Experimental Study of the Reaction $\nu n \to \mu^- p$.

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(GARGAMELLE NEUTRINO PROPANE COLLABORATION)

(ricevuto il 14 Agosto 1979)

Tha aim of this study is to measure the total cross-section for the quasi-elastic reaction $\nu n \to \mu^- p$ as well as the differential cross-section with respect to the four-momentum transfer squared and to estimate the mass M_A appearing in the usual parametrization of the axial form factor (ref. (1)). Results on this reaction have already

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

been obtained in bubble chamber experiments using D_2 (ref. [2,3]) and heavy liquids (ref. [4,5]). In the present experiment (ref. [5]) Gargamelle filled with a light propane-freon mixture was exposed to the CERN-PS neutrino beam. The data are based on the analysis of 115000 pictures, corresponding to a total neutrino flux of $(1.9 \pm 0.2) \cdot 10^{15}\,\nu/m^2$ through a $3\,m^3$ fiducial volume.

All 2-prong events having a topology compatible with the $\mu^- p$ final state are selected. A μ^- candidate is defined as a noninteracting negative particle. Stopping protons are unambiguously identified and a leaving or interacting positive particle that is not identified as a π^+ (ref. [6]) is taken as a p candidate.

In the selection of the events it is required that:

there is no possible upstream source,

no additional stub is present in order to reduce the channel mixing due to secondary interactions in the nucleus,

the proton has a projected length greater than 1 cm. This corresponds to a momentum cut at about 210 MeV/c,

the visible energy of the event is greater than 1 GeV,

the visible longitudinal momentum along the beam axis is greater than 0.6 GeV/c.

A sample of 556 events is selected in this way.

These events have then to satisfy, with a χ^2 probability greater than 5%, a kinematical fit where the Fermi momentum of the target nucleon is taken into account. The projections of the Fermi momentum on the three axes are introduced as additional variables with starting values (0 ± 110) MeV/c. Before doing this, 12% of the events having badly measured tracks ($\Delta p/p$ greater than 30%) were removed from the sample.

The 337 events surviving the fit have to be corrected for background and losses. The background, considerably reduced by the fitting procedure, is essentially due to 3 sources:

a) the reaction $\nu n \to \mu^- p \pi^0$, where the π^0 remains undetected. To estimate this contribution, a sample of $\mu^- p \gamma(\gamma)$ candidates satisfying the same cuts as the $\mu^- p$ ones was recorded and fitted to $\mu^- p$, ignoring the γ-rays. Taking into account the γ-ray detection efficiency of (55 ± 2)%, this background is found to be 6 ± 2 events;

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(4) I. Budagov, D. C. Cundy, C. Franzinetti, W. B. Fretter, H. W. Hopkins, C. Manfredotti, G. Myatt, F. A. Mezrick, 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).

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(6) W. Krenz, W. Lerche, J. Morfin, M. Pohl, G. Bertrand-Coremans, M. Dewit, H. Mulkens, C. Van Der Velde-Wilquet, P. Vilain, I. Danilchenko, D. Haidt, C. Matteuzzi, D. Pittuck, B. Degrange, T. François, P. Van Dam, D. Blum, M. Jaffré, C. Longuemare, C. Pascaud, E. Calimani, S. Ciampolillo, G. Miari and A. Sconza: *Nucl. Phys. B*, **135**, 45 (1978).

b) the reaction $\nu n \to \mu^- n \pi^+$, where the π^+ is not identified. As in point *a*) a sample of candidates to this reaction with an identified π^+ was fitted to $\mu^- p$, and this background was computed taking into account the π^+ detection efficiency (ref. (6)). It amounts to 2 ± 2 events;

c) the reactions $\nu n \to \nu p \pi^-$ and $nn \to np\pi^-$, where the π^- is taken as a μ^- candidate. Using the identified $\pi^- p$ found and the π^- detection efficiency the number of events due to this source is estimated to be 1 ± 1.

The signal losses resulting from the cuts applied are the following:

a) 12% of events having badly measured tracks must be added to the sample;

b) the confidence level distribution of the fit is flat for genuine $\mu^- p$ events. The signal loss due to the probability cut is thus taken to be 5%;

c) from the mean number of events per picture the rate of two independent neutrino events appearing associated can be determined. It was found that a candidate can have a random upstream source with a probability of 3%.

Finally a correction must be introduced to take into account the nuclear effects. After a secondary interaction in the nucleus, the event is lost either because the topology has changed or because the event fails the fitting procedure.

The number of events which still survive the fit after a secondary interaction is negligible. This was tested in the channel $\mu^- p \pi^+$ by comparing the fitted data with the results of the Monte Carlo calculation used for nuclear corrections (ref. (6)). Therefore, the loss due to nuclear effects, computed by Monte Carlo as being the probability that the p reinteracts in the nucleus, is found to be 35%.

After these corrections the final number of events becomes 622 ± 37 (plus a systematic error of 10% coming from the nuclear corrections).

To check the fitting procedure, the total number of events was computed independently by using the initial sample of 556 $\mu^- p$ candidates and evaluating the backgrounds and losses affecting this sample. The two results are in perfect agreement. Since the background is less in the fitted events, only these events have been used for further analysis.

In the framework of the classical $V - A$ theory and assuming charge symmetry, time-reversal invariance and CVC hypothesis, the differential cross-section with respect to q^2 is given by (ref. (1))

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

where M is the nucleon mass, s, u and $q^2 = t$ are the Mandelstam invariants, G is the Fermi coupling constant, θ_C the Cabibbo angle and

$$A(q^2) = \frac{q^2 + m_\mu^2}{4M^2}\left\{F_V^2\left(\frac{q^2}{M^2} - 4\right) + F_M^2\frac{q^2}{M^2}\left(1 - \frac{q^2}{M^2}\right) + 4F_V F_M \frac{q^2}{M^2} + \right.$$
$$\left. + F_A^2\left(4 + \frac{q^2}{M^2}\right) - \frac{m_\mu^2}{M^2}\left|(F_V + F_M)^2 + F_A^2 + 4F_A F_V - \frac{q^2}{M^2}F_V^2\right|\right\},$$
$$B(q^2) = q^2(F_V + F_M)F_A/M^2,$$
$$C(q^2) = \tfrac{1}{4}(F_V^2 + q^2 F_M^2/4M^2 + F_A^2).$$

It is assumed that the form factors F_V, F_M and F_A (the contribution of F_ν, multiplied by m_μ^2, is negligible) can be parametrized as follows:

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

with $F_V(0) = 1$, $F_M(0) = 3.71$, $F_A(0) = -1.24$.

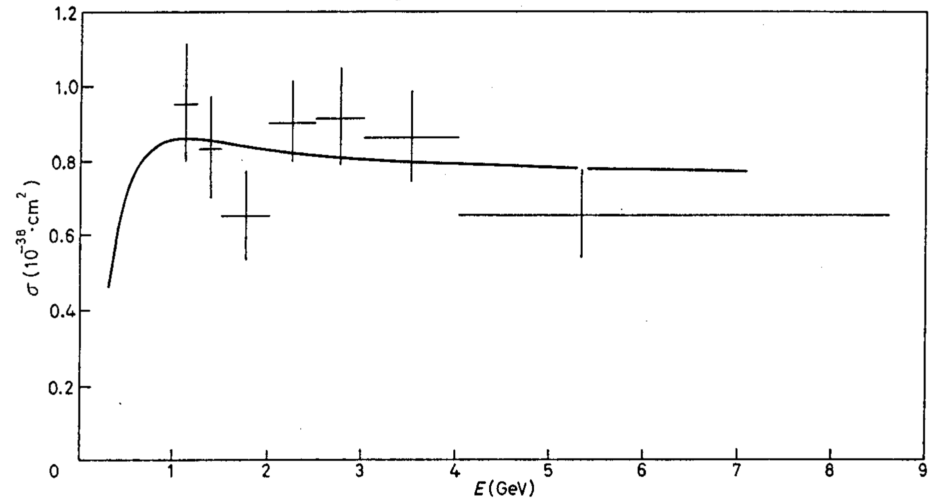

Fig. 1. – Cross-section for the reaction $\nu n \to \mu^- p$ as a function of the ν energy. The theoretical curve corresponds to $M_A = 0.87$.

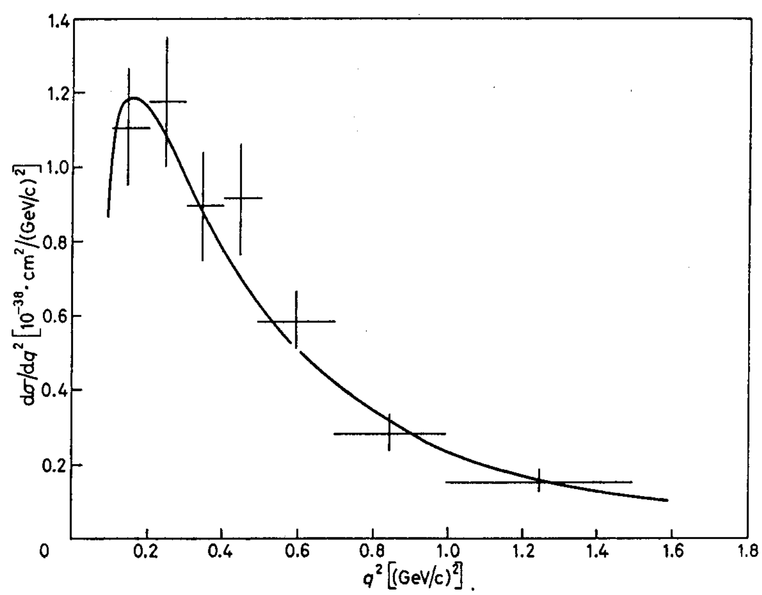

Fig. 2. – Differential cross-section $d\sigma/dq^2$ integrated over the ν energy spectrum. The theoretical curve is evaluated for $M_A = 0.99$.

The value given for F_A is an average of various experimental results (ref. [7]).

Assuming for M_V and M_M the value of 0.84 GeV determined by experiments using electrons, the mass M_A can be deduced either from the differential cross-section $d\sigma/dq^2$ integrated over the ν-energy spectrum (fig. 1) or from the total elastic cross-section as a function of the neutrino energy (fig. 2). To compare with our data, the theoretical curves have been distorted to take into account both the effects of Fermi motion and of the cut applied on the proton momentum. The errors quoted on the figures are purely statistical but the total cross-section is also affected by a systematic error of 10% coming from the nuclear corrections and by errors on the shape and on the absolute value of the ν flux. The fitted values for M_A are

$$\sigma(E), \qquad M_A = 0.87 \pm 0.05 \text{ (statistical)} \pm 0.17 \text{ (systematic)},$$

$$d\sigma/dq^2, \qquad M_A = 0.99 \pm 0.12 \text{ (statistical)}.$$

These results are in good agreement with the predictions of the $V - A$ theory and also agree with the results given by previous experiments.

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