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Precision Neutron Polarimetry for Neutron Beta Decay

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The abBA collaboration is developing a new type of field-expansion spectrometer for measurement of the three correlation coefficients *a*, *A*, and *B* and shape parameter *b*. The measurement of *A* and *B* requires precision neutron polarimetry. We will polarize a pulsed cold neutron beam from SNS using a ^{3}He neutron spin filter. The well-known polarizing cross section for n-^{3}He has $1/v$ dependence, which is used to determine the absolute beam polarization through a time-of-flight (TOF) measurement. We show that measuring the TOF dependence of *A* and *B*, the coefficients and the neutron polarization can be determined with small loss of statistical precision and negligible systematic error. We conclude that it is possible to determine the neutron polarization averaged over a run in the neutron beta decay experiment to better than 10^{-3}. We discuss various sources of systematic uncertainties in the measurement of *A* and *B* and conclude that they are less than 10^{-4}.

Key words: neutron beta decay; neutron polarimetry; neutron time of flight; neutron polarization.

1. Introduction

Systematic uncertainties in the measurement of neutron polarization introduce important systematic uncertainties in measurements of the neutron decay correlation coefficients *A* and *B*. The proposed abBA experiment [1] will polarize pulsed cold neutrons from the SNS by transmitting the neutron beam through a polarized ^{3}He spin filter cell. An adiabatic RF spin flipper (RFSF) is used for pulse-by-pulse neutron spin reversal. After the RFSF the neutrons are guided from the low magnetic field region, a few10 G, into the decay volume of the spectrometer at 3.2 T. The pulse nature of the SNS beam and a parametric dependence of neutron polarization on energy are used to determine accurately beam polarization through a TOF measurement.

The beam polarization after the ^{3}He spin filter is $P_n = \tanh(P_3\, t/\tau)$, where P_3 is the ^{3}He polarization, $\tau = \frac{L}{n_3 \sigma_1 v_1}$, n_3 is the helium density, σ_1 is the polarizing cross section at v_1, and L is the flight path length. The polarizing cross section has the well-known energy (velocity) dependence, $\sigma = 848 \frac{\sqrt{1\ \mathrm{eV}}}{\sqrt{E}}$ barns. The decay spectrometer that detects coincidences between electrons and protons, measures simultaneously the beta decay asymmetries $\varepsilon_A = \frac{N\uparrow - N\downarrow}{N\uparrow + N\downarrow} = A\tanh(t/\tau)(1+\Delta)$ and $\varepsilon_B = B\tanh(t/\tau)(1+\Delta)$ as a function of neutron TOF, here $N\uparrow$ ($N\downarrow$) is a measured electron spectrum for neutron spin up (down). The quantity Δ includes corrections to polarization as discussed below. We show that $\Delta \sim 10^{-3}$ and the uncertainty in $\Delta < 10^{-4}$. The neutron energy dependence of these asymmetries arises from the energy dependence of polarization. From TOF spectrum of BP_n, since $B\sim 1$, it requires less counting statistics for the same relative accuracy than $A = \sim -0.1$, the coefficient B and the neutron polarization P_n can be determined without an auxiliary neutron polarization measurement by performing two parameter fits to the asymmetries *vs* TOF. Then P_n is used to determine A. The above approach has the distinct advantage that the neutron polarization is determined by the neutrons which are also used to determine A and B.

4. Systematic uncertainties from drifts in the ^{3}He polarization

Drifts in the neutron polarization introduce corresponding drifts in the measured asymmetries. The ^{3}He polarization in the spin filter cell may change by 1% in a few hours. The time is set by typical ^{3}He polarization build-up and decay rates, which are intrinsically slow because the coupling of the ^{3}He spin to its environment is weak. However, we seek to measure B (and A) ten times better than the typical drift. In order to understand how this is possible, first, consider a set of asymmetry data taken over a long period of time, T, with the ^{3}He polarization constant. One could analyze the complete data set, or divide the data set into N subsets and analyze the N subsets separately and average the results. The error in B for each subset would be increased by $\sqrt{N}$ but when the results are averaged over the N subsets, the value of B and the error in B would be the same as for the analysis of the complete run. Next, consider a data set where the polarization is a slowly-varying function of time. As the time span of subsets, T/N, approaches zero, the polarization may be taken to drift linearly. There is no loss in statistical precision associated with subdividing the data. We estimate the shift in the asymmetry caused by the linear drift and show that the shift in B is negligible. In figure 1 we show pseudo-random data generated for $P_3 = 0.7$, $\tau = 10$ ms, and B=-1 over the time range from 7 ms to 31 ms and for the 17 m long flight path. We assume a beta count rate of 100 Hz. The fitted asymmetry is –1.023±.0156 and the fitted average neutron polarization is 0.794±0.012. The time-average neutron polarization is determined from the time dependence of the asymmetry signal and B is determined from the average asymmetry. B will be determined from a large number of such runs. Although the neutron polarization has a statistical uncertainty of ~1.5% in each run, the asymmetry B can be determined to 0.1% in ~250 runs. The (uninteresting) time-average neutron polarization averaged over all runs would have an error of 0.0008. Although the neutron polarization in any given 20-minute run is uncertain by 1.2%, B can be determined with an uncertainty of 0.1% by averaging over many runs.

3. Inhomogeneous ^{3}He thickness

If the ^{3}He thickness, n_3, is not equal across the neutron beam, then the relationship between polarization and TOF is modified. $P_n = \tanh(P_3\, t/\tau)\left(1 - \frac{2t^2}{\tau^2}\operatorname{sech}(P_3\, t/\tau)^2 \frac{\sigma_n^2}{n^2}\right)$,

where $\frac{\sigma_n}{n}$ is the fractional variation in the thickness. For P_3=0.7, $\tau = 10$ ms, and $\frac{\sigma_n}{n}$= 1%, the correction term ~ 2×10^{-5}. The small variation of the cell thickness can be measured by observing the attenuation of a pencil beam of cold neutrons as the cell is scanned across the beam. This source of uncertainty is manageable.

4. Depolarization of the neutron spin in windows

After being polarized in the ^3He cell the neutron spin can be depolarized when interacting with nuclei with non-zero-spin or with unpaired atomic electrons. This can take place when the neutrons passing through material like the exit wall of the ^3He glass cell or aluminum windows of the RFSF or the entry window of the spectrometer. GE180 glass, used in the ^3He spin filter cells, have several metal oxides most of them as small residuals. The spin-flip cross sections = 2/3 of the incoherent cross sections were used to calculate the probabilities for the spin flips in a 3 mm thick GE180 glass. The largest spin-flip probability of 124×10^{-6} is for BaO_2 which is 18.2% by weight in the glass. The total spin-flip probability for the GE180 glass is 305×10^{-6}. However, the neutrons are scattered into 4π and the solid angle of the decay volume is $\sim4\pi\times10^{-3}$. The depolarization is thus $\sim3\times10^{-7}$ and is negligible. GE180 has also a small amount, 0.03 % by weight, of Fe_2O_3 component that can depolarize the neutron beam by spin-flip scattering by the unpaired electron. The total cross section for this spin flip is $\sim4\pi(\gamma e^2/mc^2)^2$=3.6 b which gives the spin-flip scattering probability of $\sim6\times10^{-6}$. This makes also the depolarization by electron scattering negligible.

5. Depolarization in inhomogeneous magnetic fields

We have studied neutron spin depolarization in inhomogeneous magnetic fields. The neutron beam is polarized by the ^3He spin filter, then the beam passes through RFSF and finally enters the high-field decay region in the field-expansion spectrometer. The function of the RFSF is to provide a fast spin flip with efficiency very close to unity. It is necessary that the spin be transported from the RFSF to the decay region with negligible loss of polarization. Depolarization can take place when a neutron passes through the fringing field of the spectrometer and/or in the adiabatic RF spin flipper. We have developed approximate expressions for the neutron spin wave function and the projection of the spin on the field as the neutron moves in space where the field direction and magnitude changes. The basic adiabaticity requirement is that the rate of a change of the field direction, has to be smaller compared to the Larmor frequency $\omega = \mu B/\hbar$, then the projection of the spin on the field direction is approximately conserved; the projection of the neutron spin on the field direction is an adiabatic invariant. In the design of the abBA experiment we will have a field configuration of $\vec{B} = B_0\hat{x} + \frac{dB}{dz}vt\hat{z}$, here the x-axis is the axis of the spectrometer magnet and the z–axis is the beam axis, in two situations. First, the polarized neutrons must make transition through the zero in the vertical component of the spectrometer magnet when entering the spectrometer. We plan to apply an additional horizontal field that transports the spin adiabatically through the zero region. Second, we will flip the neutron spin using an adiabatic RF spin flipper. In such a device, the vertical field has a small gradient. The RF is applied horizontally at a frequency that matches the Larmor frequency at some point along the neutron trajectory. In the Larmor frame, the neutron spin adiabatically follows the combination of RF and vertical field. A perturbative solution for the spin wave function in the coordinate system with the magnetic field in the z direction yields the asymptotic form for the depolarization, $D = \frac{\pi}{6}e^{\frac{4}{3}-\frac{\pi\lambda}{2}}$, where the adiabaticity parameter

$$\lambda = \frac{\mu B_0^2}{2\hbar\frac{dB}{dz}v} = \frac{\omega_1 B_0}{2\frac{dB}{dz}v},$$

where ω_1=1.8×10^4 rad/s/G is the angular precession rate of the neutron spin in a 1 Gauss field. The gradient in the vertical field for our magnet design is ~2×10^3 G/cm. A 10 meV neutron has a velocity of ~1.4×10^{5}cm/s. Solving λ=6 gives B_0=0.43 kG for a horizontal guide field in the neighborhood of the vertical field zero. A practical RF field strength is a few gauss. For B_{RF} = 5 G, we obtain a field of dB/dz=0.27 G/cm. Neither of these numbers presents difficulty.

6. Neutron energy calibration and intrinsic neutron pulse width

In addition to the proton pulse width of about 1μs at SNS, further time broadening is introduced by the neutron moderation process. In a simplified model a shape of a cold neutron pulse for single neutron energy is a Maxwell-Boltzmann TOF distribution. The width of the pulse is about 250 μs with a 600-μs tail. A number of the neutrons in the 600-μs tail has a $1/E$ dependence. The width of the neutron pulse has to be considered when determining the neutron energy by a TOF measurement. A 5-meV neutron has a 17 ms TOF. The first order shift in the TOF is ~ 400 μs/17 ms ~ 0.023. The moderation time can be measured *in situ* with a single crystal that scatters a monochromatic portion of the neutron beam. TOF of monochromatic neutrons gives the time profile for moderation of the neutrons of this energy. The moderation time profile will be measured for several neutron energies and the results fitted by adjusting the parameters needed to describe the moderator. For the above example, the first order correction to the average polarization is 2×10^{-3} and the second order correction is 1×10^{-7}. A measurement of the TOF with an accuracy of 5 % will reduce the uncertainty of the polarization from the neutron moderation time to 10^{-4}.

References

[1] W.S. Wilburn *et al,*.in these proceedings.

Figure caption

Figure 1. Pseudo-random data for the neutron spin – neutrino momentum correlation coefficient, *B*. Data represents a 20-min run with a 100-Hz decay rate. Red curve is the exact asymmetry and blue curve is the fitted asymmetry.

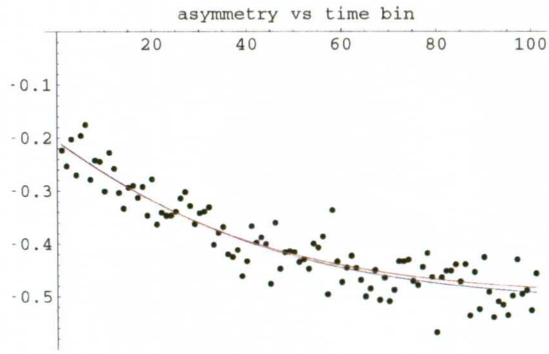

Fig. 1.