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THE STRUCTURE OF BARYON RESONANCES IN πN SCATTERING*

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We present a coupled channel model for πN scattering, based on meson and baryon exchange processes. The inclusion of the reaction channels $\pi N, \pi\Delta, \sigma N$ and ηN leads to a good description of πN phase shifts and inelasticities up to c.m. energies of 1600 MeV. The coupling between the channels $\pi N, \pi\Delta$ and σN turns out to be large in the P_{11} and the $N^*(1440)$ (Roper) resonance can be explained solely by meson-baryon dynamics, *i.e.* without the inclusion of a genuine $N^*(1440)$ resonance. For the investigation of the $N^*(1535)$ resonance, the model is extended by including the ηN reaction channel. A genuine $N^*(1535)$ resonance is needed for a quantitative description of the πN phase shift in the S_{11}, but the background from meson and baryon exchanges is large and cannot be neglected.

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1. Introduction

The interaction of a pion and a nucleon is one of the most fundamental and interesting hadronic reactions in medium energy physics. It is the lightest meson–baryon system and therefore a testing ground for the description of meson–baryon interactions in general. Furthermore the low energy part of πN scattering is dominated by the spontaneously broken chiral symmetry of the underlying QCD Lagrangian, which has proven to be a very important symmetry for low energy meson–meson [1] and meson-baryon interaction [2].

At energies above 1300 MeV, πN scattering is closely related to the observed baryonic spectrum. Most of the the N^* and Δ resonances decay into πN. The coupling of these resonances to other decay channels is characterized by the opening of the inelasticities in corresponding partial

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waves. There are several attempts to describe the baryonic spectrum in the framework of the quark model [3–5]. However, none of them accounts for any meson-baryon interaction. Here the question has to be addressed: How strong is the meson-baryon interaction and can it shift the position of or even generate baryonic resonances as quasi bound meson-baryon states. A good example to illustrate the importance of the background contribution in the mesonic sector is the decay of the $a_1(1260)$. Mass and width of the the a_1 extracted from leptonic decays ($\tau \rightarrow \nu_\tau a_1 \rightarrow \nu_\tau 3\pi$) are about 100 MeV larger than the mass and the width extracted from hadronic reactions ($\pi p \rightarrow 3\pi p$ and $\pi p \rightarrow 3\pi n$). This shift is generated by the strong $\pi\rho$ background contribution in the hadronic reactions, which is not present in the lepton decay [6].

Meson and baryon exchange models, based on effective Lagrangians — *i.e.* Lagrangians formulated in mesonic and baryonic degrees of freedom — have proven to be very successful in describing medium energy hadronic reactions such as $\pi\pi$ [7,8], elastic πN [9–12] and NN [13] scattering. In order to investigate the importance of background contributions and the structure of the lowest lying baryonic resonances, namely $N^*(1440)$ and $N^*(1535)$, we have extended the πN scattering meson exchange model of Ref. [12] by including the reaction channels $\pi\Delta, \sigma N$ and ηN. The next section gives a short review of the basic features of our model and will then concentrate on the $N^*(1440)$ resonance. The 3rd Section deals with the $N^*(1535)$ resonance and it's coupling to the ηN channel. More details of the calculation can be found in Refs. [12, 14].

2. The $N^*(1440)$ (Roper) resonance

The $N^*(1440)$ (Roper) resonance occupies a special place in the spectrum of nucleon and delta resonances. It does not show up as a clear resonance peak in the total πN cross section — only after performing a partial wave analysis, the Roper resonance can be found as resonant behavior of the phase shift and inelasticity in the P_{11}. The first direct experimental confirmation of the Roper resonance was obtained in $\alpha p \rightarrow \alpha' X$ reactions [16]. Furthermore, the $N^*(1440)$ is the lowest lying nucleon resonance with the quantum numbers of the nucleon (*i.e.* $J^P = 1/2^+$), whereas the first negative parity states are located higher in energy, namely around 1530 MeV and 1675 MeV. These resonances can be immediately understood in a simple quark model where the a quark interactions are modeled by a confining oscillator potential plus two-body forces based on one gluon exchange. The $1\hbar\omega$ excitation, corresponding to a three quark state of angular momentum $L = 1$, results in a doublet and a triplet of N^* resonances ($N^*(1520)$, $N^*(1535)$) and $N^*(1650), N^*(1700), N^*(1675)$, respectively). An excitation of the quarks of $2\hbar\omega$ ($L = 0$ and $L = 2$) leads to a state with positive parity, but this state should lie higher in energy than the negative parity states. The explanation of the Roper resonance in this simple quark picture requires additional mechanisms to bring the positive parity state below the first negative parity resonances [3]. Glozman and Riska [4] attribute the lowering of the positive parity state to a flavor symmetry breaking quark-quark interaction due to the exchange of a pseudoscalar meson. Brown *et al.* introduce a anharmonic collective oscillation of the bag surface to explain the mass of the Roper resonance [5].

All these additional mechanisms can be avoided if the Roper resonance is not assumed to be a genuine three quark state: the first positive parity three quark state is then above the negative parity states. To address this issue quantitatively, we have extended the πN model of Ref. [12] by coupling the πN system to $\pi\Delta$ and σN reaction channels. In the basic πN model the potential contains N and Δ pole and crossed pole diagrams and correlated two pion exchange in the sigma and rho channel. This potential is used as a driving term in a relativistic scattering equation. The iteration guarantees unitarity but violates crossing symmetry and chiral symmetry. However the low energy theorems are obeyed to the order m_π^2 through a proper choice of the parameters.

Above 1300 MeV inelasticity starts to open especially in the P_{11}. Our extension therefore has to take pion production mechanisms into account. This is achieved by treating the $\pi\Delta$ and σN states not as intermediate states of stable particles but as effective description of $\pi\pi N$ states. Thus, the $\pi\Delta$ channel describes a $\pi\pi N$ state in which one pion and the nucleon form a P_{33} state, and the σN system represents a $\pi\pi N$ state with a interacting $\pi\pi$ state in the scalar-isoscalar channel. In order to simulate these $\pi\pi N$ systems, we have included the Δ and σ self-energies in the intermediate two particle propagator of the scattering equation. The self-energies are calculated in one loop approximation with simple separable potentials. The parameters of these potentials are fixed by reproducing the P_{33} partial wave of πN scattering and the $IJ = 00$ partial wave of $\pi\pi$ scattering, respectively.

We start with the coupling to the $\pi\Delta$ channel. This coupling acts in partial waves with isospin $I = 1/2$ and $I = 3/2$, whereas the σN channel only contributes to the interaction with $I = 1/2$. The transition potential $\pi N \to \pi\Delta$ as well as the direct $\pi\Delta$ interaction are built up by nucleon, Δ, and ρ exchange processes, which are all attractive in the P_{11}. The coupling constants are taken from the SU(2)$\times$ SU(2) quark model [15]. To ensure the convergence of the scattering equation, all potentials are supplemented by form-factors and the cut-off parameters are fixed by a fit to the data.

The σN channel is coupled to the πN channel by nucleon exchange. The direct σN potential contains nucleon and sigma exchange diagrams.

The coupling constant $g_{\sigma NN}$ is taken from Ref. [17], whereas there is no source for determining the $\sigma\sigma\sigma$ coupling, which we therefore treat as a free parameter together with the cutoffs.

After having described the basic features of our model, we now proceed in the discussion of the Roper resonance. In doing so, we aim at a simultaneous description of the P_{11} partial wave together with all πN scattering data for $J \leq 3/2$, providing a consistent procedure to fix the background contributions, arising from t- and u- channel exchange processes.

The elastic πN scattering model of Ref. [12] already gave a good description of the P_{11} phase shift up to energies of about 1450 MeV (dashed line in Fig. 1). The rise of the phase shift above 1300 MeV is provided by the attraction of the ρ exchange in πN interaction. However, the inelasticity in the P_{11} opens at about 1300 MeV, where the elastic model fails. The coupling to the $\pi\Delta$ channel already results in a resonant behavior of the P_{11} phase shift but the inelasticity is only slightly affected (dotted-dashed curve in Fig. 1). By increasing the cutoffs in the $\pi N \to \pi\Delta$ transition potential, it is indeed possible to improve the inelasticity — but only at the cost of a much worse description of the P_{33}. It is also important to mention, that in the P_{11} ρ, N and Δ exchange are attractive, whereas the nucleon exchange changes sign in the $I = 3/2$ states. Therefore nucleon exchange cancels partially the other contributions, which results in a very small inelasticity in the P_{31} — in agreement with the data. Considering only ρ exchange for the coupling to the $\pi\Delta$ channel would result in a large inelasticity in the P_{31}, which is not observed.

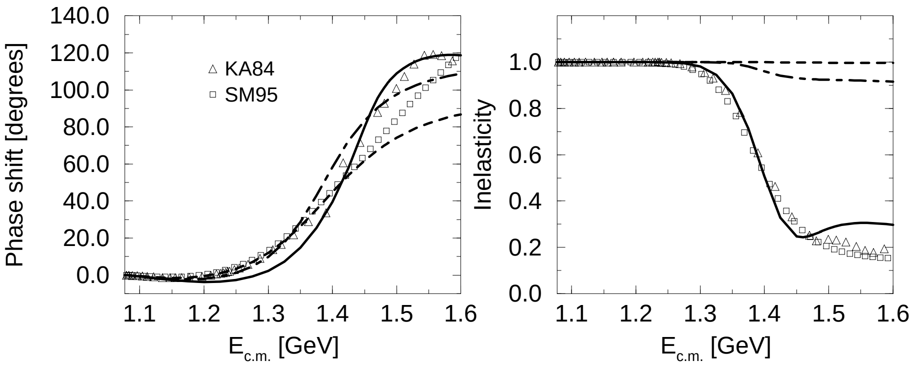

Fig. 1. Phase shift and inelasticity in the P_{11} partial wave in πN scattering. The dashed line is the basic πN model without coupling to other channels. The dotted-dashed line is the coupled $\pi N/\pi\Delta$ model. The solid line corresponds to the coupled channel $\pi N/\pi\Delta/\sigma N$ model.

The description of the data can be improved significantly by including the coupling to the σN channel. As can be seen from the solid line in Fig. 1, the σN channel accounts for most of the inelasticity in the P_{11}. The coupling to the σN channel is much larger than the coupling to $\pi\Delta$, because the σN state is in a relative S-wave, whereas the $\pi\Delta$ forms a P-wave state. The quantitative description of the inelasticity requires a contribution from the direct σN interaction. The $\sigma\sigma\sigma$ coupling was treated as a free parameter and was adjusted to the inelasticity. This coupling is therefore a measure for the strength of the diagonal interaction in the σN channel. Note that in this calculation no genuine $N^*(1440)$ resonance is included. The resonant behavior of the P_{11} is completely generated by meson-baryon dynamics. Thus, in our model the Roper resonance appears as a quasi bound $\pi\pi N$ state.

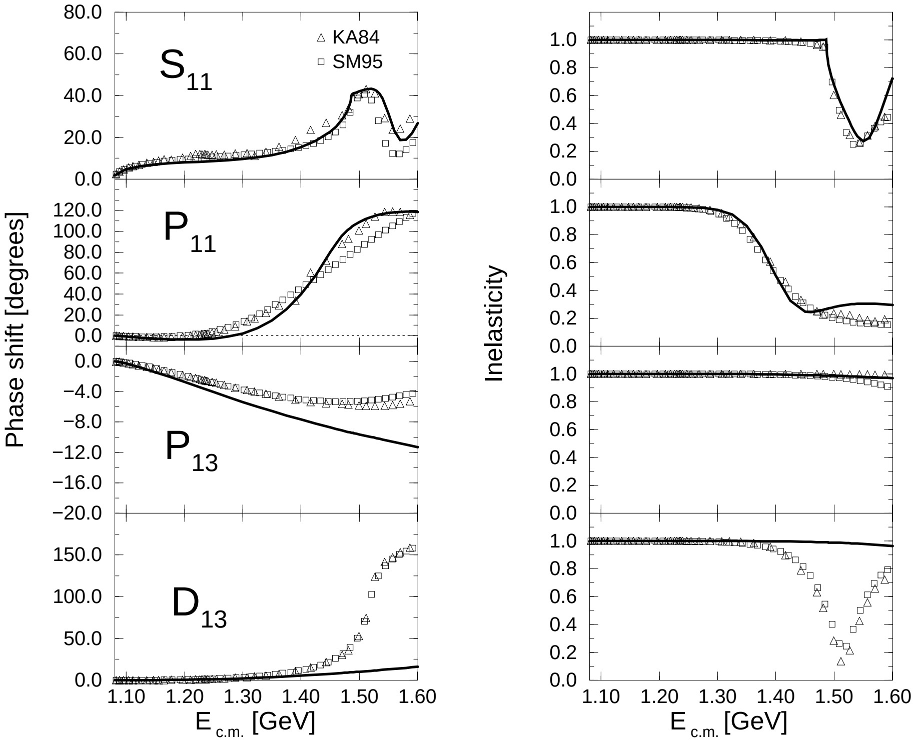

Fig. 2. Phase shift and inelasticity for partial waves with $I = 1/2$ and $J \leq 3/2$. The solid line corresponds to the full $\pi N/\eta N/\pi\Delta/\sigma N$ model.

The coupling to the $\pi\Delta$ and σN channel leads to a good description of the P_{11} without genuine $N^*(1440)$ resonance. As already mentioned, our aim is a consistent description of the πN scattering data in all partial waves with $J \leq 3/2$. The complete results of the coupled channel $\pi N/\eta N/\pi\Delta/\sigma N$ model for isospin $I = 1/2$ are shown in Fig. 2 and those for isospin $I = 3/2$ in Fig. 3. The inclusion of the ηN channel only affects the S_{11}, so the results discussed in this section are also valid for the model including the ηN channel. For the isospin $I = 1/2$ S_{11} (which will be discussed in the next section) as well as the P_{11} are well described. We get a little too much repulsion in the P_{13} and our model yields only a background to the resonant shape of the D_{13}. Since the $N^*(1520)$ couples strongly to the ρN channel, this channel has to be included for a detailed investigation of the structure of this resonance.

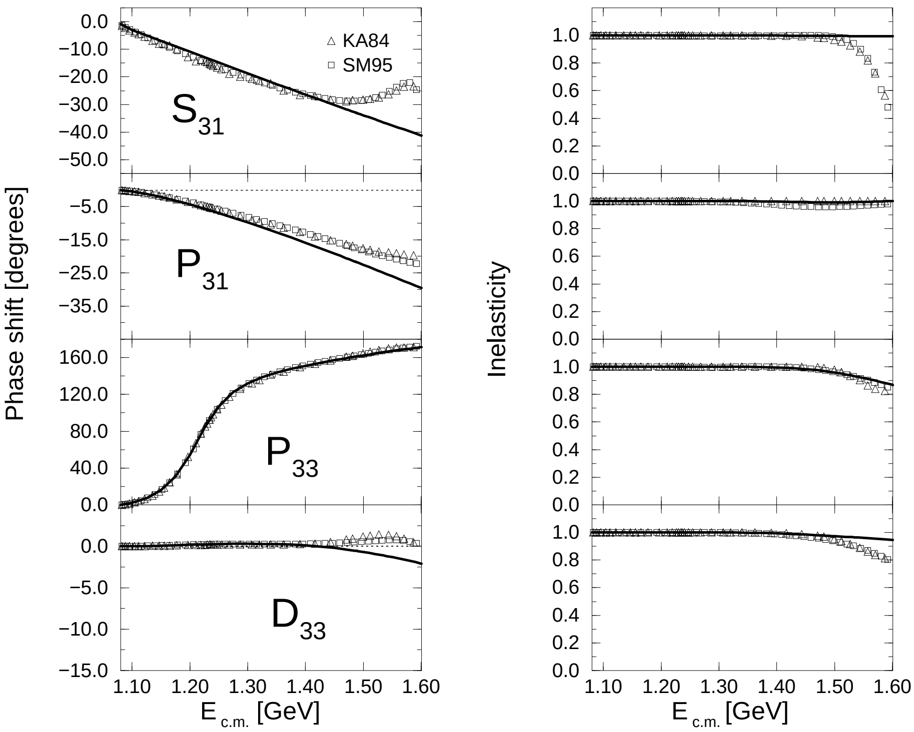

Fig. 3. Phase shift and inelasticity for partial waves with $I = 3/2$ and $J \leq 3/2$ calculated with the full $\pi N/\eta N/\pi\Delta/\sigma N$ model.

The partial waves with isospin $I = 3/2$ are well reproduced up to 1500 MeV. In the S_{31} we do not find a structure around 1.6 GeV, where the $\Delta(1620)$ is located, because the $\pi\Delta$ system cannot form a relative S-wave and the $\pi N \to \pi\Delta$ transition is therefore weak.

3. The coupling to the ηN channel and the $N^*(1535)$

The $N^*(1535)$ resonance plays an outstanding role in the baryonic spectrum, because it is the only resonance which couples strongly to the ηN channel. In fact, the branching ratio $N^*(1535) \to \eta N$ (30-55 % [18]) is about as large as into the πN decay channel. Furthermore, this resonance is located near the ηN threshold (1486 MeV) and in a recent speed plot analysis of the S_{11} πN partial wave by Höhler and Schulte [19], the resonance position was indistinguishable from the ηN threshold. This raised up the question, whether the $N^*(1535)$ is a genuine three quark resonance or if it can be understood by the dynamics of the opening of the ηN threshold. In iterating the S-wave amplitude of the SU(3) chiral meson-baryon Lagrangian in a Lippmann–Schwinger equation, Kaiser *et al.* [20] found the $N^*(1535)$ to be a quasi bound $K\Sigma$ state.

In our model the coupling to the ηN channel is realized by the following diagrams: the $\pi N \to \eta N$ transition potential is built up by nucleon and a_0 exchange and by nucleon and f_0 exchange for the direct ηN interaction. Furthermore we have included a $N^*(1535)$ pole graph coupling to πN and ηN channels These diagrams form the basis of our analysis of the structure of the $N^*(1535)$. Above the $N^*(1535)$ region the S_{11} phase shift rises rapidly. This rise is due to the $N^*(1650)$ resonance, which we have additionally included in the direct πN interaction. Since we do not investigate the structure of this resonance here, the inclusion of this diagram is a parameterization of the high energy tail of the $N^*(1535)$ resonance region.

In the first step of our analysis, we would like to see to what extend the S_{11} can be described as pure threshold phenomenon without including the $N^*(1535)$ pole graph. As one can see from the dotted-dashed curve in Fig. 4, this model leads to a cusp like structure exactly at ηN threshold, which cannot be shifted to higher energy, where the relative maximum of the phase shift is located in the data. In addition, the rapid decrease of the

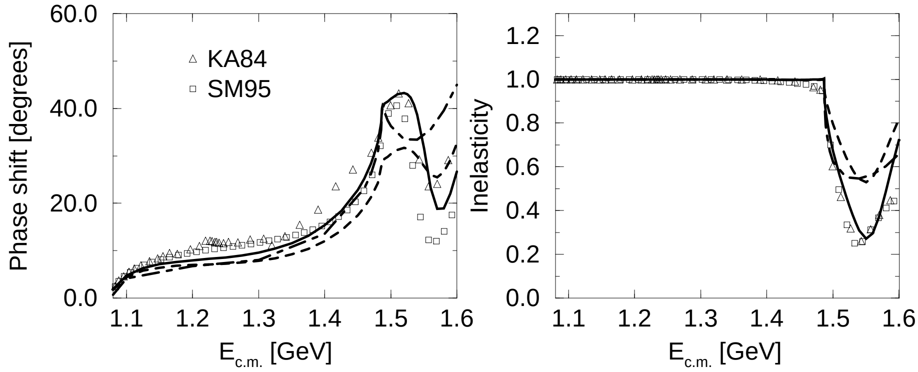

Fig. 4. Phase shift and inelasticity in the S_{11}. The solid line is the full $\pi N/\pi\Delta/\sigma N/\eta N$ model (with genuine $N^*(1535)$ resonance). The dashed line corresponds to the full model and reduced $a0$ coupling. The dotted-dashed curve was calculated without genuine $N^*(1535)$ diagram.

phase shift around 1540 MeV cannot be explained quantitatively. However, without including the $N^*(1535)$ resonance explicitly, the coupling to the ηN channel is generated only by t- and u-channel processes. The fact, that the S_{11} can be reproduced, at least qualitatively, illustrates the importance of the background contributions. The situation can be improved when the $N^*(1535)$ resonance diagrams are included into the potential. The cusp like structure at ηN threshold is still present but the maximum is now shifted to higher energy and agrees with the data. Also the rapid decrease mentioned above can be reproduced quantitatively. The improvement of describing the data after including the $N^*(1535)$ resonance is in our model a clear sign that this resonance contains a genuine three quark core.

To illustrate the importance of the background contribution from the t- and u- channel graphs in the presence of the $N^*(1535)$ resonance, we have reduced the a_0 exchange potential in the $\pi N \to \eta N$ transition by 25 %. The result is shown as dashed line in Fig. 4. The maximum of the phase shift as well as the inelasticity is substantially reduced by lowering the background contributions, which therefore are large also in the case where the $N^*(1535)$ resonance is included explicitly.

4. Summary

We presented a coupled channel $\pi N/\eta N/\pi\Delta/\sigma N$ meson and baryon exchange model for investigating two prominent baryonic resonances: the $N^*(1440)$ and the $N^*(1535)$. We found, that the opening of the ηN threshold leads to a cusp effect at ηN threshold. The inclusion of the $N^*(1535)$ improves the description of the S_{11} significantly, which indicates, that the $N^*(1535)$ contains a three quark core and cannot be generated by meson-baryon dynamics only. However, the background contributions from t- and u-channel meson and baryon exchange processes are large and cannot be neglected. The situation for the Roper resonance is quite different. Here we find a large coupling to the $\pi\Delta$ and especially the σN channel, which generates the Roper dynamically. In contrast to the PDG [18], we found the σN channel to be more important than the $\pi\Delta$ channel. The meson and baryon exchange diagrams which couple the πN to the $\pi\Delta$ and σN system are not only fixed by their contribution to the P_{11} but also by their effects in other partial waves. This results in a good description of all πN partial waves with $J \leq 3/2$.

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