Subatomic Physics 2016/20017

Exam Subatomic Physics 2016/2017
Tuesday, 31 - January - 2017

70 points

Please mark your name and your student number on every sheet.
Please put consecutive page numbers on your pages.

You receive 4 A4 pages:

- pages 2 and 3 contains questions relating to topics from the lecture.
- page 4 gives relevant Constants, Relations and Conversion Factors
- Note: For some of the questions different approaches are possible, such that you may not necessarily need all of the given constants and equations.
- The final results are sufficient, if given correct to 2 significant figures (2 leading digits).
- Note: The exam has questions worth 70 points. They translate linearly into grades up to 10. In case your results from the homework resulted in a better grade, the average of the two grades will be used to determine your final grade for the course. If you have less favourite homework results recorded, we do not use these and your final grade will be from the exam only.

Groningen, 31 January, 2017
Best wishes for your exam,
Klaus Jungmann

1 Main Exam

1.1 Radioactivity - Radioactive Decays (15 points)

For the chemical elements we have more instable than stable isotopes.

(a) Which types of radioactive decay processes do we know? Give one sentence of description for each known decay. (2 points)

(b) Where on a nuclear chart do we find the α-decaying isotopes, where the β^- decaying isotopes ? What are typical α-decay energies? What are typical β^--decay energies? What are typical β^+-decay energies ?(If you don't remember by heart, you can approach this problem with parameters available in the section *Constants of Relevance* below?) (3 points)

(c) Please explain why there are more radioactive than stable isotopes for each chemical element ? (3 points)

(d) Up to which energy range can we expect α- and β-decay energies? Why? (2 points)

(e) Why is α-decay not found for very light nuclei, but well for heavy nuclei? (2 points)

(f) ^{56}Fe is the the most stable nucleus. Can you name at least two essential consequences which relate to this fact (in the universe and in technology)? (3 points)

1.2 Neutrino Experiments (10 points)

(a) In the major process in the sun 4 protons are fused into ^{4}He nuclei. Each individual cycle releases about 24.7 MeV energy. The distance sun-earth is $1.5 \cdot 10^8$ km. We receive (at the equator) about 1.4 kJ of solar energy per m^2 and per second. What is the flux Φ_ν of neutrinos at the earth which originate from the sub process $p + p \to d + e^+ + \nu_e$ of the cycle? (4 points)

(b) What can we say about the energy of these neutrinos? How big is it ? (2 points)

(c) What is the difference between *Dirac* and *Majorana* particles? Give a possible (realistic) experiment that could clarify the question whether neutrinos are *Dirac* or *Majorana* particles. (2 points)

(d) One reaction used for solar neutrino detection is $\nu_e + {}^{37}_{17}\mathrm{Cl} \to {}^{37}_{18}\mathrm{Ar} + \mathrm{e}^-$. Based on the knowledge given in section 2. below, please estimate the energy, which the neutrinos need to have at least, in order to detect them with this reaction? (2 points)

1.3 Weak Interactions (15 points)

The weak eigenstates and the mass/flavour eigenstates of neutrinos and quarks are not identical.

(a) In general, which three different types of weak interactions can be distinguished ? (3 points)

(b) Give one example for each of them with a Feyman diagram. (3 points)

(c) How do the processes differ in strength ? (3 points)

(d) What is meant by the term *lepton universality* (2 points)

(e) For neutrinos, give please one example each of a physical process where (i) pure flavour eigenstates are involved and (ii) where pure mass eigenstates are involved. (2 points)

(f) In the neutrino mass measurement experiment *KATRIN* (where the β-decay of tritium is exploited using energy spectroscopy of the electrons born in the β-decay), which mass is actually measured? Please explain. How is this measured mass value related to the mass eigenstate? (2 points)

1.4 Allowed and Forbidden Processes (15 points)

Which of the following processes are allowed and which are forbidden? Please give reasons for your judgment. For allowed processes note which of the fundamental interactions is responsible. We assume here that there is always sufficient energy, e.g. in a collision process, such that you do not have to worry about energy conservation.

(a) $p + \overline{p} \rightarrow K^0 + \mu^+ + e^-$ (1.5 points)

(b) $\nu_e + n \rightarrow e^- + p$ (1.5 points)

(c) $\overline{\nu_e} + p \rightarrow e^+ + K^0 + \Lambda^0$ (1.5 points)

(d) $\mu^+ + e^- \rightarrow \mu^- + e^+$ (1.5 points)

(e) $\tau^- \rightarrow e^- + e^- + e^+ + \nu_\tau + \overline{\nu_e}$ (1.5 points)

(f) $n \rightarrow p + \mu^- + \overline{\nu_\mu}$ (1.5 points)

(g) $\mu^- \rightarrow e^- + e^+ + e^- \nu_e + \overline{\nu_\mu}$ (1.5 points)

(h) $J/\Psi(2^1S_0) \rightarrow J/\Psi(1^1S_0) + 2\gamma$ (note: $J/\Psi = (c\overline{c})$ bound state) (1.5 points)

(i) $p + p \rightarrow c\overline{c} + \tau^+ + \mu^- + \nu_\tau + \overline{\nu_\mu}$ (1.5 points)

(h) $n +^{235} U \rightarrow^{235} Pu + p + \gamma$ (1.5 points)

1.5 Particles, Forces and their Ranges (15 points)

Forces are mediated by the exchange of particles.

(a) Which particles mediate electromagnetic interactions?(1 point)

(b) Which particles mediate weak interactions? (1 point)

(c) Which particles mediate the strong interactions within nucleons? (1 point)

(d) Which particles mediate the strong force that holds nuclei together, e.g., the proton and neutron in a deuteron nucleus? (1 point)

(e) What do we know about the spin of the force carrying particles? (1 point)

(f) What is the difference between their spins and the spins of quarks and electrons? (1 point)

(g) Which relativistic wave equation describes best the charge carriers? (1 point)

(h) Which relativistic wave equation describes best quarks and leptons? (1 point)

(i) Name at least two important consequences related to the answers in (g) and (h)? (2 points)

(j) Estimate the ranges of i) the electromagnetic interaction, ii) the weak interactions, iii) the nuclear force between nucleons. Indicate your line of reasoning. (3 points)

(k) What is the role of the Higgs boson and why was its discovery in 2012 so exciting? (2 points)

2 Some Constants, Relations and Conversion Factors

2.0.1 Constants of Relevance

Speed of light	c	$2.998 \cdot 10^8$	m/s
Planck constant	h	$4.136 \cdot 10^{-24}$	GeVs
	$\hbar = \frac{h}{2 \cdot \pi}$	$6.582 \cdot 10^{-25}$	GeV/c
Electron charge	e	$1.602 \cdot 10^{-19}$	C
Electron mass	m_e	0.510998918(44)	MeV/c^2
Proton mass	m_p	938.272029(80)	MeV/c^2
Neutron mass	m_n	939.565360(81)	MeV/c^2
Deuteron mass	m_d	1875.61282(16)	MeV/c^2
Deuteron binding energy	$E_{b,d}$	2.224575(9)	MeV
Helium-3 mass	$m_{^3He}$	2809.41334(24)	MeV/c^2
Alpha particle mass	m_α	3727.37917(32)	MeV/c^2
^{37}Cl nuclear mass	$m_{^{37}Cl}$	36.965903(5)	MeV/c^2
Alpha particle binding energy	E_α	28.3	MeV/c^2
Electron neutrino mass	m_{ν_e}	< 2.2	eV/c^2
Muon mass	m_μ	105.658369(9)	MeV/c^2
Charged Pion mass	$m_{\pi^\pm}$	139.57018(35)	MeV/c^2
$W^\pm$- boson mass	m_W	80.403(29)	GeV/c^2
Z^0-boson mass	m_Z	91.1876(21)	GeV/c^2

2.0.2 Relations

Mass of Atom (Bethe-Weizaecker):

$$M(A,Z) = Nm_n + Zm_p + Zm_e - a_v A + a_s A^{2/3} + a_c \frac{Z^2}{A^{1/3}} + a_a \frac{(N-Z)^2}{4A} + \frac{\delta}{A^{1/2}}$$

with

$a_v = 15.67 MeV/c^2$

$a_s = 17.23 MeV/c^2$

$a_c = 0.714 MeV/c^2$

$a_a = 93.15 MeV/c^2$

$\delta = 0$ (odd A) or -11.2 MeV/c^2 (Z and N even) or +11.2 MeV/c^2 (Z and N odd)

2.0.3 Conversion Factors

Electronvolt	eV	$1.60217653(14) \cdot 10^{-19}$	J
Tesla	T	$0.561 \cdot 10^{30}$	MeV/($c^2 \cdot$ C $\cdot$ s)
Kilogram	kg	$5.60958896(48) \cdot 10^{35}$	eV/c^2
barn	b	$1 \cdot 10^{-28}$	m^2

Note: For some of the questions different approaches are possible, such that you may not necessarily need all of the given constants and equations. Unless differently stated, the final results are sufficient, if given to 2 significant figures (2 leading digits and order of magnitude).