Subatomic Physics 2008/2009

Main Exam

Tuesday, 14 - April - 2009, 14:00 - 17:00, 5111.0080

70 points

(Please mark name on student number on every sheet.)

1 Exam

1.1 Radioactivity (15 points)

(a) The half-lifetime (T_{Ra}) of ^{226}Ra is 1600 years ? How many decays per second do you have from 1 mg of ^{226}Ra? [5 pts]

(b) ^{226}Ra α-decays into ^{222}Rn. Give the reaction equation and estimate the α-particle energy. Please sketch the α energy spectrum qualitatively. [5 pts]

(c) The isotope ^{23}Na is the only stable isotope of the element. The isotope ^{21}Na shows β-decay. Would you expect β^+ into a Ne isotope or β^--decay into a Mg isotope ? Why? Give the reaction equation. Please sketch the β-decay spectrum. What is the difference compared to an α-decay spectrum and why? [5 pts]

1.2 Fundamental Forces (15 points)

We know 4 fundamental forcess. Electromagnetic forces are carried by the exchange of photons (γ), for gravitation one assumes the exchange of gravitons (g), the strong interactions are carried at the fundamental level by gluons (G) and in nuclei one assumes according to Yukawa the exchange of pions (π^0, π^+, π^-) between nucleons. The weak interactions are due to the exchange of the bosons W^+, W^- and Z^0.

(a) Which wave equation would be appropriate to describe these force carrying particles? Can you write it down using the material provided in the Appendix? What wave equation would describe the particles they connect to? [4 pts]

(b) Give a simple line of reasoning that allows to estimate the range of forces. Can you derive a simple expression? [4 pts]

(c) What is the range of
(i) the weak interactions, [1 pt]
(ii) the strong force between nucleons in a nucleus, [1 pt]
(iii) the electromagnetic interaction ? [1 pt]
(Either use expression obtained in (a) or recollect order of magnitude. 20% accuracy is enough.)

(d) Where do these force carriers come from? What about energy conservation in e.g. the deuteron (deuterium nucleus ^{2}H), where the neutron and the proton are held tohether by pions and the sum of the masses of these particles exceeds the deutron mass? [2 pts]

(e) Does the infinite range of the gravitation force say anything about the mass of the not yet observed gravitons? [2 pts]

1.3 Allowed and Forbidden Processes (10 points)

Which of the following processes are allowed and which are forbidden. Please give reasons for your judgment. For allowed processes please name the interaction. (Assume that the kinetic energy of the incoming particles plus their masses is high enough such that all outgoing particles could be produced.) [1 pt each]

(a) $e^+e^- \rightarrow \Lambda^+ + \Lambda^- + \rho^0 + \rho^- + \rho^+$

(b) $\overline{\nu_e} + p \rightarrow e^+ + n$

(c) $\nu_\mu + n \rightarrow \mu^- + pi^0 + \Lambda^0$ Charg

(d) $e^- + e^- \rightarrow \mu^- + \mu^- + \gamma$

(e) $^{128}\text{Xe} \rightarrow ^{128}\text{Ba} + e^- + e^-$

(f) $p \rightarrow \pi^0 + e^- + e^+ + \gamma$

(g) $\mu^- + e^+ \rightarrow e^+ + e^- + \nu_\mu$

(h) $J/\Psi(2^1S_0) \rightarrow J/\Psi(1^1S_0) + 3\gamma$ (note: $J/\Psi = (c\overline{c})$ bound state, charmonium)

(i) $p + \overline{p} \rightarrow b\overline{b}$

(h) $p +^8 \text{B} \rightarrow^8 \text{B} + n + \pi^+ + \pi^- + \pi^+$ Charge

1.4 Neutrinos (10 points)

The nature of the neutrinos is an urgent issue in modern physics. Big detectors are operated or are being set up to detect neutrinos. Among them are the ICE-CUBE in Anartica and the KM3 in the Mediterranian Sea. Both use either 1 km^3 of antarctic ICE respectively sea water as active detector medium. For this, photomultipliers are deployed in the ice, respectively the water. Those detect Cherenkov light from reaction products of the neutrinos.

(a) Give an example of a reaction that could be used to detect an muon neutrino (ν_μ) respectively antineutrino($\overline{\nu_\mu}$). What interaction is needed for a neutrino reaction? [3 pts]

(b) The incoming neutrinos have energies well beyond 50 GeV. Photomultipliers are used to detect the signal. Do you think, that one can find back the direction from where the neutrinos came and thereby do neutrino astronomy? [3 pts]

(c) At the highest up to date observed energies (about 10^{20}eV) the cross section for neutrino reactions is estimated to be of order 10^{-31} cm^2 to $10^{-34}cm^2$. How big must the flux of neutrinos at these energies be at minimum to observe at least one event per day in one of these detectors with 1 km^3 active volume. (water/ice (H_20: density 1 g/cm^3, n_p =10 protons per molecule, n_n =8 neutrons per molecule.) [4 pts]

1.5 Weak Interactions (10 points)

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

(a) How are they related to each other? Explain briefly. [2.5 pts]

(b) What consequences does this have for quark and lepton flavours? [2.5 pts]

(c) What would change, if somebody would observe in future the process $(\mu^+e^-) \rightarrow (\mu^-e^+)$. [2 pts]

(d) Give one example each of a (i) leptonic, (ii) semileptonic and (iii) non-leptonic weak interaction process. Draw the corresponding Feynman diagram. Explain difference in strength for these processes. [3 pts]

1.6 Nuclear Reactor 10 points

The so-called *thorium reactor* may have many advantages over present nuclear reactors and is therefore interesting as a possible power reactor concept for the future. Let's look into some basic physics connected to it. The *lightest* six actinies are Actinium (Ac, Z=89), Thorium (Th, Z=90), Palladium (Pa, Z=91), Uranium (U, Z=92), Neptunium (Np, Z=93), Plutonium (Pu, Z=94). There is relative high natural abundance of the Thorium isotpe $^{232}_{90}$Th which normally decays via β^--decay into palladium (Pa).

(a) Give the full reaction equation for this β-decay including the proper isotope of the daughter nucleus. [2 pt]

(b) $^{232}_{90}$Th has a thermal neutron capture cross section of 7 b. Which isotope is then produced? [1 pt]

(c) This new isotope decays by two subsquent β^--decays into the isotope ^A_ZX. What is the name of the resulting element and its isotope ? [1 pt]

(d) ^A_ZX is an isotope that shows induced fission through thermal neutrons with a cross section of 531 b.The fission products have a mass ratio of about 3:2 (assume that ratio is the same for A and Z). 3 neutrons are realeased per fission on average. How much ^{232}Th is minimally needed for a 100 MW power station? (Don't shoot for better than 10% accuracy.) [4 pts]

(e) Why is the information on the cross sections relevant for a reactor? [2 pts]

2 Constants, Relations and Conversion Factors

2.1 Constants that could be 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
Alpha particle mass	m_α	3727.37917(32)	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
Neutral pion mass	m_{π^0}	134, 9766(6)	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
Avogadro's number	N_A	$6.02214179(30) \cdot 10^{23}$	mol^{-1}

2.2 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)

Schroedinger equation:

$$\frac{-\hbar}{i}\frac{\partial}{\partial t}\Psi(\vec{r},t) = [-\hbar^2/2m\vec{\nabla}^2 + V(\vec{r},t)]\Psi(\vec{r},t) \quad (1)$$

classical momentum-energy relation free particle

$$E = \frac{p^2}{2m} \quad (2)$$

classical momentum-energy relation free particle

$$E^2 = p^2c^2 + m_0^2c^4 \quad (3)$$

2.3 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).

2009 Å eV
$2 \cdot 10^{-10}$