Physics of the Quantum Universe

Test 1 (online)

20 November 2020

Exam instructions

Dear students

Welcome to this online exam for the course PoQU. It consists of THREE questions in total (in addition to the initial pledge). There is an assignment corresponding to each question. Carefully read and answer each question. After you have answered ALL subquestions in an assignment submit your answer for this assignment. Only then will the next question appear. You will NOT be able to go back and edit afterwards. For answering, you can use the text box under Write submission. If you need to add a picture or graph, you can upload this as well but for this exam we believe this will probably not be necessary). In calculations, you may include intermediate results but you don't have to Indicate the units of your answer and include two digits. In total there are three questions and you have one hour (17h-18h) (except for students with special needs) to complete them. In total you can earn 9 points with the three questions, and this will determine your grade between 1 and 10.

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Good luck. Diederik

1 Diffraction Pattern (3 points)

Consider a material with a simple cubic lattice with lattice spacing equal to 3 Angstrom. You are illuminating this material with photons that give rise to a diffraction pattern. Consider an angle equal to (in degrees) the last two digits of your student number (clearly indicate these numbers in your answer) - where an angle of zero degree corresponds to bouncing straight back. What is the longest wavelength (of the incident photons) for which you see negative interference at this angle?

2 Electron Capture (3 points)

Consider a hypothetical ionized atom X^+ (which is one electron short of being neutral) in its ground state. This ion captures an incoming electron with zero (or negligible) kinetic energy, and in the process emits two photons whose wavelength (in nm) are given by the first three digits of your student number (photon 1) and the last three digits of your student number (photon 2). Clearly indicate these numbers in your answer. What is the binding energy in eV) of this outermost electron?

3 Bohr Model (3 points)

Two crucial developments in the early stages of quantum theory are Planck's derivation of the blackbody spectrum and Bohr's derivation of the hydrogen spectrum. As discussed during the lectures, the classical limit of the blackbody spectrum yields the Raleigh-Jeans formula which is correct at large wavelength but wrong for short wavelength. In this question you are asked to think about the classical limit of the Bohr model. In particular, address the following two points: what happens to the allowed radii at which the electron can orbit and what are the possible frequencies that it can emit? Answer these questions both using (very brief) physical reasoning and by outlining what happens to the expressions for the admissible radii and energies in the Bohr model when sending Planck's constant to zero.

Physics of the Quantum Universe

Test 2 (online)

04 December 2020

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1 Quantum Tunneling (3 points)

X- the first two digits of your student number (if zero, take 34)
Y- the last two digits of your student number (if zero, take 45)

Define Max as the highest of these two numbers and Min as the smallest (if equal, increase Max by 10) Imagine an electron coming in from the left with an amount of Min eV kinetic energy that runs into a barrier that is Max eV high and 1 nm wide. We are interested in the probability that the particle tunnels through this barrier.

a) What is the probability that the electron tunnels through this barrier?

b) Qualitatively describe what happens if the particle would be a proton instead, would the probability of tunnelling through be higher or lower?

2 Particle in a Box (3 points)

Consider a quantum particle in a box in its ground state.

a) Find the expectation value of momentum for the ground state of the quantum particle in a box in terms of eg, Planck's constant, the mass m and the width of the box

b) if we were to measure the momentum of the particle in this state, would this always coincide with your answer at a)? Briefly explain why (not).

3 Heisenberg Uncertainty (3 points)

X- the first two digits of your student number (if zero, take 34)
Y- the last two digits of your student number (if zero, take 45)

A certain atom is measured to have an excited state that is an amount of X ev above the energy of the ground state. Moreover, it generically remains in this excited state for a period of V ns before transitions to the ground state.

a) Briefly explain what the Heisenberg uncertainty principle implies for the accuracy with which we can measure the energy of an unstable state.

b) Estimate the uncertainty in the frequency of the photon that is emitted during this quantum transition.

Physics of the Quantum Universe

Test 3 (online)

18 December 2020

Exam instructions

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1 Spin (3 points)

Consider a hypothetical atomic element that has no orbital angular moment and has a spin that equals one unit (s=1).
(a) In a Stern-Gerlach experiment with a magnetic field that is orthogonal to the motion of the atoms, into how many bands would a beam of these elements split up?
(b) What are the values of the magnetic dipole moment of this particle for the possible outcomes of the previous question?
(c) Given a known magnetic field, can one observationally tell the difference between elements with one unit of angular momentum (and no spin) and elements with one unit of spin (and no angular momentum) using the Stern-Gerlach set-up? Briefly explain your answer.

2 Atomic Structure (3 points)

(a) Briefly explain the orbital structure of the electrons of Lithium; which quantum states do the three electrons occupy?
(b) Briefly explain what is special about the orbital structure of the Z=19 element K (Potassium) of the periodic table.
(c) What would be the orbital structure in terms of 1s etc) of the Z=10 element if an electron would have spin -1 instead of spin -1/2?

3 Wavefunctions (3 points)

Consider the n=2 wavefunctions of the electron in a Hydrogen atom. In this question you can neglect the spin of the electron.
(a) How many distinct quantum states are possible for n=2? Indicate the possible values of the relevant quantum numbers.
(b) Which n=2 wavefunctions are spherically symmetric? Briefly explain your answer.
(c) At which distance from the nucleus are you most likely to find an electron if it is in the n=2, l=1 quantum state?

Physics of the Quantum Universe

Test 4 (online)

15 January 2021

Exam instructions

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Good luck. Diederik

1 Strong Force (3 points)

1. Briefly explain (in at most two sentences) why there needs to be a powerful nuclear force in order for stable nuclei to exist.
2. Using the Heisenberg uncertainty principle, determine the range of the strong force if this force is produced by the exchange of pions.
3. Draw the Feynman diagram corresponding to the exchange of a neutral pion between two protons. Clearly indicate the quark content of the nuclei and pion.

2 Standard Model (3 points)

1. For each of the three forces in the Standard Model, indicate what the corresponding force particles are.
2. Can the following kaon decay process take place: $(K^+) - > (\mu^+) + (\nu_\mu)$
3. The matter of the Standard Model is divided into quarks and leptons. Does the Standard Model contain a force that can convert a quark into a lepton? Briefly explain your answer in at most two sentences.

3 Big Bang (3 points)

1. On average, how far away are galaxies that are moving away from us at 2 percent of the speed of light?
2. Briefly explain (in at most two sentences) what observed property of the Cosmic Microwave Background was seen as strong evidence for the Big Bang.
3. Briefly explain (in at most two sentences) which observation led to the introduction of Dark Energy in our understanding of the Universe.