PHYSICAL REVIEW D VOLUME 45, NUMBER 11 1 JUNE 1992

Nucleon-nucleon partial-wave analysis to 1.6 GeV

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(Received 10 January 1992)

An energy-dependent analysis and set of energy-independent analyses are presented for the nucleon-nucleon elastic-scattering data below 1.6 GeV. The database from which the energy-dependent and 25 *pp* (18 *np*) single-energy solutions are obtained consists of 11 880 *pp* and 7572 *np* data. A resonancelike structure is found to occur in the $^1D_2$, $^3F_3$, and $^3P_2$-$^3F_2$ partial waves; this behavior is associated with poles in the complex energy plane. The pole positions and residues are obtained through analytic continuation of the "production" piece of the T matrix obtained in the energy-dependent solution.

PACS number(s): 13.75.Cs, 11.80.Et, 14.20.Pt

I. INTRODUCTION

This analysis of elastic nucleon-nucleon scattering data updates and expands the content of Ref. [1], which is now five years old. In the intervening period, a great deal of new and precise data has been accumulated. In Sec. II we describe the additions which have been made to the data base since the work of Ref. [1]. Our previous results [1] covered the region from threshold to 1.1 GeV in the laboratory kinetic energy. The present work extends to 1.6 GeV. In Sec. III we present the results of our energy-dependent and energy-independent analyses. Here we also indicate a minor change in the parametrization scheme of Ref. [1]. In Sec. IV complex-plane pole positions and residues are given for the $^1D_2$, $^3F_3$, and $^3P_2$-$^3F_2$ resonancelike structures. Section V gives a summary of our results as well as the outlook for future studies.

II. NUCLEON-NUCLEON DATA BASE

The last *NN* scattering analyses published by the VPI group [1] employed 7223 *pp* and 5474 *np* data up to a laboratory kinetic energy of 1.1 GeV. The present database is considerably larger because of both the expanded energy range and the addition of new data. The distribution of recent (post-1986) *pp* and *np* data is given in Fig. 1. These precise new data are spread over many different observables, as is indicated in the caption of Fig. 1. The total database has more than doubled in the last decade, with the additional *pp* data exceeding *np* data by about a factor of 2. The trend since 1951 is displayed in Fig. 2.

We have reviewed this extensive database and take this opportunity to comment on some of the measurements. Many publications list only statistical uncertainties in the data tables and discuss systematic errors in the text. We will not discuss those cases in which the systematic uncertainties are clear to a careful reader, though we have detailed notes which we would be glad to share on request. In other publications the systematic uncertainties are implied rather than stated. These are discussed below.

The *np* cross sections of Hartzler, Siegel, and Opitz [2] were normalized to the total cross sections of Nedzel [3] and are therefore floated in the analysis. An error of 3% has been added quadratically to all data points, in accordance with the comment on p. 191 of the first paper listed in Ref. [2].

In the *np* polarization measurement at 350 MeV of Siegel, Hartzler, and Love [4], the beam polarization was not reversed, and so the data are subject to instrumental

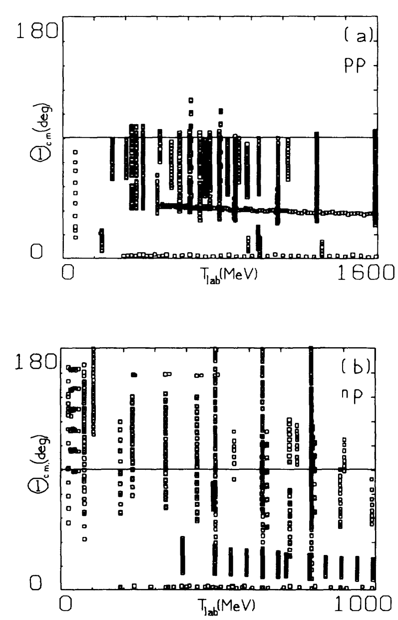

FIG. 1. Distribution of recent (post-1986) (a) *pp* and (b) *np* data. *pp* data are [observable (number of data)]: $d\sigma/d\Omega(80)$, $P(491)$, $D(148)$, $D_t(141)$, $A_{yy}(126)$, $A_{zz}(408)$, $A_{zx}(286)$, $R(59)$, $R'(12)$, $A(67)$, $A'(13)$, $A_t(109)$, other(378). *np* data: $d\sigma/d\Omega(656)$, $P(293)$, $D(13)$, $D_t(2)$, $A_{yy}(81)$, $A_{xx}(110)$, $A_{zz}(127)$, $A_{zx}(117)$, $R(8)$, $R'(8)$, $A(8)$, $A'(9)$, $R_t(86)$, $R_t'(80)$, $A_t(82)$, $A_t'(85)$, other(49).

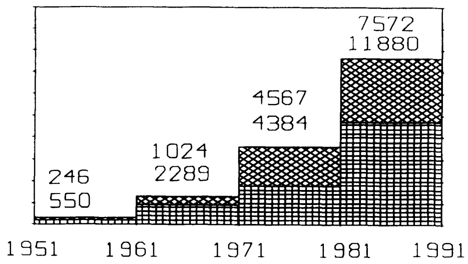

FIG. 2. Data accumulation from 1951 to the present. Cumulative totals are given as *np* over *pp* data. Square (diamond) hatching is used in the *pp* (*np*) histograms.

asymmetries estimated by the authors to be 0.01/0.16=0.06. Consequently, these data have been omitted.

Following the discussion on p. 1058 of Ref. [5], we have added 0.007/0.19=0.04 quadratically to the uncertainties given in the *pp* polarization measurement of Bareyre [5].

In the *pp* depolarization measurement at 596 MeV of Bourquin *et al.* [6], the value assumed for the carbon analyzing power was not corrected for energy loss in the carbon, and so this measurement has been omitted.

Following discussions with the authors, we have added 0.01 quadratically to the *pp* polarization data from 328 to 736 MeV of Betz *et al.* [7].

While quasifree polarization measurements have been shown to be reliable (except at forward angles), the same cannot be said for cross sections. In Ref. [8] both *pp* and *np* cross sections were measured, but the *pp* cross sections disagree with the well-established *pp* free cross sections. No corrections have been made for shadowing, and so these data have been omitted.

We have added 0.01 quadratically to the uncertainties in the *pp* polarization data from 1730 to 4300 MeV of Parry *et al.* [9], as discussed on p. 54 of this reference.

To the *np* cross-section data from 58 to 391 MeV of Bersbach, Mishke, and Devlin [10], we have included the systematic uncertainties discussed on p. 552 of this reference.

Following the discussion in the publication of Zulkarneev, Murtazaev, and Khachaturov [11], we have added 0.02 quadratically to the *np* polarization data at 635 MeV.

In the *pp* cross-section measurement at 647 and 800 MeV of Willard *et al.* [12], the dead time was monitored with an Ortec 439 digitizer which has a delay between the analog input and digitized output. Consequently, the dead time was sampled after the end of the LAMPF macropulse, leading to underestimation of the dead time and therefore cross sections that are too small. These data have been omitted.

The *pp* polarization measurements from 643 to 796 MeV of Bevington *et al.* [13] have been renormalized by 0.7% as recommended in Ref. [14].

We have omitted several of the *np* polarization data at 425 and 495 MeV of Clough *et al.* [15], as recommended on p. 2710 of Ref. [16].

The *pp* polarization and spin-correlation data of Bell *et al.* [17], taken from 500 to 2000 MeV, have been omitted. Spinka has pointed out [18] that there was significant depolarization in the Argonne National Laboratory Zero Gradient Synchrotron (ZGS) which could have decreased the data by as much as 15%. Unfortunately, this was not constant and could affect the angular distribution.

The *pp* spin correlations from 500 to 800 MeV of Bhatia *et al.* [19] have also been modified. After discussions with the authors, we conclude that the correct energies are 492, 592, 643, 694, 729, and 796 MeV, that point-to-point uncertainties are 2%, and that the overall normalization uncertainty is 5.5%.

Following discussions with the authors, we have added 0.01 quadratically to the *pn* quasifree analyzing-power uncertainties at 800 MeV of Barlett *et al.* [20]. This is consistent with the discussion on p. 398 of Ref. [21].

After discussion with the authors, we have added 0.005 quadratically to the polarization data of Aprile [22], as discussed in Sec. 7.4 of Hausammann's thesis [22].

There is a typographical error in Table 1 of the *np* spin-correlation paper of Ball *et al.* [23]. The last four points at 0.63 GeV should be modified [23]. The figure is correct.

In 1983 Spinka reconsidered [18] the beam-polarization measurements at the ZGS and concluded that the original estimates ranged from 17% too low to 24% too high. For beam energies less than 1500 MeV, the range was 11% low to 9% high, with an average of 7% and an uncertainty of ±7%. So we have increased the beam-polarization uncertainty to 7% in several data sets. (Note that the measurement of Diebold *et al.* [24] was normalized to previous data, and so this normalization is floated in the phase-shift analysis.) In both the *pp* and *np* polarizations of Marshak *et al.* [25] and the *pn* polarizations of Makdisi *et al.* [26], the beam-normalization uncertainty is assumed to be 7%. In the *pp* spin-dependent total cross sections of Auer *et al.* [27], the beam-normalization uncertainty of 7% is combined with other uncertainties for a total of 8.6%. For the *pp* spin correlations of Auer *et al.* [28], the total uncertainty is 7.7%.

Those LAMPF *np* measurements which used the polarized neutron beam were normalized to the measurements of K_{LL} for ^{2}H(p,n) by Riley *et al.* [29] and Chalmers *et al.* [30]. These in turn were normalized to the analyzing-power data of Newsom *et al.* [31], which have a normalization uncertainty of 7–10%. The 1991 measurements [32] of K_{LL} for ^{2}H(p,n) indicate that these data need to be renormalized by 10–16%. Final renormalization factors await further measurements to be made in 1992. The relevant data are the following. (a) Newsom *et al.* [31] (*np* analyzing power at 375–775 MeV, 1989): After consulting with the authors, we have increased the normalization uncertainty to 10%. (b) Ransome *et al.* [33] (*np* spin transfer at 790 MeV, 1982): Ransome *et al.* normalized to Riley *et al.* [29], and so we have renormalized by a factor of 0.64/0.72. (c) Nath *et al.* [34] (*np* spin correlation at 790 MeV, 1989) and Glass *et al.* [35] (*np* analyzing power at 790 MeV, 1990): Both Nath *et al.* and Glass *et al.* normalized to Chalmers *et al.* [30] near 800 MeV, and so we have renormalized by a factor of 0.604/0.720. (d) Garnett *et al.* [36], Rawool *et al.* [36], and Shima *et al.* [36] (*np* spin correlation at 484–788 MeV, 1987–1992): These data were all normalized to Chalmers *et al.* [30]. Each energy has been renormalized by the ratio of the value of Chalmers *et al.* to the most recent value for $K_{LL}(d)$ for the $^2H(p,n)$ reaction. (e) Beddo *et al.* [37] (*np* $\Delta\sigma_L$ at 484–788 MeV, 1991). These data were normalized to Chalmers *et al.* [30] (and interpolations; see p. 145 of Ref. [38]). These data have been renormalized by the ratio of the old/new values for $K_{LL}(d)$.

III. ENERGY-DEPENDENT AND ENERGY-INDEPENDENT SOLUTIONS

As in Ref. [1], we have decomposed the *NN S* matrix into "production" (S_p) and "exchange" (S_x) pieces such that

$$S = S_x^{1/2} S_p S_x^{1/2} = 1 + 2iT \tag{1}$$

and

$$T = T_x + S_x^{1/2} T_p S_x^{1/2} \ . \tag{2}$$

Details of the parametrization are given in Ref. [1]. The "production" piece (T_p) is mapped in the complex energy plane to find the poles listed in Sec. IV.

The methods of analysis used here have not changed from those outlined in our previous work. We have, however, used the lower πNN coupling $g^2_{\pi NN}/4\pi = 13.5$, found in recent analyses [39], of πN, NN, and $\bar{N}N$ data.

Our energy-dependent and energy-independent solutions are given for the isoscalar and isovector partial waves in Figs. 3 and 4, respectively. A summary of our energy-independent fits is also given in Table I. Considering the isoscalar waves first, we see relatively little change from the previously published solution [1] (SM86) below 400 MeV. The largest changes in our results to 1 GeV come in the mixing parameters ϵ_3 and ϵ_5. A rapid departure from SM86 is also seen in the $^1H_5$ partial wave. We initially performed single-energy searches up to 1.25 GeV, but found unacceptably large error bounds on our results above 900 MeV. This is the highest single-energy isoscalar solution we have retained. Above 900 MeV the existing *np* database does not seem able to support a reliable energy-independent analysis.

Our previous isovector analysis terminated at 1.1 GeV. The present upper limit is 1.6 GeV. The results given in Fig. 4 thus display both the modification to SM86 mandated by recent measurements, and new predictions

TABLE I. Comparison of present (FA91) and previous (SM86) energy-dependent partial-wave analyses. The energy-independent analyses of *pp* data (Pxxx) and combined *pp* and *np* data (Cxxx) are also listed along with the χ^2/data for each energy bin.

Solution	Range (MeV)	*pp* data [χ^2(FA91)]	*np* data [χ^2(FA91)]	Parameters
SM86	0–1100	11 900/7223	8871/5474	115
FA91	0–1100 (*np*) 0–1600 (*pp*)	20 600/11 880	13 711/7572	123
C15	11–19	17/22	116/148	7
C25	19–31	30/51	203/234	8
C50	32–68	190/215	526/412	11
C75	60–90	36/68	361/278	11
C100	75–125	111/129	464/322	12
C150	125–175	186/220	316/255	13
C200	175–225	100/101	621/394	16
C300	275–325	280/258	625/523	17
C400	375–425	540/433	709/505	18
C450	425–475	868/648	698/576	18
C500	475–525	1284/1027	909/599	20
C550	525–575	762/647	294/293	29
C600	575–625	746/618	319/296	32
C650	625–675	746/568	1012/750	34
C700	675–725	769/668	362/333	36
C750	725–775	766/639	264/246	41
C800	775–825	1716/1073	966/679	44
C850	810–890	1337/1033	268/252	44
C900	850–950	1459/1124	417/344	45
P950	920–980	903/604		27
P999	960–1040	1274/900		27
P105	1000–1100	1160/645		28
P110	1050–1150	805/389		28
P125	1200–1300	846/518		28
P130	1250–1350	864/560		28
P160	1550–1650	464/347		29

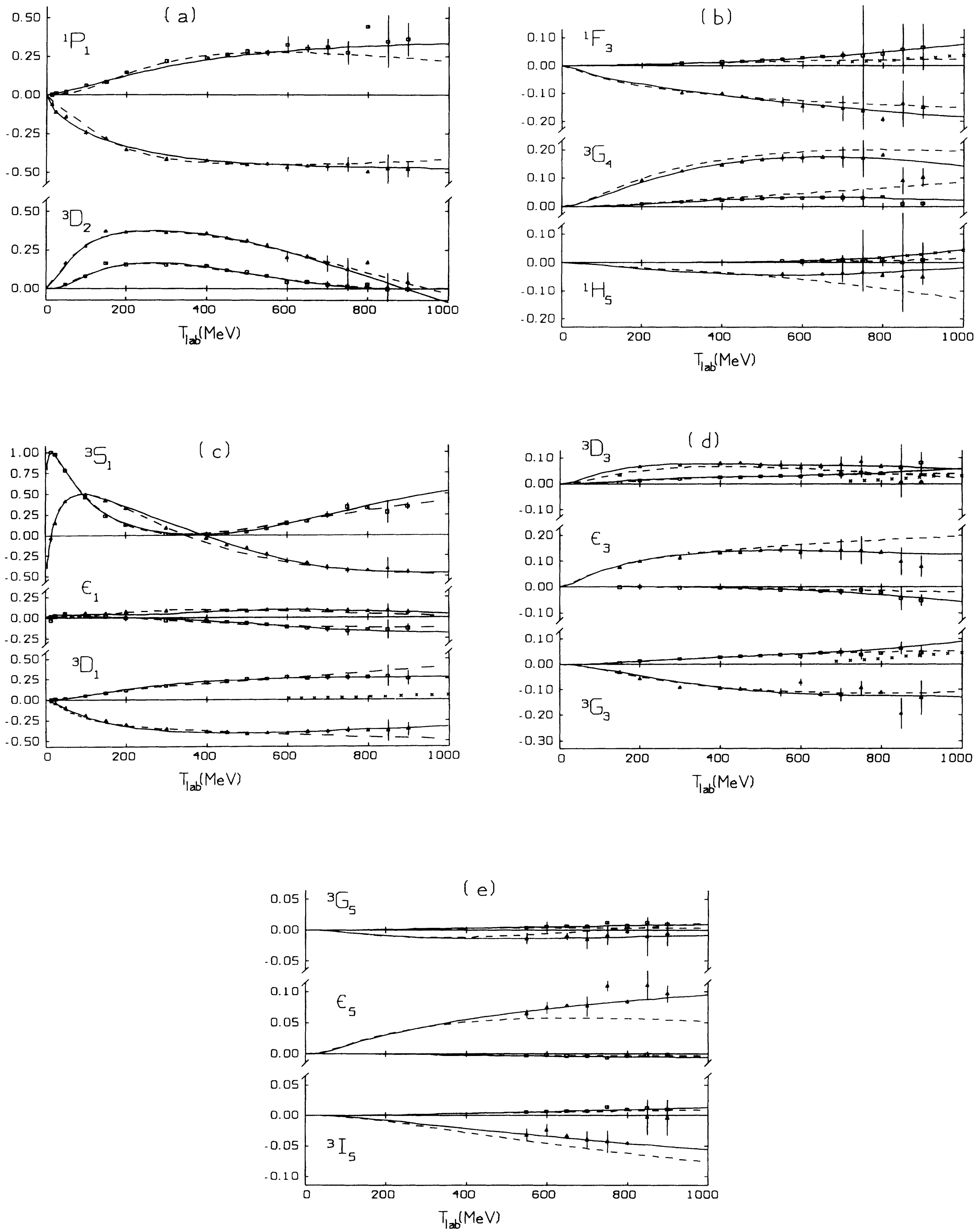

FIG. 3. Isoscalar partial-wave amplitudes from 0 to 1 GeV. Solid curves are FA91; dashed curves are from SM86. Real and imaginary parts of the single-energy solutions are, respectively, plotted as triangles and squares. The × points give the value of $\mathrm{Im}T - T^2 - T_{sf}^2$, where T_{sf} is the spin-flip amplitude.

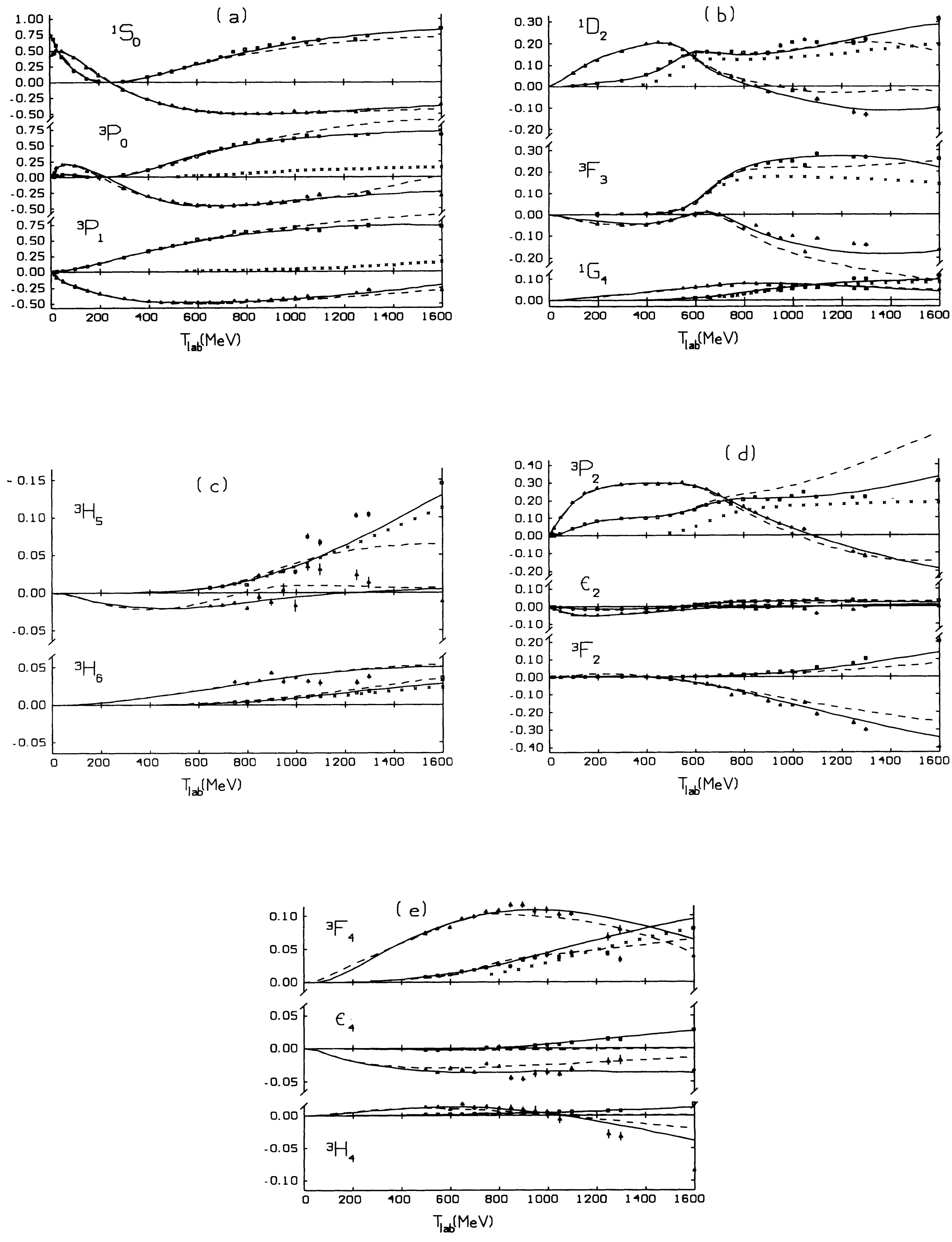

FIG. 4. Isovector partial-wave amplitudes from 0 to 1.6 GeV. Notation as in Fig. 3.

beyond 1.1 GeV. Above 1.1 GeV the dashed lines give an extrapolation of SM86. The deviations from FA91 (solid curves), shown in the $^3P_2$, $^3F_3$, and $^3H_5$ partial waves, illustrate the pitfalls of pushing these energy-dependent solutions beyond their range of validity. Below 1.1 GeV, where one can make meaningful comparisons with SM86, the isovector solution has remained fairly stable. Some deviations are evident near 1 GeV in the $^3F_3$ partial wave and at lower energies in the rather small $^3H_5$ wave.

IV. DIBARYONS

As in Ref. [1], we have searched the complex energy plane for poles in the production T matrix T_p. Our results are listed in Table II. Results from our previously published solution [1] are also given. In comparing the pole values and residues, we see little change for those resonancelike structures found in the $^1D_2$, $^3F_3$, and $^3P_2$-$^3F_2$ partial waves. A weak structure previously [1] seen in the $^3F_4$-$^3H_4$ partial waves was not found in the present solution.

TABLE II. Pole positions and residues for partial waves exhibiting resonancelike behavior. W_p is the pole position. G gives the function $(W_p - W)T_p$ evaluated at the pole. G_r=ReG and G_i=ImG. Values from SM86 are given in square brackets.

State	W_p	$\|G\|$ (MeV)	arctan(G_i/G_r) (deg)
$^1D_2$	2148−i59	8.8	−11
	[2148−i63]	[10]	[−15]
$^3F_3$	2170−i72	9.4	74
	[2183−i79]	[14]	[−78]
$^3P_2$	2167−i86	11	59
	[2163−i75]	[7.7]	[52]
$^3F_2$	2167−i86	0.3	85
	[2163−i75]	[0.3]	[86]

V. RESULTS AND DISCUSSION

In summary, we find qualitative agreement with our previous solution (SM86) below 1 GeV. Above 1.1 GeV our predictions are new and show sizable deviations from an extrapolation of SM86 to 1.6 GeV. While some modifications of our pole positions and residues have been required, resonancelike structures still arise in the $^1D_2$, $^3F_3$, and $^3P_2$-$^3F_2$ partial waves. We no longer see any pole structure in the $^3F_4$-$^3H_4$ partial waves. The evidence for this structure was also quite weak in SM86. Although we attempted to extend our $I=0$ single-energy solutions beyond 900 MeV, the present np database was found to be insufficiently constraining.

Tables of partial-wave amplitudes and database information as well as predicted observables may be obtained either from our interactive dial-in program [40] (SAID) or directly from the authors. The results obtained through SAID are continually being updated to reflect the current database. Previously obtained solutions are also retained for comparison.

The effect of inelasticity in high partial waves has recently been studied by several groups [41]. We are currently examining the effect of the $N\Delta$ channel on these waves, which are presently calculated assuming a real $1-\pi$ exchange. A more detailed analysis of the near-threshold np database is also underway.

ACKNOWLEDGMENTS

This work was supported in part by U.S. Department of Energy Grant No. DE-AS05-76ER04928.

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[40] SAID is an interactive program which may be accessed through Telnet (connect to VTINTE.PHYS.VT.EDU, login/password: PHYSICS/QUANTUM). It allows the user to plot/list the presently existing database and make comparisons with several recent partial-wave analyses and potential models. Information regarding its use is available from the authors either through the mail or via Bitnet: PHYS0 at VTVM1.

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