ELSEVIER

Physics Letters B 527 (2002) 23–28

PHYSICS LETTERS B

www.elsevier.com/locate/npe

New results on a search for a 33.9 MeV/c^2 neutral particle from π^+ decay in the NOMAD experiment

NOMAD Collaboration

P. Astier [n], D. Autiero [h], A. Baldisseri [s], M. Baldo-Ceolin [m], M. Banner [n],
G. Bassompierre [a], K. Benslama [i], N. Besson [s], I. Bird [h,i], B. Blumenfeld [b], F. Bobisut [m],
J. Bouchez [s], S. Boyd [u], A. Bueno [c,y], S. Bunyatov [f], L. Camilleri [h], A. Cardini [j],
P.W. Cattaneo [o], V. Cavasinni [q], A. Cervera-Villanueva [h,w], G. Collazuol [m],
G. Conforto [v], C. Conta [o], M. Contalbrigo [m], R. Cousins [j], D. Daniels [c], H. Degaudenzi [i],
T. Del Prete [q], A. De Santo [h], T. Dignan [c], L. Di Lella [h], E. do Couto e Silva [h],
J. Dumarchez [n], M. Ellis [u], T. Fazio [a], G.J. Feldman [c], R. Ferrari [o], D. Ferrère [h],
V. Flaminio [q], M. Fraternali [o], J.-M. Gaillard [a], E. Gangler [h,n], A. Geiser [e,h], D. Geppert [e],
D. Gibin [m], S.N. Gninenko [h,l], A. Godley [u], M.C. Gonzalez-Garcia [w],
J.-J. Gomez-Cadenas [h,w], J. Gosset [s], C. Gößling [e], M. Gouanère [a], A. Grant [h],
G. Graziani [g], A. Guglielmi [m], C. Hagner [s], J. Hernando [w], D. Hubbard [c], P. Hurst [c],
N. Hyett [k], E. Iacopini [g], C. Joseph [i], F. Juget [i], M.M. Kirsanov [l], O. Klimov [f],
J. Kokkonen [h], A.V. Kovzelev [l,o], N.V. Krasnikov [l], A. Krasnoperov [a,f], S. Lacaprara [m],
C. Lachaud [n], B. Lakić [x], A. Lanza [o], L. La Rotonda [d], M. Laveder [m],
A. Letessier-Selvon [n], J.-M. Levy [n], L. Linssen [h], A. Ljubičić [x], J. Long [b], A. Lupi [g],
A. Marchionni [g], F. Martelli [v], X. Méchain [s], J.-P. Mendiburu [a], J.-P. Meyer [s],
M. Mezzetto [m], S.R. Mishra [c,t], G.F. Moorhead [k], D. Naumov [f], P. Nédélec [a],
Yu. Nefedov [f], C. Nguyen-Mau [i], D. Orestano [r], F. Pastore [r], L.S. Peak [u],
E. Pennacchio [v], H. Pessard [a], R. Petti [h,o], A. Placci [h], G. Polesello [o], D. Pollmann [e],
A. Polyarush [l], B. Popov [f,n], C. Poulsen [k], P. Rathouit [s], J. Rico [y], C. Roda [h,q],
A. Rubbia [h,y], F. Salvatore [o], K. Schahmaneche [n], B. Schmidt [e,h], M. Sevior [k], D. Sillou [a],
F.J.P. Soler [h,u], G. Sozzi [i], D. Steele [b,i], U. Stiegler [h], M. Stipčević [x], Th. Stolarczyk [s],
M. Tareb-Reyes [i], G.N. Taylor [k], V. Tereshchenko [f], A.N. Toropin [l], A.-M. Touchard [n],
S.N. Tovey [k], M.-T. Tran [i], E. Tsesmelis [h], J. Ulrichs [u], L. Vacavant [i],
M. Valdata-Nappi [d,p], V. Valuev [f,j], F. Vannucci [n], K.E. Varvell [u], M. Veltri [v], V. Vercesi [o],
G. Vidal-Sitjes [h,w], J.-M. Vieira [i], T. Vinogradova [j], F.V. Weber [c,h], T. Weisse [e],
F.F. Wilson [h], L.J. Winton [k], B.D. Yabsley [u], H. Zaccone [s], K. Zuber [e], P. Zuccon [m]

PII: S0370-2693(01)01486-1

[a] *LAPP, Annecy, France*
[b] *Johns Hopkins University, Baltimore, MD, USA*
[c] *Harvard University, Cambridge, MA, USA*
[d] *University of Calabria and INFN, Cosenza, Italy*
[e] *Dortmund University, Dortmund, Germany*
[f] *JINR, Dubna, Russia*
[g] *University of Florence and INFN, Florence, Italy*
[h] *CERN, Geneva, Switzerland*
[i] *University of Lausanne, Lausanne, Switzerland*
[j] *UCLA, Los Angeles, CA, USA*
[k] *University of Melbourne, Melbourne, Australia*
[l] *Inst. Nucl. Research, INR, Moscow, Russia*
[m] *University of Padova and INFN, Padova, Italy*
[n] *LPNHE, University of Paris VI and VII, Paris, France*
[o] *University of Pavia and INFN, Pavia, Italy*
[p] *University of Perugia and INFN, Perugia, Italy*
[q] *University of Pisa and INFN, Pisa, Italy*
[r] *Roma Tre University and INFN, Rome, Italy*
[s] *DAPNIA, CEA, Saclay, France*
[t] *University of South Carolina, Columbia, SC, USA*
[u] *University of Sydney, Sydney, Australia*
[v] *University of Urbino, Urbino, and INFN Florence, Italy*
[w] *IFIC, Valencia, Spain*
[x] *Rudjer Bošković Institute, Zagreb, Croatia*
[y] *ETH Zürich, Zürich, Switzerland*

Received 11 December 2001; accepted 18 December 2001

Editor: L. Montanet

Abstract

We report on a direct search in NOMAD for a new 33.9 MeV/c^2 neutral particle (X) produced in pion decay in flight, $\pi \to \mu X$ followed by the decay $X \to \nu e^+ e^-$. Both decays are postulated to occur to explain the time anomaly observed by the KARMEN experiment. From the analysis of the data collected during the 1996–1998 runs with 4.1×10^{19} protons on target, a single candidate event consistent with background expectations was found. The search is sensitive to a pion branching ratio $\mathrm{BR}(\pi \to \mu X) > 3.7 \times 10^{-15}$, significantly smaller than previous experimental limits. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Neutrino mixing; Neutrino decay

The Karmen Collaboration at the ISIS spallation neutron facility of the Rutherford Appleton Laboratory has reported on an anomaly in the time distribution of neutrino interactions from muon decay at rest [1]. The anomaly is an enhancement in the time distribution of ν_e and $\bar{\nu}_\mu$ induced events which was expected to be well described by the single exponential from muon decay at rest. This anomaly, seen in the KARMEN1 data, is not statistically significant in the KARMEN2 data. However, a substantial effect still persists in the combined data from both experiments [2]. The KARMEN Collaboration interpreted the anomaly as being due to an exotic decay of π^+-mesons into a muon and a 33.9 MeV/c^2 new fermion X. They reported values for the pion branch-

---

E-mail address: sergei.ginenko@cern.ch (S.N. Gninenko).

ing ratio $\mathrm{BR}(\pi^+ \to \mu^+ + X)\,\mathrm{BR}(X \to \text{visible})$ as a function of the X-lifetime, τ_X, needed to explain this effect with a branching ratio $BR(\pi^+ \to \mu^+ + X)$ as small as 10^{-16} [1]. The $X \to$ visible decay is presumably associated with the $X \to \nu e^+e^-$ mode favoured by the energy distribution measured in the KARMEN detector. This and other hypotheses explaining the anomaly have been recently extensively investigated both theoretically [3,5] and experimentally [6,7,9].

Barger et al. [3] associated the new particle with a 33.9 MeV/c^2 isosinglet neutrino dominantly mixing with ν_τ. This interpretation has been studied by NOMAD [8] resulting in a small X lifetime window between $\simeq 10^{-2}$ s and the Big Bang Nucleosynthesis (BBN) lower limit of Ref. [4] of 0.1 s left untested.

The new X particle has been directly searched for at PSI by looking for a peak in the momentum spectrum of muons from this two-body pion decay. The result gives a limit on the branching ratio of $BR(\pi^+ \to \mu^+ + X) < 6.0 \times 10^{-10}$ at 95% CL [6]. A result on the search for the $X \to e^+e^-\nu$ decay in flight has also been recently reported by the NuTeV Collaboration [9].

In this Letter we have studied the decay $X \to \nu e^+e^-$ as a possible manifestation of the presence of X's in the neutrino beam. The occurrence of $X \to \nu e^+e^-$ decays would appear as an excess of isolated e^+e^- pairs in NOMAD above those expected from standard neutrino interactions. The present analysis as well as the experimental signature of the signal events are similar to those of our published heavy neutrino search [8].

An essentially pure ν_μ beam is produced from decays of secondary pions in a 290 m long evacuated decay tunnel. The pions are generated in a beryllium target irradiated by 450 GeV protons from the CERN SPS. The NOMAD detector is located 835 m from the target.

The detector is described in Ref. [11]. It consists of a number of sub-detectors most of which are located inside a 0.4 T dipole magnet with a volume of $7.5 \times 3.5 \times 3.5\ \mathrm{m}^3$: an active target of drift chambers (DC) with a mass of 2.7 tons (mainly carbon), an average density of 0.1 $\mathrm{g/cm}^3$ and a total thickness of about one radiation length ($\sim 1.0 X_0$) followed by a transition radiation detector (TRD), a preshower detector (PRS), and a lead-glass electromagnetic calorimeter (ECAL). A hadron calorimeter (HCAL) and two muon stations are located just after the magnet coils. A plane of veto scintillation counters, V, in front of the magnet and two planes of scintillation counters T_1 and T_2 located before and after the TRD were used to form the $\overline{V}T_1T_2$ trigger for neutrino interactions or decays in the DC target.

The electron identification in NOMAD is provided mainly by the TRD which has an efficiency of more than 90% for isolated electrons of momentum 1–50 GeV/c for a charged pion rejection factor greater than 10^3 [12].

The flux and energy spectrum of π's produced in the Be target by primary protons were calculated using the Monte Carlo simulation described in [13]. The X flux was calculated assuming a branching ratio $BR(\pi \to \mu X) = 1$ and $m_X = 33.9\ \mathrm{MeV}/c^2$ as a function of the X lifetime. Note that due to the small Q value (≈ 5 keV) in $\pi \to \mu X$ and the high value of the pion γ-factor ($\gamma \approx 10^3$) the X particle follows the π^+ direction. Once the X flux is known, the next step consists in calculating the e^+e^- energy spectrum based on the $X \to \nu e^+e^-$ decay model used for the heavy neutrino search [8]. The decay electrons and positrons were tracked through the DC target taking into account the emission of photons, their conversion and multiple scattering in the target. The details of the NOMAD simulation and reconstruction are described elsewhere [8,13].

The search for $X \to \nu e^+e^-$ described in this Letter uses the full data sample collected with the $\overline{V}T_1T_2$ trigger [11] during the years 1996–1998. The data correspond to a total number of protons on target (pots) of 4.1×10^{19}.

The following initial selection criteria were applied to identify isolated e^+e^- pairs: (i) the presence of two tracks with at least one identified as an electron and forming a vertex within the DC fiducial volume; (ii) no other tracks incompatible with conversions of photons emitted by the primary e^+e^- pair; (iii) the total energy of the pair must be greater than 4 GeV and its invariant mass $m_{e^+e^-}$ must be lower than 95 MeV/c^2 to remove background from pairs of particles other than e^+e^-; (iv) no additional significant activity in the ECAL, HCAL and muon stations.

Only 207 events passed these criteria. At the next step we used a collinearity variable $\mathcal{C} \equiv 1 - \cos\Theta_{\nu e^+e^-}$, where $\Theta_{\nu e^+e^-}$ is the angle between the average neutrino beam direction and the total momen-

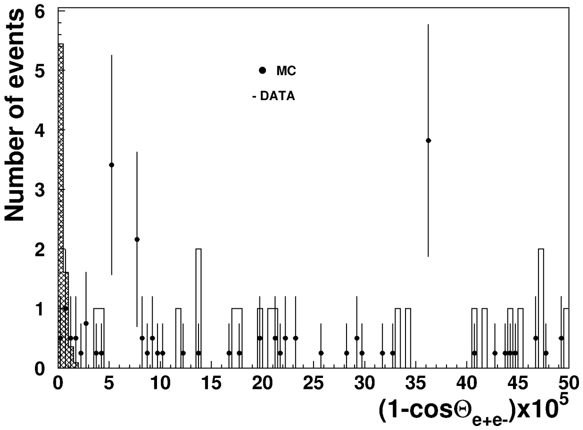

Fig. 1. The final $(1-\cos\Theta_{\nu e^+e^-})$ distribution for the data and MC. The dashed histogram represents the distribution expected from signal events.

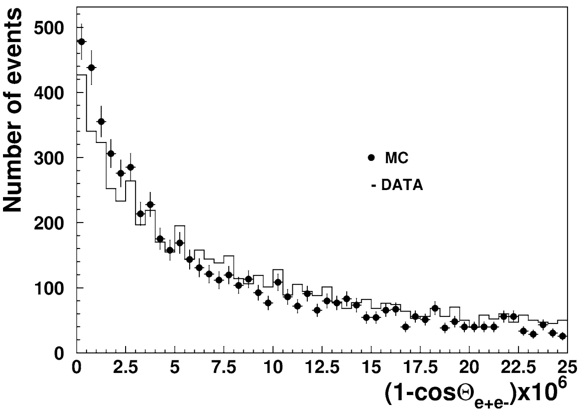

Fig. 2. The $(1-\cos\Theta_{e^+e^-})$ distribution for e^+e^- pairs from photons converted in the DC target at large distances from the primary vertex for the data and MC.

tum of the reconstructed e^+e^- pair. A cut on this variable, used very effectively in our previous search [8], allowed a strong background suppression. A MC simulation of $X \to \nu e^+e^-$ decays shows (see Fig. 1) that the $X \to \nu e^+e^-$ events have $\mathcal{C} < 2 \times 10^{-5}$. The contribution to the broadening of the signal distribution from the angular divergence of the pion beam is much smaller than the expected resolution in the variable $\mathcal{C}$. In order to avoid biases in the determination of selection criteria, a blind analysis was performed. Events in a signal box defined by $\mathcal{C} < 2 \times 10^{-5}$ were excluded from the analysis of the data until the validity of the background estimate in this region was demonstrated. This was done by verifying that the MC simulation of standard processes reproduced the data outside the box.

The accuracy of the collinearity determination obtained with MC simulations was checked using a $\nu_\mu CC$ data sample with an e^+e^- pair from a photon converted in the DC target at a large ($\gtrsim 100$ cm) distance from the primary vertex. Fig. 2 shows the $(1-\cos\Theta_{e^+e^-})$ distribution of such events in the data and simulation, where $\Theta_{e^+e^-}$ is the angle between the e^+e^- pair momentum and the line joining the primary vertex to the conversion point. The two distributions are in reasonable agreement at all energies studied. This validates the resolution in the variable $\mathcal{C}$ (a few mrad in $\Theta_{\nu e^+e^-}$) predicted by the MC program.

The reconstruction efficiency for the $X \to \nu e^+e^-$ decay in the NOMAD fiducial volume was calculated from the MC simulation as a function of e^+e^- energy in the range 4 to 50 GeV. The MC simulation was used to correct the data for acceptance losses, experimental resolution and reconstruction efficiencies. Two methods using both data and MC simulation samples of reconstructed π^0's and γ's, described in detail elsewhere [8], have been used to verify the reliability of the simulation and to estimate the systematic uncertainties in the e^+e^- pair efficiency reconstruction in the energy range predicted by the simulation.

It was found that the two methods agree quite well in the low energy region and yield a correction factor close to 1. However, in the high energy region the e^+e^- efficiency correction factor varied from 0.7 ± 0.04 to 0.4 ± 0.03 depending on the e^+e^- energy.

The largest contribution to the background is expected from neutrino interactions in the material upstream of the decay volume yielding a single π^0 with little hadronic activity in the final state. Because of the large mass of this upstream material the study of this background would require the simulation of a very large number of events resulting in a prohibitively large amount of computer time. Consequently, only about 10% of the required statistics for $\nu_\mu CC(NC)$ inelastic reactions were simulated, while other background components, such as $\nu_e CC$, coherent π^0 production, quasi-elastic reactions and $\nu_\mu e$ scattering were simulated with statistics comparable to the number of events expected in the data from these reactions.

The distribution of the variable $\mathcal{C}$ for the sum of all the MC samples is shown in Fig. 1. The plot covers the region $\mathcal{C} < 5 \times 10^{-4}$, which is 25 times larger than the size of the signal box. No $\nu_\mu CC(NC)$ event is found in this region. The data outside the box, also shown in Fig. 1, are consistent with the MC prediction (19 evens observed and 20 ± 4 events predicted). The estimate of background from $\nu_\mu CC(NC)$ in the signal box is based on the observation that there are *no physical reasons* for this background to be other than flat in the region $\mathcal{C} < 5 \times 10^{-4}$.

Two independent methods based on the MC and on the data themselves, described in detail elsewhere [8], were used for the background estimation in the signal region. The final background estimates with the two methods are $N_{\text{bkg}}^{\text{MC}} = 2.5^{+0.9}_{-0.8}(\text{stat}) \pm 0.6(\text{syst})$ events from the MC and $N_{\text{bkg}}^{\text{Data}} = 2.4^{+0.9}_{-0.9}(\text{stat}) \pm 0.7(\text{syst})$ events from the data. The systematic error includes the uncertainties in the number of *pots* (5%) and in the coherent π^0 production cross section (25%). The total systematic uncertainty was calculated by adding all errors in quadrature. It was decided to use the background estimate extracted from the data themselves.

Upon opening the signal box we have found one event that passes our selection criteria. This is consistent with the expected background and hence no evidence for the decay $\pi^+ \to \mu^+ X$ has been found. We can then determine the 90% CL upper limit for the corresponding value of $\text{BR}(\pi \to \mu X)\,\text{BR}(X \to \nu e^+ e^-)$ from the 90% CL upper limit for the expected number of signal events, $N^{\text{up}}_{X \to \nu e^+ e^-}$. Using the frequentist approach of Ref. [14] and taking into account the uncertainties in the background estimate we obtain $N^{\text{up}}_{X \to \nu e^+ e^-} = 2.1$ events. The probability to obtain an upper limit of 2.1 or lower is 29% given the background estimates.

The final 90% CL exclusion region in the $\text{BR}(\pi \to \mu X)\,\text{BR}(X \to \nu e^+ e^-)$ vs τ_X plane is shown in Fig. 3 together with the NuTeV [9] and PSI [6] exclusion regions for τ_X as well as the NOMAD lower limit [8] and BBN upper limit [10] obtained for the scenario of Ref. [3]. Our result is sensitive to a pion branching ratio $\text{BR}(\pi \to \mu X) > 3.7 \times 10^{-15}$ which is significantly smaller than the previous limit from the NuTeV experiment [9].

We gratefully acknowledge the CERN SPS accelerator and beam-line staff for the magnificent performance of the neutrino beam. The experiment was supported by the following funding agencies: Australian Research Council (ARC) and Department of Industry, Science, and Resources (DISR), Australia; Institut National de Physique Nucléaire et Physique des Particules (IN2P3), Commissariat à l'Energie Atomique (CEA), France; Bundesministerium für Bildung und Forschung (BMBF, contract 05 6DO52), Germany; Istituto Nazionale di Fisica Nucleare (INFN), Italy; Russian Foundation for Basic Research, Institute for Nuclear Research of the Russian Academy of Sciences, Russia; Fonds National Suisse de la Recherche Scientifique, Switzerland; Department of Energy, National Science Foundation (grant PHY-9526278), the Sloan and the Cottrell Foundations, USA.

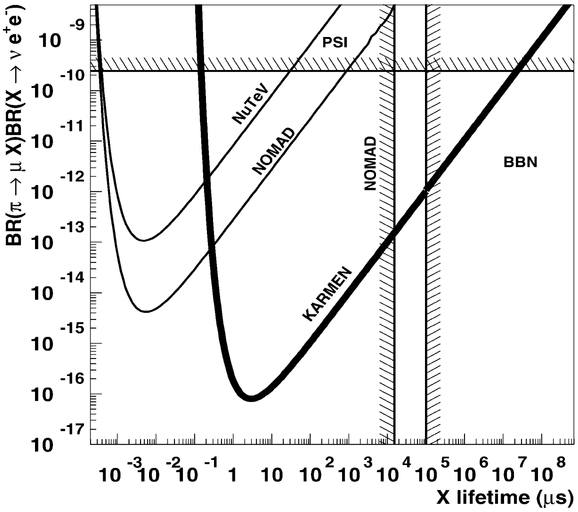

Fig. 3. The NOMAD 90% CL upper limit as a function of the X lifetime together with the NuTeV [9] and PSI [6] limits. The NOMAD lower limit [8] and BBN upper limit [10] on X lifetime for the interpretation of X as a sterile neutrino mixing with the τ neutrino are also shown.

References

[1] KARMEN Collaboration, B. Armbruster et al., Phys. Lett. B 348 (1995) 19;
KARMEN Collaboration, B. Zeitnitz, WIN '99, Cape Town, ZAR (2000).
[2] K. Eitel et al., Nucl. Phys. B, Proc. Suppl. 91 (2001) 191.
[3] V. Barger, R.J.N. Phillips, S. Sarkar, Phys. Lett. B 352 (1995) 365;
V. Barger, R.J.N. Phillips, S. Sarkar, Phys. Lett. B 356 (1995) 671, Erratum.
[4] A.D. Dolgov et al., Nucl. Phys. B 580 (2000) 331.
[5] J. Govaerts, J. Deutsch, P.M. Van Hove, Phys. Lett. B 389 (1996) 700;

D. Choudhury, S. Sarkar, Phys. Lett. B 374 (1996) 87;
D. Choudhury et al., Phys. Rev. D 61 (2000) 095009;
M. Kachelrieß, hep-ph/0001160;
I. Golman, R. Mohapatra, S. Nussinov, Phys. Lett. B 481 (2000) 151;
S.N. Gninenko, N.V. Krasnikov, Phys. Lett. B 434 (1998) 163;
J.M. Levy, F. Vannucci, hep-ph/0003194;
A. Lukas, A. Romanino, hep-ph/0004130.

[6] M. Daum et al., Phys. Rev. Lett. 85 (2000) 1815;
M. Daum et al., Phys. Lett. B 361 (1995) 179.

[7] R. Bilger et al., Phys. Lett. B 363 (1995) 41;
D.A. Bryman, T. Numao, Phys. Rev. D 53 (1996) 558;
R. Bilger et al., Phys. Lett. B 446 (1999) 363.

[8] NOMAD Collaboration, P. Astier et al., Phys. Lett. B 506 (2001) 27.

[9] NuTeV Collaboration, J.A. Formaggio et al., Phys. Rev. Lett. 84 (2000) 4043.

[10] A.D. Dolgov et al., Nucl. Phys. B 590 (2000) 562.

[11] NOMAD Collaboration, J. Altegoer et al., Nucl. Instrum. Methods A 404 (1998) 96.

[12] G. Bassompierre et al., Nucl. Instrum. Methods A 403 (1998) 363;
G. Bassompierre et al., Nucl. Instrum. Methods A 411 (1998) 63.

[13] NOMAD Collaboration, P. Astier et al., Prediction of neutrino fluxes in the NOMAD experiment, in preparation.

[14] G.J. Feldman, R.D. Cousins, Phys. Rev. D 57 (1998) 3873.