MiniBooNE Anomaly and Heavy Neutrino Decay

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The anomaly in the low-energy distribution of quasielastic neutrino events reported by the MiniBooNE Collaboration is discussed. We show that the observed excess of electronlike events could originate from the production and decay of a heavy neutrino (ν_h) in the MiniBooNE detector. The ν_h with the mass around 500 MeV is created by mixing in ν_μ neutral-current interactions and decays radiatively into $\nu\gamma$ with the lifetime $\tau_{\nu_h} \lesssim 10^{-9}$ s due to a transition magnetic moment between the ν_h and a light neutrino ν. Existing experimental data are found to be consistent with a mixing strength between the ν_h and the ν_μ of $|U_{\mu h}|^2 \simeq (1-4)\times 10^{-3}$ and a ν_h transition magnetic moment of $\mu_{\rm tr} \simeq (1-6)\times 10^{-9}\mu_B$. Finally, we discuss the reason why no significant excess of low-energy events has been observed in the recent antineutrino data.

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The MiniBooNE Collaboration, which examined the liquid scintillator neutrino detector (LSND) oscillation signal at Fermilab, has observed an excess of low-energy electronlike events in charge-current quasielastic (CCQE) neutrino events over the expected standard neutrino interactions [1]. This anomaly has been recently confirmed by the finding of more excess events [2]. While the Collaboration has not yet clarified the origin of the excess, several models involving new physics were considered to explain the discrepancy [3].

In this Letter we show that the excess could be explained by the production and decay of a heavy neutrino (ν_h). Such type of neutrinos are present in many interesting extensions of the standard model, such as GUT, superstring inspired models, left-right symmetric models, and others. The massive neutrino decays were also considered to explain the LSND signal [4].

The neutrino weak flavor eigenstates ($\nu_e, \nu_\mu, \nu_\tau, \ldots$) can be different from the mass eigenstates ($\nu_1, \nu_2, \nu_3, \nu_4, \ldots$), but they are related to them, in general, through a unitary transformation. A generalized mixing:

$$\nu_l = \sum_i U_{li}\nu_i; \qquad l = e, \mu, \tau, \ldots, \qquad i = 1, 2, 3, 4, \ldots \tag{1}$$

results in neutrino oscillations when the mass differences are small, and in neutrino decays when the mass differences are large. If the ν_h exists, it could be a component of ν_μ, and, as follows from Eq. (1), it would be produced by any source of ν_μ according to the proper mixing $|U_{\mu h}|^2$ and kinematic constraints. The ν_h can be Dirac or Majorana type [5] and can decay radiatively into $\nu\gamma$, if there is a nonzero transition magnetic moment between the ν_h and a light neutrino ν_i [6].

The MiniBooNE detector is described in detail in Ref. [7]. It uses an almost pure ν_μ beam originated from the π^+ decays in flight, which are generated by 8 GeV protons from the Fermilab booster. The detector consists of a target, which is a 12.2 m diameter sphere filled with 800 t of mineral oil, surrounded by an outer veto region. The Cherenkov light rings generated by muon, electron, and converted photon tracks are used for the reconstruction of the events. The resolutions reached on the vertex position, the outgoing particle direction, and the visible energy are 20 cm, 4°, and 12%, respectively, for CCQE electrons [8]. The ν_μ beam is peaked around ~600 MeV, has a mean energy of ~800 MeV, and a high energy tail up to ~3 GeV [9].

An excess of $\Delta N = 128.8 \pm 20.4 \pm 38.3$ electronlike events has been observed in the data accumulated with 6.64×10^{20} protons on target. For the following discussion several distinctive features of the excess events are of importance [2]: (a) the excess is observed for single track events, originating either from an electron, or from a photon converted into a e^+e^- pair with a typical opening angle $\simeq m_e/E_{e^+e^-} < 1°$ (for $E_{e^+e^-} > 200$ MeV), which is too small to be resolved into two separate Cherenkov rings (here, m_e, $E_{e^+e^-}$ are the electron mass and the e^+e^- pair energy); (b) the reconstructed neutrino energy is in the range $200 < E_\nu^{\rm QE} < 475$ MeV, while there is no significant excess for the region $E_\nu^{\rm QE} > 475$ MeV. The variable $E_\nu^{\rm QE}$ is calculated under the assumption that the observed electron track originates from **a** ν_e QE interaction; (c) the visible energy $E_{\rm vis}$ is in the narrow region $200 \lesssim E_{\rm vis} \lesssim 400$ MeV for events with $E_\nu^{\rm QE} > 200$ MeV; (d) the angular distribution of the excess events with respect to the incident neutrino direction is wide and consistent with the shape expected from ν_eCC interactions. To satisfy the criteria (a)–(d), we propose that the excess events are originated from the decay of a heavy neutrino ν_h. The ν_h's are produced by mixing in ν_μ neutral-current (NC) QE interactions and deposit their energy via the visible decay mode $\nu_h \to \nu\gamma$, as shown in Fig. 1, with the subsequent conversion of the decay photon into e^+e^- pair in the MiniBooNE target. To make a quantitative estimate, we performed simplified simulations of the production and decay processes shown in Fig. 1. In these simulations we used a ν_μ energy spectrum parametrized from the reconstructed ν_μCCQE events [9]. Since in the MiniBooNE experiment ν_h's decay over an average distance of $\lesssim 5$ m from the production vertex, the sensitivity is restricted to the mass range 100–600 MeV and to ν_h lifetimes $\tau_{\nu_h} < 10^{-7}$ s.

In Figs. 2–4 the distributions of the kinematic variables $E_\nu^{\rm QE}$, $E_{\rm vis}$, and $\cos(\Theta_{\gamma\nu})$ for the $\nu_h \to \gamma\nu$ events are shown for $m_{\nu_h} = 400$ and 600 MeV and $\tau_{\nu_h} = 3 \times 10^{-8}$ and 10^{-10} s. These distributions were obtained assuming that the e^+e^- pair from the converted photon is misreconstructed as a single track from the ν_eQE reaction.

Simulations are in reasonable agreement with the experimental distributions. For instance, for the distribution shown in Fig. 2, the comparison with MiniBooNE data yields a χ^2 of 10.2 (17.2) for 8 DF corresponding to 27% ($\simeq$5%) C.L. for $m_{\nu_h} = 400(600)$ MeV and $\tau_{\nu_h} = 3 \times 10^{-8}$ s. The simulated excess events, shown in Fig. 3, are mainly distributed in the narrow region $200 \lesssim E_{\rm vis} \lesssim 400$ MeV. The fraction of events in the region $200 < E_{\rm vis} < 400$ MeV is $\sim$70%. The remaining events are distributed over the region $400 \lesssim E_{\rm vis} \lesssim 1200$ MeV, where they can be hidden by the low statistics. The simulations showed that the shape of the $E_\nu^{\rm QE}$ and $E_{\rm vis}$ distributions is sensitive to the choice of the ν_h mass and lifetime: the shorter the ν_h lifetime the broader the visible energy spectrum. The best fit results suggest that the ν_h mass is in the region $200 \lesssim m_{\nu_h} \lesssim 600$ MeV and the lifetime is $\tau_{\nu_h} < 10^{-7}$ s. The estimate of the mixing parameter $|U_{\mu h}|^2$ was performed by using the following relations. For a given flux of heavy neutrinos, $\Phi(\nu_h)$, the expected number of the decays in the MiniBooNE detector is given by $\Delta N = \int \Phi(\nu_h) P_{\rm dec} P_{\rm conv} \epsilon dE_{\nu_h} dV$, where $P_{\rm dec}$ and $P_{\rm conv}$ are the probabilities of the ν_h decay and the photon conversion in the detector, ϵ is the overall detection efficiency, and the integral is taken over the detector fiducial volume.

The flux $\Phi(\nu_h)$ was estimated from the expected number of the ν_μNC events times the mixing $|U_{\mu h}|^2$, taking into account the threshold effect due to the heavy neutrino mass. The total number of reconstructed ν_μCC events in the detector [9] was used for normalization. The probability of the heavy neutrino to decay radiatively in the fiducial volume at a distance r from the primary vertex is given by $P_{\rm dec} = [1 - \exp(\frac{-r m_{\nu_h}}{p_{\nu_h}\tau_{\nu_h}})]\frac{\Gamma(\nu_h \to \gamma\nu)}{\Gamma_{\rm tot}}$, where the last term is the branching fraction ${\rm Br}(\nu_h \to \gamma\nu) \simeq 1$ (see below). Taking into account the ratio $\nu_\mu{\rm NCQE}/\nu_\mu{\rm CCQE} \sim 0.43$, the number of ν_μCCQE events observed [1,2] and assuming that almost all $\nu_h \to \gamma\nu$ decays occur inside the fiducial volume of the detector, we estimate the $|U_{\mu h}|^2$ to be in the range

$$|U_{\mu h}|^2 \simeq (1\text{–}4) \times 10^{-3}. \qquad (2)$$

This result is mainly defined by the uncertainty on the number of excess events. Equation (2) is valid for the mass region $400 \lesssim m_{\nu_h} \lesssim 600$ MeV. The lower limit is set to 400 MeV to avoid stringent constraints on $|U_{\mu h}|^2$ for the mass region $m_{\nu_h} \lesssim 400$ MeV from experiments searching for a peak from π, $K \to \mu + \nu_h$ decays [10]. The ν_h lifetime due to a transition moment $\mu_{\rm tr}$ is given by [6]

$$\tau_{\nu\gamma}^{-1} = \frac{\alpha}{8}\left(\frac{\mu_{\rm tr}}{\mu_B}\right)^2\left(\frac{m_{\nu_h}}{m_e}\right)^2 m_{\nu_h} \qquad (3)$$

and for $\tau_{\gamma\nu} < 10^{-7}$ s results in $\mu_{\rm tr} > 10^{-10}\mu_B$. The total ν_h decay width is $\Gamma_{\rm tot} = \Gamma(\nu_h \to \nu\gamma) + \Sigma\Gamma_i$, where $\Gamma(\nu_h \to \nu\gamma)$ is the $\nu_h \to \gamma\nu$ decay rate, and $\Sigma\Gamma_i$ is the sum over decay modes whose decay rate is proportional to the square of the mixing $|U_{\mu h}|^2$. The dominant contribution to $\Sigma\Gamma_i$ comes from $\nu_h \to \nu_\mu ee$, $\nu_\mu\pi^0$, $\nu_\mu\nu\nu$, $\mu\pi$

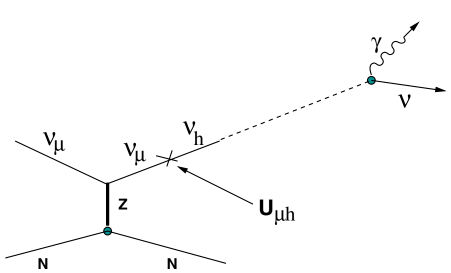

FIG. 1 (color online). Schematic illustration of the NCQE production and decay of heavy neutrino.

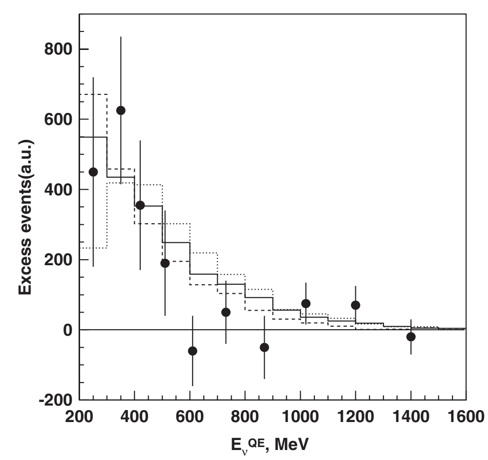

FIG. 2. Distributions of the excess events from the $\nu_h \to \gamma\nu$ decay reconstructed as ν_eCC events as a function of $E_\nu^{\rm QE}$ for $|U_{\mu h}|^2 = 1.5 \times 10^{-3}$ and (a) $m_{\nu_h} = 400$ and $\tau_{\nu_h} = 3 \times 10^{-8}$ s ($\mu_{\rm tr} = 2 \times 10^{-10}\mu_B$) (solid); (b) $m_{\nu_h} = 400$ and $\tau_{\nu_h} = 10^{-10}$ s ($\mu_{\rm tr} = 3 \times 10^{-9}\mu_B$ (dashed); (c) $m_{\nu_h} = 600$ and $\tau_{\nu_h} = 3 \times 10^{-8}$ s (dotted). The dots are experimental points for the excess events in the MiniBooNE detector. Error bars include both statistical and systematic errors [2]. The comparison of the distributions with the experimental data yields a χ^2 of 10.2, 11.2, and 17.2 for 8 DF corresponding to 27%, 24%, and $\simeq$ 5% C.L. for (a), (b), and (c), respectively.

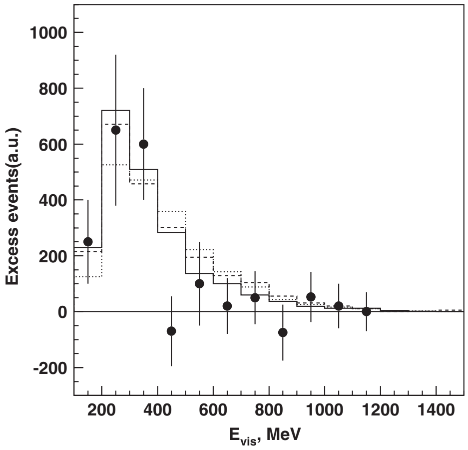

FIG. 3. Distributions of the excess events from the $\nu_h \to \gamma\nu$ decay reconstructed as ν_eCC events as a function of $E_{\rm vis}$ for $E_\nu^{\rm QE} > 200$ MeV. The comparison of the distributions with the experimental data yield a χ^2 of 9.7, 10.3, and 16.8 for 8 DF corresponding to 28%, 27%, and $\simeq 5\%$ C.L. for (a), (b), and (c), respectively. The legend is the same as in Fig. 2.

decays, for which the rate calculations can be found, e.g., in [11]. For $m_{\nu_h} \simeq 500$ MeV and $\mu_{\rm tr} > 10^{-10}\mu_B$, we found that the radiative decay is dominant, ${\rm Br}(\nu_h \to \gamma\nu) > 0.5$. For example, for $\mu_{\rm tr} = 10^{-9}\mu_B$ and $|U_{\mu h}|^2 = 1.5 \times 10^{-3}$, the expected ratio of decay rates for $\gamma\nu{:}\mu\pi{:}e\mu\nu{:}\mu\mu\nu$ is 0.984:0.011:0.0016:0.000 67.

One may wonder if the mixing strength of Eq. (2) is consistent with the results of previous searches for ν_h decays. The ν_h mass region around 500 MeV was covered by many experiments [10–12]. However, none of these experiments has reported a bound on the mixing strength $|U_{\mu h}|^2$ or on the combination $|U_{\mu h}|^2\mu_{\rm tr}$, for the radiative

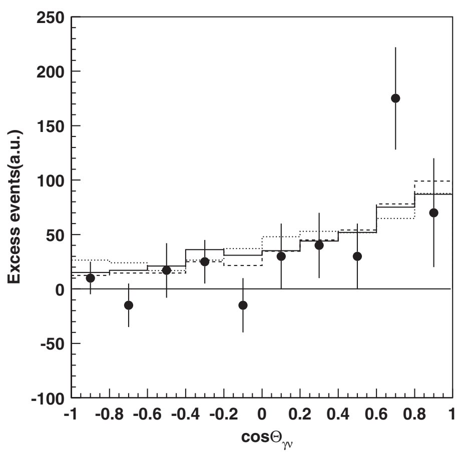

FIG. 4. Distribution of the excess events from the ν_h decay reconstructed as ν_eCC events as a function of $\cos\Theta_{\gamma\nu}$ for $300 < E_\nu^{\rm QE} < 400$ MeV. The comparison of the distributions with the experimental data yields a χ^2 of 11.6, 11.1, and 15.6 for 8 DF corresponding to 23%, 24%, and $\simeq 5\%$ C.L. for (a), (b), and (c), respectively. The notation is the same as in Fig. 2.

$\nu_h \to \gamma\nu$ neutrino decay. The best limit $|U_{\mu h}|^2 \lesssim 10^{-6}$ for the mass region $m_{\nu_h} \simeq 500$ MeV was derived from a search for $\nu_h \to \mu\pi$, $\mu\mu\nu$, $\mu e\nu$ decays in the NuTeV beam dump experiment [13] (see also [14–16]). It was assumed that these decay modes are dominant and that the ν_h is a relatively long lived particle, i.e., $\frac{Lm_{\nu_h}}{p_{\nu_h}\tau_{\nu_h}} \ll 1$, where $L \simeq 1.4 \times 10^3$ m is the distance between the target and the detector. Consider now our case with $|U_{\mu h}|^2 = (1–4) \times 10^{-3}$, $m_{\nu_h} = 500$ MeV, and $\mu_{\rm tr} = 10^{-9}\mu_B$. This gives the ν_h lifetime $\tau_{\nu_h} = (1.5 - 1.4) \times 10^{-9}$ s. Because of the larger mixing the ν_h flux at the target would increase by a factor $\simeq (1–4) \times 10^3$. However, taking into account the attenuation of the flux due to the rapid decay of ν_h's, the total number of signal events in NuTeV would decrease by a factor (10-3) compared to the number of events expected for a long lived ν_h's produced and decaying through the mixing $|U_{\mu h}|^2 = 10^{-6}$. In this estimate the average ν_h momentum is $\langle p_{\nu_h}\rangle \simeq 100$ GeV and the decay region length is $l = 34$ m [13]. Finally, we find that for

$$\mu_{\rm tr} \gtrsim 10^{-9}\mu_B \qquad (4)$$

the NuTeV limit is not constraining mixing of Eq. (2). Note that a short ν_h lifetime is also necessary to avoid the constraints coming from cosmological and astrophysical considerations [17].

The best limit for the large mixing (short lifetimes), $|U_{\mu h}|^2 \lesssim 10^{-3}$ for the masses around 500 MeV, was derived by CHARM-II from a search for the ν_h production and $\nu_h \to \mu\mu\nu$ decays within their detector [15]. Taking into account the $\nu_h \to \gamma\nu$ decay, the $\langle p_{\nu_h}\rangle \simeq 24$ GeV and $l = 35$ m, we find that the number of the expected $\mu\mu\nu$ signal events in CHARM-II is $N_{\mu\mu\nu} \simeq 0.46 \times 10^{-12}\frac{|U_{\mu h}|^4}{(\mu_{\rm tr}/\mu_B)^2}$. For $\mu_{\rm tr} \geq 3 \times 10^{-9}\mu_B$ and for mixing of Eq. (2) this results in $N_{\mu\mu\nu} < 0.05–0.8$ events. To evade the CHARM-II limit for the region $10^{-9} < \mu_{\rm tr} < 3 \times 10^{-9}\mu_B$ the mixing is required to be in a slightly more restricted range $10^{-3} < |U_{\mu h}|^2 < 1.5 \times 10^6 \frac{\mu_{\rm tr}}{\mu_B}$ compared to that of Eq. (2). For example, for $\mu_{\rm tr} = 2 \times 10^{-9}\mu_B$ the allowed range is $10^{-3} < |U_{\mu h}|^2 < 3 \times 10^{-3}$. Thus, we see that most of the allowed $(\mu_{\rm tr}; |U_{\mu h}|^2)$ parameter space corresponding to Eqs. (2) and (4) is not constrained by the CHARM-II limit.

Consider now bounds from LEP experiments [10]. For the mass region around 500 MeV, the model-independent limit from the searches for the $Z \to \nu\nu_h$ decay is $|U_{\mu h}|^2 \lesssim 10^{-2}$ (see, e.g., [18]) which is compatible with Eq. (2). Direct searches for radiative decays of an excited neutrino $\nu^* \to \gamma\nu$ produced in $Z \to \nu^*\nu$ decays have been also performed [10]. The best limit from ALEPH is ${\rm Br}(Z \to \nu\nu^*){\rm Br}(\nu* \to \gamma\nu) < 2.7 \times 10^{-5}$ [19]. As the experimental signatures for the $\nu* \to \gamma\nu$ and $\nu_h \to \gamma\nu$ decays are the same, we will use this bound for comparison. The number of expected $\nu_h \to \gamma\nu$ events in ALEPH is proportional to

$\mathrm{Br}(Z \to \nu\nu_h)\mathrm{Br}(\nu_h \to \gamma\nu)[1 - \exp(-\frac{l m_{\nu_h}}{p_{\nu_h}\tau_{\nu_h}})]$, with $l \simeq 1$ m and $p_{\nu_h} \simeq 45$ GeV. Taking into account $\frac{\mathrm{Br}(Z\to\nu\nu_h)}{\mathrm{Br}(Z\to\nu\nu)} \simeq |U_{\mu h}|^2$ and using Eq. (3), we find

$$|U_{\mu h}|^2 \times \left(\frac{\mu_{\mathrm{tr}}}{\mu_B}\right)^2 < 3.5 \times 10^{-20}. \quad (5)$$

Using Eq. (2) results in $\mu_{\mathrm{tr}} \lesssim (6 - 3) \times 10^{-9}\mu_B$, which is consistent with Eq. (4).

The limit on the μ_{tr} between the ν_h and the ν_μ has been obtained in Ref. [20], based on the idea of the Primakoff conversion $\nu_\mu Z \to \nu_h Z$ of the muon neutrino into a heavy neutrino in the external Coulomb field of a nucleus Z, with the subsequent $\nu_h \to \gamma\nu$ decay. By using the results from the NOMAD experiment [21,22], a model-independent bound $\mu_{\mathrm{tr}}^{\mu h} \lesssim 10^{-8}\mu_B$ was set for the ν_h masses around 500 MeV (see Table 1 and Fig. 2 in Ref. [20]), which is also consistent with Eq. (4).

The low statistics antineutrino ($\bar{\nu}_\mu$) data collected by the MiniBooNe seem to show no low-energy excess [23]. An analysis of these data within the framework discussed above suggests that the excess is not seen due to the lower $\bar{\nu}_\mu$ energy. Indeed, the $\bar{\nu}_\mu$ flux peaks at ~400 MeV and has a mean energy of ~600 MeV [9]. If the $\bar{\nu}_h$ mass is around 500 MeV, the $\bar{\nu}_h$ production is kinematically suppressed for $\bar{\nu}_\mu$ energies below the mean energy. Instead of the expected excess of ~40 events [23], a smaller excess of ~23 events is expected in the antineutrino data.

In summary, we see that the interpretation of the MiniBooNe anomaly based on the production and visible decay of a heavy neutrino is compatible with all the four constraints (a)–(d). The shape of the excess events in several kinematic variables is found to be consistent with the distributions obtained within this interpretation. The reason why the excess is not observed in the recent antineutrino data [23] is clarified. A definite conclusion on the presence of $\bar{\nu}_h \to \bar{\nu}_\mu\gamma$ events can be drawn when the $\bar{\nu}_\mu$ statistics is substantially increased. Our results for the mixing strength $|U_{\mu h}|^2 \simeq (1\text{–}4) \times 10^{-3}$ and for the magnetic moment $\mu_{\mathrm{tr}} \simeq (1\text{–}6) \times 10^{-9}\mu_B$ are compatible with the results from previous experiments. Values of μ_{tr} larger than $10^{-10}\mu_B$ could be obtained, e.g., in the framework of the Zee model [6]. Our analysis gives a correct order of magnitude for the parameters $|U_{\mu h}|^2$ and μ_{tr} and may be improved by more accurate and detailed simulations of the MiniBooNE detector, which are beyond the scope of this work. We note that an analysis of the excess of events due to the $\nu_h \to \gamma\nu$ decay may also be possible with existing neutrino data. New results could be obtained with NOMAD [21], SciBooNE [24], and K2K near detectors [25]; see also [26].

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