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OBSERVATION AND STUDY OF THE $\nu_\mu e^- \rightarrow \nu_\mu e^-$
REACTION IN GARGAMELLE AT HIGH ENERGY

Gargamelle Collaboration

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ABSTRACT

A search for the reaction $\nu_{\mu} + e^{-} \rightarrow \nu_{\mu} + e^{-}$ was made in the bubble chamber Gargamelle exposed to the wide-band neutrino beam of the CERN-SPS. Ten isolated e^{-} were found above 2 GeV energy. All of them were emitted at an angle smaller than 1.5° with respect to the beam. The background is 0.2 ± 0.2 events. Results on cross-section are given in terms of vector and axial vector coupling constants. A comparison is made with the standard SU (2) $\otimes$ U (1) model: no agreement is found with the currently accepted value of the mixing angle. Possible sources other than the above reaction are discussed.

The purely leptonic reactions

$$\nu_{\mu} + e^{-} \rightarrow \nu_{\mu} + e^{-} \quad (1) \quad \text{and} \quad \bar{\nu}_{\mu} + e^{-} \rightarrow \bar{\nu}_{\mu} + e^{-} \quad (2)$$

are of great importance for the study of weak interaction processes induced by neutral currents since only the leptonic current is involved. However, only limited results [1,2,3] have been obtained so far, due to the exceedingly low cross-sections and to difficult background problems.

A search for reaction (1) has been made in the heavy liquid bubble chamber Gargamelle exposed to the wide-band neutrino beam of the CERN-SPS which peaks at 25 GeV neutrino energy and extends up to 200 GeV (fig. 1). The chamber was filled with a mixture of propane (90.5% in moles) and freon CF_3Br (9.5%), yielding a radiation length $X_0 = 61$ cm. This mixture ensured a very good efficiency for the signature of electrons, either by spiralization or by electromagnetic shower development, and on the other hand it allowed a clear separation between γ -rays and electrons. The experimental arrangement was completed by two MWPC placed respectively upstream and downstream against the chamber body (fig. 2) for detecting charged particles entering or leaving the chamber, and by two planes of MWPC interspersed with an iron shielding (EMI) for the identification of muons above 2.5 GeV.

A sample of about 128 000 pictures taken was scanned for spiralizing tracks or electromagnetic showers with no charged hadron at the vertex and no visible source in the chamber. Events were retained only if they occurred in a fiducial volume of 5.1 m^3 inside a visible volume of 7.2 m^3 , and if they satisfied the condition $E > 2 \text{ GeV}$. Such events were classified as "isolated e^{-} " candidates if there was only a single track at the vertex of the interaction. Furthermore no e^{+} nor e^{-} above 30 MeV had to exist on the track within the first seven centimetres, and no e^{+} above 2.5 MeV within the first centimetre. The other events were classified as "isolated γ -rays", and were used for background calculations.

Ten e^{-} events were found which fulfilled these conditions (table 1). One of these is shown in fig. 5. Remarkably enough all the e^{-} events have an angle to the beam direction smaller than 1.5° (fig. 3). This is what was expected from the kinematics of reaction (1), which imposes that

$$\theta_e \ll \sqrt{\frac{2 m_e}{E_e}},$$

when taking into account a mean uncertainty of 0.5° from track measurement. For the background analysis, an extended angular region of 3° was defined, in which 13 isolated γ -rays were found. The separation between electrons and γ -rays (i.e. e^+e^- pairs) was checked by comparing the bubble density near the vertex to that of minimum ionizing electrons in the same shower. A ratio between 0.8 and 1.2 was found for each of the 10 e^- candidates, whilst the same ratio was found to be greater than 1.5 for identified γ -rays. We conclude that our 10 e^- candidates are actually single electron tracks. The signal had to be corrected for scanning efficiency and electron identification. A subsample of 36% of the films was scanned twice and the scanning efficiency was found to be 85% per scan, within the cuts, or $(90 \pm 6)\%$ on average in the total sample.

The probability for an isolated electron to be identified by electromagnetic processes is found equal to 99% by a Monte-Carlo method. This high efficiency is due to a potential path for the tracks of four radiation lengths on average. The probability of misclassifying a genuine electron as a γ -ray because of early showering, estimated in the same calculation, was found to be $(8 + 3.7 \ln E_{\text{GeV}})\%$. Thus, the overall detection efficiency for electrons is:

$$\beta(E) = 0.90 \text{ (scanning)} \times 0.99 \text{ (ident.)} \times (0.92 - 0.037 \ln E_{\text{GeV}}) \text{ (misclas.)}.$$

Three background processes could give rise to isolated single electrons:

- high energy γ -rays, by asymmetric e^+e^- pair creation, Compton effect, or annihilation of the e^+ close to the vertex of the e^+e^- pair created;
- isolated μ^- 's or π^- 's energetic enough to develop an electromagnetic shower and imitate an electron;
- charged current interactions of ν_e with nuclei in which the hadrons escape detection.

The photon background was estimated experimentally using a sample of 183 e^+e^- pairs or $e^\pm$ in the 2 to 20 GeV energy range, associated with interactions of neutrinos in the chamber. Indeed, no single e^- was found in this sample, giving a limit to the probability for a γ -ray to simulate a single electron of 1.2% at 90% CL. This is in excellent agreement with theoretical calculations. From the sample of isolated γ -rays the photon background is found to be smaller than 0.13 events.

To estimate the muon background, it was verified that none of the 10 e^- candidates were associated with hits in the EMI. This background is negligible since the EMI efficiency is almost 100% for μ 's produced in the beam direction.

Concerning the π^- background, the probability for a π to give an electromagnetic shower was experimentally determined to be less than 2%. On the other hand, all the isolated negative particles leaving the chamber without shower were found to hit the EMI. Thus, no isolated leaving π^- were observed in the beam direction, and consequently this background is also negligible.

The charged current reaction $\nu_e + n \rightarrow e^- + p$ (3) could fake a $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$ reaction if no protons are seen. The probability that the proton escapes detection was computed from the similar reaction $\nu_\mu + n \rightarrow \mu^- + p$. The ratio

$$R_\mu = \frac{\mu^- (\theta_\mu < 3^\circ) + \text{proton unseen}}{\mu^- + p}$$

was estimated in two ways. First, the q^2 distribution of $\mu^- p$ events was compared to the prediction of a Monte-Carlo using $M_A^2 = 0.9 \text{ GeV}^2/c^4$ for the axial mass M_A in the form-factor and taking nuclear re-interactions into account. From the loss of events at low q^2 , attributed to events classified as isolated μ^- , $R_\mu = (0.06 \pm 0.03)$. Secondly, R_μ was computed from the 15 isolated μ^- events observed. At energy above 11 GeV, some of these isolated μ^- are produced through the reaction $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$. From the theoretical cross-section, this contribution amounts to 6 ± 3 events and is subtracted from the observed 15 μ^- events. This leads to $R_\mu = 0.05 \pm 0.03$, in agreement with the previous determination. This value

compares well with the one obtained at CERN PS energy (0.11 ± 0.02) [4] as is expected from the energy independence of the q^2 distribution. Since three e^-p events are observed, the background from reaction (3) is equal to 0.2 ± 0.2 events. Of course, the experimental ratio R_μ takes into account any neutrino reaction on hadronic target yielding a single muon in the final state (e.g. $\nu_\mu + C^{12} \rightarrow \mu^- + N^{*12}$ [5]). Thus, the contribution of the corresponding ν_e reactions yielding a single electron is included in the previous background estimate. Finally, the background from reaction $n + e^- \rightarrow n + e^-$ is completely negligible.

To conclude, the signal of isolated e^- consists of 10 events, with a total background of 0.2 ± 0.2 events.

An additional source of isolated e^- is the reaction $\nu_e + e^- \rightarrow \nu_e + e^-$ which is allowed by charged and neutral current processes. However, these events cannot be experimentally separated from the $\nu_\mu e$ events, and furthermore the $\nu_e e$ contribution depends not only on the experimental cuts, but also on the vector and axial vector constants, which are related to those for the $\nu_\mu e$ reaction. So it was decided not to subtract a possible ν_e contribution to the signal, but to compare the signal to the sum of the predicted ν_μ and ν_e cross-sections weighted by the corresponding fluxes ϕ_{ν_μ} and ϕ_{ν_e} .

In order to obtain the $\nu_\mu e$ cross-section, the neutrino flux was computed by a Monte-Carlo method. The production spectra of the π and K parents of the ν 's were taken from the thermodynamical model [6], taking into account experimental points obtained by hadronic experiments at Fermilab [7]. The resulting spectrum is shown in fig. 1. From this flux, and with a value of the total cross-section

$$\sigma_{\text{tot}}(\nu_\mu + N \rightarrow \mu^- + X) = 0.7 \cdot 10^{-38} E_\nu \text{ cm}^2/\text{nucleon} \times \text{GeV}$$

measured in other high energy experiments [8], the total number of inclusive charged current ν_μ -events expected is 23 600 in the fiducial volume. This number was checked by looking at a sample of pictures and counting the number of interactions in the fiducial volume with a μ^- signed in the EMI. After normalization to the total number of pictures we find $24\,500 \pm 3000$ in excellent agreement with the previous estimate. The calculated flux

is also in very good agreement with the number of μ^-p events observed. From these consistency checks the error on the integrated ν_μ flux is about 10%. The calculated ν_e flux is about 2% of the ν_μ flux. This is confirmed by the rate of ν_e events observed in BEBC exposed to the same neutrino beam [9].

Assuming that the weak current is made only of V and A components, the $\nu_\mu e$ and $\nu_e e$ cross-sections are written as

$$\frac{d\sigma}{dE_e} = \frac{G^2 m_e}{2\pi} \left\{ (g_V + g_A)^2 + (g_V - g_A)^2 \left(1 - \frac{E_e}{E_\nu}\right)^2 \right\},$$

where

$$g_{V,A}^{\nu e} = 1 + g_{V,A}^{\nu \mu}.$$

The constant 1 for the $\nu_e e$ reaction comes from the charged current contribution.

Thus, the expected number of events is

$$N(g_V, g_A) \propto \iint_{E_e > 2} \left\{ \phi_{\nu_\mu} \frac{d\sigma^{\nu_\mu}}{dE_e} + \phi_{\nu_e} \frac{d\sigma^{\nu_e}}{dE_e} \right\} \beta(E_e) dE_e dE_\nu,$$

where $\beta(E_e)$ is the function of detection of the electron defined above. $\beta(E_e)$ varies slowly as a function of electron energy, E_e , so that the efficiency stays uniform through the g_V, g_A plane within 10%.

Fig. 4 shows the limits, at 90% confidence level, of the domain in the g_V, g_A plane allowed by the signal of 10 events, using the Poisson distribution.

Depending on the $\frac{g_A}{g_V}$ ratio, the value of the slope

$$S = \frac{\sigma_{\text{tot}} (\nu_\mu + e^- \rightarrow \nu_\mu + e^-)}{E_\nu}$$

is always found in the range

$$(0.73^{+0.33}_{-0.26}) 10^{-41} \text{ cm}^2/\text{GeV} \leq S \leq (0.82^{+0.37}_{-0.28}) 10^{-41} \text{ cm}^2/\text{GeV}$$

It must be mentioned that this slope is much higher than those measured in experiments on the same reaction at PS energies, namely $(0.11 \pm 0.06) 10^{-41} \text{ cm}^2/\text{GeV}$ for ref. 2 and $< 0.3 \times 10^{-41} \text{ cm}^2/\text{GeV}$ for ref. 3.

In the framework of the standard $SU(2) \times U(1)$ model, at 90% confidence level $\sin^2 \theta_w$ is found to be greater than 0.74. With the currently accepted value $\sin^2 \theta_w \approx 0.25$ [10], 1.7 ± 0.2 events are expected whereas 10 are observed. The expected number includes a contribution of 0.15 events from $\nu_e e$ reaction. Note that the $\nu_e e$ contribution is at most 0.6 events for $0 \leq \sin^2 \theta_w \leq 1$. This value is reached at $\sin^2 \theta_w = 1$.

The probability of observing 10 events when 1.7 are expected is about 10^{-4} , taking into account the uncertainty on the neutrino flux.

It is certainly possible to invoke unconventional sources of single electrons to explain at least part of the signal. Nevertheless, they should satisfy strict requirements: first, the events are very likely due to reactions on atomic electrons, since only electrons and no positrons are observed. Secondly, no high mass is present in the reaction since only very small q^2 are involved.

In conclusion, the signal is more likely due to reaction

$$\nu + e^- \rightarrow \nu + e^-.$$

We wish to thank the SPS, beam, chamber and scanning teams for their co-operation.

FIGURE CAPTIONS

- Fig. 1 Neutrino fluxes in the fiducial volume.
- Fig. 2 Experimental set-up.
- Fig. 3 Plot of energy versus angle to the beam for isolated electrons and γ -rays.
- Fig. 4 Domain allowed in the g_A, g_V plane from the reaction
$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-.$$
- Fig. 5 One of the ten isolated electrons.

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TABLE I

Event	Topology	Energy (GeV)	x_{cm} (along the beam)	(Angle to the beam) ² (mrad ²)
5941 642	$e^{\pm}$	34 ± 17	178	234 ± 123
6022 411	e^{-}	35^{+30}_{-10}	230	68 ± 66
5972 262	e^{-}	3.3 ± 1.3	259	565 ± 265
6008 041	e^{-}	2.2 ± 0.8	158	313 ± 280
5948 192	e^{-}	67 ± 35	272	8 ± 23
5953 261	e^{-}	13.3 ± 1.5	300	314 ± 142
6041 477	$e^{\pm}$	60^{+60}_{-20}	81	104 ± 82
5949 389	e^{-}	9 ± 2	183	120 ± 800
5969 272	e^{-}	3.3 ± 0.3	153	260 ± 370
6102 081	e^{-}	47 ± 10	89	40 ± 51
5931 229	e^{-}/γ	21 ± 10	136	314 ± 142
6036 260	e^{-}/γ	32 ± 15	106	780 ± 230

Fig. I ν FLUXES in the FIDUCIAL VOLUME

Fig.2 Experimental set up

Fig.3 ENERGY VERSUS ANGLE TO THE BEAM

Fig4 DOMAIN ALLOWED IN THE $g_v - g_A$ PLANE
FROM THE REACTION $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$