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Study of Quasi-Elastic Reactions of ν and ν̄ in Gargamelle.

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Summary. — The quasi-elastic cross-sections σ_{el}^{tot} and $d\sigma/dq^2$ for the reactions 1) $\nu n \to \mu^- p$ and 2) $\bar{\nu} p \to \mu^+ n$ have been measured by using the data of the ν Gargamelle collaboration. 687 ν events, candidates for reaction 1), and 476 ν̄ events, candidates for the reactions 2), have been used for the analysis. Because the ν and ν̄ interactions are on nuclei, suitable corrections for nuclear effects have been taken into account. In the framework of the «usual» $V-A$ theory, by assuming for the axial form factor the dipolar form $F_A(q^2) = 1.23/(1 + q^2/M_A^2)^2$, our data have been fitted to the differential cross-section $d\sigma/dq^2$ integrated over the ν and ν̄ energy spectra and to the total cross-section σ_{el}^{tot} as a function of the ν, ν̄ energy to determine the best value for the parameter M_A.

Introduction.

Up to now, the ν quasi-elastic interactions of the type

$$\nu n \to \mu^- p \tag{1}$$

have been analysed both in D_2 [1] and in heavy-liquid bubble chamber [2];

(*) CERN, Geneva.
(1) D. H. Perkins: *International Symposium on Lepton and Proton Interactions at High Energy* (Stanford, Cal., 1975).
(2) I. Budagov, D. G. Cundy, C. Franzinetti, W. B. Fretter, H. W. K. Hopkins, C. Manfredotti, G. Myatt, F. A. Nezrick, M. Nikolic, T. B. Novey, R. B. Palmer, J. B. M. Pattison, D. H. Perkins, C. A. Ramm, B. Roe, R. Stump, W. Venus, H. W. Wachsmuth and H. Yoshiki: *Lett. Nuovo Cimento*, **2**, 689 (1969).

no experimental information on the reaction

$$\bar{\nu}p \to \mu^+ n \tag{2}$$

has been published.

An experimental analysis of both reactions (1) and (2) is presented in this paper (*).

The experimental set-up used is the heavy-liquid bubble chamber « Gargamelle », filled with heavy freon (CF_3Br) and exposed to the CERN ν and ν̄ beams. The selection criteria of the events, their energy determination and the experimental cuts are described in sect. **1**; background, losses and distortions mainly induced by the presence of the nucleus are discussed in sect. **2**; finally, in sect. **3** our data are compared with the predictions of the « classical » $V-A$ theory of weak interactions, to give an estimate of the mass M_A appearing in the usual parametrization of the axial form factor.

1. – Experimental procedure.

Event selection. The data described are based on the analysis of 140 k pictures for ν and 110 k pictures for ν̄, scanned and measured by the 7 laboratories (**) of the Gargamelle freon collaboration.

All the events of the type

$$\nu_\mu + N \to \mu^- + m p_f + n p_s + l n_s + N' , \tag{3}$$

where N = target nucleus,

N′ = residual nucleus,

m = 0, 1,

n, l = any,

were retained as candidates for reaction (1), that is all the events with only one negative-lepton candidate, at most one fast proton (p_f) ($T > 30$ MeV), and any number of slow protons (p_s) and neutrons (n_s) ($T < 30$ MeV).

All the events of the type

$$\bar{\nu}_\mu + N \to \mu^+ + m n_f + n p_s + l n_s + N' , \tag{4}$$

(*) Preliminary results have been published in *La physique du neutrino a haute énergie* (Paris, 1975), p. 349.

(**) Aachen, Bruxelles, CERN, Ecole Polytechnique, Milano, Orsay, UCL London.

where N, N′ = target and residual nucleus

$$m = 0, 1\,,$$
$$n, l = \text{any}\,,$$

were retained as candidates for reaction (2), that is all the events with only one positive-lepton candidate and any number of slow protons (p_s) and neutrons (n_s) and at most one fast neutron (n_f).

With these selection criteria, the slow nucleons are assumed as due to the nuclear evaporation following the primary interaction.

In the topologies (3) and (4) muons and protons are defined as follows:

any negative track leaving the chamber or decaying or stopping in it without visible interactions has been retained as a possible μ^-,

any positive track leaving the chamber or decaying in it without visible interactions has been retained as a possible μ^+,

any positive track stopping in the chamber without decaying has been assumed as an unambiguous proton,

positive interacting particles not surely identified as π^+ (by δ-ray, range-curvature, etc.) are in some cases identified as protons by ionization, but, in general, they remain ambiguous between p and π; this type of ambiguity has been treated in a statistical way (³), based on a δ-ray analysis, a comparison of the momentum distributions of negative and positive interacting particles and of the range distribution of stopping protons. Figure 1 shows the prob-

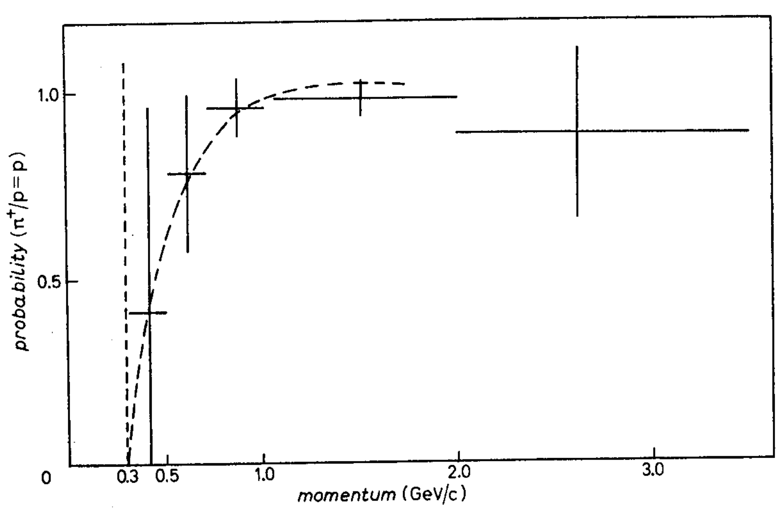

Fig. 1.

(³) A. M. LUTZ: Thesis, Orsay (1975).

ability for an ambiguous track to be a proton as a function of the particle momentum. This function has been used to give the proper weight to each mass hypothesis.

Energy definition. Since the experiment is carried out in a wide-band ν, ν̄ beam, the energy must be determined for each event. In reaction (1) the ν energy E_ν is evaluated as the sum of the total energy of μ^- and the kinetic energies of nucleons, whereas in reaction (2) a fraction of the ν̄ energy (generally a small one) is taken by a neutron (detected only in $\sim 20\,\%$ of cases), thus the ν̄ energy $E_{\bar\nu}$ is obtained by adding to the total energy of μ^+ the kinetic energy of the neutron calculated from the energy-momentum balance at the vertex, under the hypothesis of an elastic interaction on free proton. This procedure to determine the ν̄ energy introduces only a small error ($\simeq 6\,\%$) on $E_{\bar\nu}$; in fact, in the ν case we see the recoiling proton and we can compare the measured value T^m of its kinetic energy with that calculated from the energy-momentum balance T^c. Figure 2 shows the distribution of the difference $\Delta = T^m - T^c$;

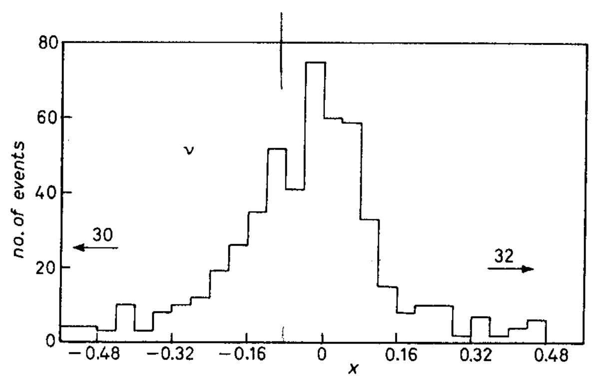

Fig. 2. – $\Delta = T^m - T^c$.

the average value of Δ (0.125 GeV) has to be compared with the average energy of the incoming ν ($\langle E_\nu \rangle = 2$ GeV). An error of the same order of magnitude ($\simeq 6\,\%$) is induced on the determination of the momentum transfer $q^2 = 2E_\mu E_{\bar\nu}(1 - \cos\theta_\mu)$.

Experimental cuts. The events are required to have the vertex inside a fiducial volume of 2.95 m³ (over $\simeq 7.0$ m³ of visible volume) to ensure good visibility and measurability of tracks. To cut the energy region where the flux estimation is affected by a large error and to eliminate the background due to the charged incoming particles simulating a ν event, we have accepted only events with

$$E_{\nu,\bar{\nu}} > 1.5 \text{ GeV}$$

$$p_x = \text{longitudinal momentum} > 0.6 \text{ GeV}/c\,.$$

In table I we report the number of elastic candidate events as well as the total number of ν and ν̄ interactions and the corresponding number of pictures and protons on the target:

TABLE I.

	Number of pictures	Number of protons	Number of interactions	Elastic candidates
ν	140 k	$1.41 \cdot 10^{17}$	3424	687
ν̄	110 k	$4.53 \cdot 10^{17}$	1250	476

2. – Background and losses.

The possible sources of background are the following:

a) Neutral-current reactions with a π^- leaving the chamber or stopping in it without interactions may simulate the topology (3); also the topology (4) may be reproduced by a neutral-current–type event with a π^+ leaving the chamber or decaying in it. From the observed number of neutral-current events with interacting $\pi^\pm$ we have calculated that this background is negligible ($< 1\,\%$).

b) Reactions in which a single π is produced:

$$\nu \text{N} \to \mu^- \pi \text{N}'\,, \tag{5}$$

$$\bar{\nu} \text{N} \to \mu^+ \pi \text{N}'\,, \tag{6}$$

when the pion is absorbed by the nucleus and the remaining topology simulates an « elastic » event according to the selection criteria quoted above.

In ν films we have considered only the absorption of π^+ and π^0 and in ν̄ films only the absorption of π^- and π^0, because of the small number of π^- in ν events and π^+ in ν̄ events. (π^+/π^- in ν̄ and π^-/π^+ in ν are nearly 10 %).

An elastic event is kinematically determined by E_ν and q^2, so we have calculated this background (B) as a function of these two variables. B is given by the relation

$$B(q^2, E_{\nu,\bar{\nu}}) = N_{5(6)} \frac{P}{1-P} R^{\nu(\bar{\nu})}\,,$$

where $N_{5(6)}$ is the number of events of categories 5(6), P is the absorption probability of a π in a nucleus, $R^{\nu(\bar{\nu})}$ is the probability of conserving the topologies (3) and (4) after the π absorption.

$N_{5(6)}$ have been directly counted in our sample of events; P has been evaluated by a Monte Carlo calculation ([4]) and its energy dependence is shown

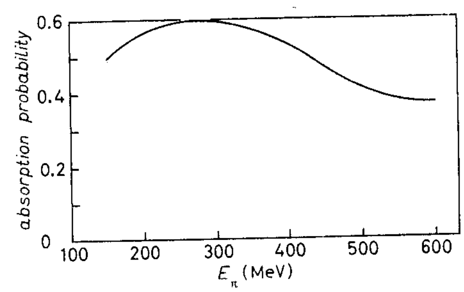

Fig. 3.

in fig. 3; the R values have been obtained by studying the interactions in freon of the pions produced by ν and $\bar{\nu}$; we have found, on the average,

$$R^{\bar{\nu}}_{\pi^-} = 0.50 , \qquad R^{\nu}_{\pi^+} = 0.15 , \qquad R^{\nu}_{\pi^0} = 0.31 , \qquad R^{\bar{\nu}}_{\pi^0} = 0.30 .$$

The values of $B(q^2, E)$ range between 10% and 30% of the signal.

Two kinds of loss have to be taken into account:

a) « scanning » loss: it is negligible in the ν sample, where the configuration is a 2-prong event, but on the contrary is of the order of 10 % in the $\bar{\nu}$ sample, where single isolated muons may be confused with cosmic muons crossing the chamber;

b) modification of the « elastic » topology due to a rescattering of the struck nucleon inside the nucleus: according to our selection criteria, we miss the elastic events when the produced nucleon has a rescattering inside the nucleus, giving in the final state a multinucleon configuration:

$$\nu + N \to \mu^- + p$$
$$\quad \hookrightarrow + p \to pp ,$$

$$\bar{\nu} + N \to \mu^+ + n$$
$$\quad \hookrightarrow + p \to np ,$$

where the final protons have an energy > 30 MeV.

([4]) W. Venus: CERN 67-12 (1967), p. 103.

For ν events, this loss has been evaluated by a Monte Carlo calculation (5) giving the probability p_R to see at most one fast proton at the interaction vertex as a function of the kinetic energy of the outgoing nucleon (fig. 4).

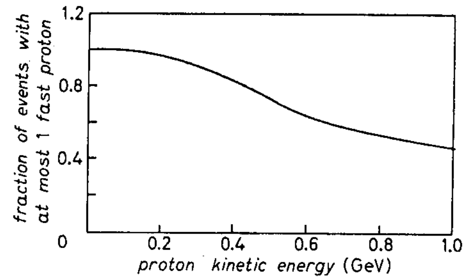

Fig. 4.

Weighting the observed number of events with only 1 fast proton (after subtraction of background) by the function $1/p_R$, we evaluated the corrected number of events with at most one fast proton as a function of E_ν and q^2.

A similar calculation has been carried out for $\bar{\nu}$ events.

The number of events before and after the corrections are reported in table II as a function of $E_{\nu,\bar{\nu}}$.

TABLE II.

E	Noncorrected	Corrected for background	Corrected for background and losses	Noncorrected	Corrected for background	Corrected for background and losses
	ν	ν	ν	$\bar{\nu}$	$\bar{\nu}$	$\bar{\nu}$
1.5 ÷ 2.0	218	183.3	210.7	157	128.5	156.4
2.0 ÷ 2.5	163	132.6	154.3	115	95	114.5
2.5 ÷ 3.0	106	82.6	100.1	71	57.7	69.4
3.0 ÷ 3.5	77	59.9	67.8	48	34.9	44.3
3.5 ÷ 4.0	44	35.7	46.4	34	29.8	39.2
4.0 ÷ 4.5	18	11.4	13.9	15	10.2	12.7
4.5 ÷ 5.0	13	12	15.8	10	8.2	9.4
5.0 ÷ 10	44	35.2	45.4	25	18.2	23.9
> 10	4	2.1	5.3	1	— 1.5	0
total	687	554.8	659.7	476	381	470

(5) G. MYATT: CERN 67-12 (1967), p. 74.

3. – Comparison with theory.

Our results have been compared with the predictions of the classical $V-A$ theory, with the assumption of the validity of the CVC [6]:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}q^2}(\nu,\bar{\nu}) = \frac{G^2\cos^2\theta_C M^2}{8\pi E_\nu^2}\left[A(q^2) \pm B(q^2)\frac{s-u}{M^2} + C(q^2)\left(\frac{s-u}{M^2}\right)^2\right],$$

where M is the nucleon mass, s, u and $q^2(=t)$ are the usual Mandelstam invariants, G is the coupling constant for weak interactions, θ_C is the Cabibbo angle and

$$A(q^2) = \frac{q^2+m^2\mu}{4M^2}\left\{F_V^2\left(\frac{q^2}{M^2}-4\right) + F_M^2\frac{q^2}{M^2}\left(1-\frac{q^2}{M^2}\right) + 4F_VF_M\frac{q^2}{M^2} + \right.$$
$$\left. + F_A^2\left(4+\frac{q^2}{M^2}\right) - \frac{m\mu^2}{M^2}\left|(F_V+F_M)^2 + F_A^2 + 4F_AF_P - \frac{q^2}{M^2}F_P^2\right|\right\},$$

$$B(q^2) = q^2(F_V+F_M)F_A/M^2\,,$$

$$C(q^2) = \tfrac{1}{4}(F_V^2 + q^2F_M^2/4M^2 + F_A^2)\,.$$

The usual dipolar parametrization is assumed for the form factors F_V, F_M, F_A (the contribution of F_P, multiplied by m_μ^2, is negligible),

$$F_i(q^2) = \frac{F_i(0)}{(1+q^2/M_i^2)^2}$$

with the normalization

$$F_V(0) = 1\,,\qquad F_M(0) = 3.71\,,\qquad F_A(0) = 1.23\,.$$

If we assume for M_V and M_M the values determined by the electromagnetic experiments, M_A is the only free parameter of the theory. The best value of M_A has been estimated by using two different experimental pieces of information:

total elastic cross-sections of ν and $\bar{\nu}$ as a function of energy,

differential elastic cross-sections $(\mathrm{d}\sigma/\mathrm{d}q^2)_{\nu\bar{\nu}}$ integrated over ν and $\bar{\nu}$ energy spectra (fig. 5).

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(6) C. H. LLEWELLYN-SMITH: *Phys. Rep.*, **3** C, 261 (1972).

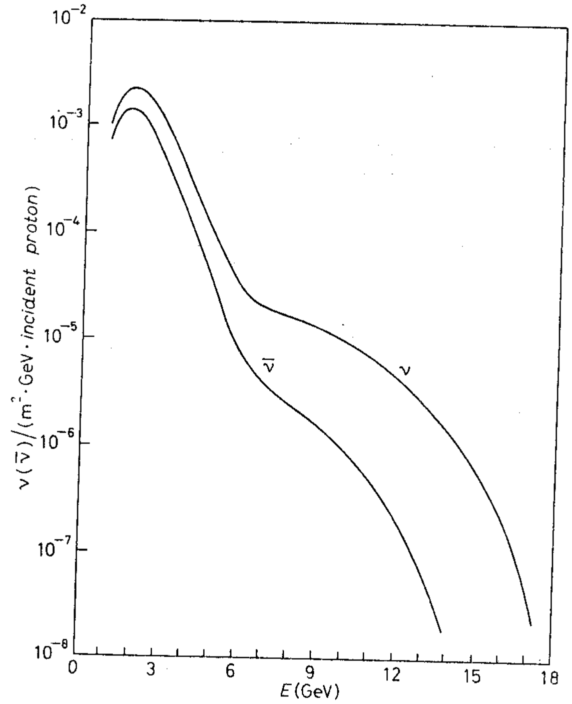

Fig. 5. – Neutrino and antineutrino spectra.

To compare our results obtained on nuclei with the theoretical predictions, we have corrected the theoretical curves for the Fermi motion and the Pauli exclusion principle using a simple Fermi-gas model for our nuclei (7).

The errors in the experimental data contain the statistical fluctuation and the indeterminations on the ν and $\bar{\nu}$ fluxes; the theoretical curves are also distorted to take into account our experimental energy resolution ($\simeq 10\%$). In fig. 6*a*), *b*) the experimental elastic cross-sections as a function of $E_{\nu,\bar{\nu}}$ are compared with the theoretical curves for the best-fit value of M_A. In fig. 7*a*), *b*) the experimental differential cross-sections $(d\sigma/dq^2)_{\nu,\bar{\nu}}$ integrated over the whole range of $E_{\nu,\bar{\nu}}$ are shown. In table III the fitted values of M_A are summarized.

TABLE III. – *Results of fits on the parameter* M_A.

	$\sigma(E)$	$d\sigma/dq^2$
ν	$M_A = (0.88 \pm 0.19)$ GeV/c^2	$M_A = (0.96 \pm 0.16)$ GeV/c^2
	$\chi^2 = 7.7$ (13 ND)	$\chi^2 = 16$ (12 ND)
$\bar{\nu}$	$M_A = (0.69 \pm 0.44)$ GeV/c^2	$M_A = (0.94 \pm 0.17)$ GeV/c^2
	$\chi^2 = 9.8$ (10 ND)	$\chi^2 = 13.5$ (8 ND)

(7) J. LOVSETH: CERN 63-37 (1963), p. 203.

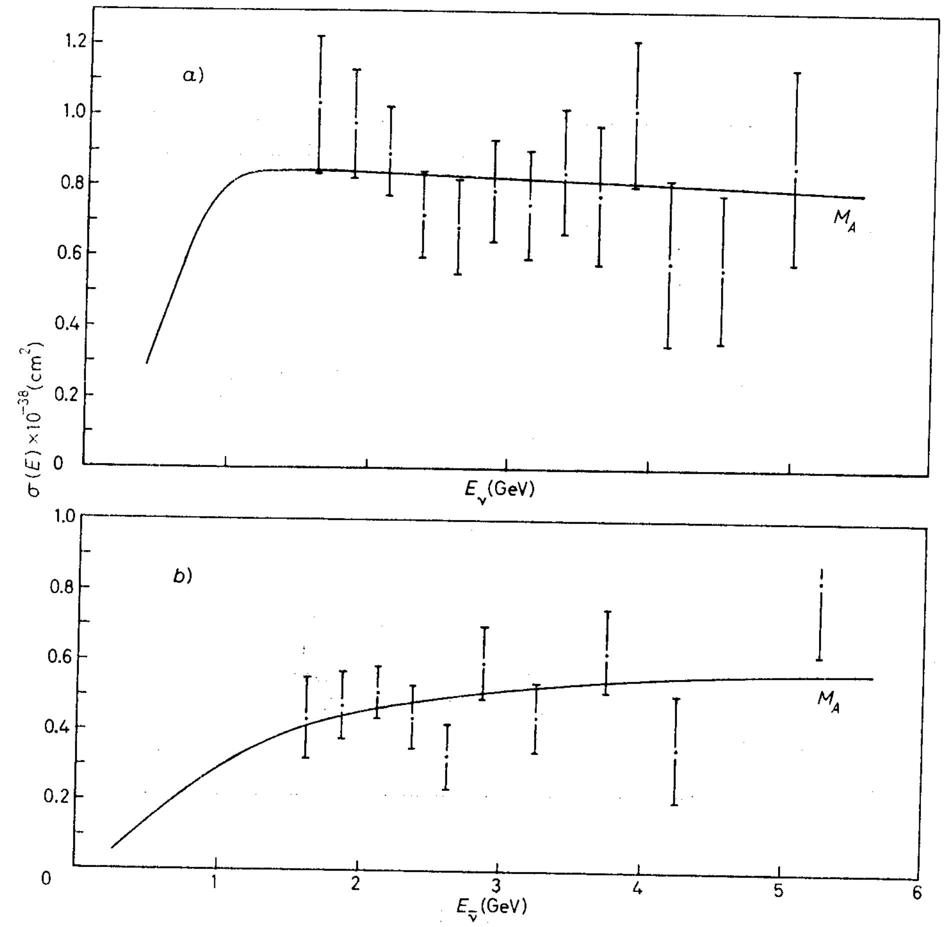

Fig. 6. – Total cross-sections *vs.* energy *a*) for ν, *b*) for $\bar{\nu}$.

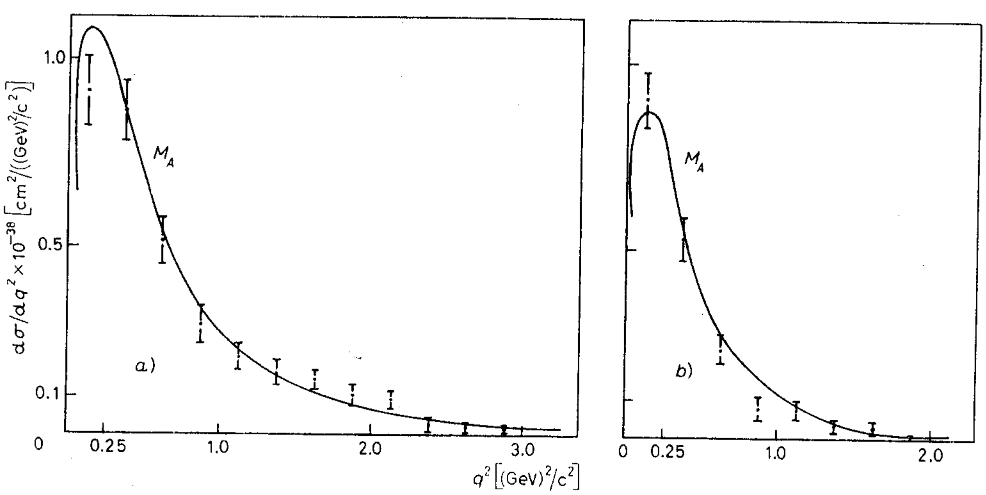

Fig. 7. – Differential cross-sections $d\sigma/dq^2$ *a*) for ν, *b*) for $\bar{\nu}$.

4. – Conclusions.

We may conclude that both ν and $\bar{\nu}$ data are in good agreement with the predictions of the « classical » $V-A$ theory. The axial form factor is well described by a dipolar parametrization and the values of M_A obtained from ν and $\bar{\nu}$ data are well consistent.

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We would like to thank our colleagues of the Gargamelle collaboration for their essential work of data collection and for discussions.

● RIASSUNTO

Si sono misurate le sezioni d'urto totali σ_{el}^{tot} e differenziali $d\sigma/dq^2$ per le reazioni 1) $\nu n \to \mu^- p$ e 2) $\bar{\nu} p \to \mu^+ n$ con i dati della collaborazione Gargamelle (687 eventi neutrino e 476 eventi antineutrino). Dato che le interazioni avvengono su nuclei complessi, si sono introdotte correzioni per gli effetti nucleari. Adottando per il fattore di forma assiale la forma dipolare $F_A(q^2) = 1.23/(1+q^2/M_A^2)^2$, si sono confrontati i risultati con le predizioni della usuale teoria « $V-A$ ». Si è stimato il miglior valore del parametro M_A adattando le sezioni d'urto totali e differenziali teoriche a quelle sperimentali per diversi valori dell'energia dei neutrini e antineutrini incidenti.

Исследование квазиупругих реакций с ν и $\bar{\nu}$.

Резюме (*). — Были измерены квазиупригие поперечные сечения для реакций 1) $\nu n \to \mu^- p$ и 2) $\bar{\nu} p \to \mu^+ n$. Проведен анализ 678 ν событий, кандидатов для первой реакции, и 476 $\bar{\nu}$ событий, кандидатов для второй реакции. Так как взаимодействия ν и $\bar{\nu}$ происходят на ядрах, то производится учет соответствующих поправок, связанных с ядерными эффектами. В рамках « обычной » $V-A$ теории, предполагая для аксиального форм-фактора дипольную форму $F_A(q^2)=1.23/(1+q^2/M_A^2)^2$, наши данные подгоняются к дифференциальному поперечному сечению $d\sigma/dq^2$, проинтегрированному по энергетическим спектрам ν и $\bar{\nu}$, и полному поперечному сечению $\sigma_{\text{упр}}^{\text{полн}}$ как функции энергии ν, $\bar{\nu}$, для того чтобы определить наилучшее значение для параметра M_A.

(*) *Переведено редакцией.*