Introduction to Mesoscopic Physics and Quantum Dots

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Preface and Motivation

"Anything we can do in classical physics, we can do better in quantum physics!"
Dan Kleppner, MIT

Quantum physics seems to be the supreme, overarching theory of the universe and is crucially relevant to atomic, nucelar and microscopic physics, chemistry, electronics, materials science, stars, black holes and the universe, to name just a few areas[1]. Yet, in our everyday lives, most of us are only aware of the classical physics that Newton founded centuries ago. In this sense, quantum physics appears to be very limited, applicable and relevant only at the atomic or microscopic level. At this microscopic scale, strange and unexpected phenomena can be explained and understood by quantum mechanics, but these effects disappear in the macroscopic world. This is a very limited and irrelevant scope for a theory that is supposed to be the profound and overarching theory of the universe.

Moreover, by some people, particularly in the semiconductor industry, quantum physics has been regarded as a nuisance or even road block that might hold back technological progress. Over the past few decades, the stunning miniaturization and integration of transistors and digital logic circuits has driven the information revolution that characterized the last half of the twentieth century. As transistors become smaller and smaller, the classical behavior that is exploited for the functionality of today's computers and electronics gadgets might be replaced by quantum physics, which—so it was and is thought by some—might slow down further technological progress, presenting a problem for industry, the economy and ultimately society.

Science over the last few centuries has been very successful at explaining and predicting our world as well as driving technological revolutions that deeply affect our societies. A few good examples are industrialization, the electronics revolution and the information age. Today, a century after the first discovery of quantum physics and fifty years after the invention of the digital computer, we are witnessing a scientific revolution that could put quantum theory into greater public prominence, while transforming our understanding of both physics as well as computer science. The realization is that physics and computation are closely related. Indeed, over the last decade, it has become clear that quantum physics can not only be harnessed to do computation, but can do it in a revolutionary new way that is not just simply better than classical physics but appears to be *unimaginably* more powerful.

"The nineteenth century was known as the machine age.
The twentieth century will go down in history as the information age.
I believe that the twenty first century will be the quantum age."
Paul Davies, 1999

[1] Large parts of this preface were taken from "*The Quest for the Quantum Computer*", by Julian Brown, Simon and Schuster, (2000), and the foreword thereof by David Deutsch.

This new way of doing computation, of course, is commonly referred to as *quantum computation* or *quantum information processing*. It is a relatively young field, maybe a couple of decades since it's original conception. Certainly, Feynman, Landauer, Deutsch, Bennett and Shor played important roles, among many others. It is only over the last several years that this movement has really gained momentum in the scientific community and even beyond. A tremendous amount of progress has been made recently, both on the theoretical side as well as experimentally. Still, many challanges lie ahead. Particularly the physical implementation of quantum computation has proven to be a very difficult problem to solve, both for fundamental as well as technological reasons. Among numerous proposed physical qubits, the candidates that (by public opinion) are currently thought to be the most promising include: electron spin, non-Abelian anyons and photon polarization (see http://www.iqi.caltech.edu/ for current poll results). The aim of this short course is to introduce the participants to recent experimental progress in coupled quantum dot spin-qubits in GaAs heterostructures, and, if time allows, give a very short introduction/overview of topologically protected computation, i.e. qubits in non-Abelian anyons.

This goal will (hopefully) be achieved in two steps: In a first part, written down in these notes here, I intend to introduce basic concepts from mesoscopic physics—mostly put together from already written textbooks—that are required to understand the recent experiments that we will discuss in the second part of the course by reading and discussing the original research papers.

One of the key concepts that will continue to be of central importance, throughout this course as well as in significant portions of current condensed matter research, is *quantum coherence*. In quantum computation, coherence is crucial because the loss of coherence is equivalent to the irreversible loss of quantum information and is therefore fundamentally detrimental. In fundamental quantum physics, the loss of quantum coherence—shorty termed decoherence—is what makes a quantum system behave as a classical, Newtonian system. Investigation of the physics controlling coherence is at the forefront of modern condensed matter physics.

Taking a step back from this, it is interesting to note that over the last few centuries, science had unparalleled success both at predicting the behavior of physical processes and at harnessing them to meet human needs. Yet, focusing only on the practical and technological aspects is a fairly efficient way to bring scientific discovery to a halt. The only effective engine of fundamental discovery is the desire to understand the world better, and therefore that must also be the primary objective of scientific research.

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