Study of charm production by neutrinos in nuclear emulsion
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Chapter 1

Charming neutrinos

I have committed the ultimate sin, I have predicted the existence of a particle that can never be observed.
Wolfgang Pauli [1]

Neutrinos are not only charming but also very peculiar particles: postulated by a theorist, detected in an experiment and studied now for 40 years. But still today neutrinos remain enigmatic, newspapers title it *The Ghost Particle* and they are subject of research for many experiments all around the world.

In the work described in this thesis some properties of neutrinos have been studied, in particular concerning their interaction with matter. It emphasizes that neutrinos are not only charming themselves but that they can also produce so called *charmed particles*.

In the following introduction we give an overview of the intriguing field of neutrino physics.

How did it all start?

In the beginning of the 20th century a fundamental problem teased the physicist: in certain radioactive decays the energy did not seem to be conserved. In 1931 Wolfgang Pauli suggested that this missing energy could be carried away by an unknown neutral particle which was escaping detection. In 1934 Enrico Fermi developed a comprehensive theory of radioactive decays, including Pauli's hypothetical particle and coined it *neutrino* (which means in Italian *little neutron*). Since the neutrino (\(\nu\)) interacts very weakly with matter it took until 1959 to observe it. In that year Clyde Cowan and Fred Reines detected the neutrino for the first time in an experiment. For this discovery they received
CHAPTER 1. INTRODUCTION

Family | Flavour | Electric Charge | Mass (MeV) |
--- | --- | --- | --- |
First | (anti-)electron electron (anti-)neutrino | $e^-$ ($e^+$) | $\nu_e$ ($\bar{\nu}_e$) | -1 (+1) | 0 | 0.511 | $< 3 \times 10^{-6}$ |
Second | (anti-)muon muon (anti-)neutrino | $\mu^-$ ($\mu^+$) | $\nu_\mu$ ($\bar{\nu}_\mu$) | -1 (+1) | 0 | 105 | $< 0.19$ |
Third | (anti-)tau tau (anti-)neutrino | $\tau^-$ ($\tau^+$) | $\nu_\tau$ ($\bar{\nu}_\tau$) | -1 (+1) | 0 | 1777 | $< 18.2$ |

Table 1.1: The lepton families.

the 1995 Nobel Prize in physics. Since the discovery, in numerous experiments it was tried to measure properties of the neutrino and to find answers to various questions. Is the neutrino stable? Are there other neutrino species? Is the neutrino its own antiparticle? Does a neutrino have a mass? How and where are neutrinos produced? Does the neutrino have a magnetic moment? How do neutrinos interact with matter? It goes beyond the scope of this thesis to give the status of the answers to all of these questions, but a comprehensive overview can be found in Reference [2]. One of the questions that is discussed in detail in this thesis is how neutrinos interact with matter and how they can produce charmed particles.

How does the neutrino fit into today’s picture of the world?

In 1962 experiments at Brookhaven and CERN made a surprising discovery: there are at least two types of neutrinos. One is associated with the electron ($e$), the other with the muon ($\mu$), the heavier partner of the electron. Later in 1975 a third type (flavour) of particle from this lepton family was found, the tau ($\tau$) particle. The existence of the corresponding tau neutrino was already fully accepted for many years because of indirect evidence [3], before it was directly observed in 2000 by an experiment at Fermilab [4]. All leptons have anti-particles; this completes our present picture of three lepton families as represented in Table 1.1.

Not only in the neutrino field but also in other sectors of particle physics dramatic progress has been made during the past decades. In an experiment in 1968 at the Stanford Linear Accelerator (SLAC) it was found that nucleons, when probed at high space-time resolution, contain partons, later identified as quarks. Hence, the leading theoretical description is called the Quark-Parton-Model (QPM). Particles called baryons, such as the proton, are bound states of...
<table>
<thead>
<tr>
<th>Family</th>
<th>Flavour</th>
<th>Electric Charge</th>
<th>Mass (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>(anti-)up</td>
<td>$u (\bar{u})$</td>
<td>+2/3 (-2/3)</td>
</tr>
<tr>
<td></td>
<td>(anti-)down</td>
<td>$d (\bar{d})$</td>
<td>-1/3 (+1/3)</td>
</tr>
<tr>
<td>Second</td>
<td>(anti-)charm</td>
<td>$c (\bar{c})$</td>
<td>+2/3 (-2/3)</td>
</tr>
<tr>
<td></td>
<td>(anti-)strange</td>
<td>$s (\bar{s})$</td>
<td>-1/3 (+1/3)</td>
</tr>
<tr>
<td>Third</td>
<td>(anti-)top</td>
<td>$t (\bar{t})$</td>
<td>+2/3 (-2/3)</td>
</tr>
<tr>
<td></td>
<td>(anti-)bottom</td>
<td>$b (\bar{b})$</td>
<td>-1/3 (+1/3)</td>
</tr>
</tbody>
</table>

Table 1.2: The quark families.

three quarks; *mesons* are composed of a quark and an antiquark.

The quarks and anti-quarks also come in three families and their (trivial) names can be found in Table 1.2. In the QPM, the nucleon contains three *valence* quarks surrounded by a *sea* of virtual quark-antiquark pairs. For instance, the valence quarks of the proton are two $u$ quarks, each with electric charge 2/3, and one $d$ quark with charge -1/3, whereas the sea can consist of all quark-antiquark flavours.

Both, quarks and leptons, are fermions with half integer spin (intrinsic angular momentum).

Furthermore, it has been found that all interactions in nature are governed by four fundamental forces: the electromagnetic, weak, strong and gravitational force. They are all four\(^2\) mediated by bosons (with integer spin) summarized in Table 1.3.

Neutrinos are only subject to the weak force. In the case of a (charged) $W$ exchange the interaction is denoted as charged current (CC), in the case of a (neutral) $Z$ exchange as neutral current (NC).

In a CC interaction, there is a transition between different quark flavours. In technical terms, the quark mass eigenstates are no weak flavour eigenstates but linear combinations of these (flavour mixing). This results in particular

\(^2\)Until today no quantum theory for gravity has been developed. Hence, the graviton is only a hypothetical particle.

<table>
<thead>
<tr>
<th>Force</th>
<th>Mediator</th>
<th>Relative Strength</th>
<th>Range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>strong</td>
<td>gluon ($g$)</td>
<td>1</td>
<td>$&lt; 10^{-15}$</td>
</tr>
<tr>
<td>electromagnetic</td>
<td>photon ($\gamma$)</td>
<td>$10^{-2}$</td>
<td>$10^{-18}$</td>
</tr>
<tr>
<td>weak</td>
<td>$W^\pm$ and $Z^0$</td>
<td>$10^{-5}$</td>
<td>$10^{-18}$</td>
</tr>
<tr>
<td>gravity</td>
<td>graviton ($G$)</td>
<td>$10^{-42}$</td>
<td>$\infty$</td>
</tr>
</tbody>
</table>

Table 1.3: The known forces.
probabilities for different transitions. Important for charm production, the subject of this thesis, are the CC quark flavour transitions \( d \rightarrow c \) and \( s \rightarrow c \). Experimentally it has been observed that transitions between quark flavours of different families are less probable than transitions within the same family. This experimental phenomenon is called Cabibbo suppression, and thus charm production on \( d \) quarks is Cabibbo suppressed with respect to the production on \( s \) quarks. The flavour mixing for all quark transitions is expressed in a \( 3 \times 3 \) matrix, called the Cabibbo-Kobayashi-Maskawa (CKM) matrix and can be parameterized by three mixing angles and a phase [5].

When neutrinos interact with matter, another concept becomes important: the detailed theoretical description of the internal dynamics of the nucleon. This can be well described by Quantum Chromodynamics (QCD), the fundamental theory of strong interactions. In analogy with Quantum Electrodynamics (QED), the theory of the electromagnetic force, in QCD the quarks and gluons carry a 'charge' called colour being responsible for the strong force. Colour comes in three varieties, usually denoted as 'red', 'blue' and 'green'. Since the gluons carry colour themselves, they can interact not only with quarks but also with other gluons. Single bare quarks have not been observed in a detector. They are confined in colour neutral ('white') hadrons, the colour force increasing with inter-quark distance. However, for increasingly smaller distances the inter-quark coupling becomes weaker and the quarks behave as if they are almost free. This phenomenon is called asymptotic freedom and it allows the use of perturbation theory within QCD at small distances. Structure functions expressed in terms of quark and gluon distribution functions are used to describe the structure of hadrons in scattering processes on nucleons.

Are neutrinos oscillating?

No overview of the field of neutrino physics is complete without a discussion of the recent compelling evidence for neutrino oscillations, in particular coming from the Super-Kamiokande [6] experiment in Japan. Here neutrinos are measured that are generated by cosmic rays in the Earth's atmosphere. After decades of theoretical expectations and earlier experimental indications (see Reference [7] for a review), the experiment finds a specific neutrino flavour \((\nu_\mu)\) disappearing.

The most natural explanation is that the neutrino flavour can change temporarily from \( \nu_\mu \) to \( \nu_\tau \). The latter neutrinos are not detected in the Super-
Kamiokande experiment. Theoretically the possibility that neutrinos *oscillate* between flavours implies that at least one of them has a non-zero mass.

The CHORUS experiment was designed to search for this $\nu_\mu \rightarrow \nu_\tau$ oscillation phenomenon. It uses the CERN neutrino beam and investigates a different regime of mass and mixing parameters than the Super-Kamiokande experiment. The CHORUS experiment does not observe a signal for neutrino oscillation within its accessible parameter space, which is different from that of the Super-Kamiokande experiment. More details of the present CHORUS oscillation search result can be found in Reference [8].

**What is in this thesis?**

The thesis is structured as follows. After the current introductory chapter, in Chapter 2 a theoretical introduction is given on charm production by neutrinos. Furthermore, an overview of the present experimental situation can be found there. Chapter 3 describes the experimental setup of the CHORUS detector and explains the state-of-the-art scanning techniques of nuclear emulsion. Chapter 4 deals with our study of deep-inelastic charm production, whereas in Chapter 5 a different charm production process, diffractive production, is discussed.

In summary, the research reported in this thesis has been performed to increase our insight concerning properties of the neutrino in relation to the quark structure of the nucleon. Not only the knowledge itself is important and interesting, but also the consequences it has for the understanding of the world around us.

Quoting a recent paper [9], "[...] *The relic tau neutrinos* [may] *have sufficient energy density to close the university*", the impact of neutrino properties may even be larger for society than usually assumed.