Onderwerpen van Natalie Jachowicz

37374: Cross sections for neutrino-oscillation experiments

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Aantal studenten:	1
Aantal masterproeven:	1
AJ:	2024-2025

Probleemstelling:

The experimental confirmation of neutrino oscillations, rewarded with a Nobel prize in 2015, sparked off an enormous experimental and theoretical interest in the oscillation properties of these elusive particles. Worldwide, several collaborations are working on extending our knowledge about neutrino masses and mixing angles.

In oscillation experiments, oscillation parameters are determined by ‘counting’ neutrinos in a ‘near’ (close to the neutrino source) and ‘far’`(typically a couple of hundreds of kilometers away) detector. The ‘counting’ is done by detecting neutrinos, usually by means of neutrino-nucleus interactions because these processes result in relatively high interaction probabilities for these particles only interacting by means of the weak nuclear force. The difference in numbers then settles the oscillation probability of the neutrino. This quantity however depends on the energy of the incoming neutrino. As neutrinos cannot be produced in monochromatic beams but always come with a broad energy distribution, the reconstruction of the energy of the incoming neutrino in the detector is equally important as its interaction probability. Up to now, the most important dynamical mechanism in the energy region important for current experiments is charged-current quasi-elastic scattering. where the neutrino scatters off a neutron bound in the nucleus, transforms it in a proton and is itself changed into a charged massive lepton of the same flavor. Based on the incomplete information provided by the outgoing lepton’s kinematics in this type of interactions, experimental analyses try to reconstruct the incoming neutrino’s energy and identify the neutrino-oscillation signal. Theoretical models have to be able to provide an accurate prediction of neutrino-nucleus cross sections and their energy dependence, as well as provide and describe the ways in which experiments can establish the energy of the interacting neutrino.

Doelstelling:

Our research group recently joined the ESSnuSB (https://essnusb.eu/) collaboration. This is a European effort aiming at installing a long-baseline neutrino experiment at the European Spallation Source in Lund (Sweden) and detecting the neutrinos at a far detector 360 km away in the Zinkgruvan mine. The project stands out as it concentrates fully on the second neutrino resonance region making it complementary to other collaborations, and as it operates in a lower energy range than other accelerator-based programs. This makes this program both challenging and extra interesting, from the point of view of oscillation studies, interaction physics as well as BSM searches. With this master thesis project, we aim at using the cross section modeling tools developed in our research group to provide dedicated cross section predictions for targets and reaction channels in the energy regime relevant for ESSnuSB. .

Locatie:

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Website:

Meer informatie op: compphys.ugent.be

37208: Detecting supernova neutrinos on Earth

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Probleemstelling:

While the future generation of accelerator-based neutrino experiments are built with the primary aim of enhancing our knowledge on neutrino oscillations and determing the CP violating phase, the detectors that are constructed are also able to observe the low-energy neutrinos reaching the Earth from a galactic supernova.
These neutrinos are produced in enormous amounts at the end of the life of a massive star when the center of the star implodes and neutronization processes take place. When the central density of the star reaches and exceeds nuclear density values, the star core bounces and a shock wave sets off. Densities drop, the neutrinos produced during the neutronization processes are released and can reach detectors on Earth, carrying with them precious information about the processes going on in the very center of the supernova event, information that is not accessible with optical observations. In 1987, the handful of neutrinos from supernova 1987A that were observed showed these basic ideas to be correct and proved that it is indeed possible to detect these neutrinos. Nowadays, several experiments (e.g. DUNE) are planning for a much more detailed study of these neutrinos, their flavor, energy, arrival time, etc.

Doelstelling:

For the detection of supernova neutrinos one often relies on their interaction with atomic nuclei. Recent measurements of low energy neutrino cross sections (e.g. by the COHERENT collaboration) however show strong discrepancies between predictions and data for these reactions, indicating that in this energy regime, the interaction and the influence of nuclear effects is only poorly understood.
The aim of this master proof is to study these low energy neutrino-nucleus cross sections and investigate the role of nuclear effects and uncertainties for supernova neutrino detection.

Locatie:

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Meer informatie op: http://compphys.ugent.be/

37365: Final state interactions in coherent pion production

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Probleemstelling:

Coherent pion production refers to pion-nucleus scattering that leaves the nucleus intact. Coherent pion production in neutrino experiments is relatively rare, but neutral-current coherent interactions contribute to one of the main backgrounds in oscillation analyses, for example, at the T2K experiment. The identification of these processes is carried out through measuring the pion decay into two photons, which can mimic the electron neutrino appearance signal. This motivates the development of a realistic and sophisticated treatment of coherent pion production on nuclei. In general, two methods are used to model this interaction. The first one involves making use of the partially conserved axial vector current (PCAC) principle to relate neutrino-induced coherent pion production to elastic pion-nucleus scattering amplitudes. The second one is to adopt a fully relativistic and quantum mechanical point of view, making a nuclear description identical to the one used for incoherent pion production.

Doelstelling:

In this project, we aim to model coherent pion production following the second method, based on the Gent model for pion production with a relativistic mean field (RMF) model for the bound nucleon states, which has proven to be successful in reproducing lepton-induced single pion production on nuclei. The impact of final state interactions (FSI) between the pion and the nucleus after the interaction, and medium modifications must be studied in order to develop a full coherent pion production model. This thesis subject offers the opportunity to spend a research stay in the neutrino research group of Complutense University of Madrid or University of Seville.

Locatie:

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Website:

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37378: Modeling kaon production for neutrino oscillation experiments

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Probleemstelling:

In long-baseline neutrino oscillation experiments, neutrinos are produced with a broad energy range. This results in several competing reaction mechanisms for the neutrino-nucleus interaction used for detecting the neutrino, that all need to be modeled in order to fully understand the oscillation signal.
At sufficiently high neutrino energies, mesons begin to be created in the neutrino-nucleon interaction. The most common interaction mechanism of this type is pion production. Alternatively, kaons (mesons containing a strange quark) can be produced. The kaon production signal is usually small compared to the the more common pion production, as it is Cabibbo suppressed, but it will provide an important contribution to the signal in the detector. In the detectors of the short-baseline neutrino (SBN) program (https://sbn.fnal.gov/) and in the future Deep Underground Neutrino Experiment (DUNE https://www.dunescience.org), kaon production is expected to be an important interaction mechanism. A proper modeling of the process will hence be important to reduce systematic errors in the neutrino energy reconstruction and the oscillation analysis.

Doelstelling:

The goal of this project is to explore the development of a kaon production model for lepton-induced charged-current kaon production. Firstly, modeling the vertex in which the kaon is produced and then applying final state interactions to model the propagation of the kaon through the nuclear medium. This thesis subject offers the opportunity to spend a research stay in the neutrino research group of Complutense University of Madrid or University of Seville.

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37373: Neutrino-induced single pion production on the nucleon

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Probleemstelling:

In neutrino-nucleus scattering experiments, neutrino energies typically span a broad range. Neutrino-induced single pion production constitutes a large part of the signal in present and future oscillation experiments aiming at measuring the CP violating phase in the leptonic sector. Depending on the energy of the process, characterized by the hadronic invariant mass W, different approaches are used.

At low invariant mass, single pion production can be modeled by combining background diagrams for the pion-nucleon system (originating from a chiral perturbation theory Lagrangian) and a subsequent decay of nucleon resonances like the Delta resonance. To push the model to higher invariant masses, one has to incorporate an increasing number of resonances and higher-order background diagrams. This approach quickly becomes intractable. In the models developed in our research group, we therefore describe electroweak pion production at higher energies by making use of an approach based on Regge theory. In general, a transition amplitude for a hadronic process can be described by an infinite summation of all partial waves in the t-channel. This infinite sum is cast into a contour integral in the complex angular momentum plane. In this way, Regge theory provides one with the s-dependence of the amplitude.

Doelstelling:

This model for single pion production is under development, especially at higher values of the invariant masses. Recently, we reformulated the model in the language of a multipole expansion. This procedure yields a lot more freedom to finetune the model and to incorporate physical constraints like the unitarity of the scattering matrix. A master thesis in this research line aims to extend the electroweak single pion production model and implement the new developments in the computational model.
In this context, several topics are available for the thesis research. For instance, better unitarization methods need to be implemented, especially at higher energies. The dispersion relations of scattering amplitudes can be used to tackle this problem. Another example concerns the second resonance region that contains more resonances, that need to be implemented to complete the model.

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37230: One-nucleon detection scenarios in neutrino-nucleus interactions

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Probleemstelling:

The precise measurement of neutrino properties is among the highest priorities in fundamental particle physics, involving extensive experimental efforts worldwide. Neutrinos are tiny, elusive particles that interact only weakly, making their detection with matter remarkably challenging. In our group, we study interactions of neutrinos with bound nucleons inside atomic nuclei, providing essential theoretical input needed to conduct neutrino measurements and experimental analyses. Modeling neutrino-nucleus scattering processes is a complex many-body problem, traditionally performed in the independent-particle picture, focusing on the quasielastic neutrino-nucleon interactions or the excitation of nucleon resonances. Improving our knowledge of such cross sections to the levels required by modern neutrino-oscillation experiments involves research beyond this first approximation, incorporating the effects of nucleon correlations and multinucleon knock-out processes.

This project involves the state-of-the-art interaction model developed by our research group, i.e., a non-relativistic, mean-field-based model with dynamically generated short-range nucleon correlations and explicit two-body dynamics with meson-exchange currents. This framework, exhaustively compared against electron scattering, provides predictions of inclusive, semi-inclusive, and exclusive cross sections for neutrino-nucleus interactions leading to final states with one- or two-nucleon emission. Using this as a starting point, we aim to model exclusive processes where exactly one knocked-out nucleon is detected. Apart from the intuitive one-nucleon emission reaction, the contributions to such processes also come from two-nucleon scenarios in which the second nucleon remains undetected. An accurate description of these reactions is an essential input to support experimental analyses, approaching the precision era of neutrino measurements.

Doelstelling:

Having chosen this project, the student will work directly with our numerical code, contributing to its further development. The multidimensional cross section calculations involve extensive numerical calculations on the computer cluster, which utilize analytical and numerical integration methods depending on the final purpose. We expect to compare such results extensively to the available electron and neutrino scattering data, identifying the essential impact of nucleon correlations and other model ingredients. The practical tools intended to be used involve basic knowledge of particle and nuclear physics, programming skills, numerical integration methods, large-scale numerical computations, interpretation of comparisons to experimental data, and dissemination of research results.

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