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Search for the decay $\pi^0 \to \gamma X$

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We present the results of a search for exotic bosons produced in the decay $\pi^0 \to X\gamma$. A low energy π^- beam at TRIUMF was stopped in a liquid hydrogen target to produce the reactions $\pi^- p \to n\gamma$ and $\pi^- p \to n\pi^0$, $\pi^0 \to \gamma\gamma$. The γ rays from these reactions were detected in a sodium iodide crystal. From the energy distributions we extract a branching ratio limit for $\Gamma(\pi^0 \to \gamma X)/\Gamma(\pi^0 \to \gamma\gamma)$ of (2–7) $\times 10^{-3}$ for X masses of 25–100 MeV/c^2 (90% C.L.). In contrast with other experimental limits this branching ratio limit is valid for all reasonable X lifetimes ($> 10^{-23}$ sec).

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INTRODUCTION

The standard model of particle physics has been very successful in describing all available experimental data on subatomic interactions. Physics beyond the standard model must be either on a larger mass scale than hitherto available to experimenters, or more weakly coupled than the currently observed phenomena. In this latter scenario, it is expected that if gauge bosons responsible for new interactions have masses on the same scale as currently observed particles, then their coupling constants would have to be very small. Such situations arise in several existing models and include particles such as the axion, the right-handed neutrino, the "axigluon," and particles associated with extensions to the Higgs sector [1–3]. Rare decays can provide an excellent arena in which to perform searches for such new bosons, which we will denote by X.

Previous searches [4, 5] have set limits on the existence of new bosons by studying their production via $\pi^0 \to \gamma X$, where in this case the X must be a vector particle. Limits on this branching ratio have been obtained by the nonobservation of $\pi^0 \to \gamma +$ nothing [4], or $\pi^0 \to \gamma X$ followed by $X \to e^+e^-$ [5]. Dobroliubov [1] has enumerated the various X decay modes and associated X lifetimes, and the experimental limits must be interpreted in the light of this information, which we summarize below and in Table I.

If the X couples only to quarks at the tree level, then the branching ratio $\Gamma(\pi^0 \to \gamma X)/\Gamma(\pi^0 \to \gamma\gamma)$ is expected to be $\simeq 10^{-3}$ and the lifetime of the boson is thought to be long, $\simeq 10^{-6}$ sec. By looking for events in which a tagged π^0 is associated with only a single γ, limits for this branching ratio of $< 5 \times 10^{-4}$ for $m_X < m_\pi$ (and $\tau_X > 2 \times 10^{-7}$ sec) have been obtained in [4].

If the X couples at tree level to both quarks and leptons, the lifetime of the X boson in this case is short, $< 10^{-6}$ sec. For X boson masses in the range $2m_e < m_X < 2m_\pi$, the main decay mode is expected to be $X \to e^+e^-$. By searching for e^+e^- pairs resulting from X decays within the detector volume, an upper limit for $\Gamma(\pi^0 \to \gamma X\ ,\ X \to e^+e^-)/\Gamma(\pi^0 \to \gamma\gamma)$ of $< 4 \times 10^{-6}$ (90% C.L.) for 60–100 MeV/c^2 bosons is reported in [5].

Both of the previous experiments are hence subject to lifetime caveats: the X must either leave the volume of the detector before decaying ($\tau_X > 2 \times 10^{-7}$ sec) [4], or it must decay in the target ($\tau_X < 10^{-11}$ sec) [5]. We present the results of an experiment to obtain a measurement of the branching ratio for $\pi^0 \to \gamma X$ by studying the γ spectrum associated with X production. This result

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TABLE I. Summary of theoretical and experimental constraints on the existence of new vector bosons X. The first three columns are the theoretical expectations, as outlined in [1,2], and the last two columns summarize the experimental limits.

X decay mode	τ_X(theory)	$\frac{\Gamma(\pi^0\to\gamma X)}{\Gamma(\pi^0\to\gamma\gamma)}$	Observed B	Comments
$X \to$ anything			$<(2\text{–}7)\times10^{-3}$	$\tau_X > 10^{-23}$ sec
			This work	$25< m_X < 100$ MeV/c^2
$X \to$ anything	$\approx 10^{-6}$ sec	$\approx 10^{-3}$	$< 5 \times 10^{-4}$	$\tau_X > 2 \times 10^{-7}$ sec
			Ref. [4]	$m_X < m_\pi$
$X \to e^+e^-$ only	$< 10^{-6}$ sec	$\approx 10^{-6}$	$< 4 \times 10^{-6}$	$10^{-23} < \tau_X < 10^{-11}$ sec
			Ref. [5]	$40 < m_X < 100$ MeV/c^2

is therefore independent of τ_X (insofar as it is a state narrow enough to see, i.e., $\tau_X \gtrsim 10^{-23}$ sec).

DATA ACQUISITION AND ANALYSIS

The experimental setup has been described in detail in Ref. [6]; it was designed for a measurement of the π^0 electromagnetic transition form factor. A beam of 90 MeV/c π^-'s from TRIUMF's M13 beam line was brought to rest in a cylindrical liquid hydrogen target (7.6 cm diameter), producing π^0's by the charge exchange reaction, $\pi^- p \to \pi^0 n$. For the purposes of this measurement, single photons from π^0 decay as well as from the reaction $\pi^- p \to n\gamma$ were detected in a sodium iodide crystal ("SOPHIE" [7], 25 cm diameter, 30 cm long) placed 1.5 m from the target. In front of SOPHIE were two plastic veto scintillators and a conical lead collimator of 5 cm radius, which defined a narrow angular acceptance well matched to the dimensions of the crystal. Figure 1 shows SOPHIE and its position relative to the target. The beam rate was approximately 10^5 π^-'s per second, resulting in a very low rate of approximately 50 photons per second in SOPHIE. The photon energies were binned into histograms on line using buffered analogue to digital converters (ADC's), on a run-by-run basis. The results for a sample run are shown in Fig. 2. The peak visible at 129 MeV represents the NaI response to the photons from $\pi^- p \to n\gamma$. The broad "boxlike" structure to the left of the peak is the response to single photons from $\pi^0 \to \gamma\gamma$ (98.8% branch) and $\pi^0 \to e^+e^-\gamma$ (1.2% branch); the edges of this box lie at 55 and 83 MeV in the laboratory frame.

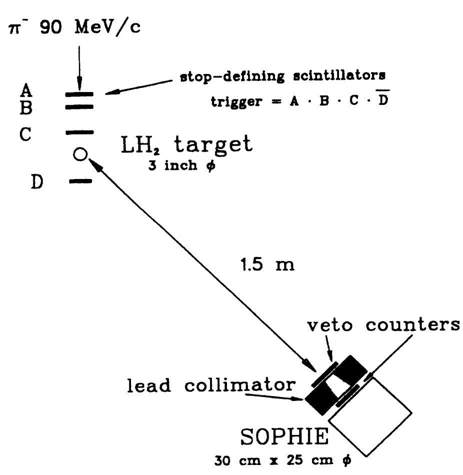

FIG. 1. Details of the experimental geometry.

The photons associated with X bosons from the decay $\pi^0 \to X\gamma$ also have a boxlike energy distribution, the edges of the box being dependent on the mass of the X:

$$E_{\text{low}} = \frac{m_\pi^2 - m_X^2}{2(E_\pi + p_\pi)}, \tag{1}$$

$$E_{\text{high}} = \frac{m_\pi^2 - m_X^2}{2(E_\pi - p_\pi)}, \tag{2}$$

with

$$p_\pi = 28 \text{ MeV}/c. \tag{3}$$

Table II lists the expected box edges for some representative X masses. A massless X boson is associated with a photon indistinguishable from those of π^0 decay and hence would be invisible. As the X boson increases in mass, the associated photon becomes less and less energetic, and its box spectrum narrows and moves towards lower energies, as illustrated in Fig. 3. The effect of the X bosons are therefore expected to be visible below 83 MeV, the upper edge of the π^0 photon box.

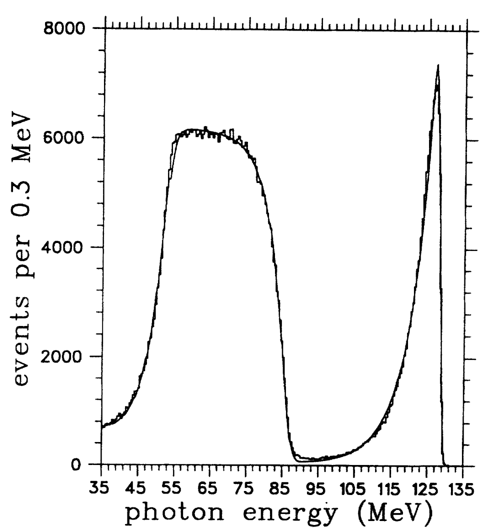

FIG. 2. Calibrated data for a single run. The peak at 129 MeV is due to photons from the reaction $\pi^- p \to n\gamma$, and the box to the left is the NaI response to photons from π^0 decays. There are 4.6×10^5 photons in this histogram. The solid line shows the result of the fit.

TABLE II. Expected upper and lower edges of the photon box spectrum in the process $\pi^0 \to \gamma X$, for various X masses, as per Eqs. (1) and (2).

X mass (MeV/c^2)	Lower edge (MeV)	Upper edge (MeV)
0	54.88	82.97
20	53.68	81.15
60	44.04	66.57
100	24.75	37.42

EXTRACTION OF LIMITS ON BOSON PRODUCTION

The raw data histograms were first calibrated by fitting the raw data with a $\pi^- p \to n\gamma$ peak and a π^0 box, convoluted using an NaI response function with four free parameters [8]:

$$f(E) = A \exp\left(\frac{E-b}{d}\right)\left[1 - \mathrm{erf}\left(\frac{E-b}{c}\right)\right].$$

The parameters c and d were further allowed to vary with energy according to the power laws

$$c(E) = c_0\, E^{\alpha},$$
$$d(E) = d_0\, E^{\beta}.$$

An exponential background was also superimposed:

$$B(E) = B_0 \exp\left(-E \cdot \eta\right).$$

The entire γ-ray spectrum was fitted with these parameters using MINUIT [9] and the known γ-ray energy distribution for π^0 decays. The result for one run of 5×10^5 events is shown in Fig. 2.

The fitted values of c and d corresponded to a full width at half maximum (FWHM) energy resolution [$\approx (c+d)/E$] of 10% for the π^0 box and 6% for the 129 MeV peak. The fitted values of α and β were about -0.4, close to the previously found value of -0.55 [10] which was the result of data taken over a larger energy range. The background decay constant η, which is somewhat dependent on detector and collimator geometry, was found to be $(22 \text{ MeV})^{-1}$. The exponential form was found to be a reasonable approximation to reality, even under the π^0 box, by Spuller *et al.* [11], who found a value for $(17 \text{ MeV})^{-1}$ for a different geometry.

Many runs were performed in the course of the experiment, each run consisting of approximately 5×10^5 photon events. Unfortunately, however, the detailed response of NaI crystals is in general not very well understood, and the systematic errors associated with fitting the data with the empirical response function above are of the same order as the statistical errors on a single run. Monte Carlo shower codes such as EGS do no better, as photonuclear effects and variations in photon detection throughout the volume of the crystal have to be handled in an *ad hoc* manner [8]. Our measurement is therefore limited entirely by these systematic errors, and it is meaningless to attempt to extract limits on the existence of X bosons using more than one run.

Figure 3 shows the π^0 box and the shape of the contributions of X bosons of various masses to the spectrum. To extract limits on boson production it was necessary to fit the data with an additional boxlike structure for each putative boson mass. This had to be approached carefully as the addition of a second box made the refitting procedure time consuming and unreliable. We found that by fitting in a narrow region (30 MeV/c^2) around the left or the right hand edges (depending on boson mass) of the putative X contribution, we could maximize our sensitivity while minimizing the time required for the refitting process.

For $m_X < 50$ MeV/c^2, we fitted the right hand edge of the π^0 box (the left hand edge is hardly affected by the new boson). Thus the key parameters to refit were c_0 and α, and we were insensitive to d_0, β, B_0, and η. Likewise for $m_X > 50$ MeV/c^2, we fitted the left hand edge of the π^0 box where the key parameters to refit were d_0 and β, and we were insensitive to c_0, α, and the 129 MeV peak. In each case we let the X branching ratio and *all* other

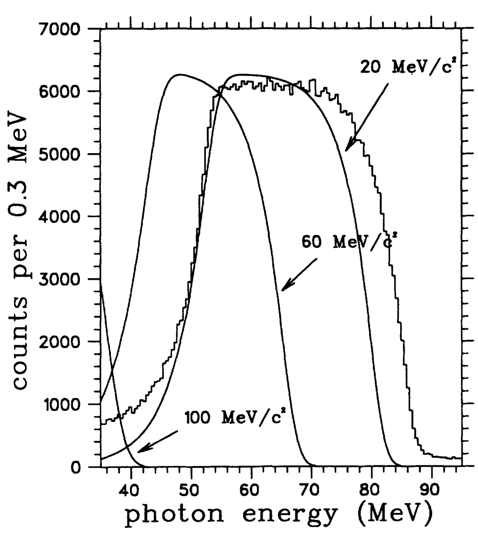

FIG. 3. The solid line represents the expected response of the NaI crystal to photons from $\pi^0 \to X\gamma$, for X masses of 20, 60, and 100 MeV/c^2, plotted without the contribution from the exponential background. The histogram shows the experimental data.

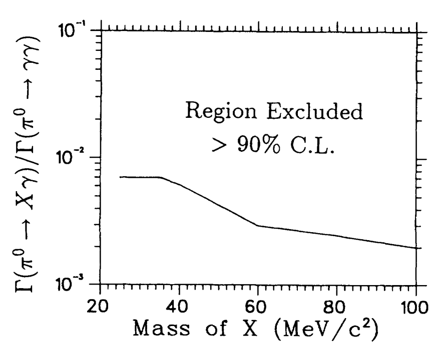

FIG. 4. The 90% confidence limits on the $\pi^0 \to X\gamma$ branching ratio, normalized to $\pi^0 \to \gamma\gamma$, for $\tau_X > 10^{-23}$ sec.

parameters vary but fit only a small region around the relevant box edge. The fitting process was now efficient in computer time and produced stable fits.

Typical χ^2 values of the fit to a single run (5×10^5 events) were 1.2–1.5 per degree of freedom. We obtained the branching ratio limits for $\Gamma(\pi^0 \to \gamma X)/\Gamma(\pi^0 \to \gamma\gamma)$ shown in Fig. 4, of (2–7) $\times 10^{-3}$ for X masses of 25–100 MeV/c^2 (90% C.L.).

CONCLUSIONS

By searching for structure in the photon spectrum of π^0 decays, we set a limit on the existence of new bosons of $\Gamma(\pi^0 \to \gamma X)/\Gamma(\pi^0 \to \gamma\gamma) < (2-7) \times 10^{-3}$ for $25 < m_X < 100$ MeV/c^2. In contrast to previous work [4, 5], which is subject to X lifetime caveats, this limit is valid for any X which has a lifetime of more than 10^{-23} seconds (i.e., its width is such that the effect on the spectrum could be resolved by our detector). We therefore provide a limit which is independent of X boson coupling; this is the most sensitive *general* search for new bosons yet reported in this mass range. These results could be improved by a better understanding of the NaI response function. This would require a very detailed simulation, taking into account photonuclear and hadronic reactions, as well as macroscopic nonuniformities inside the NaI crystal. It may not be possible to do this well enough, but if it were, one could then obtain limits low enough to challenge models which require new bosons.

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