Updated analysis of NN elastic scattering data to 1.6 GeV

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(Received 13 July 1994)

An energy-dependent and set of single-energy partial-wave analyses of NN elastic scattering data have been completed. The fit to 1.6 GeV has been supplemented with a low-energy analysis to 400 MeV. Using the low-energy fit, we study the sensitivity of our analysis to the choice of πNN coupling constant. We also comment on the possibility of fitting np data alone. These results are compared with those found in the recent Nijmegen analyses.

PACS number(s): 11.80.Et, 13.75.Cs, 25.40.Cm, 25.40.Dn

I. INTRODUCTION

This analysis of elastic nucleon-nucleon scattering data updates the content of Ref. [1]. In the intervening period, a substantial amount of new np data has been accumulated. These additions to the database are the subject of Sec. II. In Sec. III, we give the results of our analyses and compare with our previous solutions [1–3] and those produced by the Nijmegen group [4].

The Nijmegen group has continued to analyze data in the low-energy region and now [5] claims the ability to fit both the $I = 0$ and $I = 1$ phases using np data alone. In order to explore the low-energy region more closely, an analysis to 400 MeV (VZ40) was carried out. Using VZ40 we considered the sensitivity of our fits to the choice of pion-nucleon coupling constant, and carried out fits to the pp and np data separately. We have also studied the effect of pruning high-χ^2 data from the database. Our finding are summarized in Sec. IV.

II. THE DATABASE

Our previous NN scattering analyses [1] were based on 11 880 pp and 7572 np data. In Ref. [1] the pp analysis extended up to a laboratory kinetic energy of 1.6 GeV; the np analysis was truncated at 1.1 GeV. The present database is considerably larger due both to an expanded energy range for the np system (up to 1.3 GeV) and the addition of new data. The distribution of recent (post-1991) pp and np data is given in Fig. 1. The total database has doubled over the last decade (see Table I). New np data, mainly produced by LAMPF and Saclay since 1991, have resulted in a better balance between pp and np datasets. In fact, the np database has increased by a factor of 1.3 since 1991. Unfortunately, we cannot extend our analysis of the $I = 0$ system up to a nucleon kinetic energy of 1.6 GeV, due to the lack of np data between 1.3 and 1.6 GeV.

Since most of the new data [6–45] are from high-intensity facilities, they have added weight against the older data. Most of new pp data were produced between 500 and 800 MeV. LAMPF, for instance, has produced differential cross sections [36], polarization variables P [31], and correlation parameters A_{zz}, A_{zx} [19], and A_{yy} [41]. Excitation measurements of P were carried out at KEK [42] for $37\pm2°$ between 491 and 1600 MeV and Saclay [15] for 43° between 523 and 708 MeV.

Most of new np were either measured below 100 MeV or between 350 and 1100 MeV. The sources of low energy data are TUNL, PSI, and Uppsala which gave $d\sigma/d\Omega$ [23]; P [13], [17], [24]; A_{zz} [9]; A_{yy} [43]; and D_t [11]. LAMPF has completed a 10 year np program, producing data for $d\sigma/d\Omega$ [34]; A_t, A_t', R_t, R_t' [10] and [20]; A_{yy}, A_{xx}, A_{zx} and A_{zz} [18], [35], and [45]; D_t and P [33] and [31]. A detailed study of np polarization quantities was carried out at Saclay, producing data for P [25], [26]; A_{yy} [27]; A_{zz} [28]; A_{zx} [29]; A_t, N_{0nkk}, $D_{0s''0k}$, R_t, N_{0nsk}, D, and D_t [39]. Total np cross sections in pure spin states were also measured [6,8,30,32,37,40].

III. PARTIAL-WAVE ANALYSIS

As mentioned in the Introduction, this analysis extended to 1.6 GeV, with an np component up to 1.3 GeV. The energy-dependent solution required 77 isovector and 44 isoscalar parameters. The solution (FA91) described in Ref. [1] had 123 free parameters. The present energy-dependent solution gives a χ^2/datum of 22371/12838 for

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0556-2813/94/50(6)/2731(11)/$06.00

TABLE I. Comparison of present (SM94, VZ40) and previous (FA91, SM86, and SP82) energy-dependent partial-wave analyses. The χ^2 values for the previous FA91, SM86, and SP82 solutions correspond to the published results [1–3].

Solution	Range (MeV)	χ^2/pp data	Range (MeV)	χ^2/np data	Ref.
SM94	0 – 1600	22371/12838	0 – 1300	17516/10918	Present
	(0 – 400)	3443/2170	(0 – 400)	5290/3367	Present
VZ40	0 – 400	3098/2170	0 – 400	4595/3367	Present
FA91	0 – 1600	20600/11880	0 – 1100	13711/7572	[1]
SM86	0 – 1200	11900/7223	0 – 1100	8871/5474	[2]
SP82	0 – 1200	9199/5207	0 – 1100	9103/5283	[3]

pp data and 17516/10918 for *np* data. A comparison with several of our previous solutions is given in Table I. In addition to the energy-dependent analysis, single-energy fits of the *pp* and *np* data were obtained up to 1.25 GeV. Two further analyses of *pp* data alone were added at 1.3 and 1.6 GeV. These are described in Table II, where we list the number of varied parameters in each single-energy fit and compare with the χ^2 found in the energy-dependent solution. These single-energy results are plotted with uncertainties in Fig. 2.

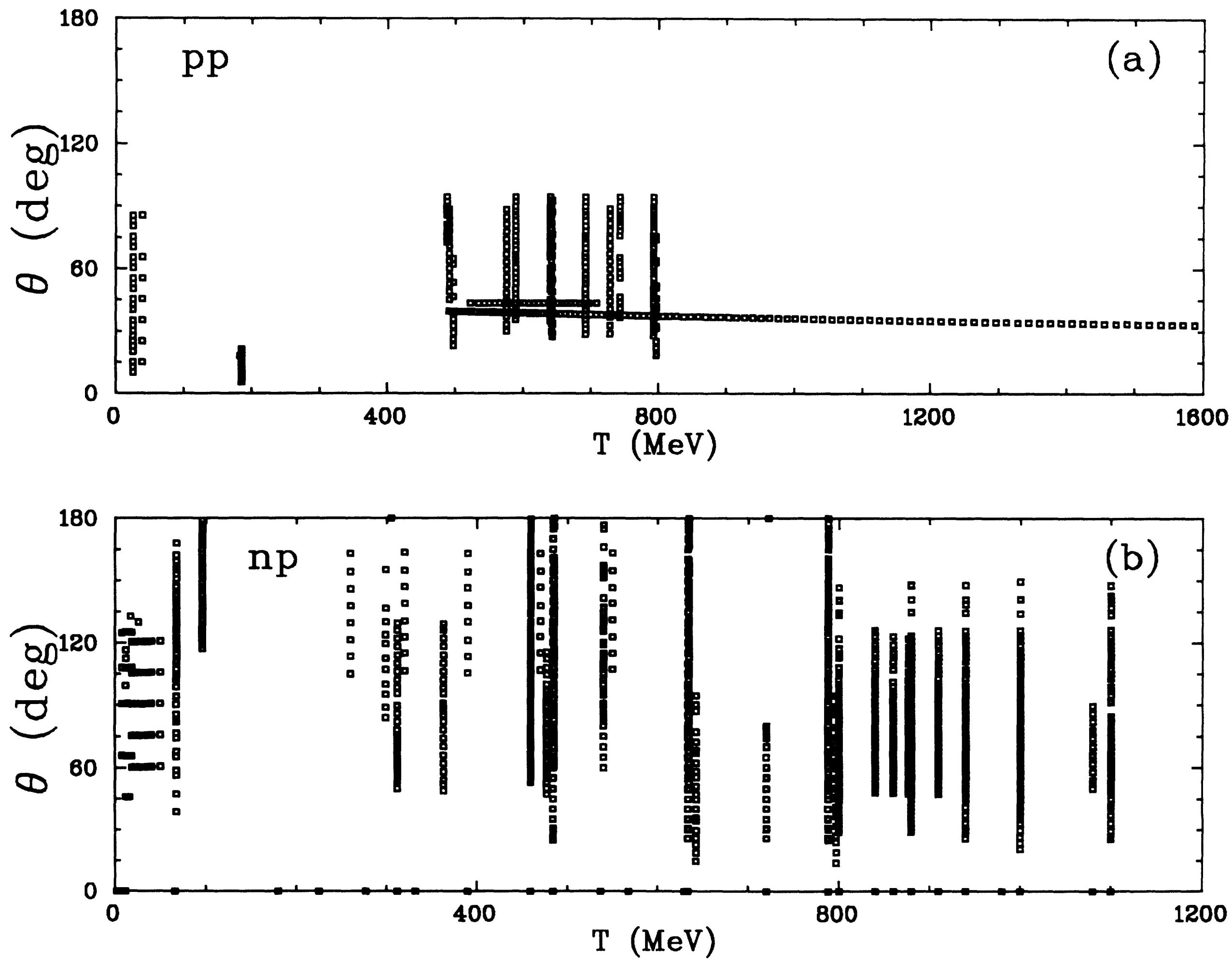

FIG. 1. Energy-angle distribution of recent (post-1991) (a) *pp* and (b) *np* data. *pp* data are [observable (number of data)] $d\sigma/d\Omega$ (81), P (383), D (8), R (6), A (2), A_{yy} (10), A_{zz} (147), and A_{xz} (64). *np* data are $d\sigma/d\Omega$ (221), P (924), D (30), D_t (128), A_{yy} (389), A_{xx} (159), A_{zz} (415), A_{xz} (425), R_t (103), R_t' (80), A_t (142), A_t' (85), N_{0nsk} (20), $D_{0s''0k}$ (20), N_{0nkk} (20), $\Delta\sigma_T$ (31), $\Delta\sigma_L$ (23), and other (5). Total cross sections are plotted at zero degrees.

TABLE II. Single-energy (binned) fits of *pp* data (*Pxxx*) and combined *pp* and *np* data (*Cxxx*), and χ^2 values. χ^2_E is given by the energy-dependent fit, SM94, and N_{prm} is the number parameters varied in the fit.

Solution	Range (MeV)	χ^2/pp data	χ^2_E	χ^2/np data	χ^2_E	N_{prm}
C 5	4 − 6	22/28	39	50/53	65	6
C 10	7 − 12	79/88	126	134/72	189	6
C 15	11 − 19	17/27	45	176/213	344	8
C 25	19 − 31	121/114	213	257/264	334	8
C 50	32 − 68	300/224	392	616/465	684	10
C 75	60 − 90	46/72	53	396/311	500	10
C100	80 − 120	136/154	177	428/344	472	11
C150	125 − 175	293/287	415	317/262	519	13
C200	177 − 225	165/146	220	605/396	697	13
C250	225 − 275	66/64	146	236/220	278	13
C300	276 − 325	284/256	352	631/528	893	17
C350	325 − 375	296/246	341	496/354	664	17
C400	375 − 425	556/436	648	766/552	837	17
C450	425 − 475	861/647	999	796/622	852	18
C500	475 − 525	1378/1067	1509	1337/851	1349	18
C550	525 − 575	822/702	984	620/493	695	26
C600	575 − 625	1067/703	1198	425/364	575	29
C650	625 − 675	859/643	860	1432/978	1727	33
C700	675 − 725	809/723	851	419/407	493	34
C750	725 − 775	930/768	1204	508/372	621	41
C800	775 − 825	1549/1116	2096	1536/999	1633	41
C850	827 − 875	1187/882	1347	380/366	421	41
C900	876 − 925	310/333	434	751/628	808	41
C950	926 − 975	795/623	975	347/352	449	41
C110	1078 − 1125	705/360	835	467/326	625	46
C125	1200 − 1296	890/540	1297	290/154	482	48
P130	1261 − 1346	908/583	1390	0/0	0	28
P160	1554 − 1639	438/344	768	0/0	0	29

The most significant changes to FA91 [1] were made in the parametrization of the S waves and in the tuning of the deuteron pole parameters. The solutions FA91 and SM94 differ little in the isovector partial waves; only the isoscalar waves are plotted in Fig. 2. Here we have displayed both SM94 and FA91 for the purpose of comparison. Large variations are seen in the $^3D_2$ partial wave, and at low energies in ϵ_1. In Fig. 3, some prominent partial waves are plotted in an Argand diagram [46].

In order to ascertain that the full fit to 1.6 GeV (1.3 GeV for *np*) was not seriously degraded at low energies, a 0−400 MeV fit was also developed. The resultant solution, VZ40, used 26 $I = 1$ and 27 $I = 0$ variable parameters to give a χ^2/datum of 3098/2170 (*pp*), and 4595/3367 (*np*). The global fit, SM94, produced, for the same energy range, a χ^2/datum of 3443/2170 (*pp*) and 5290/3367 (*np*). We consider this quite reasonable given that the number of variable parameters per datum is nearly twice as large for VZ40 as it is for SM94. A comparison of selected phases is given in Fig. 4. Here we have also compared with the Nijmegen analysis [4]. Note that while substantial differences are seen between the Nijmegen and SM94 results for the $^1P_1$ and $^3P_0$ phases, the VZ40 and Nijmegen results are quite consistent. The most noticeable disagreement is seen in ϵ_1.

To illustrate the stability of our solution (either VZ40 or SM94) against pruning of the database, we performed the following exercise with VZ40. The data set was first pruned by discarding all data with χ^2 contributions greater than 9; this resulted in the removal of 74 data (27 pp and 47 *np*) with a consequent decrease in χ^2 of about 1000. The solution was then searched and χ^2 decreased by a mere 45. When we further pruned data giving χ^2 contributions in excess of 7, 71 more points were removed with a reduction of 590 in χ^2. Further searching reduced χ^2 by only 14. The resultant, pruned fit gave a χ^2/datum of 2397/2112(pp) and 3643/3280(*np*) with virtually *no* detectable change in the resultant phases. Our χ^2 values are clearly dependent upon the existence of poorly fitted data. However, the solution itself appears quite insensitive to the removal of high-χ^2 data.

In joint analyses of *pp* and *np* data, it is commonly assumed that the $I = 1$ phases are essentially determined by the *pp* data. If $I = 1$ phases could be determined directly from the *np* data, this would provide an interesting check on charge independence. Until recently, this was not possible. However, the Nijmegen group claims [5] to have succeeded in an analysis of the *np* data alone, and

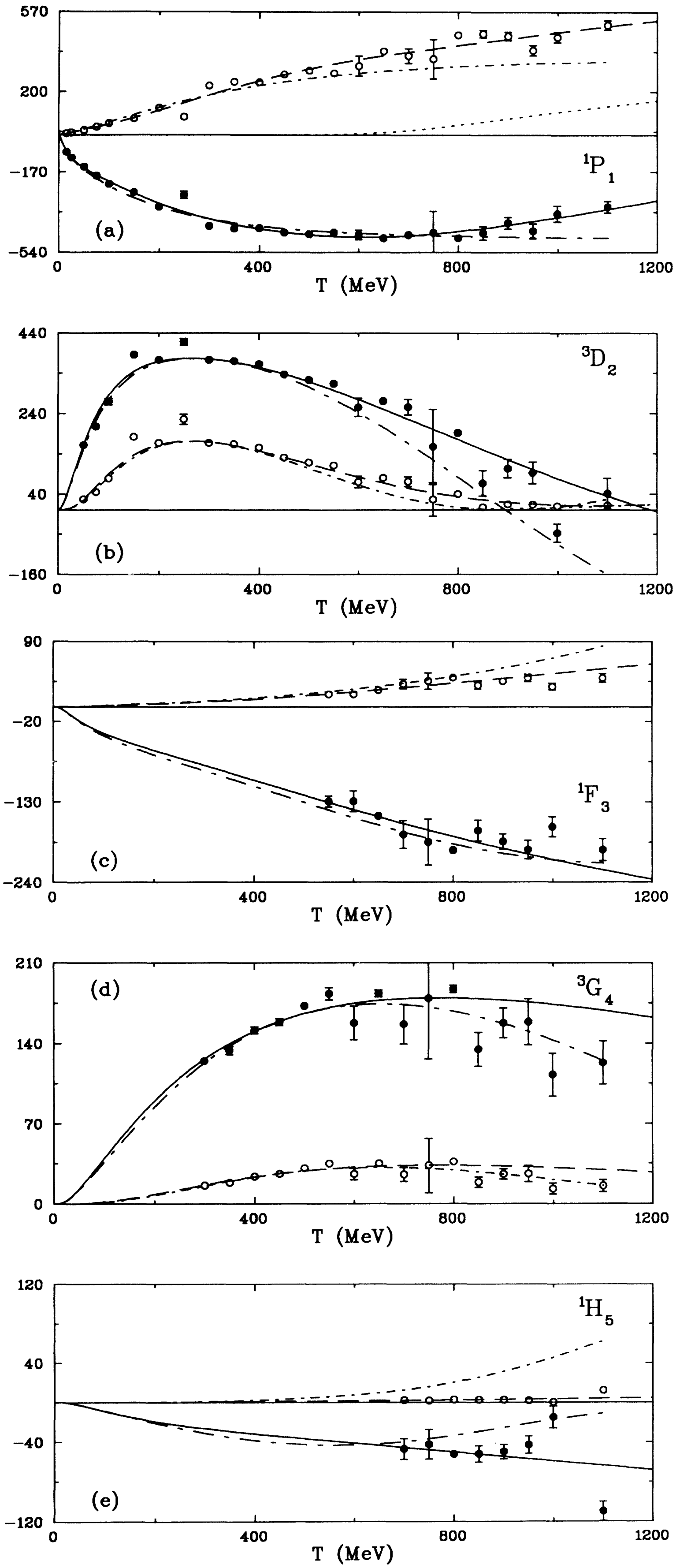

FIG. 2. Isoscalar partial-wave amplitudes from 0 to 1.2 GeV. Solid (dashed) curves give the real (imaginary) parts of amplitudes corresponding to the SM94 solution. The real (imaginary) parts of single-energy solutions are plotted as filled (open) circles. The previous FA91 solution [1] is plotted with long dash-dotted (real part) and short dash-dotted (imaginary part) lines. The dotted curve gives the value of Im $T - T^2 - T^2_{sf}$, where T^2_{sf} is the spin-flip amplitude. All amplitudes have been multiplied by a factor of 10^3 and are dimensionless.

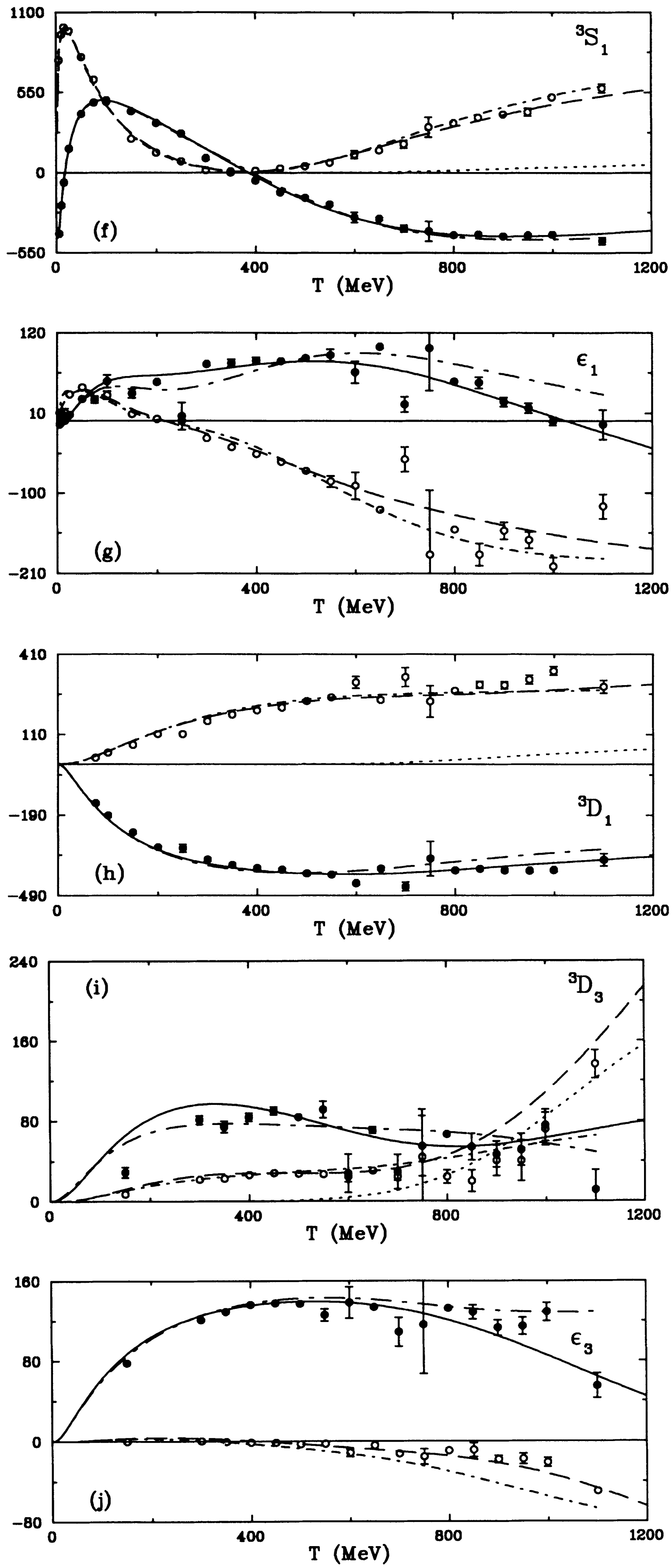

FIG. 2. (*Continued*).

have compared their results to those coming from analyses of the pp data alone. We have attempted this using our VZ40 solution and find that it is indeed possible to fit the np data separately.

We first attempted to fit the pp data alone, in order to determine the effect of np data on the $I = 1$ phases. The np data were removed and the solution adjusted to best fit the pp measurements. The χ^2 for the pp data dropped from 3098 to 3083. This is what one would expect if only the pp data were significantly influencing the $I = 1$ phases. More surprising was the effect of removing all pp data from the 0–400 MeV database. A stable solution was found with χ^2 changing from 4595 to 4422 for the np data. The small decrease in χ^2 suggests that charge independence is a reasonable assumption in joint analyses of np and pp data. In these tests the charge de-

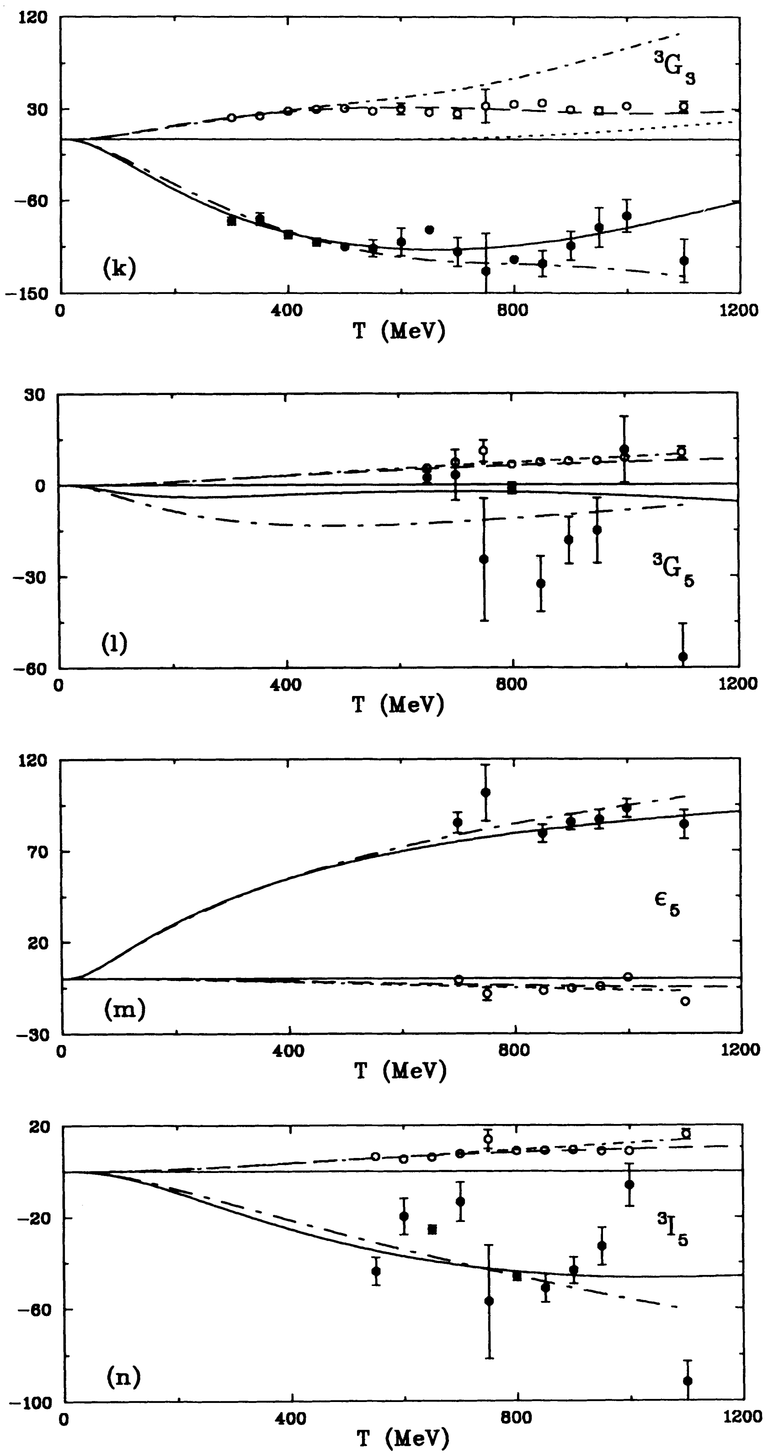

FIG. 2. (*Continued*).

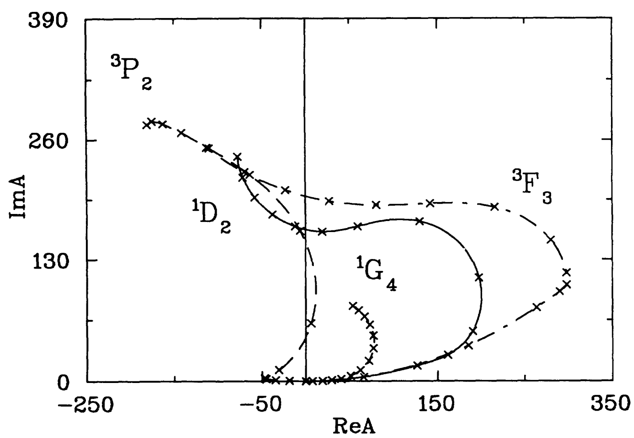

FIG. 3. Argand plot of the *NN* partial-wave amplitudes $^1D_2$, $^3P_2$, $^3F_3$, and $^1G_4$. (Compare Figures 7 of Refs. [47] and [48]). The "X" points denote 100 MeV steps. All amplitudes have been multiplied by a factor of 10^3 and are dimensionless.

pendence of the $^1S_0$ partial wave was imposed through an effective range formalism [the Coulomb corrected $^1S_0(pp)$ effective range expansion included vacuum polarization corrections]. In the fit to *np* data alone, we fixed the $^1S_0(np)$ scattering length and effective range to values determined in our joint analysis, but allowed the remaining phenomenological parameters to vary.

Sensitivity to the pion-nucleon coupling $g^2/4\pi$ was probed by mapping χ^2 versus $g^2/4\pi$ for the solution VZ40. The results are illustrated in Fig. 5 where we have plotted the change in χ^2 for *pp*, *np*, and combined data. The resulting parabola for combined data shows a consistency with our chosen value (13.7), but with a rather weak sensitivity. We do not consider this to be a reliable determination of $g^2/4\pi$ because it is dependent upon the particular way in which we account for the one-pion exchange in our representation. In Fig. 5, *H* waves and higher were treated in a one-pion-exchange approxima-

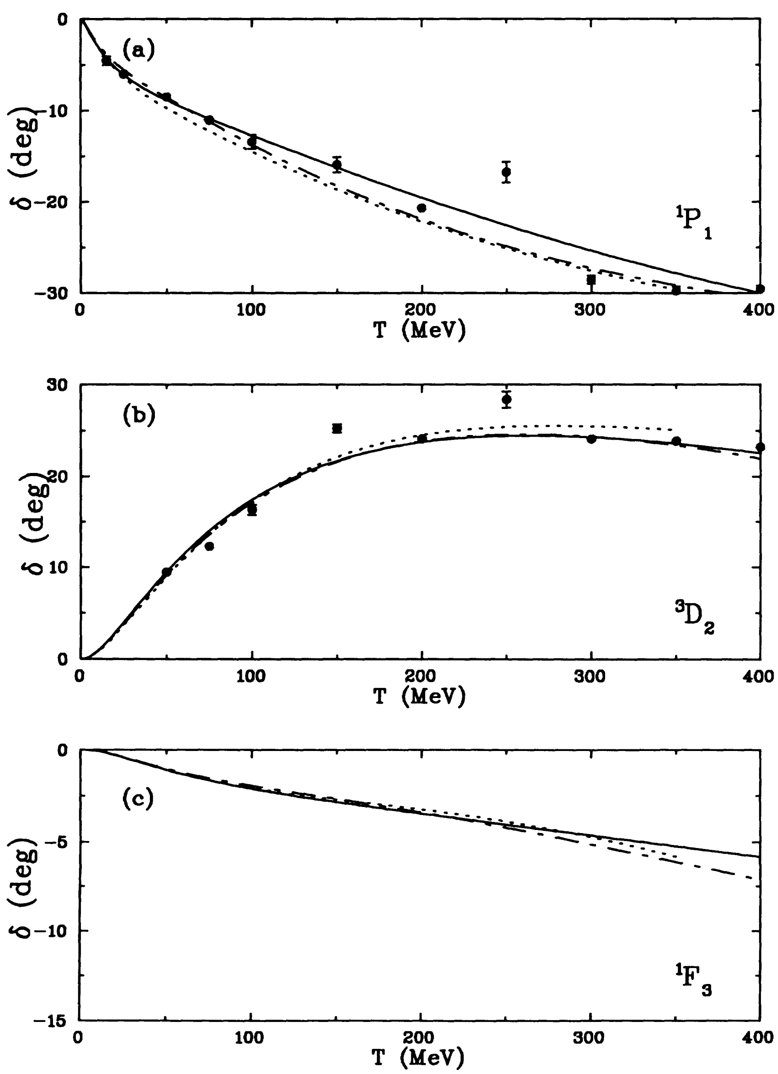

FIG. 4. Phase-shift parameters from 0 to 400 MeV. The SM94 and VZ40 solutions are plotted as solid and dash-dotted curves, respectively. Single-energy solutions are given by filled circles. A recent solution from the Nijmegen group [4] is plotted as a dashed curve.

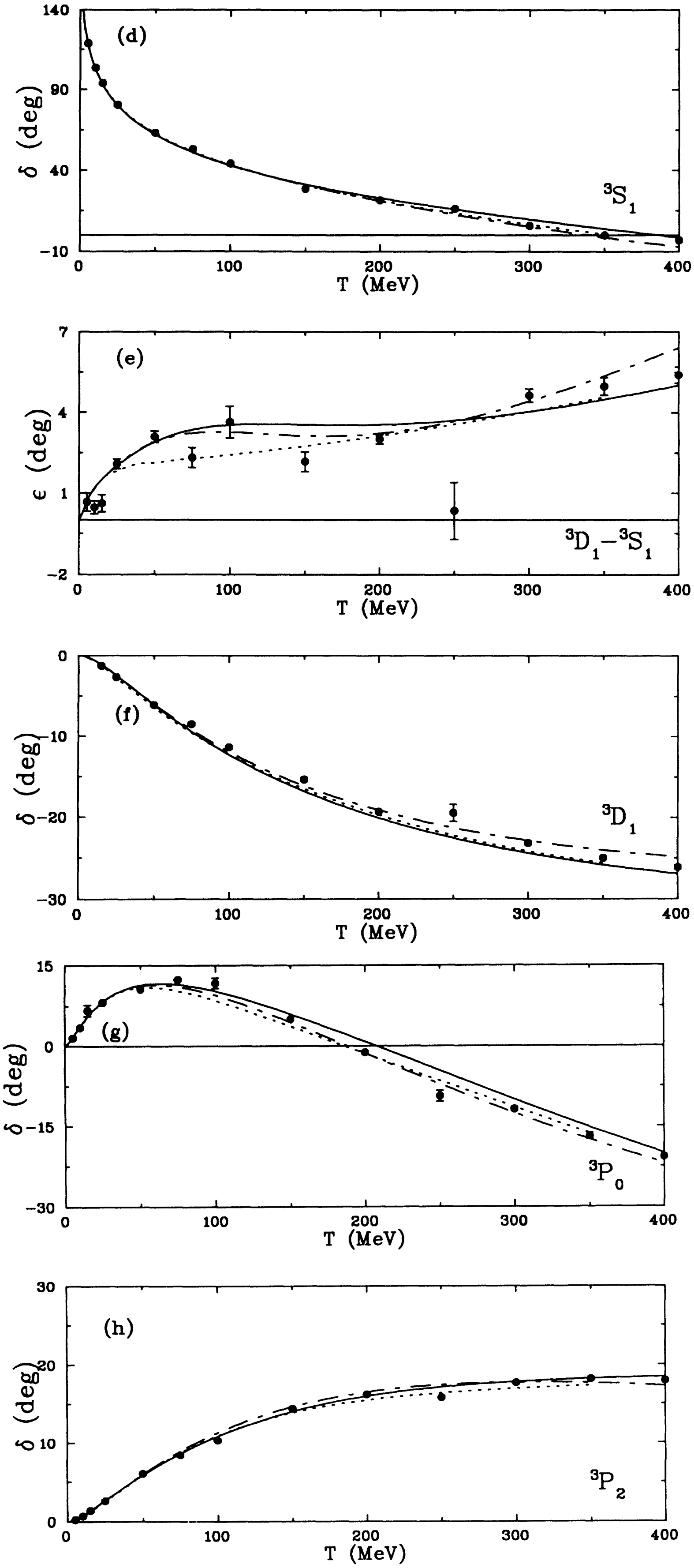

FIG. 4. (*Continued*).

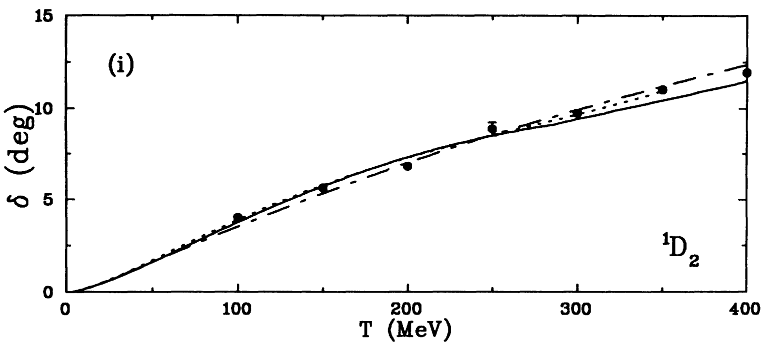

FIG. 4. (*Continued*).

tion. Purely for comparison purposes, we have included in Fig. 5 the parabola which resulted from a χ^2 mapping in our pion-nucleon analysis [49] to 2.1 GeV in the pion laboratory kinetic energy. This analysis was based on more data (by a factor of 4) than were used in the VZ40 fit, but the sensitivity is clearly much greater in our pion-nucleon analysis. The value of $g^2/4\pi$ determined in Ref. [49] was 13.75±0.15.

IV. RESULTS AND COMPARISONS

We have incorporated a large new set of *NN* elastic scattering data into our analyses. This set was mainly comprised of *np* measurements, and these produced noticeable changes in some isoscalar partial waves. The isovector waves remained fairly stable. At low energies, ϵ_1 changed significantly from the FA91 results. Also at low energies, apart from ϵ_1, comparisons between VZ40 and the Nijmegen results show good agreement.

In other tests with VZ40, we found that our solution was quite stable to the removal of high-χ^2 data. We also verified that the *np* data could be analyzed separately. The χ^2 values for separate fits of the *pp* and *np* data were not very different from results found in combined analyses. We also demonstrated that a value for the πNN coupling, consistent with our πN elastic scattering results, could be determined from VZ40. We should emphasize that this was a consistency check and not a determination of the coupling.

Some new TUNL measurements [50] of the *P* parameter for the *np* elastic scattering at 8 and 12 MeV will soon be available. While only a few polarization quantities have been measured at medium energies, some new PSI measurements [51] of R_T and D_T between 260 and 550 MeV and a few new Indiana data [52] of *P* and A_{YY} at 180 MeV will soon be available.

This reaction is incorporated into the SAID program [53], which is maintained at Virginia Tech. Detailed information regarding the database, partial-wave amplitudes, and observables may be obtained either interactively, through the SAID system (for those who have access to TELNET), or directly from the authors.

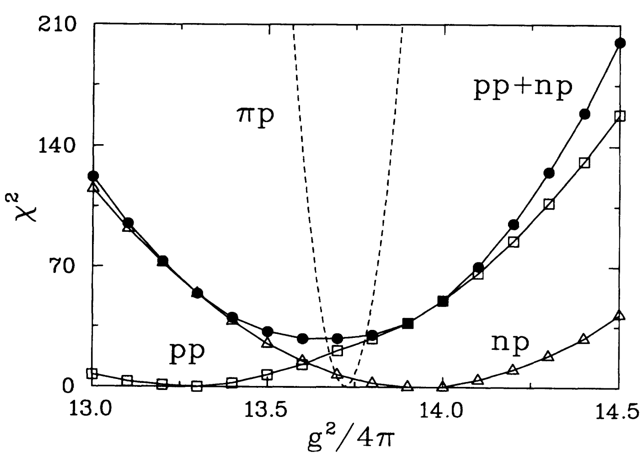

FIG. 5. A plot of χ^2 versus $g^2/4\pi$. χ^2 values are plotted as deviations from the *pp* and *np* minima. The open squares (triangles) give the VZ40 results of *pp* (*np*) data. The black circles give the result of a combined fit to both *pp* and *np* data. Solid lines drawn are to guide the eye. For the purpose of comparison, a χ^2 map for the recent FA93 πN solution [49] has been added as a dashed curve.

ACKNOWLEDGMENTS

The authors express their gratitude to R. Abegg, J. Ball, D.V. Bugg, T. Bowyer, F. Bradamante, J.M. Durand, G. Glass, L.G. Greeniaus, R. Henneck, G.A. Korolev, H. Klages, F. Lehar, C. Lechanoine-LeLuc, M.W. McNaughton, D.F. Measday, W. Kretschmer, V.N. Nikulin, W.K. Pitts, J. Rapaport, E. Rössle, H. Shimizu, H.M. Spinka, W. Tornow, P. Truoel, S. Vigdor, R. Weidmann, W.S. Wilburn, and A. Yokosawa for providing experimental data prior to publication or clarification of information already published. We thank H. von Geramb for a number of useful communications regarding the deuteron parameters. I.S. acknowledges the hospitality extended by the Physics Department of Virginia Tech. This work was supported in part by the U.S. Department of Energy Grant DE-FG05-88ER40454.

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