Pion photoproduction
in a dynamical coupled-channels model

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May 23, 2011
Outline

- Introduction
- Jülich $\pi N$ dynamical coupled-channels model
  - Dynamical model ingredients
  - $\pi N$ partial wave amplitudes from Jülich model
- $\pi$ photoproduction
  - Photoproduction amplitudes
  - Gauge invariance
  - Cross sections & photon spin asymmetries
  - Multipole amplitudes & target asymmetries
- Summary & perspectives
Methodology for $N^*$ study

There are lots of high precision data from JLab, MIT-Bates, BNL-LEGS, Mainz-MAMI, Bonn-ELSA, GRAAL, Spring-8, et al.

$N^*$’s are unstable and couple strongly to baryon-meson states

Build coupled-channels meson-baryon reaction models to

- analyze the meson production data
- extract $N^*$ parameters
- understand the reaction mechanisms
- understand the structures and dynamical origins of $N^*$

Most widely used models: K matrix approximation, chiral unitary approach, dynamical coupled-channels model, et al.
Dynamical model ingredients

(a) $T |F\rangle S \langle F| + X$
(b) $T = V + V G_0 T$
(c) $V = |f\rangle S_0 \langle f| + U$
(d) $X = U + U G_0 X$

$T$: full amplitude
$S$: dressed res. propagator
$S_0$: bare res. propagator
$|F\rangle$: dressed res. vertex
$|f\rangle$: bare res. vertex

(a) $S = S_0 + S \langle F| G_0 |f\rangle S_0$
(b) $|F\rangle = |f\rangle + X G_0 |f\rangle$

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May 23, 2011 4 / 19
Jülich model: $\pi N \rightarrow \pi N$ [Solution 2002]

$\pi N \oplus \eta N \oplus \pi \Delta \oplus \rho N \oplus \sigma N$

$S_{11}(1535), \ S_{11}(1650), \ S_{31}(1620), \ P_{31}(1910), \ P_{13}(1720), \ D_{13}(1520), \ P_{33}(1232), \ D_{33}(1700)$ (all are 4-star $N^*$’s)
To get $M^\mu$ & $J^\mu$, attach a photon everywhere to

\[ M^\mu = M_s^\mu + M_u^\mu + M_t^\mu + M_{int} \]
Gauge invariance

- In a full theory (no form factors & truncations), gauge invariance is respected (minimum coupling, \( \partial_\mu \rightarrow D_\mu \equiv \partial_\mu + ieA_\mu(x) \))

- Real-world calculations require form factors & truncations

- Inclusion form factors will destroy gauge invariance, since form factors are usually functions of the momenta of exchanged particles

- Truncations usually also destroy gauge invariance

- The vast majority of existing models does not satisfy gauge invariance

- Our model is gauge invariant \( \iff \) we introduce a prescription to restore gauge invariance
Prescription to restore gauge invariance

\[ M^\mu = M^\mu_s + M^\mu_u + M^\mu_i + M^\mu_{int} \]

\[ M^\mu_c \equiv m^\mu_{KR} + U^\mu G_0 |F\rangle + X G_0 (M^\mu_u + M^\mu_i + m^\mu_{KR} + U^\mu G_0 |F\rangle)_L \]

\[ M^\mu_{int} = M^\mu_c + X G_0 (M^\mu_u + M^\mu_i + M^\mu_c)_T \]

**Generalized Ward-Takahashi Identity (GWTI) for \( M^\mu \)**

\[ k_\mu M^\mu = - |F_s\tau\rangle S_{p+k} Q_i S_p^{-1} + S_{p'}^{-1} Q_f S_{p'-k} |F_u\tau\rangle + \Delta_{p-p'+k}^{-1} Q_\pi \Delta_{p-p'} |F_t\tau\rangle \]

**Constraints on \( M^\mu_c \) & \( M^\mu_{int} \)**

\[ k_\mu M^\mu_c \equiv k_\mu M^\mu_{int} = - |F_s\tau\rangle Q_i + Q_f |F_u\tau\rangle + Q_\pi |F_t\tau\rangle \]
Choosing the generalized contact current $M^\mu_c$

- Constraints: gauge invariance; contact term; crossing symmetry

Choosing the generalized contact current $M^\mu_c$ as

$$M^\mu_c = -g_\pi \gamma_5 \left\{ \left[ \lambda + (1 - \lambda) \frac{q}{2m} \right] C^\mu + (1 - \lambda) \frac{\gamma^\mu}{2m} e_\pi f_i \right\}$$

$$C^\mu = e_\pi \frac{(2q - k)^\mu}{t - q^2} \left( f_i - \hat{F} \right) + e_f \frac{(2p' - k)^\mu}{u - p'^2} \left( f_u - \hat{F} \right) + e_i \frac{(2p + k)^\mu}{s - p^2} \left( f_s - \hat{F} \right)$$

$$\hat{F} = 1 - \hat{h} (1 - \delta_s f_s) (1 - \delta_u f_u) (1 - \delta_t f_t)$$

$k, p, q, p'$: 4-momenta for incoming $\gamma, N$ & outgoing $\pi, N$

$\hat{h}$: fit parameter

$f_x$: form factors for corresponding channels

Check gauge invariance:

$$k^\mu M^\mu_c = - |F_s\rangle e_i + |F_u\rangle e_f + |F_t\rangle e_\pi$$

- If no form factors, i.e. $f_x = 1$,

$$C^\mu \to 0, \quad M^\mu_c \to -g_\pi \gamma_5 (1 - \lambda) \frac{\gamma^\mu}{2m} e_\pi \quad \text{(Kroll-Ruderman term)}$$
Application

\[ M^\mu = |F\rangle S J^\mu + B^\mu + X G_0 B_T^\mu \]

\[ M^\mu = |F\rangle S \tilde{J}_s^\mu + B^\mu + T G_0 B_T^\mu \]

\[ B^\mu = M_u^\mu + M_t^\mu + M_c^\mu \]

\[ J^\mu = \tilde{J}_s^\mu + \langle F | G_0 B_T^\mu \]

\[ \tilde{J}_s^\mu = J_0^\mu + \langle m_{KR}^\mu | G_0 | F \rangle + \langle f | G_0 B_L^\mu \]

\( \tilde{J}_s^\mu \): minimal current. For more details, see:
H. Haberzettl, F. Huang, and K. Nakayama, arXiv:1103.2065
Results: $d\sigma/d\Omega \ & \Sigma_\gamma$ for $\gamma + p \rightarrow \pi^+ + n$

Differential cross sections for $\gamma + p \rightarrow \pi^+ + n$

Photon spin asymmetries for $\gamma + p \rightarrow \pi^+ + n$

$s_{11}(1535), \ s_{11}(1650), \ s_{31}(1620), \ p_{31}(1910), \ p_{13}(1720), \ d_{13}(1520), \ p_{33}(1232), \ d_{33}(1700)$
Results: $d\sigma/d\Omega & \Sigma_\gamma$ for $\gamma + p \rightarrow \pi^0 + p$

Differential cross sections for $\gamma + p \rightarrow \pi^0 + p$

Photon spin asymmetries for $\gamma + p \rightarrow \pi^0 + p$

$S_{11} (1535), S_{11} (1650), S_{31} (1620), P_{31} (1910), P_{13} (1720), D_{13} (1520), P_{33} (1232), D_{33} (1700)$

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May 23, 2011
Results: $d\sigma/d\Omega \& \Sigma_{\gamma}$ for $\gamma + n \rightarrow \pi^- + p$

Differential cross sections for $\gamma + n \rightarrow \pi^- + p$

Photon spin asymmetries for $\gamma + n \rightarrow \pi^- + p$

$S_{11} (1535), S_{11} (1650), S_{31} (1620), P_{31} (1910), P_{13} (1720), D_{13} (1520), P_{33} (1232), D_{33} (1700)$
Contribution from the loop integral is important

The terms apart from the Kroll-Ruderman term in $M^\mu_c$ give significant effects

⇒ keeping gauge invariance is important
$\gamma N \rightarrow \pi N$ total cross sections

- $\gamma p \rightarrow \pi^+ n$:
  - Full calculation
  - No loop integral
  - No $M^{\mu}_c$ apart from Kroll-Ruderman term

- $\gamma p \rightarrow \pi^0 p$:
  - Data not included in the fit
  - Contribution from the loop integral is important

- $\gamma n \rightarrow \pi^- p$:
  - Effect of the terms apart from Kroll-Ruderman term in $M^{\mu}_c$ is significant for $\gamma p \rightarrow \pi^+ n$
  - For $\gamma p \rightarrow \pi^0 p$, the effect of $M^{\mu}_c$ on $d\sigma/d\omega$ is largely suppressed at backward angles by $\sin \theta$
Multipole amplitudes

- SAID’s PWA not included in the fit

- $I = 1/2$:
  - $E_{0+}$: $S_{11}(1535), S_{11}(1650)$
  - $M_{1-}$: $P_{11}(1440)$
  - $E_{1+}$: $P_{13}(1720)$

- $I = 3/2$:
  - $M_{1+}$: $P_{33}(1232)$
  - $E_{1+}$: $P_{33}(1232)$
  - $M_{1-}$: $P_{31}(1910)$

- More data needed in the fit for further constraints
Target asymmetries for $\gamma + p \rightarrow \pi^+ + n$

Data are not included in the fit

Good at low energies

More partial waves needed

$J = 5/2$: $E_{2+}, M_{2+}$

More channels needed

$\Lambda K, \Sigma K$, et al.
Summary & perspectives

- Jülich dynamical coupled-channels model
  - $\pi N \oplus \eta N \oplus \pi \Delta \oplus \rho N \oplus \sigma N$ (version 2002)
  - Wess & Zumino chiral Lagrangian + $\Delta, \omega, \eta, a_0, \sigma$
  - $S_{11}(1535), S_{11}(1650), S_{31}(1620), P_{31}(1910), P_{13}(1720), D_{13}(1520), P_{33}(1232), D_{33}(1700)$
  - $\pi N \rightarrow \pi N$ scattering described successfully

- $\pi$ photoproduction
  - Field-theoretical approach
  - Gauge invariance strictly respected
  - $d\sigma/d\Omega$ & $\Sigma_\gamma$ described well up to 1.65 GeV
  - Loop integral & $M^\mu_c$ (apart from K.R.) are important

- Next step work:
  - Resonances’ electromagnetic couplings
  - High spin resonances
  - $\Lambda K, \Sigma K$ & $\omega N$ channels
  - Photoproduction of $\eta, K, \omega$
  - Electroproduction
Covariance & 3-D integral equation

- Jülich $\pi N$ model — TOPT

\[
T_{\text{TO}}(p', p; \sqrt{s}) = V_{\text{TO}}(p', p; \sqrt{s}) + \int d^3p'' \ V_{\text{TO}}(p', p''; \sqrt{s}) \ G_{\text{TO}}(p'', \sqrt{s}) T_{\text{TO}}(p'', p; \sqrt{s})
\]

\[
G_{\text{TO}}(p'', \sqrt{s}) = \frac{1}{\sqrt{s - E(p'') - \omega(p'')} + i0}
\]

- Converting to a covariant 3-D reduction like equation

\[
V(p', p; \sqrt{s}) \equiv (2\pi)^3 \sqrt{2E(p')} 2\omega(p') \sqrt{2E(p)} 2\omega(p) \ V_{\text{TO}}(p', p; \sqrt{s})
\]

\[
T(p', p; \sqrt{s}) \equiv (2\pi)^3 \sqrt{2E(p')} 2\omega(p') \sqrt{2E(p)} 2\omega(p) \ T_{\text{TO}}(p', p; \sqrt{s})
\]

\[
T(p', p; \sqrt{s}) = V(p', p; \sqrt{s}) + \int \frac{d^3p''}{(2\pi)^3} \ V(p', p''; \sqrt{s}) \ G_0(p'', \sqrt{s}) T(p'', p; \sqrt{s})
\]

\[
G_0(p'', \sqrt{s}) \equiv \frac{1}{2E(p'')} 2\omega(p'') \sqrt{s - E(p'') - \omega(p'')} + i0
\]

- Similarly, make 3-D reduction of the covariant photoproduction equation