The role of $S_{11}$ resonance in $\pi N$ Scattering

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Abstract

We analyze Pion Nucleon Scattering up to 700 MeV using a simple, relativistic, unitary model. The kernel of the integral equation includes nucleon, roper, delta, $D_{13}$ as well as $S_{11}$ poles with their corresponding crossed pole terms approximated by contact interactions. The $s$- and $p$- wave phase shifts are calculated from the model and shown to agree very well with the values derived from $\pi N$ scattering data. All parameters which involve $S_{11}$ are presented.
I. Introduction

Even though pion-nucleon scattering has been extensively studied for many years, there still remains a number of interesting problems to be explored, especially with the construction of powerful new facilities such as TJNAF (Thomas Jefferson National Lab) in Virginia, USA. In this brief paper we analyze pion nucleon scattering up to 700 MeV laboratory kinetic energy of pion using a simple, covariant and unitary model of $\pi N$ scattering.

In this work, the $\pi N$ scattering amplitude is obtained as a solution of a relativistic wave equation in which the pion and eta is restricted to their mass shell in all intermediate states. The rationale for this approach has been discussed by Gross and Surya. The kernel of the relativistic integral equation includes undressed delta ($\Delta$), roper($N^*$), $D_{13}$ and $S_{11}$ poles in addition to the undressed nucleon ($N$) pole. The kernel also includes contributions derived from crossed $N, \Delta, N^*, D_{13},$ and $S_{11}$ diagrams, as well as from $\sigma$- and $\rho$-like exchange terms. To keep the model simple the crossed terms are approximated by contact interactions as described in reference [1].

The $\pi NN$ coupling is taken to be the superposition of both pseudoscalar and pseudovector coupling and the $\pi NS_{11}$ coupling is taken as a superposition of both scalar and vector coupling. However for simplicity we take only scalar coupling for the $\eta NS_{11}$ coupling (the results obtained also show this tendency). The Feynman rule for the $\pi NN$ and $\pi NS_{11}$ vertex are given as follows,

\[
\pi NN \text{ vertex} : \quad \Gamma_{0N} = g_{\pi NN} \left( \lambda + \frac{1 - \lambda}{2m} \gamma^\mu k_\mu \right) \gamma^5 \tau_i
\]

\[
\pi NS_{11} \text{ vertex} : \quad \Gamma_{0S} = ig_1 \left( g_2 \frac{\gamma^\mu k_\mu}{m} \right) \tau_i
\]

\[
\eta NS_{11} \text{ vertex} : \quad \Gamma_{0\eta} = ig_\eta \tau_0
\]

$k$ is the pion momentum, $\lambda$ is a mixing parameter that is determined by the requirement that the nucleon mass be unshifted by the interaction, $g_1$, $g_2$ and $g_\eta$ are the coupling constants adjusted to fit data and $m$ is the nucleon mass. The $\pi NN$ coupling $g_{\pi NN}$ is chosen to be equal to 13.5 the same as in the reference [1].

II. The model

The model has been described in detail in reference [1] except for the $S_{11}$ resonance. Figure (1) shows additional kernels that one needed to describe
the $S_{11}$ resonance. Consistent with the previous model, the crossed diagram is approximated as a contact interaction.

Figure (2) shows the self energy of $S_{11}$. $M_c$ is the infinite sum of iterated the contact diagrams. The $M_c^{\pi\pi}, M_c^{\pi\eta}, M_c^{\eta\pi}$ and $M_c^{\eta\eta}$ are treated as a coupled channel.

III. Results

Due to the contact interactions approximation, the model allows us to fit the spin $\frac{1}{2}$ and spin $\frac{3}{2}$ phase shifts separately. Our fit to $S_{11}, S_{31}, P_{11}$ and $P_{31}$ phase shifts are given in Figures 3 and 4. The fit is good. The $S_{11}$ phase shifts are particularly interesting. Figure 5 shows how the total is
built up from individual contributions, the curves in the figures show the result when the kernel \((i)\) includes only the direct nucleon pole term and the contact term derived from crossed nucleon exchange plus the combined \(\sigma\)- and \(\rho\)-like contact terms (the dot line), \((ii)\) the terms in \((i)\) plus the additional \(\rho\)-like \(\pi\pi NN\) contact term (the dot-dashed line), \((iii)\) the terms in \((ii)\) plus roper driving terms (dashed line) and finally \((iv)\) the total result, which includes the terms in \((iii)\) plus \(S_{11}\) driving terms (solid line).

From our calculation the contribution from \(S_{11}\) (including \(\eta N\) channel) plays an important role to pion nucleon interaction at energies above 600 MeV as shown in Figure 5.

Table 1 shows parameters that are used to fit the data (column 2). The table includes effective masses \((m)\) and widths \((\Gamma)\) of the resonances (column 3). In the table, \(\Lambda\) represents the baryon cut off mass, \(g'\) is the inelastic coupling in the roper channel. We found the \(S_{11}\) width is smaller compared to Particle data group (\(\sim 100\) to \(250\) MeV). This maybe is related to our smaller value of \(g_{\eta NS_{11}} = 1.19\) as compared to effective models results or QCD sum rules using interpolating field results which is around 2.

| parameter \((m)\) | value  | effective value |
|------------------|--------|-----------------|
| \(\Lambda\) \((N^*)\) | 1205.8 | 1961.3          |
| \(g_{\pi NN^*}\)  | 6.924  |                 |
| \(m_{N^*}\)      | 1458.0 | 1463.5          |
| \(\Gamma_{N^*}\) |        | 244.3           |
| \(C_{\rho}\)     | 0.911  |                 |
| \(g'\)           | 0.793  |                 |
| \(g_2\)          | 1.910  |                 |
| \(g_1\)          | 1.222  |                 |
| \(\Lambda_{s11}\) | 2666.3 |                 |
| \(m_{s11}\)      | 1540.6 | 1567.0          |
| \(\Gamma_{s11}\) |        | 57.4            |
| \(g_{\eta NS_{11}}\) | 1.19  |                 |

**IV. Conclusions**

We have successfully extended the relativistic, simple and unitary model of pion nucleon scattering to analyze the pion nucleon scattering up to 700 MeV which includes the \(S_{11}\) resonance. We find that the model works well despite of our meson on-shell approximation in all intermediate states. We also find that the inclusion of \(\eta N\) channel tends to give the correct high energy
behavior. The coupling of pion and eta to the nucleon and $S_{11}$ is smaller than expected. This would be clarified by some quark model calculations.

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Figure 3: $S_{11}$ phase-shifts
Figure 4: P-wave phase shifts
Figure 5: S-wave phase shifts
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