Search for a new light gauge boson with the Crystal Barrel Detector

F Ould-Saada†

Physik-Institut, Universität Zürich, Winterthurerstra190, CH-8057 Zürich

representing the Crystal Barrel Collaboration[1]

Abstract

We have searched for new light gauge bosons produced in π^0, η and η' decays by studying the kinematically well-constrained reactions $\overline{p}p \rightarrow \pi^0\pi^0 P$, where $P \equiv \pi^0, \eta, \eta'$ decays through the emission of a single photon recoiling against a missing state X (where X is a long-lived weakly interacting particle or $X \rightarrow \nu\overline{\nu}$). No signal has been observed and branching ratio upper limits (90 % $C.L.$) of 6×10^{-5} have been obtained for masses of the gauge boson lying between ~ 65 MeV and 125 MeV (π^0 decay), 6×10^{-5}, for X masses between ~ 200 MeV and 525 MeV (η decay), and 4×10^{-5}, for X masses between ~ 50 MeV and 925 MeV (η' decay). The π^0-decay limit represents a factor of 4 to 8 improvement when compared to the existing limit, whereas the η and η' decay limits have been measured for the first time, thereby extending the m_X range from 130 MeV up to 925 MeV.

1. Introduction

There exist various extensions of the Standard Model ($SU(3) \times SU(2) \times U(1)$) of strong and electroweak interactions. Some of them require an extra gauge group $U'(1)$ and, hence, a new gauge boson X. This possibility is realised in grand unified theories [2], in supersymmetric theories [3], in superstring-inspired models [4] and in models including a new long-range interaction, the fifth force [5]. Some X bosons could be light enough to be detected in rare or (Standard Model) forbidden decays of light mesons (π, K, η, ...) [6, 7]. To look for such new light particles, with masses of the order of the pion mass and with small couplings, high rates and precision are needed. Constraints on branching ratios for the decay of a pseudoscalar $P \rightarrow \gamma X$, P being a π^0, an η or an η' are summarised in ref. [7]. Two possibilities are considered depending on the interaction of the X boson: (I) X interacts weakly with both leptons and quarks, in which case it decays in our detector ($P \rightarrow \gamma e^+e^-$ or $P \rightarrow \gamma\nu\overline{\nu}$). The decay $X \rightarrow \nu\overline{\nu}$ is experimentally more favourable to study since $X \rightarrow e^+e^-$ is overwhelmed by the Dalitz decay $\pi^0 \rightarrow \gamma e^+e^-$; (II) X interacts weakly with quarks only and hence has a long lifetime and does not decay in our detector. In both cases the analysis consists of looking for a photon and a missing mass. The decay $X \rightarrow e^+e^-$ is not considered in this work.

Consider the decay $P \rightarrow \gamma\gamma$. In the rest frame of the decaying pseudoscalar P, the photon energy is given by $E^*_\gamma = m_P/2$, where m_P is the mass of the pseudoscalar P. Because of detector inefficiencies, one of the two photons can be lost. This leads to a peak in the energy distribution with a width determined by the experimental resolution. If one replaces the missing photon by a missing massive gauge boson X, the photon energy distribution peaks at $E^*_\gamma = \frac{m_P}{2}\,(1 - \frac{m_X^2}{m_P^2})$, where m_X is the mass of the gauge boson X.

To look for a hypothetical gauge boson X in the decays $P \rightarrow \gamma X$, we exploit the fact that the annihilation of antiprotons with protons is a rich source of mesons (e.g., $\pi^0, \eta, \eta', \omega$) and that the Crystal Barrel detector is ideally designed for measurements of final

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states with many photons. We use the well-constrained reactions $\overline{p}p \to \pi^0\pi^0 P$ because of the relatively high branching ratios $BR(\overline{p}p \to \pi^0\pi^0\pi^0) = (0.63 \pm 0.10)\%$ [8], $BR(\overline{p}p \to \pi^0\pi^0\eta) = (0.65 \pm 0.07)\%$ [9] and $BR(\overline{p}p \to \pi^0\pi^0\eta') = (0.40 \pm 0.08)\%$ [10] at rest in liquid hydrogen.

2. The data

The data have been collected using the Crystal Barrel detector at the Low Energy Antiproton Ring (LEAR) at CERN. Antiprotons with a momentum of 200 MeV/c are stopped in a 4-cm-long liquid hydrogen target. A matrix of silicon counters in front of the target defines and monitors the incident $\overline{p}$ beam (typically 10^4 $\overline{p}/s$). The target is surrounded by two cylindrical proportional wire chambers (PWCs), a jet drift chamber (JDC) to track charged particles, and a barrel-shaped calorimeter consisting of 1380 CsI(Tl) crystals, 16 radiation lengths deep, with photodiode readout. A detailed description of the detector, the trigger conditions and the reconstruction procedure is given in Ref. [11].

The analysis is based on 15×10^6 (18×10^6 for η') triggered all-neutral events. The triggering was performed using the PWCs and the inner layers of the JDC to veto charged tracks. One Million events containing exactly 5 electromagnetic showers (PEDs) with energy deposits exceeding the threshold energy $E_{cut} = 20$ MeV are selected. Events with a PED induced in the last crystal rows around the beam entrance and exit pipes are removed to suppress energy leakage. The next step is to reconstruct two π^0's out of the 5γ sample (818,655 events). The invariant masses of all combinations of two photons are calculated and events containing two π^0's and a single γ are kept. The surviving data sample consists of 187,145 events. Once the $\pi^0\pi^0\gamma$ events are selected, a kinematic fit with 3 constraints (3-C fit) ($\pi^0\pi^0 P_{miss}$, where P_{miss} is a missing π^0, η or η') is performed, ignoring the remaining single photon. A confidence level greater than 15% is required. We are left with $95,392$ $\pi^0\pi^0\pi^0_{miss}$, $17,943$ $\pi^0\pi^0\eta_{miss}$ and $4,165$ $\pi^0\pi^0\eta'_{miss}$ fit events.

The method used to search for an X signal now consists of plotting the energy E^*_γ of the single γ in the rest frame of P_{miss}. The measured energy and momentum of the fifth photon and the fit values of P_{miss} are used to calculate E^*_γ.

3. The background

The background contribution can be split into two categories: 5γ final states without and with missing energy and momentum. The first source of background comes from real $\pi^0\pi^0\gamma$ events, due to the finite resolution of the detector. Here it is mainly the channel $\overline{p}p \to \omega\pi^0$ ($\omega \to \pi^0\gamma$) which feeds into the fit $\pi^0\pi^0\pi^0_{miss}$ and to a lesser extent into $\pi^0\pi^0\eta_{miss}$. To reduce this background the selected 5γ data events are kinematically fit to the following final states: $\overline{p}p \to \pi^0\omega$ (7-C fit), $\overline{p}p \to \eta\omega$ (7-C fit), $\overline{p}p \to \pi^0\eta\gamma$ (6-C fit) and $\overline{p}p \to \eta\eta\gamma$ (6-C fit). If one of the 5γ combinations fits one of the above final states with a $C.L. > 1\%$, the event is rejected. About 25% of events are rejected for $\pi^0\pi^0\pi^0_{miss}$, while the proportion of rejected events is negligible in the case of $\pi^0\pi^0\eta_{miss}$ and $\pi^0\pi^0\eta'_{miss}$. The second source of background consists of the following final states: $\overline{p}p \to \pi^0\pi^0 P$, where one photon from a P is undetected. In order to reduce the missing photon contribution, an event is discarded if $\mid cos(\theta_{\gamma_{miss}}) \mid \geq 0.95$ or $\mid cos(\theta_{\gamma_{miss}}) \mid \leq 0.02$. We are left with $48,158$ $\pi^0\pi^0\pi^0_{miss}$, $10,827$ $\pi^0\pi^0\eta_{miss}$ and $2,848$ $\pi^0\pi^0\eta'_{miss}$ events.

For the η decay we also take into account the channel $\overline{p}p \to K_S K_L$, where $K_S \to \pi^0\pi^0$ and K_L interacts in the barrel and produces one PED. The K_L and K_S emerge back to back and therefore events are rejected for which the invariant mass of the two π^0's is in the region $455 \leq M_{\pi^0\pi^0} \leq 506$ MeV/c^2 and the angle between the K_S direction and the fifth photon is greater than $167°$. About 50% of the events far from the $\eta \to \gamma\gamma$ peak are rejected. This reduces the $\pi^0\pi^0\eta_{miss}$ sample to $8,961$ events.

The remaining background events tend to accumulate along the line of maximum possible γ energy in the laboratory, E^{lab}_γ, in a two dimensional plot E^{lab}_γ vs. E^*_γ. This happens for events where the fifth photon has the same direction as P_{miss}. This is the case for the small fraction of $\pi^0\pi^0\gamma$ events ($K_L K_S$, $\omega\pi^0$, ...) that have not been removed by the above cuts. The following cuts are therefore applied: $E^{lab}_\gamma / E^*_\gamma \leq 2.6$ for η decay, $E^{lab}_\gamma / E^*_\gamma \leq 1.7$ for η' decay and $E^{lab}_\gamma / E^*_\gamma \leq 10.0$ for π^0 decay. About 30% of the remaining background events are rejected by these cuts, without affecting the signal. The final sample consists of $24,503$ $\pi^0\pi^0\pi^0_{miss}$, $5,121$ $\pi^0\pi^0\eta_{miss}$ and $2,198$ $\pi^0\pi^0\eta'_{miss}$ events.

The acceptance and energy resolution are obtained using Monte Carlo simulation [12]. The photon energy resolution is $\sigma \sim 5$ MeV. The following efficiencies are obtained: $\epsilon_{\pi^0} = (11 \pm 1)\%$ for the π^0 decay, $\epsilon_\eta = (16 \pm 1)\%$ for the η decay, and $\epsilon_{\eta'} = (22 \pm 2)\%$ for the η' decay. The uncertainties include the dependence of the efficiency on m_X. The number of expected events for a given branching ratio $BR(X) = BR(P \to \gamma X)$ is $N_X = N_{\overline{p}} \times BR(\overline{p}p \to \pi^0\pi^0 P) \times BR(X) \times \epsilon$. For the $3\pi^0$ final state, a multiplicative factor 3 is included, to allow for the possible decay of any of the three π^0's. The 15×10^6 analysed 0-prong events correspond to $N_{\overline{p}} = (360 \pm 20) \times 10^6$ annihilations at rest. We then expect $N^{\pi^0}_X = 76 \pm 11$, $N^\eta_X = 35 \pm 7$, and $N^{\eta'}_X = 38 \pm 7$

signal events assuming a branching ratio $BR(X)$ of 10^{-4}.

4. Results

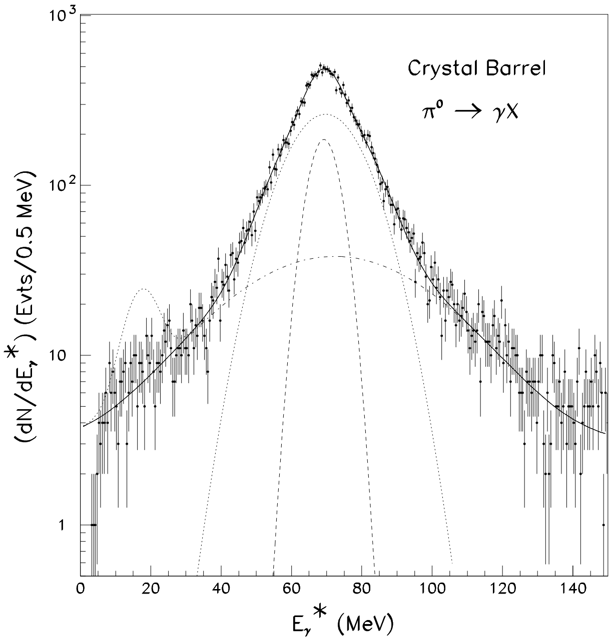

Figure 1. Energy of the single γ in the P_{miss} rest frame for the $\pi^0\pi^0 P_{miss}$ kinematically fit sample after background suppression, . The different contributions to the ten-parameter fit (full line) described in the text are shown separately: a narrow gaussian corresponding to $\pi^0\omega$ (dashed line), a broader gaussian corresponding to $\pi^0\pi^0\pi^0$ (finely dotted line), a much broader gaussian corresponding to other final states (like $\pi^0\pi^0\omega$), where two photons are lost (dashed-dotted line) on top of a constant background. A signal corresponding to a branching ratio for $\pi^0 \to \gamma X$ with $m_X = 120$ MeV/c^2 of 5×10^{-4} is also drawn (dotted line).

The energy of the single γ in the π^0 rest frame is shown in fig.1. A ten-parameter fit to the data includes the sum of three gaussians and a constant background term. The three gaussians have maxima around $m_{\pi^0}c^2/2$ (at 69.2, 69.7 and 72.0 MeV). These peak positions and the resolutions (4.2, 10.3 and 26.0 MeV) are in agreement with what we expect for $\pi^0\omega$ events (no missing photon), $\pi^0\pi^0\pi^0$ events (where one photon is missing), and other smaller background sources like $\omega\pi^0\pi^0$ (where 2 photons are missing). The third gaussian is, as expected, wider than the first two and its amplitude much smaller (32 events/0.5 MeV compared to 187 for the first and 263 for the second gaussian). The background term is due to events where the fifth photon found does not belong to the missing π^0. The global fit shows that the spectrum is well understood. The amplitudes are consistent with Monte Carlo predictions using the experimental branching ratios. To look for a signal, various fits have been performed, with similar results[12]. An upper limit of $BR(\pi^0 \to \gamma X) < 6 \times 10^{-5}$ is obtained at 90% $C.L.$ for m_X lying between 65 MeV/c^2 and 125 MeV/c^2. Near $m_X = 0$ we obtain $BR(\pi^0 \to \gamma X) < 2.8 \times 10^{-4}$. A signal corresponding to $BR(\pi^0 \to \gamma X) = 5 \times 10^{-4}$, the existing direct measurement [16] is also indicated in fig.1.

In the case of η and η' the photon energy distribution shows a flatter and lower background than in the π^0 case (fig.2 and 3, respectively). The main reason is the

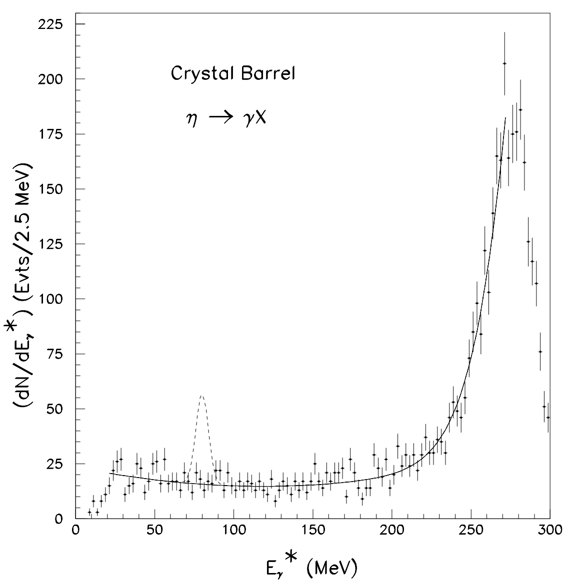

Figure 2. Energy of the single γ in the η_{miss} rest frame for the $\pi^0\pi^0\eta_{miss}$ kinematically fit sample after background suppression. The full curve corresponds to a six-parameter fit to the data (gaussian + 2^{nd} order polynomial). A signal corresponding to a branching ratio for $\eta \to \gamma X$ with $m_X = 460$ MeV/c^2 of 5×10^{-4} is also indicated (dashed line).

reduced contribution from 6γ events ($\pi^0\pi^0 P$, where one photon from the P is lost). This is due to the smaller BR for $\eta, \eta' \to \gamma\gamma$ ($\sim$ 2% for $\eta' \to \gamma\gamma$ and $\sim$ 39% for $\eta \to \gamma\gamma$ compared to $\sim$ 99% for $\pi^0 \to \gamma\gamma$), the higher γ efficiency for the η and η' decays and the lower combinatorial background (one for $\pi^0\pi^0\eta$ and $\pi^0\pi^0\eta'$ vs. three for $\pi^0\pi^0\pi^0$). In fig.2 a six-parameter fit to the data is performed which includes one gaussian and a background term (second-order polynomial). No significant signal is found on top of the background curve. An upper limit of $BR(\eta \rightarrow \gamma X) < 6 \times 10^{-5}$ is obtained at 90% $C.L.$ for masses of the X boson between 200 MeV/c^2 and 525 MeV/c^2. A weaker upper limit of $BR(\eta \rightarrow \gamma X) < 3 \times 10^{-4}$ is obtained down to $m_X \sim 50$ MeV. From fig.3 an upper limit of $BR(\eta' \rightarrow \gamma X) <$

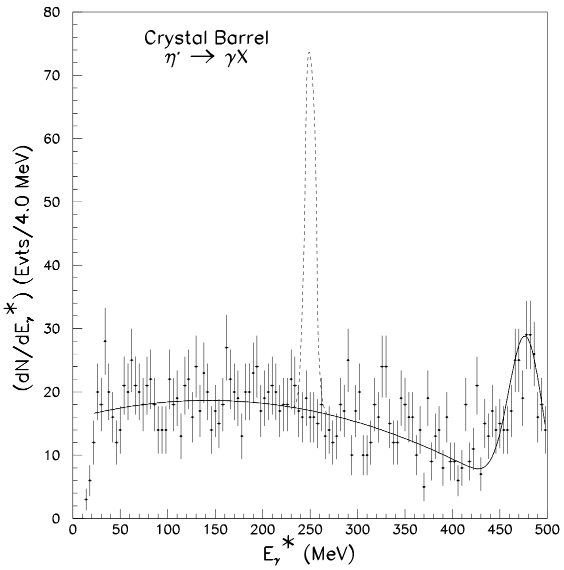

Figure 3. Energy of the single γ in the η'_{miss} rest frame for the $\pi^0\pi^0\eta'_{miss}$ kinematically fit sample after background suppression. The full curve corresponds to a six-parameter fit to the data (gaussian + 2^{nd} order polynomial). A signal corresponding to a branching ratio for $\eta' \rightarrow \gamma X$ with $m_X = 662$ MeV/c^2 of 5×10^{-4} is also indicated (dashed line).

4×10^{-5} is obtained at 90% $C.L.$ for masses of the X boson between 50 MeV/c^2 and 925 MeV/c^2. A signal corresponding to $BR(P \rightarrow \gamma X) = 5 \times 10^{-4}$ is indicated in fig.2 and 3 (dashed curves). The upper limit for the decay $P \rightarrow \gamma X$ as a function of mass is given in fig. 4 for the three pseudoscalars.

5. Summary

To summarise, we have searched for new light gauge bosons produced in π^0 η, and η' decays. No signal has been observed and branching ratio upper limits (90 % $C.L.$) of 6×10^{-5} have been obtained for m_X in the range between 65 MeV and 125 MeV (π^0 decay), of 6×10^{-5}, for X masses lying between 200 MeV and 525 MeV (η decay), and of 4×10^{-5}, for X masses lying between 50 MeV and 925 MeV (η' decay). The π^0-decay limit improves the existing limit [16, 17] by a factor of

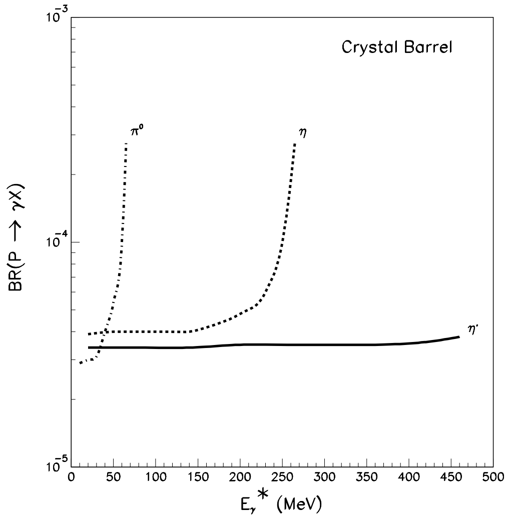

Figure 4. Branching ratio upper limit for the decays $\pi^0 \rightarrow \gamma X$ (dashed-dotted line), $\eta \rightarrow \gamma X$ (dotted line) and $\eta' \rightarrow \gamma X$ (full line) as function of E^*_γ (lower x-axis).

4 to 8, whereas the η and η' upper limits have been measured for the first time, thereby extending the m_X range from 130 MeV up to 925 MeV.

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