6 Oscillation Experiments Involving $v_e(\bar{v}_e)$

6.1 Reactor Disappearance Experiments

As discussed above in Chapter 3, reactors produce an abundant flux of \bar{v}_e 's, a flux whose energy spectrum is well understood and whose intensity is directly correlated in a known way with the power of the reactor. Because the energy of \bar{v}_e 's is relatively low, namely in the MeV range, \bar{v}_{μ} 's or \bar{v}_{τ} 's produced by potential oscillations will be too low in energy to interact via charged current interactions. Thus, in reactor experiments one is limited to disappearance studies, i.e., looking for a decrease in flux and/or distortion of the expected spectrum in the detector which is located some distance from the reactor.

6.1.1 Results from Completed Experiments

As of the time of these lectures (August 1997) there were several negative results from the reactor experiments, the most sensitive one coming from an experiment studying the flux from the reactors at Bugey, France.⁸⁶ The $\bar{\nu}_e$'s are detected by the sequence of reactions

$$\overline{\nu}_{e}^{} + p \rightarrow e^{+} + n ,$$

 $n + {}^{6}\text{Li} \rightarrow {}^{4}\text{He} + {}^{3}\text{H} + 4.8 \text{ MeV}$

One demands a coincidence between the positron from the initial reaction and a signal from the subsequent neutron capture. The \bar{v}_e source in the Bugey experiment is actually two reactors about 90 m apart; by utilizing detectors at two different locations, neutrino flux and spectrum can be measured for three different reactor-detector distances. The results can be compared with each other, to see if the flux intensities differ just by $1/r^2$ ratios, as expected in the absence of the oscillations, as well as with the theoretically expected spectra.

The Bugey experiment finds no evidence of oscillations. The ratios of measured and calculated (assuming no oscillation) integrated fluxes at the three distances are given in Table 3.

TABLE 3.

Ratios of measured and calculated (no oscillations) integrated yields.

Position	Ratio		
15 m	0.996 ± 0.004 (stat) ± 0.05 (syst)		
40 m	$0.994 \pm 0.010 \text{ (stat)} \pm 0.05 \text{ (syst)}$		
95 m	$0.915 \pm 0.132 \text{ (stat)} \pm 0.05 \text{ (syst)}$		

The same ratio, plotted as a function of the positron energy, is shown for these three distances in Fig. 37. The \bar{v}_e energy is, to a high precision, given by

$$E_{\bar{v}} = E_{v^+} + 1.8 \text{ MeV}$$



FIG. 37. The ratio of the observed and predicted positron spectra (assuming no oscillations) from the Bugey reactor experiment at detector distances of 15 m, 40 m, and 95 m. The indicated band corresponds to the estimated systematic error.

The limits imposed by the Bugey experiment, together with the limits from two other reactor experiments, at Krasnoyarsk⁸⁷ and Gösgen,⁸⁸ are shown in Fig. 38. Also shown is the region suggested by the Kamiokande results if they are interpreted under

the hypothesis of $\nu_{\mu} \rightarrow \nu_{e}$ and $\nu_{e} \rightarrow \nu_{\mu}$ oscillations. As can be seen, most of the Kamiokande suggested region, except for the lowest Δm^{2} , is excluded by the reactor data.



FIG. 38. The 90% C.L. exclusion contour from the Bugey experiment. Also shown are the previous limits from the Gösgen and Krasnoyarsk experiments, and the favored region from the Kamiokande experiment calculated on the basis of $v_u \rightarrow v_e$ oscillation hypothesis.

6.1.2 Experiments in Progress: CHOOZ and Palo Verde

The desire to explore fully the Kamiokande region by extending the sensitivity to smaller values of Δm^2 motivated initiation of two experiments with much longer baselines, about 1 km. One of these was with the \bar{v}_e flux from the reactor near the village of Chooz in France;⁴⁸ the other at Palo Verde in Arizona, USA.⁴⁹ The detection methodology is quite similar in both cases; its main difference from the method employed at Bugey lies in the fact that one uses gadolinium (dissolved in liquid scintillator), rather than lithium to capture the neutrons. Neutron capture on gadolinium is accompanied by the release of 8 MeV of γ ray energy. The similarities and differences between the CHOOZ and Palo Verde experiments are shown in Table 4.

Comparison of CHOOZ and Palo Verde Experiments					
Experimental Characteristics	CHOOZ	Palo Verde			
Reactor Power (Thermal)	8.4 GW	10.9 GW			
No. Reactor Units	2	3			
Reactor-Detector Distance	1000/1100 m	850/740/850 m			
Detector	Homogeneous	Segmented			
Detector Mass	5 Tons	12 Tons			
Event Rate (no osc.)	25/Day	51/Day			
Efficiency of Detection	80%	26%			
Overburden	300 mwe	46 mwe			
Calculated Background Rate	1-3/Day	34/Day			
Start of Data Taking	March 1997	Spring 1998			

TABLE 4.

As can be seen from the Table the main advantages of the CHOOZ experiment are the earlier start-up and a much lower background rate due to better shielding of the detector. The latter is due to the fact that the CHOOZ detector is located in a tunnel under a mountain; the Palo Verde detector is in a cavern, specially excavated for this experiment. At the time of these lectures no physics results were available from either experiment; since that time, however, CHOOZ has obtained significant negative results.⁸⁹ We discuss them next.

The CHOOZ experiment recently reported results based on data taken during the period from March to October, 1997, when the two reactor units ran at power levels varying from zero to full power. Thus, both the background level and the full power neutrino rate could be measured and compared with the predictions. The neutrino events were identified by having appropriate neutron capture energy (about 8 MeV), not too long a delay between the positron and neutron signals (2-100 msec) and spatial cuts on the positron and neutron locations (n--e⁺ distance < 100 cm, and distance from the vessel wall > 30 cm). The relevant experimental distributions are shown in Fig. 39. The resulting neutrino counting rate as a function of the reactor power is shown in Fig. 40. The measured background rate (both from extrapolation to zero

reactor power and from reactor-off measurement) is consistent with the estimated rate of 1.03 ± 0.21 /day. The ratio of measured to expected neutrino signal is

$$R_{\text{meas/exp}} = 0.98 \pm 0.04 \text{ (stat)} \pm 0.04 \text{ (syst)}$$

indicating no evidence for neutrino oscillation.



FIG. 39. Distribution of: (a) energy released by *n*-capture on Gd, (b) *n*-capture delay, (c) positronneutron distance, measured and MC expected; the reactor-off background distribution is also shown. The histograms in (b) and (c) are normalized to the background-subtracted experimental data.



FIG. 40. Number of $\bar{\nu}_e$ -candidates per day, as a function of the reactor power.

In addition, one can compare the measured and the expected positron energy spectra. This comparison is shown in Fig. 41 and confirms the conclusion of no oscillations. The resulting 90% C.L. exclusion plot, together with the results of other relevant experiments is shown in Fig. 42. In summary, no evidence for disappearance $\bar{v}_e \rightarrow \bar{v}_x$ is seen for the parameter region corresponding to $\Delta m^2 > 0.9 \times 10^{-3} \text{ eV}^2$ for maximum mixing and $\sin^2 2\theta > 0.18$ for large Δm^2 .



FIG. 41. (a) Positron energy spectrum and corresponding reactor-off background for the same livetime; the neutrino-signal expected positron spectrum is also shown. (b) Ratio of the measured (background subtracted) to the expected positron spectrum.



FIG. 42. The 90% exclusion contour from the CHOOZ experiment, together with the previous experimental limits and the favored region from the Kamiokande experiment calculated on the basis of $\nu_{\mu} \rightarrow \nu_{e}$ oscillation hypothesis. Note that a linear scale is used for the sin²2 θ axis.

The Palo Verde experiment should begin to start data taking early in 1998. As discussed above, its main challenge will be to overcome the much higher cosmic ray associated background rates due to its relatively shallow depth. The main estimated background source are the chance coincidences of neutrons produced around the detector by cosmic ray muon interactions. To reduce background as much as possible, the detector has been segmented into many individual modules, so as to get cleaner identification of the neutrino events. This segmentation allows one to require a four-fold coincidence for the signal: positron, the two annihilation γ rays, and neutron capture γ rays. The first three signals are prompt; the neutron capture signal is delayed. The detection principle is illustrated in Fig. 43. The expected sensitivity of this experiment is comparable to that of CHOOZ.



FIG. 43. The detection principle of the Palo Verde experiment.

6.2 $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}$ at Low Energies

At the present time the only positive indication of neutrino oscillations from accelerator or reactor experiments comes from an experiment at LAMPF looking for oscillations of $\bar{\nu}_{\mu}$ from μ^+ decays at rest and from ν_{μ} from π^+ decays at relatively low energies. These results are controversial because they still wait to be confirmed by an independent experiment. In this section we discuss the current situation in this area.

6.2.1 LSND Experiment

The initial LSND (Liquid Scintillator Neutrino Detector) experiment searched for $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}$ oscillations using $\bar{\nu}_{\mu}$ from μ^{+} decays at rest.⁹⁰ A low energy beam of π^{+} , produced by protons in a water target, was allowed to stop in a copper dump downstream; π^{+} would decay into μ^{+} which subsequently would decay into e^{+} , $\bar{\nu}_{\mu}$, and ν_{e} . The overall layout of the experiment is shown in Fig. 44. The detector is a cylindrical tank filled with 167 tons of liquid scintillator viewed by 1280 8" photomultipliers placed on the inside walls of the tank. The fluor concentration is rather low so that Cherenkov and scintillator signals are comparable. To achieve good sensitivity one needs to suppress $\bar{\nu}_{e}$ from other sources, the most obvious one being the $\pi^{-} \rightarrow \mu^{-} \rightarrow e^{-}\nu_{\mu}\bar{\nu}_{e}$ decay chain. This is accomplished by suppressing the unwanted $\bar{\nu}_{e}$ in the following ways:

(a) Having the proton beam interact on a water target enhances π^+ production over π^- by roughly a factor of eight.

- (b) π^{-} are captured when stopped. Thus the only π^{-} decays which can occur are those from π^{-} in flight, i.e., only about 5% of the total π^{-} flux.
- (c) μ^{-} , when stopped in copper, undergo preferentially a nuclear capture, with only 12% of them decaying.



FIG. 44. Detector enclosure and target area configuration in the elevation view for the LSND experiment.

All of these factors taken together give a relative suppression of 7.8 x 10^{-4} of $\bar{\nu}_e$ from the $\pi^- \rightarrow \mu^- \rightarrow e^-$ decay chain with respect to $\bar{\nu}_{\mu}$ from the $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ sequence.

The two other important backgrounds that need to be considered are v_e interactions (the LSND detector does not measure sign of the electrons) and cosmic ray interactions. The first contribution is suppressed mainly by the requirement that one requires observation not only of the signal from the e⁺, produced via

$$\overline{\nu}_{e} + p \rightarrow e^{+} + n$$

but also the signal from the subsequent neutron capture

$$n + p \rightarrow d + \gamma$$
,

i.e., the 2.2 MeV γ ray. The v_e's will not give a correlated neutron. Furthermore, the two dominant v_e capture reactions:

$$v_e + {}^{12}C \rightarrow e^- + {}^{12}N$$

and $v_e + {}^{12}C \rightarrow e^- + n + {}^{11}N$

yield maximum electron energies of 36 and 20 MeV respectively. Thus, a cut on the observed electron energy can provide a significant additional suppression.

The cosmic ray background can be measured very accurately by utilizing the fact that the duty cycle of LAMPF is only 7%. Thus accumulating data during the beam-off period can give a good statistical measurement of that background.

As the above discussion should indicate, a key feature of the experiment must be its ability to identify <u>correlated</u> positron signals and neutron capture signatures. This is done by using an algorithm dependent on the following measurements: temporal separation of e^+ and n capture signals, spatial separation of these two signals, and number of photomultiplier hits composing the putative signal due to the γ from neutron capture. One can study these distributions for both correlated and uncorrelated signals using the cosmic ray neutron data. In the cosmic ray data the correlated signals will originate from a neutron scatter followed subsequently by neutron capture. The results of such a study are shown in Fig. 45.



FIG. 45. Distributions obtained from cosmic-ray neutron data for γ 's that are correlated (solid) or uncorrelated (dashed) with the primary event: (a) the time between the photon and the primary event;

(b) the number of photon PMT hits; (c) the distance between the photon and primary event. The raw data points are also shown in (a).

Based on the distributions discussed above, one can calculate a discriminant function R defined by:

$$R = \frac{\text{likelihood that the prompt (i.e., e^+) and delayed signals are correlated}}{\text{likelihood that the two signals are accidential}}$$

where the likelihood for each possibility is defined as the product of the three individual probabilities for each hypothesis, i.e.,

$L = P(\# \text{ of hits}) P(\Delta t) P(\Delta r).$

The candidate events are subjected to a number of cuts (including $20 < E_e < 60$ MeV) and the R value is calculated for the remaining sample, both for the beam-on and beam-off conditions. The true accelerator sample can then be obtained by subtracting an appropriate fraction of the beam-off distribution. The R distribution for this sample is shown in Fig. 46, together with the best fit to the data and the expected contributions from both the correlated and uncorrelated (i.e., background) components. Clearly an excess at large R is observed if compared with the distribution due to the uncorrelated component only. This excess is interpreted as possible $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}$ oscillations and the sample with R > 30 is used for subsequent studies of this hypothesis.



FIG. 46. The R distribution, beam-on minus beam-off excess, for events that satisfy selection criteria and that have energies in the range $20 < E_e < 60$ MeV. The solid curve is the best fit to the data, the dashed curve is the uncorrelated γ component of the fit, and the dotted curve is the correlated γ component.

The various checks performed on the data lead the authors to argue that the data are consistent with the hypothesis of $\bar{v}_{\mu} \rightarrow \bar{v}_{e}$ oscillations; after tight cuts, 22 events have been identified with the e⁺ energy between 36 and 60 MeV where only 4.6 ± 0.6 background events were expected. This corresponds to an oscillation probability of $(0.31 \pm 0.21 \pm 0.05)\%$ when averaged over the experimental energy and spatial acceptance. The experiment is not able to discriminate well between different values of the two oscillation parameters, Δm^2 and $\sin^2 2\theta$. The level of its sensitivity in this area is shown in Fig. 47 where the signal events are displayed as a function of L/E_v and compared with the expected distributions for three different oscillation hypotheses.



FIG. 47. Distribution of L/E_V for the beam-on data with high R compared with the expected distributions at $(19 \text{ eV}^2, \sin^2 2\theta = 0.006$: solid line), $(4.3 \text{ eV}^2, \sin^2 2\theta = 0.01$: dashed line), and $(0.06 \text{ eV}^2, \sin^2 2\theta = 1.: \text{ dotted line})$.

A parallel effort has been made to investigate the behavior of v_{μ} from π^+ decay in flight.⁹¹ The systematics for this search will be quite different, but the investigation is made more difficult by the fact that there is no supplementary neutron capture signature, the searched-for reaction being

$$\nu_e + C \rightarrow e^- + N.$$

Two different analyses, labeled A and B, have been performed and they both find an excess of events above what one would expect from the known background sources. Their results are shown in Table 5.

Results from Decay-in-Flight Analyses							
	0. 1	Backgrounds					
Analysis S	Signal Events	Beam Unrelated	Beam Correlated	Excess	Oscillation Probability		
А	23	5.3 ± 2.3	5.3 ± 2.0	12.4 ± 5.7	$(3.4 \pm 1.3) \ge 10^{-3}$		
В	25	8.5 ± 2.9	5.9 ± 2.5	10.1 ± 6.3	$(1.7 \pm 0.8) \ge 10^{-3}$		

IABLE 5.

The allowed contours in the $\Delta m^2 - \sin^2 2\theta$ space from the two experiments are compatible with each other. They are displayed together in Fig. 48. The data taking is continuing, with slightly altered conditions to change the systematics, and the experiment is scheduled to run for about eight months of data taking in 1998.



FIG. 48. The 95% confidence region for the decay-in-fight $\nu_{\mu} \rightarrow \nu_{e}$ analysis (solid) along with the favored regions for the LSND decay-at-rest measurement for $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}$ (dotted).

6.2.2 KARMEN Experiment

An experiment similar to LSND, named KARMEN (KArlsruhe Rutherford Medium Energy Neutrino experiment) has been performed at the ISIS spallation source at Rutherford-Appleton Laboratory in Great Britain by a British-German collaboration. The main differences between the two experiments are:

- (a) The KARMEN detector is smaller, having only 58 tons of liquid scintillator.
- (b) The KARMEN detector is segmented, which permits tighter spatial correlation and very good determination of L/E_v (to a few percent).
- (c) Gadolinium-loaded paper is used in KARMEN around each module to decrease the temporal and spatial separation between the e^+ and neutron capture signals.
- (d) The KARMEN detector is only 17.6 m away from the neutrino source.
- (e) ISIS is a pulsed machine, which decreases cosmic ray background and allows one to separate by time the neutrinos from π and μ decay.

On the whole, taking all of these differences into account, the sensitivity of KARMEN is about a factor of 2-3 worse than of LSND. They find no statistically significant signal;⁹² 171 events are observed whereas the estimated background due to both cosmic ray and v_e induced events, is 140 events. Even this small excess cannot be readily accounted for by a neutrino oscillation hypothesis. For the LSND oscillation probability, with $\Delta m^2 = 3.9 \text{ eV}^2$, one would expect 77 excess events. The expected relative excess of events, for three different values of Δm^2 , is shown in Fig. 49.



FIG. 49. The relative number of $\bar{\nu}_e$ events expected in the KARMEN experiment for three different values of Δm^2 .

In addition, because of the available beam time structure and good energy resolution, KARMEN is able to make two additional measurements:

(a) Search for $v_{\mu} \rightarrow v_e$ via the reaction

$$v_e + {}^{12}C \rightarrow e^- + {}^{12}N.$$

Many examples of this process are seen, the reaction being induced by v_e 's from μ^+ decay. An oscillation signal would correspond to the process $\pi^+ \rightarrow \mu^+ v_{\mu} \rightarrow v_e$, whose signature would be an excess of events with $E_v = 30$ MeV and occurring a short time (t $\approx \tau_{\pi}$) after each proton pulse. No excess is seen,⁹³ yielding $P(v_{\mu} \rightarrow v_e) \ \pm \ 2.6 \ x \ 10^{-2} \ (90\% \ C.L.)$.

(b) Search for $v_e \rightarrow v_x$ via observation of depletion of the reaction discussed above in (a). The normalization is obtained from the neutral current process

$$\mathbf{v} + {}^{12}\mathbf{C} \rightarrow \mathbf{v} + {}^{12}\mathbf{C}^*.$$

No depletion is observed,⁹⁴ giving a limit $P(v_e \rightarrow v_x) \# 0.197$ (90% C.L.).

In the data taken so far, the sensitivity of the KARMEN search for $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}$ process has been limited by the neutrons produced by cosmic ray μ 's passing through the shielding in the vicinity of the detector. Neutron scattering can simulate the positron signature, and this signal together with the one from their subsequent capture, can give a false $\bar{\nu}_{e}$ signal. To reduce this background, the Collaboration has just finished installing a 300 m² solid scintillator shield⁹⁵ around the detector which will veto out most of this background and has been estimated to provide an additional background reduction of about a factor of 40. Preliminary results from the data taken recently with the shield appear to confirm this estimate. The current KARMEN limits for the three processes discussed above, as well as the anticipated future limit for the $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}$ search, are illustrated in Fig. 50.



FIG. 50. The exclusion contour plots from the 3 KARMEN oscillation search measurements as well as the expected sensitivity for $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}$ in the new experiment. Limits for $\Delta m^{2} = 100 \text{ eV}^{2}$ and $\sin^{2}2\theta = 1$ are indicated. The 90% C.L. LSND suggested contour is shown as the shaded area.

6.3 Searches for $v_{\mu} \rightarrow v_{e}$ at High Energies

There have now been reported several searches for $\nu_{\mu} \rightarrow \nu_{e}$ oscillations using accelerator beams in the energy range of 1 GeV and above. They all give negative results. In this section we first discuss these experiments and then summarize the results by showing the combined exclusion plot in the oscillation parameter space.

6.3.1 BNL E776 Experiment

This experiment, even though performed several years ago,⁹⁶ still has some of the best limits on $\nu_{\mu} \rightarrow \nu_{e}$ (and $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}$) oscillations in the intermediate Δm^{2} range. The experiment searched for the appearance of $\nu_{e}(\bar{\nu}_{e})$ from a wide band $\nu_{\mu}(\bar{\nu}_{\mu})$ beam. The detector was relatively fine grained and was composed of concrete/drift tube layers followed subsequently by a muon spectrometer. It was located 1 km away from the neutrino source.

The analysis relied on an algorithm based principally on the event shape which was optimized to separate e^{\pm} events from π^{o} showers. The data collecting was split evenly between neutrino and antineutrino beams. No statistically significant excess of v_{e} or \bar{v}_{e} events was observed, as can be seen from Table 6 below.

Summary of the BNL E776 Analysis					
	+ Polarity	- Polarity			
v_e/v_μ in beam	6.8 x 10 ⁻³	6.3 x 10 ⁻³			
No. of events	136	47			
Calculated background	$131 \pm 12 \pm 20 \pm 19$	$62 \pm 8 \pm 13 \pm 9$			

The three errors in the Table correspond to statistical error, statistical error on the background estimation, and systematic error. The actual data for the much more statistically significant positive polarity run (neutrino beam) are shown in Fig. 51.



FIG. 51. The results of the BNL E776 experiment. (a) The contributions to the background from v_{μ} -induced π° events (dashed line) and from beam v_e and \overline{v}_e (solid line). (b) The spectrum of events passing the electron cuts and the sum of the backgrounds (solid line).

6.3.2 CCFR Experiment

This experiment has been able to set limits on possible $v_{\mu} \rightarrow v_e$ oscillations at high Δm^2 using two different techniques. The first one of these, comparison of the measured NC/CC ratio with the prediction based on the best value of $\sin^2\theta_w$, was already discussed in Sec. 5.3 in connection with the $v_{\mu} \rightarrow v_{\tau}$ oscillation search.²³ Oscillations into v_e would also enhance the measured NC/CC ratio, even more so than oscillations into v_{τ} , because of the larger v_e CC cross section and the fact that all v_e CC events would be classified as NC events.

The other method relies on study of the longitudinal energy distribution of the apparent NC events⁹⁷ (i.e., "short" events). The v_e CC events will deposit a large fraction of their energy early in the hadronic shower; the true NC events will have a much broader distribution. Quantitatively, one defines a parameter η

$$\eta = 1 - (E_1 + E_2 + E_3)/E_{vis}$$
,

where E_i is the energy deposited in the i'th scintillator plane (recall that CCFR detector is composed of 10 cm thick Fe plates each one followed by a scintillator plane) after the v interaction. One can then calculate the expected number of events as a function of η for different values of E_{vis} , both for the v_e CC events and for the true NC events. The latter distribution can be obtained from the v_{μ} CC events by ignoring the energy deposited by the muon. The observed distributions can then be fit to a sum of the two component distributions. The actual data and these two component distributions are shown in Fig. 52 for four different neutrino energy bins: 40-50 GeV (a), 90-105 GeV (b), 150-175 GeV (c), and 250-300 GeV (d).



FIG. 52. Histograms of η distributions from the CCFR experiment for four different energy bands showing expected contributions from v_e CC events (peaking near $\eta = 0$) and the NC events, and the observed experimental distributions.

Since there are some v_e 's in the beam (~2%), there should be a nonzero v_e CC component. An oscillation signal would manifest itself as an excess of this component above and beyond what is expected from the knowledge of the beam composition. The study of the shape of the difference between these two energy spectra (the observed one and the predicted one assuming no oscillations) as a function of energy could then be used to obtain the best values of the oscillation parameters (if the difference is statistically significant) or set limits on these parameters if there are no statistically significant differences. The results of the analysis are shown in Fig. 53. No evidence for $v_{\mu} \rightarrow v_e$ oscillation is seen.



FIG. 53. Limits on oscillations from the CCFR experiment, based on the analysis of the longitudinal deposition of energy.

6.3.3 NOMAD Results on $\nu_{\mu} \rightarrow \nu_{e}$

The NOMAD detector has two characteristics that are important for possible v_e CC event identification: good electron identification (through TRD's and electromagnetic calorimetry) and fine-grained tracking. These two characteristics allow one to identify v_e CC interactions and also separate v_e from \bar{v}_e events. Thus v_{μ} , \bar{v}_{μ} , v_e , and \bar{v}_e charged current events can be separated from each other and their energy spectra measured. Furthermore, the v_e spectrum can be uniquely predicted from the other three spectra.

The argument is basically the following. The $\nu_{\mu}(\bar{\nu}_{\mu})$ spectra allow one to predict the primary yields of K⁺ and π^+ (K⁻ and π^-). One can then predict the contribution of K⁻ flux to the $\bar{\nu}_e$ spectrum, and after its subtraction, the residual $\bar{\nu}_e$ spectrum is used to determine the flux of K_L^0 's. These calculated yields of π^{\pm} , K^{\pm} , and K_L^0 predict uniquely the v_e spectrum, the v_e 's originating primarily from K⁺ and K⁰_L decays, with a small contribution from the decays of secondary μ^+ 's. Any possibly observed excess of v_e events would then be evidence for $v_{\mu} \rightarrow v_e$ oscillations. Furthermore, the energy dependence of this excess would allow one to determine the oscillation parameters. No excess is observed,⁸⁵ yielding a limit of $\sin^2 2\theta < 2 \times 10^{-3}$ at high Δm^2 . The calculated contribution of each kind of parent particle to the total neutrino flux is shown in Fig. 54.



FIG. 54. Contribution of different parent particles to the different beam components in the CERN neutrino beam.

Figure 55 shows the exclusion plots in the oscillation parameter space of the four results discussed above: BNL E776, the two measurements from CCFR, and the NOMAD limits. Combining all the relevant exclusion plots, we can see that a small part of the LSND suggested region is still compatible with all of the currently existing data. The future KARMEN experiment, however, should be able to confront this region directly as has been discussed above.



FIG. 55. 90% C.L. exclusion contours for $v_{\mu} \rightarrow v_{e}$ oscillations from the two CCFR measurements, BNL E776, and NOMAD experiments. The 90% C.L. LSND suggested region is indicated as the shaded area.