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Neutrino-induced pion production and proton decay

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A quantitative account of the reaction $\bar{\nu}_e + p \rightarrow e^+ + n + \pi^0$ is given and its implications with regard to proton-decay experiments are discussed.

Currently running or planned proton-decay experiments[1] looking in particular for the decay mode

$$p \rightarrow e^+ + \pi^0 \tag{1}$$

clearly envision π^0 production from cosmic-ray antineutrinos in a charged-current reaction

$$\bar{\nu}_e + p \rightarrow e^+ + n + \pi^0 \tag{2}$$

as a possible background reaction. Although the effect of this process is grossly known, more detailed and quantitative predictions could be useful. Particularly those neutrino-initiated events with a large opening angle ($\theta_{\pi e} > 120°$) and invariant mass close to the nucleon's mass ($M_{\pi e} \simeq M_N$) are invariably indistinguishable from the true proton-decay events of reaction (1), thus calling for a reliable quantitative estimate of their contribution.

Reaction (2)—especially at low energies—is largely dominated by resonance production, and among resonances the $\Delta(1234)$ plays the dominant role.[2] There is no coherent contribution to reaction (2) and any nonresonant (diffractive) component is estimated to be small. Single pions emitted from the Δ resonance are distributed nearly isotropically in the Δ's rest frame,[2,3] as witnessed by the measured density-matrix elements of $\Delta \rightarrow \pi N$. The same decay characteristics are also assumed for the higher resonances excited (marginally) by the incoming $\bar{\nu}_e$. Thus, employing a model for neutrino excitation of resonances,[4] various kinematical quantities of interest can be calculated. We have considered in this way the opening angle between the outgoing lepton and pion in the laboratory system and plotted the corresponding $\theta_{\pi e}$ distribution in Fig. 1. This figure displays the result of a Monte Carlo calculation incorporating the following conditions: The basic input is our resonance model,[4] which has proved to describe quite successfully a wealth of data in various πN channels and energy domains. The Fermi motion of the nucleons was included with a Fermi momentum of 250 MeV. The invariant mass of the outgoing $e\pi^0$ system was centered around the nucleon's mass M_N with a spread of $\Delta M = 200$ MeV. The calculation was performed using the known flux of atmospheric neutrinos at ground level,[5] assuming it to be the same at the site of the underground experiments. This flux contains neutrinos and antineutrinos of both electron and muon type in nearly equal proportion, the $\bar{\nu}_e$ component[6] amounting to roughly 20% of the total and exhibiting with confident presumption the same energy dependence as the overall flux.[5–7]

The total flux-averaged cross section of reaction (2), corrected for Fermi motion *and* restricted by $(M_N - \Delta M) \leq M_{e\pi} \leq (M_N + \Delta M)$, with $\Delta M = 200$ MeV, turns out to be rather small:

$$\sigma_{\rm tot}(\bar{\nu}_e p \rightarrow e^+ n \pi^0) = 2.9 \times 10^{-42}\ {\rm cm}^2 \ . \tag{3}$$

This value is considerably smaller than the π^0 production cross section measured at the CERN Proton Synchrotron or BNL accelerator (see Ref. 4). The reason is that the atmospheric flux (although similar in shape above $E_\nu \approx 1$ GeV) is much softer than the corresponding accelerator neutrino flux containing $\sim 90\%$ of the intensity within 0 to 1 GeV. For neutrino energies below 1 GeV, however, resonance excitation decreases rapidly with decreasing energy, thus suppressing the pion-production cross section by almost 2 orders of magnitude; an additional factor-4 reduction is due to the cuts on $M_{e\pi}$. Further reduction results from angular cuts. As may be read off Fig. 1, only $\sim 20\%$ of the cross section (3) is found for opening angles $\theta_{e\pi} > 120°$, and not

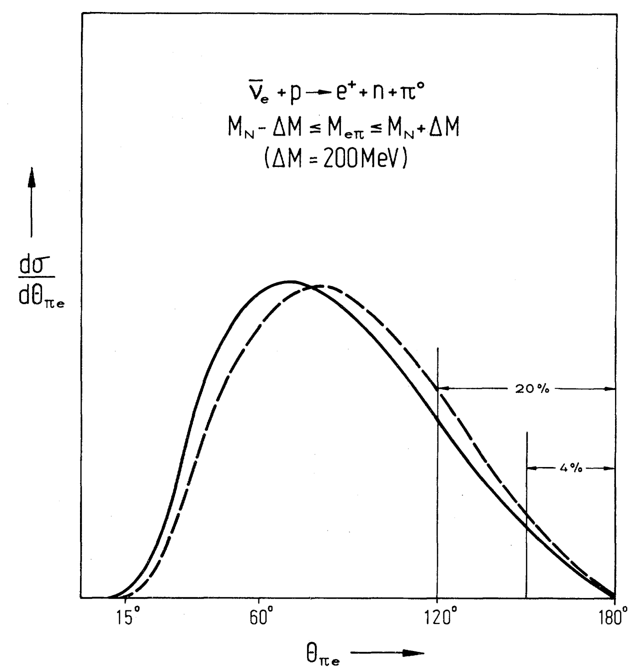

FIG. 1. Distribution of the laboratory πe opening angle for π^0 production induced by the atmospheric $\bar{\nu}_e$ flux, obeying the mass restriction $M_N - 200\ {\rm MeV}/c^2 \leq M_{e\pi} \leq M_N + 200\ {\rm MeV}/c^2$. The corresponding distribution for ν_e-induced π^0 production is also shown for completeness (dashed curve).

more than 4% of the cross section is contained within 30° around the collinear configuration. In the forward direction, the angular distribution drops off rapidly, leaving less than 0.1% of the cross section within $\theta_{\pi e} < 15°$. (Relaxing the mass cuts, this fraction could increase up to $\sim 4\%$.) This lends strong support to the view taken by the NUSEX (nucleon-stability experiment) collaboration[8] that it is highly improbable to interpret their nucleon-decay candidate event as originating from neutrino-induced single-pion production.

Given the theoretical cross-section information contained in Fig. 1 and the total $\bar{\nu}_e$ flux,

$$\Phi_{\bar{\nu}_e} = \int_0^{4\pi} d\Omega \int_0^{\infty} dE\, \phi_{\bar{\nu}_e}(E,\Omega) \ , \tag{4}$$

we may proceed to estimate the number of background events of reaction (2) expected in various experiments. The integral intensity of all atmospheric neutrinos with energies above 1 GeV is quoted[5] to be 3.0×10^{-2} $\mathrm{cm^{-2}s^{-1}sr^{-1}}$ (horizontal direction) and 2.0×10^{-2} $\mathrm{cm^{-2}s^{-1}sr^{-1}}$ (vertical direction) at a geomagnetic latitude of 50°, around which most of the proton-decay experiments are located. Since approximately 90% of this intensity is confined to $E < 1$ GeV we obtain a total $\bar{\nu}_e$ (ν_e) flux of about

$$\Phi_{\bar{\nu}_e} \approx \Phi_{\nu_e} = 4\pi \times 2.5\times 10^{-2} \times 10 \times 0.2\ \mathrm{cm^{-2}s^{-1}} = 0.6\ \mathrm{cm^{-2}s^{-1}} \ . \tag{5}$$

From this, the expected number of neutrino-induced $e\pi^0$ events with the topology of a proton-decay event ($M_{e\pi}$ within $M_N \pm 200$ MeV, $\theta_{e\pi} > 120°$) per kiloton (kt) of detector ($\cong 3\times 10^{32}$ protons or neutrons) and year is easily found:

$$N_{\mathrm{BG}}(e\pi^0) = 3.5\times 10^{-3} \ . \tag{6}$$

This includes a small contribution from the charge conjugate of reaction (2) with the recoiling proton too slow to be detected. Inclusion of nuclear corrections could only reduce this value, but this effect is probably small, not exceeding the other uncertainties inherent in the flux and cross section used.

A similar consideration applies to the decay of the neutron

$$n \to e^{\pm}\pi^{\mp} \ , \tag{7}$$

which is experimentally subject to confusion with the following neutrino-induced background reactions:

$$\nu_e + n \to e^- + n + \pi^+ \ , \tag{8a}$$

$$\bar{\nu}_e + n \to e^+ + n + \pi^- \ . \tag{8b}$$

(The corresponding reactions on a proton can only marginally contribute to a final state of signature $e^{\pm}\pi^{\mp}$.) The cross sections for reactions (8a) and (8b) were calculated along the same lines and under the same restrictions on $M_{e\pi}$ as that of Eq. (3) with the following results:

$$\sigma(\nu_e n \to e^- n\pi^+) = 7.3\times 10^{-42}\ \mathrm{cm^2} \ , \tag{9a}$$

$$\sigma(\bar{\nu}_e n \to e^+ n\pi^-) = 9.1\times 10^{-42}\ \mathrm{cm^2} \ . \tag{9b}$$

Adding up and using the atmospheric neutrino fluxes of Eq. (5), we obtain a background-event number of the right topology of

$$N_{\mathrm{BG}}(e^{\pm}\pi^{\mp}) = 1.8\times 10^{-2}/\mathrm{kt\,yr} \ ,$$

which is about a factor of 5 larger than $N_{\mathrm{BG}}(e\pi^0)$ from Eq. (6).

In conclusion, we quote the implication of our results on the natural limits of nucleon-lifetime measurements in present detectors. According to Eq. (6) a 7-kt detector[9] particularly sensitive to the proton-decay signature ($e\pi^0$) would have to run for about 40 years in order to see one neutrino-induced background event of the right topology (and about 2 years if the mass and angular constraints were not applied). Thus an upper limit on the product of the proton's lifetime τ_p and its branching ratio η into ($\pi^0 e^+$) could be given:

$$\tau_p \eta \gtrsim 40\times 7\times 3\times 10^{32} \approx 8\times 10^{34}\ \mathrm{yr} \ , \tag{10}$$

beyond which any real proton decay would appear to be drowned in neutrino-induced $\pi^0 e$ background when viewed by a detector with 200-MeV mass resolution and angular resolution of 60°. This limit might be still pushed up if the angular and/or invariant-mass constaints were sharpened. But the characteristics of proton decay *within* a nucleus are probably such that further kinematical cuts would not be very meaningful.[10]

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