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First Observation of the Neutral Current Nuclear Excitation $^{12}C\,(\nu, \nu')^{12}C^*\,(1^+, 1)$

KARMEN Collaboration
Institut für Kernphysik

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$^{12}C(\nu, \nu')^{12}C^{*}$ (1 +, 1)

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Erste Beobachtung der neutralen schwachen Kernanregung $^{12}C(\nu, \nu')^{12}C^*$ (1+, 1)

Zusammenfassung

Die durch den neutralen Strom der schwachen Wechselwirkung induzierte Kernanregung $^{12}C(\nu, \nu')^{12}C^*$ (1+, 1; 15.1 MeV) wurde erstmalig beobachtet. Für ν_e und $\bar{\nu}_\mu$ aus dem μ^+-Zerfall in Ruhe wurde der über den Neutrinofluß gemittelte Wirkungsquerschnitt dieser Reaktion zu $< \sigma_{NC} (\bar{\nu}_\mu + \nu_e) > = \{ 10.8 \pm 5.1 \text{ (stat)} \pm 1.1 \text{ (syst)} \} * 10^{-42}$ cm^2 bestimmt.

First Observation of the Neutral Current Excitation $^{12}C(\nu, \nu')^{12}C^*$ (1+, 1)

Abstract

The neutral current nuclear excitation $^{12}C(\nu, \nu')^{12}C^*$ (1+, 1; 15.1 MeV) has been observed for the first time. For ν_e and $\bar{\nu}_\mu$ from μ^+-decay at rest the flux averaged cross section was determined to be $\langle \sigma_{NC} (\nu_e + \bar{\nu}_\mu) \rangle = \{ 10.8 \pm 5.1 \text{ (stat)} \pm 1.1 \text{ (syst)} \} * 10^{-42}$ cm^2.

KARMEN Collaboration

G. Drexlin, V. Eberhard, H. Gemmeke, G. Giorginis[(1)], W. Grandegger,
M. Kleifges, J. Kleinfeller, R. Maschuw, P. Plischke, F. Raupp[(2)], J. Wochele,
J. Wolf, S. Wölfle, B. Zeitnitz

Institut für Kernphysik I, Kernforschungszentrum Karlsruhe, and
Institut für Experimentelle Kernphysik, Universität Karlsruhe, Postfach 3640,
D-7500 Karlsruhe, FRG

B. Bodmann, F. Burtak, E. Finckh, A. Glombik, T. Hanika, W. Kretschmer,
R. Meyer, F. Schilling

Physikalisches Institut, Universität Erlangen-Nürnberg, Erwin-Rommel-Strasse 1,
D-8520 Erlangen, FRG

J.A. Edgington, T. Gorringe[(3)], A. Malik, B. Seligmann

Physics Department, Queen Mary and Westfield College, Mile End Road,
London E14NS, UK

A. Dodd

Rutherford Appleton Laboratory, Chilton, Didcot, OX11 0QX, UK

N.E. Booth

Department of Nuclear Physics, Oxford University, Keble Road, Oxford OX1 3RH,
UK

[(1)] **Present address : CBNM / JRC , 2440 Geel, Belgium.**

[(2)] **Present address : ESG , 8000 München, Germany.**

[(3)] **Present address : Univ. of Kentucky, Lexington, KY 40502, USA.**

The KArlsruhe Rutherford Medium Energy Neutrino Experiment KARMEN [1,2] is operating at the spallation facility ISIS of the Rutherford Appleton Laboratory using the pulsed beam dump neutrino source of ν_μ, ν_e and $\bar{\nu}_\mu$. Monoenergetic ν_μ with energy 29.8 MeV emerge from π^+-decay at rest while the subsequent μ^+-decay provides ν_e and $\bar{\nu}_\mu$ with energies up to 52.8 MeV. Due to the different lifetimes of π^+ (26 ns) and μ^+ (2.2 μs) there is a prompt burst of ν_μ during the 0.5 μs of proton beam-on-target whereas subsequently one is left with ν_e and $\bar{\nu}_\mu$ from the slower μ^+-decay. This pattern recurs with the ISIS acceleration cycle of 50 Hz.

Neutrinos are detected by a 56 tonne high resolution liquid scintillation calorimeter in a 6000 tonne shielding blockhouse (for details of the experimental setup see Reference 3). Major physics aims of the experiment are the search for neutrino oscillations $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ and the observation of neutrino nucleus interactions with their implications for specific weak couplings and μ-e universality.

KARMEN has been taking data since November 1989. From these data we have determined [4] the exclusive cross section for the charged current (CC) reaction $^{12}C(\nu_e, e^-)^{12}N_{g.s.}$. In this Letter we report the first measurement of the neutral current (NC) nuclear excitation $^{12}C(\nu, \nu')^{12}C^*$ $(1^+, 1; 15.1\ \mathrm{MeV})$. The data analysed were taken during 88 days running in 1990 corresponding to 570 Coulombs of protons of 750 MeV on target.

The signal for the inelastic ν-scattering process is the detection of a localised scintillation event at 15 MeV from photons emitted as the $(1^+,1)$ analogue state of ^{12}C decays with a γ-decay branching ratio [5] of 94 % to the ground state. Transitions induced by ν_e and by $\bar{\nu}_\mu$ cannot be distinguished by timing. Their joint event rate is expected, on account of the energy dependence of the interaction, to be about four times that of ν_μ-induced reactions which have only poor statistics. We therefore searched for neutral current nuclear excitations during the $(\nu_e, \bar{\nu}_\mu)$-time window only. After about two muon life times there is little increase in signal. Thus in order to maximise the signal to background ratio the present analysis was restricted to times between 0.5 μs and 3.5 μs after beam-on-target. Background due to interactions of cosmic rays was reduced by a factor of ten by requiring that none be detected in the detector or its veto shield during a 20 μs period preceding a candidate event within the fiducial volume.

The energy spectrum of events satisfying these criteria is shown in fig. 1. Also shown is the spectrum of residual non-beam background (shaded area) measured with high statistical precision during the 80 μs just before beam-on-target. The sources of this muon induced background have been studied closely and are understood; the major contribution at low energies comes from electrons ($E_{max} = 13.4$ MeV) from ^{12}B - decay following $^{12}C(\mu^-, \nu_\mu)^{12}B$ reactions. Owing to the ^{12}B lifetime of 30 ms the initial muon capture reaction can occur several beam periods before decay, so evading the usual cosmic ray veto. A smaller portion of background extending to higher energies stems from bremsstrahlung of electrons from the decay of stopped muons. At low energies there is another background contribution (black area), rising fast with decreasing energy, known from measurements up to 100 μs after beam-on-target to be due to beam-associated low energy neutrons detected by the $Gd(n,\gamma)$ - reaction [6]. These events dominate the low energy region so we apply a software threshold of 10 MeV though our result is insensitive to the precise value of this cut.

After subtraction of background the energy distribution of neutrino induced events is shown in fig. 2. Above about 17 MeV there is a broad distribution of events corresponding to inclusive charged current reactions, with no evidence for events above the kinematic limit. At about 15 MeV lies a clearly recognisable peak which we ascribe to the $^{12}C(\nu, \nu')^{12}C^*$ $(1^+, 1; 15.1$ MeV$)$ reaction.

Fig. 3 shows the time distribution of all events above 10 MeV of fig. 2. The distribution is fitted by an exponential function having a decay constant of 2.5 ± 0.5 μs consistent with its being due entirely to neutrinos from μ^+ - decay at rest which also holds if only the events of the 15 MeV peak area are considered; the 2.2 μs decay curve is superimposed on fig. 3.

The distribution of fig. 2 is well fitted by a Monte Carlo simulation including both inclusive charged current reactions, normalised to the energy interval 17 - 50 MeV and the neutral current reaction $^{12}\mathrm{C}(\nu,\nu')^{12}\mathrm{C}^*$ with an adjustable norm. Evaluation of the data between 11 and 16 MeV yields 38.1 ± 9.3 events of which 16.6 ± 4.1 are contributed by the tail of the inclusive reaction distribution leaving 21.5 ± 10.1 events to be attributed to the $^{12}\mathrm{C}(\nu,\nu')^{12}\mathrm{C}^*\ (1^+, 1; 15.1\ \mathrm{MeV})$ - reaction. We calculate the overall detection efficiency for this process to be 0.29 ± 0.01 where, in addition to the detector response function, the effects of energy and timing cuts are included. Taking the neutrino flux to be that corresponding to a π^+ - to - proton ratio [7] of 0.032 ± 0.003 we derive an interaction cross section for ν_e and $\bar{\nu}_\mu$ jointly of

$$\langle \sigma_{\mathrm{NC}}(\nu_e + \bar{\nu}_\mu) \rangle^{\mathrm{exp}} = [\,10.8 \pm 5.1\,(\mathrm{stat}) \pm 1.1\,(\mathrm{syst})\,] \times 10^{-42}\ \mathrm{cm}^2$$

where the average is over the neutrino energy distributions (Michel spectra) from muon decay.

This result is in agreement with recent calculations for the weak neutral current excitation of the $^{12}\mathrm{C}(1^+, 1)$ state performed by several authors [8,9,10,11] using the elementary particle approach yielding almost identical results i.e.

$$\langle \sigma_{\mathrm{NC}}(\nu_e + \bar{\nu}_\mu) \rangle^{\mathrm{theo}} = [\,9.9 \pm 1.0\,] \times 10^{-42}\ \mathrm{cm}^2$$

So within the limitations of these experimental and theoretical uncertainties the elementary particle approach using standard model weak interaction couplings seems successfully to describe this previously unobserved neutral current nuclear excitation.

Provided the neutrino has a non-vanishing magnetic moment the same transition can be mediated by the electromagnetic interaction. However, even for $\mu_\nu = 4 \times 10^{-10}$ μ_{Bohr} which is the current upper laboratory limit for a neutrino magnetic moment its contribution to the cross section of the $^{12}\mathrm{C}(\nu,\nu')^{12}\mathrm{C}^*\ (1^+, 1; 15.1\ \mathrm{MeV})$ reaction is negligible [12].

The KARMEN experiment is scheduled to run for four more years. With increased ISIS beam energy (to 800 MeV) and intensity and recent shielding and trigger improvements we are aiming to reduce overall cross section uncertainties for this reaction to $\simeq 10\%$ for both ν_μ and $(\nu_e + \bar{\nu}_\mu)$. These measurements will provide information on the isovector axialvector weak coupling which mediates this NC nuclear transition. Moreover comparison of ν_μ and ν_e induced cross sections will test the equivalence of ν_μ, ν_e coupling to the Z^0 - boson (μ - e universality).

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[12] The electromagnetic cross section for a neutral current nuclear excitation due to a neutrino magnetic moment has recently been calculated by A. Dodd, E. Papageorgiu and S. Ranfone (submitted to Phys. Lett. B). For the energy range of the KARMEN experiment it is comparable to the NC weak cross section only for values of $\mu_\nu > 10^{-8}\ \mu_{Bohr}$ (S.L. Mintz, M. Pourkaviani, H. Gemmeke : private communication).

Figure Captions :

Figure 1

Visible energy of single prong events during the (ν_e , $\bar{\nu}_\mu$) - time window in the energy range between 10 MeV and 50 MeV. The shaded area represents the non-beam background measured with high precision during the 80 μs before beam-on-target; the black area corresponds to beam associated slow neutron background detected via Gd (n,γ) capture.

Figure 2

Visible energy of neutrino induced events (i.e. same as fig. 1 but with background subtracted). The dashed and dotted lines indicate the Monte Carlo distributions for inclusive charged current reactions and the neutral current $^{12}C(\nu, \nu')^{12}C^*$ (1^+ , 1 ; 15.1 MeV) reaction respectively.

Figure 3

Event time with respect to beam-on-target for all neutrino induced events above 10 MeV of fig. 2, the dashed line represents the 2.2 μs decay curve of μ^+ at rest.

Figure 1

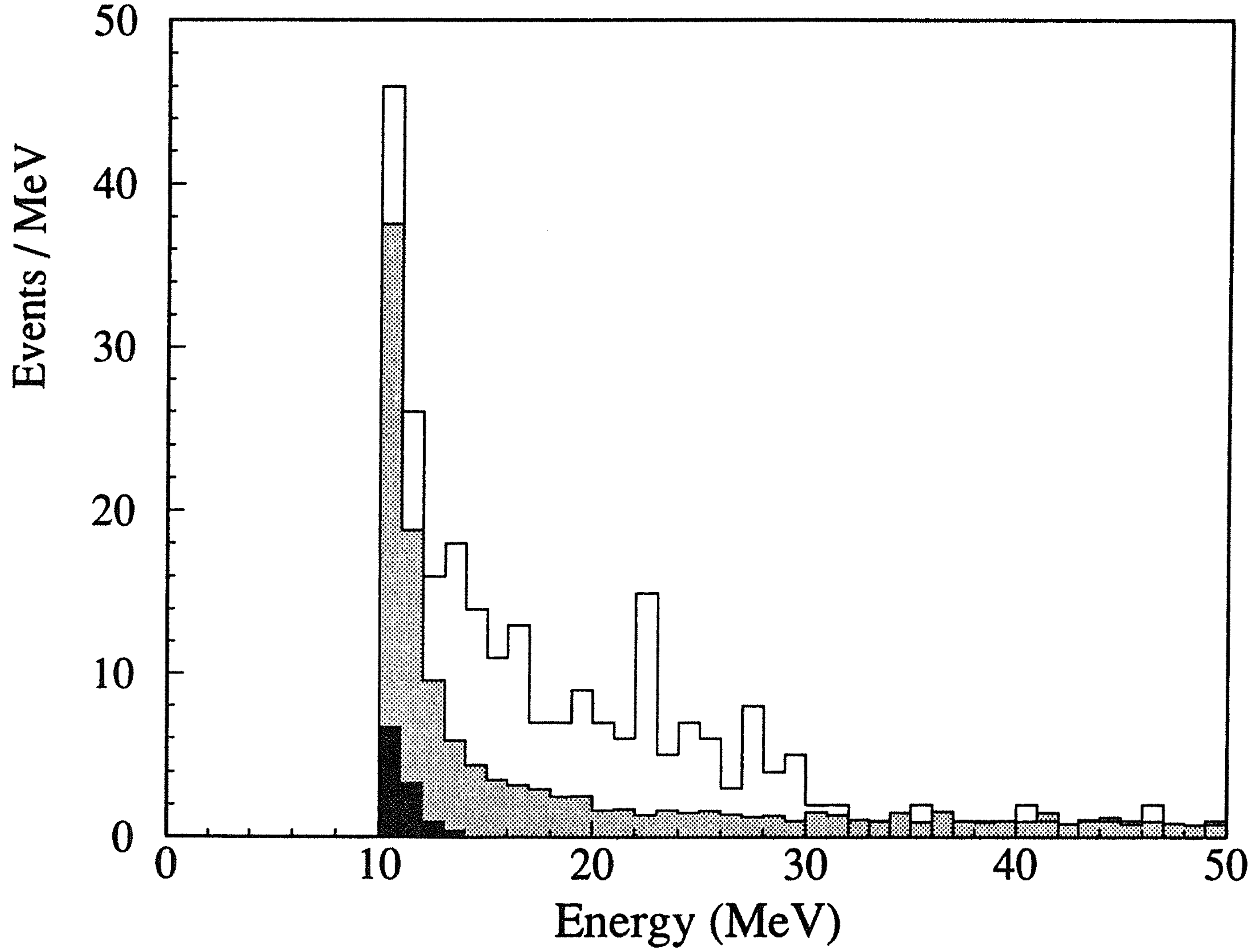
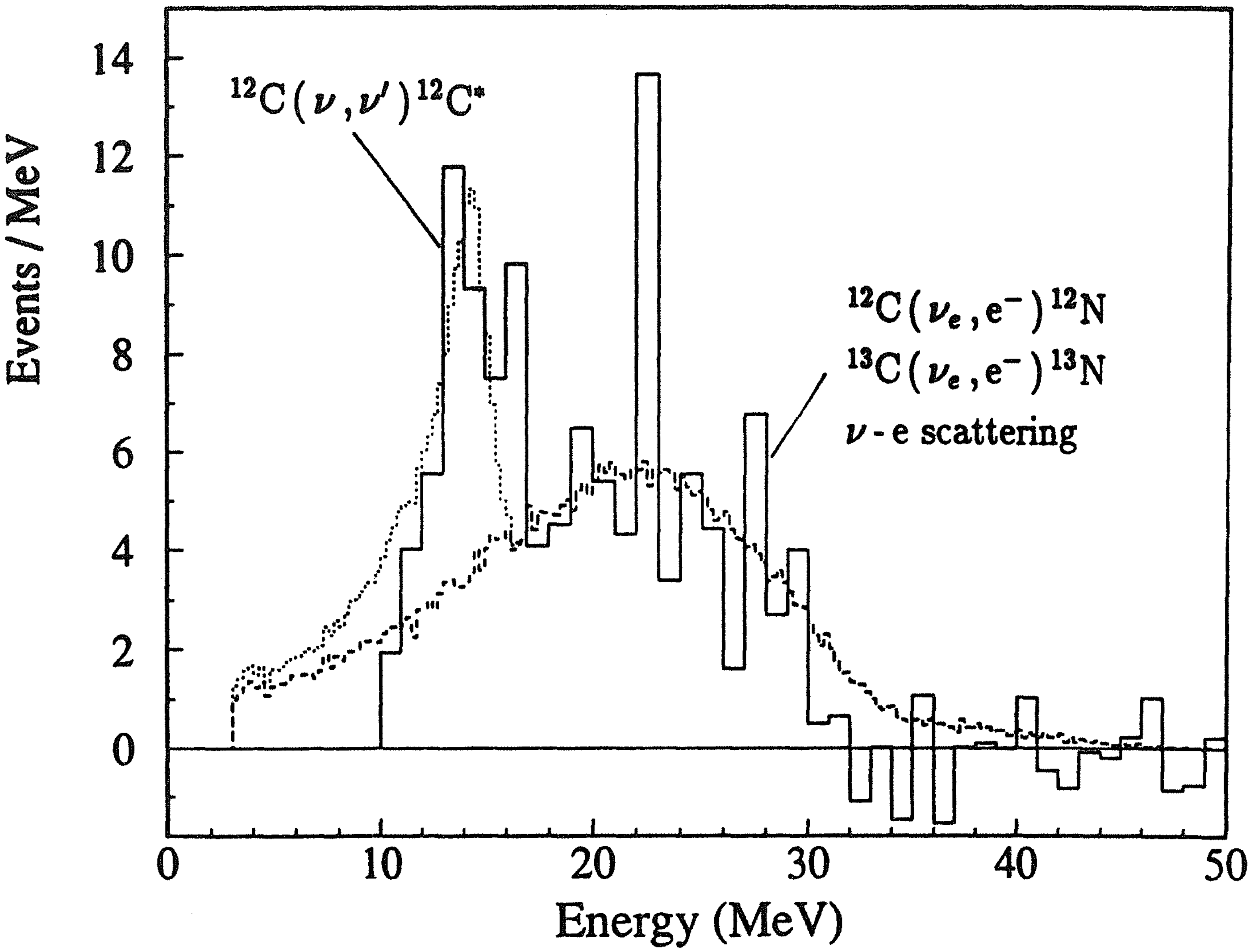


Figure 2



Events / MeV
Energy (MeV)
$^{12}C(\nu,\nu')^{12}C^*$
$^{12}C(\nu_e,e^-)^{12}N$
$^{13}C(\nu_e,e^-)^{13}N$
ν - e scattering
0
2
4
6
8
10
12
14
0
10
20
30
40
50

Figure 3