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Quasielastic nucleon and hyperon production by neutrinos and antineutrinos with energies below 30 GeV

SKAT-Collaboration

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Abstract. The cross sections of neutrino and antineutrino quasielastic reactions $\nu n \rightarrow \mu^- p$, $\bar{\nu} p \rightarrow \mu^+ n$, $\bar{\nu} p \rightarrow \mu^+ \Lambda$ were studied in the neutrino energy range between 3 and 30 GeV. In comparison with $V-A$ theory axial mass parameters of $M_A = (1.06 \pm 0.05 \pm 0.14)$ GeV/c^2 from neutrino and $M_A = (0.71 \pm 0.10 \pm 0.20)$ GeV/c^2 from antineutrino data were found. The total cross-section for the hyperon production process can be described by $M_A = 1.0$ GeV/c^2.

1 Introduction

In this paper we study the quasielastic reactions

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

and

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

These reactions have been studied mainly in the low neutrino energy region up to 5 GeV [1–17]. We overlap with this region and give information for reactions (1) and (2) up to neutrino energies of 30 GeV. We have previously published an investigation of these reactions using the first part of our data sample [18].

For the quasielastic hyperonproduction

$$\bar{\nu} p \rightarrow \mu^+ \Lambda, \tag{3}$$

there are only three published results [19–21].

The experimental procedure and the event selection are described in Sect. 2, the experimental cross section calculations are discussed in Sect. 3, the results are compared in Sect. 4 with predictions of the $V-A$ theory to give an estimate of the axial form factor mass M_A.

In the following informations about antineutrino data will be given in brackets.

2 Experimental procedure

The data were obtained in an experiment using the bubble chamber SKAT filled with heavy freon (CF_3Br) exposed to the ν ($\bar{\nu}$)-wide-band beam of the Serpukhov proton synchrotron. The (anti)neutrino energy spectrum ranges between 3 and 30 GeV, the mean event energy is about 9 GeV.

The volume of the chamber is 6.5 m^3, the chosen fiducial volume is 1.7 m^3.

Our analysis is based on final samples of 15060 (2150) charged current events. These samples are used for the cross section normalization of the quasielastic event samples. A charged current event is demanded to have at least one negative (positive) noninteracting leaving track – the muon. To remove background due to incoming neutral hadrons two cuts were imposed on this sample: The sum of all longitudinal momenta has to be greater than zero and the muon momentum has to be greater than 0.5 (1.0) GeV/c. This reduces our sample to 14560 (1910) charged current events; the (anti)neutrino energy of 13590 (1730) events was greater 3 GeV.

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We have in our heavy liquid to tackle events with stubs, i.e. low energetic nucleon tracks. These slow nucleons with kinetic energies $T < 30$ MeV (mainly stopping protons) are assumed to originate from nuclear evaporation of the nucleus – they were not considered in our data selection.

For the analysis we reject events where interacting tracks have a momentum error greater 60% and correct this loss with a subsequent weighting procedure [22]. The average event weight for our sample is 1.11.

540 events with a negative muon and one stopping proton were selected as candidates for the quasielastic reaction (1). For reaction (2) we selected 159 events with a positive muon and neither a charged hadron nor a gamma. For reaction (3) we observe 3 events where the muon is accompanied by a lambda with the decay $\Lambda \to p\pi^-$.

To calculate the neutrino energy E_ν for reaction (1) and the antineutrino energy $E_{\bar{\nu}}$ for (3) we use the visible energies of muon and baryon. $E_{\bar{\nu}}$ for reaction (2) was determined as the sum of the energy of the muon and the kinetic energy of the neutron (calculated from four-momentum balance of the reaction under the hypothesis of an interaction on free proton). This method one has to introduce because only 13% of the events have a visible fast neutron inside the chamber volume. It was checked with neutrino events where we omitted the identified proton. The procedure introduces an error below 5% on $E_{\bar{\nu}}$.

The four-momentum-transfer was calculated with E_ν, E_μ and p_μ^L (the energy and longitudinal momentum of the muon) as $Q^2 = 2 \cdot E_\nu \cdot (E_\mu - p_\mu^L)$.

3 Experimental cross sections

The main sources of background and losses in the investigated reactions are:

- scan inefficiency
- the topology modification due to intranuclear hadron cascading
- chamber inefficiency such as invisibility of neutral hadrons or the simulation of muons by noninteracting charged pions in neutral current interactions.

The scanning losses are small in the event sample for (1) (3.7%) but important in the antineutrino reaction (2) (13.6%).

To obtain the number of corrected, i.e. truly produced quasielastic events N_{qu}^{prod} from the number of observed events N^{obs} we use

$$N^{obs} = \varepsilon_{qu} \cdot N_{qu}^{prod} + \varepsilon_{bg} \cdot N_{bg}^{prod}, \tag{4}$$

where N_{bg}^{prod} is the primary produced background and the probabilities ε are described below.

For reactions (1) and (2) the background is dominated by events from single pion production channels with primary hadronic final states $p\pi^+$, $p\pi^0$, $n\pi^+$ ($n\pi^-$, $p\pi^-$, $n\pi^0$). For the $N\pi$-production cross-sections we use the information from the quark model described in [23], these reactions and the applicability of this model we investigated previously [24]. The event numbers N_{bg}^{prod} are calculated normalizing these cross-sections on the total charged current cross-sections measured in our experiment [25].

ε_{qu} and ε_{bg} are the probabilities for primary quasielastic and background events to be observed as a quasielastic event with the above mentioned criteria. We obtain them with a Monte Carlo program [22] taking into account effects of the nuclei (Fermi motion, Pauli principle and hadron rescattering) and experimental properties of the bubble chamber. The calculation also includes the energy determination method and the smearing between chosen bins of variables. ε_{qu} is in the order of 0.30 (0.70), ε_{bg} is smaller 0.01.

Applying all described corrections for the quasielastic signal we observe 1465.9 ± 199.6 neutrino respectively 256.7 ± 51.2 antineutrino events. The corresponding cross-section was derived by scaling the number of events on the total cross-section [25]. Figure 1 shows the total quasielastic cross-section $\sigma(E)$ and the differential cross-section on the momentum transfer $d\sigma/dQ^2$ for neutrinos. The corresponding antineutrino cross-sections are shown in Fig. 2. One observes an energy independence of $\sigma(E)$ and a steep decrease of $d\sigma/dQ^2$.

For reaction (3) we correct the number of observed events on losses in the bubble chamber; we neglect losses and backgrounds ($\varepsilon_{bg} = 0$) due to intranuclear inelastic reactions. The correction factor for the visibility of Λ-particles $\varepsilon_{qu} = 0.40$ we take from the investigation of neutral strange particle production in SKAT [26]. It includes losses from the fitting procedure, Λ-interaction inside the chamber, geometrical acceptance and branching ratio in $p\pi^-$. We calculate the cross-section normalizing the number of events on total charged current cross-section. The cross-section is shown together with the results from other experiments in Fig. 3.

4 Comparison with theory

Our results have to be compared with predictions of the $V-A$ based theory. The cross-section for the quasielastic process can be written as [27]

$$\frac{d\sigma}{dQ^2} = \frac{G^2 \cdot M^2 \cdot \cos^2 \Theta_c}{8\pi \cdot E^2} \left\{ A(Q^2) \mp B(Q^2) \left(\frac{s-u}{M^2}\right) + C(Q^2) \left(\frac{s-u}{M^2}\right)^2 \right\}. \tag{5}$$

The upper sign yields for the neutrino, the lower for the antineutrino-reaction. G is the weak interaction coupling constant, E the neutrino energy, M the nucleon mass and Θ_c the Cabbibo angle. s, u and $t=-Q^2$ are the Mandelstam variables and the structure functions A, B and C are functions of Q^2 and the form factors F_1, F_2 and F_A. The isovector form factors F_i $(i=1,2)$ are adequately represented by the dipole form of the related electric and magnetic form factors of protons and neutrons [27] $F_i=F_i^p(Q^2)-F_i^n(Q^2)$ with a vector mass parameter of $M_V=0.84$ GeV [28]. We assume the dipole form also for the axial-vector form factor

$$F_A(Q^2)=F_A(0)/(1+Q^2/M_A^2)^2. \tag{6}$$

Alternatively we try a quark model vector-dominance motivated parametrization [29]

$$F_A(Q^2)=F_A(0)/(1+Q^2/M_A^2) \cdot \exp(-Q^2 R^2/6(1+q2/4\,M^2)) \tag{7}$$

with $R^2=6\ \mathrm{GeV}^{-2}$. The value of $F_A(0)=-1.254$ is taken from neutron decay [30] – it is essentially the ratio of vector to axial vector coupling strength. The axial-vector mass M_A is the only unknown parameter.

For the Cabibbo suppressed reaction (3) the cross-section functions A, B and C are modified in comparison to the case of reactions (1) and (2) because the mass difference of the initial and final state baryons becomes important. The weak current form faktors F_i $(i=1,2)$ are given with the electromagnetic form factors of protons [27] $F_i(Q^2)=F_i^p(Q^2)$.

The dipole parametrization (6) also holds in this case with normalization from Λ-decay $F_A(0)=-0.694$ [30].

For the estimation of M_A we use the experimental total cross-section $\sigma(E)$ and the differential cross-section $d\sigma/dQ^2$. We compare them with integrals of the theoretical differential cross-section $(d\sigma/dQ^2(E))_{\mathrm{theor}}$ (5)

$$\sigma(E)=\int dQ^2\left(\frac{d\sigma}{dQ^2}\right)_{\mathrm{theor}},$$

$$\frac{d\sigma}{dQ^2}=\frac{\int d\,\Phi(E)\left(\frac{d\sigma}{dQ^2}(E)\right)_{\mathrm{theor}}}{\int dE\,\Phi(E)}$$

$\Phi(E)$ is the neutrino energy distribution. We perform a χ^2-fit to extract from our four experimental distributions the free parameter M_A. The results for the neutrino cross-sections are $M_A=(1.08\pm0.07)\ \mathrm{GeV/c^2}$ from $\sigma(E)$ and $M_A=(1.05\pm0.07)\ \mathrm{GeV/c^2}$ from $d\sigma/dQ^2$. Fitting both distributions together gives $M_A=(1.06\pm0.05)\ \mathrm{GeV/c^2}$ with a χ^2/NDF of 7.1/15. Antineutrino data give $M_A=(0.62\pm0.16)\ \mathrm{GeV/c^2}$

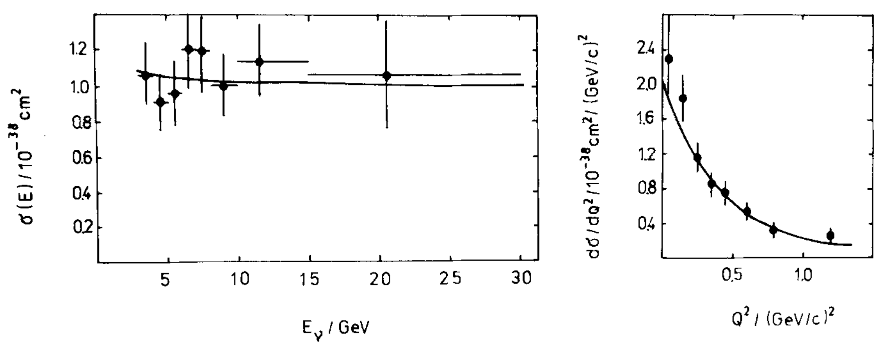

Fig. 1a, b. Cross-section for $\nu n\to\mu^- p$. **a** Total cross-section $\sigma(E)$, (solid line: $V-A$ with $M_A=1.08\ \mathrm{GeV/c^2}$) **b** Differential cross-section $d\sigma/dQ^2$ (solid line: $V-A$ with $M_A=1.05\ \mathrm{GeV/c^2}$)

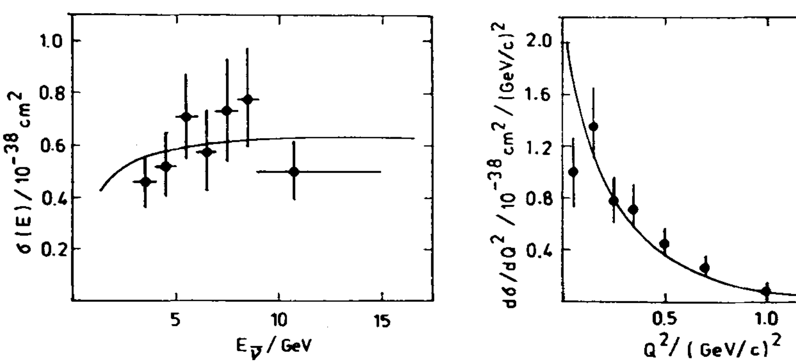

Fig. 2a, b. Cross-section for $\bar{\nu}p\to\mu^+ n$. **a** Total cross-section $\sigma(E)$ (solid line: $V-A$ with $M_A=0.62\ \mathrm{GeV/c^2}$). **b** Differential cross-section $d\sigma/dQ^2$ (solid line: $V-A$ with $M_A=0.79\ \mathrm{GeV/c^2}$)

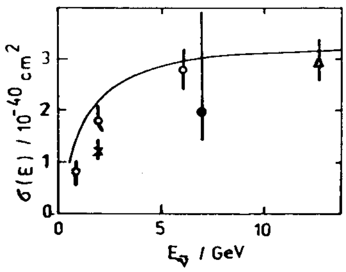

Fig. 3. Total cross-section (●) for $\bar{\nu}p \rightarrow \mu^+ \Lambda$, (×) [19], (△) [20], (○) [21]. Solid line: $V-A$-cross-section with $M_A = 1.0$ GeV/c^2

Table 1. Results of quasielastic neutrino scattering

Experiment	M_A (GeV/c^2)	Ref.	Par.
ANL streamer ch.	1.05 ± 0.20	[1]	(6)
12′ BC D_2	1.00 ± 0.05	[2]	
BNL 7′ BC D_2	1.07 ± 0.06	[3]	
D_2	1.10 ± 0.05	[4]	
PS BC Freon	$1.00^{+0.35}_{-0.20}$	[5]	
Propan	0.7 ± 0.2	[6]	
Freon	$0.75^{+0.24}_{\ 0.20}$	[7]	
Streamer ch.	$0.65^{+0.45}_{-0.40}$	[8]	
GGM Freon	0.88 ± 0.19 0.96 ± 0.16	[9]	
Propan	$0.87 \pm 0.05 \pm 0.17$ 0.99 ± 0.12	[10]	
U70 Spark ch.	1.00 ± 0.04	[11]	
SKAT Freon	$1.06 \pm 0.05 \pm 0.14$	this exp.	
SPS BEBC D_2	1.29 ± 0.09	[12]	
FNAL 15′ BC Ne	1.08 ± 0.08	[13]	
D_2	$1.05^{+0.12}_{-0.16}$	[14]	
ANL 12′ BC D_2	1.11 ± 0.16	[2]	(7)
BNL 7′ BC D_2	1.31 ± 0.16	[3]	
U70 SKAT Freon	1.22 ± 0.14	this exp.	

from $\sigma(E)$ and $M_A = (0.79 \pm 0.11)$ GeV/c^2 from $d\sigma/dQ^2$, fitting both distributions together yields $M_A = (0.71 \pm 0.10)$ GeV/c^2 with χ^2/NDF of 15/12. Assuming a 10% systematic error on the data (due to normalization on total cross-section and the nuclear Monte Carlo) yields an estimated systematic error in M_A of 0.14 GeV/c^2 and 0.20 GeV/c^2 in ν- and $\bar{\nu}$-interactions respectively.

If one fits in the dipole parametrization M_A and M_V simultaneously one yields e.g. in the neutrino case

Table 2. Results of quasielastic antineutrino scattering

Experiment	M_A (GeV/c^2)	Ref.
BNL 7′ BC H_2	$0.9^{+0.4}_{-0.3}$	[15]
PS GGM Freon	0.69 ± 0.44 0.94 ± 0.17	[9]
U70 Spark ch.	1.04 ± 0.04	[11]
SKAT Freon	$0.71 \pm 0.10 \pm 0.20$	this exp.
SPS GGM Propan	0.91 ± 0.40	[16]
FNAL 15′ BC Ne	0.99 ± 0.11	[17]

Table 3. Results of quasielastic Λ-production

Experiment	# events	M_A (GeV/c^2)	Ref.
PS GGM Freon	13	–	[19]
Propan	15+45	0.86 ± 0.19	[20]
U70 SKAT	3	–	this exp.
FNAL 15′ BC Ne	14	1.0 ± 0.3	[21]

from $d\sigma/dQ^2$ $M_A = (1.25 \pm 0.41)$ GeV/c^2 and $M_V = (0.73 \pm 0.23)$ GeV/c^2 with χ^2/NDF of 4.2/7 in good agreement with the results above.

A fit of the neutrino data with the F_A parametrization (7) yields $M_A = (1.22 \pm 0.14)$ GeV/c^2 with χ^2/NDF of 7.3/15.

For reactions (1) and (2) we show in Figs. 1 and 2 cross-section curves (solid lines) calculated with the parameters from the corresponding fits with (6). In Tables 1 and 2 we compare our results for M_A with those of other experiments and find consistent results for the neutrino reaction and a somewhat lower value for the antineutrino reaction. Averaging all values in Tables 1 and 2 one yields $M_A = (1.01 \pm 0.02)$ GeV/c^2 for ν- and $M_A = (1.00 \pm 0.03)$ GeV/c^2 for $\bar{\nu}$-experiments.

For reaction (3) one can find in Table 3 results from other experiments. As one can see in Fig. 3 the cross-section curve with $M_A = 1.0$ GeV/c^2 describes all data well.

5 Summary

We studied quasielastic reactions with nucleons and Λ-hyperons induced by (anti)neutrinos. From 540 (ν) and 159 ($\bar{\nu}$) candidates for the quasielastic nucleon reaction we determined the total cross-sections $\sigma(E)$ and differential cross-sections $d\sigma/dQ^2$. We extracted the axial mass parameter for the $V-A$ parametrization using these cross sections. The dipole ansatz fit of neutrino cross-sections yields $M_A = (1.06 \pm 0.05 \pm 0.14)$ GeV/c^2, from antineutrino data we found

$M_A=(0.71\pm0.10\pm0.20)$ GeV/c^2. This has to be compared with world averages of $M_A=(1.01\pm0.02)$ GeV/c^2 (ν) and $M_A=(1.00\pm0.03)$ GeV/c^2 ($\bar{\nu}$). The cross-section for quasi-elastic hyperon production by antineutrinos can be described by $M_A=1.0$ GeV/c^2.

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