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POSSIBLE ROLE OF THE ρN COUPLING IN PION PHOTO-PRODUCTION *

K. Nakayama[a,b], S. Krewald[a], and J. Speth[a]

[a] Institut für Kernphysik, Forschungszentrum Jülich
52425 Jülich, Germany
[b] Department of Physics and Astronomy, University of Georgia
Athens, GA 30602, USA

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We explore the role of the ρN coupling in the pion photo-production reaction within a dynamical model approach based on a meson-exchange model of hadronic interactions. So far, all the existing dynamical models of pion photo-production consider only the πN intermediate states. Within such an approach, the pion photo-production reaction requires very soft hadronic form factors in order to reproduce the data. We show that the coupling to the ρN intermediate states may allow the use of much harder form factors which are more in line with those used in the description of other processes.

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1. Introduction

Pion photo-production off nucleons has been studied for many years since the pioneering work by Chew, Goldberger, Low, and Nambu [1]. The major purpose of studying such a reaction (and more generally, photo- and electro-production of mesons off nucleons) is to learn about the nucleon excited states. In order to extract accurate information on nucleon resonances, such a study requires, in addition to precise and extensive measurements, a reliable reaction theory which allows us to disentangle the resonance contribution from the background contribution to the observables. Recent efforts in developing such a theory have been carried out by a number of authors [2,3] within meson-exchange models of hadronic interactions where the Final State Interaction (FSI) is treated dynamically. This approach requires

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the introduction of the so-called form factors at hadronic vertices which account, among other things, for the composite nature of hadrons. At present, the lack of a theoretical understanding of these vertex form factors forces us to introduce phenomenological form factors — usually parametrized in terms of a monopole or dipole form — whose parameters are adjusted to fit the data. Calculations of the pion photo-production reaction based on the dynamical model approach show that this reaction is very sensitive to these form factors [2,3]. In particular, it requires very soft form factors compared to those obtained from other reactions. For example, the form factor at the πNN vertex used in Ref. [2] has a complicated form but it corresponds roughly to an equivalent monopole form factor

$$f_{\pi NN}(\vec{q}^{\,2}) = \frac{\Lambda^2}{\Lambda^2 + \vec{q}^{\,2}}\,, \tag{1}$$

with the cutoff parameter $\Lambda \sim 300$ MeV. The πNN form factor used in Ref. [3] is of a dipole shape which corresponds to an equivalent monopole form factor with $\Lambda \sim 425$ MeV (model-L). We mention that the models of Ref. [2,3] also reproduce consistently the πN scattering data (which are rather insensitive to the form factors) using soft form factors. The soft form factors, however, are *required* in order to reproduce the pion photo-production data.

The above considerations lead to the following questions:

1. Why is the pion photo-production reaction so sensitive to the form factors?
2. Are there "compensating" mechanisms which might enable us to "live with" harder form factors more in line with those obtained from other processes?

The present work addresses these issues.

2. Theoretical framework

In our model, the πN scattering amplitude is obtained by solving the Bethe–Salpeter equation with the (Thompson) three-dimensional reduction approximation

$$M_{\pi\pi} = V_{\pi\pi} + V_{\pi\pi} G_{\pi N} M_{\pi\pi}\,, \tag{2}$$

where $V_{\pi\pi}$ denotes the $\pi N \to \pi N$ potential. $G_{\pi N}$ is the Thompson two-body πN propagator [4]. Similarly, the pion photo-production amplitude obeys the scattering equation

$$M_{\pi\gamma} = V_{\pi\gamma} + M_{\pi\pi} G_{\pi N} V_{\pi\gamma}\,, \tag{3}$$

where $V_{\pi\gamma}$ denotes the $\gamma N \to \pi N$ transition potential.

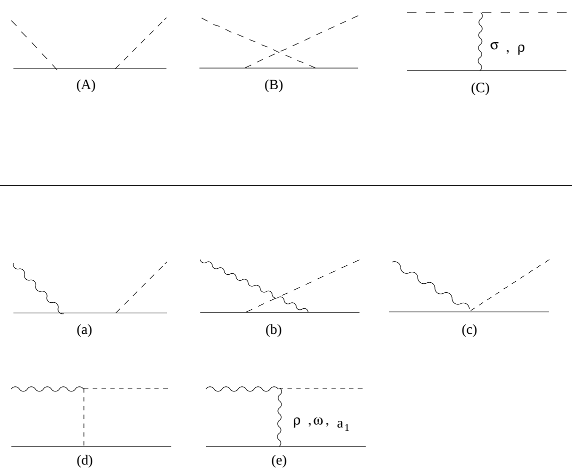

Fig. 1. Diagrams contributing to the πN scattering potential (upper part) and photo-production transition potential (lower part). The solid lines represent the nucleon, dashed lines the pion, and wiggly lines the photon. The internal solid lines may be either nucleon or Δ-isobar, while the internal wiggly line represents σ-, ρ-, ω- or a_1-meson.

In order to solve Eqs (2,3), we need a model that specifies the driving potentials $V_{\pi\pi}$ and $V_{\pi\gamma}$. For the πN scattering potential, $V_{\pi\pi}$, we take the nucleon and Δ-isobar direct- and cross-pole diagrams which are illustrated in Figs 1(A) and 1(B) (upper part), respectively. We also include in $V_{\pi\pi}$ the t-channel σ- and ρ-meson exchange contributions which are illustrated in Fig. 1(C). Here, however, we use the t-dependent coupling strengths [5] which effectively account for the correlated 2π exchange contribution in the scalar-isoscalar $[J = T = 0(\sigma)]$ and vector–isovector $[J = T = 1(\rho)]$ channels. The model for $V_{\pi\pi}$ described above is supplemented with hadronic form factors. So, each hadronic vertex is multiplied by a form factor of either a monopole or dipole type depending on the type of the vertex, with the cutoff parameter in the range of $\Lambda = 1200$–1600 MeV. These form factors are much harder than those used in Refs [2,3]. In particular, the πNN form factor here corresponds to an equivalent monopole form factor of Eq. (1) with $\Lambda \sim 800$ MeV. The model described above is essentially the same as that developed in Ref. [5]; however, it is not identical.

Our model for the photo-production transition potential, $V_{\pi\gamma}$, is derived from a chiral-invariance-motivated phenomenological Lagrangian. The resulting potential is illustrated diagrammatically in the lower part of Fig. 1. Some of the hadronic vertices entering in the construction of $V_{\pi\pi}$ also enter in $V_{\pi\gamma}$ and, as such, one should use the same form factors in these vertices in both $V_{\pi\pi}$ and $V_{\pi\gamma}$. This, however, immediately poses a problem of maintaining gauge invariance of the model [6]. In order to honour gauge invariance in a technically simple way, we use a common form factor of the monopole type

$$f(\vec{q}^{\,2}) = \frac{\bar{\Lambda}_\pi^2}{\bar{\Lambda}_\pi^2 + \vec{q}^{\,2}}\,, \tag{4}$$

multiplying $V_{\pi\gamma}$. This approximation is physically reasonable if the value of the cutoff momentum adopted corresponds to the average of the cutoff momenta used in the πN sector.

3. Results

Some of the parameters of our model are adjusted to reproduce the experimental phase-shifts in the πN scattering sector. This leaves three free parameters: the cutoff parameter $\bar{\Lambda}_\pi$ of Eq. (4) and the bare electromagnetic transition coupling constants, G_M and G_E, in the $N\Delta\gamma$ vertex. These are adjusted to reproduce best the pion photo-production data. We obtain a good fit to the πN phase-shifts with our model, very similar to that shown in Ref. [5]; therefore, we do not show the phase-shift results here.

In Table I we show the electric dipole amplitude, E_{0^+}, for $\gamma + p \to \pi^0 + p$ process at threshold. The contributions from the individual diagrams displayed in the lower part of Fig. 1 are shown separately. The column indicated as “rest” sums all diagram contributions not indicated explicitly in the previous columns. The last column labelled “sum” corresponds to the sum of all diagrams. The row labelled “**BORN**” corresponds to the contributions from the first term of the r.h.s. of Eq. (3), while the row labelled “**FSI**” corresponds to those from the second term of Eq. (3). The row labelled “**SUM**” corresponds to the sum “**BORN**+**FSI**”. First of all, it is interesting to note that since the Born term alone already yields a value of $E_{0^+} = -1.85 \times 10^{-3}/m_{\pi^0}$ — which is near the low energy theorem value of $E_{0^+} = -1.16 \times 10^{-3}/m_{\pi^0}$ obtained in Chiral Perturbation Theory [7] or the recently extracted value of $E_{0^+} = (-1.3 \pm 0.2) \times 10^{-3}/m_{\pi^0}$ from a multipole analysis [8] — the FSI contribution should yield a relatively small positive contribution if it is to reproduce the data. The total FSI contribution is a result of delicate cancellations among various diagrams. In particular, one sees a large cancellation between the large contact Fig. 1(c) and pion-exchange Fig. 1(d) diagram contributions. Since the integrands in Eq. (3) corresponding to different diagrams have different momentum dependence, the net result is very sensitive to the form factor in Eq. (4). This is illustrated in the bottom row of Table I where the predicted results for the FSI contribution using the cutoff parameter of $\bar{\Lambda}_\pi = 450$ MeV are shown. Compared to the results with $\bar{\Lambda}_\pi = 200$ MeV (just below the Born contribution), we see the change in the relative contribution from different diagrams.

TABLE I

Real part of the E_{0+} amplitude for the threshold π^0 photo-production off a proton in units of $10^{-3}/m_{\pi^0}$. The parameters used: $\bar{\Lambda}_\pi = 200$ MeV, $G_M = 1.45$ and $G_E = 0.08$. In the columns indicated as (a) and (b), only the nucleon pole contribution is included. The last row corresponds to the FSI contribution using $\bar{\Lambda}_\pi = 450$ MeV.

	diagrams of Fig. 1 (lower part)					
	(a)	(b)	(c)	(d)	rest	sum
BORN	−1.26	−1.26	—	—	0.66	−1.85
FSI	−0.40	−0.21	3.36	−2.45	0.03	0.71
SUM	−1.66	−1.47	3.36	−2.45	0.69	−1.14
FSI	−1.04	−0.60	6.25	−7.25	0.16	−2.48

The net FSI contribution in Table I is $E_{0+} = 0.71 \times 10^{-3}/m_{\pi^0}$. Together with the Born contribution — which does not depend on the form factor given by Eq. (4) at threshold — these contributions yield the combined amplitude of $E_{0+} = -1.14 \times 10^{-3}/m_{\pi^0}$. Although this is close to the low energy theorem value, the extremely soft form factor with $\bar{\Lambda}_\pi = 200$ MeV is in sharp contradiction with much harder form factors used in the πN sector. We might expect that this problem is an artefact of our approximation; namely, the use of a common form factor multiplying the transition potential $V_{\pi\gamma}$. Had we used a distinct (but harder) form factor at each hadronic vertex, the momentum dependence of the individual diagram contribution in Eq. (3) may be modified by the corresponding form factor, thereby changing the net contribution to E_{0+} from the FSI. Of course, these different form factors should be such that the resulting photo-production amplitude is gauge invariant and that they should also be consistent with the form factors used in the πN sector. Such calculations have been carried out by Surya and Gross [2] and, more recently, by Sato and Lee [3]. They all need very soft form factors, as mentioned in the introduction, in order to reproduce both the πN and photo-production data simultaneously. This indicates that the use of different form factors will not resolve the problem of using soft form factors.

We now turn our attention to the second question mentioned in the introduction. The fact that all the existing dynamical models of pion photo-production require very soft form factors might be an indication that these models omit some reaction mechanism(s) which is compensated by the use of soft form factors. An example of this situation is the nucleon–nucleon(NN) tensor force. In fact, the NN tensor force is built up by a long range one-pion-exchange and a shorter range ρ-meson exchange contributions. The latter contribution cancels the short range part of the pion-exchange tensor force. This cancellation has extremely important consequences in many nuclear phenomena. Instead of considering the ρ-exchange contribution explicitly, we may introduce artificially a softer form factor in the pion-exchange potential as well which suppresses its short-range part. In this way, the softer form factor would effectively take into account the effect of the ρ-exchange contribution. We might think a similar situation occurring in the pion photo-production reaction. Motivated by this fact, we investigate effects of ρN coupling in this reaction.

The FSI contribution to the pion photo-production amplitude due to intermediate ρN states is given by

$$M_{\pi\gamma}^{\rho(\mathrm{FSI})} = M_{\pi\rho} G_{\rho N} V_{\rho\gamma} \ , \tag{5}$$

where $G_{\rho N}$ denotes the ρN propagator. $V_{\rho\gamma}$ denotes the $\gamma + N \rightarrow \rho + N$ transition potential which is obtained from a phenomenological Lagrangian and is diagrammatically displayed in the lower part of Fig. 2. As has been done for the transition potential $V_{\pi\gamma}$, $V_{\rho\gamma}$ is multiplied by a common form factor

$$f(\vec{q}^{\,2}) = \frac{\bar{\Lambda}_\rho^2}{\bar{\Lambda}_\rho^2 + \vec{q}^{\,2}} \, . \tag{6}$$

The amplitude $M_{\pi\rho}$ in Eq. (5) denotes the $\rho + N \rightarrow \pi + N$ transition amplitude which should, in principle, be derived from a coupled-channel scattering equation. In the present work we approximate it as

$$M_{\pi\rho} = V_{\pi\rho} + V_{\pi\rho} G_{\pi N} M_{\pi\pi} \ , \tag{7}$$

where $V_{\pi\rho}$ denotes the $\rho + N \rightarrow \pi + N$ transition potential derived from a phenomenological Lagrangian and supplemented by phenomenological form factors. The resulting transition potential is shown diagrammatically in the upper part of Fig. 2. The above approximation for $M_{\pi\rho}$ suffices for the present exploratory purpose.

We mentioned that all the coupling constants required in $V_{\pi\rho}$ are fixed from chiral symmetry considerations following Ref. [9] or from other sources. The only free parameters in $V_{\pi\rho}$ are the cutoff parameters of the phenomenological form factors which were chosen to be in the range of $\Lambda \sim$ 1400–1800 MeV depending on the type of form factor (monopole/dipole) used at each vertex. In a quantitative calculation these parameters should be fixed in conjunction with the parameters of the πN potential. The coupling constants in $V_{\rho\gamma}$ are fixed using vector dominance model.

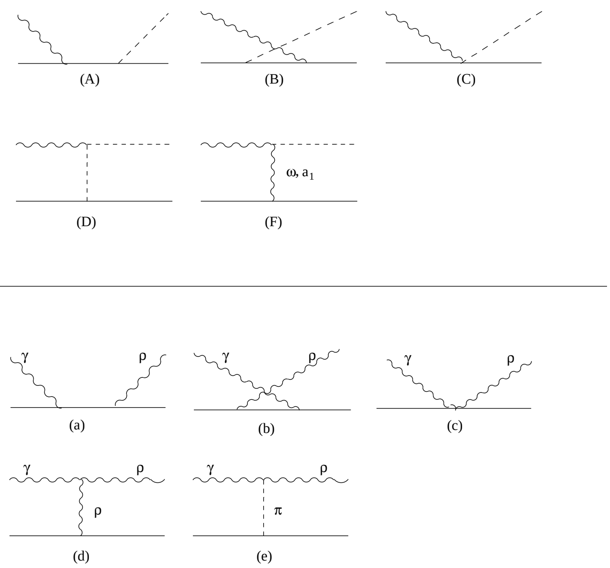

Fig. 2. Diagrams contributing to the $\rho + N \to \pi + N$ transition potential (upper part) and the $\gamma + N \to \rho + N$ photo-production transition potential (lower part). The solid lines represent the nucleon, dashed lines the pion, and wiggle lines either the ρ-meson (upper part) or the photon (lower part). The internal solid lines represent either nucleon or Δ-isobar, while the internal wiggle lines represent ρ-, ω- or a_1-meson.

TABLE II

Same as Table I except that, here, $\bar{\Lambda}_\pi = 800$ MeV. The table includes also the ρN intermediate state contributions with $\bar{\Lambda}_\rho = 1300$ MeV.

	diagrams of Figs 1,2 (lower parts)					
	(a)	(b)	(c)	(d)	rest	sum
BORN	−1.26	−1.26	—	—	0.66	−1.85
FSI-(πN)	−1.85	−0.96	8.18	−13.27	0.39	−7.51
FSI-(ρN)	6.13	3.80	−0.67	−2.05	0.23	7.44
SUM	3.02	1.58	7.51	−15.32	1.28	−1.93

Table II shows the results for the real part of the E_{0^+} amplitude from the FSI contributions due to both the intermediate πN and ρN states. The row denoted by "$\mathbf{FSI} - (\pi N)$" corresponds to the FSI contribution due to the πN intermediate state, while the row denoted by "$\mathbf{FSI} - (\rho N)$" corresponds to the FSI contribution due to the ρN intermediate state. In contrast to the results obtained before, here, we use $\bar{\Lambda}_\pi = 800$ MeV in the common form factor given by Eq. (4) which multiplies the transition potential $V_{\pi\gamma}$.

This value is more in line with the hard form factors used in the πN sector. In the form factor given by Eq.(6) which multiplies the transition potential $V_{\rho\gamma}$, we use $\bar{\Lambda}_\rho = 1300$ MeV. As we can see from Table II, since the coupling to ρN intermediate states may lead to a large positive contribution to the E_{0^+} threshold amplitude, it is now possible to use a much harder form factor multiplying $V_{\pi\gamma}$ than used before, and yet, obtain a reasonable value for the total E_{0^+} amplitude. Quantitative results, however, require a more complete calculation than done here.

4. Summary

In the present work we have explored the role of the ρN coupling in the pion photo-production reaction. It has been shown that the inclusion of this coupling may allow the use of much harder form factors than otherwise required in order to reproduce the threshold E_{0^+} amplitude extracted from the data. A more complete calculation is, however, necessary in order to quantify effects of the ρN coupling in a definitive way. Certainly, there is still a lot to do before the role of the FSI in the pion photo-production reaction is better understood, especially, in view of delicate cancellations among various contributions.

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