Chapter 8

Summary and Discussion

We have succeeded in constructing a successful model for the photoproduction of pions from the nucleon for energies from the threshold for single pion production up to the threshold for two-pion production. The model is both Poincaré and gauge invariant. The dynamics is based on a mass operator that describes the coupling of single baryon channels (B), meson–baryon channels (μB), and photon–baryon channels (γB). The structure of the most general mass operator interactions, which determine these couplings, has been derived. Our result for the general form for the $\gamma + B \to \mu + B'$ interaction is also the most general form for the transition amplitude for the process $\gamma + B \to \mu + B'$ and thereby provides an important generalization for the well–known CGLN amplitude for $\gamma + N \to \pi + N$ [2].

The baryons that we have included in our present model are $N - P_{11}(938)$, $R - P_{11}(1440)$, $\Delta - P_{33}(1232)$, and $D - D_{13}(1520)$, while the only meson we have included is the pion, π. Using effective Lagrangians we have derived vertex functions for the following processes: $N \Leftrightarrow \gamma N$, $\pi N \Leftrightarrow N$, $\pi\Delta \Leftrightarrow N$, $\Delta \Leftrightarrow \gamma N$, $\pi N \Leftrightarrow \Delta$, $R \Leftrightarrow \gamma N$, $\pi N \Leftrightarrow R$, $\pi\Delta \Leftrightarrow R$, $D \Leftrightarrow \gamma N$, $\pi N \Leftrightarrow D$, $\pi\Delta \Leftrightarrow D$. These vertex functions have been used to construct the effective, "pole term" potentials for the processes: $\pi N \Leftrightarrow N \Leftrightarrow \gamma N$, $\pi\Delta \Leftrightarrow N \Leftrightarrow \gamma N$, $\pi N \Leftrightarrow \Delta \Leftrightarrow \gamma N$, $\pi N \Leftrightarrow R \Leftrightarrow \gamma N$, $\pi\Delta \Leftrightarrow R \Leftrightarrow \gamma N$, $\pi N \Leftrightarrow D \Leftrightarrow \gamma N$, $\pi\Delta \Leftrightarrow D \Leftrightarrow \gamma N$.

The effective Lagrangians have also led to interactions which couple the γN channel to the πN channel through more complex intermediate states. The potential that describes this coupling is given by (7.21), i.e., $\mathbf{U}_{\pi N,\gamma N} = \mathbf{U}^{\pi\pi N}_{\pi N,\gamma N} + \mathbf{U}^{\rho}_{\pi N,\gamma N} + \mathbf{U}^{\omega}_{\pi N,\gamma N}$ with $\mathbf{U}^{\pi\pi N}_{\pi N,\gamma N}$, $\mathbf{U}^{\rho}_{\pi N,\gamma N}$, and $\mathbf{U}^{\omega}_{\pi N,\gamma N}$ given by (7.11), (6.185), and (6.186), respectively. The potential $\mathbf{U}^{\pi\pi N}_{\pi N,\gamma N}$ is constructed out of the vertices $\pi N \Leftrightarrow N$, $N \Leftrightarrow \gamma N$, and $\gamma\pi \Leftrightarrow \pi$ and has 4 distinct contributions; referred to here as the *anti–nucleon term* (FIG. 7.2), the *crossed term* (FIG. 7.3), the *contact term* (FIG. 7.4), and the *pion–exchange term* (FIG. 7.5). The potentials $\mathbf{U}^{\rho}_{\pi N,\gamma N}$, and $\mathbf{U}^{\omega}_{\pi N,\gamma N}$ are referred to here as *rho–exchange* and *omega–exchange* interactions (FIG. 7.5). In a time–ordered picture the anti–nucleon term describes the process $\pi N \Leftrightarrow \gamma\pi NN\overline{N} \Leftrightarrow \gamma N$, the crossed term describes the processes $\pi N \Leftrightarrow \gamma\pi N \Leftrightarrow \gamma N$ and $\pi N \Leftrightarrow NN\overline{N} \Leftrightarrow \gamma N$, and the meson–exchange contributions describe the processes $\pi N \Leftrightarrow \gamma\mu N \Leftrightarrow \gamma N$ and $\pi N \Leftrightarrow \pi\mu N \Leftrightarrow \gamma N$ where $\mu = \pi,\ \rho$, or ω. The contact term has no intermediate state and arises from making the minimal substitution in the Lagrangian $L_{\pi NN}$ given by (6.54).

With the model actually used for the calculations of Chap. 7 the complete transition operator for $\gamma + N \to \pi + N$ is of the form

$$T_{\pi N,\gamma N}(W + i\varepsilon) = V_{\pi N,\gamma N}(W + i\varepsilon) + \sum_{B=N,\Delta} T_{\pi N,\pi B}(W + i\varepsilon)\frac{1}{W + i\varepsilon - M_0}V_{\pi B,\gamma N}(W + i\varepsilon), \qquad (8.1)$$

where the electromagnetic potentials have the structure

$$V_{\pi N,\gamma N}(z) = U_{\pi N,\gamma N} + V^{\rm pole}_{\pi N,\gamma N}(z), \quad V_{\pi\Delta,\gamma N}(z) = V^{\rm pole}_{\pi\Delta,\gamma N}(z). \tag{8.2}$$

The first term on the right hand side of (8.1) is frequently called the "Born term". By itself it is not a satisfactory approximation for multipole amplitudes in that it violates Watson's theorem [7] relating the phase of these amplitudes to the pion–nucleon phase shifts. To first order in *e* Watson's theorem is a rigorous consequence of the unitarity of the *S*–matrix. Our amplitudes satisfy this theorem due to the presence of the second term on the right hand side of (8.1). This term is often referred to as the rescattering term since it describes to first order in *e* the photoproduction of a meson–baryon pair followed by meson–baryon scattering. In the model used in Chap. 7 the only meson–baryon pairs that contribute to the rescattering term are πN and $\pi\Delta$. The coupling to the $\pi\Delta$ channel comes about only through the processes $\pi\Delta \Leftrightarrow N \Leftrightarrow \gamma N$, $\pi\Delta \Leftrightarrow R \Leftrightarrow \gamma N$, and $\pi\Delta \Leftrightarrow D \Leftrightarrow \gamma N$, i.e., through the pole terms in the electromagnetic potential which describe the so–called direct processes.

As pointed out at the end of Chap. 7, our model does a good job of reproducing 14 complex multipole amplitudes with 20 parameters. In the future an effort should be made to determine at least some of these parameters from independent analyses and calculations. As was stated in Chap. 7, 6 of the parameters [see Table 7.3], i.e., $f_{\rho NN,}\ \kappa_\rho,\ \Lambda_\rho,\ f_{\omega NN,}\ \kappa_\omega,\ \Lambda_\omega$, should be determined by strong interaction processes. For example, these parameters occur in meson–exchange models of nucleon–nucleon scattering, however there is still enough ambiguity in such models so as to prevent an accurate determination of these parameters.

There have been efforts to calculate strong interaction coupling constants and form factors from the constituent quark model. In the usual constituent quark model calculations of baryon structure the spectrum is obtained from a three–body calculation with some assumed quark–quark interaction, and the coupling of a baryon *B* to a meson–baryon channel μb is calculated by assuming a strong interaction transition operator T_s and evaluating the matrix element $\langle \mu b | T_s | B \rangle$. In general the baryon state vectors are taken from the three–quark calculation while the treatment of the meson depends on the nature of the assumed transition operator. In one class of models the mesons μ are treated as elementary particles and the transition operator describes a $q \Leftrightarrow q' + \mu$ coupling where the *q*'s are quarks [76–78]. Another type of model is the so–called *pair creation model*. In such models both the baryons and the mesons have some structure, and the transition is brought about by the creation of a quark–anti–quark pair from the vacuum. The created anti–quark combines with one of the quarks in the original baryon *B* to form the meson μ while the created quark becomes part of the baryon *b*. The so–called ${}^3P_0$ pair creation model has been popularized by LeYaouanc *et al.* [79] and applied extensively by Capstick and Roberts [80–82]. Other pair creation models are the string–breaking models [83,84] and the flux–tube breaking models [85–88]. In principle the $\mu b \Leftrightarrow B$ couplings derived from the constituent quark model can be used as input to models of the pion–nucleon system and nucleon–nucleon system. A nice feature of this approach is that the form factors that take into account the non–pointlike nature of the hadrons emerge from these models and don't have to be assumed arbitrarily. If this type of approach is successful in deriving the vertices that come into play in the pion–nucleon and nucleon–nucleon systems then the derived strong interaction coupling constants and form factors can be used with confidence in photoproduction models such as ours.

In principle it should also be possible to derive the electromagnetic coupling constants and form factors for the process $\gamma b \Leftrightarrow B$ from the constituent quark model. Useful guidance on this can be obtained from the analyses of Capstick [89]. Capstick has calculated electromagnetic transition rates for such processes using a relativized quark model and the Close–Li transition operator [90].

It should be noted that the general photoproduction model we have developed can be used to calculate the photoproduction of mesons other than the pion, so, for example, we can also model the processes $\gamma + N \to \eta + N$, $\gamma + N \to \rho + N$, and $\gamma + N \to \omega + N$. A more ambitious extension of the work reported here is to electroproduction processes such as $e + N \to e' + \pi + N$. In the one photon exchange approximation such a process can be viewed as photoproduction with a virtual photon so much of the analysis carried out here can be extended to treat electroproduction.

Clearly the study reported here opens up many possibilities for future research.