Subatomic Physics
2021-2022

Exam

1 February 2022, 16:00-18:00 CET

Remarks and instructions

- Please mark your name and your student number on every sheet.
- Please put consecutive page numbers on your pages.
- Provide your answers with clear context and explanations
- Grade: There are 13.5 points and 1 bonus point, grade is 1+9*min(number of points,13.5)/13.5
- Amount of points are listed in front of each sub-question

1 General concepts (3 point)

Please keep your answer to a maximum of a few sentences.

a) (0.5) Give a description of the concept of a particle in modern physics (QFT)

b) (1.0) The electromagnetic interaction is considered long range. However, the weak and the strong force are both short range, but caused by markedly different reasons. Describe how this comes about for both cases.

c) (0.5) How come we have never observed quarks directly, i.e. what quantum number causes this in combination with the properties of the strong force?

d) (1.0) To detect subatomic particles, it is needed to transform a microscopic interaction to a macroscopic effect. Describe one such process, going from the type of material interaction to detection.

2 Nuclear decay (2.5 point)

The Lithium isotope $^8_3$Li has a half-life of about 0.8 s and decays to $^8_4$Be which has a mass of about 8.0053 u.

a) (1.0) What type of decay is this and which interaction(s) is(are) responsible? Write down the reaction mechanism of the aforementioned decay.

b) (0.5) Name a model to estimate the mass of $^8_3$Li.

c) (1.0) What is the maximum energy of the electron released by this decay, given that the mass of $^8_3$Li is about 8.0225 u?

3 Neutrinos from accelerators (2 point)

To study neutrinos, one needs a source. Aside from cosmic and atmospheric sources, one can study them in a lab by creating a neutrino beam. One such way is to use a proton beam from an accelerator on a target to produce (mainly) pions that decay to muons in combination with neutrinos. To have an as-dense-as-possible beam of neutrinos, the pions will be collimated as much as possible. However, the decay of the pions will give a spread that is insurmountable.
The angle in the lab frame of highly relativistic decay products w.r.t the origin particle is given by,

$$\tan\theta = \frac{\sin\theta'}{\gamma(1+\cos\theta')}$$

where γ is the Lorentz factor and θ' is the angle in the frame of the particle that decays.

a) (1 0) Give a conservative estimate of the order of magnitude of the angles the spread of the beam has, given the pions have about $1\mathrm{GeV}/c$ in momentum.

b) (1.0) To measure neutrino oscillations, multiple detectors are placed at different distances from the beam origin. Assuming one detector is placed at a 100 km from the source and has a 1000 m^3 of volume of water, what does the luminosity have to be of the neutrino beam at the source to produce 1 neutrino event per day, given neutrinos are of 1 GeV energy at which they have a total cross-section of about $1\cdot 10^{-38}$ cm^2 and have the aforementioned spread.

4 Flavour anomalies (6 + 1* points)

Currently, a number of measurements of decays of B-hadrons are causing a stir in the high-energy physics community. One of those is the measurement of the branching faction ratios of $B^0 \to K^0\mu^+\mu^-$ versus $B^0 \to K^0e^+e^-$. Both the BELLE and LHCb experiments have performed measurements, of which the one from the latter experiment came out in October 2021.

4.1 Detection of the decay products (2.5 points)

The neutral kaon, K^0, is a particle with neutral-meson mixing and hence has two mass eigenstates. The mass eigenstate of the neutral kaon that decays quickest, K^0_{S}, has a lifetime of $9\cdot 10^{-11}$ s; the long-lifetime version, K^0_{L}, has a lifetime of $5\cdot 10^{-8}$ s. For our intends and purposes the muon can be considered effectively stable.

a) (1.0) Given the lifetimes of the aforementioned kaons and the fact that momenta of these particles at the LHC are of the order of 10 GeV/c, is the typical size of charged-particle-tracking sub-detectors of 1 to 10 meters sufficient to detect the charged pions coming from the kaon decay (answer per mass eigenstate)?

b) (0.5) A background for the kaon detection are $\Lambda^0 \to p\pi^-$ decays. Give a detection principle to distinguish them from $K^0_{\mathrm{S}} \to \pi^+\pi^-$.

c) (1.0) Momenta of charged (stable) particles are usually measured in tracking sub-detectors in combination with bending in a known magnetic field. The material of the detector also causes energy loss to the electrons and muons and hence interferes with the momentum measurement. Would you expect either muons or electrons to have different energy losses? If so, by which interaction? Which decay mode is, i.e. would be your guess given this information, then the bottle neck in such a measurement?

4.2 Old and new physics? (3.5 + 1* points)

Similar ratios of branching fractions, like,

$$R_{K^+} = \frac{\mathrm{BR}(B^+ \to K^+\mu^+\mu^-)}{\mathrm{BR}(B^+ \to K^+e^+e^-)}\ ,$$

are showing stronger deviations from the Standard Model, but *not* (yet) at the 5σ significance level.

a) (0.5) Ignoring mass differences between the muon and electron, the value of R_{K^+} is 1 in the Standard Model. What does this mean for the coupling of different charged leptons in the Standard Model?

b) (1.0) Draw a Feynman diagram contributing to the process, given the fact that first-order diagrams contain loops with couplings of e.g. W bosons to a Z boson; and the quark content of B^+ and K^+ is $\bar{b}u$ and $\bar{s}u$ respectively.

c) (1.0) Similar type of decays occur for example with $D^+ \to \pi^+\mu^+\mu^-$. Draw the Feynman diagram of the previous question for this example, given the quark content of D^+ and π^+ are $c\bar{d}$ and $u\bar{d}$ respectively. Estimate the ratio in CKM matrix elements between the B^+ and the D^+ decays.

d) (1.0) Another property is important in the amplitude considering the momentum exchanged in these decays, which is that? Which decay, i.e. from B^+ or D^+, would you expect to have a higher amplitude? How does this relate to the weak interaction (properties)?

e) (1.0*) One suggestion to resolve the anomalies is the introduction of a particle called the leptoquark. Such a particle would couple directly to both a quark and a lepton. Draw the first order Feynman diagram for the decays in question via a leptoquark.

Formulas and constants[1]

Constants

Speed of light	c	$3.0 \cdot 10^8$	m/s
Electron mass	m_e	0.51	MeV/c^2
Pion mass	m_π	139.57	MeV/c^2
Neutral kaon mass	m_{K^0}	498	MeV/c^2
Atomic mass unit	u	931.49	MeV/c^2

Relations and models

Relativistic mechanics

$$E^2 = p^2c^2 + m^2c^4$$
$$E = \gamma mc^2$$

Decay

$$N(t) = e^{-t/\tau} ,$$

where t is proper-time and τ is the lifetime of the particle.

CKM matrix and Wolfenstein parametrization

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$V_{\text{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4) ,$$

where A, λ, ρ and η are dimensionless parameters. Values are roughly 0.8, 0.23, 0.14 and 0.35 respectively.

Taylor series

$$\tan x = x + \frac{x^3}{3} + \mathcal{O}(x^5)$$

[1]Up to relevant precision, measurement uncertainties are neglected.