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Super-light baryo-photons, weak gravity conjecture and exotic instantons in neutron-antineutron transitions

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Abstract: In companion papers (A. Addazi, Nuovo Cim. C, **38**(1): 21 (2015); A. Addazi, Z. Berezhiani, and Y. Kamyshkov, arXiv:1607.00348), we have discussed current bounds on a new super-light baryo-photon, associated with a $U(1)_{B-L}$ gauge, from current neutron-antineutron data, which are competitive with Eötvös-type experiments. Here, we discuss the implications of possible baryo-photon detection in string theory and quantum gravity. The discovery of a very light gauge boson should imply violation of the weak gravity conjecture, carrying deep consequences for our understanding of holography, quantum gravity and black holes. We also show how the detection of a baryo-photon would exclude the generation of all $B-L$ violating operators from exotic stringy instantons. We will argue against the common statement in the literature that neutron-antineutron data may indirectly test at least the 300−1000 TeV scale. Searches for baryo-photons can provide indirect information on the Planck (or string) scale (quantum black holes, holography and non-perturbative stringy effects). This strongly motivates new neutron-antineutron experiments with adjustable magnetic fields dedicated to the detection of super-light baryo-photons.

Keywords: neutron-antineutron, baryon and lepton violations, string phenomenology

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1 Introduction

B and L are accidental symmetries of the Standard Model. Their conservation is in agreement with all current data. Some symmetry principles could be behind the accidental conservation of B and L. The simplest idea is to recover B and L number conservation as residual discrete symmetries of spontaneously broken global $U(1)_L$, $U(1)_B$, or a linear combination of the two (such as $U(1)_{B-L}$ or $U(1)_{B+L}$ and so on). This class of models predicts the existence of new pseudo-goldstone bosons known in the literature as majorons [1–3][2)]. An alternative way is to gauge the B and L symmetries. However, it is well known that gauged $U(1)_B$ and $U(1)_L$ are anomalous. The only way out from anomalies is to consider a gauged $U(1)_{\zeta(B-L)}$, where ζ is an arbitrary constant which can be redefined in particle charges, i.e. $U(1)_{B-L}$ for convention. In particular, the $U(1)_{B-L}$ gauge group may be spontaneously broken by a new Higgs singlet field (Higgs mechanism) or a Stueckelberg gauged axion (Stueckelberg mechanism). Usually, $U(1)_{B-L}$ is thought of as a spontaneously broken gauge group at high scales, i.e. a new Z′ boson possibly testable at the LHC or future colliders. On the other hand, from the point of view of quantum field theory consistency, a gauge $U(1)_{B-L}$ could also be massless. But certainly, this would be not phenomenologically healthy: it would be in contradiction with baryogenesis, which requires a violation of $B-L$[3)]. If we desired to break $B-L$ at an intermediate or high scale with a semi-massless gauge boson, we would introduce a very weakly coupled $B-L$ boson with $M_b^2\sim\alpha_{B-L}v_{B-L}^2$ and $\alpha_{B-L}<<1$. Such a scenario would be *technically natural*: such a tiny coupling remains stable against renormalization gauge group corrections. In fact, all corrections in the renormalization group equation (RGE) are controlled by an overall factor g^3_{B-L} (as can be understood by counting two-loop corrections in Landau gauge). For example the two-loop RGE (in Landau gauge) contributions are suppressed as $g^3_{B-L}\mathrm{Tr}[Y^\dagger Y]$ (from Yukawa's couplings Y) and $g^3_{B-L}g_i^2$ (from gauge fields g_i). This is not the case for gauged $U(1)_B$ or $U(1)_L$, which would be corrected by quadratically divergent contributions and should be enormously fine-tuned from their mass scale to the Planck scale. However, the

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2) Majorons can also provide a good candidate for (warm) dark matter [3, 4]. See also Refs. [7–12]

3) See Ref. [48] for recent considerations on baryogenesis and $n\bar{n}$ transitions.

new Higgs field χ introduced to spontaneously break $U(1)_{B-L}$ can mix with the ordinary Higgs field as $\chi^{\dagger}\chi\bar{H}H$ and this could introduce a new hierarchy problem. This is connected with the old hierarchy problem of the Higgs mass, which still remains unsolved.

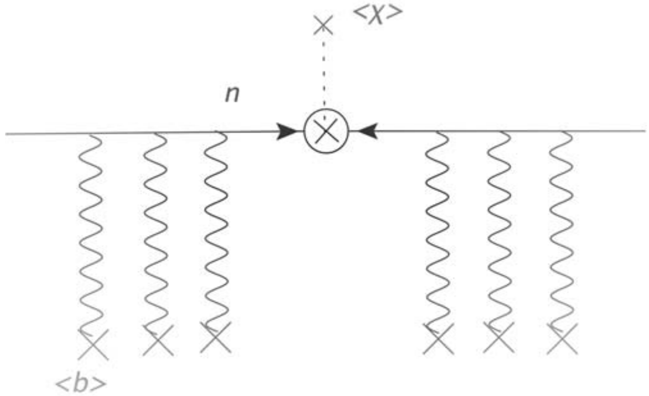

Fig. 1. Neutron-antineutron transition in a baryo-photon background $\langle b_0\rangle$. The presence of a baryo-photon background field generates a mass splitting among neutron and antineutron. A Majorana mass term for the neutron can be generated by the spontaneous symmetry breaking of $U(1)_{B-L}$ induced by the VEV of χ.

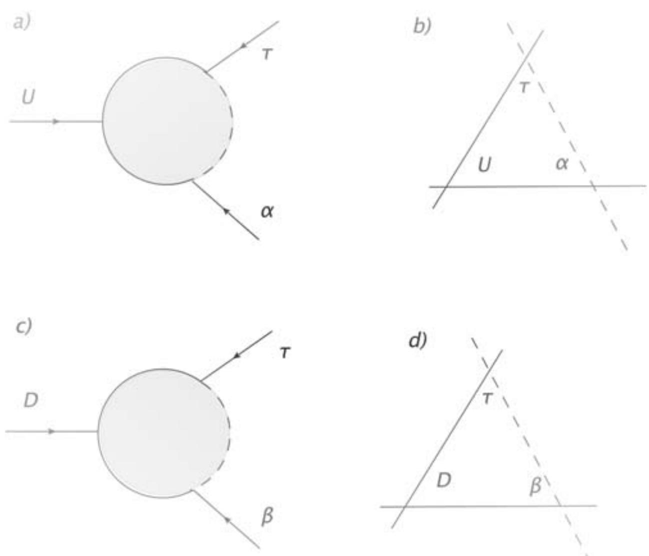

Fig. 2. (a) The mixed disk amplitude coupling the physical RH (super)quark U with two instantonic zero modes τ and α, and (b) the mixed disk amplitude dual picture in terms of intersecting D-branes. (c) The mixed disk amplitude coupling the physical RH (super)quark D with two instantonic zero modes τ and β, and (d) the mixed disk amplitude dual picture in terms of intersecting D-branes.

However, not all possible allowed gauge interactions in quantum field theories decoupled by gravity seem to be compatible with quantum gravity. For instance, the weak gravity conjecture (WGC) states that the weakest interaction is gravity and it excludes the presence of new very light $U(1)$ bosons like $U(1)_{B-L}$ coupled to ordinary matter. This means that for each interaction, there must exist a particle satisfying

$$\frac{m}{q}\leqslant M_{Pl}, \tag{1}$$

where m,q are the mass and U(1)-charge of the particle respectively [11].

At present, the WGC is only based on heuristic arguments sustained by holography and the absence of global symmetries in quantum gravity and string theory. In particular, L. Susskind suggested that, according to holography, black hole (BH) remnants should be impossible [12]. The WGC argument is the following: let us consider an hypothetical interaction of a particle with mass m and $\tilde{\alpha}<1$, where $\tilde{\alpha}=\alpha_{YM}/G_N m^2$. In this case a black hole can have a charge from 0 to $\bar{Q}=\tilde{\alpha}^{-1}$ (for example $\tilde{\alpha}\sim 10^{-10}$, i.e. $\bar{Q}\sim 10^{10}$) and these charges cannot be radiated away as Hawking radiation. This should imply a final remnant extremal BH with $M=QM_{Pl}$ and Q in range $(0,\bar{Q}]$, contradicting Susskind's arguments. This seems to lead to the conclusion that the WGC is sustained from the holographic principle.

One could think that a heuristic argument is not satisfying enough and that the conjecture should be tested with high precision. Testing WGC is crucial for our understanding of quantum gravity, holography and black holes. For instance, a violation of the WGC would imply that some fundamental aspect in our understanding of black holes and quantum gravity is still missing. In particular, it is commonly held that holography is a crucial feature of black hole physics and a violation of the WGC would lead to revisiting this concept.

However, the detection of a super-light baryo-photon could lead to the rethinking of semi-classical non-perturbative solutions in string theory. In particular, exotic D-brane instantons can generate $B-L$ violating operators and their implications in particle physics were recently discussed in our papers [23–33]. $B-L$ violating exotic instantons need to be synchronized with a Stueckelberg mechanism for $U(1)_{B-L}$, sending the B–L gauge boson mass to a large scale. This means that a super-light baryo-photon would be in tension with exotic instanton effects, which should be suppressed by non-perturbative stringy corrections beyond the semi-classical approximation. The detection of a baryo-photon would therefore imply a prohibition of exotic instanton effects from the spontaneous symmetry breaking scale v_{B-L} up to the string scale!

In this article, we suggest tests of both the weak gravity conjecture and non-perturbative stringy effects from neutron-antineutron oscillation data. The neutron-antineutron transition has not been observed, and the most recent limits were obtained by Baldo-Coelin et al. [13]. From these data, Z. Berezhiani, Y. Kamyshkov and the author of this paper have recently discussed limits on a new baryo-photon coupled to the (anti)neutron from neutron-antineutron experiments [? ?]. The possibility of improving current neutron-antineutron limits was discussed in Ref. [14]. However, the authors of Ref. [14][1)] have emphasized aspects of neutron-antineutron experiments as a test for the effective $\Delta B{=}2$ Majorana mass operator $(udd)^2/M^5$, in order to indirectly test the $M\simeq 1000\,\mathrm{TeV}$ scale. It was therefore suggested to search for n–$\bar{n}$ transitions with very suppressed external magnetic field ($B<10^{-4}\,$Gauss). According to our work [? ?], however, a neutron-antineutron transition should be suppressed by the presence of an external baryo-photon background field. For example, for a baryo-photon background field with scale 10^{-11}–$10^{-13}\,$eV on the Earth's surface, neutron-antineutron transitions would be enhanced in strong magnetic field conditions of $B\sim 1$–10 Gauss rather than suppressed ones. In this article, we suggest that the search for a baryo-photon can provide a test for Planck (and string) scale physics, even if $M_{Pl},M_s>>1000$ TeV. In fact, according to our considerations above, the detection of a baryo-photon in neutron-antineutron experiments should violate the weak gravity conjecture as well as being a test for exotic D-brane instantons. In other words, detection of a baryo-photon would lead to re-discussion of the same basic principles of quantum gravity and string theory, such as holography, stringy instantons, black hole remnants and so on. In this sense, searches for baryo-photons in neutron-antineutron experiments can indirectly test quantum gravity.

2 Baryo-photons

The baryo-photon model is based on a Standard Model gauge group extension with an extra $B-L$ gauge symmetry: $SU(3)_c\times SU(2)_L\times U(1)_Y\times U(1)_{B-L}$.

The B–L baryo-photon gauge coupling with neutron, proton and lepton currents is

$$\mathcal{L}_{B-L}=gb_\mu(\bar{n}\gamma^\mu n+\bar{p}\gamma^\mu p-\bar{e}\gamma^\mu e-\bar{\nu}\gamma^\mu\nu), \tag{2}$$

where b_μ is the baryo-photon associated with $U(1)_{B-L}$. With an exact $U(1)_{B-L}$, the neutron-antineutron transition is forbidden, otherwise a gauge symmetry is violated. So, $U(1)_{B-L}$ has to be spontaneously broken, and this can be synchronized with the generation of an effective Majorana mass for the neutron. For example, one can introduce effective operators like

$$\frac{\chi}{M^6}(udd)(udd),\ \frac{\chi}{M^6}(qqd)(qqd),\ \frac{\chi}{M^6}(udd)(qqd) \tag{3}$$

($qq=\epsilon^{\alpha\beta}q_\alpha q_\beta/2=u_Ld_L$), where χ is a Higgs scalar field with charge $Q_{B-L}=-2$ and there is a vacuum expectation value $\langle\chi\rangle=v_\chi$. In this case, a $n-\bar{n}$ transition is generated with an effective suppression scale $\mathcal{M}_{n\bar{n}}=(M^6/v_\chi)^{1/5}$ and consequently a Majorana mass term $\delta m_{n\bar{n}}=\Lambda_{QCD}^6/\mathcal{M}_{n\bar{n}}$. An example of UV completion of such an operator was suggested in Refs. [15?] as a see-saw mechanism for the neutron. Alternatively, it is also possible that the generation of the effective Majorana mass term for the neutron is totally disconnected by the spontaneous symmetry breaking mechanism and it happens after the spontaneous breaking. Then, in full generality, one can also consider the more complicated case in which $U(1)_{B-L}$ is spontaneously broken by a combination of scalars χ,η_i:

$$v=[v_\chi^2+(Q_i/Q_\chi)^2]^{1/2},\ M_b=2^{3/2}gv, \tag{4}$$

where Q_i,Q_χ are the B-L charges of the scalars while M_b is the mass of the baryo-photon. As a consequence, the baryo-photon mediates a spin-independent force among SM particles with baryon and lepton charges:

$$V_i=\alpha_{B-L}\frac{Q_iQ_A}{r}e^{-r/\lambda},\ \lambda=M_b^{-1}, \tag{5}$$

$\alpha_{B-L}=g^2/4\pi$ and where

$$\lambda\simeq 0.6\times(10^{-49}/\alpha_{B-L})^{1/2}(1\mathrm{keV/v})\times 10^{16}\,\mathrm{cm}$$

An external $B-L$ static background therefore generates an effective mass splitting term between the neutron ($Q_{B-L}{=}+1$) and the antineutron ($Q_{B-L}{=}-1$):

$$\frac{V_{n\bar{n}}}{V_n^G}=\pm\tilde{\alpha}q_A, \tag{6}$$

where V_n^G is the gravitational potential, $q_A=Q_Am_n/(M_A)$ and $\tilde{\alpha}=\alpha_{B-L}/\alpha_G$ and $\alpha_G=G_Nm_n^2$. If a $\tilde{\alpha}<<1$ gauge boson was detected, the WGC would be violated.

The Yukawa radius is larger than Earth's radius:

$$\lambda>R_{\mathrm{Earth}}\to\alpha_{B-L}<10^{-49},\ \tilde{\alpha}<1.7\times 10^{-11}. \tag{7}$$

The Earth induces a gravitational energy for the neutron at its radius of $V_{\mathrm{Earth}}^E=-Gm_nM_{\mathrm{Earth}}/R_{\mathrm{Earth}}\simeq 0.66\mathrm{eV}$, while the Sun gives $V_{\mathrm{Sun}}^G=-Gm_nM_{\mathrm{Sun}}/AU\simeq 10\mathrm{eV}$, and the Galaxy gives $V_{\mathrm{Galaxy}}^G\simeq 1\mathrm{keV}$. The total energy potential contribution from baryo-photons on a (anti)neutron in the laboratory frame is

$$\begin{aligned}V_n\ =\ &\tilde{\alpha}(0.5V_{\mathrm{Earth}}^Ge^{-R_{\mathrm{Earth}}/\lambda}+0.13V_{\mathrm{Sun}}^Ge^{-AU/\lambda}\\&+0.13V_{\mathrm{Galaxy}}^Ge^{-10\mathrm{kpc}/\lambda}).\end{aligned} \tag{8}$$

The effective interaction enters into the oscillation

1) See also related discussion on perturbative renormalization of $n\bar{n}$ operators [46] and on experimental aspects [47].

probability as

$$P_{n\bar{n}}=P^{+}+P^{-} \tag{9}$$

$$P^{\pm}=\frac{\delta m^2_{n\bar{n}}}{\delta m^2_{n\bar{n}}+\Delta^2_{\pm}}\sin^2\left(t\sqrt{\delta m^2_{n\bar{n}}+\Delta^2_{\pm}}\right)$$

where $\Delta_{\pm}=V\mp\Omega_B$, $\Omega_B=|\mu_n\cdot\mathbf{B}|\simeq 6\cdot 10^{-12}(\mathrm{B}/1\mathrm{G})$ eV (the Zeeman energy shift induced by the external magnetic field), $\pm$ corresponds to the two polarization states, and $\delta m_{n\bar{n}}$ is the effective Majorana mass term.

In Fig. 3, we show various exclusion plots for (λ,α_{B-L}) parameter space compared with Eötvös-like experiments. As one can see, for $\lambda>10^9$cm, which is comparable with the Earth's radius, for $v_{B-L}>1$GeV the parameter space is very constrained. On the other hand, $v_{B-L}<1$meV is not possible in a minimal model: it would imply a spontaneous breaking of $U(1)_{B-L}$ only in the very late Universe (1–10 Gyrs), which is clearly excluded by baryogenesis. However, we suggest that this scenario could have a subtle way out: it is possible that B–L was broken in the early Universe because of thermal bath induced expectation values to one (or more) scalar Higgs, allowing baryogenesis, and restored later. Our idea is inspired by various old models of high temperature symmetry breaking suggested in Refs. [16–21]. An interesting possibility could be a phase transition mechanism from an electroweak conserving and $B-L$ broken vacuum (G_{SM}) to an electroweak breaking and B–L preserving vacuum $G'=(SU(3)_c\times U(1)_{em}\times U(1)_{B-L})$. In this case, CP-violating scatterings of primordial plasma to expanding bubbles associated with the broken-restored phase G' can generate a baryon asymmetry as in standard electroweak baryogenesis (see Ref. [22] for a review).

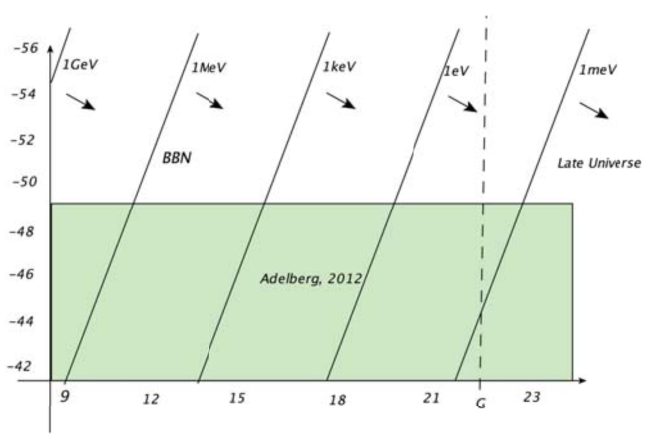

Fig. 3. (color online) The parameter space of $(\log_{10}\lambda(cm),\log_{10}\alpha_{B-L})$ is constrained by Eötvös type experiments, as displayed in this figure (in green, Adelberg (2012)) (we applied the limits discussed in Ref. [45] for a $B-L$ baryo-photon). We display the range from $\Delta\lambda=10^9$–10^{23}cm and $\Delta\alpha_{B-L}=10^{-42}$–$10^{-56}$. We report several different excluded regions for various values of VEV v_{B-L} (from 1 meV to 1 GeV) (the region down the black lines is excluded by neutron-antineutron data). (With G we label the Galaxy range scale). See also Figs. 1-2 of Ref. [**?**].

Among the landscape of parameters, we would like to point out that $v_{B-L}\simeq 1$keV allows $\Delta V=|V_n-V_{\bar{n}}|\simeq 10^{-11}$eV for $\lambda\simeq 10^{16}$cm, which would correspond to a magnetic field of 5Gauss (about 10 times the Earth's magnetic field) coupled to the neutron magnetic moment. As a consequence, such a strong background would completely suppress a $n-\bar{n}$ transition searched for in conditions of $|B|<10^{-4}$Gauss as suggested in Ref. [14]. In this case a neutron-antineutron transition should be searched for in the resonant condition $|\mu_n\cdot B|\simeq\Delta V$. Roughly speaking, neutron-antineutron experiments seriously risk not detecting any new physics if they have the wrong magnetic field set-up.

3 Weak gravity conjecture and holography

The weak gravity conjecture states that *gravity is the weakest force*. This implies that a new interaction with charges smaller then the particle mass cannot exist [11] (normalized in Planckian units):

$$|M/Q|<1$$

where Q is the particle charge of every gauge interaction different from gravity.

An extremal black hole of $M/|Q|=1$ corresponds to a violation of the WGC. However, the extra new $U(1)$ effective gauge theory has to break down at an effective scale Λ which is below the Planck scale, as $\Lambda\sim gM_{Pl}$, where g is the new gauge coupling – in the case of B–L, $g\equiv g_{B-L}$.

The weak gravity conjecture is related to the no-remnant conjecture, suggested from the holographic principle [12]. For example, let us consider $g_{B-L}\sim 10^{-21}$ lying in a testable range for neutron-antineutron transitions, and consider a black hole with a mass of $10M_{Pl}$. For such a tiny charge, the black hole coupling can have any charge between 0–10^{21}, still consistent with the bound for a black hole solution $M\geqslant QM_{Pl}$. However, this situation leads to the existence of a remnant after the Hawking evaporation of the black hole down to the Planck scale. In fact, if there are no massless charged particles, these charges cannot be radiated away as Hawking radiation. This implies a Planckian remnant black hole with possible total charge in the range of 0–10^{21}.

In Ref.[12], Susskind has shown the inconsistency of black hole remnants storing the information falling into black holes. In particular, the existence of remnants in the thermal atmosphere of Rindler space would necessarily imply that the Newton constant should be zero. The remnant is incompatible with the holographic formula of entropy, only dependent on the black hole area. The Hawking entropy $S=A/4G$ is in the case of exact thermal equilibrium, described by the Unruh density matrix $\rho_u=\exp(-2\pi H_r)/Z$, where H_r is the Rindler Hamiltonian and Z is the partition function. The thermal state is associated with a thermal atmosphere of particles, which can be detected by observers in the rest frame with respect to the accelerated Rindler coordinate system. The temperature that can be detected by the observer in the rest frame is $T(\rho)=1/2\pi\rho$, where ρ is the proper distance from the horizon to the observer. In the thermal atmosphere, there will be all particle species, in thermal equilibrium at temperature $T\equiv T(\rho)$, with a density of each i-species $N_i\sim\exp(-2\pi\rho M_i)$. Let us consider the hypothetical remnants in the thermal atmosphere, with a Planckian mass: the density of any Planckian remnant species is $N_i\sim\exp(-2\pi\rho M_{Pl})$. The number of distinct species scales as $\exp S_R$. So, the total remnant density is $N_R\sim\exp[S_R–2\pi\rho M_{Pl}]$. However, let us suppose a macroscopically large S_R. In this case, the saddle solution, maximalising the number density, is just $S_R=2\pi\rho M_{Pl}$. This implies that, filling all the Rindler space with remnants ($S_R\to\infty$), the distance ρ arbitrarily grows to infinity, losing any control in the theory [12]. This seems to be a serious contradiction between the holographic entropy formula and the existence of remnants.

4 Exotic instantons

The possible detection of such light baryo-photons would also rule-out $B-L$ violating exotic instantons. In Ref. [30], we have shown how the intersection of E2-branes, wrapping different 3-cycles on CY_3, with D6-brane stacks, can generate new non-perturbative neutron-antineutron operators. For instance, the effective Lagrangian is

$$\mathcal{L}_{E2}=c^{(1)}_{ff'f''}\tau_{i,f}U^i_{f'}\alpha_{f''}+c^{(2)}_{f}\tau_{i,f'''}D^i_{f^{IV}}\beta_{f^V}, \qquad (10)$$

where τ,α,β are chiral fermionic zero modes (or modulini) associated with the exotic instanton, while U,D are RH up and down quarks. In Fig. 2, we show the mixed disk amplitudes generating the effective Lagrangian, Eq. (10), from string theory. Integrating over the modulini space,

$$\mathcal{W}=\frac{\mathcal{Y}_{f_1f_2f_3f_4f_5f_6}\mathrm{e}^{-S_{E2}}}{M_S^3}U_{f_1}D_{f_2}D_{f_3}U_{f_4}D_{f_5}D_{f_6}, \qquad (11)$$

where $\mathcal{Y}$ is a 3×6 flavor matrix, a combination of $c^{(1),(2)}$ couplings. The same Lagrangian, Eq. (10), can be considered with the number of modulini families reduced by half, providing a trilinear $\Delta B=1$ term

$$\mathcal{W}=y_{f_1f_2f_3}\mathrm{e}^{-S_{E2'}}U_{f_1}D_{f_2}D_{f_3}. \qquad (12)$$

This operator can generate a neutron-antineutron transition mediated by a gluino exchange connecting quark-squark reduction currents. There are several different exotic instanton solutions which cannot preserve $U(1)_{B-L}$ even if not directly connected to $n-\bar{n}$ transitions. For example, exotic instantons with an effective Lagrangian

$$\mathcal{L}_{E2'}=k^{(1)}_{ff'f''}N_f\alpha_{f'}\beta_{f''} \qquad (13)$$

integrated over the modulini space generates a Majorana mass matrix for the RH neutrino

$$\mathcal{W}_{E2}=M_S\mathrm{e}^{-S_{E2''}}NN. \qquad (14)$$

Such an operator can generate a Majorana mass for the LH neutrino from a see-saw type I mechanism. Alternatively, a Weinberg superpotential $\mathcal{W}=\mathrm{e}^{-S_{E2'''}}HLHL/M_S$ can be directly generated by

$$\mathcal{L}=h_1\gamma_\alpha L^\alpha\delta+h_2\gamma'_\alpha H^\alpha\delta'. \qquad (15)$$

However, the generation of this superpotential is incompatible with a $B-L$ light baryo-photon. In fact, the generation of $n-\bar{n}$ is necessarily synchronized with a Stueckelberg mechanism of $U(1)_{B-L}$. In fact, all the $\mathrm{e}^{-S_{E2}}$ factors have a structure

$$\mathrm{e}^{-S_{E2}}=\mathrm{e}^{-\mathcal{V}_\Pi/g_s+i\sum_r c_r a_r}, \qquad (16)$$

where $\mathcal{V}_\Pi$ is the volume of Π-cycles wrapped by an E-brane on the internal CY; a_r are RR axions and c_r are E-brane couplings to them, and g_s is the string-coupling constant associated with the vacuum expectation value of the dilaton field ($g_s=\mathrm{e}^{\langle\phi\rangle}$). Equation (17) is not invariant under RR axion shifts, i.e. under $U(1)_{B-L}$ in our case:

$$\mathrm{e}^{-S_{E2}}\to\mathrm{e}^{-i\sum_A N_A(I_{MA}-I_{MA^*})\Lambda_A}\mathrm{e}^{-S_{E2}}, \qquad (17)$$

where I is the number of intersections among the E-brane M and the background D-brane M, N_A is the number of A D-brane stacks, and Λ is an axion shift constant[1]. This is exactly compensated by the shift factor of the superpotential combinations. The shift is associated with a Stueckelberg mechanism for $B-L$. As a consequence, the associated $B–L$ boson gets a huge mass, typically of the order of the string scale or so.

Therefore, we can argue that the observation of a very light baryo-photon would have strong implications for string phenomenology. In fact, this could imply that a *non-perturbative protection mechanism* would suppress all possible $B–L$ exotic instantons for many orders magnitude from the string scale to the low scale of $B–L$ spontaneous symmetry breaking. For instance, the effects of RR and NS-NS fluxes wrapped by Euclidean D-branes

1) See Refs. [36–44] for more details of these aspects.

could strongly suppress the mixed disk amplitudes associated with exotic instantons.

5 Conclusions and remarks

In this article, we have discussed possible implications of the detection of a super-light baryo-photon coupled to (anti)neutrons in quantum gravity and string theory. Current available measurements from $n-\bar{n}$ experiments impose unexpectedly stringent bounds on the baryo-photon mass and coupling constant[1)]. We have discussed how the detection of a super-weak baryo-photon may rule out the weak gravity conjecture as well as the generation of non-perturbative ($B-L$)-violating operators from exotic D-brane instantons. It is commonly held that neutron-antineutron experiments would indirectly test at least 1000 TeV scale physics in the next generation of experiments [14]. However, we want to argue against such a statement. In fact, following our arguments, neutron-antineutron experiments could indirectly test the weak gravity conjecture with very high precision.

We also have stressed how the detection of a super-weak baryo-photon may rule out the presence of $B-L$ violating exotic stringy instantons up to the string scale. In fact, exotic instantons must be associated with a Stueckelberg mechanism, providing a large mass to the $B-L$ gauge field. In other words, such a light baryo-photon should be *sequestered* by exotic instantons, generating, for example, a mass term for the neutrino, or other R-parity violating operators.

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References

1 Y. Chikashige, R. N. Mohapatra, and R. D. Peccei, Phys. Lett. B, **98**: 265 (1981)
2 J. Schechter and J. W. F. Valle, Phys. Rev. D, **25**: 774 (1982)
3 E. K. Akhmedov, Z. G. Berezhiani, R. N. Mohapatra, and G. Senjanovic, Phys. Lett. B, **299**: 90 (1993) doi: 10.1016/0370-2693(93)90887-N [hep-ph/9209285]
4 V. Berezinsky and J. W. F. Valle, Phys. Lett. B, **318**: 360 (1993) doi: 10.1016/0370-2693(93)90140-D [hep-ph/9309214].
5 Z. G. Berezhiani, A. Y. Smirnov and J. W. F. Valle, Phys. Lett. B, **291**: 99 (1992) doi: 10.1016/0370-2693(92)90126-O [hep-ph/9207209]
6 Z. G. Berezhiani and A. Rossi, Phys. Lett. B, **336**: 439 (1994) doi: 10.1016/0370-2693(94)90556-8 [hep-ph/9407265]
7 M. Kachelriess, R. Tomas, and J. W. F. Valle, Phys. Rev. D, **62**: 023004 (2000) doi: 10.1103/PhysRevD.62.023004 [hep-ph/0001039]
8 M. Lattanzi and J. W. F. Valle, Phys. Rev. Lett., **99**: 121301 (2007) doi: 10.1103/PhysRevLett.99.121301 [arXiv: 0705.2406 [astro-ph]]
9 M. Lattanzi, S. Riemer-Srensen, M. Tortola, and J. W. F. Valle, Nucl. Instrum. Meth. A, **742**: 154 (2014) doi: 10.1016/j.nima.2013.09.009
10 S. M. Boucenna, S. Morisi, Q. Shafi, and J. W. F. Valle, Phys. Rev. D, **90**(5): 055023 (2014) doi: 10.1103/PhysRevD.90.055023 [arXiv: 1404.3198 [hep-ph]]
11 N. Arkani-Hamed, L. Motl, A. Nicolis, and C. Vafa, JHEP, **0706**: 060 (2007) doi: 10.1088/1126-6708/2007/06/060 [hep-th/0601001]
12 L. Susskind, hep-th/9501106
13 M. Baldo-Ceolin et al, Z. Phys. C, **63**: 409 (1994)
14 D. G. Phillips, II et al, Phys. Rept., **612**: 1 (2016) doi: 10.1016/j.physrep.2015.11.001 [arXiv: 1410.1100 [hep-ex]]
15 Z. Berezhiani, Eur. Phys. J. C, **76**(12): 705 (2016) doi: 10.1140/epjc/s10052-016-4564-0 [arXiv: 1507.05478 [hep-ph]]
16 D. A. Kirzhnitz, JETP Lett., **15**: 529 (1972)
17 D. A. Kirzhnitz and A. D. Linde, Phys. Lett. B, **42**: 47 (1972)
18 S. Weinberg, Phys. Rev. D, **9**: 3357 (1974)
19 L. Dolan and R. Jackiw, Phys. Rev. D, **9**: 3320 (1974)
20 R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett., **42**: 1651 (1979); Phys. Rev. D, **20**: 3390 (1979)
21 P. Langacker and S.-Y. Pi, Phys. Rev. Lett., **45**: 1 (1980)
22 D. E. Morrissey and M. J. Ramsey-Musolf, New J. Phys., **14**: 125003 (2012) doi: 10.1088/1367-2630/14/12/125003 [arXiv: 1206.2942 [hep-ph]]
23 A. Addazi and M. Bianchi, JHEP, **1412**: 089 (2014) doi: 10.1007/JHEP12(2014)089 [arXiv: 1407.2897 [hep-ph]]
24 A. Addazi, JHEP, **1504**: 153 (2015) doi: 10.1007/JHEP04(2015)153 [arXiv: 1501.04660 [hep-ph]]
25 A. Addazi and M. Bianchi, JHEP, **1507**: 144 (2015) doi: 10.1007/JHEP07(2015)144 [arXiv: 1502.01531 [hep-ph]]
26 A. Addazi and M. Bianchi, JHEP, **1506**: 012 (2015) doi: 10.1007/JHEP06(2015)012 [arXiv: 1502.08041 [hep-ph]]
27 A. Addazi, Mod. Phys. Lett. A, **31**(17): 1650109 (2016) doi: 10.1142/S0217732316501091 [arXiv: 1504.06799 [hep-ph]]
28 A. Addazi, Electron. J. Theor. Phys., **13**(35): 39 (2016) [arXiv: 1505.00625 [hep-ph]]
29 A. Addazi, Int. J. Mod. Phys. A, **31**(16): 1650084 (2016) doi: 10.1142/S0217751X16500846 [arXiv: 1505.02080 [hep-ph]]
30 A. Addazi, Phys. Lett. B, **757**: 462 (2016) doi: 10.1016/j.physletb.2016.04.018 [arXiv: 1506.06351 [hep-ph]]
31 A. Addazi, M. Bianchi, and G. Ricciardi, JHEP, **1602**: 035 (2016) doi: 10.1007/JHEP02(2016)035 [arXiv: 1510.00243 [hep-ph]]
32 A. Addazi, J. W. F. Valle, and C. A. Vaquera-Araujo, Phys. Lett. B, **759**: 471 (2016) doi: 10.1016/j.physletb.2016.06.015 [arXiv: 1604.02117 [hep-ph]]
33 A. Addazi and M. Khlopov, Mod. Phys. Lett. A, **31**(19): 1650111 (2016) doi: 10.1142/S021773231650111X [arXiv: 1604.07622 [hep-ph]]
34 A. Addazi, Mod. Phys. Lett. A, **32**(02): 1750014 (2016) doi: 10.1142/S0217732317500146 [arXiv: 1607.01203 [hep-th]]
35 A. Addazi, X. W. Kang, and M. Y. Khlopov, arXiv: 1705.03622 [hep-ph], to appear in Chinese Phys. C
36 L. E. Ibanez and A. M. Uranga, JHEP, **0703**: 052 (2007) doi: 10.1088/1126-6708/2007/03/052 [hep-th/0609213]
37 R. Blumenhagen, M. Cvetic, and T. Weigand, Nucl. Phys. B, **771**: 113 (2007) doi: 10.1016/j.nuclphysb.2007.02.016 [hep-th/0609191]
38 L. E. Ibanez, A. N. Schellekens, and A. M. Uranga, JHEP, **0706**: 011 (2007) doi: 10.1088/1126-6708/2007/06/011 [arXiv:

1) Inspired by Refs. [49–51], an intriguing possibility is that the VEV scale of $U_{B-L}(1)$ at 1meV may provide a candidate for dark energy, connecting baryon violating processes with an explanation of Universe expansion.

0704.1079 [hep-th]]

39 R. Blumenhagen, M. Cvetic, S. Kachru, and T. Weigand, Ann. Rev. Nucl. Part. Sci., **59**: 269 (2009) doi: 10.1146/annurev.nucl.010909.083113 [arXiv: 0902.3251 [hep-th]]

40 R. Blumenhagen, M. Cvetic, R. Richter, and T. Weigand, JHEP, **0710**: 098 (2007) doi: 10.1088/1126-6708/2007/10/098 [arXiv: 0708.0403 [hep-th]]

41 R. Blumenhagen, M. Cvetic, D. Lust, R. Richter, and T. Weigand, Phys. Rev. Lett., **100**: 061602 (2008) doi: 10.1103/PhysRevLett.100.061602 [arXiv: 0707.1871 [hep-th]]

42 M. Cvetic, J. Halverson, P. Langacker, and R. Richter, JHEP, **1010**: 094 (2010) doi: 10.1007/JHEP10(2010)094 [arXiv: 1001.3148 [hep-th]]

43 H. Abe, T. Kobayashi, Y. Tatsuta, and S. Uemura, Phys. Rev. D, **92**(2): 026001 (2015) doi: 10.1103/PhysRevD.92.026001 [arXiv: 1502.03582 [hep-ph]]

44 M. Cvetic, J. Halverson, and R. Richter, JHEP, **0912**: 063 (2009) doi: 10.1088/1126-6708/2009/12/063 [arXiv: 0905.3379 [hep-th]]

45 T. A. Wagner, S. Schlamminger, J. H. Gundlach, and E. G. Adelberger, Class. Quant. Grav., **29**: 184002 (2012) [arXiv: 1207.2442 [gr-qc]]

46 M. I. Buchoff and M. Wagman, Phys. Rev. D, **93**(1): 016005 (2016) doi: 10.1103/PhysRevD.93.016005 [arXiv: 1506.00647 [hep-ph]]

47 E. D. Davis and A. R. Young, Phys. Rev. D, **95**(3): 036004 (2017) doi: 10.1103/PhysRevD.95.036004 [arXiv: 1611.04205 [nucl-ex]]

48 D. McKeen and A. E. Nelson, Phys. Rev. D, **94**(7): 076002 (2016) doi: 10.1103/PhysRevD.94.076002 [arXiv: 1512.05359 [hep-ph]]

49 E. J. Copeland, M. Sami, and S. Tsujikawa, Int. J. Mod. Phys. D, **15**: 1753 (2006) doi: 10.1142/S021827180600942X [hep-th/0603057]

50 J. Frieman, M. Turner, and D. Huterer, Ann. Rev. Astron. Astrophys., **46**: 385 (2008) doi: 10.1146/annurev.astro.46.060407.145243 [arXiv: 0803.0982 [astro-ph]]

51 Y. F. Cai, E. N. Saridakis, M. R. Setare, and J. Q. Xia, Phys. Rept., **493**: 1 (2010) doi: 10.1016/j.physrep.2010.04.001 [arXiv: 0909.2776 [hep-th]]