Update on the search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations by the KARMEN2 experiment

M. Steidl[a] representing the KARMEN collaboration

[a] Forschungszentrum Karlsruhe, Postfach 3640, 76021 Karlsruhe, Germany
Institut f. Kernphysik

The neutrino experiment KARMEN sets the most stringent exclusion limits for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations. Analyzing the data set recorded from Feb.1997 up to March 2000 with the upgraded experimental configuration, the search of $\bar{\nu}_e$ appearance via the $\mathrm{p}\,(\,\bar{\nu}_e\,, e^+\,)\,\mathrm{n}$ reaction yields no hints for neutrino oscillations. Applying a likelihood method to the measured event sample of 11 events (background expectation 12.3 events), we deduce an upper limit of $\sin^2(2\Theta) < 1.3 \cdot 10^{-3}$ for large $\Delta m^2 > 100$ eV^2 and $\Delta m^2 < 0.049$ eV^2 for $\sin^2(2\Theta)$=1.

1. Introduction

KARMEN (**KA**rlsruhe **R**utherford **M**edium **E**nergy **N**eutrino **E**xperiment) is searching for neutrino oscillations in different appearance modes ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, $\nu_\mu \rightarrow \nu_e$[1]) and disappearance ($\nu_e \rightarrow \nu_x$[2]) modes. KARMEN is sensitive to neutrino masses with far-reaching implications for astrophysics and cosmology. Furthermore KARMEN is currently the only experiment, which is sensitive to test $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations, with parameters claimed by the LSND experiment[3].

2. Neutrino Source and Detector

The KARMEN experiment is being performed at the neutron spallation facility ISIS of the Rutherford Appleton Laboratory (Chilton,UK). The neutrinos are produced by stopping 800 MeV protons in a beam dump Ta–D_2O–target: ν_μ, ν_e and $\bar{\nu}_\mu$ emerge with equal intensities from the decay chain $\pi^+ \rightarrow \mu^+ + \nu_\mu$ and $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$. The ν_μ from π^+–decay at rest are monoenergetic ($E_\nu = 30$ MeV) whereas the continuous energy distributions of ν_e and $\bar{\nu}_\mu$ up to 52.8 MeV can be calculated using the V–A theory. Two parabolic proton pulses of 100 ns base width and 325 ns apart are produced with a repetition frequency of 50 Hz. The different lifetimes of π^+ ($\tau = 26$ ns) and μ^+ ($\tau = 2.2\,\mu$s) allow a clear separation in time of the ν_μ–burst from the following ν_e and $\bar{\nu}_\mu$ and provide duty cycles of 1×10^{-5} and 5×10^{-4} respectively.

The neutrinos are detected in a 56 ton liquid scintillation calorimeter with an active volume of 96%. The detector is segmented into 512 optically individual modules by double acrylic walls with an air gap allowing efficient light transport via total internal reflection. Gd_2O_3 coated paper within the module walls provide efficient detection of thermal neutrons via Gd (n,γ) capture. A massive 7000 ton iron blockhouse in combination with three layers of active anti counters provides shielding against beam correlated spallation neutron background and suppression of hadronic and muonic cosmic background. The third veto counter has been commissioned in Feb. 1997, leading to a cosmic background reduction of a factor 40 [4] compared to the KARMEN1 configuration.

2.1. $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signature

The signature for $\bar{\nu}_e$ detection is a spatially and delayed correlated coincidence between a high energetic positron from the $\mathrm{p}\,(\,\bar{\nu}_e\,, e^+\,)\,\mathrm{n}$ reaction and the subsequent γ emission from neutron capture. The positrons show the 2.2 μs exponential decrease due to the μ^+–decay and are therefore expected in a time window of several μs after beam on target. The energies of the positrons reach up to 51 MeV. The shape of the expected energy spectrum strongly depends on Δm^2 , reflecting the Δm^2 dependence of the oscillation formula and an excellent energy resolution of the detector. In the data reduction we demand positron energies from 16-50 MeV and event times in the range of 0.6-10.6 μs. Neutrons are captured either on protons, emitting a single monoenergetic 2.2 MeV γ, or they are captured on Gd emitting on average 3 γ quanta with sum energy of 8 MeV. The time difference between e^+ and γ's from neutron capture shows an exponential decrease of 120 μs lifetime. A delayed coincidence is accepted with γ's in a delayed time window of 5-300 μs after the prompt event and to be within a coincidence volume of 1.2 m^3.

3. The $\bar{\nu}_\mu \to \bar{\nu}_e$ search

3.1. Data set

Here, data taken since the commissioning of the new veto in February 1997 until March 2000 are presented. In total 7160 Coulomb protons on target have been accumulated, which means a total neutrino production of 2.1 $\times$ 10^{21} $\bar{\nu}_\mu$. This corresponds to $\sim$ 75% of the total expected neutrino flux of the KARMEN2 experiment. Besides the characteristic sequential structure of a $\bar{\nu}_e$ induced event, we demand no previous activities in the various detector parts up to 24 μs. These cuts lead to a well defined, small event sample of 11 sequences, which in case of a small oscillation signal ensures a very good signal to background ratio. As it turns out from detailed background studies, the main background for the $\bar{\nu}_\mu \to \bar{\nu}_e$ search emerges from irreducible ν induced events. The cosmic induced background amounts to only 3.2 ± 0.2 events, which is remarkably low for a measuring time of 3 years. The neutrino induced background is dominated by sequences from the conventional ν_e- ^{12}C charged current reaction (see table 1) and random sequences between a prompt ν–nucleus interaction and an uncorrellated, subsequent low energetic event. Table 1 summarizes the background situation for the $\bar{\nu}_\mu \to \bar{\nu}_e$ search. In total, we expect a background of 12.3 ± 0.8 events. The small error of the background expectation is due to the fact that KARMEN is able to determine the contributions and signatures of background reactions a)-c) directly out of the neutrino data set. Only in the case of the intrinsic ISIS $\bar{\nu}_e$–contamination

Table 1
Total background expectation for $\bar{\nu}_e$ search

background reaction	events
a) cosmic induced	3.2 ± 0.8
b) $^{12}C(\nu_e, e^-)^{12}N_{g.s.}$	3.9 ± 0.5
c) ν induced random coincidences	3.5 ± 0.3
d) ISIS $\bar{\nu}_e$contamination	1.7 ± 0.2
Total background	12.3 ± 0.8

we have to rely on simulations.

In the examined neutrino data set we find 11 events fulfilling all conditions for the $\bar{\nu}_e$ signature. Applying Zechs formula one can deduce an upper limit for an oscillations signal of $N^{osci} < 6.3$ events (90% C.L.). This has to be compared to 2443 oscillation events for maximal mixing ($\sin^2(2\Theta)= 1$; Δm^2¿ 100 eV^2). Thus in the most simple approach we can deduce an upper limit of $\sin^2(2\Theta) < 2.6 \times 10^{-3}$ (90 % C.L.) for large Δm^2.

3.2. Likelihood Analysis

The 11 measured sequences are in good agreement with a pure background expectation not only quantitatively, but also they neither do not show obvious deviations in their signatures in comparison to the background expectation. Due to the very good resolution of the KARMEN detector in time, energy and position we apply an event-based likelihood analysis to determine the strength of a possible $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation signal in the experimental data.
The likelihood analysis maximizes the likelihood function:

$$L = \prod_{i=1}^{N} f(\vec{x}_i, \Delta m^2, \sin^2(2\Theta))$$

under the usage of the signatures $\vec{x}$ of all measured events (index i) in respect to the unknown parameters $\sin^2(2\Theta)$ and Δm^2. To construct the probability density function $f(\vec{x}, \sin^2(2\Theta), \Delta m^2)$ one needs as input an accurate knowledge of the probability functions in the specified signatures for all background components and signal. In the analysis presented here we make use of the following signatures: time and energy of prompt

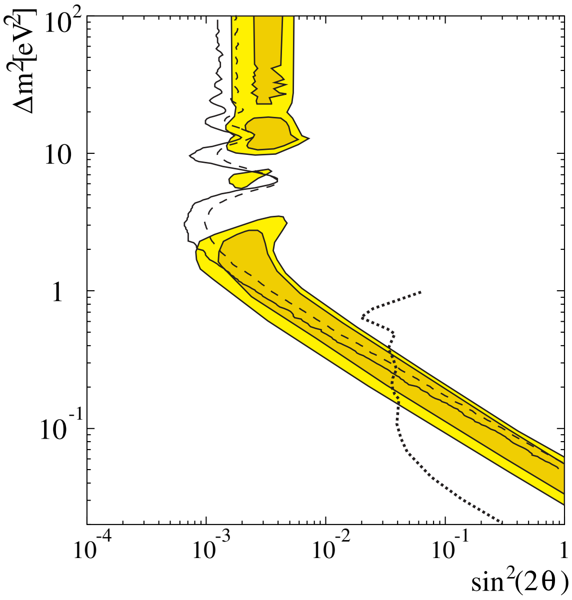

Figure 1. $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ search. Solid line: KARMEN2 exclusion curve 90% C.I.; broken line: KARMEN2 sensitivity; Dotted line: Bugey 90% C.L.; Shaded areas: LSND evidence (favored regions only).

event, time and energy of delayed event, and the spatial correlation between prompt and delayed event $\Rightarrow \vec{x} = (T_p, E_p, \Delta T, E_d, \Delta X)$.

Using the experimental signatures of the 11 measured events of the current KARMEN2 data, the likelihood function has its maximum for $\sin^2(2\Theta)$=0, i.e. the no oscillation hypothesis. So, even the more complex data analysis using the likelihood method does not find any hint for the presence of a $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal in the KARMEN2 data. To infer an upper limit from the likelihood function for the oscillation signal, respectively mixing angle, we apply a unified approach [5], thus constructing confidence intervals (C.I.) for $\sin^2(2\Theta)$ and Δm^2.

3.3. Results and Conclusions

For large $\Delta m^2 \geq 100$ eV^2 KARMEN excludes in the 90% C.I. an oscillation signal larger then 3.1 events. This corresponds to an upper limit of $\sin^2(2\Theta) < 1.3 \times 10^{-3}$. Figure 1 shows the latest $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ exclusion plot of the KARMEN2 experiment. The black solid line corresponds to the upper bound of the 90% C.I.. As can be seen, KARMEN2 excludes most of the parameter space of the reported LSND evidence. Even the 95% C.I. exclusion curve, not shown in the plot, excludes the LSND Likelihood favored regions above Δm^2=2eV^2. Below Δm^2 = 2eV^2 the KARMEN2 90% exclusion curve restricts most of the LSND parameter space and together with the Bugey result only a marginal region of the LSND area remains. Of course, these arguments are only a crude approach to assess the compatibility of the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ results as the 90% confidence levels do not represent all information which one can gain out of the LH functions. For this purpose a common analysis of the experiments as presented in [6] is needed.

Finally, it should be noted that the actual KARMEN2 limit is very close to the sensitivity, which is defined as the average limit on the oscillation parameters, expected from pure bg-measurements. KARMEN2 continues data taking until spring 2001. The final data set will help to draw further conclusions on the KARMEN2-LSND compatibility with more statistics from KARMEN2. According to Monte Carlo simulations KARMEN2 will have definitively the sensitivity to answer the existence of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ for $\Delta m^2 > 2$eV^2 given by LSND. For the LSND parameter space with $\Delta m^2 < 2$eV^2, a further restriction is expected based on pure bg-measurements, decreasing the overall likelihood for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations with parameters in the LSND region.

REFERENCES

1. B. Zeitnitz *et al.*, Prog. Part. Nucl. Physics **40**, 169 (1998).
2. B. Armbruster *et al.*, Phys. Rev. C **57**, 3414 (1998).
3. C. Athanassopoulos *et al.*, Phys. Rev. C 54, 2685 (1996).
4. G. Drexlin *et al.*, Prog. Part. Nucl. Physics **40**, 193 (1998).
5. G. Feldman, Phys. Rev. D **57** (1998) 3873
6. K. Eitel, New J. Phys. **2** (2000) 1.1