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THE $J^P=2^+$ DIBARYON IN $\pi NN$ CALCULATION OF $pp\to\pi^+pn$ PROCESS

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Abstract - For $pp\to\pi^+pn$ reaction at $E_{lab}=400-1000$ MeV the theoretical $J^P=2^+$ amplitude due to the $\pi NN$ dynamics makes an anticlockwise looping behavior in the Argand plot and provides an evidence in favour for the existence of the $J^P=2^+$ dibaryon.

1 - The $\pi NN$ dynamics

So far the question whether the dibaryons exist or not has been controversial among many people/1-8/. Among them the existence of the $J^P=2^+$ and $J^P=3^-$ dibaryons has been claimed on the basis of the theoretical calculation due to the $\pi NN$ dynamics by the present author/1,3-8/. The pole structures of the $p-p$ scattering amplitudes for the $^1D_2$ and $^3F_3$ states have been shown/4/.

On the other hand an partial-wave analysis of $pp\to\pi^+pn$ data has recently been made and an evidence against the dibaryons has been claimed/9/.

The present theoretical amplitude/8/ of the $pp\to\pi^+pn$ process has been obtained simultaneously with those of the $pp\to pp$ and $pp\to \pi d$ processes by the $\pi NN$ three-body calculation. The inputs for this calculation are not only the standard ones: The $\pi N-P_{11}$ and $-P_{33}$, and $NN-^3S_1,-^3D_1,-^1S_0$ and $-^3P_2$ interacions, but also involve the additional elements: (1) The pion contribution going backward in time, (2) the coupling with $\rho NN$ system, (3) a careful choice of the off-shell structure of the $\pi N-P_{33}$ interaction and (4) the OBE contribution. These elements characterize this calculation.

Without the elements (1), (2) and (3) the structures in the $pp\to^1D_2$ and $-^3F_3$ amplitudes are not reproduced. The combined effect of an off-shell structure of the $\pi N-P_{33}$ interaction and the backward and forward going pion contributions in fig. 1 is remarkable on the $pp\to^1D_2$ and $-^3F_3$ amplitudes such as to make a structure in the energy regions around the incident proton laboratory energies $E_{lab}=600$ and 800 MeV respectively/6/. The coupling of the $\pi NN$ to $\rho NN$ system works to moderate the enhancement in the $^1D_2$ amplitude. Without this coupling the enhancement in this amplitude is too large/5/. Thus the additional elements are quite important to reproduce the structures. With these elements the dip and bump structures in the controversial $\Delta\sigma_L$ data at $E_{lab}=500-900$ MeV are reasonably reproduced/1/. The OBE contribution is important to the non-resonant parts of the $pp\to pp$ amplitudes, of course. Examples of the fits to the data in the $pp\to pp$ and $pp\to\pi^+pn$ sectors are shown in figs. 2(A) and (B). As a whole, the results of the $\pi NN$ calculation fit reasonably the observable data of $p-p$ scattering/7/, $pp\to \pi d/1$ and $pp\to\pi^+pn$ reactions/8/.
Fig. 1 The pion contributions going forward and backward in time for the \( NN \rightarrow N\Delta \) driving term are shown in the left and the right, respectively.

Fig. 2 Comparison of theoretical results with the data. (A) The \( ^1D_2 \) and \( ^3F_3 \) phase shifts and absorption coefficients in \( pp \) scattering. See ref. 7 about other observables. (B) The differential crosssection and the analysing power \( A_y \) vs. the final proton momentum \( p \) (MeV/c) in \( pp \rightarrow \pi^+pn \) process at \( E_{lab} = 800 \text{ MeV} \). The solid and broken curves indicate the results with the full channels and only with the \( P_{33} \) channels in Table 1, respectively. See ref. 8 about other observables.

Table 1 The angular-momentum channels in the final state. The "two-body state" indicate the quantum numbers of the interacting pair. The "\( S3 \)" and "\( L3 \)" represent the total spin and the orbital angular-momentum, respectively, possessed by the interacting pair and the spectator.

<table>
<thead>
<tr>
<th>two-body state</th>
<th>( P_{11} )</th>
<th>( P_{33} )</th>
<th>( ^3P_2 )</th>
<th>( ^3S_1 - ^3D_1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S3 )</td>
<td>0</td>
<td>2 2 1</td>
<td>2</td>
<td>1 1</td>
</tr>
<tr>
<td>( L3 )</td>
<td>2</td>
<td>0 2 2</td>
<td>0</td>
<td>1 3</td>
</tr>
</tbody>
</table>

2 - Analysis of the \( J^P = 2^+ \) \( pp \rightarrow \pi^+pn \) amplitude and conclusion

In the present calculation /8/ the \( J^P = 2^+ \) amplitude for \( pp \rightarrow \pi^+pn \) process is as follows. The seven angular-momentum channels in Table 1 are taken into account for the final state. Let us take out the amplitude where \( S3 = 2 \) and \( L3 = 0 \) with the \( \pi N \)
interacting pair in the $P_{33}$ state. The amplitude for this channel is most important and makes a major contribution to the peak in the differential cross-section in fig.2(B).

The amplitude is written in the following form.

$$X(E,p) = a(E,p) \exp[i\delta(E,p)] f(p),$$  \hspace{1cm} (1)

where $E$ is the total energy of the three-body system and $p$ is the internal relative momentum of the $\pi N - P_{33}$ subsystem; $f(p)$ is the Breit-Wigner like function arising from the final $\pi N - P_{33}$ interaction. Namely,

$$f(p) = [-1 - \int_0^\infty dk k^2 \frac{|g(k)|^2}{w(p) + i\epsilon - w(k)}]^{-1} g(p),$$  \hspace{1cm} (2)

where $g(k)$ is the form-factor of the $\pi N - P_{33}$ separable potential; the $w(p)$ is the invariant mass of the subsystem, given in its rest system by,

$$w(p) = \sqrt{p^2 + m_\pi^2} + \sqrt{p^2 + m_N^2}.$$  \hspace{1cm} (3)

The $a$ and $\delta$ in eq.(1) are the absolute value and the phase, respectively, of the amplitude except $f(p)$, which is obtained by solving the three-body equation. Since the three-body equation is formulated in the kinematics that the pion is relativistic, while the two nucleons non-relativistic, eq. (3) is used in the same approximation.

One makes the Argand plots of $X(E,p)$ and $a(E,p) \exp[i\delta(E,p)]$ at $E_{lab} = 300 - 800$ MeV and also the plot of the phase $\delta(E,p)$ in figs.3(A)-(C). In the plots the curves and lines indicate the range where $p$ varies from 0 to the kinematical maximum with $E(E_{lab})$ fixed. In Figs.3(A) and (B) one observes the curves moving anticlockwise with the energy increasing and the moving of the curves is very rapid at $E_{lab} = 500 - 650$ MeV. Especially one should note the anticlockwise moving in fig. 3(B), where the final state interaction $f(p)$ is removed and hence the genuine three-body interaction is embodied. In Fig.3(C), in turn, one observes the considerable increase and decrease of the phase $\delta(E,p)$. The change is comparable with that of the $J^P = 2^+$ $pp \rightarrow pp$ amplitude shown in fig.2(A). These results indicate an evidence in favour for the existence of dibaryon.

Another evidence is seen in the perturbation series of the amplitude. As is shown in Table 2, the terms from the first to the eighth are in the same order of magnitude. Thus the convergence is very bad. This suggests a pole to exist near the real axis.

Let us make the comment on ref./9/ that the $p$ dependence in $a(E,p)$ and $\delta(E,p)$ is ignored there, while the dependence is so large as is seen in our theoretical amplitude displayed in figs.3(A)-(C). Finally one notes the two references /10/ stating that the partial wave analysis result of ref./9/ is compatible with the existence of the resonance.

In conclusion one finds the evidence in favour for the existence of the $J^P = 2^+$ dibaryon both in the $pp \rightarrow pp$ and $pp \rightarrow \pi^+pn$ theoretical amplitudes.

<table>
<thead>
<tr>
<th>order</th>
<th>Real</th>
<th>Imaginary</th>
<th>order</th>
<th>Real</th>
<th>Imaginary</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-3.76E-4</td>
<td>0.0</td>
<td>6</td>
<td>-2.91E-5</td>
<td>-3.02E-4</td>
</tr>
<tr>
<td>2</td>
<td>5.01E-4</td>
<td>-5.63E-4</td>
<td>7</td>
<td>1.65E-4</td>
<td>-8.56E-5</td>
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<tr>
<td>3</td>
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<td>6.31E-4</td>
<td>8</td>
<td>1.22E-4</td>
<td>7.40E-5</td>
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<tr>
<td>4</td>
<td>-4.28E-4</td>
<td>4.22E-4</td>
<td>9</td>
<td>-1.86E-5</td>
<td>9.65E-5</td>
</tr>
<tr>
<td>5</td>
<td>-3.32E-4</td>
<td>-1.42E-4</td>
<td>10</td>
<td>-6.42E-5</td>
<td>2.08E-5</td>
</tr>
</tbody>
</table>
Fig. 3(A) and (B) The Argand plots of the $J^P = 2^+ \, pp \rightarrow \pi^+pn$ amplitudes. (A) and (B) indicate $X(E,p)$ and $a(E,p) \exp\left[i\delta(E,p)\right]$ respectively. In the plots $p$ varies from 0 to its kinematical maximum with $E$ ($E_{lab}$) fixed. The numbers associated to the curves indicate $E_{lab}$ in units of MeV. (C) The plot of the phases $\delta(E,p)$ where the lines indicate the range for $p$ varied from 0 to the kinematical maximum.

References
[2] See references 1-4, 9, 11, 14-17, 19-21, 26) and 27) in ref./1/.