Evidence for Neutrino- and Antineutrino-Induced Coherent π^0 Production

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The angular distribution of isolated photon conversion pairs, collected during the proton-synchrotron–Gargamelle ν and $\bar{\nu}$ Freon experiments, has been examined to determine whether any anomalous small-angle production is present. There is a definite excess of conversion pairs over what is expected from resonantly produced and neutron-induced π^0's. This excess is in accord with ν- ($\bar{\nu}$-) induced coherent π^0 production off nuclei.

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The "isolated gamma" sample of the early proton-synchrotron (PS)–Gargamelle ν- ($\bar{\nu}$-) Freon experiment collected for background studies in the $\bar{\nu}_\mu e$ search[1] has attracted new interest through the recent observation of electromagnetic showers of allegedly unconventional origin in other low-energy neutrino and beam dump experiments.[2-5] One source of isolated photons just recently observed[2] and not envisaged in earlier experiments is ν- ($\bar{\nu}$-) induced coherent π^0 production off a nucleus as a whole. In addition, the suggestion has been made that a light penetrating particle, decaying into two photons with almost zero opening angle, could appear as one isolated electromagnetic shower.[3-5] In a recent review[5] of the subject, attention has been drawn to the possibility that the data of the PS (27-GeV protons)–Gargamelle Freon experiment contain an excess of low-angle ($< 10^\circ$) showers which is not easily explained by ν or $\bar{\nu}$ interactions. This prompted us to undertake a more refined and quantitative analysis of this isolated gamma sample,[1,6] incorporating the stringent geometrical cuts and gamma detection efficiencies determined by Blietschau *et al.*

The film sample used in the ν and $\bar{\nu}$ experiments as well as the corresponding protons on target and energy-integrated neutrino flux is summarized in Table I. The various criteria used to define the sample of isolated gammas (any e^+e^- pair without visible source) were applied rigorously after the gammas were measured. However, these criteria were often applied, in a more approximate form, at the scanning stage. Thus we can depend on an unbiased and complete sample only within the following cuts: (1) $E_\gamma > 0.2$ GeV; (2) $\theta_\gamma < 30^\circ$, where θ_γ is the angle between the gamma and neutrino direction; and (3) fiducial volume of 6.3 m^3. This fiducial-volume cut corresponds to the total useful volume and was necessary to ensure that there was no scanning bias in the sample of gammas analyzed and that invisible neutrino interactions were not possible sources of (otherwise) isolated gamma conversions. The fiducial cut is the same as that employed in Ref. 1b. Note, however, that the sample displayed in Fig. 2 of that reference contains also additional gamma events *outside* of the 6.3-m^3 volume which were *not* used in their analysis, and which are likewise excluded here. The resulting distributions are shown in Figs. 1(a) and 1(b).

In order to unravel the source of these showers we consider the following known processes which could, in principle, contribute to a distribution of apparently isolated γ's: (1) neutral-current π^0 production off nucleons (dominated by resonance production[7]), (2) neutron-induced π^0 production, (3) coherent ν ($\bar{\nu}$-) induced π^0 production, where one of the two γ's from the subsequent π^0 decay is lost. In addition there are sources of genuine single showers: (4) coherent 1γ production, (5) $\bar{\nu}_e + N \rightarrow e^{(\pm)} + N$, (6) $\nu_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$, where, in (5) and (6), the outgoing e (e^+) is confused with an e^+e^- pair. The low[6] confusion probability between

TABLE I. Sample considered for this analysis.

	Pictures	Protons	Flux/cm^2
ν	525 000	1.35×10^{18}	0.7×10^{12}
$\bar{\nu}$	1 400 000	5.0×10^{18}	1.1×10^{12}
Ratio $\nu/\bar{\nu}$	0.38	0.27	0.64

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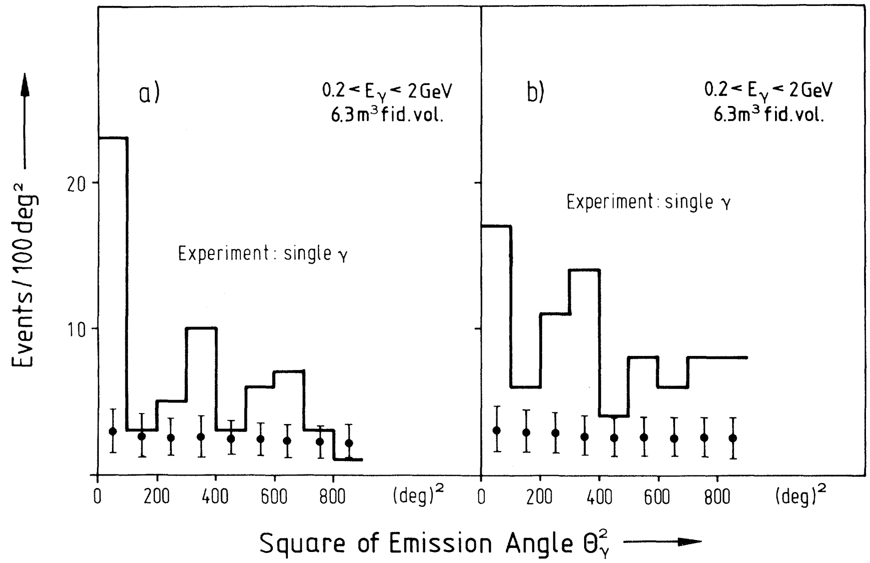

FIG. 1. Angular distribution of single-γ events within the fiducial volume of 6.3 m^3, for (a) neutrinos and (b) antineutrinos, together with the theoretical expectation of single γ's originating from resonant and neutron-induced π^0 production. The error bars indicate the amount of uncertainty both of the experimental cross section and of the single γ efficiency.

electron and e^+e^- pairs in combination with the 2-GeV upper energy cut eliminates (5), while the confusion probability in combination with the low cross section eliminates (6). This leaves sources (1)–(4). Coherent single-photon production has a cross section[8] $\lesssim 1\%$ of coherent π^0 production but may compete at the 5% level when gamma detection efficiences are considered. Here we will neglect it. Sources (1) and (2) have been firmly experimentally established, whereas the present analysis is one of the first to confirm the existence of source (3).

Since this data sample does not contain fully reconstructed π^0's, we have used either measured distributions or theoretical models as input to a Monte Carlo simulation which determined the fraction of π^0's which would be interpreted as single isolated showers. The decision as to whether an event would be interpreted as an isolated gamma or 2γ ($=\pi^0$) event was based on the results of the Gargamelle collaboration and in particular of Blietschau[6] who determined that the gamma detection efficiency fell rapidly for $E_\gamma \lesssim 35$ MeV (reflecting the critical energy of CF_3Br).

With use of the model of Rein and Sehgal,[7] the contribution of resonant π^0 production to the isolated gamma sample in a given $(E_\gamma, \theta_\gamma^2)$ region has been estimated. The absolute event numbers are based[9] on $\sigma_{res}(\nu n \rightarrow \nu n \pi^0) = (8.6 \pm 3.0)\times 10^{-40}$ cm^2/n and $\sigma_{res}(\bar{\nu} n \rightarrow \bar{\nu} n \pi^0) = (5.3 \pm 1.7)\times 10^{-40}$ cm^2/n. The neutron-induced background was estimated with values from the Gargamelle-PS Freon background measurements to $1\pi^0$ production[10] and scaling to the number of protons and shielding conditions corresponding to the isolated gamma sample. It was determined that the ratio of neutron-induced to neutral-current resonance-induced π^0's was $\sim 30\%$ for the ν and $\sim 35\%$ for the $\bar{\nu}$ samples.

Both the resonantly produced and neutron-induced π^0's are subject to nuclear corrections. These consist of nuclear absorption and charge-exchange reactions. The net effect is that fewer π^0's are observed than are produced. The size of this reduction factor has been determined with use of the nuclear correction matrices of Kluttig, Morfín, and Van Doninck, of Kluttig, and of Pohl[11] which imply that $\sim 40\%$ of the produced π^0's do not emerge from the nucleus. The predicted contribution of resonant π^0 production and neutron-induced π^0's, including nuclear corrections, is also displayed in Fig. 1. The 60% uncertainty in the predictions come from the errors in the total cross section ($\sim 30\%$) and the error in the theoretically estimated acceptance ($\sim 50\%$) which includes the uncertainty in the maximum energy an e^+e^- pair can have and still remain undetected.

After subtraction of the resonantly produced and neutron-induced π^0's, corrected for nuclear effects, the remaining sample is shown in Fig. 2. The excess γ's, those isolated gammas not explained by

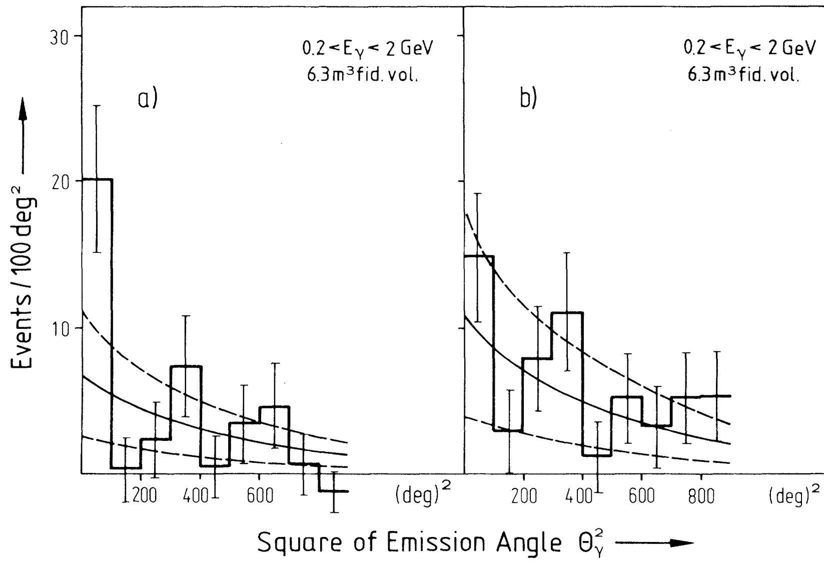

FIG. 2. Angular distribution of excess single-γ events over and above resonant and neutron-induced π^0 production, for both (a) neutrinos and (b) antineutrinos, compared with the theoretical prediction of single γ's from coherent π^0 production. The error band corresponds to one standard deviation.

sources (1) and (2), are presumably from coherent π^0 production and possibly from other sources not yet considered. In order to ascertain if there is any evidence for non-neutrino-induced isolated γ events in the very forward direction ($< 10^\circ$) of this sample, as suggested by Ref. 5, we first determine the coherent π^0 production cross section by assuming that *all* of the excess γ's with $\theta > 10^\circ$ are due to this coherent process. By use of the model of Rein and Sehgal[12] to predict the fraction of coherently produced π^0's contributing isolated gammas to this θ_γ range, it was found that the observed number of excess gammas with $(10°)^2 < \theta^2 < (30°)^2$ corresponds to a *total* cross section

$$\sigma_{\rm coh}^{\bar\nu} = (45 \pm 24) \times 10^{-40}\ {\rm cm}^2/{\rm nucleus}\ ,$$

$$\sigma_{\rm coh}^{\nu} = (31 \pm 20) \times 10^{-40}\ {\rm cm}^2/{\rm nucleus}\ ,$$

where the errors include the statistical error of the sample and the 50% error on the predicted acceptance. The two cross sections can be considered to be equal within errors. Since this equality is also expected theoretically it is reasonable to form the combined result to give a total cross section of

$$\sigma_{\rm coh}^{\nu+\bar\nu} = (40 \pm 21) \times 10^{-40}\ {\rm cm}^2/{\rm nucleus}\ .$$

These results are consistent with the recently measured[2] value from the Aachen-Padua group $\sigma_{\rm coh}^{\rm tot} = (27 \pm 7) \times 10^{-40}$ cm^2/Al nucleus. With use of our above experimentally determined value of $\sigma_{\rm coh}^{\rm tot} = (40 \pm 21) \times 10^{-40}$ cm^2/nucleus and the Rein-Sehgal model to predict the angular distribution, Fig. 2 also shows the expected contribution of coherent π^0 production compared to the observed excess. For $\theta_\gamma^2 < (10°)^2$ there is no remaining excess of isolated gamma production in the $\bar\nu$ case while there is a 2 standard deviation excess in the ν sample.

In conclusion, this analysis of isolated electromagnetic showers from the Gargamelle Freon experiment demonstrates that there is an excess number of events above that which is expected from resonantly produced or neutron-induced π^0's. If this excess is ascribed to the process of coherent π^0 production off a nucleus, there is reasonable agreement between the coherent π^0 cross section thus determined and recent observations of the Aachen-Padua experiment, as well as theoretical expectations of Ref. 12.

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