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Meson Production by Neutrinos Incident on Nucleons.

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Summary. — Production and exchange of nonstrange pseudosealar and vector mesons are considered in the peripheral model. For nonstrange mesons a consequence of this model is that the corresponding ν and $\bar{\nu}$ cross-sections are equal, assuming that ν and $\bar{\nu}$ eouple to the same isospin multiplet. The cross-section for production or ρ and ω with π exchange, with and without simultaneous excitation of the $\frac{3}{2}$, $\frac{3}{2}$ resonance, is found to he a fraction (with strong dependence on badly known form factors) of the « elastic » cross-section, $\sigma(\nu+n\to p+\mu^-)$, at a few GeV incident-neutrino energy. Production of π and η mesons with ρ and ω exchange is computed also, and is found to be very small.

1. - Introduction.

It is conceivable that vector mesons play an important role in the inelastic pion production by neutrinos incident on nucleons as observed in the CERN neutrino experiment ([1]). Production of single pions ([2,3]) and kaons ([4,5]) has

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([1]) H. H. BINGHAM, H. BURMEISTER, D. CUNDY, P. G. INNOCENTI, A. LECOURTOIS, R. MØLLERUD, G. MYATT, M. PATY, D. PERKINS, C. A. RAMM, K. SCHULTZE, H. SLETTEN, K. SOOP, R. P. G. VOSS and H. YOSHIKI: *Proceedings of the International Conference on Elementary Particles*, vol. **1** (Sienna, 1963), p. 555; J. S. BELL, J. LØVSETH and M. VELTMAN: *Proceedings of the Interna.ional Conference on Elementary Particles*, vol. **1** (Sienna, 1963), p. 584; M. M. BLOCK, H. BURMEISTER, D. CUNDY, B. EIBEN, C. FRANZINETTI, J. KEREN, R. MØLLERUD, G. MYATT, M. NIKOLIC, A. ORKIN-LECOURTOIS, M. PATY, D. PERKINS, C. A. RAMM, K. SCHULTZE, H. SLETTEN, K. SOOP, R. STUMP, W. VENUS and H. YOSHIKI: to be published.

([2]) J. S. BELL and S. M. BERMAN: *Nuovo Cimento*, **25**, 404 (1962); P. DENNERY: *Phys. Rev.*, **127**, 664 (1962); N. DOMBEY: *Phys. Rev.*, **127**, 653 (1962); N. CABIBBO and G. DA PRATO: *Nuovo Cimento*, **25**, 611 (1962).

([3]) S. M. BERMAN and M. VELTMAN: to be published.

([4]) A. FUJII and E. CELEGHINI: *Nuovo Cimento*, **28**, 90 (1963).

([5]) G. R. HENRY, J. LØVSETH and J. D. WALECKA: to be published.

been discussed by several authors. Here we consider peripheral meson production involving nonstrange vector and pseudoscalar mesons.

In Sect. 2 we compute cross-sections for events of the type $\nu+\mathcal{N}\to\mathcal{N}'+\mu^-+\mathrm{b}$ where b is a ρ or ω. In Sect. 3, cross-sections for events of the type $\nu+\mathcal{N}\to\to\mu^-+\mathrm{b}+\mathrm{X}$ are considered, where X represents the final state in the reaction $\pi+\mathcal{N}\to\mathrm{X}$. Production of π, η mesons by vector-meson exchange is computed in Sect. 4 and is found to be very small.

2. - Cross-sections for ρ and ω production.

The cross-section for ρ and ω production are computed according to the peripheral Peynmau diagram in Pig. *la*. The four-momentum associated with

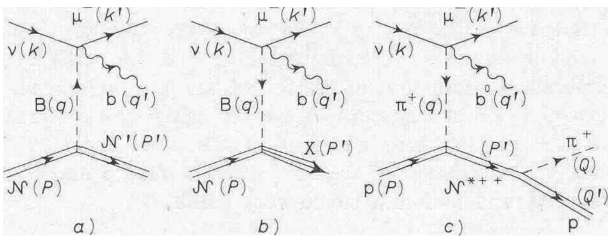

Fig. 1. - a) Peripheral Feynman diagram for $\nu+\mathcal{N}\to\mathcal{N}'+\mu^-+\mathrm{b}$. The four-momenta of the particles are indicated in parentheses; dashed lines correspond to pseudoscalar mesons, wavy lines to vector mesons. 6) Peripheral diagram for $\nu+\mathcal{N}\to\mu^-+\mathrm{b}+\mathrm{X}$. *e)* Diagram for $\mathcal{N}^*$ production with vector meson production; expected to be a major contributor to diagram 1*b*.

each particle is indicated in parentheses. Considering only nonstrange particles, the possible reactions indicated in graph 1» are:

$$\nu+\mathrm{n}\to\mathrm{p}+\mu^-+\omega \qquad (\pi^- \text{ exchanged}),$$
$$\nu+\mathrm{p}\to\mathrm{p}+\mu^-+\rho^+ \qquad (\pi^0 \text{ exchanged}),$$
$$\nu+\mathrm{n}\to\mathrm{n}+\mu^-+\rho^+ \qquad (\pi^0 \text{ exchanged}),$$
$$\nu+\mathrm{n}\to\mathrm{p}+\mu^-+\rho^0 \qquad (\pi^- \text{ exchanged}).$$

In these reactions the meson current coupled to the leptons transforms supposedly as the (+) component of an isovector. The antineutrino reactions are found by replacing ν by $\bar{\nu}$ and taking the isospin (—) part of the meson current; apart from very small effects of electromagnetic origin *(e.g.*, n,p mass difference, etc.) the corresponding neutrino and antineutrino cross-sections are equal. This is a situation peculiar to this model, and depends entirely on the assumption that ν and $\bar{\nu}$ couple to the same isospin multiplet, or equivalently (if time-reversal invariance holds), that the meson current is of the first kind under *G*-parity (6). Prom the isospin properties we find, apart from small electromagnetic effects again,

$$\sigma(\nu + \mathrm{p} \to \mathrm{p} + \mu^- + \rho^+) = \sigma(\nu + \mathrm{n} \to \mathrm{n} + \mu^- + \rho^+) = \tfrac{1}{2}\sigma(\nu + \mathrm{n} \to \mathrm{p} + \mu^- + \rho^0) .$$

Thus there are two independent cross-sections which wo take to be $\sigma(\nu+\mathrm{n} \to \to \mathrm{p}+\mu^- +\omega)$ and $\sigma(\nu+\mathrm{p} \to \mathrm{p}+\mu^- +\rho^+)$.

The lepton-meson vertex of graph. 1*a* is given by

(1) $$i\overline{U}_\mu(k')\gamma_\alpha(1+\gamma_5)\,U_\nu(k)\langle b|J^V_\alpha + J^A_\alpha|B\rangle \;.$$

The leptonic part is as usual, and J^V and J^A are the vector and axial vector components of the mesonic weak current (*). Requiring now that $GJ^VG^{-1} = J^V$ and $GJ^AG^{-1} = -J^A$ (wlere *G* is the *G*-parity operator) implies that either $\langle b|J^V|B\rangle$ or $\langle b|J^A|B\rangle$ is absent, for under 6

(2) $$\langle b|J^V + J^A|B\rangle = g_\mathrm{b} g_\mathrm{B} \langle b|J^V - J^A|B\rangle \,,$$

where g_b and g_B are the *G*-parities of b and B (equal to ± 1), and therefore

$$\langle\omega|J^A|\pi\rangle = \langle\varrho|J^A|\eta\rangle = \langle\varrho|J^V|\pi\rangle = 0 \;.$$

Considering omega production by pion exchange $(\mathrm{b}=\omega,\ \mathrm{B}=\pi^-)$, the coupling strength of the π-ω current to the iepton current for $(k-k')^2 = 0$ may be found from the observed (purely $\Delta I = 1$) $\omega \to \pi^0 + \gamma$ decay rate (') and CVC theory (8). The lepton-meson vertex is then given by (momenta denned in Fig. *la)*

(3) $$ig_V\overline{U}_\mu\gamma_\alpha(1+\gamma_5)\,U_\nu\varepsilon_{\alpha\beta\varrho\sigma}S_\beta q'_\varrho q_\sigma\, F_1([k-k']^2) \;,$$

where F_1 is a form factor with $F_1(0) = 1$. Furthermore, $g_V = \lambda G$ and λ^2 is found (5) to be $7.5\ \mathrm{GeV}^{-2}$; G is the weak coupling constant $GM_\mathrm{p}^2 \approx 10^{\wedge 5}$, and S_β is the omega linear polarization vector with $S_\beta q'_\beta = 0$. Note that the meson current is conserved, *i.e.*, $(q'-q)_\alpha\,\varepsilon_{\alpha\beta\varrho\sigma}\,S_\beta q_\varrho q'_\sigma = 0$. Thus, according to ADLER (9),

(6) T. D. LEE: Lecture Notes, CERN 61-30 (1961); S. WEINBERG: *Phys. Rev.*, **112**, 1375 (1958).

(*) We use the metric $k'^2 = \boldsymbol{k}'^2 + k_4'^2 = \boldsymbol{k}'^2 - k_0'^2 = -m_\mu^2$.

(7) M. ROOS: *Nucl. Phys.*, 52, 1 (1964).

(8) R. P. FEYNMAN and M. GELL-MANN: *Phys. Rev.*, **109**, 193 (1958).

(9) S. L. ADLER: *Phys. Rev.*, **135**, B 963 (1964).

if the lepton factor is proportional to $(q'-q)$, as happens if the μ (with m_μ taken to bo 0) is in the forward direction, the cross-section will be zero. At the nucleon-pion vertex the usual pseudoscalar coupling is used, namely,

$$i\sqrt{2}\,g_{\mathcal{N}\pi}\overline{U}_{\mathcal{N}'}\gamma_5\,U_{\mathcal{N}}\,F_{\mathrm{B}}(q^2)\,, \tag{4}$$

where $g^2_{\mathcal{N}\pi}/4\pi\approx 15$, and F_B is a form factor with 2^(0) = 1.

With these vertices the following differential cross-section is obtained for oniega production (averaging over incident spins and summing over outgoing spins):

$$\begin{aligned}\mathrm{d}_9\sigma = {}&\frac{\lambda^2G^2g^2_{\mathcal{N}\pi}F_1^2([k-k']^2)\,F^2_{\mathrm{B}}(q^2)\,(q^2+\Delta M^2)}{(2\pi)^5(-p\cdot k)(q^2+m^2_{\mathrm{B}})^2}\,\delta_4(k'+q'+p'-p-k)\,\cdot\\ &\cdot\{k\cdot q'[(q\cdot q')(k'\cdot q)-q^2(q'\cdot k)]+k\cdot q[(q\cdot q')(k'\cdot q')+m^2_{\mathrm{b}}(q\cdot k')]\}\,\frac{\mathrm{d}_3\boldsymbol{q}'}{q'_0}\,\frac{\mathrm{d}_3\boldsymbol{k}'}{k'_0}\,\frac{\mathrm{d}_3\boldsymbol{p}'}{p'_0}\,,\end{aligned} \tag{5}$$

where momenta are again defined in Fig. la, and $\Delta M = M_{\mathcal{N}}-M_{\mathcal{N}'}$. The total eross-secrion may be trivially reduced to a four-dimensional integral, and it was then numerically integrated. All numerical integrations wez'e done on the CERN 7090 computer.

The form factors were taken to be of the Clementel-Villi type ([10]):

$$F_1(\{k-k'\}^2)=\left[1+\frac{\{k-k'\}^2}{M^2_{\mathrm{F1}}}\right]^{-1},\qquad F_{\mathrm{B}}(q^2)=\left[1+\frac{q^2}{M^2_{\mathrm{FB}}}\right]^{-1}. \tag{6}$$

The total cross-section is very dependent on the choices of M_{F1} aud M_{FB}. The pseudoscalar π-$\mathcal{N}$ coupling gives rise to the $(q^2+\Delta M^2)$ factor in eq. (5), partly cancelling the $(q^2+m^2_{\mathrm{B}})^{-2}$ of the propagator and making high-q^2 values more important (which is, in fact, contrary to the spirit of the peripheral model). The strong dependence on M_{F1} arises from the fact that σ is zero if the muon is in the forward direction, as noted above. Explicitly this may be verified by observing that the dot products in the {} in eq. (5) may be reduced to

$$\{\,\}=-\tfrac{1}{2}(k-k')^2\left[(k\cdot q')^2+(k'\cdot q')^2+\frac{m^2_{\mathrm{b}}}{2}(k-k')^2\right],$$

where terms in m^2_μ are neglected. Thus F_1 clearly plays an important role in the cross-section obtained from eq. (5). Table *I* lists the total production cross-section for several choices of form factors. We see that the cross-section is approximately proportional to the lepton form factor mass squared $(\sigma\sim M^2_{\mathrm{F1}})$.

([10]) E. CLEMENTEL and C. VILLI: *Nuovo Cimento*, 4, 1207 (1956).

Finally it is now immediately possible to estimate ρ production by η exchange on the basis of graph 1« (*). Generalizing the Cabibbo weak coupling scheme ([11]) by requiring that the meson current be an octet (**), the η, ρ and π, ω couplings

TABLE I. – $\sigma(\nu+n\to p+\mu^-+\omega)$ *and* $\sigma(\nu+p\to p+\mu^-+\rho^+)$ *in units of* $10^{-40}\,\text{cm}^2$.

	$\sigma(\nu+n\to p+\mu^-+\omega)$			$\sigma(\nu+p\to p+\mu^-+\rho^+)$		
Form factor M_{FI}	0.66	0.75	0.66	0.66	0.75	0.66
masses, GeV M_{FB}	0.939	0.939	1.2	0.939	0.939	1.2
E_ν (lab), GeV						
2	1.0	1.25	1.39	0.40	0.47	0.53
3	3.76	4.93	5.34	1.15	1.39	1.57
5	9.3	12.8	13.4	2.22	2.71	3.06
7	14.0	19.7	20.4	2.90	3.54	4.02
10	19.7	28.4	28.8	3.56	4.38	4.97

$\sigma(\nu+p\to p+\mu^-+\rho^+)=\sigma(\nu+n\to n+\mu^-+\rho^+)=\frac{1}{2}\sigma(\nu+n\to p+\mu^-+\rho^0)$.

to the leptonic current are identical. Therefore eq. (5) is valid for p production by η exchange if we make the substitution $2g^2_{\mathcal{N}\pi}\to g^2_{\mathcal{N}\eta}$ and if wo use the masses appropriate to the ρ, η case. The coupling constant $g^2_{\mathcal{N}\eta}$ has been estimated by DE SWART ([13]) on a unitary-symmetry model, and he finds $g^2_{\mathcal{N}\eta}\ll g^2_{\mathcal{N}\pi}$. The high mass in the propagator also reduces production. Therefore, ρ production by η exchange is very much smaller than ω production by π exchange.

Graph *la* may also be used to compute ρ production with π exchange. In this case the meson-lepton coupling is pure axial vector, and we take for the leptou vertex

$$ig_A\overline{U}_\mu\gamma_\alpha(1+\gamma_5)\,U_\nu S_\alpha F_1(\{k-k'\}^2)\,, \tag{7}$$

where S_α is the linear ρ polarization vector $(q'_\alpha S_\alpha=0)$ and derivative couplings

(*) We can treated the ρ as a stable particle because:

a) $\Gamma(\rho\to\pi+\pi)$ is a slowly varying function of m_ρ $(\Gamma\sim m_\rho)$,

b) $[\Gamma(\rho\to\pi+\pi)/2m_\rho]^2\ll 1$, and

c) $\sigma(\nu+\mathcal{N}\to\mathcal{N}+\mu^-+\rho^+)$ can be closely approximated by a linear function of the ρ mass in the interval $0.75\,\text{GeV}-\frac{1}{2}\Gamma_\rho<\rho$ mass $<0.75\,\text{GeV}+\frac{1}{2}\Gamma_\rho$.

(11) N. CABIBBO: *Phys. Rev. Lett.*, **10**, 531 (1963).

(**) We are indebted to Prof. V. TELEGDI for suggesting to us this generalization of the Cabibbo scheme.

(12) J. J. DE SWART: *Rev. Mod. Phys.*, **35**, 916 (1963).

are ignored. This interaction is equivalent to the usual β-decay or μ-capture axial vector interaction in the sense that the quantum numbers of the exchanged systems are the same. In addition there will be a term like the induced pseudoscalar, presumably dominated by the one-pion pole. The coupling constant g_A may now be estimated by a Goldberger-Treiman ([13]) argument. In analogy with the β-decay case,

$$\langle \varrho | J^A_\alpha | \pi \rangle = g_A S_\alpha + \frac{S_\beta (q'-q)_\beta (q'-q)_\alpha \, g_{\pi\pi\rho} \, g_{\pi l}}{(q'-q)^2 + m_\pi^2}$$

and

$$\langle \varrho | \frac{\partial J^A_\alpha}{\partial x_\alpha} | \pi \rangle = S_\alpha (q'-q)_\alpha \left\{ g_A + g_{\pi\pi\rho} g_{\pi l} \left(1 - \frac{m_\pi^2}{(q'-q)^2 + m_\pi^2} \right) \right\}.$$

As usual, the divergence of the axial current is supposed to be dominated by the one-pion pole. Thus, we must have

$$g_A = - g_{\pi\pi\rho} g_{\pi l} ,$$

where $g_{\pi\pi\rho}$ and $g_{\pi l}$ are the coupling constants at the $\rho\pi\pi$ vertex and the $\pi\nu\mu$ vertex. These coupling constants are taken at their values for each particle on the mass shell:

$$\Gamma(\rho \to \pi_1 + \pi_2) = \left(\frac{g^2_{\pi\pi\rho}}{4\pi} \right) \frac{1}{48 m_\rho^2} \left[(m_\rho^2 - m_{\pi_1}^2 - m_{\pi_2}^2)^2 - 4 m_{\pi_1}^2 m_{\pi_2}^2 \right]^{\frac{3}{2}}$$

and

$$\Gamma(\pi^+ \to \mu^+ + \nu) = \left(\frac{g^2_{\pi l}}{4\pi} \right) \left(\frac{m_\mu}{m_\pi} \right)^2 \frac{1}{m_\pi} \left[1 - \frac{m_\mu^2}{m_\pi^2} \right]^2 .$$

Using the constants compiled by Eoos ([7]), we have

$$g^2_{\pi\pi\rho} = 114 , \qquad g^2_{\pi l} / m_\pi^2 = 2.21 \cdot 10^{-14}$$

and

(8) $$g_A^2 = \lambda^2 G^2 \approx \lambda^2 \frac{10^{-10}}{M_p^4} ,$$

with $\lambda^2 = 1.0$ GeV^{-2}.

([13]) M. L. GOLDBERGER and S. B. TREIMAN: *Phys. Rev.*, **110**, 354, 1178 (1958).

With the lepton vertex of expression (7) we find for $\sigma(\nu+p\to p+\mu^-+\rho^+)$

$$(9)\qquad d_9\sigma=\frac{g^2_{\mathcal{N}\pi}g^2_A F^2_B(q^2)F^2_1([q-q']^2)(\Delta M^2+q^2)}{4(2\pi)^5(-p\cdot k)(q^2+m^2_B)^2}\delta_4(k'+q'+p'-p-k)\cdot \cdot\left\{-k\cdot k'+\frac{2}{m^2_b}(k\cdot q')(k'\cdot q')\right\}\frac{d_3\boldsymbol{p}'}{p'_0}\frac{d_3\boldsymbol{k}'}{k'_0}\frac{d_3\boldsymbol{q}'}{q'_0},$$

where the notation of eq. (5) is followed. The total p production cross-section was also computed as a four-fold numerical integral. The results are listed in Table I. The dependence 011 form factors is still important, with $\sigma\sim M_{F1}$, roughly.

3. - Cross-sections for $\nu+\mathcal{N}\to\mu^-+b+X$.

If in the peripheral graph la the outgoing nucleon is replaced by a state X (where $B+\mathcal{N}\to X$) we arrive at a new graph (1*b*) which may also be important for ρ, ω production. Since the most prominent feature of π, $\mathcal{N}$ scattering is the $\frac{3}{2}\frac{3}{2}$ resonance ($\mathcal{N}^*$) we are led to consider the special case of graph lc. This graph is evaluated using the Earita-Schwinger formalism ([14]), and following closely the treatment of ref. ([3]) for the $\mathcal{N}^*$.

The $\pi\mathcal{N}\mathcal{N}^*$ interaction is taken to be of the form

$$(10)\qquad (g_{\pi\mathcal{N}\mathcal{N}^*}/m_\pi)\,\mathcal{N}^*_\alpha\left(\frac{\partial}{\partial x_\alpha}\pi\right)\mathcal{N},$$

where the form of the interaction and the coupling constant are chosen to yield the observed cross-section for $\mathcal{N}^*$ production ($g_{\pi\mathcal{N}\mathcal{N}^*}=2.32$ = renormalized $\pi\mathcal{N}\mathcal{N}^*$ coupling constant). The $\mathcal{N}^*$ propagator, $D_{\mu\nu}(M')$, is given by ([3])

$$D_{\mu\nu}(M')=\left[\delta_{\mu\nu}-\frac{1}{3}\gamma_\mu\gamma_\nu-\frac{i}{3M'}(\gamma_\mu p'_\nu-p'_\mu\gamma_\nu)+\frac{2}{3M'^2}p'_\mu p'_\nu\right]\cdot \cdot(-ip'_\alpha\cdot\gamma_\alpha+M')(p'^2+M'^2)^{-1},$$

where a prime refers to the $\mathcal{N}^*$ (see Fig. lc) and

$$M'=M_0-\frac{i}{2}\Gamma([-p'^2]^{\frac{1}{2}})(-p'^2)^{\frac{1}{2}}/M_0\,,\qquad M_0=1.238\text{GeV},$$

and

$$\Gamma(x)=\frac{g^2_{\pi\mathcal{N}\mathcal{N}^*}}{m^2_\pi}\frac{1}{6\pi\,(2x)^5}\left[(x+M_p)^2-m^2_\pi\right]\cdot\left[(x^2-M^2_p-m^2_\pi)^2-4M^2_p m^2_\pi\right]^{\frac{3}{2}}.$$

([14]) W. RARITA and J. SCHWINGER: *Phys. Rev.*, 60, 61 (1941).

Since $\Gamma \ll M_0$ for the $\mathcal{N}^*$, we neglect all terms of order Γ/M_0 or smaller everywhere except in the denominator of the $\mathcal{N}^*$ propagator where the term of first order in Γ/M_0 is kept. Graph lc then gives the following cross-section:

$$\text{(11)} \qquad \mathrm{d}_6\sigma = \frac{2(g_{\pi\mathcal{N}\mathcal{N}^*}/m_\pi)^2 |l_\mu J_\mu|^2 k_0 k_0' F_\mathrm{B}^2(q^2) P_0' \Gamma}{3(p\cdot k)(2\pi)^6 (q^2+m_\mathrm{B}^2)^2[(p'^2+M_0^2)^2 - p'^2\Gamma^2]} \cdot \left[q^2 + \left(\frac{q\cdot p'}{M_0}\right)^2\right][M_0 M_\mathcal{N} - p\cdot p'] \frac{\mathrm{d}_3\boldsymbol{k}'}{k_0'} \frac{\mathrm{d}_3\boldsymbol{q}'}{q_0'},$$

where the momenta are defined in Pig. lc, and $l_\mu J_\mu$ represents the lepton-meson vertex (for π exchange, ω production, $l_\mu J_\mu$ is expression (3); for π exchange, ρ production $l_\mu J_\mu$ is expression (7)).

Again there aie only two independent cross-sections, taken as

$$\sigma(\nu + \mathrm{p} \to \mu^- + \rho^0 + \mathcal{N}^{*++}) = \tfrac{3}{2}\sigma(\nu + \mathrm{p} \to \mu^- + \rho^+ + \mathcal{N}^{*+}) = = \tfrac{3}{2}\sigma(\nu + \mathrm{n} \to \mu^- + \rho^+ + \mathcal{N}^{*0}) = 3\,\sigma(\nu + \mathrm{n} \to \mu^- + \rho^0 + \mathcal{N}^{*+}$$

and

$$\sigma(\nu + \mathrm{p} \to \mu^- + \omega + \mathcal{N}^{*++}) = 3\,\sigma(\nu + \mathrm{n} \to \mu^- + \omega + \mathcal{N}^{*+}).$$

The corresponding antineutrino reactions are obtained as before.

From eq. (11) the total production cross-sections were computed as five-fold numerical integrals; they are listed in Table II.

Equation (11), as can be seen from graph 1*b*, entails the cross-section $\mathrm{B} + \mathcal{N} \to \mathrm{X}$ (*i.e.*, here $\pi + \mathcal{N} \to \mathcal{N}^*$) where, however, B is virtual. The fact

TABLE II. – $\sigma(\nu+\mathrm{p}\to\mathcal{N}^{*++}+\mu^-+\omega)$ *and* $\sigma(\nu+\mathrm{p}\to\mathcal{N}^{*++}+\mu^-+\rho^0)$ *in units of* 10^{-40} cm².

		$\sigma(\nu+\mathrm{p}\to\mathcal{N}^{*++}+\mu^-+\omega)$			$\sigma(\nu+\mathrm{p}\to\mathcal{N}^{*++}+\mu^-+\rho^0)$		
Form factor	M_FB	0.66	0.75	0.66	0.66	0.75	0.66
masses, GeV	M_F1	0.939	0.939	1.2	0.939	0.939	1.2
E_ν (lab), GeV							
3		1.1	1.37	1.71	0.58	0.697	0.876
5		5.5	7.48	9.26	2.43	2.96	3.81
7		10.8	15.1	18.7	4.34	5.29	6.89
10		19.1	27.2	33.8	7.21	8.75	11.5

$$\sigma(\nu+\mathrm{p}\to\mathcal{N}^{*++}+\mu^-+\omega) = 3\,\sigma(\nu+\mathrm{n}\to\mathcal{N}^{*+}+\mu^-+\omega),$$

$$\sigma(\nu+\mathrm{p}\to\mathcal{N}^{*++}+\mu^-+\rho^0) = \tfrac{3}{2}\sigma(\nu+\mathrm{p}\to\mathcal{N}^{*+}+\mu^-+\rho^+) =$$

$$= \tfrac{3}{2}\sigma(\nu+\mathrm{n}\to\mathcal{N}^{*0}+\mu^-+\rho^+) = 3\,\sigma(\nu+\mathrm{n}\to\mathcal{N}^{*+}+\mu^-+\rho^0).$$

that the π is virtual necessitates the use of an explicit formula for the cross-section rather than directly the experimental π, $\mathcal{N}$ cross-section since in the latter case one neglects important kinematical effects. For a given pion energy (in the $\mathcal{N}^*$ rest system) a virtual pion may have as compared to a real pion considerably higher three-momentum and it therefore penetrates the angular momentum barrier more easily and has relatively a higher cross-section than a physical pion. Using the experimental π, $\mathcal{N}$ cross-section with the same form factors as before, and without allowance for the angular momentum barrier, leads to an underestimate of graph lc by roughly a factor of 4 for neutrino energies of a few GeV.

4. - Production of π, η mesons by ρ, ω exchange.

Production of π, η mesons by ρ, ω exchange has been computed on the basis of the graph in Fig. 2. All of these cross-sections are small because of the weak coupling of the vector mesons to nucleons and the high masses in the propagators. The three independent cross-sections are:

$$\begin{aligned} &\sigma(\nu+\mathrm{p}\to\mathrm{p}+\mu^-+\pi^+)= && (\omega\ \text{exchanged}),\\ =\ &\sigma(\nu+\mathrm{n}\to\mathrm{n}+\mu^-+\pi^+) && (\omega\ \text{exchanged}),\\ &\sigma(\nu+\mathrm{n}\to\mathrm{p}+\mu^-+\eta) && (\rho^-\ \text{exchanged}),\end{aligned}$$

and

$$\begin{aligned} &\sigma(\nu+\mathrm{p}\to\mathrm{p}+\mu^-+\pi^+)= && (\rho^0\ \text{exchanged}),\\ =\ &\sigma(\nu+\mathrm{n}\to\mathrm{n}+\mu^-+\pi^+)= && (\rho^0\ \text{exchanged}),\\ =\ &\tfrac{1}{2}\,\sigma(\nu+\mathrm{n}\to\mathrm{p}+\mu^-+\pi^0)\,. && (\rho^-\ \text{exchanged}).\end{aligned}$$

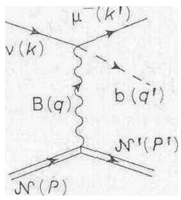

Fig. 2. – Diagram for pseudoscalar meson production by vector-meson exchange.

The matrix element for graph 2 may be written

$$\mathscr{M}=\frac{-i(2\pi)^4}{(2q_0')^{1/2}}\,(q^2+m_{\mathrm{B}}^2)^{-1}\overline{U}_{\mu}\gamma_\alpha(1+\gamma_5)U_\nu F_1([k-k']^2)\,F_{\mathbf{B}}(q^2)\cdot$$
$$\cdot\overline{U}_{\mathcal{N}'}f_V\left(T_{\alpha\beta}[\gamma_\beta+\lambda_m\sigma_{\beta\rho}q_\rho]+\frac{ig_A}{m_{\mathrm{B}}^2}\Delta M q_\alpha\right)U_{\mathcal{N}}\,,$$

where $T_{\alpha\beta}\equiv g_A\delta_{\alpha\beta}+g_V\varepsilon_{\alpha\varrho\sigma\beta}\,q_\varrho'\,q_\sigma$, with g_A and g_V as defined above (for a given reaction, of course, either g_A or $g_V\equiv 0$, according to eq. (2)), $\sigma_{\alpha\beta}\equiv i/2\cdot\cdot(\gamma_\alpha\gamma_\beta-\gamma_\beta\gamma_\alpha)$, and f_V and λ_m are coupling constants for the $\mathrm{B}\mathcal{N}\mathcal{N}'$ vertex.

These coupling constants have been estimated by Liu and Singer [15], namely:

Vertex	$f_V^2/4\pi$	λ_m
$\omega\mathcal{N}, \mathcal{N}$	1.0	0
ρ^-n, p	0.2	$-1.5\ \mathrm{GeV}^{-1}$
$\rho^0\mathcal{N}, \mathcal{N}$	0.1	$-1.5\ \mathrm{GeV}^{-1}$

in units where $g^2_{\mathcal{N}\pi}/4\pi \approx 15$.

The production cross-section is now given by

$$\mathrm{d}_9\sigma = \frac{1}{(2\pi)'^3}(\mathrm{Flux})^{-1}\delta_4(p'+k'+q'-p-k)\,\mathrm{d}_3\boldsymbol{p}'\,\mathrm{d}_3\boldsymbol{q}'\,\mathrm{d}_3\boldsymbol{k}'\,|\mathcal{M}|^2$$

where $|\mathcal{M}|^2$ is averaged over initial spins and summed over final spins. The traces in $|\mathcal{M}|^2$ are easily evaluated, but the tensor inner products lead to a

TABLE III. – *Cross-sections for pseudoscalar meson production by vector meson exchange in units of* $10^{-40}\ \mathrm{cm}^2$.

	ω exchange	ρ exchange	
Reaction	$\nu+p\to p+\mu^-+\pi^+$	$\nu+p\to p+\mu^-+\pi^+$	$\nu+n\to p+\mu^-+\eta$
E_ν (lab), GeV			
3	0.422	0.267	0.243
5	0.95	0.415	0.664
7	1.47	0.543	1.11
10	2.15	0.711	1.74

Form factor masses: $M_{\mathrm{F1}} = 0.66$ Gev, $M_{\mathrm{FB}} = 0.939$ Gev.

large number of terms. In Table III are listed the computed cross-sections for pseudoscalar meson production with vector-meson exchange.

([15]) L. S. LIU and P. SINGER: *Phys. Rev.*, **135**, B 1017 (1964).

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RIASSUNTO (*)

Si studia, col modello periferico, la produzione e lo scambio di mesoni pseudoscalari e vettoriali non strani. Per i mesoni non strani una conseguenza di questo modello è che le corrispondenti sezioni d'urto dei ν e $\bar{\nu}$ sono uguali, nell'ipotesi che ν e $\bar{\nu}$ si accoppino allo stesso multipletto di isospin. Si trova che la sezione d'urto per la produzione di ρ e ω con scambio di π, con e senza eccitazione simultanea della risonanza $\frac{3}{2}$, $\frac{3}{2}$, è una frazione (con forte dipendenza da fattori di forma poco noti) della sezione d'urto « elastica », $\sigma(\nu+n\to p+\mu^-)$, a pochi GeV di energia del neutrino incidente. Si calcola anche la produzione di mesoni π e η con scambio di ρ e ω e si trova che è molto piccola.

(*) *Traduzione a cura della Redazione.*