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Neutron-Antineutron oscillations in the NOvA experiment

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Abstract

In this work, we will examine the theory of neutron-antineutron oscillations from the perspective of quantum field theory, construct a Lagrangian accounting for the phase related to CP symmetry, and estimate the detection of these oscillations in the NOvA experiment.

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1 Introduction

There is an empirically established rule that forbids certain processes—for example, proton decay is impossible within the Standard Model. This rule is called the baryon number conservation law: baryons have a baryon number of $+1$, while non-baryons have a baryon number of 0 . ΔB (the change in baryon number) must be zero.

However, if baryon number conservation holds strictly, this raises the question of baryogenesis—a hypothetical process in the early universe (within the Big Bang model) that led to a significant excess of baryons over antibaryons. If baryon number were conserved, the amounts of baryons and antibaryons should have been nearly equal. Yet, baryogenesis apparently occurred, and most of the antimatter annihilated. Sakharov proposed three necessary conditions for baryogenesis to be possible:

- Baryon number violation ($\Delta B \neq 0$).
- C-symmetry and CP-symmetry violation (to create a matter-antimatter asymmetry).
- Departure from thermal equilibrium (to prevent reverse processes from restoring symmetry).

If all three conditions are met, baryogenesis can occur. However, in the Standard Model, baryon number violation is impossible, which leads us to consider new physics models where the law of baryon number conservation is a local symmetry rather than a global one. If the baryon number is violated by 1, proton decay becomes possible, while a violation by 2 units allows for neutron-antineutron transitions.

The next model for searching for baryon number violation could be one where the baryon number changes by 2. In this case, the process of neutron-antineutron transitions via so-called oscillations becomes possible.

There are various theoretical models describing neutron-antineutron oscillations. One such model $SU(2)_L \times SU(2)_R \times SU(4)_C$ involves light diquarks; however, in this work, I examine in greater detail a model describing the phenomenon of $n - \bar{n}$ oscillations within quantum field theory. This model describes transitions using a Lagrangian that violates the baryon number by 2 units. It includes terms with masses ϵ_1 and ϵ_5 , which affect CP violation and, consequently, the mass difference between neutrons and antineutrons during the oscillation process, enabling the transition from a neutron to an antineutron. It is also worth mentioning experiments searching for baryon number violation. Regarding proton decay, there are experiments at Super-Kamiokande: searches for proton decay into $p \rightarrow e^+ \pi^0$ or $p \rightarrow \mu^+ \pi^0$, as well as searches for proton decay into $p \rightarrow \nu K^+$ and $p \rightarrow \mu^+ K^0$ [1].

As for experiments searching for neutron-antineutron oscillations, which involve transitions from neutrons to antineutrons, there are various approaches. The search for oscillations differs depending on whether neutrons are bound or free. One method involves studying bound neutrons in nuclei, where a neutron transitioning into an antineutron would annihilate with a proton or another neutron, releasing energy of about 2 GeV and emitting hadrons. This approach is used in experiments like NOvA.

Another method involves searching for oscillations using free neutrons, which are stored in ultra-cold neutron traps where their speed is reduced to about 4 m/s. These neutrons are then released into a target, while maintaining the highest possible vacuum and suppressing background magnetic fields. Free neutrons are studied by the Laboratory of Neutron Physics at JINR [2,3]. Also, the NOvA experiment conducts research on neutrinos, magnetic monopoles, etc. [4,5]

2 Neutron-Antineutron oscillation

In the theoretical section, I would like to explain the principle of neutron-antineutron oscillations within the framework of quantum field theory, as well as show how the probability is calculated. In this model, we initially have two Dirac fields: for the neutron $n(x)$ and for the antineutron $n^c(x)$. For neutron and antineutron states Lagrangian that violates the baryon number by 2 units looks like [6]

$$L = \bar{\Psi}(x)i\gamma^\mu\partial_\mu\Psi - m\bar{\Psi}(x)\Psi(x) - \frac{1}{2}\epsilon_1[\Psi^T(x)C\Psi(x) + \bar{\Psi}(x)C\bar{\Psi}^T(x)] \\ - \frac{i}{2}\epsilon_5[e^{i\alpha}\Psi^T(x)C\gamma_5\Psi(x) + e^{i\alpha}\bar{\Psi}(x)C\gamma_5\bar{\Psi}^T(x)]$$

If baryon number conservation holds, transitions between them are impossible. However, when accounting for CP symmetries and violating baryon number conservation, the mechanical system gains the possibility of such a transition. The transition occurs in a superposition of neutron and antineutron states:

$$\psi_\pm = \frac{1}{\sqrt{2}}[n(x) \pm n^c(x)] \quad \psi_\pm^c = \pm\psi_\pm$$

This superposition represents a Majorana fermion [7], and this state describes the mixing of quantum neutron and antineutron states. Here, the transition from a neutron to an antineutron state is determined by the transition mass ϵ_1 and the phase freedom, which defines the actual mass difference. The term ϵ_1 is P-odd, and due to this oddness, two eigen Majorana states emerge for the mass part of the Lagrangian, which precisely account for the mass difference between neutrons and antineutrons. The masses are expressed as follows:

$$M_\pm = \sqrt{m^2 + \epsilon_5^2} \pm \epsilon_1$$

It can be seen that when $\epsilon_1 = 0$, the mass ambiguity disappears, and the masses no longer have distinct values, leading to degeneracy and making the oscillation process impossible.

It is also worth explaining how the oscillation probability is theoretically determined. The Schrödinger equation describing the evolution of the state is written as:

$$i\hbar\frac{\partial}{\partial t}\begin{pmatrix} n \\ \bar{n} \end{pmatrix} = \begin{pmatrix} E_n & \delta m \\ \delta m & E_{\bar{n}} \end{pmatrix}\begin{pmatrix} n \\ \bar{n} \end{pmatrix}$$

Here, δm represents the transition mass, which enables oscillations. If $\delta m = 0$, the transition is impossible.

In this case, for the $n-\bar{n}$ transition, the initial and final states are $\begin{pmatrix} n \\ 0 \end{pmatrix}$ and $\begin{pmatrix} 0 \\ \bar{n} \end{pmatrix}$ respectively. After determining the eigenvalues of the matrix, the probability of finding an antineutron is given by:

$$P_{\bar{n}} = \frac{4\delta m^2}{\Delta E^2 + 4\delta m^2} \sin^2(\sqrt{\Delta E^2 + 4\delta m^2}t) \quad \Delta E = E_n - E_{\bar{n}}$$

If we assume that $\delta m \ll \Delta E$, the expression simplifies to:

$$P_{\bar{n}} \sim \left(\frac{\delta m}{\Delta E}\right)^2 \sin^2 \Delta E t$$

There are two cases to consider:

- $\Delta E t \ll 1 \rightarrow P_{n \rightarrow \bar{n}} \sim (\delta m \cdot t)^2 = \left(\frac{t}{\tau_{n-\bar{n}}}\right)^2$ - the case of free oscillations; $\tau_{n-\bar{n}}$ - free neutron-antineutron oscillation time
- $\Delta E t \gg 1 \rightarrow P_{n \rightarrow \bar{n}} \sim \frac{1}{2} \left(\frac{\delta m}{2\Delta E_n}\right)^2$ - the case of neutrons bound in a nucleus.

3 Neutron-antineutron oscillations in experiments and NOvA experiment

When discussing experiments, we will consider studies of oscillations of bound neutrons. This implies that whether a neutron has oscillated into an antineutron can be determined by its annihilation with a nucleon within the nucleus, releasing energy on the order of 2 GeV and emitting hadrons, predominantly pions. One such experiment is the Super-Kamiokande (SK) experiment.

The SK detector consists of a tank filled with purified water and equipped with photomultiplier tubes. Initially designed to search for proton decay, it can also be used to study neutron-antineutron oscillations. In SK, the exposure is 10^{32} neutron-years. Other experiments searching for such oscillations include SNO, Frejus, KamLAND, and IMB. Their comparison is presented in the table below. In this work, I focus more on the NOvA experiment and will evaluate

Table 1. Comparison of experiments searching for neutron-antineutron oscillations.

Experiment	SK	SD2	Frejus	KAM	IMB
Source of neutrons	Oxygen	Iron	Iron	Oxygen	Oxygen
Exposure (10^{32} neutron·yr)	245	21.9	5.0	3.0	3.2
Efficiency (%)	12.1	18.0	30.0	33.0	50.0
Candidates	24	5	0	0	3
Backgrounds	24.1	4.5	2.5(2.1)	0.9	–
T_{n-n} (10^{32} yr)	1.9	0.72	0.65	0.43	0.24
Suppression factor (10^{28} sec $^{-1}$)	0.517	1.4	1.4	1.0	1.0
τ_{n-n} (10^8 sec)	2.7	1.3	1.2	1.2	0.88

its sensitivity to detect oscillations based on available data. The experiment is multipurpose, though with a strong emphasis on neutrino oscillations. It can also search for magnetic monopoles, signals from supernovae, or neutron-antineutron oscillations. The NOvA detector consists of photoelectron cells whose length spans the entire transverse dimension of the detector. The detector’s dimensions are approximately $15.5\text{m} \times 15.5\text{m} \times 60.0\text{m}$.

4 Estimation of Oscillation Detection in NOvA

Here we will calculate the approximate exposure over 10 years based on information from the NOvA experiment dissertation [8] concerning the search for oscillations. The dissertation mentions a figure of $3 \cdot 10^{33}$ neutrons per year. Therefore, over 10 years we obtain $3 \cdot 10^{33} \cdot 10 = 3 \cdot 10^{34}$ neutron-years

A detailed simulation including background contributions yields an expected number of signal candidate events of 190 above background. Taking into account NOvA's sensitivity, this corresponds to a neutron oscillation lifetime of 1.88×10^{32} years. This value is comparable to the Super-Kamiokande result of 1.9×10^{32} years.

5 Conclusions

The following results were obtained in this work:

- A model describing neutron-antineutron oscillations from the perspective of quantum field theory was investigated.
- A Lagrangian accounting for CP violation with phase β was constructed.
- The detection of oscillations in the NOvA experiment was estimated.

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