Project on searching for neutron-antineutron oscillation at the WWR-M reactor

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Abstract. Supersource of ultracold neutrons on the basis of superfluid helium is under construction in PNPI NRC KI. It must provide UCN density 2-3 orders of magnitude higher than existing sources. For the new source we propose an experiment on search for neutron–antineutron oscillations based on the storage of ultracold neutrons in a material trap. The sensitivity of the experiment mostly depends on the trap size and the amount of UCN in it. The geometric configuration of the experimental setup was developed based on the MC simulations of neutrons trajectories into the trap. To calculate detector efficiency the GEANT4 model of the detector was created.

1. Introduction

The purpose of the project is to develop an experimental apparatus which can effectively detect neutron-antineutron oscillations. The oscillations is a process in which neutron spontaneously transforms into antineutron. Such process is forbidden by baryon number conservation law, but the attempts to find processes with baryon number violation are motivated by A.D. Sakharov theorem[1], which claims that baryon number violation is one of three conditions of existing of the Universe.

In hypothesis of \( n - \bar{n} \) mixing the probability of transition of a neutron to an antineutron can be described by the expression:

\[
P(n, \bar{n}, t) = \frac{\delta m^2}{\delta m^2 + \Delta E^2} \sin^2(\sqrt{\delta m^2 + \Delta E^2} \cdot t),
\]

where \( \Delta E \) is the half of energy gap between the neutron and antineutron, \( \delta m \) is the mixing parameter.

There are two types of \( n - \bar{n} \) oscillations experiments: free neutron experiments and experiments with neutrons bounded in nuclei.

Our project is a free neutron experiment. In this case the energy gap appears due to external magnetic field. In ideal case with \( \Delta E = 0 \), \( P(n, \bar{n}, t) \approx \left( \frac{1}{\tau_{nn}} \right)^2 \), where \( \delta m = \tau_{nn}^{-1} \) and \( t \ll \tau_{nn} \). That approximation properly describes oscillation probability if so called "quasi-free" conditions \( t \ll \Delta E \) are satisfied. In that case, the amount of registered antineutrons can be estimated by the expression:

\[
\bar{N} = \varepsilon N \left( \frac{t}{\tau_{nn}} \right)^2,
\]

where \( N \) is amount of neutron collisions with target per second, \( t \) - time of flight and \( \varepsilon \) is a detector efficiency. \( \tau_{nn} \) is the period of oscillations and it is actually the parameter which we try to measure.
Nt^2 we call the setup sensitivity. It depends on the amount of neutrons and neutrons propagation in the setup, while detector efficiency is based on an antineutron interaction with matter. Currently, there were experimentally observed no oscillation events. Hence the results of the oscillations put limits on the oscillation period. Currently best result obtained with free neutrons is $\tau_{nn} \geq 0.86 \cdot 10^8$ s [2]. In corresponding experiment the method of cold neutrons beam was used. In that scheme, the beam of cold neutrons propagates through a long volume shielded from magnetic field to the annihilation target.

We propose an alternative approach to the free neutrons experiment. We want to use ultracold neutrons (UCN) stored into material trap. In that approach the annihilation target is the inner surface of the trap and UCNs bounce from one collision with trap to another. The setup sensitivity in mentioned above beam experiment was $1.5 \cdot 10^9$ and the main purpose of the project was to consider the possibility of creating the UCN based experimental setup with better sensitivity.

2. Setup sensitivity and "quasi-free" conditions

In UCN type experiment parameter $t$ is the time between neutron collisions with walls. It depends on the geometric configuration of the trap, trap size and energy of the neutron. The energy is limited by UCN bound velocity and that means neutrons in the trap has velocities of several meters per second. Time of flight is also limited. Neutrons in the trap have parabolic trajectories and increasing of trap size at some point becomes ineffective to increase the ToF, the limit of mean ToF is in vicinity of 1s. In comparison with beam experiment that means we need parameter $N$ to be at least $10^{10}$.

$N$ - the amount of collisions per second depends on the total amount of UCN in the trap, which is determined by power of the UCN source and the mean UCN lifetime in the trap. There are two sources of UCN loses in the trap: $\beta$-decay and UCN loses in collision with walls. Hence lifetime in the trap is limited by the free neutron lifetime and the deviation from free neutron lifetime is determined by collision loss probability, which depends on the material of the trap. We plan to use $^{58}$NiMo coating of the inner surface of storage volume.

The calculations revealed, that even assuming ideal conditions for UCN into the trap, at currently existing sources the UCN density in the trap would not be sufficient to achieve competitive sensitivity of setup. This is the reason why our project of the $n - \bar{n}$ oscillation experiment is connected with the creation of the new UCN source at the WWR-M reactor.

The UCN supersource at the WWR-M reactor will employ the new generation techniques. WWR-M reactor has unique conditions for installing a converter based on superfluid helium directly in close vicinity of reactor core where neutron flux is very high and hence obtain a very high flux of UCN [3]. These favorable conditions are due to availability of a reactor thermal column which is a channel of a big diameter (1 m), adjacent to the reactor core. Such channel diameter enables to locate a powerful lead shielding from $\gamma$-radiation of the reactor core, graphite pre-moderator at 20 K, and finally, UCN source based on superfluid helium at 1.2 K. The mechanism of UCN production in superfluid helium is based on transmission of energy from cold neutron to phonon in helium. Cold neutron with wavelength about 9 Å and temperature about 12 K excites the phonon in super-fluid helium and practically stops itself, hence becoming an ultracold one. Cold neutrons penetrate through a trap wall while ultracold ones are reflected, resulting in the effect of accumulation of UCN up to the density determined by the storage time in a trap with helium. The ultracold neutrons move through the neutron guide to the experimental setups. The source will allow us to obtain UCN density of $10^9$ cm$^{-3}$ [4], which approximately by 2-3 orders of magnitude exceeds the available density of ultracold neutron at existing UCN sources. UCN production by the source will be about $10^8$ n/s. The full-scale source model, including all required cryogenic and vacuum equipment, the cryostat, and the UCN source model has been created and successfully tested [5].

A wide experimental program is developed for the new source [6]. Several experimental setups will be installed in the main hall of WWR-M reactor, and hence the space available for our setup is limited. Considering the limitation we carried out Monte Carlo simulations of neutron trajectories in the trap to choose the most preferable geometric configuration of the trap. As a result, we concluded that optimal
trap is a horizontal cylinder with length 4 m and diameter 2 m. Corresponding mean time of flight of UCNs is calculated to be 0.4 s. Taking into account the calculated amount of UCNs in the trap which will be achieved with new source, the total $Nt^2$ for our setup is estimated to be 10-40 times better than in ILL beam experiments depending on the model of UCN reflection from trap walls.

The next step is to create quasi-free conditions. It is required to provide vacuum conditions and suppress magnetic field. For vacuum conditions we plan to install our trap into vacuum vessel which is constantly pumped out to obtain operational vacuum in the vessel $10^{-5}$ mbar. The vessel should be endure external pressure and hence we plan to construct the vessel of 8 mm thick aluminum. The suppression of magnetic field have to satisfy the condition $\Delta E \cdot t \ll 1$. Therefore, having mean ToF 0.4 ns we have to suppress Earth magnetic field by factor $\approx 10^4$. The calculations revealed that two layers shielding is required. The shielding will be made of 1.5 mm thick Mu-Metall with maximum magnetic permeability $2.5 \cdot 10^5$.

3. Detector efficiency
Calculation of the detector efficiency is another task in our project. The antineutron can be detected by the annihilation reaction at the inner surface of the trap. The annihilation of antineutron on the nucleon is a complicated process which requires the simulation of $\pi$-mesons propagation through the nucleus. In total, the annihilation results in emission of several particles including charged and neutral $\pi$-mesons, protons, neutrons and heavier parts of the nucleus [7]. $7.5 \cdot 10^4$ events of annihilation at Ni and Mo nuclei were simulated for calculations of detector efficiency.

The detector is to be located outside the vacuum vessel (figure 1). That means the initial annihilation particles have to propagate through the trap and wall of the vacuum vessel to reach the sensitive part of the experimental setup. Therefore, the visible signal significantly differs from the initial signal of annihilation events. There are several ways in which the "blind zone" as we call the inner part of the trap affects the signal. First of all most of protons and heavier parts of the nucleus are stopped inside the metal layers. That leads to significant loss of initial energy and decrease the amount of particles. It also changes the energy spectrum of particles which can reach the detector, hence visible energy and initial energy are different. The directions of the particles also deviate from the initial. That makes reconstruction of initial vertex rather hard task. $\pi^0$-mesons decay inside the blind zone and emitted photons can interact with the metal layers. That creates additional particles in annihilation event and obscures initial vertex and energy even more.

![Figure 1](image_url)
There is still the criterion which allows us to distinguish annihilation events. It is the fact that annihilation related particles propagate from the trap to the detector. Therefore we considered the detector aimed on determining the particle direction and focused mostly on charged particles, because there is high probability that in annihilation several charged particles will be emitted and charged particles are significantly easier to register. To be more specific, the main task is to determine for all charged particles which appears in detector if they directed from trap to the detector or from detector to the trap. Therefore, the main part of our detector is a hodoscope - the system aimed to measure time of flight of the charged particles. We consider the scheme with hodoscope constructed of two layers of plastic scintillator. Each layer consists of several plates of scintillator, arranged in cylinder form. The distance between hodoscope layers is 600 mm and it determines the required time resolution.

We do not have the problem of inner background but outer background is have to be taken into account. There are two sources of the background: cosmic rays and the reactor. Considering that hodoscope has sufficient time resolution, there are two ways to obtain false signal: the accidental coincidence of the signals in hodoscope layers and background charged particles which can penetrate the whole system and imitate the signal from inside the trap.

In order to increase space resolution of the detector and obtained more detailed information about a particle trajectory we add tracker system made of three layers of wire chambers. The inner layer is between vacuum vessel and magnetic screen, the medium layer is between hodoscope layers and outer tracker is outside the hodoscope. The tracker system is aimed to confirm that the signals in the hodoscope layers belongs to a single charged particle. The inner and medium layers consist of only two rows of wire chambers. They are designed to register the position of the particle but do not significantly change its properties. The outer layer has 12 rows of wire chambers with layers of aluminum and lead between the rows. It has several goals: provide more detailed information of the particle direction, protect the inner layers from background and discriminate particles by the form of the signal and track length in the tracker.

To calculate the efficiency of described detector the GEANT4 model of the setup was created. The propagation of particles emitted in generated annihilation events through the setup was simulated. We studied the signal in the detector and characteristic times of the events. The simulation revealed that hodoscope time resolution has to be at least 2 ns, which means that if the particle penetrates the layers with time gap of 2 ns we should be able to determine its direction (IN/OUT). The criterion to select an annihilation event is obtaining the signals of two charged particles propagating from the trap to the detector. The time window in which we can consider that two particles belongs to one event was also determined from the simulation. It was estimated to be 30 ns, and it is also the parameter for final simulation in which the detector efficiency was obtained. The detector efficiency is calculated to be (68±2)%. In final simulation we assumed that hodoscope has sufficient time resolution.

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