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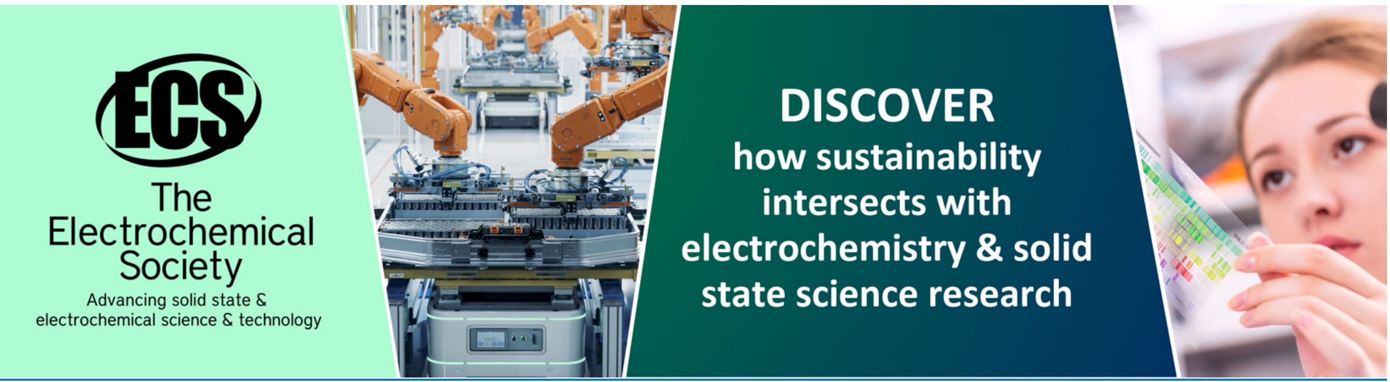

Fundamental physics with low-energy neutrons

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Abstract. Low-energy neutrons are playing a prominent role in a growing number of fundamental physics studies. This paper provides a brief description of the physics that some of the experiments in the area are addressing.

1. Introduction

In the present days, many of the new advances in fundamental physics come from experiments in high energy physics, however experiments at low energies, particularly those with high intensities of low-energy neutrons, also can shed light on some of the most fundamental questions of the physics laws that govern the Universe. The unique properties of low-energy neutrons (with energies ranging from a few meV to hundreds of neV), that can be effectively formed into intense polarized beams, or stored in traps with boundaries that are material, magnetic, gravitational, or combination of these, make it possible to use them in a variety of studies that include the properties of the neutron itself (electric dipole moment), its decay (neutron lifetime and correlation parameters), the study of fundamental interactions (hadronic weak interaction), the violation of symmetries (parity and time reversal), or the search for possible new exotic interactions, just to mention some examples.

2. Parity violation and the hadronic weak interaction

As a consequence of the non-perturbative nature of QCD at low energies and the dominance in intensity of the effects of the strong force in the nuclear interactions, we do not have a first-principles description of the weak interaction between hadrons. The weak interaction is the only fundamental interaction that can change the flavor of quarks and can violate the parity symmetry, thus the weak interaction can be studied in flavor-changing mechanisms, like the strangeness-changing non-leptonic decays of mesons and baryons, or in hadronic and nuclear processes where parity is violated. The use of polarized cold neutron beams in the study of nuclear processes that exhibit parity violation (PV) is of interest for several reasons [1, 2]. At low energies the strong interaction between nucleons is dominated by the exchange of pions, which corresponds to isospin exchange of $\Delta I = 1$; charged currents are suppressed for this isospin channel and therefore low-energy nuclear weak interactions offer the possibility to study neutral currents. Since the range of the weak bosons is small compared to the nucleon size, these studies constitute a probe for quark-quark correlations. Also a better understanding of the nucleon-nucleon weak interaction would be of help in testing nuclear structure models using PV effects in nuclear and atomic systems. In addition to this, there are observed phenomena in the strangeness-changing sector of the hadronic weak interaction (HWI) which cannot be explained in the framework of the existing theories, like the dominance of the $\Delta I = 1/2$ channel in the decay of kaons or the relatively weak amplitudes in the non-leptonic decay of hyperons [2]; the understanding of these phenomena requires input from the flavor-conserving PV sector. The theoretical attempts to describe the HWI include the one-meson exchange model, proposed more than 30 years ago by Desplanques, Donoghue and Holstein [3], effective field theories (EFT) [4] and more recently lattice QCD calculations [5]. For the first two, the experimental determination of weak coupling constants that cannot be calculated is necessary; for the last, comparison of theoretical and experimental results can guide new theoretical predictions for other systems. For several years now, a program to determine the weak coupling constants in experiments using polarized cold neutrons and light targets has been taking place [6, 7]. One of the purposes of this program is to measure PV observables in few-nucleon systems, where nuclear structure uncertainties are smaller and a more reliable correlation with the weak coupling constants can be attained. In this context, so far three low-energy neutron experimental collaborations have taken data: NPDGamma, Neutron Spin Rotation (NSR) and n-^{3}He. In the capture of polarized cold neutrons by protons, the NPDGamma experiment measures the PV asymmetry, with respect to the neutron spin direction, in the emission of gamma rays that follows the capture ($\vec{n}+p \rightarrow d+\gamma$). This asymmetry is dominated by the $\Delta I = 1 \;\; ^3S_1 - {}^3P_1$ parity-odd transition in the np system, therefore it is related to the weak coupling that characterizes the exchange of one pion in the HWI, h^1_π. The details of the experiment can be found at [1, 8, 9]. The experiment had a first stage at the Los Alamos National Laboratory Neutron Science Center (LANSCE) whose result was statistically limited [1]. A second stage of the experiment at the Spallation Neutron Source of the Oak Ridge National Laboratory (SNS-ORNL) concluded this year and results with statistical uncertainty in the 10^{-8} range will be published soon. The n-^{3}He collaboration finished data taking last year at the SNS-ORNL and analysis is in progress. This experiment measures the asymmetry, with respect to the neutron spin direction, in the direction of emission of the protons produced in the $\vec{n} + {}^3He \rightarrow t + p$ nuclear reaction. NSR is an experiment that measures the neutron spin rotation angle for polarized cold neutrons passing through unpolarized ^4He. The experiment has a statistically limited result [10] from its first stage at the Center for Neutron Research of the National Institute of Standards and Technology (NCNR), and the collaboration is preparing an improved apparatus for the second stage also to take place at the NCNR [11].

3. Probing the electroweak interaction in the neutron beta decay

The free neutron beta decay presents the possibility to measure a number of observables: the neutron lifetime τ_n, the electron-neutrino correlation coefficient a , the Fierz interference term b, and in the case of polarized neutrons, the correlation coefficients of the neutron spin and the momentum of the electron A and the neutrino B. An interesting aspect of the neutron beta decay is that in the electroweak theory three of these observables (a, A and B) depend on only one parameter, λ, the ratio of axial-vector to vector neutron coupling constants (g_A and g_V), while b should be zero. The experimental determination of these coefficients would over-constrain λ, allowing for the performance of different consistency checks of the electroweak theory and for a sensitive search for new physics. In addition, the precise determination of λ, together with τ_n, can be used to determine the V_{ud} term in the Cabibbo-Kobayashi-Maskawa (CKM) matrix. The accurate determination of the matrix elements is important for its unitarity consistency checks (weak universality), as well as to establish constraints to physics beyond the SM. At present the most precise determination of V_{ud} comes from super-allowed nuclear beta decays. Its extraction from free neutron beta decay, which would have the advantage of avoiding many-nucleon effects present in other nuclear decays, has however not been as precise due to experimental inconsistencies in λ and τ_n. While several experimental collaborations are trying to resolve the neutron lifetime puzzle [12, 13], neutron studies like Nab [14] and $abBA$ [15], to take place in the near future at the SNS-ORNL, are attempting to resolve these inconsistencies for λ, potentially making the free neutron beta decay the most accurate way to determine V_{ud}.

4. Search for possible exotic long-range spin-dependent interactions of the neutron

In the spontaneous symmetry breaking in theories with two or more Higgs doublets, a new vector boson associated with an extra axial generator acting on quark and lepton fields may appear, giving rise to an exotic interaction mediated by a light vector boson coupling to a fermion. In the non relativistic limit this interaction gives rise to potentials proportional to $g_A^2 \vec{\sigma} \cdot (\vec{v} \times \vec{r})$ and $g_A g_V \vec{\sigma} \cdot \vec{v}$ [16]. These potentials are among the 16 different operator structures that were studied by Dobrescu and Mocioiu [17] and that are part of the possible non-relativistic fermion-fermion interactions that satisfy rotational invariance. Interactions of this type have been poorly studied due to the experimental challenges that they encompass, however setting limits to these possible exotic interactions is becoming more relevant, as many theories beyond the SM propose, in some cases as a way to explain dark matter and energy, the existence of new light weakly-coupled particles that would induce interactions of relatively long range. Neutrons are a very suitable tool to probe for such interactions since they can be formed into beams with high polarization and their energy and momentum transfers can access the mesoscopic scale. In the recent years polarized low-energy neutrons have been used to set the most stringent limits in some possible exotic interactions, like the limit at distances below 1 cm for any parity-odd long-range interaction of the neutron with matter mediated by spin 1 boson exchange, the upper bound on parity-odd components of possible in-matter gravitational torsion coupled to neutrons [18], and limits for possible parity-even exotic interactions of polarized neutrons with matter from spin 1 boson exchange with axial couplings [19]. Currently the NSR collaboration is conducting an experiment at LANSCE to improve the existing limits in the possible exotic axial-vector couplings of neutrons to matter for ranges below 1 cm [16].

5. Parity and time reversal violation in compound nuclei

One of the challenging questions for the SM is the explanation of the asymmetry between matter and anti-mater in the early stages of the Universe, which led to the predominance of matter that we observe in the present. Almost 50 years ago, Andrei Shakarov [20] proposed three necessary conditions that should have been satisfied in the early Universe so that an imbalance between matter and anti-matter could have been produced: violation of baryon number, violation of C and CP symmetries, and deviation from thermal equilibrium. Regarding the second of these conditions, CP violation has been observed in the decay of Kaons and B mesons [21, 22, 23], however additional sources of CP violation, as well as CP violation in strongly interacting systems, are needed in order to account for the matter/anti-matter imbalance. Since the CPT symmetry remains as one that has to be conserved in any physics interaction, the violation of time reversal symmetry is a via to search for sources of CP violation. Electric dipole moments (EDM) and T violation in resonances of compound nuclei are possible sources of T violation and therefore CP violation in strongly interacting systems. Regarding fundamental neutron physics, significant efforts to measure the neutron EDM are taking place [24] and future experiments to find evidence of T violation in resonances of compound nuclei that can be accessed with low-energy neutrons are in preparation [25]. In the past, large amplification of PV amplitudes in compound nuclei due to nuclear structure have been observed [26], and theory indicates that similar enhancement in T violation amplitudes are to be expected.

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