The aim of this mini-project is to place the current knowledge of flavour physics in historical context. We will study four famous papers that led to the current Standard Model as we know it. In the course of this mini-project we will use booklet of the Particle Data Group [1]. The questions below are ment to guide you through the papers (which can also be found here [2]). I hope you enjoy this historical journey towards the present knowledge of flavour physics in the Standard Model!

1 Neutral Particle Mixing

Abraham Pais and Murray Gell-Mann, *Behavior of neutral particles under charge conjugation*, 1955 [3]

a) When the process $\theta^0 \to \pi^+\pi^-$ (3) is discussed, they say "for the observed decay (3) evidently cause the conversation law to break down". What converstation law do they refer to?

b) How do we nowadays call the "novel situation" of the "virtual transition" $\theta^0 \to \pi + \pi^- \to \bar{\theta}^0$?

c) How do we nowadays call the θ^0, $\bar{\theta}^0$, θ^0_1 and θ^0_2 ?

d) Why does this "novel situation" of the "virtual transitions" not occur with neutrons?

e) On page 1389, it is argued that θ^0_1 and θ^0_2 are "not completely unphysical". In fact, how do they characterize a true "particle" ?

f) They quote lifetimes of 1.5×10^{-10}s and 3.5×10^{-10}s. For curiosity, look up the present knowledge.

g) What prediction is made at the end of the paper, regarding "a neutral boson"? What particle do they refer to?

2 Cabibbo Angle

Nicola Cabibbo, *Unitary symmetry and leptonic decays*, 1963 [4]

a) Give an example of a leptonic K^0 decay.

b) Look up the partial widths of $K^+ \to \mu^+\nu$ and $\pi^+ \to \mu^+\nu$, the particle masses, and calculate the value for θ. (Hint: Remember that the *total* partial width is related to the lifetime: $\tau = 1/\Gamma$.) Compare your value of θ to the best known value today.

c) Compare the predictions of Cabibbo (Table I.) to the presently known values.

3 GIM Mechanism

Sheldon Lee Glashow, John Iliopoulos, and Luciano Maiani, *Weak interactions with lepton-hadron symmtry*, 1970 [5]

a) At the time of the writing of the paper, what was the branching fraction of the decay $K \to \mu^+\mu^-$?

b) When did Bjorken and Glashow propose the 4th quark?

c) How were the three light quarks called at that time?

d) Why is the introduction of an extra quark appealing from the point of view of symmetries?

e) What is the 2-dimensional "space" on which the 2x2 matrix in Eq.(5) acts (i.e. what are the "dimensions") ? (spin, lorentz (x, t), ... , ... ?)

f) On page 1289 the new feature of neutral current diagrams with the exchange of W^+, W^- pairs. Draw that diagram for $K^0 \to \mu^+\mu^-$. Explain why it is called a "neutral current".

g) On the same page, the W^0 is introduced, and on the page 1290 even a "daring speculation" is made. Do you know how we usually call W_S, and B nowadays? (Hint: Remember that nowadays we call the gauge field belonging to the $U(1)$ transformation B, and the three fields belonging to $SU(2)$ we call W_1, W_2, W_3. A combination of W_3 and B leads to the massless photon (A) and the massive Z.)

h) Why were charmed hadrons never been observed, the authors argue? Give an example of a charmed hadron and its decay. Look up the branching ratio of your decay. Discuss how you judge the complexity of the decay topology.

i) In Section 4, the authors state that the new quantum number charm is broken only by the weak interaction. Explain what they mean, and what it implies for its decay: is it fast or slow? So, why do the authors argue it is "short-lived" ?? Compared to what?

j) On page 1292 they discuss what the signature of the W^0 could be at low-energy experiments. What is that signature? Give the Feynman diagrams of both proposed processes.

k) Back on page 1289, the authors state that the "conventional model ... contradicts experiment", whereas in their "case, these difficulties are absent". What "difficulty" do they refer to, you think? (See also Ex. 2a.)

4 Kobayashi-Maskawa Scheme

Makoto Kobayashi, Toshihide Maskawa, *CP-violation in the renormalizable theory of weak interaction*, 1973 [6]

a) What do the authors mean with "triplet" and "quartet" model?

b) Can the transition $s \rightarrow \gamma d$ occur in the Standard Model? Can you think of a higher order diagram (with a loop) that makes this transition possible?

c) Explain what is ment with flavour changing neutral current (FCNC).

d) To what "difficulty" do the authors refer in the "triplet model" ?

e) On the first page a term $\mathcal{L}'$ is added to the Lagrangian. They only use it in their scenario iv), What is *generically* ment with $\mathcal{L}'$, you think?

f) Consider the "quartet" model. Which quarks belong to group A), and what quarks are contained in group C)?

g) Consider the cases i), ii), iii) and iv). What is the most natural choice?

h) How do we nowadays call the four quarks listed in Eq.(3) ?

i) The experimental prediction is made that "CP-violating effects appear only in $\Delta S \neq 0$ non-leptonic processes" and in the "semi-leptonic decay of neutral strange mesons". Can you specify the processes they refer to?

j) They say "CP-violating effects appear only in $\Delta S \neq 0$" processes and they are "not concerned with higher states with new quantum number". But we are... What higher states do they mean, you think?

References

[1] *PDG live*, 2013, available on `http://pdglive.lbl.gov/`.

[2] *Inspires*, 2013, available on `http://inspirehep.net/help/easy-search`.

[3] Gell-Mann, Murray and Pais, A., *Behavior of neutral particles under charge conjugation*. Phys.Rev. **97**, 1387 (1955).

[4] Cabibbo, Nicola, *Unitary Symmetry and Leptonic Decays*. Phys.Rev.Lett. **10**, 531 (1963).

[5] Glashow, S.L. and Iliopoulos, J. and Maiani, L., *Weak Interactions with Lepton-Hadron Symmetry*. Phys.Rev. **D2**, 1285 (1970).

[6] M.Kobayashi and K.Maskawa, *CP violation in the renormalizable theory of weak interaction*. Prog. Theor. Phys. **49**, 652 (1973).