5 Ultra Cold Neutrons

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in collaboration with:
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At the Paul Scherrer Institut (PSI) a new source of ultra cold neutrons (UCN) will be constructed with the goal to improve the sensitivity to the neutron electric dipole moment (nEDM), which is sensitive to possible contributions from new physics. In addition the neutron decay parameters such as its life time may be studied more accurately. Presently, we contribute to the preparation of the UCN source.

UCN (1) have a kinetic energy which is below the Fermi potential of some materials (e.g. Beryllium 258 neV) and thus are totally reflected by walls covered with such material. This neutron energy corresponds to a temperature of 3 mK, a velocity of 6.8 m/s and a wavelength of about 50 nm. When reflected on the walls, however, neutrons are lost with a small probability of order 10^{-4}. This experimental observation does not agree with theoretical predictions, which are several orders of magnitude lower. At the same time depolarization at a level of order 10^{-6} is observed, which is also unexplained.

In the past year we constructed a novel apparatus (DEPOL experiment, PSI project number R-00-03.1, see also (2)) to measure the reflection and polarization loss probabilities of various wall materials. The neutrons are stored inside a vertical tube, with walls coated by the material to be studied. This tube is closed at the bottom by a magnetic field, such that only neutrons with one polarization are kept inside. At the top of the tube the UCN can not escape, since they have not enough energy to overcome the gravitational potential.

This DEPOL experiment (see Sec. 5.1) is the thesis subject of Peter Fierlinger, who in addition developed a Monte Carlo tool to simulate UCN including their gravitational field interaction (see Sec. 5.3) to be used within the framework of GEANT4. Stefan Heule's thesis deals with the production of clean diamond-like coated (DLC) surfaces as an easier alternative to the toxic Beryllium to store UCN (see Sec. 5.2). The use of Diamond as the storage material is motivated by its high Fermi potential of 304 neV.

5.1 A measurement of depolarization and loss probabilities of stored UCN

In this experiment we tested diamond-like coatings (DLC) and Beryllium coatings on Quartz and Aluminium tubes between room temperature and 70 K. We also took data with DLC coated Polyethylene Terephthalate (PET) and Aluminium foils and found excellent storage times. To our knowledge this is the first time that UCN have been stored in containers made from plastic foils. The foils were mounted into the apparatus squeezed into a cylinder like shape in such a way that only the coated surfaces were visible to the neutrons. The experiment took place in spring 2004 at the ILL in Grenoble.

The loss probability per bounce was measured by counting the number of neutrons remain-

Table 5.1: Measured loss and depolarization probabilities per wall interaction on foils (preliminary). Data taken on a Be coated tube in the same setup are given for comparison.

sample	temperature	loss probability η	depolarization probability β
	K	$\times 10^{-4}$	$\times 10^{-6}$
DLC on PET	300	1.63 ± 0.10	15.1 ± 1.0
DLC on PET	70	0.72 ± 0.12	15.7 ± 0.9
DLC on Al	300	3.52 ± 0.06	0.70 ± 0.21
DLC on Al	70	1.73 ± 0.09	0.80 ± 0.25
Be on Al	300	4.2 ± 0.3	11.8 ± 0.5

ing in the storage volume after a certain time, at which the magnetic field is turned off, and the number of neutrons falling out of the tube is counted. Depolarization is measured by observing neutrons leaving the storage volume during the time the magnetic field is turned on. Both measurements require the knowledge of the number of wall interactions during the storage time. This number was calculated using Geant 4 (see Sec. 5.3). We found loss probabilities, which are consistent with the literature values for Beryllium. DLC turns out to have similar or even smaller loss probabilities than Beryllium. The preliminary results of the measurements with the DLC coated foils are given in Tab. 5.1. While loss probabilities seem to be temperature dependent, depolarization probabilities are not. The base material onto which DLC is coated plays an important role. It affects both the losses and the depolarization, but in opposite direction. Possible explanations for these effects are being worked on, including hydrogen contamination with different chemical bond strength on Aluminium and PET.

Storage of UCN in thin foils opens up a wide range of opportunities for new neutron β-decay experiments. Neutron bottles could be made thin enough for the β-decay electrons to pass through them. Non metallic walls allow free design of magnetic and electric fields in the decay volume. We plan to continue this experiment with an improved setup including in situ surface monitoring.

5.2 Characterization of diamond-like carbon coatings

It is planned to produce diamond-like carbon (DLC) coated films at PSI with Pulsed Laser Deposition (PLD). Natural carbon exists in two varieties, Diamond and Graphite. The carbon atoms of Diamond are connected with sp^3-bonds, those of Graphite with sp^2-bonds. Amorphous carbon with a significant amount of sp^3-bonds is called DLC. We have investigated DLC films on different substrates (Aluminium, Silicon and PET). For UCN applications the interesting parameter is the critical velocity v_C (defining the maximum storable velocity in a material container) which is directly related to the mass density ρ and total sp^3 fraction, here denoted by s$_{32}$. The limits for DLC are therefore ρ=2 g/cm^3, v_C=5.8 m/s for Graphite and ρ=3.5 g/cm^3, v_C=7.6 m/s for pure Diamond. At ρ=2.9 g/cm^3 the corresponding v_C=6.9 m/s is equal to that of Beryllium.

To find an optimum characterization procedure Raman spectroscopy, X-ray absorption near-edge spectroscopy (XANES), X-ray photoemission spectroscopy (XPS), neutron reflectometry and the Laser Acoustic Wave propagation method (LAWave) at the Fraunhofer Institut für Werkstoff- und Strahltechnik in Dresden were used.

Raman spectroscopy (here at $\lambda = 648$ nm) can be used for characterization of DLC films. For amorphous carbon films the Raman spectrum consists mainly of one broad asymmetric peak around wavenumber 1300-1500 cm^{-1}. This peak is deconvoluted into two peaks where one of them can be assigned to a specific graphite feature, called the G band. One can derive s_{32} from the width of the G band which correlates with s_{32} (3). The method works best for s_{32} above 80%. We used XPS to determine s_{32} of the uppermost film layer. It can be directly derived from the XPS spectrum around a binding energy of 285 eV by fitting multiple curves (4). With XPS an accuracy of $\sim$10% for s_{32} can be reached. In order to cross-check the XPS results, measurements with XANES have been performed at the materials beamline at the SLS. The XANES results correctly describe the systematic s_{32} variation of our samples, however, the problem of quantification is not solved yet. One can estimate s_{32} from a special feature in the XANES spectrum which is due to the graphitic structure only (5). Neutron reflectometry has been used to determine the critical velocity directly. In the LAWave method (6), a pulsed laser induces an acoustic surface wave which propagates with a velocity depending on the penetration depth of the wave and the density of the material. The density of the material can be derived from this phase velocity.

In order to quantitatively compare the different characterization methods, a series of DLC coatings with a systematic variation of the s_{32} ratio (on silicon substrates) has been produced by the Fraunhofer IWS in Dresden. As the different methods measure different parameters (e.g. s_{32}, critical velocity), all results have been converted into density. Figure 5.1 shows preliminary density values for eight different samples.

Although reliable errors have not been determined yet, the agreement between the results from the different methods is good (with the exception of sample no. 6). Since the methods have different depth sensitivities (XPS $\sim$3 nm, AMOR $\sim$10 nm, Raman through the full film, LAWave in the order of the film thickness) small deviations are to be expected if the density varies with depth. This might allow to get some information about the depth dependence of the film density.

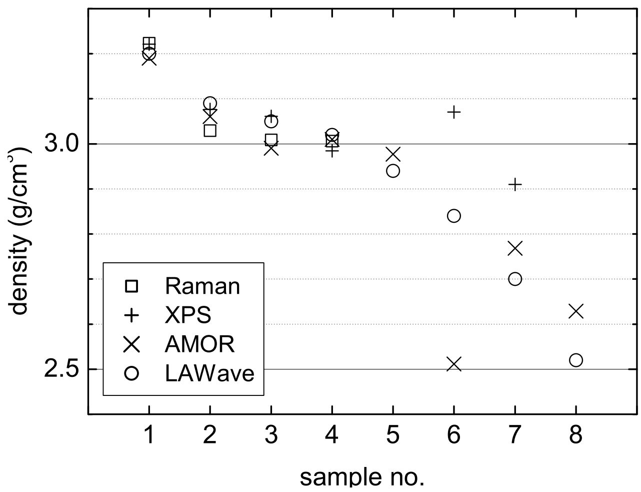

Figure 5.1:
Preliminary results for DLC films with a thickness of $\sim$100 nm (samples 1-4) and $\sim$ 10 nm (samples 5-8), measured with different characterization methods.

5.3 Simulation of ultracold neutron experiments using GEANT4

The Monte Carlo program GEANT4 (7) is a versatile, widely used toolkit for the simulation of particles passing through matter. Its application areas include high energy and nuclear physics experiments, medical, accelerator and space physics studies. As such, it can handle many physically possible processes, including decay and particle production, allowing to combine the trajectory of both, the 'parent' UCN as well as the 'daughter' decay products, e.g. in neutron decay experiments. It therefore appeared very tempting to exploit the GEANT4 advantages - versatility, completeness, easy geometry implementation and professional maintenance - and extend it to the case of UCN. The additions to the code mainly

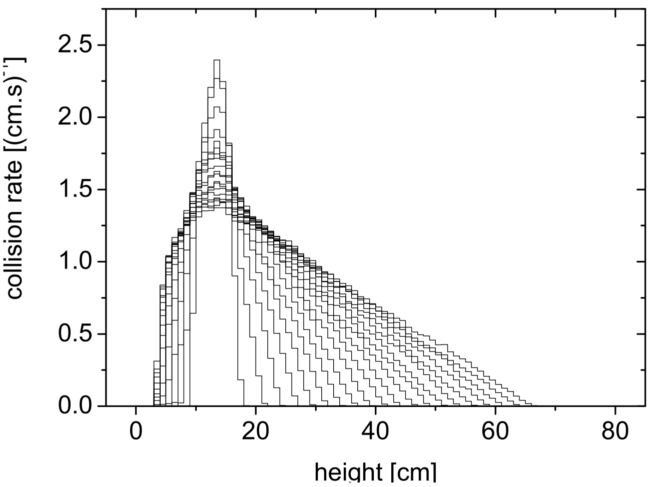

Figure 5.2:
Collision distribution for different neutron energies. The X-axis denotes the height in the tube above B-field maximum, the Y-axis the number of collisions per neutron per second on a 1 cm section of the tube in height. The curves represent energies from 12.5 to 67.5 neV in 2.5 neV steps, where the higher energies reach deeper into the magnetic field and higher up against gravity.

concern gravity and time-varying, inhomogeneous magnetic fields, reflection and scattering for UCN and new geometries(8).

Although neutrons are treated in the standard GEANT4 package we have introduced UCN as a new type of particle, being the only species to be affected by gravity. Gravity is implemented analogous to a constant homogeneous electric field for charged particles and is normalized such that the gravitational energy is $E_g = mgh = (102\,\text{neV/m})\cdot h$. The magnetic interaction is mediated by the magnetic moment of the neutron, $E_m = -\mu\cdot\mathbf{B} = (\pm 60\,\text{neV/T})\cdot B$, where the sign is determined by the relative direction of the magnetic moment and the field. Strongly inhomogeneous, time-varying magnetic fields are included for UCN in the so-called adiabatic limit, i.e. when the Larmor-precession is much faster than the time dependence of the field seen by the neutron moving through the inhomogeneous field.

As an example a vertical tube as has been used in the DEPOL experiment with inner diameter 70 mm closed by a 1.5 T magnetic valve on the bottom is simulated. Neutrons enter the tube from the bottom without magnetic field until the magnetic valve is closed. One spin component of the neutrons is trapped by the magnetic field on the bottom, gravity on the top and the reflecting walls of the tube. The simulation of the tracks inside this volume allows for the determination of the wall collision distribution (Fig. 5.2).

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