$K_L \to \pi^0\nu\bar{\nu}$ Beyond the Grossman-Nir Bound

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We do not violate the Grossman-Nir (GN) bound per se, but point out that the commonly perceived current GN bound of $B(K_L \to \pi^0\nu\bar{\nu}) < 1.4 \times 10^{-9}$ can be evaded, if a weakly interacting narrow state falls into the windows of kinematic exclusion of the $K^+ \to \pi^+\nu\bar{\nu}$ experiments. An explicit example is a $Z'$ boson motivated by the muon $g-2$ anomaly and linked with flavor physics. The model has implications for $K^+ \to \pi^+\mu^+\mu^-$, $B \to K^+\mu^+\mu^-$, $K\to\nu\bar{\nu}$ studies, the LBNF and Muon $g-2$ experiments, and possibly even LHC collider physics. But the main point is that the KOTO experiment is already breaking New Physics ground in their search for $K_L \to \pi^0\nu\bar{\nu}$.

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Introduction

The absence of any sign for New Physics (NP) so far at the Large Hadron Collider (LHC) has caused some anxiety. Perhaps one should pay more attention to the venerable rare kaon decays. The current value $[1]$ of $B(K_L \to \pi^0\nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$ from E787/949, which is not inconsistent with Standard Model (SM) expectations, the NA62 $[2]$ experiment aims at collecting $O(100)$ events during 2015 to 2017. In a similar time frame, the KOTO experiment $[3]$ aims at 3σ significance for $K_L \to \pi^0\nu\bar{\nu}$ assuming SM rate. The goal is of course to uncover NP, and KOTO has a better chance because the existing limit is weaker.

The current 90% C.L. limit $[4]$ by E391a,

$$B(K_L \to \pi^0\nu\bar{\nu}) < 2.6 \times 10^{-8}, \quad (1)$$

is still much weaker than the Grossman-Nir (GN) bound,

$$B(K_L \to \pi^0\nu\bar{\nu}) < 4.3 \times B(K^+ \to \pi^+\nu\bar{\nu}) \quad (2)$$

$$< 1.4 \times 10^{-9}. \quad (GN \ bound) \ (3)$$

The factor of $4.3$ in Eq. $[2]$ arises from isospin and $\tau_{K_L}/\tau_{K^+}$ $[2]$. The second step follows from inserting the E787/949 value $[1]$, giving the commonly perceived GN bound. Conventional wisdom is that KOTO can only probe NP after the GN bound of Eq. $[2]$ is reached. But KOTO has suffered a few inadvertent setbacks, and accumulated just 100 hours of data in 2013. Though sensitivity comparable to Eq. $[1]$ is reached $[6]$, there is one event in the signal box, compared with 0 events for E391a $[4]$. Can KOTO shake off the bound of Eq. $[3]$?

In this Letter we point out that, because of the use of kinematic rejection of certain missing mass regions for $K^+ \to \pi^+\nu\bar{\nu}$ search, if there exists some weakly interacting light boson (WILB) $X^0$ with mass falling into such window, it could cause $K_L \to \pi^0X^0 \to \nu\bar{\nu}$ to approach the limit of Eq. $[1]$, much higher than the perceived “GN bound” of Eq. $[3]$. This does not violate the genuine GN bound of Eq. $[2]$ per se, but suggests that KOTO is already starting to probe New Physics.

We are in part stimulated by the prominent and long standing indication $[7]$ of a $\sim 3.5\sigma$ discrepancy between experiment and SM expectation for the muon anomalous magnetic moment $a_{\mu}$. An increase of $\delta a_{\mu}$ by $\sim 3 \times 10^{-9}$ would suffice, and the gauged $L_\mu - L_\tau$ (muon number minus tau number) model $[8]$ provides a solution with a $Z'$ boson tailored towards the muon, but otherwise interacting only with taus or neutrinos. It is found $[9]$ that the so-called neutrino trident production on nucleons, $\nu_{\mu}N \to \nu_{\mu}N\mu^+\mu^-$, constrains

$$m_{Z'} \lesssim 400 \text{ MeV}, \quad (4)$$

which is below the kaon mass. A diagram which could induce $s \to dZ'$ is given in Fig. 1, which we return to below. Note that the Muon $g-2$, or E898 experiment $[10]$ is gearing up, aiming for a factor of four improvement in precision, with theory efforts to match $[11]$.

Experimental Loophole

Let us elaborate a bit on the experimental loophole that could allow $B(K_L \to \pi^0Z')$ to be as large as the E391a bound. The design of experiments have “accidental” features that are akin to the factor of $4.3$ in Eq. $[2]$ being not just a simple isospin factor. The E787/949 experiment observes $K^+$ decay at rest, detecting the emitted charged $\pi^+$, but nothing else. However, “in light of the brightness” of $B(K^+ \to \pi^+\pi^0) \approx 21\%$, the experiment kinematically excludes a region around $m_{\pi^0}$, i.e. excluding the range of $p_{s+}$ that corresponds to $116 \lesssim m_{\text{miss}} \lesssim 152$ MeV. The kinematic region for $m_{\text{miss}} > 261$ MeV gets below the kaon mass, as can be evaded, but nothing else. However, “in light of the brightness” of $B(K^+ \to \pi^+\pi^0) \approx 21\%$, the experiment kinematically excludes a region around $m_{\pi^0}$, i.e. excluding the range of $p_{s+}$ that corresponds to $116 \lesssim m_{\text{miss}} \lesssim 152$ MeV.
MeV is also excluded because of $K^+ \rightarrow \pi^+\pi\pi$ background. Although NA62 measures $K^+$ decay in-flight, it kinematically excludes $100 \lesssim m_{\text{miss}} \lesssim 165$ MeV and $m_{\text{miss}} \gtrsim 260$ MeV, which is slightly tighter.

A $K_L \rightarrow \pi^0\nu\bar{\nu}$ experiment, however, has no luxury for kinematic reconstruction: besides detecting two photons (assumed as $\pi^0$), it measures “nothing to nothing”. Neither the $K_L$ nor even the $\pi^0$ momentum is known. Thus, the approach is to veto as much as possible, and to learn along the way in pushing down sensitivity. One, however, cannot veto WILBs — the $\nu\bar{\nu}$ being the target. Thus, for $K \rightarrow \pi X^0$ where $X^0$ falls into the missing mass window, the $K^+$ experiment would be oblivious, but the $K_L$ experiment can have a blunt feel of it! Although the GN bound of Eq. (2) is in no way violated, the apparent or perceived bound of Eq. (3) does not apply. This is the main and rather simple point of this Letter.

An explicit $Z'$ model is now given as existence proof.

**Explicit Model**

The $Z'$ boson of the gauged $L_\mu - L_\tau$ solution to muon $g - 2$ anomaly is constrained by neutrino trident production to be light, Eq. (1). On the other hand, it is well known that a $Z'$ boson could account for the so-called “$F_\pi$ anomaly” in $B^0 \rightarrow K^0\mu^+\mu^-$ angular variables. This $Z'$ ought to be heavy, so cannot be the $L_\mu - L_\tau$ light $Z'$. However, we had been interested in the possibility of $t \rightarrow Z'c$ decay [12] but involving a very light $Z'$. Ref. [13] gave an explicit model for generating tree level $sbZ'$ and $ctZ'$ couplings, through mixing of SM quarks with vector-like doublet $Q$ and singlet $D$, $U$ quarks. We apply the model for our purpose.

As we are interested in $s \rightarrow d$ transitions, mixing in the down-type sector would become too fine-tuned, hence setting them to zero is reasonable. One is then left with $U$ mixing with up-type quarks, which is less constrained. Diagrams like Fig. 1 can start from a $K_L$ and $t, c$ mixing core where the $Z'$ is emitted, and dress it up with assistance from $SM$ into a loop-induced $s \rightarrow dZ'$ (or $b \rightarrow sZ'$) transition. The loop is finite because tree level down-type mixing is set to zero. It is intriguing that with reasonable $Uc$ and $Ut$ mixing parameters (though $Uu$ mixing is set to zero), loop diagrams as in Fig. 1 bring the $s \rightarrow d$ transition into current experimental sensitivities.

The effective $dsZ'$ coupling from Fig. 1 is

$$\frac{g'v_0^2}{32\pi^2} [c_{cc}f_{cc} + (c_{tc} + c_{ct})f_{ct} + c_{tt}f_{tt}] \bar{d}_L\gamma^\mu s_L Z'_\mu, \tag{5}$$

where $g'$ is the extra $U(1)$ gauge coupling, $v_0$ its symmetry breaking scale, $c_{ij} = V_{is}V_{jd}^*Y_{ij}Y_{ij}^*m_j/m_t^2$ with Yukawa couplings $Y_{ij}$, and

$$f_{ct} = 1 + \log \frac{m_t^2}{m_t^2} + \frac{3m_W^2}{m_t^2 - m_W^2} \log \frac{m_t^2}{m_W^2},$$

$$f_{tt} = \frac{3m_W^2}{m_t^2 - m_W^2} \left(1 - \frac{m_W^2}{m_t^2 - m_W^2} \log \frac{m_W^2}{m_t^2} \right) + \log \frac{m_W^2}{m_t^2},$$

with $f_{cc}$ obtained by $m_d^2 \ll m_s^2$. These expressions are in the large $m_U$ limit, though we use exact one-loop expressions (see Ref. [14]) in our numerics. Note that $c_{ct} \neq c_{tc}$, and $c_{ij}$ are complex, even for real $Y_{ij}$.

The E949 experiment performed a tagged search for $\pi^0 \rightarrow \nu\bar{\nu}$ inside the kinematically excluded window around $\pi^0$, giving the 90% C.L. bound

$$B(K^+ \rightarrow \pi^0 X^0) < 5.6 \times 10^{-8}, \quad (m_{X^0} = m_{\pi^0}) \tag{6}$$

which is much weaker than their $B(B^+ \rightarrow K^+\nu\bar{\nu})$. In fact, applying the analog of Eq. (2) would imply $B(K_L \rightarrow \pi^0 X^0) < 2.4 \times 10^{-7}$, which is much weaker than the E391a bound of Eq. (1). Hence Eq. (1) provides a direct and more stringent bound on $K_L \rightarrow \pi^0 X^0$ than implied by Eq. (6), which illustrates our main point.

Taking hadronic form factors [10], etc., into account, we plot in Fig. 2[left] the bound of Eq. (6) for $K^+ \rightarrow \pi^0 Z'|m_{Z'} = m_{\pi^0}$ in the $Y_{Uc} - Y_{Ut}$ (treated as real plane). We have taken $g' \sim 10^{-3}$ as fixed [9] by muon $g - 2$ excess and neutrino trident bound, and $m_U = 2$ TeV, $v_0 = 135$ GeV. We also plot $K_L \rightarrow \pi^0 Z'$ assuming the bound of Eq. (1), which turns out comparable. But if we apply Eq. (3) as a bound on $K_L \rightarrow \pi^0 Z'$, it would be much more stringent than the direct bound of Eq. (1). We have argued, however, that this application of “GN bound” is incorrect for the present case. Hence, the region between Eq. (1) and Eq. (3) is fair game for discovery! Note that $K_L \rightarrow \pi^0 Z'$ is sensitive to the imaginary part of $dsZ'$ coupling in Eq. (5), hence probes also extra CPV phases arising from $Y_{Uc}$ and $Y_{Ut}$. Other curves and regions in Fig. 2[left] would be explained shortly.

For the second exclusion zone of $m_{\text{miss}} > 260$ MeV for the $K^+$ experiments, together with $m_{Z'} < 400$ MeV, this is actually a “sweet spot” where $Z' \rightarrow \mu^+\mu^-$ decay is also allowed. We find (see Ref. [14]) that the $K^+ \rightarrow \pi^0\mu\bar{\nu}$ data by the NA48/2 experiment [17] allows for a “best possible spike” at $m_{\mu\nu} \simeq 285$ MeV, with $\delta B(K^+ \rightarrow \pi^0\mu\bar{\nu})$ up to $2.1 \times 10^{-9}$ in strength. This is plotted (grey exclusion region) in Fig. 2[right] on $Y_{Uc} - Y_{Ut}$ plane, which is as stringent as the “GN bound” of Eq. (3), hence much more stringent than Eq. (1). The model parameters are $g' = 1.3 \times 10^{-3}$, $m_U = 2$ TeV and $v_0 \sim 219$ GeV.

We have shown that KOTO is already starting to probe NP. If a genuine excess appears above the perceived “GN bound” of Eq. (3), the likely explanation would be an unobserved recoil $X^0$ particle in the “$\pi^0$ exclusion window” of $K^+ \rightarrow \pi^+\nu\bar{\nu}$ search. We note that the bound of Eq. (3) cannot improve by much, even as NA62 accumulates data, unless it finds $B(K^+ \rightarrow \pi^+\nu\bar{\nu})$ to be much smaller than SM expectation. When KOTO sensitivity reaches this bound, then NA62 should scan above 260 MeV for spiking dimuons, and could also push the bound on $\pi^0 \rightarrow \nu\bar{\nu}$ [15], as E787/949 has demonstrated sensitivity to $K^+ \rightarrow \pi^0 X^0$ outside the “$\pi^0$ exclusion window” (see Fig. 18 of Ref. [1]). With sufficient statistics, one could uncover peaking events in $m_{\text{miss}}$.

We turn now to other implications of our model.

**Further Model Implications**

We have kept $Uc$ and $Ut$ mixings but set the mixing of
For $m_{Z'} = 135$ MeV ($Z' \to \nu \bar{\nu}$ 100%), bounds for $\mathcal{B}(K^+ \to \pi^+ Z') < 5.6 \times 10^{-8}$ (dark grey exclusion region) and $\mathcal{B}(K_L \to \pi^0 Z') < 2.6 \times 10^{-8}$ (blue solid) on the $Y_{UC}-Y_{UA}$ plane. For $m_{Z'} = 285$ MeV ($Z' \to \nu \bar{\nu}$ 54%), bounds for $\mathcal{B}(K^+ \to \pi^+ Z')\mathcal{B}(Z' \to \mu^+ \mu^-) < 2.1 \times 10^{-9}$ (dark grey exclusion region) and $\mathcal{B}(B^+ \to K^+ Z')\mathcal{B}(Z' \to \mu^+ \mu^-) < 2.0 \times 10^{-8}$ (purple allowed region) on the $Y_{UC}-Y_{UA}$ plane. In both panels, we give the usual “GN bound” of $\mathcal{B}(K_L \to \pi^0 Z')\mathcal{B}(Z' \to \nu \bar{\nu}) < 1.4 \times 10^{-9}$ (red dashed) and $2\sigma$ range for $\mathcal{B}(B^+ \to K^+ Z')\mathcal{B}(Z' \to \nu \bar{\nu}) = (0.35^{+0.6}_{-0.15}) \times 10^{-5}$ (light green allowed region). The horizontal lines mark reasonable $Y_{UC}$ range, and in the backdrop we plot $10^3 \mathcal{B}(t \to e Z')$ contours.

heavy vector-like quarks with down-type quarks (as well as $u$) to zero. But Fig. 1 generates $sbZ'$ couplings alongside $dsZ'$ couplings by $W$ exchange in the loop. This brings the model in contact with rare $B$ decays, where the LHCb experiment has demonstrated its prowess recently, while Belle II is under construction.

For the $m_{Z'} = 285$ MeV case that we have just illustrated, $Z' \to \mu^+ \mu^-$ and $\nu \bar{\nu}$ rates are comparable, and the decay is prompt. Thus, it can show up in $B \to K^{(*)}\mu\mu$ decay with very low $m_{3\mu}$. The LHCb experiment has updated differential rates $13$ for $B \to K^{(*)}\mu\mu$ and $K^{+}\mu\mu$ decays to 3 fb$^{-1}$, or full Run 1 dataset. The $B^0 \to K^{*0}\mu\mu$ decay, relevant for the $D^+_s$ anomaly, has yet to be updated from 1 fb$^{-1}$ data $12$. But perhaps influenced by the latter, Ref. 13 starts at $q^2 \equiv m_{3\mu}^2 > 0.1$ GeV$^2$, or $m_{3\mu} \gtrsim 316$ MeV, which covers only half the region of $m_{3\mu}$ allowed by the diinnon threshold.

The 1 fb$^{-1}$ paper for $B^+ \to K^{+}\mu\mu$, however, does go down to $q^2 = 0.05$ GeV$^2$, or $m_{3\mu} = 224$ MeV, hence can be compared with our $m_{3\mu} = 285$ MeV case. Interestingly, in the lowest 0.05 < $q^2 < 2.00$ GeV$^2$ bin, there is a mild excess above the mean for $1.00 < q^2 < 6.00$ GeV$^2$. Treating experimental error at the $2\sigma$ level, our estimate $14$ for this excess is $\sim 2 \times 10^{-8}$. If we attribute this all to the presence of $B^+ \to K^{+}Z'\to \mu^+\mu^-$, then scaling by $\mathcal{B}(Z' \to \mu^+\mu^-) \approx 46\%$, this implies $B^+ \to K^{+}Z'$ at $4.4 \times 10^{-8}$ level. Using form factors of Ref. $15$, we plot this constraint in Fig. 2(right), which is stronger than our estimate of the NA48/2 bound. Actually, there also seems to be some excess in the first 0.1 < $q^2 < 0.98$ GeV$^2$ bin for $B \to K^{+}\mu\mu$ in the full 3 fb$^{-1}$ dataset $12$, hence there could be a $Z'$ above 316 MeV. We urge LHCb to refine their analysis, optimize binning to $q^2$ resolution, and extend a spike search down to 0.045 GeV$^2$.

The $B^0 \to K^{0}\mu\mu$ modes has less statistics, while $B \to K^{+}\mu\mu$ would have a low $q^2$ photon peak, making interpretation more difficult. Note that our estimate based on LHCb data is stronger than NA48/2, even though the former is only based on the 1 fb$^{-1}$ dataset. However, $s \to d$ and $b \to s$ processes may or may not be correlated as in our model. So, when KOTO reaches the usual “GN bound”, NA62 should still conduct a spike search above $m_{3\mu} > 260$ MeV. We note in passing that the Belle experiment has conducted $B^0 \to K^{*0}X^0$ search $20$ for light $X^0 \to \mu^+\mu^-$. The bound is e.g. roughly $5 \times 10^{-8}$ for $m_{X^0} \approx 285$ MeV. But to avoid the photon peak, we suggest Belle (and BaBar) to conduct the search for $B^+ \to K^{+}X^0\to \mu^+\mu^-$. Like our illustration in Fig. 2(left), if $m_{Z'}$ falls into the “$\pi^0$ blind spot”, NA62 would be oblivious, and so would LHCb. Fortunately, because $\mathcal{B}(B \to K\pi^0) \ll \mathcal{B}(K \to \pi^0\pi^0)$, the (super-)B factories can crosscheck in the $B \to K^{(*)}\nu\bar{\nu}$ modes, where the photon peak is absent. The BaBar experiment has lead the way here by conducting a binned $m_{\tau\bar{\tau}}$ search $21$. Surprisingly, the lowest $s_B \equiv m_{\tau\bar{\tau}}^2/m_B^2 < 0.1$ bin for both the $B^+ \to K^+\nu\bar{\nu}$ and $B^0 \to K^{0}\nu\bar{\nu}$ modes show some excess, which seems to drive a lower bound for the $K^+\nu\bar{\nu}$ mode. From Fig. 6 of Ref. $21$, we estimate $\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = (0.35^{+0.6}_{-0.15}) \times 10^{-5}$ in this bin, and plot the $2\sigma$ range in Fig. 2(left). The result is stronger than the kaon modes shown in Fig. 2(left), and extends to the usual “GN bound”. On the other hand, for the $m_{Z'} = 285$ MeV example where $Z' \to \mu^+\mu^-$ is also allowed, plotting the BaBar result in Fig. 2(right) shows some tension with our LHCb 1 fb$^{-1}$ estimate for $B^+ \to K^{+}Z'\to \mu^+\mu^-$. The latter is the most stringent. In any case, our estimates are rudimentary, and they are better done by the experiments.

In this vein, although Belle lead the way in $B^+ \to K^+\nu\bar{\nu}$ search $22$, its follow-up paper $23$ just added 40% data but followed the same analysis, including a cut on high $p_{K^+}$ for sake of rejecting $B \to K^+\gamma$, which pre-
ciscely cuts against the $B \to K^{(*)}Z'$ possibility. We urge Belle to conduct a binned $m_{Z'}^2$ study and optimize the binning according to resolution. It should also practice optimizing the $m_{Z'}^2$ or recoil mass resolution with the full B-tag method, towards a future Belle II search.

Unfortunately, a very light $Z'$, especially if it decays only via $\nu\bar{\nu}$, would be rather difficult at the LHC. We have given the $t \to cZ'$ branching ratios in the backdrop of Figs. 2. In general, these are not detectable at the LHC, even for the dimuon case. We have drawn $|Y_{Ue}| < 0.2$ bands in Fig. 2 to indicate that $|Y_{Ue}|$ should not be too large, while $|Y_{Ue}| < |Y_{Ut}|$ should hold in general. More discussion is given in Ref. [14].

**Discussion and Conclusion**

Indirectly related to flavor physics, there is one possible process [14] to search for a light $Z'$ boson at the LHC, which can potentially uncover the associated exotic Higgs boson $\phi$. The $L_\mu - L_\tau$ symmetry is broken spontaneously, and the $Z'$ is light because of very weak gauge coupling, but the symmetry breaking scale $v_\phi$ is not too different from $v$ of SM. Because the self coupling of $\phi$ is unknown, its mass is quite arbitrary, but should be at the weak scale. However, the $U$ quark mixes with the $c$ and $t$ quarks, which generates effective $gg\phi$ coupling, while $\phi$ predominantly decays via a $Z'Z'$ pair.

Our investigation [14] shows that $|Y_{Z'}|$ is accessible at the LHC for a 285 MeV $Z'$, where the signature is $(gg \to \phi \to Z'Z' \to \mu^+\mu^-|\mu^+\mu^-)$ with brackets indicating low dimuon mass. The $Z'$ decay is prompt. Interestingly, the CMS experiment conducted a search [24] with 2012 data that can be applied to $\phi \to Z'Z' \to (\mu^+\mu^-)(\mu^+\mu^-)$ where one event was found at low dimuon pair mass. The two dimuon pairs have masses $\sim 200, 300$ MeV, respectively, which is right on the spot. It is too early to tell, but with Run 2 to start soon, this study should be carefully watched, and vigorously pursued. Note that the $U$ quark, with mass in TeV range, can also be searched for.

For the original motivation of muon $g - 2$ and neutrino trident production, the former is pursued by the E989 experiment [10], while the latter can [9] be measured with higher precision by the LBNE experiment [25]. Both experiments are at Fermilab. Although the schedule is yet uncertain for these two pursuits, we have shown that the next few years could see major progress on related issues, ranging from rare kaon decays (KOTO/NA62), rare $B$ decays (LHCb/Belle [II]), and perhaps the LHC.

In conclusion, we point out a loophole in the experimental setup when comparing $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ search, and find that the KOTO experiment is already starting to explore New Physics territory, while the commonly perceived “Grossman-Nir bound” may not apply. Although the mass range for weakly interacting light boson emission seems rather restricted, our explicit model illustrates the potential wide-ranging impact of discovering $B(K_L \to \pi^0\nu\bar{\nu}) \gtrsim 1.4 \times 10^{-9}$. Conversely, many measurements at $B$ factories and the LHC could uncover correlated phenomena, which could shed light on what may be behind the muon $g - 2$ anomaly.

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