Quantum Control

This may serve as a complement to the one page "A Quantum Information Processing Initiative", submitted by Subhash Kak, Ken Schafer, and Ravi Rau.

Under the Information Technology program, it would be possible to build a very dynamic effort at LSU in the area of "Quantum Control". This could even be seen as a sixth major area to supplement the five already identified, under the rubric "Future or Emerging Technologies".

Over the last decade has emerged an area that is now being referred to as Quantum (or Coherent) Control. Various topics that have been developing in recent years in physics, chemistry, and computer science have been lumped together under this banner. These include the more familiar names of quantum computing and quantum cryptography, along with entangled states, teleportation, short-pulse laser control and atomic (or nanoscale) engineering. They are all characterized by our growing ability to manipulate matter at the single atom level with the aid in particular of carefully controlled and shaped laser pulses. In the recent words of one of the leaders in this field, Phil Bucksbaum (Ann Arbor): "… a new field of physical research devoted to manipulating quantum phenomena using the exquisite control we now have over laser fields. Quantum computing, slow light, atom lasers, and similar subjects belong in this new field of quantum control." (Nature 413, 117 (13 Sept 2001)).

In a way, this is basic quantum mechanics, the study of atoms, molecules and radiation, and their coupling to each other. As such, it is ideally suited to science and engineering departments at a university. Whereas this study goes back 75 years to the advent of quantum mechanics, until the last decade we were dealing with systems in large aggregates, inferring what happens at the single atom level. What is new now is that we can actually manipulate and study these phenomena directly at the level of single atoms and single photons. Besides contributing to a better understanding of quantum physics itself (a particular topic for instance is what is referred to as "Schroedinger cat" states), this ability now has applied interest because we can actually "engineer" atoms and their interactions. A few examples follow. But first some words about the possible impact.

Although it is difficult to say when or whether we will actually be able to build a quantum computer, there is little doubt of the profound impact of some of what is described below on future technologies. At the same time, this kind of research is one where an LSU can really compete while some other areas that are already heavily subscribed to by leading universities, and government or industrial laboratories may prove too expensive or uncompetitive for us to make a mark, even with an added 6-7 faculty in a group. As an illustration, among the leaders in quantum control are small groups in Austria, New Zealand and Brisbane (Australia). This illustrates the advantage offered by an emerging area for small groups with limited resources to make a major impact. Therefore, a new 6-7 faculty group, along with some already here at various LSU departments, can have a very visible presence and make a significant impact in the field of quantum control.

One area of coherent control is the study of chemical reactions as they happen and even "steer" them into specific pathways. Ahmed Zewail (CalTech) won the Chemistry Nobel Prize for his femtosecond-laser studies of chemical reactions. Since the time scale for a chemical reaction is in the range of femtoseconds, having short laser pulses of this order enabled him to do a "stroboscopic" study of a reaction as it happened. A "start" pulse that initiates and a "probe" pulse that interrogates the products a few femtoseconds later give a direct handle on a process such as A+B -> C+D, the very stuff of all chemical transformation. He and others have also been able to influence the reaction itself. For example, Richard Zare demonstrated selective breaking of the O-D bond as against O-H in the deuterated water molecule H-O-D, exploiting the slight difference in the associated vibrational frequencies and the ability to tune the laser to one rather than the other frequency. This is at the gross level of energies and intensities and there is no doubt of our ability to study and influence chemistry like this and use it practically in the future. But the next step of subtlety involves quantum phases. At its simplest, this is the basic two-slit arrangement of elementary quantum physics. When there are two (or more) alternative pathways, their individual contributed amplitudes can mutually interfere, the final outcome depending on this. Applied to a chemical process, this allows through control of those phases to determine which of various alternative end products are either favored or disfavored. This is coherent or quantum control, has been demonstrated in simple cases, and there is little doubt of much more extension and application in the future. Given the involvement with chemical processes, this area is likely to interest also Louisiana's chemical industry, which may be willing to invest in its own support of it.

The same theme of phases, and our ability to control them, is of course basic to the working of a quantum computer. The power of a quantum computer rests precisely on the large parameter space that these phases in the superposition state of each quantum bit ("qubit") allow us to explore. Immediately associated with this is the whole study of "decoherence", because these phases have to be protected from being disturbed by coupling to the external world during the time of a computation. Much effort is being devoted to this and again, whether or not a non-trivial quantum computer is ever built, there is no question that we will learn much of use to technology otherwise (as with the control of chemical reactions in the previous paragraph).

Among the systems being explored for the hardware of a quantum computer are nuclear magnetic resonance, trapped ions, and "cavity quantum electrodynamics" (specific highly-excited states of atoms coupled to high-Q electromagnetic cavities). In both the latter areas, there are excellent experiments that can be done, all again involving carefully controlled lasers.

Entangled states of two (or more) photons or atoms is another subject of great interest and potential. Such entangled two-photon states have been produced and interferometry demonstrated in them. Two such photons can be taken along two alternative paths each before being recorded and even when the phase differences are such that there is no interference pattern in either single-photon signal, the two-photon coincidence signal shows interference. Such studies are central to the subject of "quantum teleportation", wherein a quantum system can be projected to a spatially distant location without bodily transport. While this might remain a curiosity without practical application, there is no question that these studies help us understand quantum phenomena at a level of hitherto unprecedented detail, and that that understanding will have all kinds of practical implications as well. Entangled states are also central to quantum cryptography. Codes can both be made unbreakable and any eavesdropping detected because of its effects on the phases of the entangled superpositions. The subjects in this paragraph are often lumped together under the term quantum information.

A clear theme that emerges from even this simple sketch of the area of quantum control is the role that intense and short-pulse lasers play and their coupling to atoms or atomic beams. Laboratory research in this area will mean therefore a laser atomic-optical facility. Currently, there is little or no such activity at LSU. There is experimental work in physical chemistry in the study of molecules and their coupling to radiation (including the synchrotron photons of CAMD). Therefore, under the IT program, having 3-4 faculty in experimental laser work, along with a couple of new theorists to add to those already here in various departments (physics, chemistry, computer science, electrical engineering) could establish a very fine program with impact both on basic science and on emerging technologies that can benefit the state's economic development. It is also well recognized that there are excellent job opportunities for students who have been trained in modern optics.

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