PHYS 451/566 Quantum Electronics: atoms, molecules, and their interactions

Course information:

Course title: Quantum electronics

Course catalog and # section: PHYS 451/566

Semester: Fall 2022

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Office hours: Monday and Wednesday, 10.00-11.30 am

Course description:
Atomic, molecular and optical (AMO) physics is the area of physics that deals with the intimate life of atoms and molecules, studying how those interact. As a result, it lies in the interplay between physics and chemistry, finding applications in astrophysics, gas dynamics, quantum information, condensed matter physics, and high energy physics, among others. This course is devoted to studying the fundamentals of AMO physics by exploring the basics of molecular and atomic interactions and their dynamics. In addition, different applications of AMO physics in emerging fields like quantum information and quantum simulations will be discussed. Here is the list of topics:

- Quantum angular momentum theory
- Selected topics in quantum mechanics
- Atomic and molecular spectroscopy
- Quantum scattering theory
- Ultracold quantum gases
- Rydberg atoms and molecules
- Cold and ultracold chemistry
- Quantum chaos

A more detailed index of the course is given below:

Chapter 1. **What is AMO physics?**

In this chapter, we will introduce the AMO physics discipline and discuss its relevance in other areas of physics and chemistry, such as condensed matter physics, high energy physics, fluid dynamics, plasma physics, quantum information sciences, and chemical physics. In addition, we will introduce the essential system of units in AMO physics: atomic units.

Chapter 2. **Quantum angular momentum theory**
This chapter will cover the basics of the quantum theory of angular momentum, covering topics such as the addition of angular momenta, Clebsch-Gordan coefficients, 6j and 9j symbols, the Wigner-Eckart theorem, and irreducible spherical tensor operators.

Chapter 3. **Selected topics in quantum mechanics**
In this chapter, we will introduce some essential aspects of quantum mechanics to understand the fundamentals of AMO physics like perturbation theory, degenerate perturbation theory, time-dependent perturbation theory, and the variational principle.

Chapter 4. **Atomic spectroscopy**
This chapter will cover the essentials of atomic physics: fine and hyperfine interactions, Zeeman effect, Stark Effect, and static and dynamic polarizability.

Chapter 5. **Molecular spectroscopy**
This chapter will study the Born-Oppenheimer approximation, central to all quantum chemistry calculations, vibrational and rotational spectroscopy of molecules, and the Dunham coefficients.

Chapter 6. **Quantum scattering theory**
In this chapter, we will discuss the concept of cross section in its classical and quantum formulations. First, we will introduce the concept of quantum elastic, inelastic, and reactive cross sections and reaction rates., followed by the Wigner threshold laws and the concept of scattering length. Finally, we study Feshbach and shape resonances and their appearance in atom-molecule and molecule-molecule scattering problems.

Chapter 7. **Ultracold gases**
This chapter introduces Bose-Einstein condensation (BEC) and its excitation spectrum based on Bogoliubov's theory. Then we will study the dynamics of BEC via the Gross-Pitaevski equation and the Thomas-Fermi approximation. Finally, we will discuss the emerging field of dipolar ultracold gases made of magnetic atoms or polar molecules.

Chapter 8. **Rydberg Physics**
This chapter covers essential topics on Rydberg atoms, such as Sommerfeld orbits, quantum defects, electron-neutral collisions, ultra-long-range Rydberg molecules (trilobites and butterflies), and decay of Rydberg atoms in high-density media.

Chapter 9. **Cold and ultracold chemistry**
This chapter introduces the field of cold and ultracold chemistry, covering the following topics: hybrid atom-ion systems, Capture models for charged-neutral collisions, three-body recombination, photo association reactions to form ultracold molecules out of ultracold atoms, and phtoassociation spectroscopy.

Chapter 10. **Quantum chaos**
This chapter is about the concept of quantum chaos and how it connects to AMO physics. In this chapter, we will discuss the concept of classical chaos. Next, we will move to the concept of quantum chaos and how it connects to random matrix theory. Finally, we will study the quantum kicked rotor and how it is experimentally implemented, which is one of the essential systems showing quantum chaos.

Recommended textbooks (optional):

It is preferable to use different textbooks to cover different aspects of the same topic. In this way, students have a chance to observe different points of view and pedagogical styles, of course with the goal in mind of further developing their intuition.

- V. K. Kersonskii, A. N. Moskalev, and D. A. Varshalovich, “Quantum theory of angular momentum” (World Scientific, 1988)
- P. F. Bernath, “Spectroscopy of atoms and molecules” (Oxford,1995)
- J. Pérez-Ríos, “An introduction to Cold and Ultracold Chemistry: Atoms, Molecules, Ions, and Rydberg” (Springer, 2020)
- C. J. Pethick and H. Smith, “Bose-Einstein condensation in dilute gases” (Cambridge, 2016)
- H.-J. Stöckman, “Quantum Chaos: An introduction” (Cambridge, 1999)
- L. D. Landau and E. M. Lifshitz “Quantum mechanics” (Butterworth-Heinemann, 2003)
- T. F. Gallagher “Rydberg atoms”(Cambridge,1994)

Teaching philosophy:

Science, generally speaking, is about finding answers to questions about nature. However, these answers only make sense if one communicates them, in other words, if one generates knowledge. Indeed, this knowledge is the fundamental pillar where any scientist builds the foundations of new theories and discovers new challenges. Therefore, communicating results and motivating questions is one of the most relevant duties of a scientist.

In my view, knowledge is not having a bunch of data in your memory but the capability of developing a physical intuition to face any problem independently of its nature and stay curious about the world around you. Finally, I would like to express that everything in science is about having fun. I mean, science is a way of enjoying the wonders that nature offers us.

Learning objectives and Assessments

The first goal of this course is to teach the student how to identify and characterize fundamental processes involving atoms and molecules. Second, the student will learn to calculate atoms' and molecules' spectroscopic, scattering, and chemical properties after recognizing a physical situation. In fact, students will experience how classical mechanics, classical electromagnetism, quantum mechanics and statistical mechanics find applications in real situations. Third, students will learn how to scientifically expose, share and present ideas. Last but not least, the students will be exposed to a large variety of systems in different scenarios bringing a general view of physics and its connection to other scientific disciplines like chemistry or computer sciences.

These goals will be achieved through homework problems to exercise some concepts and methods explained in the lectures. In this way, students can test their understanding of the topics and methods discussed in the lectures and come up with questions. In addition, some invited researchers (from SBU) will give short talks about their research to keep the students up to date with the current state of the art in AMO physics and to show them the research diversity at the department of physics and astronomy. Then, students will be asked to present a report discussing the topic of the talk and its link with AMO physics. Finally, groups of 3 students (although the number may depend on the number of attendees) will present a scientific paper jointly from a list I will make available on the first day of class. The presentation will be 30 minutes duration. In addition, a detailed report of the paper must be presented. This report should explain the whole paper with detailed information and the proper bibliography. However, more importantly, it must contain two sections: a perspective of the students on the topic of the paper and a second section about what students would do differently and why.

How to succeed in this course:

- Attend all the lectures
- Complete the homework on time
- Complete the reports on the talks of the invited speakers
- Complete the joint report and presentation of a scientific paper

Learning outcomes

After taking this course, students will be able to identify and characterize atomic and molecular processes and apply classical mechanics, classical electromagnetism, statistical mechanics, and quantum mechanics to different scenarios. As a result, students will develop an intuition about how the fundamental physics learned in previous courses find applications in the world of atoms and molecules. At the same time, a student completing the course will be up to date with the current state of the art in AMO physics.

Grading, attendance and late work policies

Assessment and grading:

There will be 5-7 homework assignments that must be completed during the course. The homework will count for 30% of the final grade for PHYS451 students and 10% for PHYS566 students.

The reports for the invited talks (around 4) will count as 20% of the final grade for PHYS451 and 30% for PHYS566 students.

The joint report of a scientific paper and presentation will count as 50% and 60% of the grade for PHYS451 and PHYS566, respectively.

The grades will be given numerically between 0 and 10, 0 being very bad and 10 excellent. Then the final grade will be computed as 0.3x homework + 0.2x invited talks + 0.5 x report scientific paper, and here is the final grading correspondence:

Final numerical grade	Final grade
9.5-10	A
8.5-9.5	A-
8-8.5	B+
7.5-8	B
7-7.5	B-
6.5-7	C+
6-6.5	C
5.5-6	C-
5-5.5	D+
4-5	D
< 4.5	F

University and course policies

Academic Integrity Statement:
Each student must pursue his or her academic goals honestly and be personally accountable for all submitted work. Representing another person's work as your own is always wrong. Any suspected instance of academic dishonesty will be reported to the Academic Judiciary. For more comprehensive information on academic integrity, including

categories of academic dishonesty, please refer to the academic judiciary website at http://www.stonybrook.edu/uaa/academicjudiciary/

Electronic communication
Email to your University email account is an important way of communicating with you for this course. For most students the email address is firstname.lastname@stonybrook.edu, and the account can be accessed here: http://www.stonybrook.edu/mycloud. It is your responsibility to read your email received at this account.

Religious observances
See the policy statement regarding religious holidays at https://www.stonybrook.edu/commcms/provost/faculty/handbook/employment/religious_holidays_policy. Students are expected to notify the course professors by email of their intention to take time out for religious observance. This should be done as soon as possible but definitely before the end of the 'add/drop' period. At that time they can discuss with the instructor(s) how they will be able to make up the work covered.

Disabilities
If you have a physical, psychiatric/emotional, medical or learning disability that may impact on your ability to carry out assigned course work, you should contact the staff in the Disability Support Services office [DSS], 632-6748/9. DSS will review your concerns and determine, with you, what accommodations are necessary and appropriate. All information and documentation of disability is confidential. Students who require assistance during emergency evacuation are encouraged to discuss their needs with their professors and Disability Support Services. For procedures and information go to the website http://www.sunysb.edu/ehs/fire/disabilities.shtml

Critical incident management
Stony Brook University expects students to respect the rights, privileges, and property of other people. Faculty are required to report to the University Police and the Office of University Community Standards any serious disruptive behavior that interrupts teaching, compromises the safety of the learning environment, and/or inhibits students' ability to learn. See more here: https://www.stonybrook.edu/commcms/studentaffairs/sccs/policies/disruption

Student resources

Amazon @ Stony Brook: Order your books before classes begin. Phone: 631-632-9828; email: Bookstore_Liaison@stonybrook.edu; website: http://www.stonybrook.edu/bookstore/

Bursar: For help with billing and payment. Phone: 631-632-9316; email: bursar@stonybrook.edu; website: http://www.stonybrook.edu/bursar/

Career Center: The Career Center's mission is to support the academic mission of Stony Brook University by educating students about the career decision-making process, helping them plan and attain their career goals, and assisting with their smooth transition to the workplace or further education. Phone: 631-632-6810; email: sbucareercenter@stonybrook.edu; website: http://www.stonybrook.edu/career-center/

Counseling and Psychological Services: CAPS staff are available by phone, day or night here.

Ombuds Office: The Stony Brook University Ombuds Office provides an alternative channel for confidential, impartial, independent and informal dispute resolution services for the entire University community. We provide a safe place to voice your concerns and explore options for productive conflict management and resolution. The Ombuds Office is a source of confidential advice and information about University policies and procedures and helps individuals and groups address university-related conflicts and concerns. http://www.stonybrook.edu/ombuds/

Registrar: Having a registration issue? Let them know. Phone: 631-632-6175; email: registrar_office@stonybrook.edu; http://www.stonybrook.edu/registrar/

SBU Libraries: access to and help in using databases, ebooks, and other sources for your research.
• Research Guides and Tutorials: http://guides.library.stonybrook.edu/
• Getting Help: https://library.stonybrook.edu/research/ask-a-librarian/

Student Accessibility Support Center: Students in need of special accommodations should contact SASC. Phone: 631-632-6748; email: sasc@stonybrook.edu; https://www.stonybrook.edu/sasc/

Writing Center: Students are able to schedule face-to-face and online appointments. https://www.stonybrook.edu/writingcenter/