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Neutron-decay correlation measurements with polarized and pulsed beams

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Abstract

Neutron-decay polarization correlations arise due to the interference of amplitudes with different transformation properties, i.e. V, A, S, P, and T corresponding to vector, axial vector, scalar, pseudoscalar and tensor. Measurements of a number of these correlations are used to constrain fundamental parameters of the Standard Model as well as probe new physics. Recent and future efforts that I will discuss include time-reversal violating correlations, e.g. the *D* coefficient and its relation to the neutron EDM as well as the beta-neutrino correlation, with emphasis on systematic errors that could arise from residual polarization that can be measured with a pulsed neutron beam such as provided by the SNS or ESS.

Keywords:

1. Introduction

While the most general formulation of beta-decay allows for vector (V), axial-vector (A), scalar (S), pseudoscalar (P) and tensor (T) amplitudes, the Standard Model is written with only V and A interactions. Allowing for T-violation, there is one arbitrary overall phase and three free parameters: g_V, g_A and the relative phase of λ, which vanishes in the absence of T violation. The value of $g_V = G_F|V_{ud}|$ follows from CVC (an assumption of the Standard Model) with G_F determined from the muon lifetime and V_{ud} most precisely determined from super-allowed, $0^+ \rightarrow 0^+$, beta decays (Hardy and Towner (2005)). The parameter $g_A = |\lambda| g_V$ is determined

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from correlation-coefficient measurements, which are expected to reach precision of 0.1% and better. For polarized neutrons, the decay rate can be written (Jackson et al. 1957):

$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} = \frac{1}{\tau_n} G(E_e) \left\{ 1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \vec{P}_n \cdot \left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right) \right\} \quad (1)$$

where $\vec{P}_n$ is the ensemble average of the neutron spin. In the Standard Model, the coefficients a, A, and B depend only on λ, while Beyond-Standard-Model-Physics (BSMP) contributions from to scalar and tensor currents may also contribute. Thus a set of measurements overconstrains Standard Model Physics and can be viewed as a search for BSMP. A finite D coefficient would arise in the event of T-violation, and thus can be viewed as a measure of the phase of λ.

2. emiT: Triple correlation in neutron decay

The emiT experiment (Mumm et al. (2011)) measured the *D*-coefficient correlation by measuring proton-electron coincidences. This triple correlation is T violating, P conserving, and is small in contrast to the T-even/P-odd beta and neutrino asymmetries. The experiment was designed to optimize the tradeoffs of maximum coincidence decay rate, sensitivity to *D*, and symmetry to cancel the effects of the T-even/P-odd correlations. This triple correlation is in particular sensitive to four-quark effects due to lepto-quark exchange (Herczeg (2001)), which is also constrained by limits on the neutron EDM assuming the EDM arises only due to 4-quark interactions (Ng and Tulin (2012)). Four electron detectors consisting of plastic scintillators with phototubes at either end alternated with four planes of silicon-barrier detectors in an octagonal array surrounding the neutron beam. A total of more than 3×10^8 events formed the data set from which *D* was extracted; significant additional data were used for calibrations and systematic studies.

A blind analysis approach was adopted that required that all aspects of the data analysis including event definition, cuts, analysis techniques and all systematic effects to be finalized before revealing an artificial offset to *D*. A large range of systematic effects were identified and studied using the data, background studies, experimental details such as maps of neutron-beam and neutron-polarization distributions and a detailed Monte Carlo simulation of the experiment (Chupp et al. (2012)). Analysis included study of the effects of backgrounds, detector non-uniformities, polarization and beam distributions and a number of cuts on experimental parameters including magnetic fields, leakage currents, beta-detector multiplicity, proton acceleration voltage and a software threshold on the beta energy. The final result, $D = [-0.94 \pm 1.89(\text{stat}) \pm 0.97(\text{sys})] \times 10^{-4}$ represents the most sensitive measurement of *D* in nuclear beta decay and can be interpreted in terms of possible extensions of the Standard Model. Assuming no scalar or tensor currents, this result constrains the complex phase between the axial-vector and vector currents to $\varphi_{AV} = 180.012° \pm\ 0.028°$ (68% confidence level). If all currents are allowed there are four additional phases from scalar and tensor amplitudes, which can be constrained under specific assumptions. A more detailed discussion is presented in Chupp et al. (2012).

3. Nab: Measuring a, A, B, C

To measure a with unpolarized neutrons and *A* and *B* with polarized neutrons, a new spectrometer has been developed by the Nab/abBA/PANDA collaboration. The Nab spectrometer measures the proton velocity and electron energy in coincidence (Baessler (2012)). The first measurement planned is the beta-neutrino correlation with the goal of a 0.1% measurement of a. The Fierz-interference coefficient b, which arises in neutron decay due to a combination of scalar and tensor currents, will also be extracted by accurately measuring the electron energy spectrum. The neutrino asymmetry *B*, which is sensitive to scalar and tensor contributions in first order, can be separated from *A* by measuring the electron-energy E_e dependence of the proton asymmetry *C*. Radiative corrections to *C* have been calculated (Glück (1996)). Contributions from new physics, for example scalar leptoquarks have been proposed (Herczeg (2001)), and a detailed study of the sensitivity of C to new physics has been presented by Gudkov (2008).

In the Nab detector, charged particles produced in neutron decay are confined by strong, non-uniform magnetic field with the effect that transverse momentum components are converted to longitudinal components while the energy remains constant. Thus the proton time of flight becomes a good measure of the proton velocity and therefore proton energy. A highly pixelated silicon detector has been developed, in which each detector pixel maps to a specific position in plane of the neutron beam. Electron energy is measured in the energy-calibrated silicon detectors. Extracting the beta-neutron correlation-coefficient a requires the proton and electron energy.

The beta-neutrino asymmetry measurement with the Nab spectrometer will take place at the Oak-Ridge Spallation Neutron Source (SNS) Fundamental Neutron Physics Beamline (FP13). With expected data rates of $600\ s^{-1}$ for proton-electron coincidences, statistical precision of 10^{-3} should be possible in about 6 weeks or running; therefore Nab should not be statistics limited. A large number of systematic effects related to the spectrometer magnetic fields, stray electric fields, non-uniformities and calibrations have been studied in detail and are presented in Baessler (2012). One interesting possible systematic effect would arise if the neutron beam is polarized. The residual polarization of a nominally unpolarized neutron beam has never been measured, but is crucial for Nab: a neutron polarization of 0.01% would produce an error on a of 6×10^{-4} due primarily to the neutrino asymmetry. Measurement of the expected small polarization of the SNS FP13 beam with sufficient precision is a significant challenge, and we plan to use a polarized ^{3}He cell. The ^{3}He polarization will be flipped with losses less than 10^{-4} by adiabatic-fast-passage NMR (AFP) in a “magic box” magnetostatic cavity similar to that described by Babcock (2009). With the intense FP13 neutron beam, statistics for a 10^{-4} measurement for all practical neutron velocities can be acquired in a short time. One important issue for the neutron-polarization measurement is the guide field for neutrons. The Nab-spectrometer magnetic field is vertical, and the field reverses as the neutron beam enters and exits the spectrometer. Assuming neutrons emerging from the FP13 guide are polarized along the local field, the worst case scenario would be adiabatic transport into the Nab-spectrometer decay region. One promising way to investigate this is to set-up a guide field that would adiabatically transport polarized neutrons into the spectrometer and use a neutron spin flipper based on AFP to flip the spins of all neutron velocities with high precision. The spin transport would be set up and tuned with neutrons polarized by a ^{3}He spin filter. The a measurement would then be the average of the two neutron spin states, and if P_n is sufficiently large, *e.g.* 10^{-3}, the neutron polarization would also be revealed.

4. Neutron polarimetry

The pulsed neutron beam provides significant advantages for neutron polarimetry due to the velocity dependence of polarized neutron transmission through polarized ^{3}He, as first demonstrated by Zimmer et al. (1999). The transmission of neutrons through polarized ^{3}He is different for spin-up and spin-down neutrons so that ratios of transmissions through polarized ^{3}He measured as a function of neutron velocity are used to determine P_n and spin-flipper efficiency with high statistical precision. A large class of effects are cancelled in ratios described in Chupp (2007), however backgrounds, non-linearities or rate dependence in the neutron detectors and electronics, and uncertainty in the neutron wavelength determination may give rise to systematic effects. The sizes of these effects have not been directly measured, however we have explored the effects through simulations, which show that wavelength dependent backgrounds can account for observed systematics. Other systematic errors arise because the windows of the spin filter cell are not perfectly flat or parallel. Numerical study of the effects of curved windows shows a systematic correction of about +0.1%.

5. Neutron-beam effects on ^{3}He polarization

Neutron beam effects on spin-exchange pumped (SEOP) ^{3}He were discovered in studies of the $n + p \rightarrow d + \gamma$ spin filter and were investigated in dedicated experiments at LANSCE and ILL (Sharma (2008)). The observed drop in ^{3}He polarization was shown to be due to increased relaxation of the optically pumped alkali-metal. SEOP is the only option for long-term, steady-state operation of ^{3}He spin filters used as neutron polarizers and polarimeters. Double SEOP cells similar in concept to those we first developed for electron scattering are a promising solution.

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References

J.C. Hardy, I.S. Towner (2009). Phys. Rev. C79, 055502.
N. Severijns, M. Beck, O Navialiat-Cuncic (2006). Rev. Mod. Phys. 78, 991.
J.D. Jackson, S.B. Treiman, H.W. Wyld Jr. (1957). Nucl. Phys. 4, 206.
H.P. Mumm et al. (2011). Phys. Rev. Lett. 107, 102301.
P. Herczeg (2001). Prog. Part. Nucl. Phys. 46, 413.
J. Ng and S. Tulin (2012). Phys. Rev. D 85, 033001
T.E. Chupp et al. (2012). Phys. Rev. C 86, 035505.
S. Baeßler (2012) for the Nab Collaboration, (arXiv:1209.4663).
F. Glück (1996). Phys. Lett. B376, 25.
V. Gudkov (2008). Phys. Rev. C 77, 045502.
E. Babcock et al. (2009). Physica B 404, 2655.
T.E. Chupp et al. (2007). Nucl. Instr. Meth. A 574, 500.
M. Sharma et al. (2008). Phys. Rev. Lett. 101, 083002.
O. Zimmer et al. (1999). Phys. Lett. B 455, 62.