On search for a new light gauge boson from $\pi^0(\eta) \to \gamma + X$ decays in neutrino experiments

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Abstract

It is shown that a new light gauge boson $X$ which might be produced in the decays of pseudoscalar mesons $\pi^0(\eta) \to \gamma + X$ could be effectively searched for in neutrino experiments via the Primakoff effect, in the process of $X + Z \to \pi^0(\eta) + Z$ conversion in the external Coulomb field of a nucleus. An estimate of the $X \to \pi^0$ conversion rate for the NOMAD neutrino detector at CERN is given.

1 Introduction

New neutral gauge bosons $X$ are predicted by many models addressing the physics beyond the Standard Model (SM) such as GUTs, supersymmetric, superstring models and models including a new long-range interaction, i.e. the fifth force. The predictions for the mass of the $X$ boson are not very firm and it could be light enough ($M_X \ll M_Z$) for searches at low energies.

The detailed study of the possible manifestations of light gauge boson was performed in. It was shown that if the mass $M_X$ is of the order of the pion mass, an effective search could be performed for this new vector boson in the radiative decays of neutral pseudoscalar mesons $P \to \gamma + X$, where $P = \pi^0, \eta, \text{ or } \eta'$.

From the analysis of the data from earlier experiments, constraints on branching ratios for the decay of $P \to \gamma + X$ range from $10^{-7}$ to $10^{-3}$ depending on whether $X$ interacts with both quarks and leptons or only with quarks. In the first case $X$ is a short lived particle decaying mainly to $e^+e^-$ or $\nu\bar{\nu}$ pairs, while in the second case $X$ should be a relatively long lived particle ($\tau_X \geq 10^{-6}$ sec).

Direct searches for a signal from $\pi^0 \to \gamma + X$ decay have been performed in a few experiments. The best experimental limit on the decay $\pi^0 \to \gamma + X$ was obtained recently by the Crystal Barrel Collaboration at CERN using $\nu\overline{\nu}$ annihilations as a source of pseudoscalar mesons, see and references there. The branching ratio limit of $(3$ to $0.6) \times 10^{-4}$ ($90\%$ C.L.) has been obtained for $0 < M_X < 125$ MeV. Limit of the same order has been obtained for $BR(\eta \to \gamma + X)$ for the higher $M_X$ mass region. The results are valid for the case where $X$ is a long lived particle or the $X$ boson decays preferably into $\nu\bar{\nu}$ pairs.

In this paper we show that a new light relatively long lived gauge boson which might be produced in decays of $\pi^0(\eta) \to \gamma + X$ could be effectively searched for in neutrino experiments...
via the Primakoff effect, in the process of $XZ \rightarrow \pi^0(\eta)Z$ conversion in the external Coulomb field of a nucleus.

The paper is organised as follows. In section 2 we discuss the X-boson phenomenology. Section 3 describes the suggested method and presents the results of calculations of the cross section for $X \rightarrow \pi^0$ conversion. An estimate of the total cross section for the X-boson interaction with the matter is given in section 4. In section 5 we consider NOMAD neutrino detector at CERN as example to estimate expected $X \rightarrow \pi^0$ conversion rate in this experiment. Section 6 contains concluding remarks and discussion.

## 2 X-boson phenomenology

As it has been mentioned in the introduction many modern models predict an enlargement of the standard $SU(3) \otimes SU(2) \otimes U(1)$ gauge group by an extra $U(1)$ factor. At present there are no firm theoretical prediction on the mass of new gauge boson so we can’t exclude the possibility that new gauge boson is rather light with a mass $M_X \leq O(m_{\pi})$. The possibility of the existence of a vector boson, which interacts with the baryon current, was suggested by Lee and Yang [8]. If this boson is massless, then the results of the experiments on the check of the equivalence principle imply a strong constraint on its coupling constant $\alpha_LY \leq 10^{-47}$. However this constraint is no longer valid for massive gauge boson with microscopic Compton wavelength. Astrophysical bound on the X-boson coupling is $\alpha_X \leq O(10^{-10})$ for $M_X \leq O(100)$ KeV.

The interaction Lagrangian of the X-boson with quarks and leptons has the form [6]

$$L_{X,ql} = g_X \sum_q (g_{Vq} \bar{q} \gamma_\mu q + g_{Aq} \bar{q} \gamma_\mu \gamma_5 q) + \sum_l (g_{Vl} \bar{l} \gamma_\mu l + g_{Al} \bar{l} \gamma_\mu \gamma_5 l) X^\mu,$$  \hspace{1cm} (1)

where $(g_{Vq}, g_{Aq}, g_{Vl}, g_{Al}) \sim O(1)$. By C-parity arguments, one can find that a coupling of X-boson to the axial quark current gives a negligible small contribution to the $\pi^0 \rightarrow \gamma + X$ decay width. The $\pi^0 \rightarrow \gamma X$ decay width is determined by the formula [6]

$$\Gamma(\pi^0 \rightarrow \gamma + X) = \frac{2\alpha_X}{(4\pi)^3} \frac{1}{2g_{Vu} + g_{Vd}} \left(\frac{M_X^2}{m_{\pi}}\right)^3,$$ \hspace{1cm} (2)

where $\alpha_X = \frac{g_e^2}{4\pi}$, $f_{\pi} = 93 MeV$ and $M_X$ is the mass of the X-boson. For the $Br(\pi^0 \rightarrow \gamma + X)$ we have [6]

$$Br(\pi^0 \rightarrow \gamma + X) = \frac{2\alpha_X}{\alpha} \frac{(2g_{Vu} + g_{Vd})^2}{(1 - \frac{M_X^2}{m_{\pi}^2})^3}$$ \hspace{1cm} (3)

For the case when X-boson interacts with both quarks and leptons combined bounds from anomalous magnetic moment of leptons, elastic $\nu_e e \rightarrow \nu_e e$ scattering and beam dump experiments lead [6] to

$$\alpha_X \leq O(10^{-9}),$$ \hspace{1cm} (4)

or to

$$Br(\pi^0 \rightarrow \gamma + X) \leq O(10^{-6})$$ \hspace{1cm} (5)

The X-boson lifetime for $M_X \geq 1 MeV$ and $\alpha_X = O(10^{-9})$ is less than $\tau(X) \leq O(10^{-12})$ sec. So, X-boson is short lived particles and such scenario is not interesting for us.

In this letter we consider the case where the X is a “leptophobic” boson which interacts only with quarks. Consider the life time of the X-boson for such scenario. Experimental limits for the $Br(\pi^0(\eta) \rightarrow \gamma + X)$ [6] lead to the bound on coupling of X to quarks of

$$\alpha_X \leq 10^{-6}$$ \hspace{1cm} (6)
For $M_X < 2m_e$ the $X$-boson decay width into 3 photons via quark loop is proportional to

$$\Gamma(X \to 3\gamma) \sim \alpha^3 \alpha_X \left(\frac{M_X}{m_{q,\text{eff}}}\right)^8 M_X,$$

where $m_{q,\text{eff}} \approx 300\text{MeV}$ is an effective quark mass. Using Eq.(6) we find that $\tau_X(X \to 3\gamma) \geq O(10)$ sec. The decay width of the $X$-boson into $\nu \bar{\nu}$ via quark loop is proportional to

$$\Gamma(X \to \nu \bar{\nu}) \sim \alpha_X G_F^2 M_X^2 \left(\frac{M_X}{m_{q,\text{eff}}}\right)^4$$

For $M_X \leq 100$ MeV we find that $\tau_X(X \to \nu \bar{\nu}) \geq O(10^{-4})$ sec. For $M_X > 2m_e$ the $X$-boson decays mainly into $e^+e^-$ through the quark loop and its decay width for $M_X^2 \ll m_{q,\text{eff}}^2$ is

$$\Gamma(X \to e^+e^-) \approx \frac{1}{12\pi} \left(\frac{\alpha}{15\pi}\right)^2 \left[3\left(\frac{2}{3}g_{V_u} - \frac{1}{3}g_{V_d} - \frac{1}{3}g_{V_s}\right)^2\right] \alpha_X M_X \left(\frac{M_X}{m_{q,\text{eff}}}\right)^4$$

For $M_X \leq 100$ MeV and $[3\left(\frac{2}{3}g_{V_u} - \frac{1}{3}g_{V_d} - \frac{1}{3}g_{V_s}\right)^2] = O(1)$ we find that $\tau_X(X \to e^+e^-) \geq O(10^{-6})$ sec. So, we conclude that for the case when the $X$-boson interacts only with quarks it is long lived particle at least for $M_X \leq 100$ MeV and for $X$ boson energy $E_X > 10 \text{ GeV}$ it travels the distance more than 10 km before its decay which is much larger than the typical decay length ($\sim 1 \text{ km}$) in the current neutrino experiments.

### 3 Method of search and cross section for $X \to \pi^0$ conversion

Let us consider for simplicity the decay $\pi^0 \to \gamma + X$. The consideration for decay of $\eta$ is similar. If the decay $\pi^0 \to \gamma + X$ exists, one expects a flux of high energy $X$ bosons from a neutrino target, since $\pi^0$ are abundantly produced in the forward direction by high energy (a few hundred GeV) protons in a neutrino target. If $X$ is a long lived particle, this flux would penetrate the downstream shielding without significant attenuation (see section 4) and would be observed in a neutrino detector via the Primakoff effect, namely in the conversion process $X \to \pi^0$ in the external Coulomb field of a nucleus (see Figure 1).

Because the cross section for $X \to \pi^0$ conversion is proportional to $Z^2$, preferable search for such events is in high-Z detectors. The experimental signature of $X \to \pi^0$ conversion is a single high energy $\pi^0$ decaying into two photons which results in isolated electromagnetic showers in the detector. The occurrence of $X \to \pi^0$ conversion would appear as an excess of neutrino-like interactions with pure electromagnetic final states above those expected from SM predictions. Note that $X \to \eta$ conversion could also be identified through charged decay modes of $\eta$ mesons in the final state.

The energy spectrum of $X$-bosons at neutrino detector is expected to be harder than that of neutrinos, since there is no suppression of the high energy part due to life time of $\pi^0(\eta)$, as it is in case of charged pions those decays in flight are the main source of neutrino. Thus, one could expect that the highest energy bins have better sensitivity to $X \to \pi^0$ conversion signal.

The cross section for $X \to \pi^0$ conversion via the Primakoff mechanism is given by the minimal modification of the corresponding formula for the axion photoproduction [11]. In the lab system, we find
\[
\frac{d\sigma}{d\Omega}(X + Z \rightarrow \pi^0 + Z) = \frac{1}{2} Br(\pi^0 \rightarrow X\gamma) \frac{8 \Gamma(\pi^0 \rightarrow \gamma\gamma)}{m^2_\pi \Delta} \alpha Z^2 F^2(t) \frac{P^4 \sin^2(\theta)}{t^2}, \tag{10}
\]

where \( Br(\pi^0 \rightarrow X\gamma) = \frac{\Gamma(\pi^0 \rightarrow \gamma\gamma)}{\Gamma(\pi^0 \rightarrow \gamma\gamma)} \), \( P \) is the momentum of the \( X \)-boson, \( \alpha = \frac{1}{137} \), \( Z^2 F^2(t) \) is the target form factor, \( t = -(p_1 - p_2)^2 \) and \( \Delta = (1 - m^2_\pi m^2_X)^2 \). Since the minimal momentum square in our case \( t_{\text{min}} = \left(\frac{m^2_X - m^2_\pi}{2m}\right)^2 \), is rather small, atomic form-factors must be used when \( t \) is small and a nuclear form factor for \( t \geq t_0 = 7.39 \cdot m^2_\pi \) \cite{11}\cite{13}. It should be noted that in comparison with formula (18) of ref.\cite{11} which describes the cross section of axion photoproduction \( (\gamma + Z \rightarrow a + Z) \), a factor of \( \frac{1}{2} \) arises from photon and \( X \)-boson non-identity and the factor \( \Delta \) in the denominator comes from the kinematics of \( \pi^0 \rightarrow \gamma + X \) decay. The target form-factor \( Z^2 F^2(t) \) consists of three parts. At small \( t \leq t_0 \), we use Thomas-Fermi-Moliere model for the atomic form-factors \cite{13}:

\[
Z^2 F^2(t) = G^{el}(t) + G^{inel}(t), \tag{11}
\]

\[
G^{el}(t) = Z^2 \frac{a^4 t^2}{(1 + a^2 t)^2}, \tag{12}
\]

\[
G^{inel}(t) = Z \frac{a_1^4 t^2}{(1 + a_1^2 t)^2}, \tag{13}
\]

where \( a = \frac{1117Z^{-1}}{m_e}, a_1 = \frac{724Z^{-1}}{m_e} \). For values of \( t \geq t_0 \), we use the elastic nuclear form-factor \cite{13}:

\[
Z^2 F^2(t) = G^{nucl}(t), \tag{14}
\]

\[
G^{nucl}(t) = \frac{Z^2}{(1 + \frac{1}{d})^2}, \tag{15}
\]

where \( d = 0.164A^{-\frac{2}{3}} GeV^2 \) and \( A \) is the mass number. For \( t \)-values relevant to our case the differential cross section \( \frac{d\sigma}{dt} \) can be written in the form

\[
\frac{d\sigma}{dt} \simeq \frac{1}{2} Br(\pi^0 \rightarrow X\gamma) \frac{8 \pi \Gamma(\pi^0 \rightarrow \gamma\gamma)}{m^2_\pi \Delta} \alpha Z^2 F^2(t) \frac{1}{t}, \tag{16}
\]
where \( t \simeq 2P^2(1 - \cos \theta) \) for heavy nuclei. Using the atomic and nuclear form-factors (2-6) we find that the total cross section for \( t_0 \geq t_{\min} \) is given by

\[
\sigma(X + Z \rightarrow \pi^0 + Z) = Br(\pi^0 \rightarrow \gamma + X) \frac{8\pi \Gamma(\pi^0 \rightarrow \gamma\gamma)}{m_\pi^3 \Delta} \cdot \alpha(G_1 + G_2 + G_3),
\]

\[
G_1 = \frac{Z^2}{2} \left[ \ln \left( \frac{a^2 t_0 + 1}{a^2 t_{\min} + 1} \right) + \frac{1}{a^2 t_0 + 1} - \frac{1}{a^2 t_{\min} + 1} \right],
\]

\[
G_2 = \frac{Z}{2} \left[ \ln \left( \frac{a^2 t_0 + 1}{a^1 t_{\min} + 1} \right) + \frac{1}{a^2 t_0 + 1} - \frac{1}{a^1 t_{\min} + 1} \right],
\]

\[
G_3 \simeq Z^2 \left( \ln \left( \frac{\sqrt{d}}{m_e} \right) - \frac{3}{2} \right)
\]

For heavy nuclei and for \( X \) boson masses not too close to the \( \pi^0 \) mass and for \( P \leq 100 \text{ GeV} \), we find that \( a^2 t_0 \gg 1, a^1 t_{\min} \gg 1 \). The inelastic atomic form-factor gives a contribution to the total cross section of about 1%, which we neglect. The total cross section then takes the simple form:

\[
\sigma(X + Z \rightarrow \pi^0 + Z) \approx Br(\pi^0 \rightarrow \gamma + X) \frac{8\pi \Gamma(\pi^0 \rightarrow \gamma\gamma)}{m_\pi^3 \Delta} Z^2 \cdot \alpha \cdot \left[ \ln \left( \frac{2P \sqrt{d}}{m_\pi^2 - M_X^2} \right) - \frac{1}{2} \right]
\]

For Pb \((Z = 82, A = 207)\), we find \( a = 50.5 \text{ MeV}^{-1}, a_1 = 75.3 \text{ MeV}^{-1}, \sqrt{d} = 68.2 \text{ MeV} \). Note that the total cross section (12) depends neither on the atomic radius \( a, a_1 \) nor on the value \( t_0 \) (the border between the application of atomic and nuclear form-factors).

Numerically for \( \Gamma(\pi^0 \rightarrow \gamma\gamma) = 7.7 \text{ eV} \) and for \( X \) boson masses \( M_X < 100 \text{ MeV} \), we find that the total cross section of \( X \rightarrow \pi^0 \) conversion on lead depends rather weakly on the incoming \( X \) boson momentum as shown in Figure 2.

The approximation (12) works up to \( M_X \leq 125 \text{ MeV} \). For \( M_X \) close to \( m_\pi \) it is necessary to use formulae (8-11). The accuracy of the form-factor calculations is estimated to be better than 5%, \[13\]; so the accuracy of our formula (12) is of the same order of magnitude.

4 Estimate of the total cross section for \( X \) interactions with matter

The total cross section \( \sigma_t(X + Fe \rightarrow all) \) for \( X \)-interactions in the Fe- shielding used in neutrino experiments can be estimated in the following way. We consider the particular case where the \( X \) boson interaction with u- and d- quarks is proportional to the electromagnetic interaction, namely:

\[
L_i = g_X X^\mu \left[ \frac{2}{3} \bar{u} \gamma_\mu u - \frac{1}{3} \bar{d} \gamma_\mu d \right]
\]

In this case, one can find that the total \( X \)-proton interaction cross section is

\[
\sigma_t(Xp) = \frac{1}{2} Br(\pi^0 \rightarrow \gamma + X)(1 - \left( \frac{M_X}{m_\pi} \right)^2)^{-3} \sigma_t(\gamma p)
\]

The \( X \) boson cross section on the nuclei in the lowest order approximation is proportional to the atomic number in full analogy with the case of neutrino scattering (here we implicitly suppose that the cross section on protons is equal to the cross section on the neutrons, an approximation valid to within a factor of 2).
Figure 2: Cross section for $X \rightarrow \pi^0$ conversion on lead versus $X$ boson energy calculated for $M_X = 10 \text{ MeV}$ and $Br(\pi^0 \rightarrow \gamma + X) = 1$. The curve is a polynomial fit to the points.

\[ \sigma_t(xA) \approx A\sigma_t(Xp) \]

(24)

Numerically for laboratory beam momenta $1 \text{ GeV} \leq P_L \leq 10^3 \text{ GeV}$, one has:

\[ \sigma_t(\gamma p) = (0.12 - 0.16)\text{mb} \]

(25)

For Iron ($A = 56$) and for $M_X$ much smaller than $m_\pi$ we find that

\[ \sigma_t(xA) \approx Br(\pi^0 \rightarrow \gamma + X) \times 4\text{mb} \]

(26)

For $Br(\pi^0 \rightarrow \gamma + X) \leq 10^{-4}$, we find

\[ \sigma_t(XA) \leq 4 \times 10^{-4}\text{mb} \]

(27)

This estimate of the total cross section for $X$ interaction with matter shows that the assumption that $X$ bosons are penetrating particles is correct since for $Br(\pi^0 \rightarrow \gamma + X) \leq 10^{-4}$ we find that the $X$ boson mean free path in iron is $\geq 300$ km, as compared with the Fe and earth shielding (total length $\approx 0.4$ km) used for example in the CERN SPS neutrino beam.

5 Rate of $X \rightarrow \pi^0$ conversion in the NOMAD detector.

In this section we consider the NOMAD neutrino detector at CERN[15] as an example in order to estimate the rate of $X \rightarrow \pi^0$ conversion in this experiment. The neutrino beam is generated by 450 GeV protons delivered by the SPS to the Be neutrino target.
The expected number of $X \to \pi^0$ events can be calculated using the following relations:

$$N_{X-\pi^0} = \left[Br(\pi^0 \to \gamma + X)\right]^2 \cdot N_{\text{pot}} \cdot \int f_0(M_X) \sigma_0(M_X, E_X) \varepsilon_{\text{sel}} dE_X \cdot \frac{M_t}{S} \cdot \frac{N_A}{A}$$ (28)

where $N_{X-\pi^0}$ is the predicted number of $X \to \pi^0$ events for the given $Br(\pi^0 \to \gamma + X)$, $\varepsilon_{\text{sel}}$ is the detection efficiency, $f_0(M_X)$ is the flux of $X$ bosons per one proton on neutrino target (pot), $N_{\text{pot}}$ is the total number of pot’s, $\sigma_0(M_X, E_X)$ is the cross section of $X \to \pi^0$ conversion on target with mass number $A$, calculated for $Br(\pi^0 \to \gamma + X)$=1, and $M_t$ and $S$ are fiducial mass and fiducial area of the detector target, respectively. We note that $Br(\pi^0 \to \gamma + X)$ appears twice in the formula for $N_{X-\pi^0}$, through the $X$ boson flux from the target, and through the Primakoff mechanism.

The flux of the $X$- bosons through NOMAD detector was calculated with a detailed GEANT [12] simulation used to predict the neutrino flux at the NOMAD detector, and was found to be of the order $f_0(M_X) \simeq 0.1X/2.4 \times 2.4 m^2/pot$ for $Br(\pi^0 \to \gamma + X)$=1 and with average $X$-boson energy $<E_X>_X \simeq 50$ GeV. Note that the flux and average energy $<E_X>$ are weakly depended on mass $M_X$. This results in weak dependence of limit on branching ratio versus $M_X$.

We will consider NOMAD preshower detector[13] as a lead target with $M_t \approx 1$ ton and $S = 2.4 \times 2.4 m^2$. Using $N_{\text{pot}} = 10^{18}$ pot , $Br(\pi^0 \to \gamma + X) = 3 \times 10^{-4}$, which corresponds to the Crystal Barrel upper limit for $M_X \leq 10 MeV/c^2$, $\varepsilon_{\text{sel}} = 1$ and value of the cross section $\sigma_0(M_X, E_X) = 4.0 \, \mu$b taken for simplicity at $E_X = 5$ GeV (see Figure 2) one obtains

$$N_{X-\pi^0} \simeq Br(\pi^0 \to \gamma + X)^2 \cdot f_0 \cdot N_{\text{pot}} \cdot \varepsilon_{\text{sel}} \cdot \frac{M_t}{S} \cdot \frac{N_A}{A} \simeq 2 \times 10^3 \text{ events}/10^{18}\text{pot}$$ (29)

The main contribution to the background for the $X \to \pi^0$ conversion is expected from the neutrino processes which have a significand electromagnetic component in the final state, e.g. coherent and diffractive $\pi^0$ production, quasi-elastic $\nu_e$ scattering, etc.. Using the neutrino cross sections which are well known, the total number of background events $N_{\text{bkgd}}$ was estimated to be $\simeq 10$ events. Thus, if the decay $\pi^0 \to \gamma + X$ exists with the branching ration of the order of Crystal Barrel limit its effect would be easy seen at NOMAD detector. The limit on $Br(\pi^0 \to \gamma + X)$ could be improved by a factor of the order of $\sqrt{N_{X-\pi^0}/N_{\text{bkgd}}} \simeq 10$. The coupling to quarks could be constrained to $\alpha_X \leq 10^{-7}$.

The similar estimate for $X \to \eta$ conversion rate shows that a limit of the order of the Crystal Barrel limit on $Br(\eta \to \gamma + X)$ could be obtained, however for a longer exposure time at neutrino beam, since the production of $\eta$ mesons in the forward direction in high energy proton collision with neutrino target is suppressed by a factor of $\simeq 10^2$ compare to that of $\pi^0$'s.

6 Conclusion

We have shown that a new light gauge boson $X$ which might be produced in the decays of pseudoscalar mesons $\pi^0(\eta) \to \gamma + X$ could be effectively searched for in neutrino experiments. The $X$'s being produced in neutrino target from these decays would penetrate the downstream shielding, and be observed in a neutrino detector via the Primakoff effect, the process of $X + Z \to \pi^0(\eta) + Z$ conversion in the external Coulomb field of a nucleus.

Our estimates show, that NOMAD experiment at CERN is able to improve current limit on
$Br(\pi^0 \rightarrow \gamma + X)$ at least by a factor of 10 for the mass region $M_X \leq 10\text{ MeV}$ during $\simeq 1$ month of exposure at neutrino beam.

Note that direct searches of these rare radiative meson decays were performed in the previous experiments [7] by searching for a peak in inclusive photon spectra from two-body decay of the tagged $\pi^0(\eta)$ mesons, where background due to missing of one of the two photon from principal decay mode $\pi^0(\eta) \rightarrow 2\gamma$ is dominated for the low $M_X$ mass region. Our method is free from this disadvantage since its sensitivity is weakly depended on $M_X$. Note also that another promising way to search for a new light gauge boson from the pseudoscalar meson decays in neutrino experiments is to analyse the ratio $R = \sigma(\nu NC)/\sigma(\nu CC)$ which might result in better sensitivity. However, in this case a knowledge of the final state structure in $X$ interactions with a quarks is required. This subject is now under study.

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