PHYSICAL REVIEW D VOLUME 31, NUMBER 7 1 APRIL 1985

Amplitude description of elastic *pp* scattering at 800 MeV

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(Received 6 July 1984)

Recent polarization data on proton-proton elastic scattering at 800 MeV taken at LAMPF are used for an amplitude analysis using the optimal formalism. The direct analysis of data is done in the transversity frame, which is best suited to parity-conserving reactions. From the results, amplitudes are also obtained in the helicity frame and the "magic" frame. Agreement with previous amplitudes obtained from an energy-dependent phase-shift analysis is good. The comparison of the helicity amplitudes c and e strengthens previous suggestions for a possible triplet-state dibaryon resonance. The comparison of the amplitudes a_m and c_m in the magic frame indicates a possible domination of the process near 90° scattering angle by one-particle-exchange mechanism involving exchanged particles with natural parity.

I. INTRODUCTION

pp elastic scattering has been, together with pion-nucleon scattering, the best explored strong-interaction reaction ever since particle physics began. This reaction in the range just below 1 GeV has been of particular interest recently, since at those energies the possible limits of the partial-wave phenomenology can be tested,[1] since in that energy region dibaryon resonances may exist,[2,3] and because at those energies one can also explore the extensions of the usual one-boson-exchange models.[4–6] For these reasons there has been a vigorous experimental program[7] to measure an extensive set of polarization quantities at 800 MeV. We now report an amplitude analysis of these data at a broad range of angles, accompanied by a utilization of these newly acquired amplitudes for the testing of various dynamical models and features. The data we used in our analysis are tabulated in Table I, and were taken from Ref. 8.

TABLE I. Polarization data for *pp* elastic scattering at 800 MeV. The values were taken from Ref. 8.

$\theta_{\text{c.m.}}$ (deg)	C_{NN}	A_y	D_{LL}	D_{NN}
45.7	0.564±0.032	0.500±0.013	0.536±0.021	0.796±0.021
57.2	0.586±0.009	0.459±0.005	0.431±0.021	0.779±0.028
69.0	0.617±0.030	0.331±0.040	0.291±0.023	0.757±0.030
79.2	0.669±0.019	0.274±0.071	0.247±0.018	0.728±0.032
90.0	0.661±0.010	0.010±0.008	0.260±0.014	0.735±0.028

$\theta_{\text{c.m.}}$ (deg)	D_{SS}	D_{LS}	K_{NN}	K_{SS}
45.7	0.657±0.027	0.272±0.030	0.464±0.118	0.251±0.127
57.2	0.576±0.024	0.248±0.025	0.600±0.034	0.290±0.027
69.0	0.514±0.028	0.248±0.024	0.728±0.034	0.389±0.029
79.2	0.493±0.026	0.163±0.023	0.664±0.031	0.462±0.040
90.0	0.452±0.026	0.227±0.022	0.735±0.028	0.452±0.026

$\theta_{\text{c.m.}}$ (deg)	K_{LS}	K_{LL}
45.7	0.002±0.104	0.110±0.049
57.2	0.180±0.030	0.193±0.020
69.0	0.288±0.026	0.235±0.015
79.2	0.315±0.040	0.280±0.017
90.0	0.227±0.022	0.260±0.014

TABLE II. The magnitudes and the phases of the transversity amplitudes for pp elastic scattering at 800 MeV. The magnitudes are normalized to give unity for the differential cross section. The phase of δ is taken to be zero.

$\theta_{\text{c.m.}}$ (deg)	$\lvert\alpha\rvert$	$\lvert\beta\rvert$	$\lvert\gamma\rvert$	$\lvert\delta\rvert$	$\lvert\epsilon\rvert$
45.7	0.777±0.011	0.321±0.026	0.310±0.025	0.195±0.040	0.114±0.068
57.2	0.775±0.005	0.376±0.011	0.272±0.014	0.161±0.024	0.171±0.022
69.0	0.744±0.014	0.471±0.022	0.227±0.015	0.128±0.026	0.210±0.016
79.2	0.721±0.025	0.496±0.036	0.222±0.014	0.186±0.016	0.183±0.017
90.0	0.630±0.005	0.622±0.005	0.206±0.012	0.155±0.017	0.206±0.012

$\theta_{\text{c.m.}}$ (deg)	$\phi(\alpha)$ (deg)	$\phi(\beta)$ (deg)	$\phi(\gamma)$ (deg)	$\phi(\epsilon)$ (deg)
45.7	35±22	37±17	50±19	224±17
57.2	27±17	19±15	48±15	223±8
69.0	340±16	329±15	29±14	198±12
79.2	349±14	2±18	321±18	192±12
90.0	23±28	36±27	11±13	191±13

II. METHOD OF ANALYSIS

The method of analysis utilized the optimal formalism[9,10] which has served well in similar situations previously. From that experience we now know that for a purely phenomenological analysis of a parity-conserving reaction, the most suitable optimal formalism is the transversity frame. Our analysis was therefore carried out in that frame. The magnitudes and phases of these transversity amplitudes as determined from the data are given in Table II. We see that, as usual, the *magnitudes* of the transversity amplitudes can be determined very accurately, while the *phases* of the amplitudes have much larger uncertainties. For a comparison, therefore, with a particular theoretical model which claims to give reliable predictions for all amplitudes, the magnitudes of the transversity amplitudes serve as the most sensitive tests.

There are three other optimal formalisms which play an important role in various applications of these amplitudes to the exploration of dynamical features. They are (a) the helicity formalism, which is most convenient when looking for dibaryons, (b) the "magic-angle" formalism, which accommodates best the test of one-particle-exchange mechanisms, and (c) the "transverse-planar" formalism, in which, at 6 GeV/c, this same reaction showed some striking though unexplained features.[10,12,13] Once the transversity amplitudes have been determined, obtaining amplitudes in these three other frames is, of course, only a matter of simple mathematical transformations. The results of such transformations are shown in Table III for the helicity frame, and will be discussed in the next section in connection with the figures for the "magic" frame. The transformations between these various sets of amplitudes are given by Eqs. (7.10), (7.13), and (7.14) of the second paper in Ref. 10 and by Eqs. (A1)–(A4) of Ref. 5.

The determination of the transversity amplitudes from the data was made by the usual algebraic method, which is made possible by the simplicity of the optimal formalism, thus permitting one to avoid elaborate least-square searches. The elimination of the continuum of ambigui-

TABLE III. Magnitudes and the phases of the helicity amplitudes for pp scattering at 800 MeV. The magnitudes are normalized to give unity for the differential cross section.

$\theta_{\text{c.m.}}$ (deg)	$\lvert a\rvert$	$\lvert b\rvert$	$\lvert c\rvert$	$\lvert d\rvert$	$\lvert e\rvert$
45.7	0.415±0.080	0.114±0.057	0.449±0.086	0.016±0.082	0.274±0.083
57.2	0.435±0.072	0.102±0.057	0.405±0.069	0.048±0.075	0.321±0.067
69.0	0.413±0.063	0.073±0.058	0.354±0.064	0.212±0.076	0.371±0.065
79.2	0.392±0.061	0.065±0.057	0.408±0.061	0.040±0.057	0.402±0.062
90.0	0.440±0.062	0.036±0.056	0.380±0.061	0.115±0.069	0.380±0.061

$\theta_{\text{c.m.}}$ (deg)	$\phi(a)$ (deg)	$\phi(b)$ (deg)	$\phi(c)$ (deg)	$\phi(d)$ (deg)	$\phi(e)$ (deg)
45.7	50±10	124±29	32±10	173±74	197±17
57.2	40±8	125±37	23±10	304±17	194±13
69.0	355±1	87±1	343±12	273±3	157±12
79.2	348±7	55±17	343±7	35±34	189±6
90.0	26±8	33±46	24±9	95±4	204±9

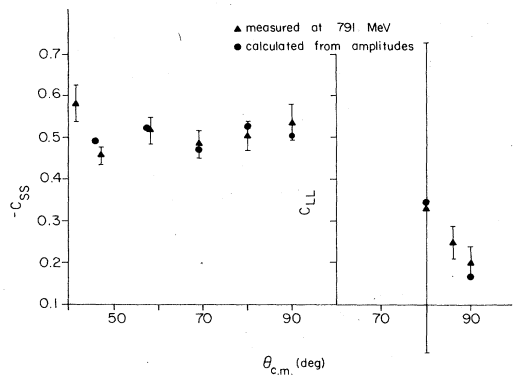

FIG. 1. Comparison of the measured values of $-C_{SS}$ and C_{LL} with the predictions of the amplitude analysis based on data other than these two.

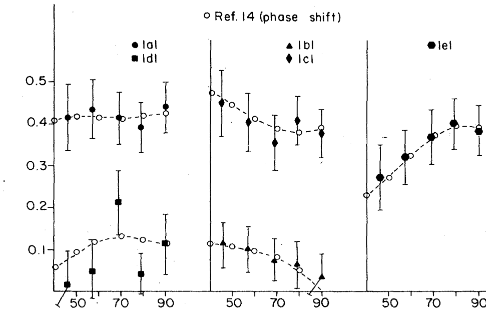

FIG. 2. Comparison of the magnitudes of the helicity amplitudes as given by the amplitude analysis and by the energy-dependent phase-shift analysis of Ref. 14.

ties was done in the way described in Ref. 11, and the references cited in that reference deal with the question of eliminating discrete ambiguities using additional observables. In determining the transversity amplitudes we used the following observables: σ, A_N, C_{NN}, D_{NN}, K_{NN}, K_{LL}, K_{SS}, K_{LS}, D_{LL}, D_{SS}, and D_{LS}.

The first five of these observables were used to determine the magnitudes of the transversity amplitudes. We then turned to the determination of the phases by choosing the one overall arbitrary phase so that $\phi(\delta)=0$. In the next step the remaining three K_{ij}'s were used to determine $\phi(\alpha)-\phi(\epsilon)$, $\phi(\beta)-\phi(\epsilon)$, and $\phi(\gamma)$. This could be done with no discrete ambiguity for the first two of these quantities but leaving a twofold discrete ambiguity for $\phi(\gamma)$. Similarly, in the third step pertaining to the phases, the remaining three D_{ij}'s were used to find $\phi(\alpha)-\phi(\gamma)$ and $\phi(\beta)-\phi(\gamma)$ without any discrete ambiguities and $\phi(\epsilon)$ with two discrete values. Next, in the fourth step, the values of $\phi(\gamma)$ obtained from the K_{ij}'s in the second step were used to find $\phi(\alpha)$ and $\phi(\beta)$, using the quantities determined in the third step. Because of the double-valuedness of the $\phi(\gamma)$ we get two solutions each for $\phi(\alpha)$ and $\phi(\beta)$. In the next, fifth step, we combine the values of $\phi(\alpha)$ and $\phi(\beta)$ just obtained with the values of $\phi(\epsilon)$ obtained in the third step to construct values for $\phi(\alpha)-\phi(\epsilon)$ and $\phi(\beta)-\phi(\epsilon)$. We thus get four solutions each for these two quantities. But these two quantities were already determined unambiguously in the second step, and so a comparison with those values allows us to select a unique solution for the whole chain of quantities, thus "closing the loop" and arriving at a unique solution. With the help of the amplitudes we then predicted the values of the remaining measured observables, namely, those of C_{SS} and C_{LL}. The agreement was excellent, as shown in Fig. 1.

III. COMPARISON WITH PARTIAL-WAVE RESULTS

At 800 MeV results of phase-shift analyses have been available. They are results of an energy-dependent partial-wave expansion, in which certain assumptions are made about the partial waves in which phase shifts appreciably deviate from being real. There are also assumptions made about the nature of the high-angular-momentum states which, after a certain maximum value of angular momentum, are taken to be represented by one-pion exchange. Thus partial-wave analyses do depend on some dynamical assumptions, however general or valid they may be. On the other hand, they have the advantage of linking together data at various angles through the use of partial waves. They also link data at different energies through the more uncertain method of parametrizing the energy dependence by some purely phenomenologically justified function.

Since the two methods of analysis are so different, it is of interest to compare their results for the amplitudes. This is done in Figs. 2 and 3. We see that the agreement is remarkably good, thus reinforcing the reliability and effectiveness of both methods of analysis.

IV. UTILIZATION FOR TESTING DYNAMICS

As mentioned earlier, we want to focus on two aspects of the dynamics which can be explored on the basis of these amplitudes.

First, the helicity amplitudes provide information on

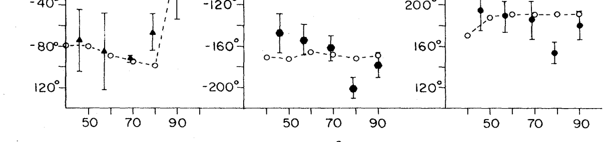

FIG. 3. Comparison of the relative phases of the helicity amplitudes as given by the amplitude analysis and by the energy-dependent phase-shift analysis of Ref. 14. The relative phases between the amplitudes c and e are also shown since they are relevant to tests of direct-channel resonances.

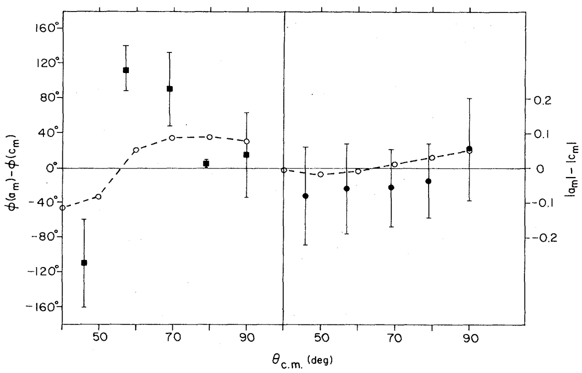

FIG. 4. Differences between the magnitudes (solid circles) and the phases (solid squares) of the two amplitudes a_m and c_m in the magic optimal frame. The open circles connected by dashed lines show the values obtained from the energy-dependent phase-shift analysis as given in Ref. 6.

direct-channel resonances. The derivation and the details of the test have been given in Ref. 3. The appropriate quantities for such a test are shown in Fig. 3. We see that the new results agree well with the analogous results obtained earlier[3] from an energy-dependent phase-shift analysis, thus reinforcing the previous conclusion that there is a suggestion of a triplet dibaryon resonance, though no conclusive proof of it. This confirmation is significant since one might otherwise argue that the energy-dependent phase-shift analysis, which is smoothed out both in energy and angle, could conceivably furnish misleading information when it comes to looking for resonances. The only conceivable disagreement between the old and new results is at 80°.

Second, the "magic" amplitudes provide information on the extent to which the one-particle-exchange mechanism with a given type of parity exchange dominate the reaction. The derivation and the details of that test were given in Ref. 5. The relevant quantities for that test are shown in Fig. 4. We see that the old and new results agree very well again with respect to the magnitudes of the two crucial amplitudes (a and c). The agreement for the differences in phases of the two amplitudes is less complete, and interpreting the new results literally, one might find more evidence in them for a predominance of one-particle exchange with natural parity close to 90°.

There is a third aspect of dynamics also that can be investigated in amplitude analysis, namely, that of new clues of dynamical structure, and, in particular, the behavior of the amplitudes in the planar transverse frame[12] which yielded interesting results at higher energies. This topic will be dealt with elsewhere.[13]

V. CONCLUSION

The previous discussion yields the following conclusions:

(1) The direct amplitude analysis of the new complete set of data yields agreement with the results of the energy-dependent phase-shift analysis, thus confirming the various assumptions that go into the latter at this energy, since the amplitude analysis depends on no assumptions other than Lorentz invariance and parity conservation.

(2) The amplitude analysis of the new results strengthens previous indications of a triplet-state dibaryon resonance at about this energy.

(3) The amplitude analysis of the new data agrees with the old results in that the *magnitudes* of the two amplitudes a_m and c_m are very closely the same. The new analysis somewhat differs from the old one in the difference between the *phases* of the two amplitudes a_m and c_m, mainly by suggesting a much smaller difference at angles close to 90° and hence a dominance of the dynamics at those angles by one-particle-exchange processes involving an exchanged particle with natural parity.

ACKNOWLEDGMENT

This work was supported in part by the U. S. Department of Energy.

[1]Partial-wave analyses cut off the angular momentum expansion or assume that the high-angular-momentum states are determined from a particular dynamics; sometimes they assume that only some of the phase shifts are complex; in energy-dependent phase-shift analyses the energy dependence is described by a purely empirical function and hence they may erase important structure as a function of energy. Amplitude analyses make no assumptions whatever, except the validity of Lorentz invariance and, if applicable, the validity of certain symmetries. For a very recent and excellent review of the status of pp phase-shift analysis, see J. Bystricky, C. Lechanoine-Luluc, and F. Lehar, Saclay Report No. D Ph P E 82-12, 1984 (unpublished).

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