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Neutron-Antineutron oscillation as a test of a New Interaction

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Summary. — We propose to search Neutron-Antineutron transitions, in condition of strong magnetic field rather than suppressed one. It is commonly accepted that such an oscillation has to be searched in no magnetic field conditions (for instance, the experiment have to be shielded by the Earth's magnetic field). But, Neutron (and Antineutron) could be coupled to a 5th force spin-independent background Φ generated by the Earth, as $e_V \Phi \bar{n} \gamma^0 n$. The background condensate simulates a difference in neutron and antineutron masses, in other words a CPT violation. Compatible with Equivalence Principle (EP) limits for a neutron inside nuclei, the 5th force background could be as high as $\Phi \sim 10^{-11} \div 10^{-10}$ eV. As consequence, the transition probability is amplified rather than suppressed with a magnetic field of $\mathcal{B} \sim 1$–10 Gauss, if we consider neutrons immersed in a background saturating the EP limit. There are intriguing connections among: the existence of a Majorana neutron, Baryon violations Beyond the Standard Model, the Matter-Antimatter asymmetry in our Universe (Baryogenesis and Leptogenesis), the possibility of a new fifth force interaction, the possible apparent violation of the Equivalence Principle and the CPT. These strongly motivate an improvement of our current best limits in n-$\bar{n}$ physics.

PACS 14.70.Pw – Other gauge bosons.
PACS 14.20.Dh – Protons and neutrons.
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PACS 11.30.Cp – Lorentz and Poincar invariance.

1. – Introduction

Is the existence of a Majorana particle possible, in our Universe? This question remains one of the most fascinating for theoretical physics. When we consider this issue, we would immediately think of neutrino. However, Ettore Majorana suggested the *neutron* as a candidate [1]. A Majorana mass $\delta m\, n^t n + h.c$ generates the neutron-antineutron transition [2]. The Baryon number B would be violated in this channel, $|\Delta B| = 2$. So, *the Majorana question* is strictly connected to a second deep question, the one about the violation of Baryon or Lepton numbers. In the Standard Model of

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Particles, the baryon number is an *accidental* symmetry, conserved at the level of the renormalizable interactions. But, it can be broken by higher-order operators. On the other hand, B and L have to be broken in the early Universe, in order to explain matter-antimatter asymmetry (baryogenesis and leptogenesis) and our life itself.

In particular, the $n-\bar{n}$ oscillation can be induced by the effective operators $\frac{1}{\mathcal{M}^5}(qqd)^2$ or $\frac{1}{\mathcal{M}^5}(udd)^2$, where $u = u_R$ and $d = d_R$ are up and down right-handed quarks, respectively, $q = (u_L, d_L)$ is a left handed quark doublet, $\mathcal{M}$ is the cutoff scale([1]).

On n-$\bar{n}$, the limits are placed by experiments on beam of slow neutrons with a speed $\sim 1000\,\mathrm{m/s}$, launched along a shielded tube for a time $\sim 0.1\,\mathrm{s}$. A condition of suppressed magnetic field $B \sim 10^{-4}$ Gauss is realized in this tube. A $\bar{n}$ could be detected at the end of the long tube: the antineutron annihilations make a typical signatures in the target. The best limit on the oscillation time in this way is actually $\tau_{n\bar{n}} = 1/\delta m > 3.3 \times 10^8\,\mathrm{s}$, corresponding to $\delta m < 10^{-23}\,\mathrm{eV}$ [4]. As a consequence, the bound on the new physics scale is $\mathcal{M} > 300\,\mathrm{TeV}$. There is the possibility in next future to enlarge the neutron propagation times to $\sim 1\,\mathrm{s}$. This enhances the experimental limit to $\tau_{n-\bar{n}} > 10^{10}\,\mathrm{s}$ [5]. A small Magnetic Field to $B \sim 10^{-6}$–10^{-5} Gauss would see necessary for an ideal experiment. In fact, a magnetic interaction $|\boldsymbol{\mu}_n \boldsymbol{B}| \gg \delta m$ would suppress the oscillation probability.

But in this short paper, we want to show how the situation can be the opposite. In fact it can be more appropriate to search for free n-$\bar{n}$ oscillation in the conditions of strong enough magnetic field. In particular we are interested to consider a background condensate Φ coupled to neutron and antineutron as $e_V \Phi \bar{n}\gamma^0 n$, with $e_V(n) = 1$ and $e_V(\bar{n}) = -1$ are the charges with respect Φ ([2]). Consider n-$\bar{n}$ in the presence of this background Φ and an external magnetic field $\boldsymbol{B}$: the Hamiltonian becomes

$$\mathcal{H}_{\mathrm{eff}} = \begin{pmatrix} m + \Phi + 2\boldsymbol{\omega}\cdot\sigma & \delta m \\ \delta m^* & m - \Phi - 2\boldsymbol{\omega}\cdot\sigma \end{pmatrix} \tag{1}$$

and we can consider $2\boldsymbol{\omega}\cdot\sigma \simeq 2\sigma_3\omega_3$ just as a convenient choice. The two mixing angles, for the two polarizations, are

$$\sin^2 2\theta_\uparrow = \frac{\delta m^2}{\delta m^2 + (\Phi + \mu_n B)^2}\,; \quad \sin^2 2\theta_\downarrow = \frac{\delta m^2}{\delta m^2 + (\Phi - \mu_n B)^2}$$

with $\Omega_\uparrow = \sqrt{\delta m^2 + (\Phi + \mu_n B)^2}$ and $\Omega_\uparrow = \sqrt{\delta m^2 + (\Phi - \mu_n B)^2}$.

The transition probability is

$$\mathcal{P}_{n\bar{n}} = \frac{1}{2}\left[\sin^2 2\theta_\uparrow \sin^2(\Omega_\uparrow t) + \sin^2 2\theta_\downarrow \sin^2(\Omega_\downarrow t)\right]. \tag{2}$$

([1]) In [7] we propose that the Majorana mass of the neutron could be indirectly generated by *exotic stringy instantons* in a string inspired standard model construction with intersecting D-brane stacks and open strings. In this model a neutron-antineutron transition can be fast as $10^{10}\,\mathrm{s}$ without a fast proton decay.

([2]) This could be induced by a *fifth force*, coupled with the baryon number, interacting with neutrons like $e_V V_\mu \bar{n}\gamma^\mu n$ (vectorial), or $e_V V_\mu \bar{n}\gamma^\mu\gamma^5 n$ (axial), as $\langle V_0 \rangle = \Phi$. V_μ can be a baryphoton of $U(1)_B$ or $U(1)_{B-L}$, coupled with the baryon number as a Baryonic charge [8]. This interaction is spin independent.

For $\Phi \ll \mu B$, $\theta_\uparrow \simeq \theta_\downarrow = \theta$: there isn't effect of the background field in the oscillation. For $\Phi \simeq \mu B$, the up-polarization channel is suppressed, but down-polarization channel is resonantly enhanced. For $\Phi \simeq -\mu B$, the down-polarization is suppressed, but the down-polarization channel is resonantly enhanced.

The Background field is bounded by the General Relativity Equivalence Principle obtained by free falling nuclei limits [6]. Saturating the Equivalence principle limit, the Background field is $\Phi \sim 10^{-11} \div 10^{-10}\,\mathrm{eV}$ for free neutrons. This corresponds to a magnetic energy of $|\boldsymbol{\mu} \cdot \boldsymbol{B}| \sim 10^{-11} \div 10^{-10}\,\mathrm{eV}$and so to a magnetic field of $|B| \sim$ 1–10 Gauss.

It is interesting to consider limits on the mass difference between neutrons and antineutrons with respect to other particles:

$$|m_{K^0} - m_{\bar{K^0}}|\,/m_{K^0} < 8\times10^{-19},\ |m_p - m_{\bar{p}}|\,/m_p < 2\times10^{-9},\ |m_n - m_{\bar{n}}|\,/m_n < (9\pm5)\times10^{-5}.$$

Limits on neutron-antineutron are midl with respect to a proton-antiproton or a neutral kaon-antikaon. So, it was proposed that n-$\bar{n}$ oscillations would be a viable test of the CPT-symmetry [3]. Also in this case, it could be more appropriate to perform the experiment in strongly magnetic field conditions about the Gauss scale. However, no one knows how to formulate a calculable CPT-violating quantum field theory: breaking explicitly CPT implies no-locality and no-unitarity. On the other hand, CPT violation for neutron could be *simulated* by a fifth force, condensing as a background Φ, like the one under our discussion, without losing quantum field theory consistence. In particular, the neutron-antineutron mass splitting could be an *apparent* effect, by the fact that n and $\bar{n}$ are immersed, not only in the gravitational field, but also in the background Φ. This can induce an apparent difference of mass, under the limit $|m_n - m_{\bar{n}}| = 2\Phi < 10^{-5} m_n \sim 10\,\mathrm{keV}$ and the stronger bounds by EP. Note that the limit on the proton m_p are $2\Phi < 10^{-9} m_n \sim 10^{-9}\,\mathrm{eV}$, not so far by EP ones.

To conclude, neutron-antineutron experiments in presence of strong magnetic field are necessary in order to test the presence of a new fifth force interaction and baryon number violations. All experimental observables, that could be tested in the next future, deserve attention, especially if their implications are so deep, and regardless of our theoretical and aesthetic prejudices.

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