensional or 2-dimensional. The propagation of a pulse in a fiber amplifier or a cw beam in a planar waveguide amplifier can be modeled by the identical (1+1)-dimensional amplified nonlinear Schrödinger equation (NSE) in form. By analogy to the temporal parabolic pulse solution, the (1+1)-dimensional parabolic beam exists and propagates self-similarly. However, the existence of self-similar propagation in (2+1) dimensions is a nontrivial question, given that spatial solitons are unstable in bulk media with nonsaturating nonlinearities. We solve the (1+1)-dimensional and (2+1)-dimensional NSEs using a method which illuminates the physical origin of self-similar propagation. Verified by numerical simulations, our asymptotic solutions predict the formation and propagation of self-similar parabolic beams. The specific roles of diffraction, SPM and gain during the propagation of the parabolic beam are identified. It is also shown that in the high-intensity limit, a parabolic beam can self-similarly propagate a certain distance even without gain. It should be noted that the parabolic beam generation and propagation rely on a sign match between diffraction and Kerr nonlinearity. Since diffraction is equivalent to anomalous dispersion, a negative nonlinearity is required. Potential materials or systems include semiconductors (such as ZnSe), Sodium vapor, electromagnetically induced transparency materials and polymers. An alternative to the real negative nonlinearity is an effective negative nonlinearity produced by cascaded quadratic processes. Properly combined with gain, the generation of a parabolic beam from such media may be anticipated. Parabolic beams may prove to be useful as well as interesting: for example, a parabolic profile falls much faster from the peak to the wings compared to a Gaussian or a hyperbolic-secant, which could be useful for applications like laser machining. By analogy to the similariton for a pulsed oscillator, it might be possible to build novel high power lasers with the help of the parabolic chirped beam amplification technique.
Self-similar parabolic beam generation

Guoqing Chang, Herbert G. Winful, Almantas Galvanauskas, and Theodore B. Norris, University of Michigan

Asymptotic solutions of the nonlinear Schrödinger equation (NSE) in (1+1) and (2+1) dimensions were obtained that predict the formation and propagation of self-similar parabolic beams.

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A nugget from FOCUS:

**Title:** Engineering an artificial atom for longer coherence times: Spin qubits for quantum computing

**Investigator:** Duncan Steel

Optical excitation of semiconductors leads to wave functions which are extended states of the crystal. Furthermore, these extended states dephase quickly and are characterized by a complex nonlinear optical response. However, as we have shown in our recent publication in *Science*, 3-dimensional confinement eliminates all of these problems. Three-dimensional confinement in a semiconductor leads to a quantum dot. In a neutral quantum dot, we have shown that a viable qubit for quantum computing is the pseudo-Bloch vector associated with the exciton transition. Unfortunately, the large oscillator strength of quantum dots also leads to fast (<100 psec) recombination and decoherence which limits the usefulness of these structures for quantum computing.

An alternative semiconductor quantum dot based qubit is a negatively charged quantum dot, similar to an ion such as Chris Monroe is studying. The qubit now becomes the spin of the electron in the quantum dot ground state. In this state, the only dephasing that can occur arises from processes that directly couple to the spin of the electron. In semiconductors, these interactions are believed to be weak. However, little is known about the behavior of optically created spin coherence in these systems. Optically, the singly charged quantum dot is very similar to the 3-level $\Lambda$-system in atoms. The neutral quantum dot behaves very similarly to the 3-level $V$-system. The quantum coherence between the two nearly degenerate ground states of the $\Lambda$-system is expected to be much longer than the coherence between the two nearly degenerate excited states of the $V$-system.

In this experiment, we have now reported the first observation of optically induced spin coherence in a quantum dot charged with a single electron. The first slide shows a comparison of the quantum oscillations of the two states for each system. The upper trace corresponds to quantum beats arising from the quantum coherence between the two spin states associated with the ground state of the $\Lambda$ system in the charged quantum dot. The lower trace shows the beats due to the quantum coherence between the two excited state of the $V$-system. Comparing the two traces clearly reveals the longer coherence time (reflected in the slower decay of the envelope of the quantum beats) associated with the charged quantum dot. The charged quantum dot measurements are done in an ensemble (the neutral dot data was obtained on a single dot). Hence, the measurement of the decoherence time is in reality decoherence rate due to inhomogeneous broadening arising from the spread in g-factors due to structurally heterogeneity. The magnetic field B=0 limit gives a decoherence time of 10 nsec. Much longer times are expected for large B in the absence of inhomogeneous broadening.
Adding a single electron to a quantum dot converts a V system to a Λ system creating a useable spin qubit for quantum computing.
A nugget from FOCUS:

Title: Coherent optical control of spin coherence
Investigator: Duncan Steel

Coherent control of quantum systems has importance to a number of fundamental and practical objectives including quantum computing. Indeed, sequential qubit operations for quantum computation are a direct manifestation of coherent control. Furthermore, a demonstration of coherent control of optically induced coherence serves to prove that the measurement of the quantum decoherence time is real and that the observed decay is of quantum coherence.

In this slide, we show a demonstration of coherent optical control of single electron spin coherence in quantum dots. The measurement utilizes two pump pulses that are carefully phase locked with respect to each other. Depending on the phase of the two pulses which are separated in time, the quantum coherences induced by each pulse are either in phase or out of phase with each other, resulting in constructive (upper dashed line) or destructive (lower dashed line) interference. In the case of the lower dashed line, the probe pulse shows the oscillations are completely suppressed, demonstrating complete destructive interference. The x-axis shows the time evolution of quantum phase of the total Raman coherence as function of the probe delay. The y-axis represents the phase difference between the two pump pulses (measured in psec). The strength of the signal is represented by the color.
Coherent Optical Control of Spin Coherence
Duncan Steel, University of Michigan

Pump pulses

\[ t = \tau_y + \tau_\phi \]

Probe pulse

\[ t = \tau_x \]

Raman coherence beats

Constructive interference of \( E_P \) and \( E_Y \) increases the Raman coherence

Destructive interference of \( E_P \) and \( E_Y \) destroys the Raman coherence

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