Work of Aligarh group 2019

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Charged current deep inelastic scattering process

 $v_l/\bar{v}_l(k) + N(p) \to l^-/l^+(k') + X(p')$



$$\frac{d^2 \pmb{\sigma}^N}{d \Omega' d E'} = \frac{G_F^2}{(2\pi)^2} \, \frac{|\mathbf{k}'|}{|\mathbf{k}|} \left(\frac{m_W^2}{q^2 - m_W^2}\right)^2 L^{\mu\nu} W^N_{\mu\nu}$$

Leptonic tensor

$$L^{\mu\nu} = k^{\mu}k^{\prime\nu} + k^{\nu}k^{\prime\mu} - k.k^{\prime}g^{\mu\nu} \pm i\varepsilon^{\mu\nu\rho\sigma}k_{\rho}k^{\prime}_{\sigma}$$

Hadronic tensor

$$\begin{split} W^N_{\mu\nu} &= \left(\frac{q_\mu q_\nu}{q^2} - g_{\mu\nu}\right) W_{1N} + \frac{1}{M^2_N} \\ &\times \left(p_\mu - \frac{p.q}{q^2} q_\mu\right) \left(p_\nu - \frac{p.q}{q^2} q_\nu\right) W_{2N} \\ &\quad - \frac{i}{2M^2_N} \epsilon_{\mu\nu\rho\sigma} p^\rho q^\sigma W_{3N} \end{split}$$

Dimensionless SF

$$\begin{array}{rcl} M_N W_{1N}(\nu,Q^2) &=& F_{1N}(x,Q^2), \\ & \nu W_{2N}(\nu,Q^2) &=& F_{2N}(x,Q^2), \\ & \nu W_{3N}(\nu,Q^2) &=& F_{3N}(x,Q^2). \end{array}$$

In terms of PDFs

$$\begin{array}{lll} F_2^{Vp} &=& 2x[d(x)+s(x)+\bar{u}(x)+\bar{c}(x)],\\ F_2^{\bar{V}p} &=& 2x[u(x)+c(x)+\bar{d}(x)+\bar{s}(x)],\\ xF_3^{Vp} &=& 2x[d(x)+s(x)-\bar{u}(x)-\bar{c}(x)],\\ xF_3^{\bar{V}p} &=& 2x[u(x)+c(x)-\bar{d}(x)-\bar{s}(x)]. \end{array}$$

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$F_{iN}^{WI}(x,Q^2)$ vs Q^2 : arXiv:1911.12573



$2xF_{1A}^{WI}(x,Q^2)$ vs Q^2 : arXiv:1911.12573



NME in Weak & Electromagnetic interactions: JPG: Invited

review



Isoscalar vs Nonisoscalar nuclei: arXiv:1911.12573



Theory vs Phenomenology: $v_l - {}^{40}Ar$: JPG: Invited review



Differential cross section ratios: $V_l - A$: arXiv:1911.12573



Differential cross section ratios: $\bar{v}_l - A$: arXiv:1911.12573



Associated Particle Production

$$\gamma(q) + p(p) \longrightarrow K^+(p_k) + \Lambda(p')$$

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$$\gamma(q) + p(p) \longrightarrow K^+(p_k) + \Lambda(p')$$



$$\begin{split} J^{\mu}|_{s} &= ieA_{s} F_{s}(s)\bar{u}(p') \ \dot{p}_{k}\gamma_{5} \frac{\dot{p}+\dot{q}+M}{s-M^{2}} \left(\gamma^{\mu}F_{1}^{\rho}(0)+i\frac{F_{2}(0)}{2M}\sigma^{\mu\nu}q_{\nu}\right)u(p), \\ J^{\mu}|_{t} &= ieA_{t} F_{t}(t)\bar{u}(p') \left[(\dot{p}-\dot{p'})\cdot\gamma_{5}\right]u(p) \frac{(2p_{k}^{\mu}-q^{\mu})}{t-M_{k}^{2}}, \\ J^{\mu}|_{u\Lambda} &= ieA_{u}^{\Lambda} F_{u}^{\Lambda}(u)\bar{u}(p') \left(\gamma^{\mu}F_{1}^{\Lambda}(0)+i\frac{F_{2}^{\Lambda}(0)}{2M_{\Lambda}}\sigma^{\mu\nu}q_{\nu}\right) \frac{\dot{p'}-\dot{q}+M_{\Lambda}}{u-M_{\Lambda}^{2}} \ \dot{p}_{k}\gamma_{5}u(p), \\ J^{\mu}|_{u\Sigma^{0}} &= ieA_{u}^{\Sigma^{0}} F_{u}^{\Sigma^{0}}(u)\bar{u}(p') \left(\gamma^{\mu}F_{1}^{\Sigma^{0}}(0)+i\frac{F_{2}^{\Sigma^{0}}(0)}{2M_{\Sigma^{0}}}\sigma^{\mu\nu}q_{\nu}\right) \frac{\dot{p'}-\dot{q}+M_{\Sigma^{0}}}{u-M_{\Sigma^{0}}^{2}} \ \dot{p}_{k}\gamma_{5}u(p), \\ J^{\mu}|_{u\Sigma^{0}} &= -ieA_{CT} \ F_{CT}\bar{u}(p') \ \gamma^{\mu}\gamma_{5}u(p), \end{split}$$

$$A_{\delta} = A_t = A_u^{\Lambda} = A_{CT} = -\left(\frac{D+3F}{2\sqrt{3}f\pi}\right), \qquad A_u^{\Sigma 0} = \left(\frac{D-F}{2f\pi}\right).$$

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$$\begin{split} J^{\mu}|_{s} &= ieA_{s} \, F_{s}(s)\bar{u}(p') \, \not{p}_{k} \gamma_{S} \, \frac{\not{p} + \not{q} + M}{s - M^{2}} \left(\gamma^{\mu} F_{1}^{\rho}(0) + i \frac{F_{2}(0)}{2M} \, \sigma^{\mu\nu} q_{\nu} \right) u(p), \\ J^{\mu}|_{t} &= ieA_{t} \, F_{t}(t)\bar{u}(p') \left[(\not{p} - \not{p}') \cdot \gamma_{S} \right] u(p) \frac{(2p_{k}^{\mu} - q^{\mu})}{t - M_{k}^{2}}, \\ J^{\mu}|_{u\Lambda} &= ieA_{u}^{\Lambda} \, F_{u}^{\Lambda}(u)\bar{u}(p') \left(\gamma^{\mu} F_{1}^{\Lambda}(0) + i \frac{F_{2}^{\Lambda}(0)}{2M_{\Lambda}} \, \sigma^{\mu\nu} q_{\nu} \right) \frac{\not{p}' - \not{q} + M_{\Lambda}}{u - M_{\Lambda}^{2}} \, \not{p}_{k} \gamma_{S} u(p), \\ J^{\mu}|_{u\Sigma0} &= ieA_{u}^{\Sigma0} \, F_{u}^{\Sigma0}(u)\bar{u}(p') \left(\gamma^{\mu} F_{1}^{\Sigma0}(0) + i \frac{F_{2}^{\Sigma0}(0)}{2M_{\Sigma0}} \, \sigma^{\mu\nu} q_{\nu} \right) \frac{\not{p}' - \not{q} + M_{\Sigma0}}{u - M_{\Sigma0}^{2}} \, \not{p}_{k} \gamma_{S} u(p), \\ J^{\mu}|_{CT} &= -ieA_{CT} \, F_{CT} \, \ddot{u}(p') \, \gamma^{\mu} \gamma_{S} u(p), \end{split}$$

$$A_{\delta} = A_t = A_u^{\Lambda} = A_{CT} = -\left(\frac{D+3F}{2\sqrt{3}f\pi}\right), \qquad A_u^{\Sigma 0} = \left(\frac{D-F}{2f\pi}\right).$$

A general dipole form for $F_x(x)$

$$F_x(x) = \frac{\Lambda_i^4}{\Lambda_i^4 + (x - M_x^2)^2}, \quad \Lambda_B = 0.52 GeV \quad \Lambda_R = 1.1 GeV$$

Davidson-Workman[PRC 63, 025210 (2001)]

$$F_{CT} = F_s(s) + F_t(t) - F_s(s) \times F_t(t).$$

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| Resonances | M_R [GeV] | J | Ι | Р | Г | $K\Lambda$ branching | <i>SKAR</i> |
|-------------------------------|-------------------|-----|-----|---|----------------------------|----------------------|-------------|
| | | | | | (GeV) | ratio (%) | |
| $S_{11}(1650)$ | 1.655 ± 0.015 | 1/2 | 1/2 | _ | 0.135 ± 0.035 | 10 ± 5 | 0.79 |
| $P_{11}(1710)$ | 1.700 ± 0.020 | 1/2 | 1/2 | + | 0.120 ± 0.040 | 15 ± 10 | 1.32 |
| $P_{13}(1720)$ | 1.675 ± 0.015 | 3/2 | 1/2 | + | $0.250\pm^{0.150}_{0.100}$ | 4.5 ± 0.5 | 2.92 |
| $P_{11}(1880)$ | 1.860 ± 0.040 | 1/2 | 1/2 | + | 0.230 ± 0.050 | 20 ± 8 | 0.91 |
| <i>S</i> ₁₁ (1895) | 1.910 ± 0.020 | 1/2 | 1/2 | — | 0.110 ± 0.030 | 18 ± 5 | 0.41 |
| $P_{13}(1900)$ | 1.920 ± 0.020 | 3/2 | 1/2 | + | 0.150 ± 0.050 | 11 ± 9 | 1.028 |
| | | | | | | | |

| Resonances | M_P [GeV] | J | Ι | Р | Г | $K\Lambda$ branching | Q KAP |
|-------------------------------|-------------------|-----|-----|---|----------------------------|----------------------|-------|
| | A L - · · J | | | | (GeV) | ratio (%) | OKAK |
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| | | | | | | | |

• The helicity amplitudes for the resonances $S_{11}(1650)$, $P_{13}(1720)$ and $P_{13}(1920)$ are taken from MAID 2011 while for the resonances $P_{11}(1710)$, $P_{11}(1880)$ and $S_{11}(1895)$, the helicity amplitudes are taken from PDG.

Hadronic current for the s-channel processes where a resonant state $R^{\frac{1}{2}}$ is produced

Hadronic current for the s-channel processes where a resonant state $R^{\frac{1}{2}}$ is produced

$$j^{\mu}\big|_{R}^{\frac{1}{2}\pm} = ie \ \bar{u}(\vec{p}\,') \frac{g_{K\Lambda R\frac{1}{2}}}{M_{K}} p_{K} \Gamma_{s} \frac{p + q + M_{R}}{s - M_{R}^{2} + iM_{R} \Gamma_{R}} \Gamma_{\frac{1}{2}\pm}^{\mu} u(\vec{p}\,),$$

The most general expression of the hadronic current for the s-channel where a resonant state $R^{\frac{3}{2}}$ (with positive or negative parity) is produced and decays to a kaon and a lambda in the final state

$$j^{\mu}\big|_{R}^{\frac{3}{2}\pm} \quad = \quad ie \; \frac{g_{K\Lambda R}}{M_{K}} \; \frac{p_{K}^{\alpha}\Gamma_{s}}{s-M_{R}^{2}+iM_{R}\Gamma_{R}} \bar{u}(\vec{p}')P_{\alpha\beta}^{3/2}(p_{R})\Gamma_{\frac{3}{2}\pm}^{\beta\mu}(p,q)u(\vec{p}\,), p_{R}=p+q,$$

where $\Gamma_s = 1(\gamma_5)$ for positive (negative) parity resonances, $g_{K\Lambda R}$ is the coupling strength for $R \to K\Lambda$, where R, determined from partial decay widths. M_R is the mass of the resonance and Γ_R is its decay width.

| Resonances | M_R [GeV] | J | Ι | Р | Г | G | G_K^{ν} | G_K^t |
|------------------------------|--------------------------------------|-----|-----|---|---------------------|--------|-------------|---------|
| | | | | | (GeV) | | | |
| Λ* (1405) | $1.405 \pm \substack{0.0013\\0.001}$ | 1/2 | 0 | - | 0.0505 ± 0.002 | -10.18 | - | - |
| Λ* (1800) | $1.800 \pm \substack{0.080\\0.050}$ | 1/2 | 0 | - | 0.300 ± 0.100 | -4.0 | - | - |
| <i>K</i> *(892) | 0.89166 ± 0.00026 | 1 | 1/2 | - | 0.0508 ± 0.0009 | - | -0.18 | 0.02 |
| <i>K</i> ₁ (1270) | 1.272 ± 0.007 | 1 | 1/2 | + | 0.090 ± 0.020 | - | 0.28 | -0.28 |

| Resonances | | J | 1 | 1 | (GeV) | U | O_K | 01 |
|-----------------------|----------------------------|-----|-----|---|---------------------|--------|-------|-----|
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The values of G, G_K^V and G_K^t are fitted to the experimental data and contains both the electromagnetic and strong coupling strengths.

The hadronic current for the Λ^* resonance exchange may be written as

$$J_{\mu}\big|_{\Lambda^*\pm} = ie\bar{u}(p')\frac{G}{M_{\Lambda}+M_{\Lambda^*}}\sigma_{\mu\nu}q^{\nu}\Gamma_5\left(\frac{p'-\not{q}+M_{\Lambda^*}}{u-M_{\Lambda^*}^2+iM_{\Lambda^*}\Gamma_{\Lambda^*}}\right)\not{p}_k\gamma_5\Gamma u(p)$$

with $G = \kappa_{\Lambda\Lambda^*} g_{pK\Lambda^*} / f_{\pi}$, M_{Λ^*} and Γ_{Λ^*} being the mass and the decay width of Λ^* .

The hadronic current for the K^* exchange is obtained as

$$I_{\mu}\big|_{K^{*}} = ie\bar{u}(p')\varepsilon_{\mu\nu\rho\sigma}q^{\rho}(p'-p)^{\sigma}\left(\frac{-g^{\nu\alpha} + (p-p')^{\nu}(p-p')^{\alpha}/M_{K^{*}}^{2}}{t-M_{K^{*}}^{2} + iM_{K^{*}}\Gamma_{K^{*}}}\right) \left[G_{K^{*}}^{\nu}\gamma\alpha + \frac{G_{K^{*}}'}{M+M_{\Lambda}}(p'-p)\gamma\alpha\right]u(p),$$

with $G_{K^*}^{\nu} = \kappa_{KK^*} g_{K^* \Lambda p}^{\nu} / \mu$ and $G_{K^*}^t = \kappa_{KK^*} g_{K^* \Lambda p}^t / \mu$. M_{K^*} and Γ_{K^*} are the mass and width of the K^* resonance,

The hadronic current for the pseudovector kaon K_1 exchange in the *t*-channel as

$$\begin{aligned} J_{\mu}\Big|_{K_{1}} &= ie\bar{u}(p')[g_{\alpha\mu}q\cdot(p-p')-q_{\alpha}(p-p')_{\mu}] \\ &\times \left(\frac{-g^{\alpha\rho}+(p-p')^{\alpha}(p-p')^{\rho}/M_{K_{1}}^{2}}{t-M_{K_{1}}^{2}+iM_{K_{1}}\Gamma_{K_{1}}}\right) \\ &\times \left[G_{K_{1}}^{\nu}\gamma_{\rho}\gamma_{5}+\frac{G_{K_{1}}^{t}}{M+M_{\Lambda}}(p'-p)\gamma_{\rho}\gamma_{5}\right]u(p), \end{aligned}$$

with $G_{K_1}^{\nu} = \kappa_{KK^*} g_{K_1 \Lambda p}^{\nu} / \mu$ and $G_{K_1}^t = \kappa_{KK^*} g_{K_1 \Lambda p}^t / \mu$. M_{K_1} and Γ_{K_1} are the mass and width of the K_1 resonance, respectively.

 σ vs. W for the process $\gamma + p \longrightarrow K^+ + \Lambda$



σ vs. W for the process $\gamma + p \longrightarrow K^+ + \Lambda$: PRD in submission



 $\frac{d\sigma}{d\cos\theta_{K}^{CM}} \text{ VS. } \cos\theta_{K}^{CM} \text{ for the process } \gamma + p \longrightarrow K^{+} + \Lambda \text{ PRD in submission}$



Hyperon production

$$\bar{\mathbf{v}}_{l}(k) + N(p) \longrightarrow l^{+}(k') + Y(p')$$
$$V^{\mu}_{B'B}(p',p) = f_{1}^{B'B}(Q^{2})\gamma_{\mu} + \frac{i\sigma^{\mu\nu}q_{\nu}}{M_{B} + M'_{B}}f_{2}^{B'B}(Q^{2}) + \frac{2q_{\mu}}{M_{B} + M'_{B}}f_{3}^{B'B}(Q^{2})$$

 $A^{\mu}_{B'B}(p',p) = g_1^{B'B}(Q^2) \gamma_{\mu}\gamma_5 + i\sigma_{\mu\nu}\gamma_5 \frac{q^{\nu}}{M_B + M'_B} g_2^{B'B}(Q^2) + \frac{2q^{\mu}}{M_B + M'_B} \gamma_5 g_3^{B'B}(Q^2)$

Hyperon production

$$\bar{v}_{l}(k) + N(p) \longrightarrow l^{+}(k') + Y(p')$$

$$V_{B'B}^{\mu}(p',p) = f_{1}^{B'B}(Q^{2})\gamma_{\mu} + \frac{i\sigma^{\mu\nu}q_{\nu}}{M_{B}+M_{B}'}f_{2}^{B'B}(Q^{2}) + \frac{2q_{\mu}}{M_{B}+M_{B}'}f_{3}^{B'B}(Q^{2})$$
Vector FF
Magnetic FF
Scalar FF
$$A_{B'B}^{\mu}(p',p) = g_{1}^{B'B}(Q^{2})\gamma_{\mu}\gamma_{5} + i\sigma_{\mu\nu}\gamma_{5}\frac{q^{\nu}}{M_{B}+M_{B}'}g_{2}^{B'B}(Q^{2}) + \frac{2q^{\mu}}{M_{B}+M_{B}'}\gamma_{5}g_{3}^{B'B}(Q^{2})$$
Axial vector FF
Electric FF
Pseudoscalar FF

σ vs $E_{\bar{v}_{\mu}}$: Phys. Rev. D. 98, 033005 (2018)



Polarization components vs Q^2 for the process $\bar{v}_{\mu} + p \longrightarrow \mu^+ + \Lambda$: Front. in Phys. 7, 13 (2019)



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Polarization components vs $E_{\bar{\nu}_{\mu}}$ for the process $\bar{\nu}_{\mu} + p \longrightarrow \mu^+ + \Lambda$: Phys. Rev. D. 98, 033005 (2018)



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Cambridge University Press

1000 pages

March 2020

The Physics of Neutrino Interactions



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