

# **Re-Exam Subatomic Physics**

## **Thursday, July 5 2012, 13:00-16:00**

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*Before you start, read the following:*

- Write your name and student number on top of each page of your exam;
- Illegible writing will be graded as incorrect;
- Final grade =  $(10 + \text{sum of points})/10$ ;
- *Good luck!*

# 1 Allowed and Forbidden Processes (15 Points)

Two of the following reactions cannot occur (as far as we know) and a third cannot occur by the strong interaction. Find them and indicate the reason in each case. (5 points each)

(a)  $K^- + p \rightarrow \bar{K}^0 + n,$

(b)  $\pi^+ + p \rightarrow K^+ + \Sigma^+,$

(c)  $\pi^- + p \rightarrow K^+ + \Sigma^0 + \pi^-,$

(d)  $\pi^- + p \rightarrow K^- + \Sigma^+,$

(e)  $\bar{K}^0 + p \rightarrow K^- + p + \pi^+,$

(f)  $\bar{p} + p \rightarrow \pi^+ + \pi^+ + \pi^- + \pi^- + \pi^+,$

(g)  $\pi^+ + p \rightarrow K^0 + \Sigma^0 + \pi^+ + K^+ + \bar{K}^0,$

(h)  $K^- + p \rightarrow \Sigma^+ + n + \pi^-,$

(i)  $\pi^- + p \rightarrow \Sigma^+ + \Sigma^- + K^0 + \bar{p} + \bar{\Sigma}^+ + n,$

(j)  $\pi^- + p \rightarrow \bar{\Sigma}^- + \Sigma^0 + p.$

The notation  $\bar{\Sigma}$  means the antiparticle to the  $\Sigma$  and the sign convention is that  $\bar{\Sigma}^+$  has charge +1 and is therefore the antiparticle to the  $\Sigma^-$ .

# 2 Terminology (15 Points)

The terms *hadron*, *lepton*, *boson* and *fermion* are used in the classification of particles. Explain their meaning, giving examples of their use. Which can be applied to *quarks*?

### 3 Cross sections (15 Points)

The TRI $\mu$ P facility at KVI aims to study precisely nuclear  $\beta$ -decay. One of the isotopes of interest is  ${}^{21}_{11}\text{Na}$ . This isotope has a half-life of  $T_{1/2} = 23$  s.

- (a) We know there is only one stable Na isotope, which is  ${}^{23}\text{Na}$ . What kind of  $\beta$ -decay is possible for  ${}^{21}\text{Na}$ ? (3 points)

- (b) Give the equation describing this decay. (3 points)

- (c) The production of the isotope happens by shooting a  ${}^{20}_{10}\text{Ne}$  beam at energy  $E_b = 23$  MeV/u (energy per nucleon of the beam particle) on a deuterium ( ${}^2_1\text{H}$ ) gas target. Give the equation for this production reaction. (3 points)

- (d) The target is 10 cm long and it is kept at liquid nitrogen temperature ( $T=77.5\text{K}$ ). The diatomic deuterium molecule can be assumed to be an ideal gas which at standard conditions (temperature  $T_0 = 273\text{K}$  and pressure  $p_0 = 1\text{ bar}$ ) has a density of  $6.023 \cdot 10^{23}$  particles per  $22.4\text{ dm}^3$ . What is the cross section for the production reaction, if one produces  $^{21}\text{Na}$  at a rate of  $\Gamma_0 = 3 \cdot 10^8$  particles per second with a  $^{20}\text{Ne}^{6+}$  beam of 1 kW power (corresponding to  $\Gamma_1 = 1.4 \cdot 10^{13}$  particles per second)? (6 points)

## 4 Weak Interaction (15 Points)

For each of the following processes or phenomena, explain qualitatively why the weak interaction must be involved (3 points each):

- (a) Beta momentum  $\vec{p}_e$  asymmetry  $A \neq 0$  in decay of polarized nuclei with spin  $\vec{J}$  :  
 $\frac{d\sigma}{d\Omega} \propto 1 + A\vec{J} \cdot \vec{p}_e$

- (b) atomic electron capture:  $^7_4\text{Be} + e^- \rightarrow ^7_3\text{Li} + \nu_e$

- (c) Matter-Antimatter asymmetry in the universe

(d) Kaon oscillations :  $K^0 \leftrightarrow \bar{K}^0$

(e) neutrino scattering:  $\nu_\mu + e \rightarrow \nu_\mu + e$

## 5 Quarks (15 Points)

The lowest mass (non-strange) baryons are:

	electric charge			
	-1	0	+1	+2
nucleons		n	p	
$\Delta$ -baryons	$\Delta^-$	$\Delta^0$	$\Delta^+$	$\Delta^{++}$

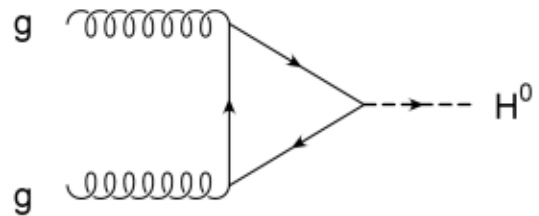
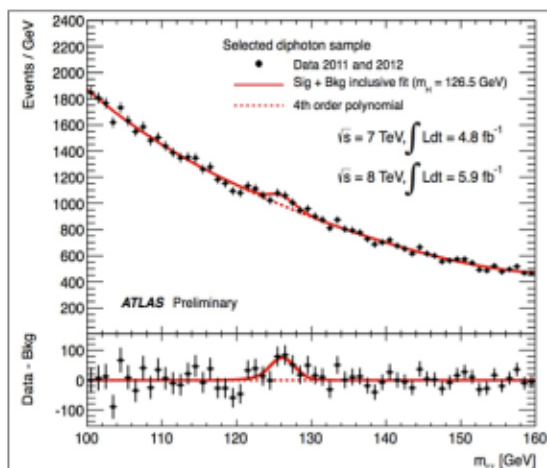
(a) What are the quark constituents of each of these states? (5 points)

(b) Assuming that the quarks are in states of zero relative angular momentum, what fundamental difficulty appears to be associated with the  $\Delta$  states, which have  $J = 3/2$ , and how is it resolved? (5 points)

(c) The  $\Delta^0$  and the  $\Lambda$  (strangeness -1) both decay to a proton and  $\pi^-$ -meson. Explain the large difference between the  $\Delta^0$  mean-life of  $\sim 10^{-23}$  s and that of the  $\Lambda$ , which is  $2.6 \times 10^{-10}$  s. (5 points)

## 6 Higgs Boson (15 points)

Yesterday an announcement was made of the discovery of a new boson at CERN. This boson could be the long searched for Higgs boson. Results were presented for two final states that could occur when a Higgs boson decays: two photons ( $2\gamma$ ; see figure below) and four leptons ( $4e$ ,  $4\mu$  and  $2e2\mu$ ).



1. Why was the conclusion that the observed bump belongs to a boson? Briefly explain your reasoning. (3 points)

2. What can you conclude about the charge of the observed boson? Briefly explain your reasoning. (3 points)

3. Explain how the mass of the decaying boson can be determined if you measure the momenta of the two photons. (3 points)

4. The theoretically most important production mechanism of the Higgs boson is gluon fusion (see figure top right). Identify what kind of particle goes around in the triangle. (3 points)

5. A Higgs boson could also decay into a quark-antiquark pair. Explain why the analysis of this decay channel is more complicated than that of two photons or 4 leptons (*hint*: what do you detect in this case?). (3 points)

## Constants

Speed of light	$c$	$2.998 \cdot 10^8$	m/s
Planck constant	$h$	$4.136 \cdot 10^{-24}$	GeV·s
	$\hbar = \frac{h}{2\pi}$	$6.582 \cdot 10^{-25}$	GeV/c
Electron charge	$e$	$1.602 \cdot 10^{-19}$	C
Electron mass	$m_e$	0.510998918(44)	MeV/c <sup>2</sup>
Proton mass	$m_p$	938.272029(80)	MeV/c <sup>2</sup>
Neutron mass	$m_n$	939.565360(81)	MeV/c <sup>2</sup>
Deuteron mass	$m_d$	1875.61282(16)	MeV/c <sup>2</sup>
Alpha particle mass	$m_\alpha$	3727.37917(32)	MeV/c <sup>2</sup>
Electron neutrino mass	$m_{\nu_e}$	< 2.2	eV/c <sup>2</sup>
Muon mass	$m_\mu$	105.658369(9)	MeV/c <sup>2</sup>
Tau mass	$m_\tau$	1776.84(17)	MeV/c <sup>2</sup>
Charged pion mass	$m_{\pi^\pm}$	139.57018(35)	MeV/c <sup>2</sup>
Neutral pion mass	$m_{\pi^0}$	134.9766(6)	MeV/c <sup>2</sup>
$W^\pm$ -boson mass	$m_W$	80.403(29)	MeV/c <sup>2</sup>
$Z^0$ -boson mass	$m_Z$	91.1876(21)	MeV/c <sup>2</sup>
Avogadro's number	$N_A$	$6.02214179(30) \cdot 10^{23}$	mol <sup>-1</sup>

## Semi-Emperical Mass Formula (Bethe-Weizsäcker)

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

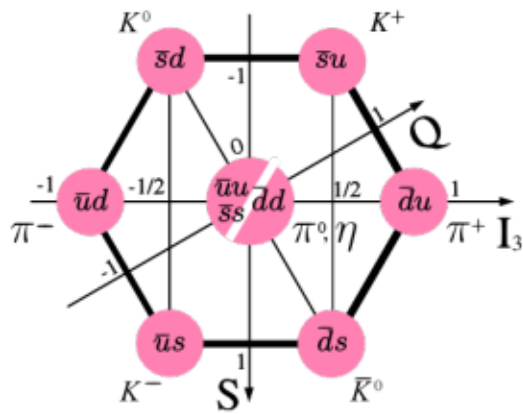
$$\begin{aligned} a_v &= 15.67 \text{ MeV}/c^2 \\ a_s &= 17.23 \text{ MeV}/c^2 \\ a_c &= 0.714 \text{ MeV}/c^2 \\ a_a &= 93.15 \text{ MeV}/c^2 \\ \delta &= 0 \text{ odd } A \\ &= -11.2 \text{ MeV}/c^2, \text{ } Z \text{ and } N \text{ even} \\ &= +11.2 \text{ MeV}/c^2, \text{ } Z \text{ and } N \text{ odd} \end{aligned}$$

## Conversion Factors

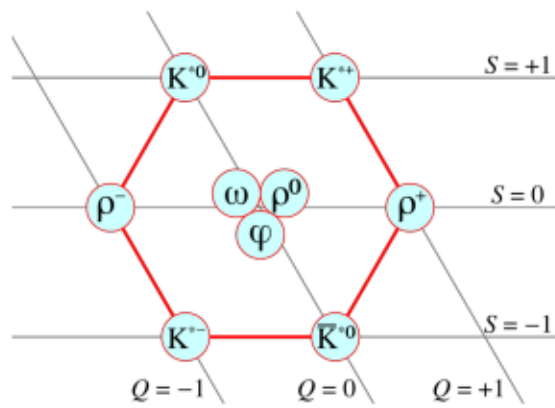
Electronvolt	eV	$1.60217653(14) \cdot 10^{-19}$	J
Tesla	T	$0.561 \cdot 1030$	MeV/c <sup>2</sup> ·C·s
kilogram	kg	$5.60958896(48) \cdot 10^{35}$	eV/c <sup>2</sup>
barn	b	$1 \cdot 10^{-28}$	m <sup>2</sup>

*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 specifically stated, the final results are sufficient if given to 2 significant figures (2 leading digits).*

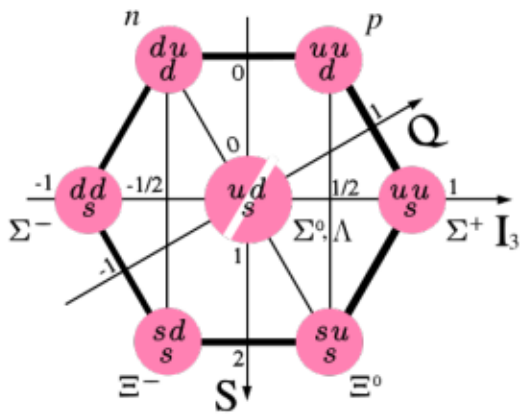
## Baryon and Meson Composition



Spin-0 Mesons



Spin-1 Mesons



Spin-1/2 Baryons

name	composition	mass [GeV/c <sup>2</sup> ]
$J/\psi$	$c\bar{c}$	3097
$D^+$	$c\bar{d}$	1869
$D^0$	$c\bar{u}$	1864
$\bar{D}^0$	$\bar{c}u$	1864
$D^-$	$\bar{c}d$	1869





