

Ratio of γ/π^0 production rates in neutrino-nucleus interactions in the Δ resonance mass region

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We study the dependence of neutrino-induced γ/π^0 production ($\bar{\nu}_\mu + A \rightarrow \bar{\nu}_\mu(\mu) + \gamma/\pi^0 + X$) on the target nucleus A , in the Δ resonance mass region. Our conclusion is based on experimental data for π^0 production rates at photon-nucleus interactions from the A2 Collaboration at the Mainz MAMI accelerator. We assume that Δ resonance decays are independent of the production mechanism (via photon, Z , or W boson). In neutral current (NC) interactions, the $1\pi^0 + X$ production scales as $A^{2/3}$. In contrast, photons from Δ decays typically escape the nucleus, resulting in a cross-section proportional to the atomic number A . Thus, in NC interactions, the ratio of γ production to π^0 production is proportional to $A^{1/3}$. In charged current (CC) ν_μ - ($\bar{\nu}_\mu$)-induced production of Δ^+ (Δ^0) will be proportional to the number of neutrons (protons) in the nucleus. After Δ decay, due to the charge universality in strong interactions, the suppression factor for π^0 escaping the nucleus must also follow $A^{-1/3}$, as in NC interactions. We predict the ratio of the γ/π^0 production rates in NC and CC interactions and for ν_μ and $\bar{\nu}_\mu$ beams: argon target, $\sim 3.1\%$ (NC/CC $\nu_\mu/\bar{\nu}_\mu$); water target, $\sim 1.9\%$ (NC), $\sim 2.3\%$ (CC ν_μ), and $\sim 1.7\%$ (CC $\bar{\nu}_\mu$); liquid scintillator target: $\sim 1.7\%$ (NC), $\sim 2.1\%$ (CC ν_μ), and $\sim 1.6\%$ (CC $\bar{\nu}_\mu$). The accuracy of our predictions is limited due to uncertainties in the decay rate $\Delta^{+0} \rightarrow p/n + \gamma$ and the presence of other (minor) channels of neutrino-induced γ/π^0 production in the Δ mass region. We also discuss solving the MiniBooNE anomaly by looking at the CC single-photon and single-neutral-pion production rates at the short baseline neutrino program experiments at Fermilab.

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In neutrino-nucleus interactions, the Δ resonance plays a crucial role at 4-momentum transfers close to the Δ resonance mass region. The T2K (and future HyperK [1]) neutrino beam has an energy range centered on 600 MeV. The short baseline neutrino (SBN) program at Fermi National Accelerator Laboratory (SBND, MicroBooNE, and ICARUS) [2] is located on the booster neutrino beam at Fermilab, which peaks at 700 MeV neutrino energy. DUNE [3] experiment's second oscillation maximum also lies in the resonance region. The decay products of the Δ resonance—single photons and neutral pions—constitute significant backgrounds that can lead to misinterpretation of neutrino oscillation results.

Reference [4] estimated the branching ratio of Δ to γ (from the measured amplitude of the $\gamma + p \rightarrow \Delta^+$) to be

$$\text{Br}(\Delta^{+0} \rightarrow p/n + \gamma) = (6 \pm 0.5) \cdot 10^{-3}, \quad (1)$$

while the corresponding branching ratio to π^0 is

$$\text{Br}(\Delta^{+0} \rightarrow p/n + \pi^0) \simeq 2/3. \quad (2)$$

Thus, the ratio of Δ^{+0} decaying channels to γ or to π^0 is [5]

$$R^0 \equiv \frac{\Gamma^\gamma(\Delta^{+0})}{\Gamma^{\pi^0}(\Delta^{+0})} \simeq (9 \pm 0.75) \times 10^{-3}. \quad (3)$$

The A2 Collaboration [6] at the Mainz MAMI accelerator investigates photon absorption on nucleons and nuclei. The incident photon beam has a very well-known energy, flux, and polarization in the energy range 40–1603 MeV, yielding precise measurements of the photon absorption cross sections with different final states.

According to the A2 Collaboration (Fig. 1) [7] the π^0 photoproduction on nuclei scales as $A^{2/3}$:

$$\sigma(\gamma + A \rightarrow 1\pi^0 + X) \propto A^{2/3}. \quad (4)$$

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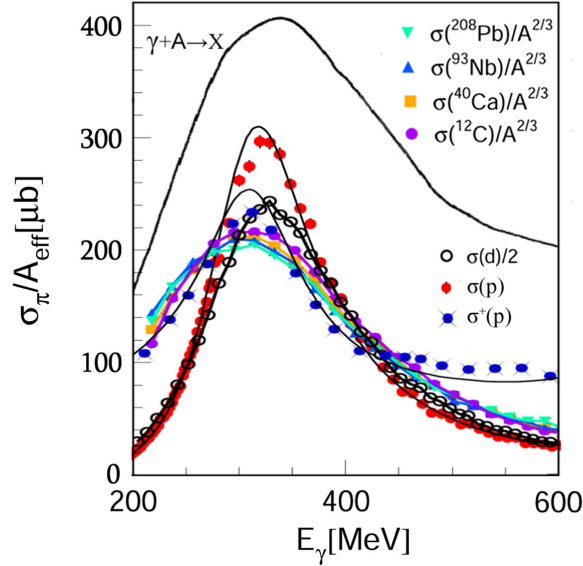


FIG. 1. All plots are taken from [7]. The effective mass number A_{eff} is 1 for the proton, 2 for the deuteron, and $A^{2/3}$ for heavier nuclei. σ^+ is the cross section of $\gamma + p \rightarrow n + \pi^+$. $\gamma + A \rightarrow X$ is (per nucleon) photoabsorption cross section on nuclei, $A_{\text{eff}} = A$.

The photon absorption cross section on the target nucleus is proportional to the atomic number of the nucleus, A (Fig. 1). This is an indication of the dominance of incoherent processes. The $A^{2/3}$ scaling of the π^0 rates (Fig. 1) indicates the suppression of neutral pions escaping the nucleus as an $A^{-1/3}$ factor.

Theoretical calculations [8] show that incoherent γ/π^0 neutrino production processes are dominating over coherent ones at the Δ resonance mass region. Thus, γ production rate must be proportional to the atomic number of the target nucleus, A . Regarding the π^0 production rate, an additional π^0 escape suppression factor must be considered. Based on the results of the A2 experiment [7], in this paper, we will assume the π^0 escape suppression factor as equal to $A^{-1/3}$. We conclude that the ratio of photon to neutral pion production via a Δ resonance in nuclei should be proportional to $A^{1/3}$.

In the nucleus, nucleons (also Δ 's) have slightly different properties than free ones [8]. In the current paper, we will neglect this and work on approximating the nucleus as a sum of free nucleons in incoherent interactions.

The Δ^{+0} resonances can be produced via neutral current (NC) and charged current (CC) interactions on the target's protons and neutrons:

$$p + Z \rightarrow \Delta^+, \quad n + Z \rightarrow \Delta^0, \quad (5)$$

$$p + W^- \rightarrow \Delta^0, \quad n + W^+ \rightarrow \Delta^+. \quad (6)$$

We define R as a ratio of the γ to π^0 production rates by the (anti)neutrino beam on different targets.

For the CC neutrino beam, we get

$$R_{\text{CC}}^{\text{target}} \equiv \frac{\sigma(\nu + \text{target} \rightarrow \mu^- + \gamma + X)}{\sigma(\nu + \text{target} \rightarrow \mu^- + \pi^0 + X)} = \frac{\sum N_i^n}{\sum N_i^p \cdot A_i^{-1/3}} R^0, \quad (7)$$

and for the CC antineutrino beam, we get

$$\bar{R}^{\text{target}} \equiv \frac{\sigma(\bar{\nu} + \text{target} \rightarrow \mu^+ + \gamma + X)}{\sigma(\bar{\nu} + \text{target} \rightarrow \mu^+ + \pi^0 + X)} = \frac{\sum N_i^p}{\sum N_i^n \cdot A_i^{-1/3}} R^0; \quad (8)$$

in the NC, the ratio of the γ/π^0 production rates is equal for neutrino and antineutrino beams:

$$R_{\text{NC}}^{\text{target}} \equiv \frac{\sigma(\nu + \text{target} \rightarrow \gamma + X)}{\sigma(\nu + \text{target} \rightarrow \pi^0 + X)} = \frac{\sum A_i}{\sum A_i^{2/3}} R^0. \quad (9)$$

Here, A_i is the atomic number of the nucleus, $A_i = N_i^p + N_i^n$, N_i^p is the number of protons in the nucleus, and N_i^n is the number of neutrons in the nucleus.

For water target (H_2O), we get

$$R_{\text{NC}}^{\text{H}_2\text{O}} = \frac{16 + 2}{16 \cdot 16^{-1/3} + 2} R^0 = 2.16 R^0 = 1.9\%, \quad (10)$$

$$R_{\text{CC}}^{\text{H}_2\text{O}} = \frac{8}{8 \cdot 16^{-1/3}} R^0 = 2.52 R^0 = 2.3\%, \quad (11)$$

$$\bar{R}_{\text{CC}}^{\text{H}_2\text{O}} = \frac{8 + 2}{8 \cdot 16^{-1/3} + 2} R^0 = 1.93 R^0 = 1.7\%. \quad (12)$$

For liquid scintillator target (methylene $\text{CH}-\text{CH}_3$, in average CH_2), we get

$$R_{\text{NC}}^{\text{CH}_2} = \frac{12 + 2}{12 \cdot 12^{-1/3} + 2} R^0 = 1.93 R^0 = 1.7\%, \quad (13)$$

$$R_{\text{CC}}^{\text{CH}_2} = \frac{6}{6 \cdot 12^{-1/3}} R^0 = 2.29 R^0 = 2.1\%, \quad (14)$$

$$\bar{R}_{\text{CC}}^{\text{CH}_2} = \frac{6 + 2}{6 \cdot 12^{-1/3} + 2} R^0 = 1.73 R^0 = 1.6\%. \quad (15)$$

For the argon target, in all cases (NC or CC interactions, for neutrino or antineutrino beams), we get

$$R^{\text{Ar}} = R_{\text{NC}}^{\text{Ar}} = R_{\text{CC}}^{\text{Ar}} = \bar{R}_{\text{CC}}^{\text{Ar}} = 40^{1/3} R^0 = 3.42 R^0 = 3.1\%. \quad (16)$$

We have used the central value of (3), $R_0 = 0.9\%$, for numerical results in (10)–(16).

The MiniBooNE experiment estimates the number of photons from the registered number of neutral pions. The photons are a background, and an underestimation of their possible number could lead to the misinterpretation of the

experimental results. The MiniBooNE experiment used the value $R_{\text{NC}}^{\text{CH}_2} = 0.9\%$ [9].

MicroBooNE claims (based on NC interactions) they rejected (94.8% CL) $\Delta \rightarrow N\gamma$ as the only source for the MiniBooNE low-energy excess events [10]. We estimate that there must be about twice ($1.7/0.9 \simeq 1.9$) as many photons in the MiniBooNE as the MiniBooNE estimation. These “additional” photons will not explain all the low-energy excess events but will substantially lower the number of unexplained electronlike events, moving the “anomaly” to just $\sim 2\sigma$ statistical fluctuations of the low-energy excess events.

Several theoretical calculations of the γ and π^0 rates at the MiniBooNE experiment exist [11]. We recommend estimating $R_{\text{NC}}^{\text{CH}_2}$ based on experimentally measured R^{Ar} . The experimentally extracted value of R^{Ar} [from (16)] at the ongoing SBN program experiments [2] will allow us to experimentally find the value R_0^{exp} .

We want to underline that although there are difficulties in measuring the single-photon rate in NC interactions (due to significant systematic errors or background [10]), the same ratio, R^{Ar} , can be easily extracted in CC interactions due to the appearance of the muon track from the same vertex. Thus, we recommend that SBN program experiments look at CC single-photon and single-neutral-pion production rates, $R_{\text{CC}}^{\text{Ar}}$ and $\bar{R}_{\text{CC}}^{\text{Ar}}$. The experimentally extracted value R_0^{exp} can be used to estimate $R_{\text{NC}}^{\text{CH}_2}$ (13) and shall answer to the long-standing low-energy events excess anomaly at MiniBooNE.

Regarding the accuracy of our estimation, we note that additional contributions exist for both γ and π^0 productions. Neutrino-induced production of neutral pions and photons

can be described as resulting from coherent and incoherent processes. The final states of these two processes (including particle content and their momentum spectra) are very different, so there is no interference between them. Coherent processes exist for both γ and π^0 production, but they are subdominant in comparison to the incoherent processes [8]. On the other hand, there are interferences between different channels of incoherent γ/π^0 neutrino production (Δ resonance, nonresonance, higher resonances, etc.). But again, as theoretical calculations show, the main contribution is from the Δ resonance. Thus, we may conclude that our results and estimations must be highly accurate.

In this note, we discussed the Δ resonance contribution to the γ to π^0 production rates ratio in neutrino-nucleus interaction. We provide semiquantitative predictions for this ratio in common detector materials such as water, liquid scintillator, and argon. A better understanding and measurement of the γ/π^0 production ratio will help constrain background models. They may provide a new avenue for investigating anomalies such as the low-energy events excess anomaly at MiniBooNE.

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DATA AVAILABILITY

No data were created or analyzed in this study.

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