Introduction to Atomic Physics

Lecturers:
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Emilia Witkowska, ewitk@ifpan.edu.pl

Organisational meeting: October 4, 2024
First lecture: October 25th, 2024

Place and time: Room D, Fridays, 10:00 - 11:30

Materials:
www.theory.ifpan.edu.pl?class=24/1/atomphy/ewitk

List of lectures

Mini projects consultation 1: Oct 10, 2024 (Thursday!) with Krzysztof Pawłowski

Mini projects consultation 2: Oct 15, 2024 (Tuesday!) with Emilia Witkowska

LECTURE 1: October 25, Krzysztof Pawłowski
The concept and history of an atom, Bohr's model, fine and hyperfine structure

LECTURE 2: November 8, Krzysztof Pawłowski
Energy quantization, quantization of orbital angular momentum and its algebra
<u>Mini-project 1:</u> Hydrogen atom spectrum a'la Schrodinger, Pauli and Heisenberg

LECTURE 3: November 15, Emilia Witkowska
Deeper into the energy structure of the atom, spin-orbit coupling, lamba shift, multielectron atoms, energy shells, relation to the periodic system of elements.

LECTURE 4: November 22, Emilia Witkowska
Connection of exotic atoms, antimatter and experiment in CERN
<u>Mini project 2:</u> exotic atoms

LECTURE 5: November 29 EMILIA,
Atoms in magnetic and electric fields: classical and quantum description, Zeeman and Stark effects

List of lectures

LECTURE 6: December 6, Emilia Witkowska
Atoms in an electromagnetic field, two-level atoms, Rabi oscillations and NMR
Mini project 3: NMR and MRI

LECTURE 7: December 13, Krzysztof Pawłowski
Spontaneous and stimulated emission, Einstein coefficients, selection rules
Mini project 4: Astrophysics & Doppler effect

LECTURE 8: January 10, Emilia Witkowska
Modern developments in atomic physics: optical cooling and trapping of atoms

LECTURE 9: January 17, Krzysztof Pawłowski
New trends in quantum optics: Metrology (frequency comb, atomic clocks),
Mini project 5: Atomic clock

LECTURE 10: January 24, Emilia Witkowska
Atomic quantum computer
Mini project 6: quantum computer and computations

LECTURE 11: January 31, Krzysztof Pawłowski
Interaction between atoms - scatterings, bound states and molecules.
Mini project 7: Van der Waals interaction

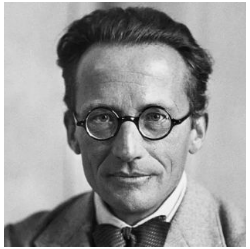
LECTURE 12: February 21, exam

Mini-projects

1. Mini-projects
   Team (1-3 persons) shall solve problems in mini-project, deepen their knowledge in the subject related to the project, prepare presentation and propose 3 questions and 1 problem.

2. Mini-projects aims to become more familiar with the subjects discussed during lectures, strengthen analytical skills, independent information search and ability to present scientific results

Mini-project 1: spectrum of hydrogen atoms

Tips & tricks – clever derivations of hydrogen spectrum

The foundations of quantum mechanics were introduced independently by many scientists. In particular, Erwin Schrödinger (waves), Wolfgang Pauli (closer to group theory), and Werner Heisenberg (operator algebra).

In this project, one must learn mathematical tricks and derive the spectrum of the hydrogen atom using three different methods.

a) Solving differential equation (standard)

b) Using "ladder" operators – clever analogy to harmonic oscillator

c) Using symmetries and analogy to the angular momentum operator.

It is remarkable that such different descriptions lead to the same result!!

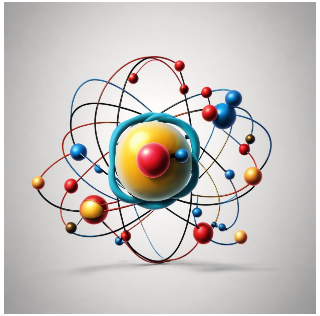
Mini-project 2: exotic atoms

This task aims to become familiar with exotic atoms. Most of them are hydrogen-like systems, composed, like the hydrogen atom, of two oppositely charged particles (of exotic or anti-matter nature), electrostatically attracted to each other.

(a) Start by searching the literature for examples of exotic atoms. Discuss the literature.

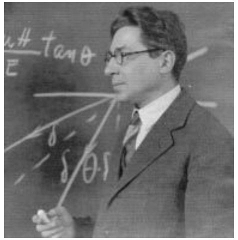
(b) Prepare a list of known exotic atoms. Compare them, e.g. their lifetimes or conditions of their observations.

(c) Improve the analytical skills by calculating various characteristics for positronium, muonium and hydrogen atoms

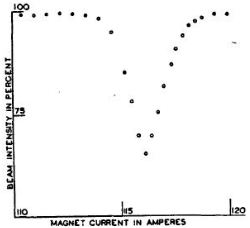


Mini-project 3: NMR

Nuclear magnetic resonance (NMR) is a physical phenomenon in which nuclei in a strong constant magnetic field are disturbed by a weak oscillating magnetic field (in the near field) and respond by producing an electromagnetic signal with a frequency characteristic of the magnetic field at the nucleus. This interaction happens near resonance, when the oscillation frequency matches the intrinsic frequency of the nuclei, which depends on the strength of the static magnetic field, the chemical environment, and the magnetic properties of the isotope involved.



While the concept and mathematical description of NMR will be introduced during the lecture, the task aims to present and discuss NMR applications in various scientific disciplines.

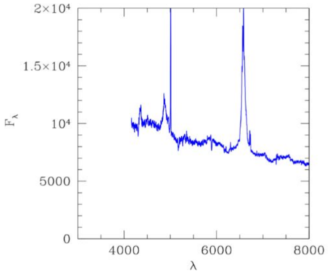


(a) Start by searching literature with a description of the resonance effect, recall the first experiments by Rabi in 1939, next Bloch and Purcel in 1945,

(b) List as many applications of NMR as possible

(c) Choose three applications and describe them in more detail

Mini-project 4: Star or galaxy – signals from cosmic space



A long time ago in a galaxy far far away ...

As early as in 1766, Cavendish discovered the hydrogen atom. In 1855 Andres Angstrom characterised part of its spectrum. Soon after, it turned out, that the same lines are in the light of the Sun. This indicates, that hydrogen is in the Sun.

Thanks to quantum mechanics, we can compute the spectra of different elements at different conditions, and use this knowledge to study the compositions of astronomical objects, their temperatures even their motion.

In this project, you will analyze the spectrum of a certain astronomical object, currently being studied by scientists at the Center for Theoretical Physics of the Polish Academy of Sciences.

Analysis of current observational data from cosmic space

Mini-project 5: atomic clock & quantum metrology

Atomic Clock

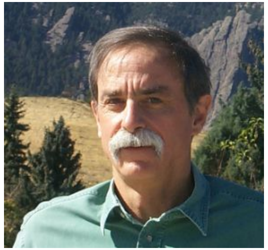
The history of improvements in time measurements is the history of scientific discoveries. Already in the XVII century, Ole Rømer by comparing the results of a pendulum clock and an astronomical clock (i) deduced the finite speed of light (ii) discovered thermal expansion (iii) introduced the new scale of temperature, known as the Rømer scale. Now atomic clocks are the most precise measuring device next to the gravitational wave detectors.

Learn how atomic clocks work, how entanglement can help to improve them and what are their applications!

a) Learn how we maintain the global time on Earth.

b) Learn how the Ramsey interferometry works and how precise it is

c) How the Schrödinger cat might be used to improve precision?



Mini-project 6:quantum computer and computations

The mini-project aims to become familiar with quantum computers and computations. Start by searching literature for example platforms for quantum computing implementation at work. Find as many as possible, prepare a list of them and discuss the one made of atoms in more detail.

Getting to Know Some Quantum Gates

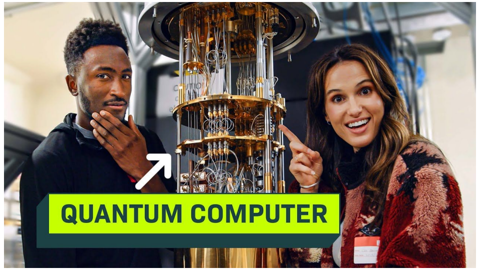
One of the most common ways of thinking about quantum computation is in terms of quantum circuits: An overall quantum computation is decomposed into smaller building blocks, typically referred to as gates. This task aims to familiarize oneself with some important gates and decompose an overall unitary operation into gates.

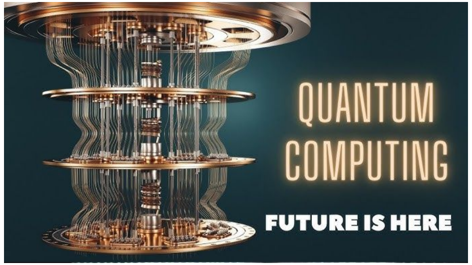
(a) Recall what is the classical NOT gate. Write down the (unitary) matrix for the single-qubit gate that implements an analogue of the classical NOT. That is, the gate should act as $|0\rangle \to |1\rangle$, $|1\rangle \to |0\rangle$.

(b) Write down the (unitary) matrix for the two-qubit controlled-NOT (CNOT) gate, which implements a computational basis flip on the second qubit controlled on the first qubit being active. That is, the gate should act as $|00\rangle \to |00\rangle$, $|10\rangle \to |11\rangle$, $|11\rangle \to |10\rangle$.

(c) Recall the Hadamard gate H. Describe a quantum circuit with two gates that, starting from $|00\rangle$, prepares the maximally entangled state $(|00\rangle + |11\rangle)/\sqrt{2}$. Prove that your circuit acts as desired.

(d) Recall what are the SWAP gate and Bell states for a pair of qubits. Calculate an explicit matrix form for the swap gate. What does this gate do to a pair of qubits in a Bell state? Why is this answer not surprising?





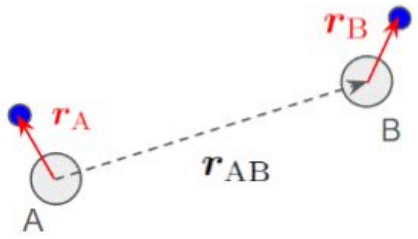
Mini-project 7: Van der Waals interaction

How do neutral atoms interact and form molecules?

Do neutral atoms interact? While they may not form molecules unless they are very close, they experience forces even at larger distances. These forces arise from fluctuations in electron density, as explained by quantum mechanics.

In this project, you will explore the origin of interactions between neutral atoms. You will derive van der Waals interaction potential, and compute C_6 parameter. Additionally, you will explore the fundamental principles that govern the formation of molecules.

Many ideas for this project are based on the lecture of Prof. J. Dalibard from the College de France.



a) Learn the origin of the van der Waals interaction

b) Derive analytically the atomic parameter C_6

c) How molecules are formed – hydrogen

General information

1. Conditions for passing the lecture
   - Exam: max. 15 points
   - Presence during lectures and presentations of the mini-project: max. 15 points

To pass: Min. 15 points