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Measurement of the Fermi potential of diamond-like carbon and other materials

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Abstract

The Fermi potential V_f of diamond-like carbon (DLC) coatings produced with laser-controlled vacuum arc deposition and that of diamond, Al, Si, Be, Cu, Fe and Ni was measured using two different methods, (i) transmission of slow neutrons through foils in a time-of-flight experiment and (ii) cold neutron reflectometry (CNR). For diamond-like carbon in transmission we obtain $V_f = (249 \pm 14)$ neV. This is approximately the same as for beryllium and consistent with the theoretical expectations for the measured diamond (sp^3) content of 45%. For an sp^3-content of 67%, we find $V_f = (271 \pm 13)$ neV from reflectometry, again in agreement with theory. These findings open new perspectives in using DLC as storage volume and neutron guide coatings for ultracold neutron sources.

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Keywords: Ultracold neutrons; Slow neutron transmission; Cold neutron reflectometry

1. Introduction

Significant improvements in experimental determinations of the electric dipole moment (or its upper limit) and the lifetime of the free neutron using ultracold neutrons (UCN) require reduction of both systematic and statistical errors. Improvements of the experiments proper need to be accompanied by increases of UCN intensity and observation time. A group based at PSI is currently involved in the design and construction of a new dedicated UCN source [1] based on the spallation neutron source principle. It should increase the UCN intensity available at experiments by about two orders of magnitude over the best presently available (at ILL [2]).

A R & D program is in progress, looking for ways to improve the quality of reflecting coatings for UCN storage vessels. An examination of several materials, including diamond-like carbon (DLC, an amorphous structure with a mixture of sp^2 and sp^3 hybridized carbon atoms with densities of about 1.92 g/cm^3 and 3.29 g/cm^3 [3], respectively) for use in and around the new source is currently ongoing.

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The interaction of neutrons at a material surface [4–6] can be described by a coherent strong interaction potential, the Fermi potential, $V_f = V - iW$, where V and W depend on the nuclear properties of the surface atoms [7,8]:

$$V = \frac{2\pi\hbar^2}{m} \cdot N \cdot b; \quad W = \frac{\hbar}{2} \cdot N \cdot \sigma \cdot v. \tag{1}$$

Here, m and v denote the neutron's mass and velocity, N the atom number density, b the bound coherent nuclear scattering length and σ the cross-section for neutron loss (absorption and up-scattering). The real part of the potential, V, determines the height of the barrier, the imaginary part, W, the absorption loss (the expected loss per bounce is determined by $\eta = W/V$). The velocity v_c, defined by $v_c = \sqrt{2V/m}$, fairly closely sets the maximum value for the component of the neutron's velocity normal to the surface for reflection. Neutrons with velocities $\leqslant v_c$ are totally reflected and designated UCN.

The lowest part of the neutron velocity spectrum from a moderator increases with the square of the neutron velocity so that the potential number of UCN that can be stored increases as v_c^3. The lifetime of the stored neutrons is determined by reflection loss and by loss through β-decay. That is, a material suitable for the reflecting walls of a UCN storage vessel should have a high nuclear density, a large coherent scattering length and a low loss cross-section. Clearly, it must also be possible to produce an adequately blemish-free surface from this material.

The problem with materials currently used for UCN is that no one combines all the required qualities: beryllium, either as metal or oxide, has a high Fermi potential (≈ 250 neV, $v_c \approx 7$ m/s) but measured loss rates per bounce have $\eta \approx 3 \times 10^{-5}$ [9,10], which is about two orders of magnitude higher than that expected from calculation using known nuclear parameters, cf. Eq. (1). To this must be added the difficulties of producing Be coatings due to its toxicity. Another potentially good material (used, for instance, in recent neutron lifetime experiments [11,12]) is Fomblin oil (liquid hydrogen-free fluoro-polymers) [13]: It has a significantly lower η value than Be (and it also agrees with the calculated value, see [14] and references therein), but a Fermi potential of only about 106 neV. Practical difficulties for Fomblin oil include its UHV incompatibility and the need for maintenance.

The element carbon has very suitable nuclear parameters but, until comparatively recently, could only be deposited in films with a quite low density and also with hydrogen contamination, which limited the Fermi potential to the region of 200 neV. Plasma-assisted chemical vapor deposition was applied to create DLC coatings for microstrip gas chambers [15] and in a modified form also using deuterated methane [16] to give films with an average carbon density of 2.1 g/cm^3 including 20% voids filled with $^2H_2$ so that the Fermi potential was of the order of 220 neV. Later investigations confirmed the qualities of DLC for UCN storage [17–20]. Further, in a recent experiment [21,22], the loss per bounce and the depolarization probability were measured simultaneously in the same apparatus. Samples with DLC and beryllium coatings were compared for UCN energies below 90 neV: the results obtained showed a factor of two to three lower loss coefficient, η, between the two materials, in favor of DLC. An added attraction of DLC is that it avoids the difficulties and extra costs of handling Be and/or BeO.

We have carried out two experiments to measure the critical velocities of several samples, including DLC. In the first experiment we used time-of-flight (TOF) to measure the transmission of very low energy neutrons as a function of energy; the second measurement used cold neutron reflectometry. A brief report with the first results of the experiment has been published [23].

2. Time-of-flight experiment

2.1. Experimental set-up

In the time-of-flight (TOF) experiment, we determined the critical velocity from the transmission of slow neutrons through a 150 nm DLC coating on 180 μm aluminium foil and of beryllium, copper, iron and nickel on silicon wafers (thickness of the coatings 200 nm, of the silicon wafers 0.525 mm). The experiment was carried out at the PF2 EDM beam line at ILL [2,24]. The arrangement is schematically sketched in Fig. 1: ultracold neutrons from the UCN turbine [25] enter the apparatus from the left and pass through a chopper [26] operating at a duty cycle of 5.5% and a frequency of 0.81 Hz. A sample holder is mounted in the neutron guide at a distance of 2.227 m behind the chopper. We used neutron guides with an inner diameter of 68.1 mm made from electropolished stainless steel. The UCN detector (a gas counter with 18 hPa ^{3}He and 10 hPa CO_2 in about 1100 hPa Ar) was installed at a distance of 50 mm behind the sample holder. The Al window of the detector was 0.1 mm and, in the first instance causes some reduction of the detector efficiency. With this setup, the (averaged) velocity component along the forward direction can be measured by their time of flight (TOF). Since all measurements are relative (i.e. the ratio of the measure-

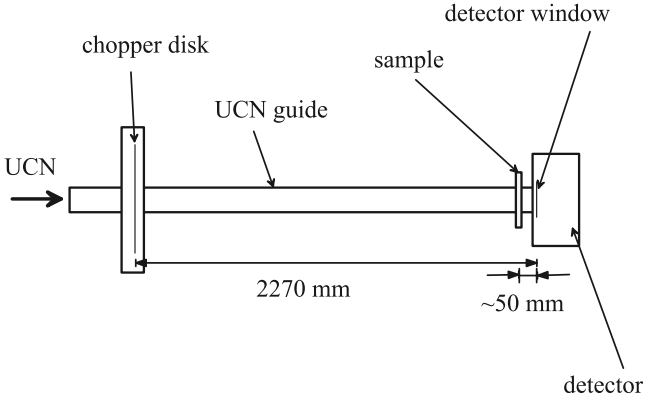

Fig. 1. Sketch of the time-of-flight apparatus.