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Fundamental physics with cold and ultracold neutrons

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Cold and ultra-cold neutrons are ideal tools for testing fundamental symmetries of the electroweak interaction. The emphasis is on precision measurements of the intrinsic properties of the neutron, the neutron lifetime and correlation coefficients from the neutron beta-decay spectrum and the determination of the strength of the hadronic weak interaction. The science opportunities are discussed with emphasis on the Spallation Neutron Source upcoming program at the Oak Ridge National Laboratory.

Keywords: Cold neutrons; fundamental symmetries; neutron beta decay; electric dipole moment.

Neutrones fríos y ultrafríos son herramientas ideales para probar las simetrías fundamentales de la interacción electrodébil. El énfasis en medidas de precisión de las propiedades intrínsecas del neutrón, su vida media y los coeficientes de correlación del espectro del decaimiento beta del neutrón y la determinación de la intensidad de la de la interacción débil hadrónica. Las oportunidades científicas se discuten con énfasis en el programa de la “Spallation Neutron Source” que se inicia en el “Oak Ridge National Laboratory”.

Descriptores: Neutrones fríos; simetrías fundamentales; decaimiento neutron; dipolo eléctrico.

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1. Introduction

Cold ($\lambda \sim 0.5$ nm) and ultra-cold neutrons (UCNs, $\lambda{\sim}50$ nm) are unique tools to test fundamental symmetries of the electroweak interaction. Most experiments consist of precision measurements of the intrinsic properties of the neutron like the search for its electric dipole moment, the neutron lifetime and correlation coefficients from the neutron β-decay spectrum and the determination of the strength of the hadronic weak interaction.

In the US, the construction of the Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory is opening the door to a new generation of these measurements that hold the promise for substantial improvements in precision. A discussion of these science opportunities is presented below as well as a brief status of the fundamental physics project at the SNS.

2. Neutron electric dipole moment

The violation of time-reversal (T) symmetry, and the closely related CP symmetry, is among the most fundamental issues in physics. The interaction of a photon with the permanent electric dipole moment (EDM) of the neutron, $\boldsymbol{d}_N$, violates both parity (P) and T invariance. Assuming that CPT symmetry is exact, this interaction would also violate CP invariance. The amount of CP violation in the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix of the Standard Model (SM) would imply a magnitude for $\boldsymbol{d}_N$ of roughly 10^{-32} e-cm [1], whereas the present experimental limits from the Particle Data Group (PDG) imply $|\boldsymbol{d}_N|$ ¡ 6.3 $\times 10^{-26}$ e-cm (90% confidence) [2].

Shapiro proposed the utilization of UCNs in EDM measurements in 1968 [3]. A future UCN experiment operating at the SNS could improve the present experimental limit by at least two orders of magnitude [4]. Should an EDM be discovered in this range, it would imply either some new CP violation outside the SM – as needed to explain the prominence of matter over antimatter in the universe – or a non-zero value for the θ parameter in the quantum chromodynamics (QCD) Lagrangian. In order to distinguish between these two possibilities, one would require EDM searches on complementary systems.

3. Neutron decay

The neutron is the simplest of all nuclear β- decays. Its decay spectrum, averaged over electron spin, is given by

$$\frac{dW}{dE_e d\Omega_e d\Omega_\nu} \propto p_e E_e (E_0 - E_e)^2$$
$$\times \left[1 + a\frac{\tilde{\mathbf{p}}e\cdot\hat{\mathbf{p}}\upsilon}{Ee} + b\frac{me}{Ee} + A\frac{\vec{\sigma}n\cdot\tilde{\mathbf{p}}e}{Ee}\right.$$
$$\left. + B\vec{\sigma}n\cdot\hat{\mathbf{p}}\upsilon + D\vec{\sigma}_n\cdot\frac{\tilde{\mathbf{p}}e\times\hat{\mathbf{p}}\upsilon}{E_e}\right]$$

where $p_{e(\nu)}$ is the electron (neutrino) momentum, $E_{e(0)}$ is the electron energy (end point energy) and σ_n is the neutron spin. The correlation coefficients a, b, A, $B$and Dall have definite predictions in the framework of the polar vector and axial vector (V-A) theory of β decay [5]. Four of the coefficients (a, A, B, D) depend on the parameter λ, the ratio of axial-vector to vector coupling constants (g_A/g_V), and they are given by

$$a = \frac{1-\lambda^2}{1-3\lambda^2}, \qquad A = -2\frac{\lambda^2+\lambda}{1-3\lambda^2},$$
$$B = 2\frac{\lambda^2-\lambda}{1-3\lambda^2}, \qquad D = \frac{2\lambda\sin\phi}{1+3\lambda^2}.$$

The Fierz interference term, b, is predicted to be 0 and a nonzero value can be generated by interference of the vector current with a possible scalar current or the axial vector current with a possible tensor current. The violation of time-reversal invariance implies a non-zero value for the coefficient D (for time-reversal invariance the angle ϕ should be 0 or π).

Because the neutron lifetime depends on a linearly independent combination of g_A and g_V, a determination of it when combined with precise measurements of parity-violating correlations in neutron β-decay, provides a determination of g_A and g_V. Using this information one can calculate the quark mixing matrix element V_{ud} in a manner independent of nuclear structure effects. This result can then be combined with other measurements to test the unitarity of the CKM matrix. Furthermore, by carefully measuring the coefficients of the allowed angular correlations (electron-neutrino (a), neutron spin-electron (A), neutron spin-neutrino (B)) one can search for the presence of right-handed currents, the effects of supersymmetric particles, and scalar and tensor terms in the weak interaction [6].

Finally, the weak coupling constants as well as the value of the neutron lifetime play a significant role in our understanding of big-bang nucleosynthesis and precision cosmology. Hence improved measurements of both the neutron lifetime and the correlation coefficients can have an important impact on our understanding of both nuclear physics and astrophysics. The availability of enhanced sources of cold and ultracold neutrons, along with the future high intensity pulsed cold neutrons from the SNS, provides the opportunity to make significant strides in reducing the uncertainties on both the neutron lifetime and the allowed correlation coefficients.

4. Nucleon-nucleon weak interactions

Quark-quark weak interactions produce very small ($\sim 10^{-7}$) parity-violation (PV) effects in the NN system [7,8]. At present, the study of hadronic PV provides the only known window on weak interactions between the up and down quarks. The range of the weak interaction between the quarks is much smaller than the size of the nucleon, and the strong repulsion of two nucleons at short distances means that the dynamical mechanism for the weak interaction between nucleons must involve meson exchange. Theoretical advances in the description of parity violation in the NN and few nucleon systems promise to make contact with QCD. The valence quark model used by Desplanques, Donoghue, and Holstein (DDH) [9] to calculate effective PV meson-nucleon couplings directly from the SM employs a weak pion-nucleon coupling constant f_π, and six other phenomenological meson couplings.

Experimentally, measurements have been performed in both few-body systems, such as the *pp* and *p*α systems, and in nuclei ranging from the p-shell nuclei like ^{18}F to heavy nuclei such as ^{133}Cs. The longest-range part of the interaction is dominated by f_π. Measurements of the circular polarization of photons in the decay of ^{18}F [10,11] imply a small value for f_π, while precision PV measurements in $p-p$ and ^{133}Cs [12] seem to imply a large value for f_π [13,14] relative to the DDH [15] estimates. The origin of these discrepancies may lie in approximations used to compute effects in nuclei, in the use of the DDH model as the basic framework, in one or more of the experiments, or some combination. Ideally one would like to obtain a set of numbers that are free from the uncertainties associated with many-body nuclear physics and that do not require a meson-exchange model for interpretation. Recently, a theoretical framework for such a program has been developed using the ideas of effective field theory (EFT) [16].

Carrying out a program of hadronic PV measurements with neutrons will allow one to arrive at a complete determination of the leading-order PV operators in a way that is independent of nuclear model approximations. The key ingredients in this project include a set of seven measurements in few-body systems and the corresponding few-body calculations. Since the theoretical technology exists for performing reliable *ab initio* few-body computations, the missing ingredient is experimental. Several different PV experiments have been suggested: measurement of the gamma asymmetries in n+p→d+γ and in n+d→t+γ reactions, and measurement of the neutron spin rotation in ^{4}He and H_2. Because the observable in each of the above experiments depends upon different linear combinations of the weak π, ρ, and ω couplings, a determination of a number of the couplings is possible. Intense pulsed spallation neutron sources such as the SNS at ORNL possess enough flux to see the effects, and the use of time-of-flight information from the pulsed source is an important aid for isolating systematic effects for these experiments.

5. The spallation neutron source

The SNS will be the most powerful pulsed, spallation neutron source for the foreseeable future. It is expected that the facility will produce the first beam in 2006 and begin providing user operations hours in 2007 at a level of 1400 hours per year and relatively low beam power. The SNS is expected to be operating at essentially full potential by the end of 2009. By 2010 the facility is expected to operate at full power and high reliability for approximately 5000 hours per year.

The primary focus of the facility is condensed-matter physics. Nuclear physics has the opportunity to capitalize on this investment and a program in fundamental neutron science at this world-class facility is under development. A dedicated beam port for cold and ultracold neutrons has been reserved for such a program by the SNS management. The new beam line at the SNS would give the US nuclear physics community access to neutrons from a state-of-the-art facility and place us in a more competitive position with our European colleagues who have, for many years, maintained strong programs in fundamental physics with neutrons at the Institut

Laue-Langevin (ILL) in France and more recently at the Paul Scherrer Institut (PSI) in Switzerland.

The fundamental neutron physics beam-line will be one of 24 beam-lines at the SNS facility. Two experimental areas are under construction for the SNS fundamental neutron physics program: a cold neutron beam line with an experimental station inside the SNS experimental hall at 18 m and a 0.89 nm beam-line and experimental area outside the SNS experimental hall at 50 m for UCN experiments. The 0.89 nm beam will be selected from the cold beam by a double-crystal monochromator so that both experimental areas may be operated simultaneously.

Work is underway in designing a multiple-purpose spectrometer to accommodate the different measurements of the neutron β-decay correlation parameters. These experiments together with those of neutron PV on few-body systems will make use of the cold neutron beamline. Experiments, such as the neutron EDM measurement, that are sensitive to acoustic and mechanical noise would benefit from the construction of the hall outside the SNS experimental hall.

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