Results from the KARMEN Neutrino Experiment

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Abstract

KARMEN denotes an experimental program of neutrino physics using a pulsed source of neutrinos ν_μ, ν_e and $\bar{\nu}_\mu$ with energies up to 52.8 MeV and a 56 t scintillation calorimeter. Major physics aims are the measurement of charged current (CC) as well as neutral current (NC) neutrino nuclear interactions on ^{12}C with their implications for specific weak couplings, nuclear formfactors and μ-e universality and the search for neutrino oscillations $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$. We present the results of the KARMEN experiment from its first two years of data taking.

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1. Introduction

The KARMEN experiment is performed at the neutron spallation facility ISIS of the Rutherford Appleton Laboratory. From the decay of stopped pions produced in the UD_2O 'beam dump' of the pulsed 800 MeV proton beam of ISIS equal numbers of ν_μ , ν_e and $\bar{\nu}_\mu$ are emitted isotropically with energies up to 52.8 MeV according to the decay sequence $\pi^+ \rightarrow \mu^+ + \nu_\mu$; $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$. Because of the different lifetime of π^+ (26 ns) and μ^+ (2.2 μs) a prompt ν_μ - burst within the first 0.5 μs after proton beam-on-target is followed by a (ν_e , $\bar{\nu}_\mu$) - pulse in the later time window of 0.5 - 9 μs, where ν_μ are no longer present. The ISIS proton extraction frequency of 50 Hz defines a duty factor of the order of 10^{-4} which allows effective suppression of cosmic background. Neutrinos are detected in a high resolution 56 t liquid scintillation calorimeter [1]. Consisting entirely of hydrocarbons the calorimeter serves as a massive live target of ^{12}C - and ^{1}H - nuclei for the investigation of various ν - induced reactions [2].

2. Neutrino – Nuclear Interactions

The observation of ν - induced transitions between discrete nuclear states is an ideal tool to study in detail the structure of the weak hadronic current as well as to investigate fundamental properties of the neutrino itself. Due to the well defined change of quantum numbers in the nuclear transitions the target nucleus acts as a spin - isospin filter selecting specific parts of the weak hadronic current. In the case of the ν - induced transitions from $^{12}C_{g.s.}$ ($0^+ 0$) to the excited state $^{12}C^*$ ($1^+ 1$; 15.1 MeV) and the analogue state $^{12}N_{g.s.}$ ($1^+ 1$), both of which are observed in the KARMEN experiment, only the isovector - axialvector weak current contributes significantly. The inverse β - decay reaction ^{12}C (ν_e , e^-) $^{12}N_{g.s.}$ allows to study the q^2 - dependence of the dominant isovector - axialvector formfactor of the weak hadronic current; investigation of the NC transition ^{12}C (ν , ν') $^{12}C^*$ ($1^+ 1$; 15.1 MeV) induced by neutrinos of different flavours, i.e. ν_μ and ν_e or $\bar{\nu}_\mu$, provides a test of the flavour universality of the ν - Z^0 coupling.

3. Exclusive CC reaction ^{12}C (ν_e , e^-) $^{12}N_{g.s.}$

Detection of the exclusive charged current reaction ^{12}C (ν_e , e^-) $^{12}N_{g.s.}$ is based on a spatially correlated delayed coincidence between an electron from the inverse β - decay on ^{12}C during the ν_e - time window and a positron from the subsequent ^{12}N - decay. This decay, which uniquely identifies ν - induced transitions to the ground state of ^{12}N , is characterized by its lifetime of $\tau = 15.9$ ms with an end point energy of $E_0 = 16.3$ MeV. In addition, electron and positron are produced at the same position in the detector thus greatly reducing random background. The data sample used for the present analysis was taken from Dec. 1989 to Dec. 1991 corresponding to 2267 C protons on target. Software cuts on the time, energy and spatial correlation of the prompt and delayed signal (for details see [3]) selected 112 coincidence events from the data sample. The proof that these ν - candidates are indeed due to exclusive CC reactions is given by fig. 1 a - d) : the measured time- and energy distributions of the prompt and delayed signal are in very good agreement with what one expects from the reaction sequence

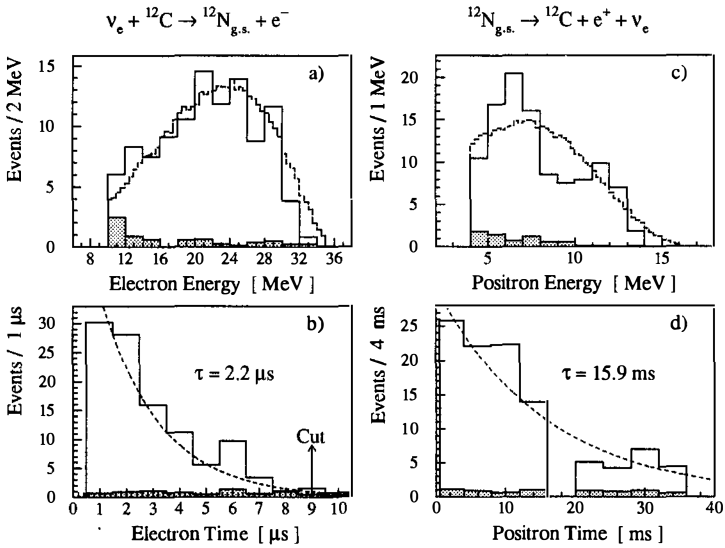

Fig. 1: Energy- and time distributions of the prompt and delayed signals of exclusive $^{12}C\,(\nu_e\,,e^-)\,^{12}N_{g.s.}$ reactions. Energy spectra are compared to MC simulations (broken lines), time distributions are shown with the decay curves of μ^+ ($\tau = 2.2\ \mu s$) and ^{12}N ($\tau = 15.9$ ms) superimposed. The normalized 'beam off' background is shown as shaded area.

$^{12}C\,(\nu_e\,,e^-)\,^{12}N_{g.s.} \rightarrow {}^{12}C + e^+ + \nu_e$. In particular the time distribution of the prompt signal (fig. 1b) clearly demonstrates the origin of these events to be induced by ν_e from μ^+-decay. From 105.2 ± 10.6 of these CC events left after background subtraction (signal-background ratio ≈ 15) the cross section for this exclusive reaction averaged over the Michel shape ν_e energy distribution (0-52.8 MeV) was deduced to be

$$\langle \sigma_{\text{excl. CC}} \rangle^{\text{exp}} = [\,8.0 \pm 0.8\,(\text{stat.}) \pm 0.75\,(\text{syst.})\,] \times 10^{-42}\ \text{cm}^2$$

This result is in good agreement with recent theoretical calculations [4, 5, 6] yielding values between $(8.0\text{-}9.4) \times 10^{-42}$ cm^2 with a 10 % uncertainty, as well as with an earlier experimental result from an experiment at LAMPF [7].

The good calorimetric properties of the KARMEN detector also allowed for the first time a measurement of the energy dependence of the $^{12}C\,(\nu_e\,,e^-)\,^{12}N_{g.s.}$ cross section. An unfolding procedure transformed the electron energy spectrum into a ν_e-energy distribution which then was subdivided into four energy bins. The resulting mean cross section in each energy interval is shown in fig. 2 in comparison with theoretical calculations without any further normalization. Where currently the measurement reflects the threshold behaviour of the reaction, improvement of statistics will allow also to investigate the q^2-dependence of the dominant axialvector formfactor.

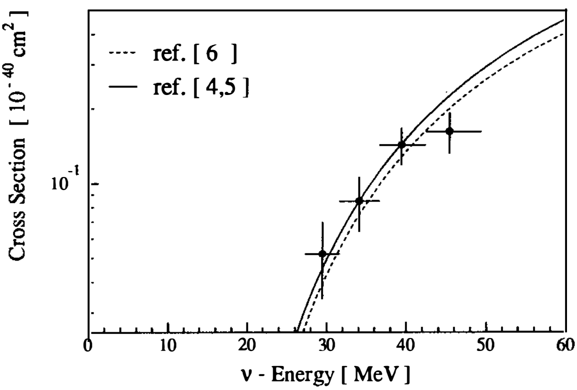

Fig. 2: Energy dependence of the ^{12}C (ν_e , e^-) ^{12}N$_{g.s.}$ cross section.

4. NC nuclear excitation ^{12}C (ν , ν') ^{12}C* ($1^+ 1$; 15.1 MeV)

Improved trigger conditions since summer 1990 allowed to identify for the first time the inelastic ν - scattering off ^{12}C - nuclei, i.e. NC events of the type $\nu + {}^{12}C \rightarrow \nu' + {}^{12}C^*$ ($1^+ 1$; 15.1MeV) [8]. The signal for this process is the detection of a localized scintillation event of 15 MeV visible energy from photons emitted as the ($1^+ 1$) analogue state of ^{12}C decays back to the ground state with a 94% γ - decay branching ratio. In order to optimize the signal to background ratio evaluation was restricted to the (ν_e , $\bar{\nu}_\mu$) - time window of 0.5 - 3.5 μs after beam-on-target. The energy spectrum of events satisfying these criteria with residual background from off beam analysis subtracted is shown in fig. 3 a). Above 17 MeV there is a broad distribution of events corresponding to inclusive charged current reactions, with no evidence for events above the kinematic limit. Between about 11 and 16 MeV lies a clearly recognizable peak which is ascribed to the ^{12}C (ν , ν') ^{12}C* ($1^+ 1$; 15.1 MeV) reaction. The time distribution of all events between 11 - 16 MeV shows an exponential time slope of 2.2 μs (fig. 3 b) above a flat cosmic background, indicating that indeed these events are induced by ν_e and $\bar{\nu}_\mu$ from μ^+ - decay. From 73.4 ± 18.6 events in the peak area between 11 and 16 MeV the flux averaged cross section for the sum of ν_e and $\bar{\nu}_\mu$ induced NC transitions was deduced to be

$$\langle \sigma_{NC} (\nu_e + \bar{\nu}_\mu) \rangle^{exp} = [9.1 \pm 2.3 \, (stat.) \pm 1.3 \, (syst.)] \times 10^{-42} \, cm^2$$

This result again is in good agreement with theoretical calculations for this reaction [4, 9, 10] giving values ranging from (9.9 - 10.3) $\times 10^{-42}$ cm^2.

5. Flavour universality of ν - NC coupling

Except for an isospin factor $1/\sqrt{2}$ the matrixelements of the dominant isovector axial-vector hadronic weak currents for the NC transition ^{12}C (ν_e , ν_e') ^{12}C*($1^+ 1$) and the CC reaction ^{12}C (ν_e , e^-) ^{12}N$_{g.s.}$ are the same [4, 6]. As the NC transition is simultaneously induced by two neutrino flavours of the same intensity, i.e. ν_e and $\bar{\nu}_\mu$, the ratio R of

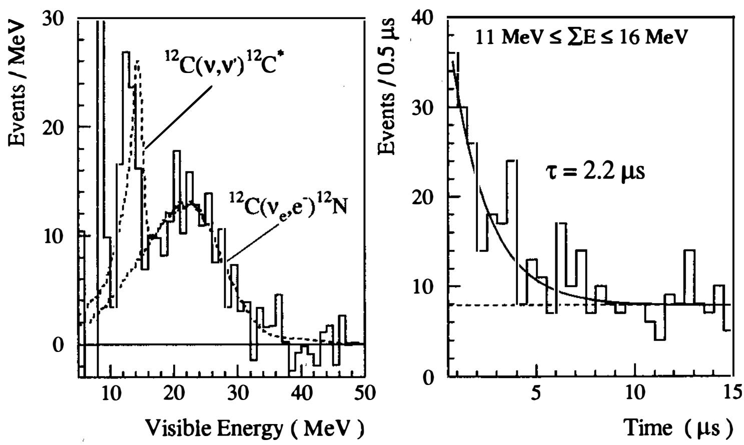

Fig. 3: a) Visible energies of single prong events in the (ν_e , $\bar{\nu}_\mu$) time window with background subtracted. The dotted line corresponds to MC simulations for inclusive CC reactions and the NC excitation of ^{12}C , respectively; b) event time with respect to beam-on-target in the neutral current energy window from 11 - 16 MeV, background not subtracted.

$\sigma_{NC}(\nu_e+\bar{\nu}_\mu)\ /\ \sigma_{CC}(\nu_e)$ is about 1, provided the ν_e couples in the same way to the Z^0 as $\bar{\nu}_\mu$. Because of the slightly different energy spectra of ν_e and $\bar{\nu}_\mu$ and also accounting for the small ν - $\bar{\nu}$ difference in the NC cross section the theoretical expectation for this ratio is $R=1.08$ [4] , where from our measurement we get $R=1.14\pm0.34$. This is a flux independent implicit test of the flavour universality in the neutrino NC coupling, which is going to be significantly improved with increasing statistics.

6. CC reaction $^{12}C\ (\nu_e\ ,e^-\ )\ ^{12}N^*$

The broad structure in the energy spectrum of single prong events of fig. 3 a) has been assigned to inclusive CC reactions. First of all, the time distribution of these events above 17 MeV again shows the typical 2.2 μs decay constant indicating these events being induced by neutrinos from μ^+ - decay. The kinematic distribution is well reproduced by a MC simulation including small contributions from ν - e scattering and from the $^{13}C\ (\nu_e\ ,e^-\ )\ ^{13}N$ reaction, where most of the events are inverse β - decay reactions on ^{12}C with only the electron being detected. The number of transitions to the ^{12}N ground state is well known from our measurement of the exclusive channel with subsequent ^{12}N - decay. The remaining events are thus ascribed to CC transitions to excited states of ^{12}N . From 99 ± 20 events above 17 MeV visible energy, assigned to $^{12}C(\nu_e\ ,e^-\ )\ ^{12}N^*$ reactions, the flux averaged cross section is determined to be

$$\langle\sigma_{CC\,excit.N}\rangle^{exp} = [\ 13.5\ \pm\ 2.8\,(stat.)\ \pm\ 1.5\,(syst.)\ ]\ \times\ 10^{-42}\ cm^2$$

This result contradicts theoretical values of 3.7×10^{-42} cm^2 calculated by Donnelly [5] and of 6.4×10^{-42} cm^2 by Kolbe et al. [12] as well as another experimental but, as we believe, less conclusive result [11] being in agreement with [5]. Currently there is no conclusive explanation for this deviation, but more elaborate theoretical work seems to be necessary to reliably calculate ν-induced transitions to excited nuclear states also with respect to solar neutrino detectors using nuclear inverse β- decay signatures.

7. Neutrino Oscillations

Having three types of neutrinos ν_μ, ν_e and $\bar{\nu}_\mu$, KARMEN is looking for appearance oscillations $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ simultaneously, whereas the actually present electron neutrinos are used for calibration and normalization purposes. Although the statistics after only two years of data taking is still very low a first preliminary analysis with respect to ν-oscillations was performed. With ν_μ from the decay $\pi^+ \to \mu^+ + \nu_\mu$ being monoenergetic, a search for $\nu_\mu \to \nu_e$ means to look for a 30 MeV ν_e during the short time window of ν_μ using the delayed coincidence signature of the exclusive CC reaction $^{12}C(\nu_e, e^-)^{12}N_{g.s.}$ described above. No event was found where one could have expected 56 events for full oscillation. From ν_e-contamination during ν_μ-time and off beam background one would have expected 0.4 and 0.3 events, respectively. Following the particle data group recommendation this means that more than 2.3 events from $\nu_\mu \to \nu_e$ oscillations can be excluded in the 90 % CL. The oscillation probability is thus $P_{\nu_\mu \to \nu_e} < 4.1 \times 10^{-2}$.

Evidence for an oscillation $\bar{\nu}_\mu \to \bar{\nu}_e$ would be the detection of $\bar{\nu}_e$ with energies up to 53 MeV during the $\bar{\nu}_\mu$ time. $\bar{\nu}_e$ not being present in the primary beam will be identified by another delayed coincidence signature, i.e. inverse β- decay on protons followed by (n, γ) capture of the thermalized neutron by a small amount of Gd in the module boundaries of the detector: $^1H(\bar{\nu}_e, e^+)n \to Gd(n,\gamma)$ with $\Sigma E = 8$ MeV. Four of such events have been found, where 206 would have been expected for full oscillation. With an expected background of 2.2 events this sets an oscillation limit of $P_{\bar{\nu}_\mu \to \bar{\nu}_e} < 2.8 \times 10^{-2}$ at 90 % CL. These limits are about an order of magnitude away from the currently published oscillation limits on this channel. After four more years of data taking KARMEN will have proven these limits with great reliability because of its good resolution figures, clear ν-signatures and well understood background conditions.

References

[1] G. Drexlin et al. (KARMEN Coll.), Nucl. Instrum. Methods **A 289** (1990) 490.

[2] G. Drexlin et al. (KARMEN Coll.), in: Neutrino Physics, Proc. of an Intern. Workshop (Heidelberg, Oct. 1987), eds. H.V. Klapdor and B. Povh (Springer, 1988) p. 147.

[3] G. Drexlin et al. (KARMEN Coll.), Phys. Lett. **B** , acc. for publ.

[4] M. Fukugita, Y. Kohyama and K. Kubodera, Phys. Lett. **B 212** (1988) 139.

[5] T.W. Donnelly , Phys. Lett. **B 43** (1973) 93 and private communication (1989).

[6] S.L. Mintz and M. Pourkaviani, Phys. Rev. **C 40** (1989) 2458.

[7] R.C. Allen et al., Phys. Rev. Letters **64** (1990) 1871.

[8] B. Bodmann et al. (KARMEN Coll.), Phys. Lett. **B 267** (1991) 321.

[9] M. Pourkaviani and S.L. Mintz, J. Phys. G: Nucl. Part. Phys. **16** (1990) 569.

[10] J. Bernabéu and P. Pascual, Nucl. Phys. **A 324** (1979) 365.

[11] D.A. Krakauer et al., Los Alamos Preprint LA-UR-91-3909 (1991).

[12] E. Kolbe et al., KFA - Report KFA-IKP(TH)-1991-48 (1991).