Reaction dynamics for photoproductions of baryon resonances*

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Abstract The study of exotic structure of hadrons is fully achieved when reaction dynamics of the associated hadron productions is well understood. We employ as the standard mechanism the effective Lagrangian method and investigate several physical observables within the framework. The parameters are constrained by microscopic description of hadrons. We discuss photoproductions of kaon associated with the ground state Λ(1116) and its resonances Λ(1405) and Λ(1520). In the former example we emphasize the meson cloud effect which significantly renormalizes the phenomenological parameters, while in the latter we discuss the features of the standard method. Finally we discuss briefly the production of ηπ associated with the nucleon resonance N(1535) for the study of chiral symmetry of baryons.

Key words photoproduction, strangeness, baryon resonances

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1 Introduction

An important current issue in hadron physics is to establish and understand exotic hadrons. They are exotic in the sense that their properties are not easily described in the conventional descriptions[1]; the typical is the constituent quark model. In the language of the quark model, the exotic hadrons are expected to contain more degrees of freedom than those expected in the standard description: three valence quarks for baryons and a quark and antiquark pair for mesons. There, it is important to understand the dynamics of the extra degrees of freedom under the colored environment which are not allowed in the conventional hadrons[2].

It is the feature of the strong interaction among the quarks which is mediated by the gluons accommodating strong color and spin dependence. In the spontaneously broken world of chiral symmetry, the Nambu-Goldstone bosons may play, where flavor dependence is also expected. Depending on the types of interactions, we expect a formation of cluster-like correlations which saturate state dependent interactions. A similar phenomenon in the strongly interacting systems is found in nuclear physics; the formation of alpha clusters in some excited states of nuclei[3]. A typical example is the Hoyle state of ^{12}C, whose wave function is largely dominated by three alpha clusters (Fig. 1). For the case of hadrons of multiquarks, we may also expect such a clustering in partial sets of quarks.

The above picture may be too naive for a quark system where the scales of mass and interactions are similar. Nevertheless, if such states (or analogues) are found, we strongly expect that we can learn new aspects of the strong interaction which we have not experienced before.

In experiments, the exotic structure may show up in the reactions of production and decay. Therefore, it is important to establish a theoretical framework

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for the reactions based on the microscopic description of hadrons which can be compared with experimental data. This is the issue we would like to discuss in this report.

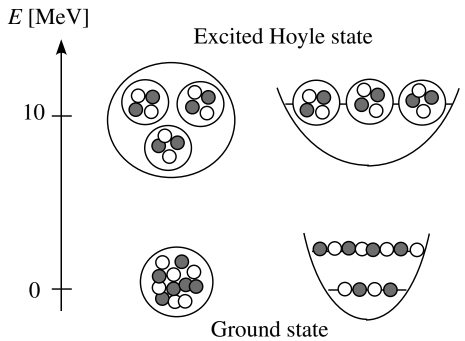

Fig. 1. Formation of strong cluster correlation in the carbon excited state, the Hoyle state, as compared to the ground state.

We employ effective Lagrangians for various interactions among relevant hadrons. Photons may be included by the standard gauging procedure. Within the two-body space, reactions occur through the four processes, s, t, u and c (contact) terms as shown in Fig. 2, where the exchanged particles in the former three channels include in principle various hadron states. The couplings appearing there are regarded as renormalized physical ones. Any diagrams in perturbation theory can be classified as either one of those diagrams.

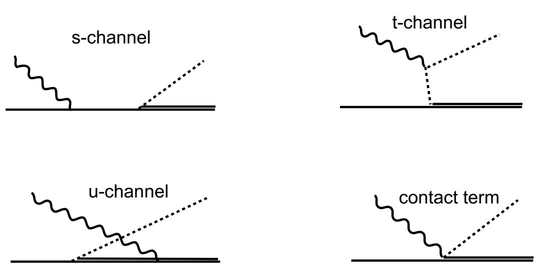

Fig. 2. Basic four types of diagrams in the effective Lagrangian method.

In our study, we use coupling constants evaluated by microscopic methods based on QCD. If our model predictions do not agree with experimental data, we need to consider more complicated processes including resonances or higher order loop corrections. The former may lead to a finding of resonances, while the latter with some new reaction processes which renormalizes one of the four processes.

In the following sections, we briefly discuss some of our theoretical studies in comparison with the new experimental developments when available; (1) Kaon photo production associated with the ground state Λ[4], (2) $\Lambda(1405)$ photoproduction[5], and (3) $\Lambda(1520)$ photoproduction[6]. In (1) we propose a new reaction process which renormalizes the contact term. In (2), the difficulty to explain the recent experimental data is discussed. The case (3) provides an example where the standard method works well. Finally, we discuss chiral symmetry of baryons which provides an alternative way to approach the structure of baryons.

2 Anomalous contribution to KΛ photoproduction

This process has been studied to a great extent[7—11]. Here what we would like to contribute is for the description of the beam asymmetry which is defined by

$$\Sigma(\theta)=\frac{\sigma(90^\circ)-\sigma(0^\circ)}{\sigma(90^\circ)+\sigma(0^\circ)}. \qquad (1)$$

Here the angle denoted in the cross sections is the azimuthal angle ϕ between the photon polarization vector and the reaction plane as shown in Fig. 3, while the angle θ on the left hand side is for the scattering angle of the kaon. An important role of the asymmetry is that they can filter the quantum numbers of the exchanged particles in the t-channel. For the kaon photoproduction, if the asymmetry is positive, then the photon couples to the t-channel exchanged particle through the magnetic interaction, while if it is negative it is electric. For the magnetic interaction the exchanged particle carries the natural spin-parity (K^*), while for the electric interaction the exchanged particle carries the unnatural one (K).

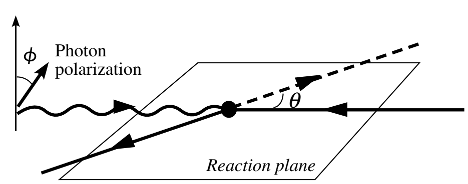

Fig. 3. Kinematics for the definition of the beam asymmetry.

The experimental data provides positive values of $\Sigma(\theta)$, indicating the magnetic dominance. In order to explain this, the previous studies treated the K^* coupling to NΛ as a parameter to reproduce the data. Another important coupling of KNΛ was fixed by $SU(3)$ flavor symmetry in a way consitstent with the πNN couplings. The problem, however, was that thus determined $K^*N\Lambda$ coupling constants were too large as compared with those established in the baryon-baryon interaction as shown in Table 1[10—13]. The latter respects approximately the $SU(3)$ symmetry together with the ρNN coupling constants. Typically, those used in the photoproduction are larger than those of the baryon-baryon interaction by about factor five, which is not acceptable. In fact, if we use the (weak) K* coupling constants as in the baryon-baryon interaction, we obtain only negative values of $\Sigma(\theta)$ as shown by the dashed line in Fig. 4.

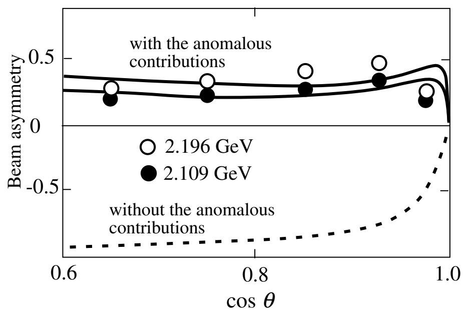

Fig. 4. The beam asymmetry $\Sigma(\theta)$ as a function of θ. Calculations are shown with and without anomalous contributions as compared with experimental data from LEPS[7].

Table 1. Various K and K* coupling constants. In the column of "Phenomenological", K* coupling constants are fitted in order to reproduce the positive Σ, while those in the column "Microscopic" are determined in the realistic baryon-baryon interaction.

couplings	phenomenological	microscopic
$g_{\mathrm{KN\Lambda}}$	−13.46	−12.65
$g_{\mathrm{KN\Sigma}}$	4.25	5.92
$g^{\mathrm{V}}_{\mathrm{K^*N\Lambda}}$	−25.21	−5.63
$g^{\mathrm{T}}_{\mathrm{K^*N\Lambda}}$	33.13	−18.34
$g^{\mathrm{V}}_{\mathrm{K^*N\Sigma}}$	−15.33	−3.25
$g^{\mathrm{T}}_{\mathrm{K^*N\Sigma}}$	−29.67	7.86

In order to resolve this discrepancy, we have proposed[4] the inclusion of a higher order process induced by the QCD anomaly, because the anomalous process can induce magnetic interactions when a photon is involved[14]. The relevant anomalous vertex contains one photon and three pseudoscalar mesons, πKK. A nice feature here is that the interaction strength is determined by QCD without ambiguity[14]. Hence, we are lead to the inclusion of a one-loop diagram as shown in Fig. 5. We emphasize that in all of our calculations, coupling constants are used as determined by the baryon-baryon interaction based on a microscopic model for QCD. The loop integral diverges, but can be regularized by a cutoff parameter. Our study here is not theoretically complete, but rather qualitative to find a direction to cure the large discrepancy in the K* couplings.

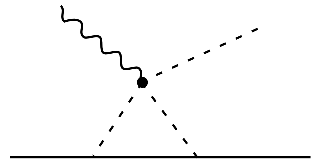

Fig. 5. Anomalous contribution to the kaon photoproduction at the one loop.

Here two remarks are in order. First, the diagram does not double count the contribution of the K* exchange, but rather it renormalizes the contact term interaction. Second the anomalous vertex contains the photon momentum, and explains the increasing behavior of the asymmetry Σ as shown in Fig. 4 as the photon energy is increased.

We compare our calculation with the inclusion of the anomalous contributions at the photon energy around 2 GeV, where the resonance contributions are smeared out[7]. The resonances are important near the threshold region. Also, the comparison is made at forward angles, where t-channel process is expected to be dominant.

It turns out that the anomalous contribution is very important when a cutoff parameter of order 1 GeV is employed. It is sufficient to flip the sign of the beam asymmetry Σ as shown in Fig. 4. The agreement with the data is not perfect, but is acceptable if we consider the crudeness of the present estimation. Another achievement is the fact that a slight increase of Σ as the photon energy is increased is consistent with the experimental data as anticipated, due to the momentum dependence of the anomalous photon vertex.

This exercise has shown that virtual meson clouds (as shown in Fig. 5) play an important role for various hadronic processes. A classic example is the neutron electric charge, where the virtual pπ⁻ component carries a significant fraction in the physical neutron state. Although less established, another example is the proton spin where a role is given to the pion to carry a fraction of the nucleon spin. In our present study of the photoproduction, we have seen a similar situation in some reaction processes in a way consistent with the microscopic inputs. Such meson cloud could be regarded as a seed of hadronic correlations which may develop in excited states.

3 Λ(1405)

An interest in this long puzzling hyperon resonance has been revised in the recent development of the chiral unitary model for hadron resonances[15, 16]. Some of s-wave resonances have been advocated to contain large components of hadron-hadron quasi-bound (molecular) structure, which is the context of the dynamical generation[17] . Λ(1405) is considered to be a candidate and is largely dominated by $\bar{K}N$ and $\pi\Sigma$ components. Much progress has been made when the on-shell approximation is made, since it simplifies an integral scattering equation into an algebraic equation. In the coupled channel analysis in a way consistent with the low energy theorem of Tomozawa-Weinberg, the chiral unitary model has predicted two pole structure[18]. Verifying such a structure in experiment is also important, since it is one possible form of exotic state of strong hadronic correlation. Such a structure must be then confirmed by some exclusive reaction process sensitive to it.

Recently, the LEPS group has reported an experimental result for the photoproduction of Λ(1405)[19]. They measure the kaon photoproduction in the forward spectrometer, which is associated with the resonance production including Λ(1405) and Σ(1385). The decaying particles from these resonances are then measured by the TPC located in the target region. Making various combinations of the decaying particles, they extract the production rates of Λ(1405) and Σ(1385), separately.

Among their findings, what is surprising is a large enhancement in the threshold production Λ(1405) followed by a rapid decrease as the photon energy is increased. The energy dependence was compared with the production rate of Σ(1385), showing a clear difference between them; the latter has much milder energy dependence. One can expect that naively, such energy dependence would be associated with the structure of the produced resonance. An extended (soft) structure is expected to be responsible for such a rapid change as a function of the energy.

In an effective Lagrangian method, the form factor is where the information of internal structure (especially size information) is. Hence, we performed calculations in the standard processes of the Born diagrams as shown in Fig. 2 with the cutoff Λ as a free parameter[5]. As usual, we performed the calculation using the gauge invariant four dimensional form factor as one of reasonable choices. The result was, however, far from the observation. Even such a small Λ as a few hundred MeV could not explain a rapid increase toward the threshold. The size of the produced particle may be sensitive to the momentum transfer t. However, in the region of the photon energy and kaon angle in the experimental setup, the momentum transfer does not change much.

Perhaps we need more experimental data with higher statistics. Once the rapid change of the cross section is established, this could be an indication either of very exotic structure or of the existence a resonance near (perhaps below) the threshold of $\bar{K}\Lambda(1405)/\Sigma(1385)$[20, 21]. A strong attraction for a virtual state may also cause such a strong enhancement of the cross section near the threshold.

4 Λ(1520)

This reaction is perhaps one of successful examples in the effective Lagrangian method. A slight technical complications arise from the fact that the resonance Λ(1520) has spin 3/2. The relativistic treatment requires the use of the Rarita-Schwinger spinor ψ_μ, which contains redundant degrees of freedom for the covariant description[22]. Because of this, interaction vertices may be formed with some requirement of gauge-like constraint[23].

Concerning the kaon coupling, the Lorentz index of ψ_μ makes the lowest order coupling unique with one derivative on the kaon. The strength of the photon coupling is then determined by the KNΛ(1520) coupling through the gauge invariance together with the t-channel kaon-exchange and s-channel electric terms.

There is one unknown term in the t-channel K^* exchange, the $K^*N\Lambda(1520)$ coupling. For this we have estimated it by the conventional quark model assuming that Λ(1520) is a flavor singlet spin 3/2 partner of Λ(1405), and in the chiral unitary model where Λ(1520) is described as a quasi-bound state of $\pi\Sigma(1385)$[24]. The resulting coupling constants were then used in the present reaction calculations. It turned out that the K^* exchange term did not have a sizable contribution. Therefore, the discussions that follow here are made essentially without the K^* exchange term, and therefore are almost parameter free except for the unknown cutoff mass in the gauge invariant four dimensional form factor.

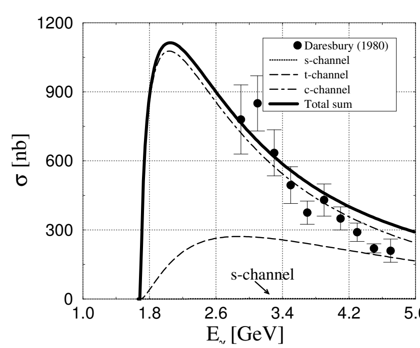

Fig. 6. The total cross section of Λ(1520) photoproduction as a function of the photon energy in the laboratory frame E_γ.

Having this strategy, shown in Fig. 6 is the total cross section as a function of the photon energy E_γ in the laboratory frame, as compared with experimental data[25]. The cut off parameter is fixed such that the calculation produces the experimental cross section value at $E_\gamma \sim 3$ GeV. The resulting energy dependence is therefore a prediction of the theory, which agrees well with experimental data.

For angular dependence, the previous data presented as a function of t is compared with the calculation in the upper panel of Fig. 7 which also agrees well data. Recent LEPS data has provided θ dependence which is shown in the lower panel of Fig. 7. Within uncertainties in the data, our prediction seem to agree here also.

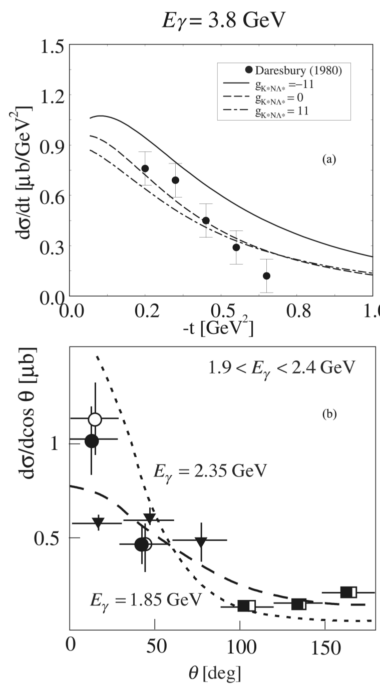

Fig. 7. t (a) and θ (b) dependences.

In the LEPS experiment, further data have been provided for the beam asymmetry and decay asymmetry[26]. The latter is related to the angular distribution of $\bar{\mathrm{K}}$ and N decaying from the resonance $\Lambda(1520)$ in its rest frame where the direction of the incoming t-channel exchanged particle (K or K*) is set the z-axis. Depending on the spin of the exchanged particle, the helicity of $\Lambda(1520)$ changes and the resulting angular dependence will be

$$\cos^2\theta + \frac{1}{3}, \quad \text{for K-exchange},$$
$$\frac{2}{3}\sin^2\theta + \frac{4}{9}, \quad \text{for K}^*\text{-exchange}. \qquad (2)$$

Turning to the beam asymmetry, the effective Lagrangian method predicts small values with some variation depending on the unknown coupling constants $g_{\mathrm{K^*N\Lambda(1520)}}$. Within reasonable values as expected from model calculations $|g_{\mathrm{K^*N\Lambda(1520)}}| \lesssim 10$, we find $\Sigma(\theta=0) \lesssim 0.1$ (Fig. 8). This estimation is compatible with the data of -0.01 ± 0.07[26]. In the theory, the contact term dominance may explain the small value of Σ.

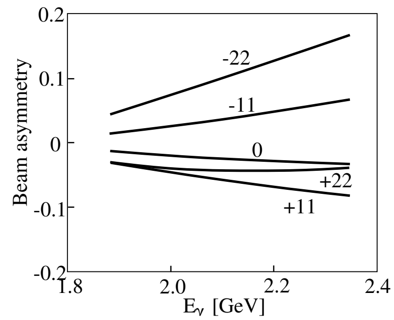

Fig. 8. Beam asymmetry for the $\bar{\mathrm{K}}\Lambda(1520)$ production.

The decay asymmetry has some discrepancy in the previous two data sets; in one data from Daresbury[25] the angular distribution was consistent with K*-exchange dominance, while in the other from J-Lab suggested K-exchange dominance. The J-Lab experiment was done with virtual photons (electron scattering), and showed also some Q^2 dependence. As Q^2 becomes smaller (approaching real photon point), the dependence, however, seems to be weakened. Recently LEPS also reported their result for the decay asymmetry. It has a rather weak θ angle dependence, except for a linear dependence in the forward direction, which is expected from interference with other terms. In the backward region, contrary, the angular dependence is found to be weak.

A theoretical calculation requires the inclusion of three body final states with possible intermediate states including the $\Lambda(1520)$. At present, a simple estimation based on the polarization of $\Lambda(1520)$ implies a small angular dependence.

To summarize shortly, we have studied the photoproduction of $\Lambda(1520)$ in the effective Lagrangian method. Although the theoretical set up is rather simple, many of the results seem to be consistent with experimental observations which were reported recently. In this regards, we can test the reaction dynamics in detail in comparison with experiment.

5 Chiral symmetry of baryons

When chiral symmetry is spontaneously broken, the axial charge of hadrons can take an arbitrary value. This is related to the fact that in the broken world the axial symmetry no longer provides algebraic relations, but rather leads to dynamical relations among the Nambu-Goldstone bosons. Because of this, the axial charge carries information of hadron structure associated with spontaneously breaking of chiral symmetry.

In this regard, as discussed by Weinberg some time ago it would make sense to consider that hadronic states may be written as superpositions of different representations of the full chiral symmetry group[27, 28]. A quantum mechanical analogue is, for instance, when translational invariance is broken by a position dependent potential, the eigenfunctions are written as superpositions of translationally invariant momentum states.

An example of effective models in the linear representation scheme of chiral symmetry is the linear sigma model. The pion and sigma mesons are assumed to belong to the four vector representation of $SU(2)\times SU(2)$ chiral symmetry, (1/2,1/2), and the nucleon to the fundamental one, (1/2,0)+(0,1/2). Properties of the model are well known and it provides a prototype description for the generation of the massless Nambu-Goldstone bosons and the massive nucleon. What is less known is that in this model the axial charge of the nucleon is $g_A = 1$, which is an algebraic consequence that the nucleon belongs to (1/2,0)+(0,1/2).

If chiral symmetry is spontaneously broken, hadrons may be superposition of different chiral symmetry representations. For instance, the nucleon can contain higher representations such as $(1,1/2)$, $(3/2,1),\cdots$, with the constraint that the minimum of the diagonal isospin value is 1/2. It can be also so called mirror representation $(0,1/2)$, where the role of left and right chirality is flipped. (Here we have denoted only representations for left helicity states.)

The mirror representation was introduced by Lee[29], and the linear sigma model including the mirror nucleon for a nucleon excited state ($N^*(1535)$) was investigated by DeTar and Kunihiro[32]. Later a more general consideration was made by Jido, Oka and Hosaka[33]. The negative parity nucleon can also take the naive representation which is the same one as the ground state nucleon. In general, it can take any combination of the naive and mirror, and even higher representations. As an interesting feature of the mirror model, it provides an alternative mechanism of mass generation which can in principle be independent of spontaneous breaking of chiral symmetry, and the negative axial charge.

The axial charge of the nucleon is related to the pion nucleon coupling constant through the Golberger-Treiman relation. The latter may be measured by experiment. Theoretically, the non-unity axial charge indicates an internal structure that is not achieved by three-quark configurations; it requires at least five quark components. Recently, lattice calculation was performed and almost vanishing value of the axial charge for N(1535) was reported[32]. Previous study based on the chiral unitary model also predicted small values[33]. These could be an indication that N(1535) contains significant component of five (or more) quark contents. Hence it would be interesting if we will be able to measure the axial charge of various nucleons, and find possibly a mirror nucleon.

The ground state nucleon is likely to be dominated by the fundamental representation, since its axial charge is $g_A^N \sim 1.25$. Therefore, a candidate of the mirror nucleon should be found in nucleon resonances. The mirror model can accommodate two nucleons with opposite parities in the mixed chiral representation of $(1/2,0)+(0,1/2)$ and $(0,1/2)+(1/2,0)$. Therefore, it is natural to consider the first negative parity nucleon N(1535). An advantage of this resonance is that it has a strong coupling to η, and therefore, in experiments eta production can be used to investigate the properties of N(1535).

Motivated by the above observations, we have proposed πη production for the measurement of g_A[31, 34]. The basic idea is to use the interference of the expected two dominated diagrams (Fig. 9), where one diagram contains $g_A(N)$ and the other $g_A(N(1535))$ ($N(1535)\equiv N^*$). Depending on the magnitude and relative sign of the two axial charges, we have either a constructive or destructive amplitude.

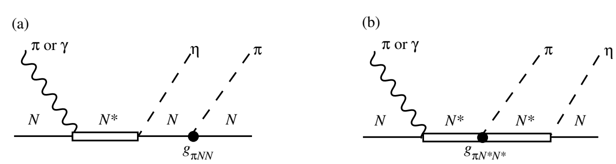

Fig. 9. Diagrams which interfere due to opposite signs of $g_{\pi NN}$ and $g_{\pi N^*N^*}$

Actual situation requires more processes. However, assuming the N(1535) dominance for the η production, we can reduce the number of relevant terms and make the calculation simpler. We have tested photo and pion induced productions, $\pi^- p\to\pi^-\eta p$ and $\gamma p\to\pi^0\eta p$. Although the interference due to the two dominant terms is not complete because of the presence of the other various terms, we can see significantly larger cross sections when the two axial charges have the same sign as shown in Fig. 10.

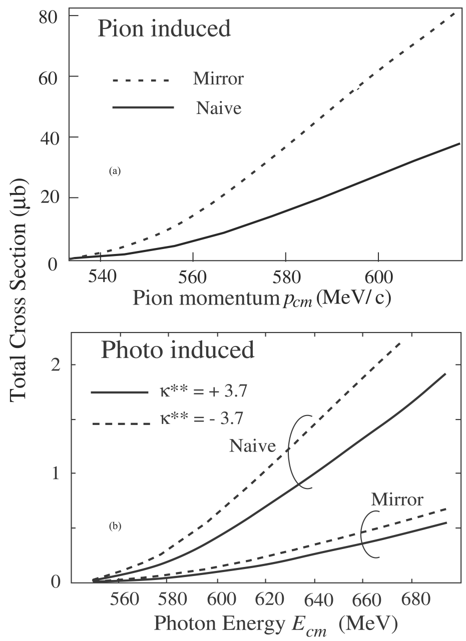

Fig. 10. Total cross sections of $\pi^- p \to \pi^- \eta p$ and $\gamma p \to \pi^0, \eta p$ reactions. The (a) and (b) panels are for pion and photon induced ones, respectively.

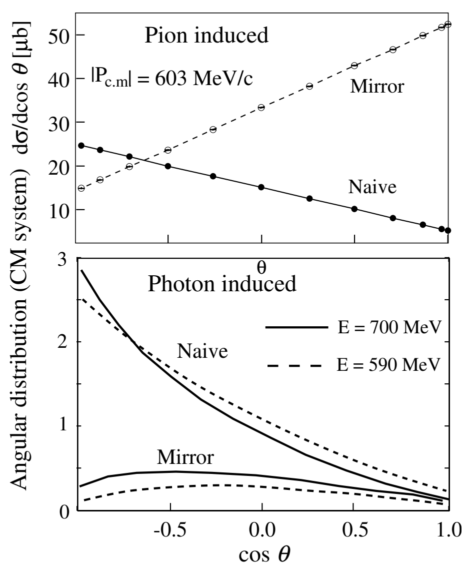

Fig. 11. Angular dependence of π.

The absolute value of the cross sections might not be sufficient to differentiate either one of them. More interesting is the angular dependence. This is particularly the case for the pion induced production as shown in Fig. 11.

6 Summary

We have discussed meson production reactions induced by the photon for the study of possibly exotic, or unconventional structure of baryon resonances. The expected exotic states may have unique structure of coloreless hadron-like or colored multiquark-like correlations, which may show up in observables of characteristic exclusive reactions.

As a standard theoretical framework, we have used an effective Lagrangian method, in which various hadrons are included as ingredients of the model. The method was applied to the kaon productions of lambda hyperons and its resonances. We have pointed out that for the ground state Λ production, the virtual meson cloud effect is important as driven by the QCD anomaly. The $\Lambda(1405)$ production has now experimental data, but its unique feature in the energy dependence of the production rate is not easy to explain by the standard method, implying its unusual structure. We have shown, on the other hand, the production of $\Lambda(1520)$ has been well compared with the new experimental data, where we can test more the standard method.

Finally we have discussed the chiral symmetry of baryons. This provides an alternative way to look into the structure of hadrons based on chiral symmetry. The relation of such view with the dynamical aspects of resonances is of great interest. Further understanding of hadron spectroscopy in this method would have a significant link to fundamental questions of the strong interaction such as mass generation.

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