COHERENT PRODUCTION OF PHOTONS BY NEUTRINOS

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Received 26 May 1981

The reaction $\nu + \mathrm{N} \to \nu + \mathrm{N} + \gamma$, involving the coherent emission of a photon in a neutrino–nucleus collision, can produce "single shower" events that simulate the reaction $\nu + \mathrm{e} \to \nu + \mathrm{e}$. The ratio of coherent photons to electrons (for an ^{27}Al target) is estimated to be 40% at $E_\nu = 2$ GeV and 10% at $E_\nu = 20$ GeV. We examine the extent to which the "excess" of showers seen in the Aachen–Padova experiment could be understood by this mechanism.

In the study of neutrino interactions with matter, one must expect to encounter, with a frequency 10^{-2}–10^{-3}, final states containing a direct (hard) photon in addition to the usual outgoing lepton and hadron system. Among such channels, there is one that possesses an exceptionally distinctive signature. This is the reaction

$$\nu + \mathrm{N} \to \nu + \mathrm{N} + \gamma\,, \tag{1}$$

in which a photon is emitted in a coherent interaction of the neutrino with the target nucleus N, the nucleus recoiling without break-up. Such events will manifest themselves as a single-photon shower within a narrow forward cone, with no other visible particle. This is precisely the signature that also characterises the process

$$\nu + \mathrm{e} \to \nu + \mathrm{e} \tag{2}$$

in any experiment that fails to distinguish between showers of electron or photon origin. The reaction (1) thus becomes relevant as a possible background to measurements of neutrino–electron scattering.

The question of a background of this nature has assumed urgency because of an indication [1] that the data obtained in the Aachen–Padova experiment [2] contain more single-shower events close to the forward direction than expected from the process (2), as calculated in the standard theory. This has prompted the speculation that htis experiment may have recorded the electromagnetic decay [1] or interaction [3] of a new type of neutral particle (the axion?) that accompanies the neutral beam [4]. The purpose of this letter is to examine carefully the magnitude and distribution of the coherent photon process (1) to see to what extent this could explain the observations in ref. [1]. Our considerations have a bearing also on other experiments [5] aimed at a measurement of the neutrino–electron cross section.

The process we wish to analyse is depicted in fig. 1. The requirement of coherence implies that the amplitude is proportional to the nuclear form factor $F_\mathrm{N}(t)$ and so is confined to values $|t| \lesssim R^{-2}$, R being the nuclear radius. This implies, in particular, that the kinetic energy of the nuclear recoil is negligible, so that the energy of the incoming neutrino is shared between the outgoing neutrino and the photon:

$$E = E' + E_\gamma\,. \tag{3}$$

In addition the 3-momenta are constrained by the relation $|\boldsymbol{p} - \boldsymbol{p}' - \boldsymbol{k}| \lesssim R^{-1}$, which has the effect of collimating the angle of the outgoing photon relative to the incident neutrino direction:

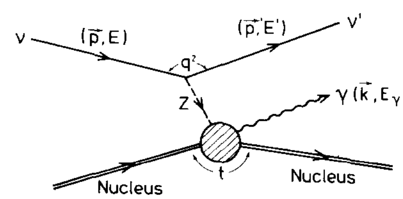

Fig. 1. Diagram and kinematical labels for $\nu\mathrm{N} \to \nu\mathrm{N}\gamma$.

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$$\theta_\gamma \lesssim (E_\gamma R)^{-1} . \tag{4}$$

One anticipates that a detailed dynamical calculation will contain these kinematical features.

The dynamics of the process (1) is governed by the matrix element $\langle N|J_\mu^{nc}J_\nu^{em}|N\rangle$ describing the transition $Z^* + N \to \gamma + N$ (Z^* being the virtual weak neutral quantum) with J_μ^{nc} and J_ν^{em} denoting the weak neutral current and electromagnetic current, respectively. The neutral current J_μ^{nc} has both vector (V) and axial vector (A) components, and we calculate the two contributions separately. In principle, a VA interference term could also be present; its effect may be eliminated by considering the *sum* of ν and $\bar{\nu}$ cross sections.

The vector matrix element $\langle N|V_\mu^{nc}J_\nu^{em}|N\rangle$ may be related to the Compton scattering matrix element $\langle N|J_\mu^{em}J_\nu^{em}|N\rangle$ making use of the quark and vector-meson-dominance hypotheses. The differential cross section in the variables $x = Q^2/2ME_\gamma$, $y = E_\gamma/E$ and t is [‡1]

$$\left(\frac{d\sigma}{dx\,dy\,dt}\right)_{\text{vector}} = \xi^2(G^2M^2E^2/4\pi^3\alpha)xy^2(E/q^*) \times\left(1+(1-y)^2+\frac{Q^2}{2E^2}\right)\left(1+\frac{Q^2}{m_\rho^2}\right)^{-2}\frac{d\sigma}{dt}(\gamma N\to\gamma N) , \tag{5}$$

where $\alpha = 1/137$ and $q^* = (E_\gamma^2 + Q^2)^{1/2}$. The parameter ξ depends on the structure of the neutral current, and may be written as

$$\xi = \frac{\sum\limits_{V=\rho,\omega,\phi} \langle\gamma|V\rangle\langle Z|V\rangle\sigma(V)}{\sum\limits_{V=\rho,\omega,\phi} |\langle\gamma|V\rangle|^2\sigma(V)} , \tag{6}$$

where $\langle\gamma|V\rangle$ and $\langle Z|V\rangle$ denote the couplings of the vector meson V to the photon and to the Z-boson, respectively, and $\sigma(V)$ denotes the total vector-meson nucleon cross section. (Our normalization is such that $\langle\gamma|\rho\rangle = 1/\sqrt{2}$, $\langle Z|\rho\rangle = (1-2x)/\sqrt{2}$, x being the electroweak mixing parameter $\sin^2\theta_W$). Using the quark model relations

$$\langle\gamma|\rho\rangle : \langle\gamma|\omega\rangle : \langle\gamma|\phi\rangle = 3 : 1 : \sqrt{2} ,$$

$$\langle Z|\rho\rangle : \langle Z|\omega\rangle : \langle Z|\phi\rangle = (1-2x) : (-\tfrac{2}{3}x) : (-\tfrac{1}{2}+\tfrac{2}{3}x) ,$$

$$\sigma(\rho) : \sigma(\omega) : \sigma(\phi) = 1 : 1 : 0.5 , \tag{7}$$

we obtain

$$\xi^2 = (\tfrac{21}{22} - 2x)^2 \tag{8}$$

which is 0.25 for $x = 0.22$–0.23. Refinements such as SU(3)-breaking effects or inclusion of the ψ contribution change this value by less than 10%.

To evaluate (5), we need the Compton cross section on a nucleus N. This is known to be well described by [‡2]

$$d\sigma(\gamma N\to\gamma N)/dt = A^2\, d\sigma(\gamma\mathcal{N}\to\gamma\mathcal{N})/dt|_{t=0}|F_N(t)|^2 , \tag{9}$$

A being the mass number, and $[d\sigma(\gamma\mathcal{N}\to\gamma\mathcal{N})/dt]_{t=0}$ being the forward Compton cross section on an average nucleon $[\mathcal{N} = (p+n)/2]$. The latter may be expressed in terms of the total photon–nucleon cross section

$$d\sigma(\gamma\mathcal{N}\to\gamma\mathcal{N})/dt|_{t=0} = \{[\sigma_{tot}(\gamma\mathcal{N})]^2/16\pi\}(1+r^2) , \tag{10}$$

r being the ratio of real to imaginary parts of the forward scattering amplitude on deuterium. These quantities have been accurately measured and parametrized [9]. As a refinement, one might envisage that the vector contribution to $\nu N \to \nu N\gamma$, because of its proportionality to $\gamma^*N\to\gamma N$ contains also a contribution from the longitudinal part of the virtual photon. We have attempted to take account of this in an approximate way by using information from the analogous process $\gamma^*\mathcal{N}\to\rho^0\,\mathcal{N}$ [10]; This was done by multiplying the expression (5) by a factor

$$(1+\epsilon\sigma_L/\sigma_T) \tag{11}$$

with

$$\epsilon = (1-y-xyM/2E)/(1-y+y^2/2+xyM/2E) ,$$

$$\sigma_L/\sigma_T = 0.6\,Q^2/m_\rho^2 . \tag{12}$$

We turn now to the axial vector contribution to

‡1 This formula, at high energies, is equivalent to the one given by Choban and Shekhter [6]. The Z–ω and Z–ϕ couplings given there are not correct. Effects of nuclear coherence were not discussed in this paper.

‡2 A correction for shadowing may be needed at high energies. For a discussion, see the reviews in ref. [8].

$\nu + \mathrm{N} \to \nu + \mathrm{N} + \gamma$. To begin with, we note that in the "forward lepton configuration" ($Q^2 = 0$) the cross section of this process is determined entirely by the divergence $\partial_\mu A_\mu^{\mathrm{nc}}$ to which one may apply the PCAC (partial conservation of axial current) hypothesis. One obtains ‡3

$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}\Omega}\right|_{Q^2=0} = \frac{G^2ME}{\pi}\,\frac{f_\pi^2}{2\pi}(1-y)\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\,(\pi^0\mathrm{N}\to\gamma\mathrm{N})|_{E_\pi=Ey} \tag{13}$$

where $\mathrm{d}\sigma(\pi^0\mathrm{N}\to\gamma\mathrm{N})/\mathrm{d}\Omega$ is the differential cross section of $\pi^0\mathrm{N}\to\gamma\mathrm{N}$ in the rest frame of the nucleus. the energy of the pion being $E_\pi = Ey$, and its direction (parallel to the vector $\boldsymbol{q}$) defining the z-axis ‡4. Eq. (13) in its integral form (that is, integrating over $\mathrm{d}\Omega = \mathrm{d}\phi\mathrm{d}\cos\phi$) is just the Adler theorem for forward neutrino scattering [11]. (The differential form is valid in an explicit model that we refer to later.) Using detailed balance, we have

$$\mathrm{d}\sigma(\pi^0\mathrm{N}\to\gamma\mathrm{N})/\mathrm{d}\Omega = 4\mathrm{d}\sigma(\gamma\mathrm{N}\to\pi^0\mathrm{N})/\mathrm{d}\Omega\,. \tag{14}$$

It follows that the axial cross section at $Q^2 = 0$ is expressible in terms of the experimentally known process of coherent photoproduction of a π^0 on a nucleus. This reaction has been studied for energies $E_\gamma = 1-2$ GeV at DESY [12] and for energies up to 7 GeV at Cornell [13]. Empirically it is known to follow the approximate formula, proposed by Morpurgo [14],

$$\mathrm{d}\sigma(\gamma\mathrm{N}\to\pi^0\mathrm{N})/\mathrm{d}\Omega = A^2C\eta\,\sin^2\theta|F_\mathrm{N}(\theta)|^2\,. \tag{15}$$

Here C is an energy dependent coefficient, and η is a factor describing the effects of π^0 reabsorption in the nucleus ‡5. From the data in refs. [14] and [15], we find that for medium nuclei, $C(E_\gamma = 1.5\ \mathrm{GeV}) \approx 0.75$ mb, and that the energy variation for $E_\gamma > 1.5$ GeV is approximately E_γ^2. For lower energies, we assumed the dependence E_γ^4: this is the characteristic dependence of the process $\gamma\mathrm{N}\to\pi^0\mathrm{N}$ if mediated by an ω-meson [17], which, presumably, provides nuclear coherence by coupling to the baryonic charge. The absorption factor η was estimated by Morpurgo [16] to be $\approx 1/4$ for $E_\gamma \gtrsim 1$.

Having fixed the scale of the longitudinal axial contribution at $Q^2 = 0$, we determine the full longitudinal cross section by assuming a Q^2-dependence $(1 + Q^2/m_\mathrm{A}^2)^{-2}$ where m_A is a characteristic axial-vector meson mass $m_\mathrm{A} \approx 1$ GeV ‡6. Away from $Q^2 = 0$, however, one must expect also the appearance of a transverse axial contribution proportional to Q^2. To estimate this, we have examined an explicit model for $\nu + \mathrm{N}\to\nu + \mathrm{N} + \gamma$, in which the axial part of the transition $\mathrm{Z}^* + \mathrm{N}\to\gamma + \mathrm{N}$ is effected by an ω-meson field coupling to the baryon number current. This calculation is exactly analogous to a calculation by Rosenberg [17] that investigated the same reaction in the nuclear *Coulomb* field. The essential feature that we abstract is the angular distribution

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}\Omega_\mathrm{lab}}\right)_\mathrm{axial} \propto |F_\mathrm{N}(t)|^2(1-\cos\theta_\mathrm{lab}\cos\theta_{\nu'\gamma})\,. \tag{16}$$

Here $\mathrm{d}\Omega_\mathrm{lab} = \mathrm{d}\phi_\mathrm{lab}\mathrm{d}\cos\theta_\mathrm{lab}$ denotes the direction of the photon in a frame in which the initial neutrino is along the z-axis and the $\nu\nu'$ plane is the x–z plane ($\theta_{\nu'\gamma}$ is the angle between the final neutrino and the photon). In the forward configuration $Q^2 = 0$, the distinction between $\mathrm{d}\Omega_\mathrm{lab}$ and $\mathrm{d}\Omega$ disappears, and

$$(1-\cos\theta_\mathrm{lab}\cos\theta_{\nu'\gamma}) \xrightarrow[Q^2=0]{} (1-\cos^2\theta) = \sin^2\theta\,. \tag{17}$$

so that we recover the PCAC result given in eqs. (13) and (15). Away from $Q^2 = 0$, eq. (16) yields a new (transverse) piece. The scale of this new contribution is set by the PCAC result, with one exception: while the longitudinal cross section is subject to the shadowing correction ($\eta \approx 1/4$), no such shadowing is assumed for the transverse part. (For a discussion relevant to this point, see ref. [18].)

Fig. 2 shows the various parts of the coherent photon cross section calculated by the above procedure for an ^{27}Al target. The charge form factor used was that given in ref. [19]. (Similar results are obtained with a gaussian form factor with an rms radius 3.0 fm.) In obtaining these results, due heed was paid to kinematical constraints, particularly the "t_min condition"

‡3 We take the axial current to be $(\bar{\mathrm{u}}\gamma_\alpha\gamma_5\mathrm{u} - \bar{\mathrm{d}}\gamma_\alpha\gamma_5\mathrm{d})/2$, neglecting the heavier quark components. $f_\pi \approx 0.96\,m_\pi$ is the pion decay constant.

‡4 In writing (12), we neglect the π-mass and treat the nucleus as infinitely heavy. In particular, setting $m_\pi = 0$ ensures that the threshold for $\pi^0\mathrm{N}$ is the same as for $\gamma\mathrm{N}$.

‡5 There is an additional contribution to eq. (15) from the Primakoff effect and its interference with the coherent nuclear amplitude. This, however, is negligibly small in the present context.

‡6 For a discussion of the uncertainties involved in this extrapolation, see ref. [16].

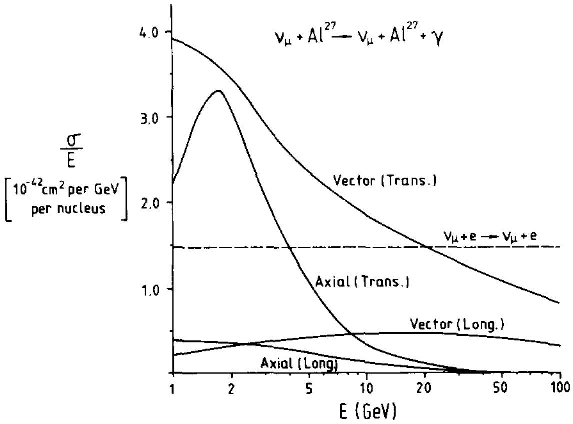

Fig. 2. Cross section for $\nu + {}^{27}Al \to \nu + {}^{27}Al + \gamma$ as a function of energy.

$$|t| > (q^* - Ey)^2 , \quad q^* = Ey(1 + 2Mx/Ey)^{1/2} . \quad (18)$$

We note that at high energies the dominant part is the transverse vector contribution. This is also the part that we believe is most reliably computed. At low energies $E = 1$–2 GeV, there is a significant transverse axial contribution as well ‡7. For comparison, we have also indicated in fig. 2 the cross section for $\nu_\mu + e \to \nu_\mu + e$ (taking $\sin^2\theta_W = 0.25$). The ratio of coherent photons to electron scatters is seen to be ‡8

$$(\gamma/e)_{^{27}Al} = 0.40 \quad \text{at } E = 2 \text{ GeV} ,$$

$$= 0.10 \quad \text{at } E = 20 \text{ GeV} . \quad (19)$$

A separation of the coherent photon background from electrons can, in principle, be achieved on the basis of differences in their angle and energy distributions. The hallmark of neutrino–electron scattering is the constraint $E_e\theta_e^2 < 2m_e = 1$ MeV, while that of coherent photons is $E_\gamma\theta_\gamma \lesssim R^{-1}$. Our investigations show that while the $E\theta^2$ distribution for photons is indeed broader than that of electrons at low energies, this distinction disappears for neutrino energies $E \gg (2m_eR^2)^{-1}$ (≈3 GeV for Al).

In fig. 3 is shown the angular distribution of single

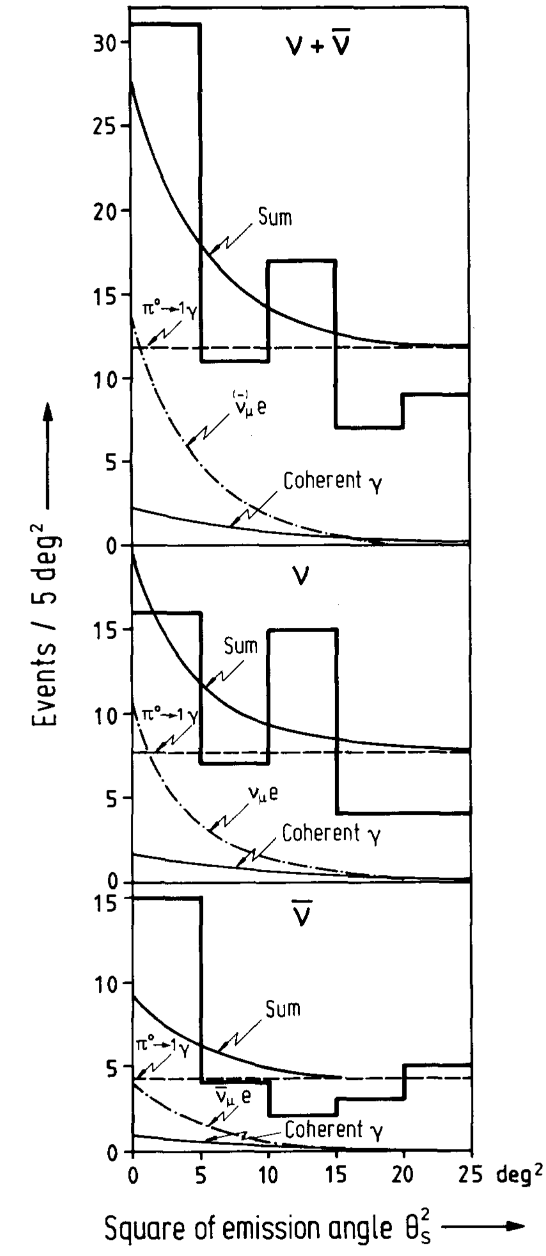

Fig. 3. Single-shower data of Aachen–Padova experiment [1,2] ($0.2 < E_{shower} < 2.0$ GeV) compared with expectations from different sources.

‡7 The A-dependence of the transverse V and A cross sections is roughly $A^{2/3}$.

‡8 Note that the νe cross section has to be scaled up by a factor $Z = 13$ for comparison with the nuclear γ cross section.

showers measured in the Aachen–Padova experiment. Also indicated are the background from $\pi^0 \to \gamma\,(+\gamma)$, the theoretically expected signal from $\overset{(-)}{\nu}_\mu e \to \overset{(-)}{\nu}_\mu e$, and the coherent-photon distribution as calculated in this paper ‡9. It would appear that the inclusion of coherent photons produces only a minor enhancement of the total single-shower rate. Furthermore, the angular distribution of this coherent component is not capable of explaining an excess that is concentrated at very forward angles ($\theta^2 < 5\ \mathrm{deg}^2$). To the extent that the data in fig. 3 hint at such an excess (especially in the $\bar{\nu}$ case) it seems unlikely that a coherent-photon mechanism could be invoked as an explanation. (The problem becomes more acute if one recognises that the data in refs. [1,2] actually suggest a surplus confined to angles as small as $\theta < 1°$.)

To conclude, we have shown that coherently produced photons can be an important contaminant among events that have the prima facie characteristics of neutrino–electron scattering. A separation can be achieved by means of the cut $E_e\theta_e^2 < 2m_e$, but this becomes increasingly ineffective at high neutrino energies. With reference to the Aachen–Padova observations, while coherent photons are predicted to be present (to the extent of 30–40% of the electron signal), an excess of showers localised to very forward directions ($\theta \lesssim 2°$) cannot be explained by the coherent-photon mechanism alone.

Details of this work will be published elsewhere.

We are grateful to Helmut Faissner for much inspiration and encouragement, and to H. de Witt and H. Reithler for indispensable help in the data analysis. We have benefited from discussions with S. Barshay R. Rodenberg, I. Bigi and P. Zerwas.

‡9 The coherent prediction shown for the ν and $\bar{\nu}$ cases could change somewhat if a VA interference term is present; however, the shape of the distributions is unlikely to be affected.

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