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To cite this version:

M. Locher. PION DEUTERON REACTIONS AT INTERMEDIATE ENERGIES. Journal de Physique Colloques, 1985, 46 (C2), pp.C2-319-C2-328. <10.1051/jphyscol:1985238>. <jpa-00224552>

HAL Id: jpa-00224552

https://hal.archives-ouvertes.fr/jpa-00224552

Submitted on 1 Jan 1985

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PION DEUTERON REACTIONS AT INTERMEDIATE ENERGIES

M.P. Locher

SIN, Swiss Institute for Nuclear Research, CH-5234 Villigen, Switzerland

Abstract - Recent trends in the analysis of pionic deuteron reactions are reviewed. In particular πd elastic scattering, π production in pp-dπ and related topics are discussed, together with implications for B=2 resonances.

1. INTRODUCTION

In this note we review our present understanding of the reactions involving a pion and a deuteron. We shall start with πd elastic scattering in order to illustrate and differentiate the sensitivities of the dynamics (Sec. 2). Numerous recent theoretical and experimental activities have concentrated on π production and absorption channels. We shall therefore discuss (in Sec. 3) the elementary reaction pp-dπ comparing advanced calculations with experiment and commenting on direct phase shift and amplitude reconstruction. Similarly we shall report on some recent results on the continuum reaction pp-πNN. Since the deuteron has baryon number two we shall briefly comment in Sec. 4 on the status of dibaryon resonances in reactions involving the pion.

2. PION DEUTERON ELASTIC SCATTERING

This reaction is helpful in clarifying some qualitative aspects of the underlying dynamics even if recent progress has been slow and an experimental puzzle remains. For the gross features we first show a comparison of the differential cross section /1 to 4/ with theory (Fig. 1). The theoretical curves are from the Lyon group /5/ showing the results for an advanced Paddeev type multichannel scattering theory. Very similar predictions were obtained by Rinat et al /6/ and Blankleider and Afnan /7/. On the basis of Fig. 1 two conclusions can be drawn:

(i) the forward cone (θ < 70°) is described almost perfectly. This regime corresponds to the peripheral part of the interaction where the long range properties of the πN amplitude and of the deuteron wave function are probed. In fact even the impulse approximation describes this part of the dynamics quite well, comp. ref. /8/, e.g.

(ii) For larger angles we probe the regime of large momentum transfers and small distances. Theory is systematically too high for Tπ > 180 MeV which is true also for refs. /6,7/. Our understanding of the intermediate and short range behaviour is therefore not perfect. The addition of heavy meson exchange by the Lyon group /9/ does not improve the situation. Note, however, that the cross section is suppressed by two
to three orders of magnitude in this region of large angles (Fig. 1).

The vector polarization $iT_{11}$ being a pure interference effect of the type $\text{Im} AB^*$ (see /10/ appendix) is a quantity sensitive to details, in principle even in the forward cone. Yet the energy dependence predicted /5,6,7/ is quite smooth. The new high quality data of Smith et al /11/ (see Fig. 2) show less structure at $T_\pi = 256$ MeV than previously reported. There is, however, still a systematic discrepancy between the calculated $iT_{11}$ of /5,6/ and experiment, particularly in the transition region of $40^\circ < \theta < 100^\circ$ from small to high momentum transfers. The discrepancy is consistent with a $^1G_4(2480)$ Argonne resonance contributing with substantial upper coupling ($L_\pi = J+1$) of the pion orbital angular momentum /11/. Some strength for $^1D_2(2200)$ lower coupling is also required in /11/ but this just represents an adjustment of the leading $N\Delta$ contribution. Generally $iT_{11}$ is not sensitive to the Argonne resonances, if lower
coupling happens to be dominating /8,12/. In such a case there are no oscillations yet the resonances can be present with their full strength.

The tensor polarization $t_{20}$ is basically a less sensitive observable than $it_{11}$ since its algebraic structure consists of absolute squares of helicity amplitudes /10/. Yet a violent structure has been reported at angles of $120^\circ$ and $150^\circ$ for $T_\pi = 134$ MeV by Grüebler et al. /13/ disappearing rapidly within some 20 MeV. The excitation curve from a similar experiment by Holt et al. /14/ is flat for an intermediate angle. The experiment by Grüebler is flat there too, but the signs of $t_{20}$ are conflicting. The corresponding figures have been shown repeatedly, see the reviews /15,16/. To resolve the controversy experiments are under way both at TRIUMF and SIN. Note that on the theoretical side a simple admixture of a Breit Wigner resonance (of unnatural parity, $1^+$, e.g.) is not likely to reproduce the oscillations of $t_{20}$ unless some of the bigger partial waves are changed as well. Note also that a finely meshed scan around 134 MeV has not revealed any structure /17/ in the heavily correlated observable $it_{11}$, comp. /18/. The confirmation of such a strongly energy dependent effect for $t_{20}$ would therefore be a real challenge to theory. Although we are dealing here with high momentum transfers such violent excursions are not likely to occur in the framework of conventional one boson exchange dynamics.

For the closely related reaction $\pi d-\pi np$ old /19/ and new measurements of the cross section and the vector polarization in the quasileastic region are available /20,21/. Agreement with theory /20,22/ in this peripheral regime is good. The break-up channel is in principle interesting for a discussion of the broad Argonne resonances which should have a strong channel coupling. However, a major experimental and theoretical effort, in particular for the spin observables would be needed.

### 3. PION PRODUCTION AND ABSORPTION CHANNELS

A remarkably rich and almost complete set of data now exists for the simplest $\pi$ production channel $pp-d\pi$ (equivalent to $d\pi$-$pp$ by time reversal invariance). A similar effort has gone into theoretical calculations trying to predict this reaction from dynamic principles without unjustified approximations. The reaction is in the high momentum transfer regime even for forward angles since a pion has to be created. We shall try to illustrate the degree to which conventional dynamics is able to describe this sensitive reaction. The data, see the compilations in /26/ and /31/, are far more complete than for $\pi d$ elastic scattering. In principle 11 observables suffice to determine the six helicity amplitudes in $pp-d\pi$ apart from (discrete) ambiguities /23,24/. At present 9 observables ($d\sigma/dQ$, $A_{zz}$, $A_{xx}$, $A_{yy}$, $A_{zx}$, $A_{zy}$, $A_{y0}$, $A_{y0}$ and $it_{11}$) for $0^\circ < \theta < 90^\circ$ are available in the $\Delta$ resonance region. They could and should be supplemented by $t_{20}$ and $t_{21}$, e.g.

The dynamical calculations are of two kinds: a) The multichannel scattering theories referred to in the elastic channel also predict $pp-d\pi$, see /5,6,7,27/; - b) also available are calculations based on relativistic perturbation theory /23,26/ (pion rescattering and single neutron exchange with distortion factors added). In both cases the two body information ($\pi N-\pi N$, $NN-NN$, the $dpn$ vertex function etc.) is input. Technically the two approaches are very different. In Fig. 3 we show the differential cross sections. Both types of calculation describe the shape quite well and in both cases the size of the cross section is controlled by the range parameter in the $\pi NN$ vertex function. In refs /5,6/ the permitted values are restricted by channel coupling and three
body unitarity, the absolute predictions then are slightly too low. In the relativistic calculation /23,26/ the nNN amplitudes have to be extrapolated off the mass-shell since the rescattered pion is virtual. The extrapolating procedure which is used has been cross-checked by demanding a simultaneous description of the three body production pp\-nNN, see /28,29/. Among the many spin observables measured for pp\-nd which all have been calculated in /6,26/ we show the results for A_{22} which are typical (Fig. 4). Qualitatively, the calculations agree with the general trend of the data for both types of theory. In ref. /26/ the remaining discrepancy in A_{22} (note the full range is -1 \leq A_{22} \leq 1) has been traced back to missing strength in the triplet pp-waves. We conclude that the most complete calculations to this date describe the differential cross section quite well but the finer spin dependent properties of the reaction only to within 10 % of the full range of the relative observables. No violent energy dependence is predicted by conventional dynamics nor is it observed in any of the spin observables measured so far.

We have mentioned that the data set is almost complete and will allow for a direct inversion of observables into helicity amplitudes as a function of energy and angle in the near future /24/. The program has been started by reconstructing the 0° and 90° amplitudes by Aprile et al. /30/. Meanwhile the traditional analysis in terms of partial waves has also been attempted in a number of papers. Such a procedure is presently not possible without some (theoretical) constraints. Watari /33/ floats a_1 to a_{10} (see Table I for notation) and Lyon phases for higher partial waves. Bugg essentially floats a_1 to a_6, and uses varying stabilising conditions in refs. /25,31,32/. Fig. 5 shows the Argand plots for a_2 (the dominant 1D_2 wave), for a_0 and a_5 (of medium size) from the fits by Bugg /31,32/ together with the theoretical prediction of /26/. Argand diagrams for the Watari solutions are not readily comparable since a floating phase convention forcing a_7 to be real at all energies is used. His solutions are certainly different from Bugg's, comp. Table I. It is obvious that the fits are not yet stable but there is hope that the situation will improve when tensor polarizations and spin transfer observables will be measured.
A recent analysis of the three body reaction pp-πNN has been given in /29/. The Deck model (one pion exchange) well describes the cross section for the different charge channels (Fig. 6) except for a deviation near $p_T = 1.5$ GeV/c. This discrepancy also shows in the inelastic longitudinal cross section difference $\Delta \sigma_{inel}$ which is dominated by the pp-πNN channel and sensitive to spin triplet pp contributions. The difference can be explained by adding a $^3F_3(2230)$ resonance with $\Gamma = 120$ to 150 MeV. For polarized differential cross sections analysed along similar lines, see /35/. Ultimately, a comprehensive analysis including more complete spin information in this and other channels will decide about the correctness of such a picture.

4. DIBARYONS

To a high degree the interest in nd reactions over the last years was stirred by the problem of dibaryon resonances. Numerous states in the $B=2$ sector have been predicted on the basis of bag models /36,37/. However, most of them are expected to be very broad and hence difficult to observe, particularly since the coupling to deuteron channels is presumably very suppressed due to poor overlap with six quark states /38/. On the other hand, some of these states might be truly exotic (hidden color) and narrow $\Gamma < 20$ MeV (with no coupling to NN, e.g.). Broad states ($\Gamma > 120$ MeV), like the Argonne candidates in pp scattering, are presumably present in nd reactions. In Sec. 2 and 3 we have shown solutions which are consistent with contributions from $^3F_3(2230)$ and...
The partial waves $a_1$ to $a_6$ for $pp+dn$ corresponding to the fits /31,32, 33/ and the calculations /5,7,26/, respectively. (Upper figure real part, lower figure imaginary part). Conventions and (phase rotated) values for Watari /33/ as in Bugg /25/. The numbers for Lyon /5/ and Blankleider /7/ are from table 4 in /34/. For the conversion of Locher and Švarc (LS) /26/ see Fig. 5 caption.

Table I

<table>
<thead>
<tr>
<th>PARTIAL WAVE</th>
<th>$pp$ STATE AND $L_\pi$</th>
<th>Bugg II</th>
<th>Bugg III</th>
<th>Watari</th>
<th>Lyon</th>
<th>Blankleider</th>
<th>L-S</th>
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<tr>
<td>$a_0$</td>
<td>$^1S_0(1)$</td>
<td>587</td>
<td>170</td>
<td>-1776</td>
<td>-266</td>
<td>-287</td>
<td>703</td>
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<td></td>
<td></td>
<td>-150</td>
<td>-19</td>
<td>1545</td>
<td>285</td>
<td>182</td>
<td>-140</td>
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<tr>
<td>$a_1$</td>
<td>$^3P_1(0)$</td>
<td>321</td>
<td>196</td>
<td>-122</td>
<td>567</td>
<td>-320</td>
<td>-393</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-491</td>
<td>-618</td>
<td>360</td>
<td>-116</td>
<td>-375</td>
<td>-392</td>
</tr>
<tr>
<td>$a_2$</td>
<td>$^1D_2(1)$</td>
<td>1072</td>
<td>1690</td>
<td>633</td>
<td>897</td>
<td>1708</td>
<td>2087</td>
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<tr>
<td></td>
<td></td>
<td>2847</td>
<td>2565</td>
<td>2742</td>
<td>2880</td>
<td>2891</td>
<td>2773</td>
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<td>$a_3$</td>
<td>$^3P_1(2)$</td>
<td>0</td>
<td>-1</td>
<td>-969</td>
<td>335</td>
<td>-164</td>
<td>197</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0</td>
<td>187</td>
<td>756</td>
<td>312</td>
<td>-36</td>
<td>88</td>
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<td>$^3P_2(2)$</td>
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<td>-795</td>
<td>-89</td>
<td>-289</td>
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<td>-280</td>
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<tr>
<td></td>
<td></td>
<td>-663</td>
<td>-556</td>
<td>-445</td>
<td>-264</td>
<td>-216</td>
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<tr>
<td>$a_5$</td>
<td>$^3F_2(2)$</td>
<td>172</td>
<td>203</td>
<td>-651</td>
<td>-25</td>
<td>-11</td>
<td>-185</td>
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<tr>
<td></td>
<td></td>
<td>124</td>
<td>64</td>
<td>333</td>
<td>-75</td>
<td>-44</td>
<td>11</td>
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<tr>
<td>$a_6$</td>
<td>$^3F_3(2)$</td>
<td>1270</td>
<td>1341</td>
<td>857</td>
<td>996</td>
<td>944</td>
<td>656</td>
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<td></td>
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<td>735</td>
<td>357</td>
<td>925</td>
<td>372</td>
<td>242</td>
<td>304</td>
</tr>
</tbody>
</table>

$^1G_4(2480)$. Note, however, that resonance loops driven by the $N\Lambda$ intermediate state must be considered as trivial background (mostly in the $^1D_2$ wave). Moreover, these broad states are certainly describable both in the conventional language involving colorless (heavy) meson exchange or in hybrid models /39,40/ where the interior is described by bag models and quarks (unfortunately the predictive power of these models is quite limited since the relation to the underlying QCD lagrangian is very loose). As far as the deuteron itself is concerned there are descriptions for scattering at high momentum transfers /41,42/ which require genuine 6-quark admixtures in the wave function. In all this, however, there is always the danger of identifying deficiencies of conventional descriptions with exotic dynamics.

A more direct evidence for exotic dynamics would be the discovery of truly narrow structures ($\Gamma<10$ to 20 MeV) in the B=2 sector. Unfortunately, several finely meshed searches were not successful. See the $90^\circ$ excitation function for $\bar{n}d+pp$ and the analysing power $A_y(18^\circ)$ in $\bar{n}d+p(pn)$ /43/ or the scan of np total cross sections between 50 and 800 MeV /44/. Some positive indications exist as well: we have mentioned the possibility of a narrow structure in $t_{20}$ for $\bar{n}d$ elastic scattering (and some difficulties of interpretation). Narrow structures
Argand plots for the partial waves $a_0$, $a_2$ and $a_6$ for $pp+dv$ (notation as in table I). The curves marked II and III are the fits by Bugg /31/ and /32/, respectively, using his normalization. (His fit ref. /25/ is not shown). The conversion of the theoretical predictions for $\phi^i$ of Locher and Svarc /26/ (marked LS) into the partial waves $T^j$ (or $a_4$) of Bugg is given by $\phi^j = (N/\pi)T^j$ where $N = -8\pi^2s^{1/2}/(mp^{1/2}k^{1/2})$ and $k$ and $p$ are the cm momenta of proton and pion, respectively. The Born terms in /26/ are real and the minus sign above has been chosen to make $\text{Im} a_2 > 0$, similar to Bugg. Within this convention a constant overall phase factor in the fits could still be adjusted. The energies are marked in the sense of the arrows, by crosses for Bugg ($T_p = 451, 493, 533, 578, 650, 700, 750, 800$ MeV) and by dots for Locher and Svarc ($T_p = 400, 451, 510, 578, 647, 799$ MeV), respectively.

All phase factor in the fits could still be adjusted. The energies are marked in the sense of the arrows, by crosses for Bugg ($T_p = 451, 493, 533, 578, 650, 700, 750, 800$ MeV) and by dots for Locher and Svarc ($T_p = 400, 451, 510, 578, 647, 799$ MeV), respectively.

in the invariant np mass have been reported for $dp+pn$ /45, 46/. Some of these measurements are in conflict with /47/. Signals have also been seen in $p^3He+dX$ /48/. Finally the invariant pp mass in $\gamma d-pp\pi^-$ might have some narrow structure /49/. All these experiments need confirmation. Establishing a narrow resonance in the $B=2$ system would be truly exciting and deserves a concerted effort.
Acknowledgement - I am grateful to Alfred Švarc for numerous discussions and help in the preparation of the figures.

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