PHYSICAL REVIEW D **94,** 054034 (2016)

Limiting equivalence principle violation and long-range baryonic force from neutron-antineutron oscillation

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(Received 1 July 2016; published 26 September 2016)

We point out that if the baryon number violating neutron-antineutron oscillation is discovered, it would impose strong limits on the departure from Einstein's equivalence principle at a level of one part in 10^{19}. If this departure owes its origin to the existence of long-range forces coupled to baryon number B (or $B - L$), it would imply very stringent constraints on the strength of gauge bosons coupling to the baryon number current. For instance, if the force mediating baryon number has strength α_B and its range is larger than a megaparsec, we find the limit to be $\alpha_B \leq 2 \times 10^{-57}$, which is much stronger than all other existing bounds. For smaller range for the force, we get slightly weaker, but still stringent bounds by considering the gravitational potentials of Earth and the Sun.

DOI: 10.1103/PhysRevD.94.054034

I. INTRODUCTION

The equivalence principle is one of the pillars of Einstein's general relativity. The success of general relativity has therefore led, over the years, to many attempts to search for deviation from this principle. These attempts have so far been unsuccessful and have provided very stringent upper limits on any possible deviation. One way to interpret a deviation from the equivalence principle is to assume that there exist long-range forces with subgravitational strengths and the above-mentioned upper limits are then reflections on the strength of these new long-range forces. A very well-known early example of such an interpretation is the work of Lee and Yang [1] who obtained a limit $\alpha_B \leq 6 \times 10^{-44}$ on the strength of the long-range force coupled to the baryon number. Subsequent experiments have improved on this limit to the level of 10^{-49} [2].

In this brief paper, we point out that if the baryon number violating process of neutron to antineutron oscillation [3] is observed, regardless of the level at which it is discovered, it will put an upper limit on the deviation of equivalence principle for neutrons and antineutrons. If this deviation is attributed to the existence of a $U(1)_B$ [or $U(1)_{B-L}$] local symmetry coupled to the baryon number with an associated long-range force, we find very stringent limits on the strength of this long-range force (denoted by α_B). The limits depend on the range of the force. The most stringent limit arises in the case when the range of the force is larger than 100 megapersec (Mpc), and is found to be $\alpha_B \leq 10^{-54}$, which is significantly stronger than that derived by Lee and Yang [1] and improved subsequently [2]. We also comment on the effect of the baryon asymmetry of the Universe on α_B.

Before we discuss our results, it is worth reminding the reader that the process of $n - \overline{n}$ oscillation has been shown in the literature to be a consequence of many extensions of the standard model [4] and results from the generation of a six-quark operator e.g. of the form $u_R d_R d_R u_R d_R d_R$ which changes the baryon number by two units. This process has been searched for in an experiment at the ILL, Grenoble in the 1990s [5] which has put an upper bound on the strength of this process: The neutron to antineutron transition time should obey the limit $\tau_{n\overline{n}} > 0.86 \times 10^8$ s. Various phenomenological issues related to searches for this process have been discussed in Ref. [6]. There is an interesting possibility that the new baryon number violating interactions that generate $n - \overline{n}$ oscillations are also responsible for generating the baryon asymmetry of the Universe [7]. Currently, there are attempts to conduct another higher sensitivity search at the European Spallation Source at Lund, Sweden [6], which could improve on the ILL sensitivity by 2 to 3 orders of magnitude.

II. NEUTRON-ANTINEUTRON OSCILLATION AND BOUND ON DEPARTURE FROM THE EQUIVALENCE PRINCIPLE

The basic equation that we use in our discussion is the quantum mechanical evolution of the two state system for n and $\overline{n}$ in the presence of an external field that distinguishes between neutrons and antineutrons:

$$\frac{d}{dt}\begin{pmatrix} n \\ \overline{n} \end{pmatrix} = \begin{pmatrix} M_1 & \delta \\ \delta & M_2 \end{pmatrix}\begin{pmatrix} n \\ \overline{n} \end{pmatrix}. \quad (1)$$

If we start with an initial beam of neutrons, the probability that an antineutron beam will appear after a transit time of t is given by

$$P_{n-\bar{n}} = \frac{\delta^2}{\Delta M^2 + \delta^2} \sin^2 \frac{\sqrt{\Delta M^2 + \delta^2} t}{\hbar} \tag{2}$$

where $\Delta M = M_2 - M_1$. This difference could arise from a magnetic field [8] or from nuclear forces, for example. In our discussion here, it will owe its origin to departure from the equivalence principle and/or new long-range forces that distinguish between neutrons and antineutrons. For a transit time t, the condition for observability of $n - \bar{n}$ oscillation [8] is that $\Delta M t \leq 3 \times 10^{-24}$ GeV-sec. For transition time of order of 1 s, which is what realistic experimental setups can achieve with current technology, this condition would imply $\Delta M \leq 3 \times 10^{-24}$ GeV as a generous upper limit. Thus, the observation of $n - \bar{n}$ oscillation will impose a constraint on the strength of the forces that are responsible for causing the mass difference. This constraint was used recently to obtain a limit on possible violation of Lorentz invariance [9].

To obtain the limit on the departure from the equivalence principle for neutrons and antineutrons, all we have to do is to calculate ΔM. We adopt the following parametrization for this purpose. Let us consider a source of gravitational potential of mass M which is at a distance r from the neutrons in the experiment searching for $n - \bar{n}$ oscillation. Assuming that the force causing the departure to be long range, we can parametrize the departure from the equivalence principle for neutrons given by the potential $\alpha_n \frac{GMm}{r} e^{-r/R_0}$ and antineutrons by $\alpha_{\bar{n}} \frac{GMm}{r} e^{-r/R_0}$ (where m is the mass of the neutron). Then we obtain

$$\Delta M = (\alpha_n - \alpha_{\bar{n}}) \frac{GMm}{r} e^{-r/R_0}. \tag{3}$$

By consideration of different astrophysical sources, which will have different M and different r, we can get different limits on $(\alpha_n - \alpha_{\bar{n}})$. Below we summarize the different limits by considering Earth, Sun and the superclusters. Clearly, the validity of the limits will depend on the range of the forces.

A. Superclusters limit

We consider a typical supercluster such as Virgo which is at a distance of 16.5 Mpc and has a mass of 2.4×10^{45} kg. For this we get $\frac{GMm}{r} \simeq 3.6 \times 10^{-6}$ GeV. Using the fact that the corresponding $\Delta M \leq 3 \times 10^{-24}$ GeV (required if $n - \bar{n}$ oscillation is observed), we get the bound

$$(\alpha_n - \alpha_{\bar{n}}) \leq 10^{-18}. \tag{4}$$

This limit on the equivalence principle violation is more stringent than any known at the moment for baryons [10]. The results of Dicke and co-workers [11a] and Braginsky and Panov [11b] are at the level of 10^{-12}. The most stringent limit from $K^0 - \overline{K^0}$ oscillations seems to be comparable to ours [12], $(\alpha_K - \alpha_{\overline{K}}) \leq 2.6 \times 10^{-18}$.

B. Limit from Earth's gravitational field

If the range R_0 of the equivalence principle violating effect is $\sim$10,000 km, then the supercluster limits will not apply (due to the $e^{-\frac{r}{R_0}}$ suppression factor for $r \gg R_0$), but there should be a limit by considering the effect of Earth. Using the mass of Earth as 6×10^{24} kg and the radius of Earth as $R_E = 6384$ km, we estimate that Earth's effect leads to $(\alpha_n - \alpha_{\bar{n}}) \leq 4 \times 10^{-15}$.

III. GAUGED BARYON NUMBER AND LIMIT ON LONG-RANGE BARYONIC FORCE FROM OBSERVATION OF $n - \bar{n}$ OSCILLATION

Gauging the baryon number has been considered for a long time as way to understand the conservation of the baryon number in the Universe [1]. In particular, Lee and Yang [1] derived a limit on the strength of the effective baryon number force α_B to be at the level of 10^{-47} if we parametrize the resulting potential as

$$V_B(r) = \alpha_B \frac{N_A N_B}{r} e^{-r/R_0} \tag{5}$$

where $N_{A,B}$ are the baryon numbers of the two objects between which the above potential is effective and R_0 is the range of the force. Understanding the baryon asymmetry of the Universe seems to require as one of its ingredients that the baryon number be violated. This has led to a new class of models where the local baryon number symmetry is spontaneously broken [13]. A similar situation also happens for $B - L$ violation [14]. Typically, in these models, one assumes that the corresponding gauge coupling g_B is of order $\sim$0.1–1 so that for the spontaneously generated vacuum expectation value $v_B \sim$ TeV, the resulting force is short range and is not relevant in the discussion of the violation of the equivalence principle at macroscopic distances. In this section, we will adopt a somewhat different point of view where even though the local baryon number symmetry is broken spontaneously at a few hundred GeV to TeV scale, the associated gauge coupling is very small. For example, if the gauge coupling is $\leq 10^{-25}$, the range of the force with $v_B = 1$ TeV is larger than Earth's radius and will in principle affect the equivalence principle between the neutron and antineutron.

Note that since in our theory, neutron-antineutron oscillation is allowed to occur at an observable rate, we must have Feynman diagrams for the $\Delta B = 2$ processes, which give strengths at the quark level of 10^{-28} GeV^{-5}. In beyond the standard model scenarios, $n - \bar{n}$ oscillation arises from the six quark operator $(udd)^2$ and its strength in a typical $B - L$ violating theory [14] is given by $G_{\Delta B=2} \sim \frac{\lambda f^3 v_{BL}}{M_\Delta^6}$.

Thus we can have observable $n-\overline{n}$ oscillation by choosing the corresponding Yukawa couplings f and Higgs masses M_Δ appropriately for TeV-scale v_B. It is important to note that in the theory of the type described in [14], the $\Delta B=2$ diagram does not involve gauge couplings. Thus we can take the theory of Ref. [14], and make the gauge coupling extremely tiny so that it produces corrections to the equivalence principle and then check what would be an upper bound on the gauge coupling in this domain of parameters.

Following the procedure above, we find that the neutron and antineutron experience equal and opposite long-range forces from an astrophysical object. Considering the effect of Earth, we find that the equivalence principle violating parameter $\frac{\Delta M}{m_n}$,

$$\frac{\Delta M}{m_n}=\frac{2\alpha_B N_B^{\text{Earth}}}{m_n R_{\text{Earth}}}\sim 1.2\times 10^{+29}\alpha_B. \tag{6}$$

Requiring that $n-\overline{n}$ oscillation be observable in the presence of this effect implies that $\frac{\Delta M}{m_n}\le 3\times 10^{-24}$ leading to $\alpha_B\le 2.5\times 10^{-53}$, which means that the corresponding gauge coupling $g_B\equiv\sqrt{4\pi\alpha_B}\le 1.7\times 10^{-26}$. This implies a range $R_0\ge 10^9$ cm which exceeds Earth's radius. This is already a much stronger bound than any known to date [15].

This bound becomes even stronger if we apply the same considerations to the Sun. First note that this would require that the gauge coupling be less than 10^{-30}. Using the mass of the Sun which is 2×10^{30} kg and the Earth-Sun distance $\sim 1.5\times 10^{13}$ cm, we get $\alpha_B\le 10^{-54}$ and hence $g_B\le 3\times 10^{-27}$. For consistency with the range requirement, we must take the symmetry breaking scale $v_B\sim 10$ GeV.

Coming to the case of the Virgo supercluster, where mass and distance are already mentioned, applying similar arguments (if the range of the force R_0 is larger than 10^{26} cm), we obtain $\alpha_B\le 2\times 10^{-57}$ leading to $g_B\le 1.2\times 10^{-28}$. Clearly to get this kind of range, we must have the symmetry breaking scale to be less than few eV. Such small vacuum expectation value, to be consistent with current limits on the strengths of $n-\overline{n}$ oscillation will require making some parameters in the model small. Our goal here is not to explore the naturalness of the theory but rather to pursue the phenomenological implications.

We have summarized in Fig. 1 the constraints from long-range baryonic forces that arise from Earth, the Sun and superclusters on the strength of the B or $B-L$ gauge interaction α_B.

We point out that if instead of the gauged baryon number, we consider a force coupled to gauged $B-L$, we will get a slightly weaker bound since typical astrophysical objects will contain hydrogen and helium atoms in comparable numbers; however the hydrogen atom has zero $B-L$ whereas the helium atom has $B-L=2$. The factor weakening the bound will depend on the relative content of these two atoms in the astrophysical object.

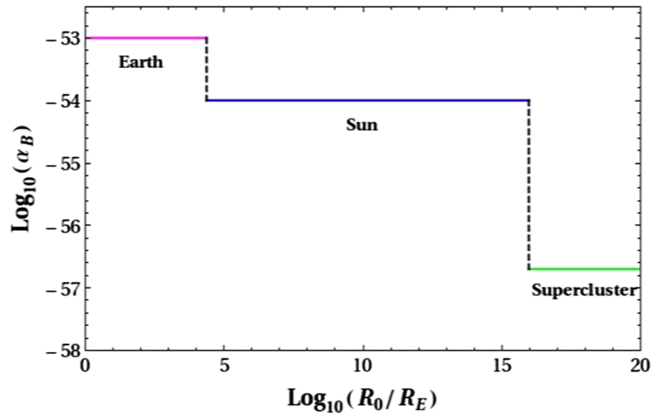

FIG. 1. Limits on α_B that would result from observation of $n-\bar{n}$ oscillation in the presence of a long-range baryonic force. Here $R_E=6.384\times 10^8$ cm is the radius of Earth, and R_0 is the range of the force.

IV. DISCUSSION

It is worth noting that if instead of $B-L$, the source of the gauge force is assumed to couple to hadronic hypercharge $Y=B+S$, where S = strangeness, applying the arguments of our paper to the kaon system, we would get a similar bound on this new force. We note however, that new gauge forces associated with B or $B-L$ charges would not couple to the kaon which is neutral under these charges.

A second question one may ask is that since the Universe is asymmetric with respect to baryon number, whether it is possible to get a bound on α_B from consideration of the effect of the Universe's baryon asymmetry on neutron-antineutron oscillation. The first point to note is that the density of baryons outside compact astrophysical objects is very small ($\sim 10^{-7}/\text{cm}^3$). Second, the effective nonrelativistic potential due to $B-L$ potential goes inversely as distance and depends on the range of the force. If the range of the force is less than 100 Mpc, the cumulative effect of the baryon asymmetry only within this range is effective and does not give a bound stronger than what we obtained before. If the range is considered to be of the order of the size of the Universe ($\sim 10^{27}$ cm) and if we assume the baryon density throughout the Universe to be uniform with a value of 10^{-7} per cubic centimeter, we roughly estimate that the $B-L$ force will split the masses of the neutron and the antineutron by $10^{34}\alpha_B$ GeV. This needs to be less than 10^{-24} GeV if $n-\overline{n}$ oscillation is to be observable. This puts a limit on $\alpha_B\le 10^{-58}$, which is more stringent than the supercluster limit derived above. In this case, the primary assumption that baryon density in the Universe is uniform all throughout could be open to debate, which will then make the above conclusion less reliable. In any case this is an interesting point to keep in mind.

In summary, in this brief paper we have pointed out that observation of neutron-antineutron oscillation, in addition to providing a key window into physics beyond the standard model and possibly solving the baryon asymmetry problem, can also provide insight into violation of the equivalence principle as well as limits on the strength of long-range baryonic gauge forces. It is important to point out that to obtain the limits discussed above, one has to carry out the search for and observe free neutron oscillation and not a $\Delta B = 2$ transition in a nucleus, where such tiny effects are masked by the larger nuclear potential difference affecting the neutron and the antineutron. It may also be worth noting that, if neutron oscillation inside a nucleus is discovered and no $n - \bar{n}$ oscillation at the same level is found in a free neutron oscillation search, that could be evidence of the existence of violation of the equivalence principle and/or existence of baryonic long-range forces. These results should provide additional impetus to carry out the search for free neutron oscillation in the laboratory.

ACKNOWLEDGMENTS

The work of K. S. B. is supported by the U.S. Department of Energy Grant No. de-sc0016013 and the work of R. N. M. is supported by the U.S. National Science Foundation Grant No. PHY-1315155. K. S. B. wishes to thank the CETUP* 2016 workshop in Lead, SD, where part of this work was done, for hospitality and support.

Note added.—After this work was completed and presented at the CPT16 meeting in Bloomington, Indiana (June 20–24, 2016), it was brought to our attention by W. M. Snow that a similar work is in progress by Berezhiani and Kamyshkov (to be published).

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