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EVALUATION OF A TEST FOR THE TAU NEUTRINO IN THE ZERO-MUON CHANNEL

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ABSTRACT

Extending previous work, we assess the feasibility of using the visible energy distribution for zero-muon events in a beam dump experiment as a possible means of observing the tau neutrino. The method would require an extremely precise knowledge of various neutrino fluxes and corresponding background reactions, and hence is not as reliable as the muon-trigger test proposed earlier.

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An outstanding experimental task at the present time is to observe the tau neutrino. The existence of this particle as the third sequential neutrino is a firm prediction of the three-doublet version of the standard $SU(2)_L \times U(1)$ model[1] of electroweak interactions. In two previous works we have studied various tests which might be used for this purpose[2]. We proposed the "muon-trigger test" as the best method because of its reliability and its sensitivity to a small signal. It was concluded that, given the expected magnitude of the $\overset{(-)}{\nu}_\tau$ fluxes, the two-shower and anomalous neutral-to-charged current cross section ratio tests were not likely to be feasible.

There is another type of test which one might consider. Again using a beam dump experiment to obtain the maximal flux of $\overset{(-)}{\nu}_\tau$ relative to the flux of $\overset{(-)}{\nu}_\ell$, ℓ = e or μ, one would study the apparent neutral current (NC) events as a function of visible shower energy, E_{SH} (which includes the $e^\pm$ energy in the case of $\overset{(-)}{\nu}_e$ charged-current reactions; see below). These events result from the NC reactions $\overset{(-)}{\nu}_\ell N \to \overset{(-)}{\nu}_\ell X$, $\ell = e, \mu$, and τ, the charged current (CC) reaction $\overset{(-)}{\nu}_\tau N \to \tau^\pm X$; $\tau^\pm \to \overset{(-)}{\nu}_\tau$ + hadrons, and, in a typical detector which cannot reliably distinguish electrons from hadrons, also the CC processes $\overset{(-)}{\nu}_e N \to e^\pm X$ and $\overset{(-)}{\nu}_\tau N \to \tau^\pm X$; $\tau^\pm \to \overset{(-)}{\nu}_\tau e^\pm \overset{(-)}{\nu}_e$. From the observed number of $\overset{(-)}{\nu}_\mu N \to \mu^\pm X$ events in a given bin in $E = E_{SH} + E_\mu$ one can try to reconstruct the $\overset{(-)}{\nu}_\mu$ neutrino spectrum. Then one can compute the number of $\overset{(-)}{\nu}_\mu$ NC events in a bin in E_{SH} by using the well-measured NC/CC cross section ratios $R^{\nu N}$ and $R^{\bar{\nu} N}$. Subtracting the number of NC events per bin, one is left with the $\overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\tau$ 0μ events. If the $\overset{(-)}{\nu}_e$ fluxes could be accurately calculated for conventional and prompt decays (i.e., K, Λ, Σ, D, F, etc.), and if the $\overset{(-)}{\nu}_\tau$ flux were sufficiently large relative to the $\overset{(-)}{\nu}_e$ flux, then one might try to establish the presence of the ν_τ signal via its contribution to the E_{SH} distribution. This test could not, of course, be applied on an event-by-event basis, but would have the merit of not requiring (as does the muon trigger test) an accurate measurement of the hadronic spray direction. It would be especially useful if the E_{SH} distribution of the $\overset{(-)}{\nu}_\tau$ events were distinctively different from that of the $\overset{(-)}{\nu}_e$ events, because of either a difference in the energy dependence of the respective fluxes or, for a given E, a difference in the E_{SH} value resulting from the $\overset{(-)}{\nu}_\tau$ versus $\overset{(-)}{\nu}_e$ 0μ reactions.

Accordingly, we have calculated the E_{SH} distribution for the $\overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\tau$ 0μ events in typical beam dump experiments. Obviously, the method depends crucially on one's knowledge of the $\overset{(-)}{\nu}_e$ flux, both from conventional and prompt sources. In addition to the Mori fluxes[3] used in Ref. 2 there are now $\overset{(-)}{\nu}_\mu$ and $\overset{(-)}{\nu}_e$ beam dump fluxes available which incorporate secondary and tertiary proton interactions in the target, as computed by Wachsmuth for the CERN experiments[4]. The Mori fluxes, it may be recalled, apply for 400 GeV protons incident on a copper beam dump, with the detector separated by a distance of 0.25 km from the target and subtending an angle of 0-2 mrad. The Wachsmuth fluxes assume that the detector is 0.8 km away from the primary proton target and, more importantly, that it subtends a similar angle of 1.2 mrad. The latter fluxes are softer than those generated by Mori, mainly because the secondary and tertiary proton interactions are characterized by smaller energies than the primary ones. The difference between these $\overset{(-)}{\nu}_e$ fluxes (see Fig. 1) serves as some measure of the uncertainty in the $\overset{(-)}{\nu}_e$ flux calculation. We have improved the $\overset{(-)}{\nu}_\tau$ flux calculation of Ref. 3 to incorporate τ polarization effects (see below); however, the changes are not very great, and therefore we shall again use these fluxes. The basic inputs for the $\overset{(-)}{\nu}_\tau$ estimates of Ref. 2, on which the more detailed calculations of

Ref. 3 were based, were first, the ratio $R_\sigma \equiv \sigma(pN \to F\,\bar{F})/\sigma(pN \to D\,\bar{D})$ (where $D\,\bar{D} = D^0\,\bar{D}^0 + D^+\,D^-$) and secondly, the branching ratio $B = B(F^- \to \tau^-\,\bar{\nu}_\tau)$. The values which were taken for these quantities were deliberately conservative; $R_\sigma = 0.1$ and $B = 0.03$. It may be observed that if the F and D mesons were degenerate, then R_σ would reach its maximum value, 0.5. Thus the $\overset{(-)}{\nu}_\tau$ flux could be somewhat larger than the estimate of Ref. 2 ; alternatively, of course, it could be smaller. Since we shall argue here that the $\overset{(-)}{\nu}_\tau$ signal is too small for the E_{SH} test to prove feasible, we are primarily interested in the former possibility. For definiteness we shall plot curves with the $\overset{(-)}{\nu}_\tau$ flux of Refs. 2,3 and, for contrast, this flux increased by a factor of four.

The results for the E_{SH} distribution calculated by Monte Carlo techniques described before[2] are presented in Fig. 1. This figure shows separately the contribution to the 0μ sample from the $\overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\tau$ fluxes. The solid curves represent the E_{SH} distribution due to the prompt charm-generated $\overset{(-)}{\nu}_e$ flux of Ref. 2 . For reference, the dot-dashed curve represents the same quantity computed using the corresponding Wachsmuth prompt charm-generated $\overset{(-)}{\nu}_e$ flux. The total 0μ E_{SH} distribution from the (prompt) $\overset{(-)}{\nu}_e$ together with the $\overset{(-)}{\nu}_\tau$ fluxes of Ref. 2 is shown by the lower dashed curve. The higher dashed curve is obtained by increasing the $\overset{(-)}{\nu}_\tau$ flux by a factor of four; the lined band defined by these two dashed curves represents a reasonable range of the 0μ event rate due to the possibility that the $\overset{(-)}{\nu}_\tau$ flux could be somewhat larger than that used in Ref. 2 . (There is, of course, also an analogous although smaller, uncertainty band <u>below</u> the central dashed curve; however, if the actual event rate in fact lay in this band it would just strengthen our conclusions.) It is clear from the graph that the $\overset{(-)}{\nu}_\tau$ signal is expected to be rather small, as was already found in the integrated NC/CC event ratios discussed in Ref. 2 (which also included $\overset{(-)}{\nu}_\mu$ events in the NC sample). Furthermore, the shape of the $\overset{(-)}{\nu}_\tau$ event distribution is not distinctively different from that of the $\overset{(-)}{\nu}_e$ distribution. Moreover, the nonprompt $\overset{(-)}{\nu}_e$ contribution from K_{e3} decays (not shown in Fig. 1) is as large as the prompt component in a typical beam dump experiment and can only be estimated with finite accuracy. Our conclusion from this study is that an analysis of the E_{SH} distribution in the 0μ channel does not provide a reliable test for ν_τ.

In the process of evaluating this test, we have generalized Mori's calculation of the $\overset{(-)}{\nu}_\tau$ flux. That calculation neglected the helicity states of the τ and ν_τ produced in the decay of the F and used a distribution of the ν_τ from the decay of the τ which was isotropic in the τ rest frame. The actual double differential decay distribution for $\tau^\pm \to \nu_\tau \ell^\pm \overset{(-)}{\nu}_\ell$, $\ell = e$ or μ, was given in Ref. 2 and is $\Gamma^{-1}\partial^2\Gamma/\partial z\partial\cos\theta = z^2[(3 - 2z) \pm (1 - 2z)\cos\theta]$ where θ is the angle between the $\overset{(-)}{\nu}_\tau$ direction and the $\tau^\pm$ spin, $z = 2E^*_\ell/m_\tau$, and the $\pm$ signs apply to τ^- and τ^+ respectively. The helicity of the initial τ does play a significant role in determining the final flux. This is a consequence of the fact that the higher energy portion of the ν_τ spectrum is due to $\nu_{\tau 2}$ from τ decay, whereas the lower energy portion arises from the $\nu_{\tau 1}$ from the initial decay of the F. Now the highest energy part of the spectrum would come from a process in which an F emitted a τ forward in the beam direction, which then in turn emitted the ν_τ forward again. However, the $\tau^\pm$ from the decay of the $F^\pm$ has the wrong helicity; for example τ^- has helicity + 1. From the expression for $\Gamma^{-1}\partial^2\Gamma/\partial z\partial\cos\theta$ it is clear that there is thus some suppression of the high energy part of the flux, since for $z = 1$ the rate for $\tau \to \nu_\tau \ell \bar{\nu}_\ell$ vanishes, i.e., the ν_τ is forbidden from being emitted along the direction of the spin (which is also the direction of motion) at maximum energy in the rest frame of the τ. Actually there is another reason why the highest part of the spectrum is suppressed: one of the important exclusive semihadronic modes, namely, $\tau \to \pi\nu_\tau$, yields very soft ν_τ's because, again due to the chiral nature of the vertices and the fact that the π has spin 0, the ν_τ must be emitted opposite to the τ spin, which is to say, opposite to the direction of motion of the τ, for the high energy τ's which were emitted forward in the initial decay of the F.

To illustrate the polarization effects, we show two $\overset{(-)}{\nu}_\tau$ neutrino spectra from the decay $\tau^\pm \to \overset{(-)}{\nu}_\tau \mu^\pm \overset{(-)}{\nu}_\mu$ computed for an initial F production cross section of the form $E d^3\sigma/d^3p \propto e^{-2p_\perp} (1 - x_F)^3$ at a beam energy of 400 GeV and a detector angular acceptance of 0–2 mrad. Fig. (2a) shows the difference between the $\overset{(-)}{\nu}_{\tau_2}$ energy spectrum in the $\tau^\pm$ rest frame for the cases where the $\tau^\pm$ polarization is included (solid curve) or neglected (dashed curve). The unpolarized distribution is proportional to $z^2(3 - z)$, whereas the polarized one is proportional to $z^2(1 - z)$, because $\cos\theta$ is close to ∓ 1 for $\tau^\pm$ in order that the $\overset{(-)}{\nu}_{\tau_2}$ be accepted in the 0–2 mrad angle. This difference is summarized by the mean energy of the $\overset{(-)}{\nu}_{\tau_2}$ in the τ center of mass, which is $\langle E^*_{\nu_{\tau_2}} \rangle = 0.54$ GeV, (0.61 GeV) if the τ polarization is included (neglected). This has the effect of shifting the $\overset{(-)}{\nu}_{\tau_2}$ laboratory flux spectrum to slightly lower energy. The effect can be seen from Fig. (2b), which shows this spectrum with the 0–2 mrad acceptance cut imposed. Again, the solid and dashed curves refer to the cases where the τ polarization is included and neglected, respectively. The mean $\overset{(-)}{\nu}_{\tau_2}$ energy is $\langle E_{\nu_{\tau_2}} \rangle = 78$ GeV and 88 GeV in these two respective cases. We have thus demonstrated that

τ polarization effects slightly soften the ν_τ flux. However, at low energies, $E < 20$ GeV, the $\overset{(-)}{\nu}_\tau$ flux is essentially unaffected, since this low energy portion is mainly due to the soft ν_{τ_1} from the initial decay of the F. Independently of this τ polarization effect, there remains some uncertainty in the energy dependence of the $\overset{(-)}{\nu}_\tau$ fluxes due to the lack of knowledge of the x and p_T dependence of the hadronic $F\,\bar{F}$ production.

Previously we analyzed the effects of possible neutrino oscillations on tests for ν_τ[2]. Here it is of interest to set a rough upper bound on the fraction of 0μ events which could be due to such neutrino oscillations. It should be noted first that there is an astrophysical constraint on the number and properties of neutrinos[5]. Taken literally, it implies that there can be only three regular left-handed (hence massless) neutrinos coupling with the usual weak strength; it thereby rules out neutrino oscillations, which require nondegenerate neutrinos. However, since there is some finite uncertainty in this constraint, it is useful to consider conventional particle physics bounds on neutrino oscillations. Let us discuss first the transitions $\nu_\mu \to \nu_e$ and $\nu_\mu \to \nu_\tau$, which would both contribute to the 0μ event sample. The CERN Gargamelle experiment set an upper limit[6]
$R_{e/\mu} = N(\nu_\mu(t)N \to eX)/N(\nu_\mu(t)N \to \mu X) < 3 \times 10^{-3}$ (90% CL), where

$\nu_\mu(t) = \sum_{j=1}^{3} U_{\mu j}\nu_j \exp(-iE_j t)$. Here ν_ℓ, $\ell = e, \mu, \tau$ denote the gauge group eigenstates, which are related to the mass eigenstates ν_j, $j = 1, 2, 3$, by the lepton mixing matrix U: $\nu_\ell = \sum_{j=1}^{3} U_{\ell j}\nu_j$. The energy range of the neutrinos in this experiment was ~ 0.5 to 10 GeV, the flux being peaked around 1.5 GeV; and the distance ℓ between the primary target and the detector (bubble chamber) was ~ 0.1 km. More recently, the Brookhaven-Columbia-FNAL (BCF) experiment has set a similar limit[7] $R_{e/\mu} < 5 \times 10^{-3}$ (90% CL) using the FNAL horn neutrino beam with energy peaked around 30-40 GeV, and $\ell \sim 1$ km. Other experiments have set comparable limits; for example, the HPWF experiment group found no evidence for electron production from $\nu_\mu(t)$ throughout a range of energies extending somewhat above those of Ref. 7 up to ~ 180 GeV, and with $\ell \sim 1$ km[8]. Thus these combined limits cover the range of energies and path length which characterize a typical beam dump experiment such as the one recently conducted at CERN by the "CHARM" collaboration[9] or the ones planned at FNAL[2]. Concerning other types of neutrino oscillations, the transition $\nu_e \to \nu_\mu$ would contribute to both the 1μ and the 0μ events sample. Since the ratio of 0μ to 1μ events would be the usual one for $\overset{(-)}{\nu}_\mu$-induced reactions, the subtraction method described above would effectively remove this source of contamination of the 0μ sample. The $\overset{(-)}{\nu}_e$ flux and hence the 0μ sample would be slightly depleted by this transition. In order to estimate an upper bound for the magnitude of the effect we set the exponential factors $\exp(-iE_j t)$ equal to unity; then the mixing angles which characterize the amplitude $\langle \nu_e \mid \nu_\mu(t) \rangle$ are the same as the ones which determine $\langle \nu_\mu \mid \nu_e(t) \rangle$, and therefore we may use the experimental limit on $\nu_\mu \to \nu_e$ to conclude that $N(\nu_e \to \mu)/N(\nu_e \to e) \lesssim 0.003$. There remains the transition $\nu_e \to \nu_\tau$. However, the constraint of $\mu - e$ universality prevents the mixing angles which determine $\langle \nu_\tau \mid \nu_e(t) \rangle$ from being very different from those which determine $\langle \nu_\tau \mid \nu_\mu(t) \rangle$[10]. Hence also in this case we may use the result of the BCF experiment to infer that $N(\nu_e \to \tau)/N(\nu_e \to e) \lesssim .025$. Thus in an ideal beam dump experiment where $N(\overset{(-)}{\nu}_\mu) = N(\overset{(-)}{\nu}_e)$ the maximum increase in the 0μ sample from neutrino oscillations might be of order 1%. In a more typical experiment in which $N(\nu_\mu) > N(\bar{\nu}_\mu) > N(\overset{(-)}{\nu}_e)$ the possible addition would be commensurately larger. As was noted in Ref. 2, these effects are not negligible compared to the expected size of the ν_τ signal. However, as was also stressed there, any test for ν_τ is always a test for the gauge group eigenstate, and its validity is unaffected by the presence or absence of neutrino oscillations. Such oscillations might be detected by their distinctive energy dependence stemming from the $\exp(-iE_j t)$ factors. But they do not alter the basic conclusion stated above, namely that the E_{SH} distribution does not provide a reliable means of searching for ν_τ.

Concerning the status of searches for ν_τ, the "CHARM" collaboration at CERN has reported preliminary evidence[9] for an excess of 0μ events in the lowest bin in E_{SH}, 2 GeV $< E_{SH} <$ 20 GeV. No such anomaly has been found by the CDHS experiment, which took data in the same beam dump run with quite similar conditions[11]. From our study we would conclude that even if the "CHARM" group's signal persists, it could not be used to provide firm evidence for the observation of ν_τ, mainly because of the lack of sufficiently precise knowledge of the reconstructed $\overset{(-)}{\nu}_\mu$ fluxes and the $\overset{(-)}{\nu}_e$ fluxes computed via Monte Carlo simulation.

Thus, the most promising method to detect ν_τ interactions unambiguously remains the one originally proposed in Ref. 2, namely the muon-trigger test. It is hoped that this test can be used in the near future to confirm the existence of the ν_τ.

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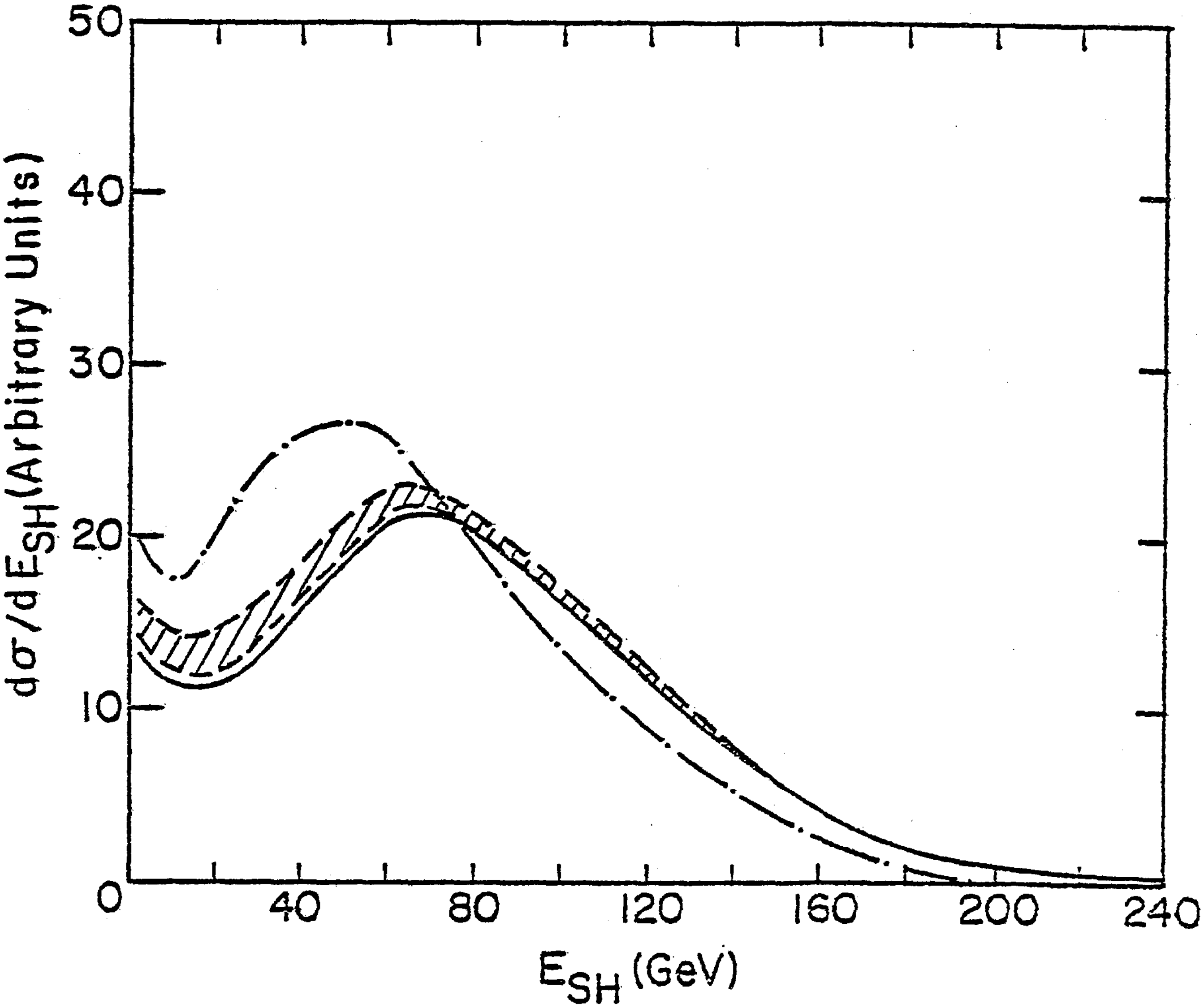
FIGURE CAPTIONS

Fig. 1 E_{SH} distribution due to prompt $\overset{(-)}{\nu}_e$ alone, as calculated with the fluxes of Ref. 3 (solid curve) and Ref. 4 (dot-dashed curve), and prompt $\overset{(-)}{\nu}_e$ plus $\overset{(-)}{\nu}_\tau$, as calculated with the $\overset{(-)}{\nu}_\tau$ fluxes of Ref. 3 multiplied by 1 (lower dashed curve) or 4 (upper dashed curve).

Fig. 2a Energy spectrum of ν_{τ_2} in the rest frame of the τ, in the case where the τ polarization is included (solid curve) or neglected (dashed curve).

Fig. 2b The ν_{τ_2} laboratory flux spectrum in the case where the τ polarization is included (solid curve) or neglected (dashed curve).



50
40
30
20
10
0
40
80
120
160
200
240
dσ/d E_SH (Arbitrary Units)
E_SH (GeV)

Fig. 1

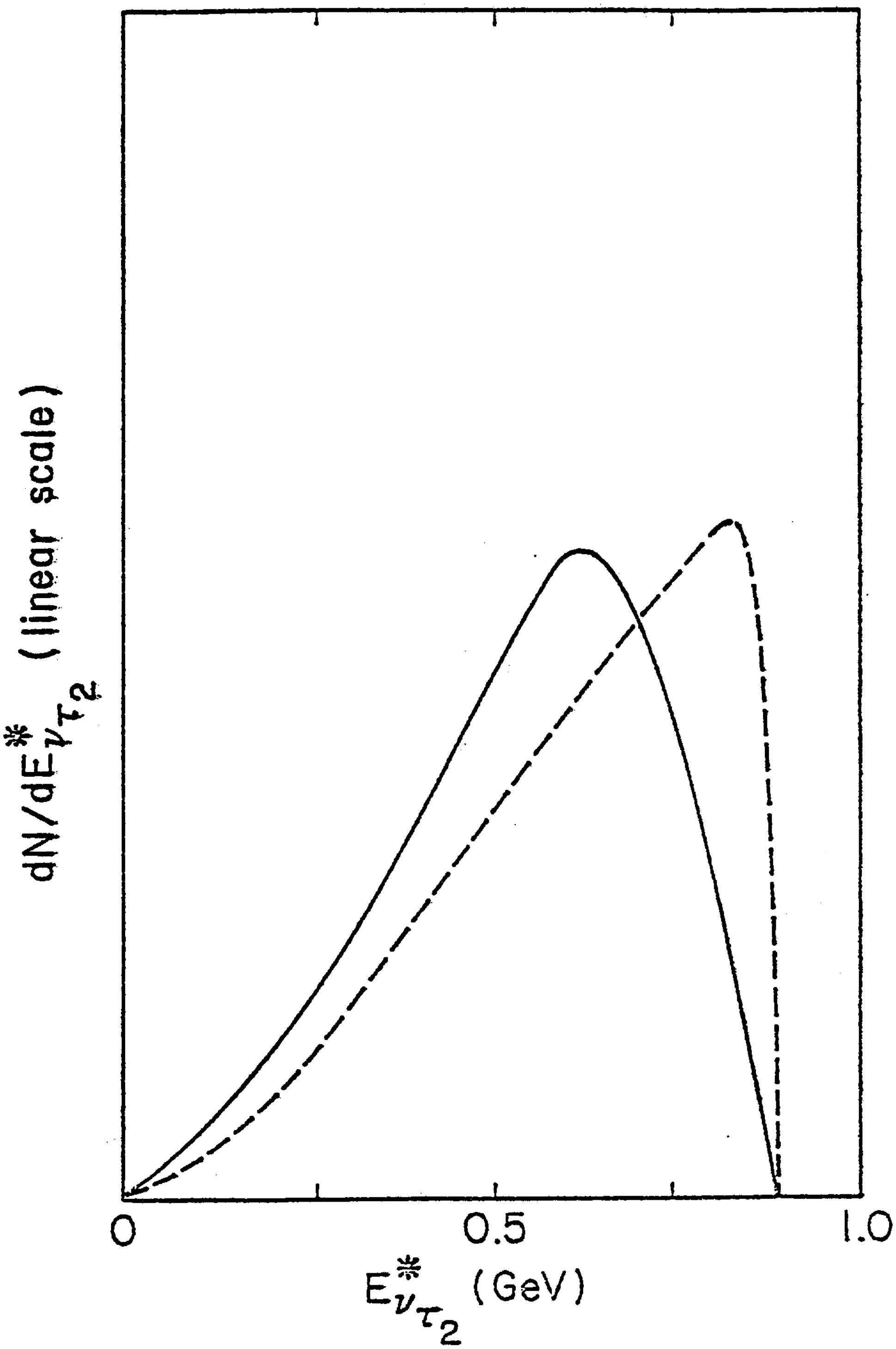


Fig. 2a

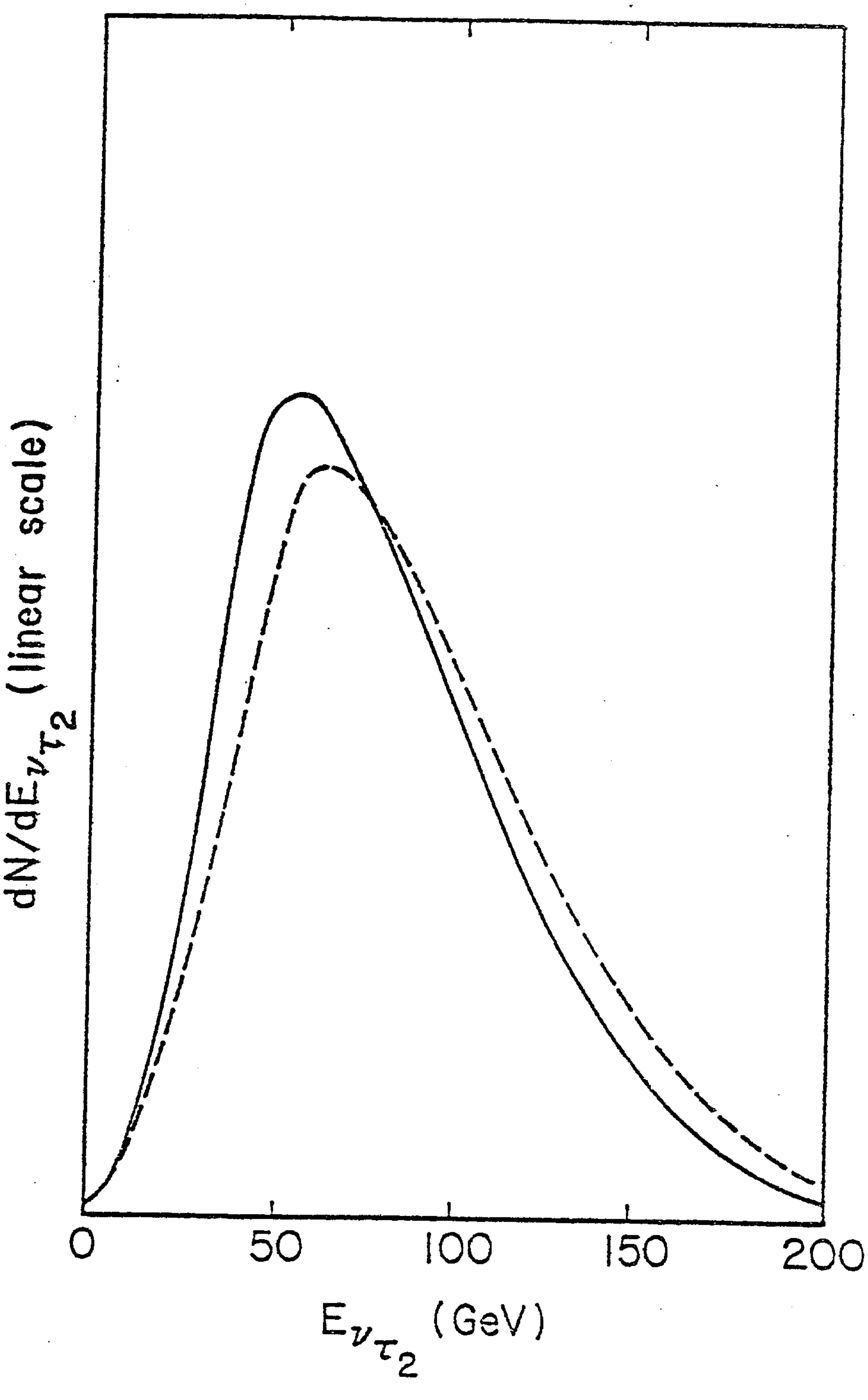


Fig. 2b