SEARCH FOR COHERENT MUON PAIR PRODUCTION BY NEUTRINOS AND ANTINEUTRINOS

CHARM Collaboration

F. BERGSMA, J. DORENBOSCH, M. JONKER, C. NIEUWENHUIS
NIKHEF, Amsterdam, The Netherlands

J.V. ALLABY, U. AMALDI, G. BARBIELLINI [1], L. BARONE [2], A. CAPONE [2], W. FLEGEL, M. METCALF, J. PANMAN, K. WINTER
CERN, Geneva, Switzerland

J. ASPIAZU, F.W. BÜSSER, H. DAUMANN, P.D. GALL, E. METZ, F. NIEBERGALL, K.H. RANITZSCH, P. STÄHELIN
II. Institut für Experimentalphysik [3], Universität Hamburg, Hamburg, Germany

A. ASRATYAN, P. GORBUNOV, E. GRIGORIEV, V. KAFTANOV, V. KHOVANSKY, A. ROSANOV
Institute for Theoretical and Experimental Physics, Moscow, USSR

and

A. BARONCELLI [4], B. BORGIA [5], C. BOSIO [4], F. FERRONI [5], E. LONGO [5], P. MONACELLI [5], F. DE NOTARISTEFANI [5], P. PISTILLI [5], C. SANTONI [4], L. TORTORA [4] and V. VALENTE [6]
Istituto Nazionale di Fisica Nucleare, Rome, Italy

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A search for coherent $\mu^+\mu^-$ pair production has been made using the CHARM neutrino detector exposed to wide-band horn-focussed neutrino and antineutrino beams at the 400 GeV CERN SPS. Out of 3.3×10^6 neutrino and antineutrino induced CC events with energy greater than 10 GeV, we find two events which can be attributed to coherent production off the target nuclei ($CaCO_3$). This allows a limit to be set on the diagonal four-lepton coupling constant $G_d < 1.5\, G_f$ (90% CL).

A study of the reactions

$$\nu_\mu + (A,Z) \to \nu_\mu \mu^+ \mu^- + (A,Z)\,, \tag{1}$$

$$\bar{\nu}_\mu + (A,Z) \to \bar{\nu}_\mu \mu^+ \mu^- + (A,Z)\,, \tag{2}$$

provides information about the diagonal four-fermion interaction [1]. A priori the coupling constant $G_d = (g_l^2 + g_r^2)^{1/2}$ of this interaction is unknown. (Here g_l and g_r are left- and right-handed coupling constants.) In general one expects it to be of the order of the Fermi coupling constant G_f [1]. In particular, in the Glashow–Salam–Weinberg mod-

[1] On leave of absence from INFN, LN Frascati, Italy.
[2] On leave of absence from Istituto di Fisica, University of Rome and INFN Sezione di Roma, Italy.
[3] Supported by Bundesministerium für Forschung und Technologie, Bonn, German Federal Republic.
[4] INFN Sezione Sanità and Istituto Superiore di Sanità, Rome, Italy.
[5] Istituto di Fisica, University of Rome and INFN Sezione di Roma, Italy.
[6] Laboratori Nazionali INFN Frascati, Italy.

el [2] $G_d = 0.77 G_f$ for $\sin^2\theta_w = 0.23$. A preliminary upper limit of $G_d < 1.6 G_f$ (90% CL) was reported by the CDHS group [3].

We have searched for reactions (1) and (2) using the fine-grain CHARM detector with marble plates as a target exposed to wide-band horn-focussed neutrino and antineutrino beams at the 400 GeV CERN SPS. A detailed description of the experimental set-up is given elsewhere [4].

The detector was triggered by requiring that at least four scintillator planes be hit, that the detected ionization be larger than 100 MeV (corresponding to an absolute energy larger than about 1 GeV [5]), and that a track penetrated at least three magnets of the muon spectrometer.

The fiducial volume was chosen to obtain the largest target mass. The vertex was required to be in a volume of 270×270 cm^2 cross sectional area and extending from plane 3 to plane 68 of the calorimeter (corresponding to a target mass of 129 tons).

In two exposures of 1.4×10^{18} and 5.7×10^{18} protons on target, respectively, 1.5×10^6 and 1.8×10^6 charged current events with energy greater than 10 GeV were observed in neutrino and antineutrino beams. Since we are interested in quantities which are symmetric with respect to μ^+ and μ^-, we have combined the neutrino and antineutrino data.

The following criteria were applied to select opposite sign dimuon candidates:

(1) The hadron energy deposited in the calorimeter (E_h) was required to be less than 3 GeV, where E_h was obtained from the detected ionization by subtracting the contribution deposited by the muons and converting the result to an absolute energy scale based on calibration measurements [5].

(2) Each of the two muons was required to penetrate the muon spectrometer. (The corresponding effective momentum cut is 7 ± 2 GeV/c).

The number of candidates after this selection is 27.

Events of the reactions (1) and (2) can be identified by the particular characteristics of the coherent production mechanism. The invariant mass of the two muons should be small and no visible recoil is expected. Consequently, the analysis aimed at selecting dimuon events without visible hadron recoil.

In fig. 1 the distribution of the ionization detected in 10 scintillator planes following the vertex is shown for the 27 candidates. The arrow indicates the ionization of 150 MeV as expected for two muons without recoil. Below 200 MeV there are 8 events. The efficiency of this 200 MeV cut (corresponding to a cut of 600 MeV in E_h [‡1]) was determined experimentally from the energy loss distribution of muons with the result $\epsilon = (89.5 \pm 1.0)\%$.

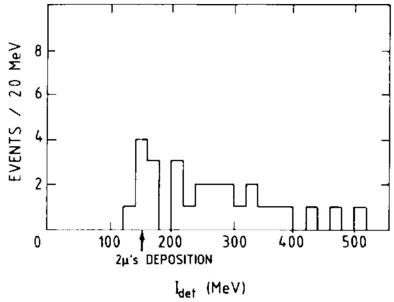

Fig. 1. Distribution of the detected ionization (I_{det}) in the first 10 scintillator planes of the calorimeter following the vertex. The arrow indicates the ionization expected for two muons without recoil.

The $\mu^+\mu^-$ invariant mass distribution for 8 candidates is shown in fig. 2. The curve given in the same figure is the distribution calculated by Monte Carlo simulation (MC), and normalized according to the

[‡1] With the cut of 200 MeV and the expected ionization of 150 MeV there is allowance of 50 MeV for additional ionization due to recoils. Converting this to an absolute scale means it corresponds to 600 MeV.

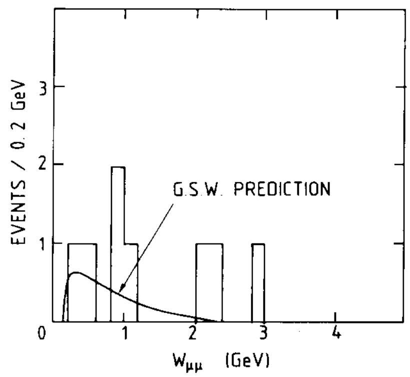

Fig. 2. The $\mu^+\mu^-$ invariant mass distribution for events with less than 200 MeV detected ionization in the first 10 scintillator planes. The curve is the MC prediction normalized according to the Glashow–Salam–Weinberg model with $\sin^2\theta_W = 0.23$.

Glashow–Salam–Weinberg model with $\sin^2\theta_w$ = 0.23. This simulation [6] included data on the actual neutrino and antineutrino spectra, the beam composition, as well as the experimental resolutions. The shape of the curve is model-independent since $W(\mu\mu)$ is symmetric in the muon momenta. According to this calculation 60% of the events of reactions (1) and (2) survive the cut $W(\mu\mu) < 0.8$ GeV, whereas most of the background due to semileptonic decays of hadrons is expected to be removed. We observe two events with $W(\mu\mu) < 0.8$ GeV. A Monte Carlo simulation of the background is unreliable; we therefore estimate the background from the data themselves. For this purpose we select events with small but visible recoil. In fig. 3 the dimuon invariant mass distribution is shown for 19 event with more than 200 MeV detected ionization in the first 10 scintillator planes and $0.6 < E_h < 3.0$ GeV. A single event is found with $W(\mu\mu) < 0.8$ GeV. Assuming that there is no essential difference in the background dimuon mass distribution for low hadron energy and for recoil-less events, we estimate the number of background events with $W(\mu\mu) < 0.8$ GeV to be 0.3 ± 0.5. The predicted number of events of reactions (1) and (2) based on the observed single $\mu\pm$ rate is $(3.0 \pm 0.4) \times (G_d/G_f)^2$.

For the diagonal four-lepton coupling constant this gives

$$G_d = (0.75 \pm 0.40) \times G_f .$$

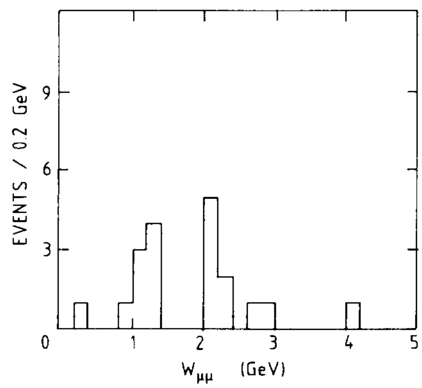

Fig. 3. The $\mu^+\mu^-$ invariant mass distribution for events with more than 200 MeV detected ionization and $0.6 < E_h < 3.0$ GeV, used to estimate the background for recoil-less events with $W(\mu\mu) < 0.8$ GeV.

In the context of gauge theories this result suggests, within the very large error, that the interference between the W and Z boson exchange diagrams for the reactions (1) and (2) is destructive rather than constructive, as is the case for the Glashow–Salam–Weinberg scheme.

The result obtained allows a limit to be set on the diagonal four-lepton coupling constant which is

$$G_d < 1.5\ G_f \text{ (90\% confidence level)} .$$

Using the same data sample we also obtain an upper limit on axion production in p–Be collisions. A limit on axion production in p–Cu collisions was reported recently by the CDHS collaboration [7].

Since axions would manifest themselves as muon pairs produced via a coherent Bethe–Heitler process off the target material nuclei

$$a^0 + CaCO_3 \to \mu^+\mu^- + CaCO_3 , \qquad (3)$$

the event signature is identical to that of reactions (1) and (2).

We assume that axions are produced in p–Be collisions analogously to π^0's. For the interaction cross section (3) we use the value given by Bardeen et al. [8]. Due to the large uncertainties in the evaluation of the production cross section, we neglect the contribution from the hadronic cascade after the primary proton interaction.

Interpreting the two observed events as being induced by axions the following limits (90% CL) are obtained:

$$(1/x^2)\sigma(p + N \to a^0 + X) < 330 \text{ pb/nucleon} ,$$

if axions are produced with the same A-dependence as π^0's and

$$(1/x^2)\sigma(p + N \to a^0 + X) < 250 \text{ pb/nucleon} ,$$

for the case of a linear A-dependence. The parameter x is the ratio of the vacuum expectation values of the two Higgs fields. Its value is not determined by the theory. Sometimes [8] it is assumed to be close to unity.

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