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Measurement of spin-flip probabilities for ultracold neutrons interacting with nickel phosphorus coated surfaces

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ABSTRACT

We report a measurement of the spin-flip probabilities for ultracold neutrons interacting with surfaces coated with nickel phosphorus. For 50 μm thick nickel phosphorus coated on stainless steel, the spin-flip probability per bounce was found to be $\beta_{\mathrm{NiP\ on\ SS}} = (3.\,3^{+1.8}_{-5.6}) \times 10^{-6}$. For 50 μm thick nickel phosphorus coated on aluminum, the spin-flip probability per bounce was found to be $\beta_{\mathrm{NiP\ on\ Al}} = (3.\,6^{+2.1}_{-5.9}) \times 10^{-6}$. For the copper guide used as reference, the spin flip probability per bounce was found to be $\beta_{\mathrm{Cu}} = (6.\,7^{+5.0}_{-2.5}) \times 10^{-6}$. The results on the nickel phosphorus-coated surfaces may be interpreted as upper limits, yielding $\beta_{\mathrm{NiP\ on\ SS}} < 6.2 \times 10^{-6}$ (90% C.L.) and $\beta_{\mathrm{NiP\ on\ Al}} < 7.0 \times 10^{-6}$ (90% C.L.) for 50 μm thick nickel phosphorus coated on stainless steel and 50 μm thick nickel phosphorus coated on aluminum, respectively. Nickel phosphorus coated stainless steel or aluminum provides a solution when low-cost, mechanically robust, and non-depolarizing UCN guides with a high Fermi potential are needed.

1. Introduction

Ultracold neutrons (UCNs) are defined operationally to be neutrons of sufficiently low kinetic energies that they can be confined in a material bottle, corresponding to kinetic energies below about 340 neV. UCNs are playing increasingly important roles in the studies of fundamental physical interactions (for recent reviews, see *e.g.* Refs. [1,2]).

Experiments using UCNs are being performed at UCN facilities around the world, including Institut Laue-Langevin (ILL) [3], Los Alamos National Laboratory (LANL) [4], Research Center for Nuclear Physics (RCNP) at Osaka University [5], Paul Scherrer Institut (PSI) [6], and University of Mainz [7]. One important component for experiments at such facilities is the UCN transport guides. These guides are used to transport UCNs from a source to experiments and from one part of an experiment to another. For applications that require spin polarized UCNs, it is important that UCNs retain their polarization as they are transported (see *e.g.* Ref. [8]).

In other applications in which polarized UCNs are stored for extended periods of time, such as neutron electric dipole moment experiments (see *e.g.* Ref. [9]) and the UCNA experiment (see *e.g.* Ref. [10]), it is also important that UCNs remain highly polarized while they are stored in a material bottle. In some cases, the depolarization of UCNs due to wall collisions is one of the dominant sources of systematic uncertainties in the final result of the experiment [11].

Because of its importance for these applications, the study of spin-flip probabilities and the possible mechanisms for spin flip is an active area of research [12–15]. The spin-flip probability per bounce has been measured for various materials. Refs. [12,14] report results on beryllium, quartz, beryllium oxide, glass, graphite, brass, copper, and Teflon, whereas Ref. [15] discusses results on diamond-like carbon (DLC) coated on aluminum foil and on polyethylene terephthalate (PET) foil. In addition, measurements of the spin-flip probability per bounce have been performed for DLC-coated quartz [16], stainless steel, electropolished copper, and DLC-coated copper [17]. (The results from Ref. [17] are available in Ref. [18].) The reported values for the spin-flip probability per bounce are on the order of 10^{-6} – 10^{-5} for all of these materials with the exception of stainless steel, for which a reported preliminary value for the spin-flip probability per bounce is on the order of 10^{-3} [17], two to three orders of magnitude larger.

The spin-flipping elastic or quasielastic incoherent scattering from protons in surface hydrogen contamination has been

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considered to be a possible mechanism for UCN spin flip upon interaction with a surface [12–15]. So far, however, data and model calculations have not been in agreement.

Another possible mechanism is Majorana spin flip [19] due to magnetic field inhomogeneity near material surfaces, from ferromagnetic impurities or magnetization of the material itself. In addition, the sudden change in direction that occurs when a UCN reflects from a surface can cause a spin flip in the presence of moderate gradients [13]. Gamblin and Carver [20] discuss such an effect for ^{3}He atoms. The high spin-flip probability observed for stainless steel in a large holding field [17] is likely due to magnetic field inhomogeneity near material surfaces or magnetization of the material itself.

Recently, based on the suggestion from Ref. [21], we have identified nickel phosphorus (NiP) coating to be a promising UCN coating material with a small loss per bounce and a high Fermi potential [22]. The Fermi potentials of NiP samples with a phosphorus content of 10.5 wt% (18.2 at%) coated on stainless steel and on aluminum were both found to be ≈ 213 neV [22], which is consistent with the calculated value and is to be compared to 188 neV for stainless steel and 168 neV for copper. NiP coating is extremely robust and is widely used in industrial applications. It is highly attractive from a practical point of view because the coating can be applied commercially in a rather straightforward chemical process, and there are numerous vendors that can provide such a service economically. It is important that the coating process not use neutron absorbing materials such as cadmium. Furthermore, alloying nickel with phosphorus lowers its Curie temperature (see *e.g.* Refs. [23–25]). As a result, when made with high enough phosphorus content, NiP is known to be non-magnetic at room temperature. Therefore, it is of great interest to study its UCN spin depolarization properties and how depolarization depends on the material used for the substrate.

In this paper, we report a measurement of the spin-flip probabilities for UCNs interacting with NiP-coated surfaces. We investigated aluminum and stainless steel as the substrate. The results obtained with NiP-coated surfaces are compared to those obtained with copper guides. This measurement was performed as part of development work for a new neutron electric dipole moment experiment at the LANL UCN facility [26] and an associated UCN source upgrade [27].

This paper is organized as follows. In Section 2, the experimental apparatus and method are described. Section 3 describes the analysis of the data. In Section 4, we discuss the implication of the results on future experiments using UCNs. Section 5 provides a short summary of the content of this paper.

2. Experiment

2.1. Apparatus and method

The measurement was performed at the LANL UCN facility [4]. Spallation neutrons produced by a pulsed 800-MeV proton beam striking a tungsten target were moderated by beryllium and graphite moderators at ambient temperature and further cooled by a cold moderator that consisted of cooled polyethylene beads. The cold neutrons were converted to UCNs by a solid deuterium (SD_2) converter. UCNs were directed upward 1 m along a vertical guide coated with ^{58}Ni and then 6 m along a horizontal guide made of stainless steel before exiting the biological shield. At the bottom of the vertical UCN guide was a butterfly valve that remained closed when there was no proton beam pulse striking the spallation target in order to keep the UCNs from returning to the SD_2 where they would be absorbed.

A schematic diagram of the experimental setup for the depolarization measurement is shown in Fig. 1. When the UCN gate valve was opened, UCNs transported from the source entered the apparatus. UCNs in one spin state, the so-called “high-field seekers” for which $\boldsymbol{\mu}\cdot\boldsymbol{B} < 0$ where $\boldsymbol{\mu}$ is the magnetic dipole moment of the neutron and $\boldsymbol{B}$ is a magnetic field, were able to move past the 6 T magnetic field provided by a superconducting solenoidal magnet. UCNs in the other spin state, the so-called “low-field seekers”, were reflected back by the potential barrier due to $\boldsymbol{\mu}\cdot\boldsymbol{B} > 0$. For $|\boldsymbol{B}| = 6$ T, $|\boldsymbol{\mu}\cdot\boldsymbol{B}| = 360$ neV, much larger than the kinetic energy of the neutrons from the LANL UCN source, which has a cutoff at ≈ 190 neV.

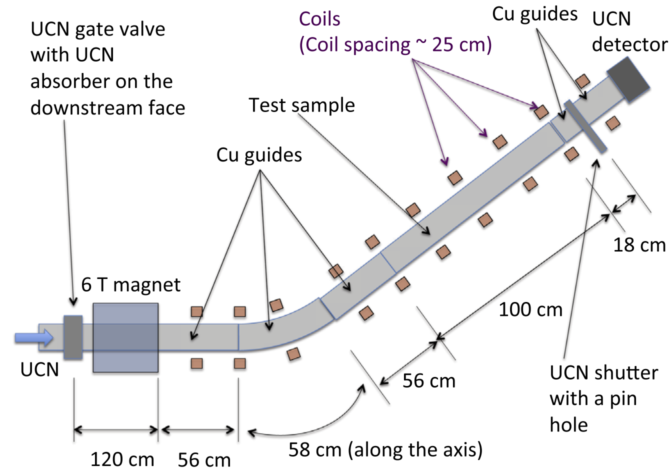

Fig. 1. Schematic diagram of the experimental setup.

On the other side of the high-field region was a UCN guide system (76.2 mm in OD, 72.9 mm in ID) that consisted of a set of copper guide sections, a NiP-coated guide section, a section of a copper guide with a UCN shutter, and a short section of a copper guide followed by a UCN detector [28]. The guides were placed in a ~2 mT magnetic field provided by a set of coils in order to retain the polarization of the UCNs. The UCN shutter, made of copper, had a pinhole 5 mm in diameter. The gap between the UCN shutter and the end of the guide leading to it was measured to be ~0.05 mm.

The high-field seekers were able to move freely through the high magnetic field region, colliding with the inner walls of the guide system. The number of collisions per second for the high-field seekers in the guide system downstream of the 6 T field region is given by

$$R_{\rm hfs} = \frac{1}{4} A_{\rm tot} \langle v_{\rm hfs} \rangle n_{\rm hfs}, \tag{1}$$

where $A_{\rm tot}$ is the total inner surface of the system that the high field seekers interacted with in the guide system downstream of the 6 T field region, $\langle v_{\rm hfs} \rangle$ is the average velocity of the high-field seekers, and $n_{\rm hfs}$ is the density of the high-field seekers. The rate of collisions for the high field seekers was monitored during this time by detecting neutrons that leaked through a pinhole on the shutter in the downstream end of the test guide assembly. If UCNs are detected at a rate of $R_{\rm h}$ and the area of the pinhole is $A_{\rm h}$, $R_{\rm hfs}$ can be inferred to be

$$R_{\rm hfs} = \frac{A_{\rm tot}}{A_{\rm h}} R_{\rm h}, \tag{2}$$

assuming that the distribution of UCNs inside the system is uniform and isotropic. We discuss the validity of this assumption in Section 3. For our geometry, $A_{\rm tot}/A_{\rm h} = 3.36 \times 10^4$.

While the high-field seekers collided with the inner wall of the system at the rate of $R_{\rm hfs}$, spin-flipped neutrons were produced at a rate of