Syllabus, Texas Tech Fall Semester, 2023

PHYS-5300-19, Special Topics
Physical Sciences at the Nanometer-Scale, and Quantum Sensor Design

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Meets 8:00– 9:20 AM Tuesdays and Thursdays, Hybrid format On-line
ZOOM Meeting at:
https://texastech.zoom.us/j/99198276685?pwd=d0lycnBYcWpLTlRPV2M1UjVhVU9Ldz09&from=addon

Office Hours will be held on TR immediately following class, or by appointment.
In-person lab meetings will be held at the laboratories and locations listed by date in the detailed class plan below.

We will not use a textbook in this class, but rather we will study journal articles and other materials that are posted by date on the TTU Physics and Astronomy CEES Web page under the 'Instruction' tab page at: https://www.depts.ttu.edu/phas/cees/

There are no formal prerequisites for this course since we will cover all necessary background material in class. A prior understanding of undergraduate upper-division-level electromagnetism, quantum, and condensed matter physics will be very helpful in this class.

This course will consist of both lectures and hands-on laboratory exercises and demonstrations. In lecture, either in person or by hybrid online delivery, we will discuss the principles of physics and chemistry as a function of size, down to the sub-nanometer scale, which leads to a discussion of the nature of the onset of macroscopic quantum coherence phenomena in materials (for example, mesoscopic devices, quantum Hall effects, superconductors, superfluids, quantum-dot arrays, and Bose-Einstein Condensates (BEC), to list a few). Lectures will also provide an introduction to the laboratory exercises, and to methods that are needed to interpret the data, and to understand the quantum phenomena that are observed.

Laboratory safety is of paramount importance within this class, and in all subsequent laboratory work. Students are required to obtain the necessary online training from Texas Tech regarding laboratory safety before they are admitted to the laboratories. Specific laboratory hazards, and how they are mitigated, will be discussed in lecture before each laboratory module.

In the lab, students will learn to the basics of operation of various electron microscopes, and the Zeiss 540 Crossbeam Focused Ion Beam (FIB) system, which we will use to fabricate quantum dot arrays that we will subsequently study experimentally. Students will then learn the basic operations of the Quantum Design 'DynaCool' Physical Properties Measurement System (PPMS), which we will use to study physical properties of the quantum dot arrays which we will relate back to the underlying emergent quantum phenomena at the nanometer scale.

In addition to these ‘top - down’ approaches to engineering nanostructures, students will learn about ‘bottom – up’ self-assembly techniques to produce various nanoparticles and their associated structures.

Finally, students will learn about quantum sensing hands-on, by their operation of Superconducting Quantum Interference Devices (SQUIDs), and the applications of SQUIDs to low-frequency, ultra-precise magnetic flux measurements in a range of applications, and the use of ‘Shapiro steps’ in near-quantum-limited electromagnetic radiation detection. Finally, we will discuss the new sub-fields of quantum nucleonics nano-nuclear physics, which are pioneering new approaches to ultra-precise timing and navigation, and to new methods in nuclear energy conversion.

Objectives

Students in this course will develop an understanding of, and basic competency in the associated laboratory practice, in the following areas:

1) Physics and the associated properties of materials and the associated engineering principles, as a function of size and scale.
2) Multi-scale imaging, focused-ion beam fabrication, and quantum dot arrays
3) Magnetic properties of materials, and magnetic critical phenomena
4) Self-assembly and characterization of nanoparticles
5) Quantum coherence, superconductivity, Josephson Effects, superfluidity and BEC
6) Quantum sensing using SQUIDs and associated quantum phase-coherent circuits

Grading

Attendance at, and participation in, all class and laboratory activities are mandatory, and this counts for 50% of your grade. Each student will be asked to plan, structure, deliver, and summarize in notes a presentation to the class during the term, and the quality and effectiveness of this presentation will count for 25% or your grade. Numerous quizzes will be given throughout the term, to assure that the essential concepts of each sub-topic are well understood. These quiz grades will count towards 25% of the overall course grade. There will be no final exam.

Required and Recommended Syllabus Statements are provided by the TTU Provost’s Office, and they are linked below. They will be updated by the Provost’s Office as needed throughout this semester:

https://www.depts.ttu.edu/tlpdc/RequiredSyllabusStatements.php

- https://www.depts.ttu.edu/tlpdc/RecommendedSyllabusStatements.php

AI use encouraged

Daily Course Plan

Due to advanced laboratory equipment availability, maintenance, and outages, his detailed plan is subject to change with advanced notice to the class by email. The locations in the table below will be more precisely defined ahead of each class meeting. All class meetings are held from 8:00 – 9:20 AM on Tuesdays and Thursdays. Class attendance is mandatory.

Date	Location	Topic
8/24	ON-LINE	Introduction to the class, grading, laboratory safety (Duncan) High-level introduction to nanoscience and quantum sensing How are things different at the nanometer-scale? Bottom-up and top-down nanofabrication technology Introduction to assigned reading: Richard Feynman, “Plenty of Room at the Bottom” (1959) (Duncan)
8/29	ON-LINE	More on size dependence in physics (Duncan) Single-electron charging of quantum dots – setting the scale Intuition and quantum mechanics (Duncan)
8/31	ON-LINE	Introduction to the production of nanoparticles (Duncan, Adeosun) Safety in working with nanomaterials
9/05	ON-LINE	Techniques for producing nanoparticles in the lab (Duncan, Adeosun) Nanoparticle synthesis and experimentation
9/07	Reese B61 (carpool)	Follow-up on nanoparticle synthesis (Duncan, Adeosun) More on instrumentation: diagnostics & applications
9/12	Imaging Center (IC)	Imaging nanoparticles with TEM (Duncan, Lin, Zhao, Adeosun) Assign: Lawrie, *et al.*, “Quantum Dot Arrays in Si and Ge”
9/14	IC	Quantum dot arrays and applications (Duncan, Lin, Zhao) Quantum coherence in nanodot arrays Discuss: Lawrie, *et al.*, “Quantum Dot Arrays in Si and Ge”

9/19	IC	Introduction to the Zeiss Crossbeam 540 SEM and FIB Examples of sample preparation and fabrication Introduction to Hitachi 3400 (Duncan, Lin, Zhao)
9/21	IC	More SEM / FIB lab (Duncan, Lin, Zhao) Design and fabrication of nanodot arrays in Pt
9/26	IC	Continuation on nanodot array fabrication (Duncan, Lin, Zhao)
9/28	Physics 118	Wire bonding (Duncan, Eo, Lin Zhao) Continuation on nanodot array fabrication
10/3	ESB 153	Nuclear measurements – alpha, beta, gamma spectroscopy (Duncan, Lin) Nano-nuclear fuels & fission / fusion fragment (FFF) nuclear Rockets Nuclear Rocket data and analysis Nanoparticle nuclear energy Nuclear laboratory safety
10/5	ESB 153	Tritium assays / P&E Quantulus instrument (Duncan, Lin)
10/10	ON-LINE	Mossbauer effect and nuclear spectroscopy (Duncan) Introduction to Quantum Nucleonics Lattice magnon excitations to control nuclear quantum dynamics
10/12	ON-LINE	Physical properties of materials, theory and experiment (Duncan) Resistance, magneto-resistance, susceptibility, heat capacity, others
10/17	Science 118	Introduction to the Quantum Design PPMS (Eo, Duncan, Lin) Lock-in amplification
10/19	Science 118	Measurements of magnetoresistance, Hall conductance (Duncan, Eo, Lin) susceptibility, and other physical properties using the Quantum Designs PPMS
10/24	Science 118	Quantum Hall Effect Measurements (Eo, Duncan, Lin) 2D electrons and topological effects in quantum materials
10/26	Science 118	Custom measurements using the PPMS (Duncan, Eo, Lin) Measurements of the Pt quantum dot array using the PPMS Continuation of Pt quantum dot array measurements
10/31	Science 118	Magnetic susceptibility measurements with coils & SQUIDs (Duncan, Lin)
11/02	ON-LINE	Magnetic inductance and kinetic inductance (Duncan) Superconductivity: Macroscopic quantum coherence Measuring magnetic and thermal properties of superconductors
11/07	ON-LINE	Competition between superconductivity and magnetism (Duncan) High-Temperature superconductors and 'Mr. SQUID'
11/09	ESB 153	Quantum sensing using Josephson Junction technology Flux-locked loops (Duncan, Lin) Electromagnetic radiation detection Stewart – McCumber Model of Josephson Junctions Shapiro steps / SIS quasiparticle mixers
11/14	ESB 153	Continuation of the above (Duncan, Lin)

11/16	ON-LINE	Macroscopic quantum circuits containing SQUIDs (Duncan) Fundamental physics measurements using these techniques Ultra-precise temperature and power dissipation measurements
11/21	ON-LINE	Mean-field theory, exchange, and critical phenomena (Duncan) Superfluidity, SOC, Non-equilibrium superfluids Superfluid Helium Inertial Gyroscopes (SHIGs)
11/23	@Home	Thanksgiving Holiday, no classes
11/28	ESB 153	More SQUID-based quantum sensing (Duncan) SQUID-based proximity measurements and STEP
11/30	ESB 153	London moment, rotor precession, and Gravity Probe B (Duncan)
12/05	ESB 153	Class summary and future research opportunities (Duncan)