Subatomic Physics 2024-2025
Exam

Monday, 27 January 2025, 18:15 - 20:15 CET

Student name: ______________________________

Student number: ______________________________

Question	1	2	3	4	$\sum$	Grade
Points	30	25	15	20	90	
Score		X				

Remarks

- Please write the following on every sheet:
  - your name
  - your student number
  - consecutive page numbers
- The exam consists of 4 parts with subquestions. You receive a total of 4 A4 pages. The questions start on page 3.
- Please provide your answers with clear context and explanations.
- You can achieve up to 90 points in the exam. The amount of points per (sub-)question is listed.
- The grade of the exam is $1 + 1/10 \times$ (number of points achieved).
- You are allowed to use a simple scientific (not graphical) calculator and a handwritten formula sheet of size A4 (both sides).

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1 General Questions (30 points)

Please give a brief answer to these questions. Only around one to three sentences and/or a quick calculation are necessary.

a) (6) What is the velocity of a π^0 meson with a kinetic energy of 0.20 GeV? You can give your answer in multiples of the speed of light in vacuum c.

b) (6) What would be a typical range of a hypothetical force that is mediated by neutral kaons K^0?

c) (6) The energy loss of which interaction of particles with matter is described by the Bethe-Bloch equation? Explain the interaction briefly and state which particles interact in this way.

d) (12) Are the following processes allowed in the Standard Model of Particle Physics or not? For allowed reactions, please draw one possible Feynman diagram. For not allowed processes, please explain why this is the case.

   i) (3) $\eta \to \gamma\gamma$

   ii) (3) $\pi^+ n \to \pi^- p$

   iii) (3) $D^- \to K^0 \pi^-$ (Note: the D^- is a $d\bar{c}$ meson.)

   iv) (3) $\mu^+ \to e^+ e^+ e^-$

2 Dating of Documents (25 points)

This question is not relevant for the upcoming Particle Physics 2025 exam.

3 Decays of J/ψ (15 points)

The $J/\psi(1S)$ is a spin-1 $c\bar{c}$ bound state with mass $m = 3096.900\,\text{MeV}$ and decay width $\Gamma = 92.6\,\text{keV}$.

a) (4) The D^0 is a $c\bar{u}$ meson and it is the lightest charmed meson ($m = 1864.84\,\text{MeV/c}^2$). Can the $J/\psi(1S)$ decay to $D^0\overline{D}^0$? Give reasons.

b) (5) $J/\psi(1S)$ decays to $\gamma\gamma\gamma$. Determine the eigenvalue C of charge conjugation for $J/\psi(1S)$ knowing that C becomes -1 for the photon.
Then, explain why a decay to $\gamma\gamma$ is not possible.

c) (6) Consider the following decay channels of the $J/\psi(1S)$.
(The superscript * indicates a virtual particle.)

$$J/\psi \to ggg \quad (\to \text{hadrons}) \quad \text{with } \mathcal{B} = (64.1 \pm 1.0)\,\% \tag{1}$$
$$J/\psi \to \gamma^* \to q\bar{q} \quad (\to \text{hadrons}) \quad \text{with } \mathcal{B} = (13.46 \pm 0.07)\,\% \tag{2}$$
$$J/\psi \to \gamma^* \to \ell^+\ell^- \quad \text{with } \mathcal{B} = (11.93 \pm 0.05)\,\% \tag{3}$$

The part ($\to$ hadrons) indicates that the gluons and quarks will not be observed freely but that they will hadronize.

Notice the different coupling strengths for the strong and electromagnetic interaction. For $J/\psi(1S)$, we have $\alpha_s \approx 0.28$ (strong interaction) and while $\alpha \approx 1/137$ (electromagnetic interaction) is much smaller. However, the total branching fraction of electromagnetic decays $J/\psi \to \gamma^* \to X$ (decays (2) and (3)) is about 25 %.

Why is the total branching fraction of electromagnetic $J/\psi(1S)$ decays so large despite the much smaller coupling strength?

4 *B* Mesons (20 points)

The B^+ is a $u\bar{b}$ meson and the D^0 a $c\bar{u}$ meson. Consider the Feynman diagrams shown in Fig. 1 describing $B^+ \to \overline{D}^0 K^+$ decays and in Fig. 2 describing $B^+ \to D^0 K^+$ decays.

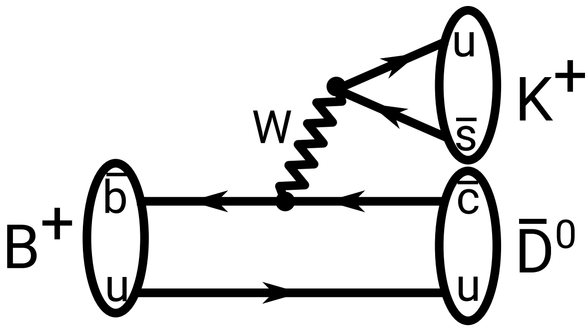

Figure 1: $B^+ \to \overline{D}^0 K^+$ decays.

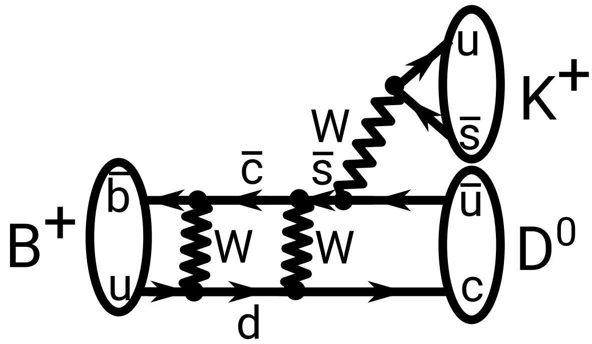

Figure 2: $B^+ \to D^0 K^+$ decays.

a) (7) Which CKM matrix elements $V_{\alpha\beta}$ are involved in each case? Comment also on the size of the involved matrix elements based on the transitions between generations.

b) (4) Based on the Feynman diagrams in Fig. 1 and Fig. 2, which of the two decays is more likely? Give at least one reason.

c) (4) In Fig. 2, the $\bar{c}$ and d quark could be replaced by a quark and antiquark of different flavor. Which antiquarks could replace the $\bar{c}$ and which quarks could replace the d?

d) (5) The above Feynman diagrams are not the only diagrams contributing to these decays. Consider the Feynman diagram for $B^+ \to \overline{D}^0 K^+$ in Fig. 3. Does this diagram contribute equally, more or less to the decay rate of $B^+ \to \overline{D}^0 K^+$ than the diagram in Fig. 1? Give reasons.

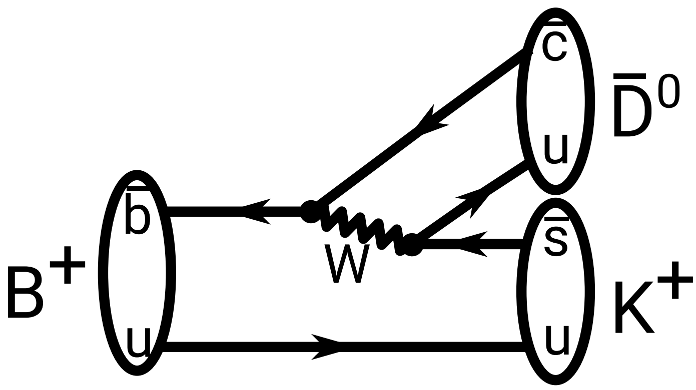

Figure 3: Additional Feynman diagram for $B^+ \to \overline{D}^0 K^+$ decays.