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Implementations of neutron/antineutron ($n/\bar{n}$) guides in experiments searching for $n-\bar{n}$ oscillations

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An observation of neutron-antineutron oscillations ($n-\bar{n}$), which violate both B and $B-L$ conservation, would constitute a scientific discovery of fundamental importance to physics and cosmology. A stringent upper bound on its transition rate would make an important contribution to our understanding of the baryon asymmetry of the Universe by eliminating the post-sphaleron baryogenesis scenario in the light quark sector. We show that one can design an experiment using slow neutrons that in principle can reach the required sensitivity of $\tau_{n-\bar{n}}{\sim}10^{10}$ s in the oscillation time, an improvement of $\sim 10^4$ in the oscillation probability relative to the existing limit for free neutrons. The improved statistical accuracy needed to reach this sensitivity can be achieved by allowing both the neutron and antineutron components of the developing superposition state to coherently reflect from mirrors. For sufficiently small transverse momenta of $n/\bar{n}$ and for certain choices of nuclei for the $n/\bar{n}$ guide material, the relative phase shift of the n and $\bar{n}$ components upon reflection and the $\bar{n}$ annihilation rate can be small enough to maintain sufficient coherence to benefit from the greater phase space acceptance the mirror provides. We point out a possible step-by-step implementation of the new method.

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1. Introduction

An observation of neutron-antineutron oscillations ($n - \bar{n}$) would be a major scientific discovery with fundamental implications for physics and cosmology. This process would violate baryon number (B) by 2 units. Although baryon number violation has not yet been seen in any laboratory experiment, it is the most obvious necessary ingredient in any attempt to explain the matter-antimatter asymmetry of the universe in terms of the Big Bang theory, as Sakharov suggested long ago [1]. Based on our present understanding of both particle physics and cosmology, we expect that baryon number is violated [2-3]. The scales associated with $\Delta B = 2$ operators can be slightly below the electroweak scale and still be consistent with present experiments, leading to the idea of post-sphaleron baryogenesis [4] (PSB). These reasons strongly motivate sensitive searches for ($n - \bar{n}$) oscillations both for free n and n bound in nuclei.

The best existing constraint on $n - \bar{n}$ oscillation time $\tau_{n-\bar{n}} > 0.86 \cdot 10^8\ s$ [5] with free n used an intense cold neutron beam PF1 at the Institut Laue-Langevin, Grenoble, France. The n beam propagated through a long tube with a sufficiently good vacuum and low magnetic fields satisfies the “quasi-free” condition, which means that the probability of oscillations is not suppressed. An $\bar{n}$ annihilation detector installed at the exit of the tube didn’t count any annihilation event for the whole duration of this experiment.

In Section 2, we present a new experimental approach based on coherent n and $\bar{n}$ mirror reflection from the walls of a $n/\bar{n}$ guide, which potentially allows a significant increase in sensitivity. In Section 3, we discuss possible implementations of this new method and the potential sensitivity using this method.

2. Experimental approach to search for free neutron-antineutron oscillations based on coherent neutron and antineutron mirror reflection

A natural development of the experiment [5] seems to consist of pushing all its parameters to the limit in order to increase the sensitivity. This approach is considered at the European Spallation Source [6]. As the total neutron fluxes (mean phase-space densities) are approaching the saturation and cannot be increased by orders of magnitude, the available parameters to improve are the total length of the experiment and the spread of perpendicular-to-the-beam velocity components in the initial n beam. Provided one delivers all $n/\bar{n}$ to the $\bar{n}$ annihilation detector and the quasi-free condition is maintained, the sensitivity is proportional to the square of the total length multiplied by the square of the maximum spread of perpendicular velocities.

However, the price to pay for the increase in these two parameters is very large. The beam size increases proportionally to the experiment length multiplied by the mean transverse velocity spread, even in the absence of gravity. Gravity acting on the broad velocity distribution in the beam further increases the size. This is particularly unfortunate because slower neutrons provide the long observation times and contribute disproportionally to the experiment sensitivity, thus should not be collimated out. A larger beam size is associated with the need to build a larger annihilation detector, to provide a high vacuum and a low magnetic field in a larger volume, to build much bulkier and more sophisticated radiological protection, etc. Starting from a certain size, the experiment price and the technical difficulties make the experiment difficult to realize.

These problems (costs, annihilation detector, vacuum, magnetic fields, radiological protection) could become much less severe simultaneously if one can use a guide both for n and

$\bar{n}$ [7-10]. Also, the total experimental length can become larger thus increasing quadratically the experiment sensitivity, without extending the transverse dimensions of experiment.

The idea to reflect both n and $\bar{n}$ from a surface of a trap for ultracold neutrons (UCNs) was considered already in 1980 [11]. We extend this approach to higher energies (any n that can be confined in neutron guides on specular trajectories), point out conditions for suppressing the phase difference for n and $\bar{n}$, quantify the low transverse momenta of $n/\bar{n}$ required, and consider new choices for the nuclei composing the guide material. We show that, over a broad fraction of phase space acceptance of a $n/\bar{n}$ guide, the probability of coherent reflection of $n/\bar{n}$ from the walls can be high, the relative phase shift can be small, and the theoretical uncertainties in the calculation of the experimental sensitivity can be small. We show that such an experimental mode can relax some of the constraints on free n oscillation searches and in principle allows us to achieve a much higher sensitivity. More details are given in refs. [7-10] that are the basis of the present report.

Since the reflection of $\bar{n}$ from a material surface is a key feature of this method, we emphasize the reliability of the model describing it. By analogy with the interaction of slow n with matter, the interaction of slow $\bar{n}$ with matter is also described by the optical Fermi potential. The interaction of slow $\bar{n}$ with nuclei A in matter are described by the complex scattering length $b_{\bar{n}A}$; $Re(b_{\bar{n}A})$ determines the height of the optical potential, and $Im(b_{\bar{n}A})$ the losses of $\bar{n}$ due to their annihilation. Contrary to the intuitive idea that an $\bar{n}$ annihilates upon its first contact with matter, an $\bar{n}$ with a sufficiently small transverse velocity component is reflected from the matter of the $n/\bar{n}$ guide with a probability close to unity. This is a direct consequence of solving a simple quantum-mechanical problem of wave reflection from a potential step. If, in this case, the $n/\bar{n}$ guide is short enough, practically all $\bar{n}$ will reach the end of the $n/\bar{n}$ guide, and the systematic errors associated with the finite accuracy of the knowledge of the scattering amplitude are small.

Compared to standard $n-\bar{n}$ oscillation experiments with free n, this approach can preserve both the very low $\bar{n}$ detector background and the ability to confirm a nonzero signal by applying a small additional gas pressure to the flight tube [12], or a small external magnetic field to split the n and $\bar{n}$ states by $\Delta E = 2\mu B$, enough to suppress the oscillation probability. Compared to the large underground $\bar{n}$ annihilation detectors, our approach does not require the same level of detail in the understanding of the $\bar{n}$ dynamics and the subsequent annihilation products.

3. Possible implementations of the new approach and experimental sensitivities

There are several possible implementations of this idea. We will mention here only those, which we have started considering in more detail.

The first step could be an experiment at the PF1B facility at ILL. A preliminary feasibility study and a direct experiment simulation [13] show that the sensitivity could increase by a factor of up to ~10 compared to that already achieved in the best previous experiment [5]. This gain is due to the more intense neutron beam available today [14] but also to the use of a $n/\bar{n}$ guide. The experiment size could be even smaller than it was previously, and an even longer $n/\bar{n}$ guide could give a quadratically higher sensitivity. Such an extension is not practical at a user facility like ILL with an intense experimental user program whose operation would be strongly perturbed by mounting such an optimized experiment.

However, this constraint does not exist at new neutron sources under construction, where an experiment with a larger length can be planned for from the start. This is the case of HIBEAM/NNBAR [15] at ESS. We have not yet performed a proper analysis of an experiment at this facility using the method of a $n/\bar{n}$ guide but an estimation "on the back of the envelope" gives another order of magnitude gain due to the over 3 times larger length of the $n/\bar{n}$ guide possible there. A dedicated neutron extraction port at ESS with a large angular size, the use of a maximum available length (250-300 m), and a long measuring time would increase the estimation of sensitivity by more than one another order of magnitude. We are going to perform an analysis considering in detail the latter two options.

In all these three cases, the time of flight of $n/\bar{n}$ through the guide is not larger than $L/V < 0.5s$, where $L{\sim}300\ m$ is the maximum length available, and $V{\sim}700m/s$ is the minimum mean n velocity. It is still significantly shorter than a characteristic time of life of $\bar{n}$ in the guide, $1-2s$, which is defined by annihilation of $\bar{n}$ in the guide walls, mainly in the bottom of the guide. Therefore, most of generated $\bar{n}$ would reach the $\bar{n}$ annihilation detector before their annihilation in the guide walls. Thus, systematic uncertainties associated with the interaction of $\bar{n}$ with the guide walls are still not important for the estimation of $\tau_{n-\bar{n}}$. A conservative estimation for the maximum corresponding uncertainty is $\Delta\tau_{n\bar{n}}/\tau_{n\bar{n}} \sim (L\Delta|U_{\bar{n}N}|)/(2V|U_{\bar{n}N}|) \sim 5\%$, where $\Delta|U_{\bar{n}N}|/|U_{\bar{n}N}| \sim 0.2$ is a maximum uncertainty of the knowledge of the complex potential $U_{\bar{n}N}$ of interaction of $\bar{n}$ with the guide wall material.

A $n-\bar{n}$ oscillation experiment with even higher sensitivity, although possible in principle, would require solving a few more problems. In particular, an experiment longer than $\sim 300\ m$ would not fit even to the ESS spatial constraints. Moreover, if the time of flight of $n/\bar{n}$ through the guide will be comparable to their lifetime until annihilation, the importance of precise knowledge of the potential of interaction of $\bar{n}$ with the walls increases. Theoretical and experimental efforts to further increase the accuracy and reliability of this value are highly appreciated in this case.

The problem of "geometrical constraints" can be solved in an elegant way by reducing the mean velocity of $n/\bar{n}$. With the experiment length of $\sim 100\ m$ readily available at most of neutron facilities, the mean neutron velocity has to be in order to get the time of flight approximately equal to the time of life of $\bar{n}$ in the guide until their annihilation. is a typical velocity of so-called very cold neutrons (VCNs). A dedicated source of VCNs would increase the phase-space density of neutrons in this velocity range and could give another order of magnitude in sensitivity. We contribute to VCN sources developments in particular by developing ever first efficient reflectors for VCNs [16]. Further reduction of neutron velocities, say, to the range of ultracold neutrons (UCNs), would lead to the decrease in sensitivity and therefore it is less interesting from the point of view of the experiment performance. However, it might be of interest as an intermediate step which allows testing methods and equipment.

We envision a staged approach to the implementation of the method of $n/\bar{n}$ guides to $n-\bar{n}$ oscillation experiments: a short experiment at PF1B, a larger-scale experiment at ESS, an "ideal" experiment with a softer neutron spectrum or/and a larger length plus a better knowledge of the interaction of $\bar{n}$ with the $n/\bar{n}$ guide walls.

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