Standard Model of Weak Interaction

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In this course we will introduce the main elements of the Standard Model of particle physics, with special attention to the weak interaction and the various symmetries. Then we will discuss how to go beyond this theoretical paradigm in a model-independent manner, which will lead us to the concept of Effective Field Theory (EFT). We will discuss in some detail the specific case of the Standard Model EFT, which is developed to analyse experiments carried out at or below the electroweak scale. In this framework the Standard Model is the leading term and New Physics are encoded in higher-order subleading corrections. We will then discuss its low-energy EFT, relevant for experiments carried out at much lower energies, where heavy fields, such as the electroweak gauge bosons, have been integrated out. This EFT represents the quark-level starting point for studying beta decays in a model-independent way.

We will also discuss the neutrino sector, from the parametrisation of their masses and mixings to the study of their interactions within the EFT framework. We will discuss phenomenological applications, with emphasis in the importance of global and consistent studies.

We will explain how the EFT approach allows for a comparison between experiments carried out at very different scales and involving different particles, such as beta decay, neutrino oscillations and collider physics.

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Beta Decay

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Historically, the insight from nuclear beta decay experiments have played a pivotal role in the development of the Standard Model (SM) of fundamental interactions. In these lectures I will present an overview of beta decays from a broader and more modern perspective. The goal is to connect the phenomenology of beta decays to the ladder of effective field theories (EFTs) representing fundamental interactions at different energy scales. I will show how EFTs above and below the electroweak scale, which describe the SM physics as well as hypothetical interactions beyond the Standard Model, can be matched to an EFT of nucleons and nuclei. I will discuss in great detail how the beta decay rates and correlations depend on the parameters of these EFTs at the leading and subleading orders. Some time will be devoted to the possibility of measuring CP violation in beta decays, as well as to the special case of double beta decay.

The important advantage of this EFT framework is the opportunity to compare the sensitivity of different experiments operating in different energy regimes. In particular, one can compare the sensitivity of beta decays (MeV scale), pion and kaon decays (GeV scale), and lepton pair production at the high-energy tail in the LHC (TeV scale). This exercise will also allow me to formulate some general conclusions about the chances of finding new physics in beta decay experiments.

These lectures consist of four parts. The first part is a historical review of beta decays, introducing the most important concepts and observables. The second part discusses the connection between the EFT of beta decays and the quark-level EFTs below and above the electroweak scale. This matching allows one to establish the sensitivity of beta decays to new particles beyond the SM. In the third part this sensitivity is compared to the one achievable in other experiments, which highlights the most promising directions in beta decay research. The final part is focused on CP violation in beta decay and on double beta decay, with the emphasis on understanding which kind of new physics these observables may uncover.

Nuclear transitions to search for physics beyond the standard model

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Nuclear transitions have the advantage that nature provides many isotopes with many different beta-transition spin sequences, so that a proper choice can maximize the sensitivity to the physics aimed at. Typical observables are beta-transition ft-values, (angular) correlations between the spin and momentum vectors of the different particles involved in the beta decay, and the beta spectrum shape.

For many years the corrected Ft-values of the $0^+ \rightarrow 0^+$ superallowed pure Fermi transitions have been the major source leading to the value of the V_{ud} quark-mixing matrix element. Combined with the other matrix elements on the first row of this matrix (i.e. V_{us} and V_{ub}), the unitarity of the matrix can be tested, allowing to check on possible physics beyond. Recently the Ft-values from neutron decay and the beta transitions between the so-called mirror nuclei have become sufficiently precise that they start contributing to the value of V_{ud} as well. Apart from spectroscopic quantities characterizing the respective beta transitions, a correlation measurement to determine the Gamow-Teller/Fermi mixing ratio is required for the neutron and mirror beta decays as well. Making further progress on the precision of V_{ud} requires both improved experimental data for the neutron and mirror beta decays, but also improved theoretical calculations for several small corrections included in the Ft-values.

Correlation measurements with different beta transitions (including the neutron and mirror beta decays) allow addressing possible types of new physics beyond the standard model, such as right-handed currents, but also scalar or tensor type weak currents, the latter usually via the Fierz interference term. Traditionally, the beta-neutrino angular correlation and the beta-asymmetry parameter, but recently also the beta-spectrum shape, are used for this. At the present level of precision of 0.5% and better, small corrections induced by the strong interaction (often called recoil corrections, the larger of which being weak magnetism) are to be included as well. Recent beta-spectrum shape measurements provide useful additional information on the weak magnetism term, while global analysis of existing experimental data allow setting limits on the possible presence of scalar and tensor types of weak interactions.

The Quest for the Electric Dipole Moment of the Neutron

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Symmetries play a central role in the understanding of fundamental interactions, particularly the discrete symmetries P (parity), C (charge conjugation), and T (time reversal). Establishing that the weak interaction violates all three of these symmetries has been instrumental in constructing the Standard Model. The pattern of symmetry violation is subtle and interesting. While the violation of P has major observable consequences in nuclear beta decays, the violation of T is only significant for processes involving heavy quarks and has not been observed with nuclei. This feature is explained by the structure of the Standard Model of weak interactions, which allows for T violation (or CP violation) only if the model contains at least three generations of quarks. In nuclei, the virtual effects associated with the second and third generations of quarks are extremely small, and therefore T violation is also expected to be very small.

This lecture will focus on a precision test of T symmetry with neutrons, pursued in order to challenge the Standard Model of weak interactions. Specifically, we will discuss electric dipole moment (EDM) of the neutron, which is defined as the coupling between the neutron spin and an applied electric field, in the same way that the magnetic dipole moment represents the coupling between the spin and the magnetic field.

We will cover the following topics in a two-hour lecture:

- The EDM of a spin 1/2 particle is a T-violating observable. The neutron EDM is a sensitive probe of new physics beyond the Standard Model of weak interaction.

- The high precision of experiments is made possible by the use of ultracold neutrons. These extremely low-energy neutrons can be stored in material bottles and exposed to an applied electric field for long durations, comparable to the beta decay lifetime of the neutron, which is 15 minutes. We will give an introductory course on ultracold neutrons, explaining the central concept of the neutron optical potential, also called the Fermi potential.

- We will explain the basic experimental concepts of neutron spin manipulation: polarizer, analyzer, resonance methods to measure the Larmor precession frequency. In particular we will describe Ramsey's method of separated oscillating fields.

- To finish we will present and discuss concrete experiments.

Precision measurements of neutron beta decay

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Free neutrons decay into proton, electron and electron antineutrino. Neutron decay is the prototype for nuclear beta decay, with nuclear structure effects absent. Accurate neutron decay data are needed in calculations of many processes involving semileptonic weak interaction, such as primordial or stellar nucleosynthesis or the detection of reactor antineutrinos by inverse beta decay. On the other hand, neutron decay can be used to search for new physics beyond the Standard Model of particle physics: in the standard model, neutron decay is described by only two parameters, while a good dozen of observables, such as the neutron lifetime and correlations in neutron decay, are available to over-constrain the model and to search for deviations.

One lecture will be devoted to the measurement of neutron lifetime. It will discuss neutron sources, storage experiments as measurement of the total and beam experiments as measurement of a partial neutron lifetime, and the so-called neutron lifetime puzzle. In the other lecture, the geometry and symmetry properties of correlations in neutron decay will be related to concept of measurements and associated systematic effects. Experimental concepts and recent examples will be discussed. A particular focus of both lectures is the connection between the design of an experiment and its systematic effects.

Neutrinoless Double Beta Decay Searches

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One of the hottest topics in particle physics nowadays is the definition of the neutrino mass and nature, as after the neutrino oscillations discovery it was confirmed that neutrinos are massive particles. Neutrinoless double beta (0n2b) decay observation would provide essential information about neutrino properties, and it would confirm Majorana nature of the neutrino.

Numerous experiments worldwide are aiming at the discovery of this process. This is not an easy task, as 0n2b decay is predicted to be an extremely rare process (half-life > 10^(27) yr).

These lectures will review the most common technologies that are used for 0n2b decay searches, background and sensitivity evaluation for experimental searches. The overview will include the most interesting results from past experiments, as well as the current status and perspectives of 0n2b decay experiments in the next decade.

Beta Decay and Reactor Antineutrinos

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During the last 15 years, large neutrino experiments at reactors have been devoted to the measurement of the last remaining unknown mixing angle of neutrinos q_{13} [1]. While these experiments achieved its measurement with a good precision [2], anomalies have emerged affecting reactor antineutrino energy spectra. The first anomaly called the "reactor anomaly"[3] is a deficit of measured antineutrinos at short baseline reactor experiments with respect to spectral predictions[4,5]. One of the hypotheses to explain the reactor anomaly was the oscillation in sterile neutrinos[5], triggering the start of new experiments close to research reactors. Then another anomaly appeared, with the measurement of the antineutrino energy spectra by the three international reactor neutrino experiments Double Chooz, Daya Bay and Reno showing spectral distortions w.r.t the same spectral predictions[6]. This puzzle is called the "shape anomaly". The latter predictions were obtained through the conversion of integral beta energy spectra obtained at the ILL research reactor[4,5]. Several studies have shown that the underlying nuclear physics required for the conversion of these spectra into antineutrino spectra is not totally under control[7,8]. The unique alternative to converted spectra is a complementary approach consisting in determining the antineutrino spectrum through nuclear data[9,10] called the summation method. It was shown that beta decay properties of some key fission products suffer from the pandemonium effect[11] which can be circumvented through the use of the Total Absorption Gamma-ray Spectroscopy technique (TAGS) [12]. The understanding of reactor antineutrino spectra is not only useful for fundamental particle physics but also mandatory for neutrino applied physics [13]. During the last decade, TAGS experiments have been performed worldwide bringing the summation method to another level, allowing to reach an agreement with the reactor antineutrino flux measured by the neutrino experiments at the 2% level [14]. Lately short baseline experiments at research reactors have published new measurements of reactor antineutrino spectra [15-18].

In this lecture, we will first present the context of the reactor antineutrino anomalies and the models quoted above. A nice summary can be found in [19]. We will then present the actual status in light of the experimental constraints obtained by neutrino experiments and the spectrum models [16,20]. We will also describe the nuclear beta decay experiments that were performed to improve the model predictions. We will then discuss the perspectives which promise a nice interplay between neutrino physics and nuclear physics [21].

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Neutrino astrophysics: a window to new physics

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In this lecture I will first summarise the recent advances concerning neutrino oscillations in vacuum and their implications. Then I will introduce the open many-body problem of how neutrinos change their flavor in dense astrophysical environments, in particular core-collapse supernovae and binary neutron star mergers. I will discuss the novel flavor mechanisms that have been uncovered in the last years, the future observation of supernova neutrinos and the upcoming discovery of the diffuse supernova neutrino background. I will particularly emphasize the fundamental aspects of this domain and its importance for the search for new physics.