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Nucleon-nucleon elastic scattering analysis to 2.5 GeV

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A partial-wave analysis of *NN* elastic scattering data has been completed. This analysis covers an expanded energy range, from threshold to a laboratory kinetic energy of 2.5 GeV, in order to include recent elastic *pp* scattering data from the EDDA Collaboration. The results of both single-energy and energy-dependent analyses are described. [S0556-2813(97)02712-X]

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I. INTRODUCTION

This analysis of elastic nucleon-nucleon scattering data updates our previous analysis [1] to 1.6 GeV in the laboratory kinetic energy. The present analysis extends to 2.5 GeV, which is the limit for elastic *pp* differential cross sections measured [2] by the EDDA Collaboration using the cooler synchrotron at COSY.

Measurements with a laboratory kinetic energy near 2 GeV are particularly interesting as they correspond to a center-of-mass energy (2.7 GeV) which has been suggested [3] for a dibaryon resonance [4]. Near this energy, a sharp structure has been found in the polarization observable A_{yy} [5], and this was taken as support for such a resonance. A resonancelike structure, at about the same energy, has also been reported in an analysis by Hoshizaki [6]. The authors of Ref. [2] have considered this possibility, but find no evidence for a resonant excursion in their cross sections. Polarization measurements expected from COSY and SATURNE II will certainly help to clarify this issue.

The database above 1.6 GeV is mainly comprised of cross section measurements, much of this coming from Ref. [2]. In Sec. II we describe the expanded database, noting the additions below 1.6 GeV as well as the new region from 1.6 GeV to 2.5 GeV. While the most significant changes are seen in our *pp* partial-wave amplitudes, both *pp* and *np* data have been analyzed.

In Sec. III, we briefly review the formalism used in our analyses. Here we present the updated amplitudes and make comparisons with our previous solution (SM94) [1]. Fits with and without the new EDDA data are compared to show the influence of this particular measurement. Representative plots showing the agreement between our analysis (SM97) and cross section data have been generated to illustrate the quality of this fit. These results and the prospect for improvements are summarized in Sec. IV.

II. DATABASE

Our previous *NN* scattering analyses [1] were based on 12838 *pp* and 10918 *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 1.3 GeV. The present database [7] is considerably larger due both to an expanded energy range for the *pp* system and the addition of new data at lower energies. The total database is now about 20% larger than was used in our previous analysis [1].

Below we list recent additions to our database. Some data sets which we collect are not used in the analyses, but are retained so that comparisons can be made. A complete description of the database and those data not included in our analyses is available from the authors [7].

The new *pp* data have been produced mainly at COSY [2]. From this source, we have added differential cross sections ranging from 540 MeV to 2520 MeV in the proton kinetic energy and from 35° to 90° in the c.m. scattering angle. In addition to this, about 60 high quality polarized data (P, A_{xx}, A_{yy}, and A_{zx}) at 200 MeV were produced by the Indiana cooler [8]. Another 35 high accuracy differential cross sections between 490 and 790 MeV were recently published [9]. These measurements were made at LAMPF. We have also added a measurement of A_{zz} at 650 MeV produced by LAMPF [10] but missed in the SAID database [1].

In constructing the database extension from 1600 MeV to 2500 MeV, we reexamined a number of references in order to include higher energy data which had previously been neglected. This search netted additional data mainly from ANL (450 points) and Saclay (893 points). The complete set is listed [11–50] in alphabetical order.

The *np* database has not been increased significantly and, as a result, we did not extend our analysis of the $I=0$ system. New *np* polarized data have been produced mainly by TRIUMF (101 points) [51,52], IUCF (33 points) [53], and LAMPF (49 points) [54]. The ANL–LAMPF–New Mexico University–Texas A&M University Collaboration has finalized its analysis of 311 high quality *np* polarized observables (A_{xx}, A_{zz}, A_{yy}, and A_{zx}) between 485 and 790 MeV and ranging from 25° to 180° [55]. These measurements were published previously in Ref. [56]. A few total cross sections in pure spin states between 4 and 16 MeV were produced by TUNL [57] and Charles University at Prague [58,59]. Recently, the final LAMPF $\Delta\sigma_L$ measurements between 480 and 790 MeV were also published [60]. In addition, some new $\Delta\sigma_L$ measurements above 1190 MeV were made at

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TABLE I. Comparison of the single-energy (SES) and energy-dependent (SM97) fits to pp and np data. Values of χ^2 are given for the SES and SM97 fits (evaluated over the same energy bins). Also listed is the number of parameters varied in each single-energy solution.

Energy range (MeV)	χ^2 SES(SM97)/pp data	χ^2 SES(SM97)/np data	Parameters
4–6	22(39)/28	50(66)/53	6
7–12	84(132)/88	221(309)/87	6
11–19	17(49)/27	191(445)/236	8
19–30	123(275)/114	263(286)/295	8
32–67	294(375)/224	667(754)/485	10
60–90	55(64)/72	457(595)/329	10
80–120	161(185)/154	419(487)/353	10
125–174	301(310)/287	328(367)/272	11
175–225	249(354)/212	715(766)/499	13
225–270	66(91)/64	243(270)/236	13
276–325	274(309)/256	571(655)/518	17
325–375	297(320)/246	421(474)/353	17
375–425	555(601)/436	753(843)/549	17
425–475	902(1004)/665	775(799)/629	18
475–525	1322(1484)/1081	1252(1419)/787	30
525–575	861(972)/754	549(584)/432	31
575–625	1032(1154)/760	422(491)/367	36
625–675	891(863)/754	1263(1563)/875	36
675–725	838(882)/777	403(473)/386	37
725–775	990(1195)/827	512(558)/374	37
775–824	1583(1754)/1170	1518(1845)/944	38
827–874	1195(1358)/939	386(497)/366	39
876–924	341(412)/389	753(920)/628	41
926–974	790(945)/679	354(498)/352	43
976–1020	931(1131)/708	300(441)/331	43
1078–1125	528(689)/413	427(671)/326	45
1261–1299	680(972)/507	− − −	29
1481–1521	139(266)/149	− − −	29
1590–1656	472(655)/409	− − −	31
1685–1724	185(293)/118	− − −	31
1778–1818	404(628)/347	− − −	31
1929–1968	218(271)/168	− − −	31
2065–2104	673(1241)/431	− − −	31
2176–2224	1005(1325)/377	− − −	31
2330–2470	803(1257)/458	− − −	31

JINR (Dubna) [61]. Added unpolarized measurements include 15 np differential cross sections at 67 MeV from PSI [62] and 6 differential cross sections at 14 MeV from Tübingen University [63]. A few missed differential cross sections at low energies from LAMPF [64] and at 1240 MeV from Berkeley [65] were also added.

A few data sets were added to the database but not used in the analysis. These include 82 missed np total cross section measurements between 4 and 231 MeV from LAMPF [66]. We excluded these data from the analysis in order to retain the same pre-1993 database (below 350 MeV) as was used in the Nijmegen analysis [67].

III. PARTIAL-WAVE ANALYSIS

Our first attempts to extend the range of the NN analysis used the parametrization scheme of Ref. [1]. These were unsuccessful. The problem was traced to the basis functions used to expand our K-matrix elements. Many of these become nearly degenerate as the kinetic energy of the incoming nucleon (T) increases to 2.5 GeV. As a result, a modified form was used in the present analysis. Apart from this difference, the formalism used here is identical to that used in Ref. [1]. The reader is directed to Refs. [68,69] for more details. In the following we just outline the method used, in order to show how the modified basis functions fit into our parametrization scheme.

For uncoupled partial waves ($^1D_2, {}^3F_3, \dots$), an S matrix ($S = S_E S_I$) is used. This product S matrix is constructed from exchange (S_E) and inelastic (S_I) pieces. S_E is parametrized in terms of a K matrix

$$S_E = (1 + iK_E)/(1 - iK_E), \tag{1}$$

which in turn is expanded as

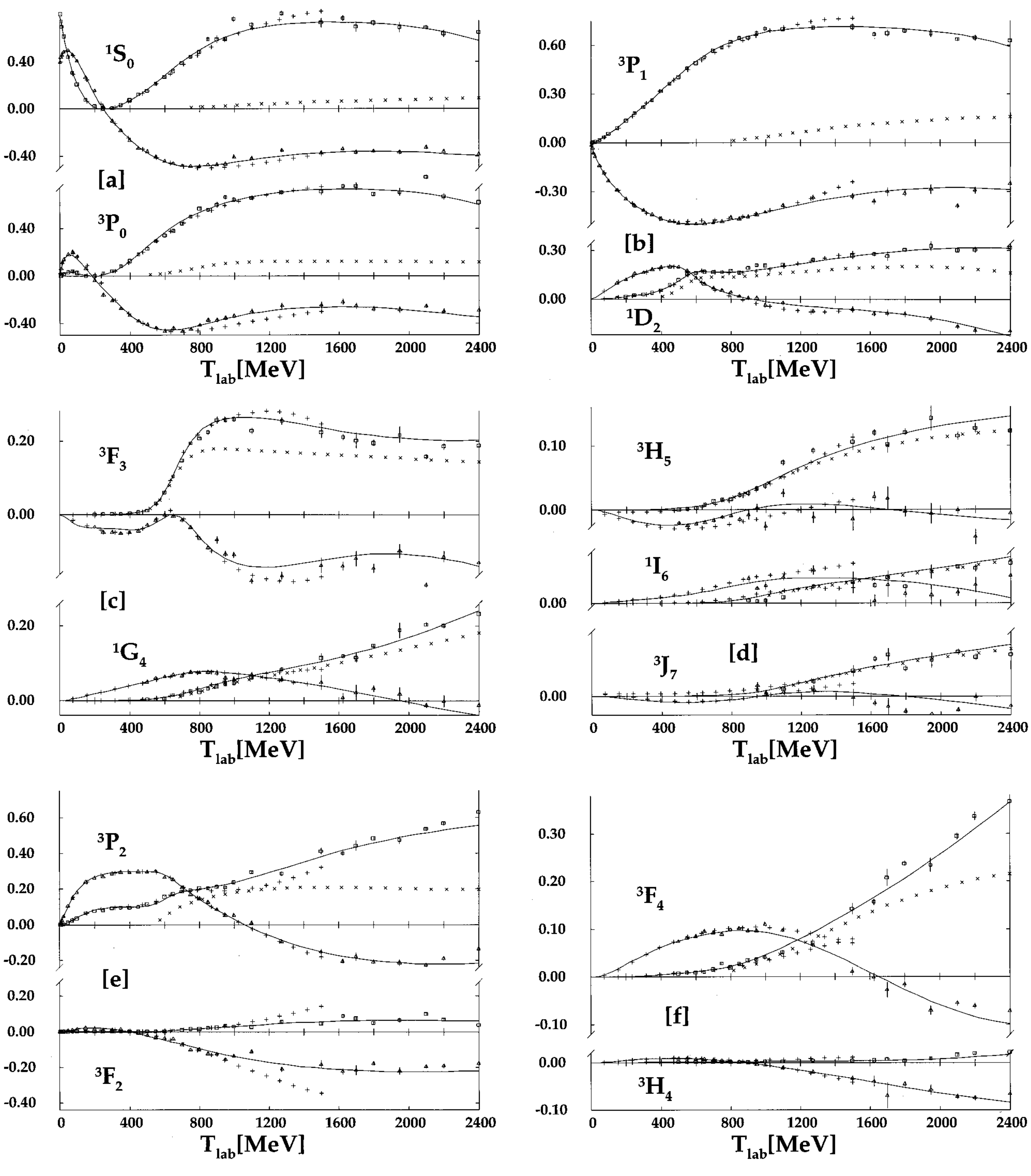

FIG. 1. Isovector partial-wave amplitudes from 0 to 2.4 GeV in the proton kinetic energy. Solid curves give the amplitudes corresponding to the SM97 solution. The real (imaginary) parts of the single-energy solutions are plotted as triangles (squares). For comparison, the previous solution SM94 [1] is plotted with (+) marks. The (×) marks give Im T-T^2-$T_{\rm sf}^2$ from SM97, where $T_{\rm sf}$ is the spin-flip amplitude. All amplitudes are dimensionless.

$$K_E=\text{Born}+\sum_i \alpha_i A_{li}. \tag{2}$$

Here the Born term gives the single-pion exchange contribution and α_i are free parameters. The expansion basis elements A_{li} are given by

$$A_{li}=F_{li}\left(\frac{T}{T+T_C}\right)^{i-1}, \tag{3}$$

where the function F_{li}, used as the expansion basis in our previous fits [1], is given by

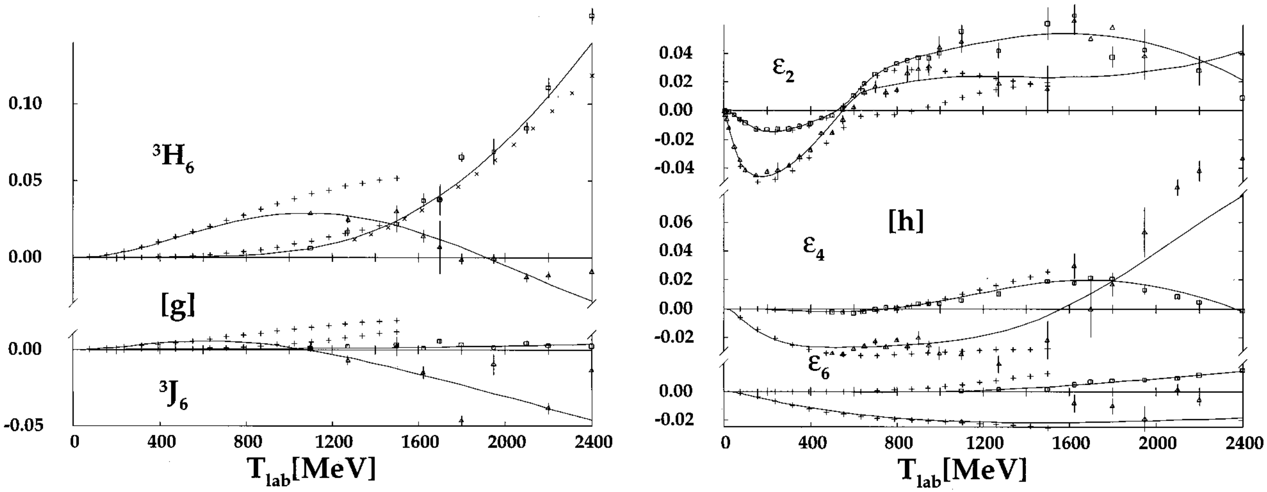

FIG. 1 (*Continued*).

$$F_{li}(T)=\frac{4\mu^2}{MT}\int_0^1 Q_l\left(\frac{x_0-x}{1-x}\right)\frac{x^{i-1/2}}{1-x}dx. \tag{4}$$

Here M (μ) is the nucleon (pion) mass and $x_0=1+(4\mu^2/MT)$. Q_l is a Legendre function of the second kind. In Eq. (3), T_C is a parameter which was chosen to be 1 GeV. (The fit was not sensitive to this choice; fits using 0.5 GeV and 1.5 GeV were also attempted.) The basis function given in Eq. (4) was derived in Ref. [69].

To ensure time-reversal invariance, the spin-coupled waves (for example, $^3P_2$-$^3F_2$) are parametrized as

$$S(2\times2)=S_E^{1/2}S_IS_E^{1/2}, \tag{5}$$

where again the matrix S_E is expanded in terms of a K matrix with the elements

$$K_m=\text{Born}_m+\sum_i A_{l_m i}, \tag{6}$$

the subscript $[m=(+,0,-)]$ labeling states with $l_m=(J+1,J,J-1)$. As in Ref. [1], the matrix S_I is taken from a Chew-Mandelstam K matrix coupling the NN channel to an appropriate $N\Delta$ state. This has been extensively described in Ref. [68]. The simple modification of the basis elements, displayed in Eq. (3), provided the added flexibility required to extend our analysis to 2.5 GeV.

In Table I, we compare the energy-dependent and single-energy fits over the energy bins used in the single-energy analyses. Also listed are the number of parameters varied in each single-energy solution. A total of 144 parameters were varied in the energy-dependent analysis.

Our single-energy and energy-dependent results for the isovector and isoscalar partial-wave amplitudes are displayed in Figs. 1 and 2. Here we also compare with our previous fit (SM94). In some cases, the changes are quite large. This is particularly true near the upper energy limit of SM94 and for the smaller partial waves. The effect of these changes can be clearly seen in Fig. 3, where we show how well the new EDDA data [2] are reproduced by both SM94 and SM97. The influence of this experiment is most pronounced in the forward direction.

In general, we find little structure over the higher energy region. This reflects the smooth, and rather flat, total and reaction cross sections between 1.5 GeV and 2.5 GeV. Our fit to these quantities is displayed in Fig. 4. Note that the reaction cross sections were excluded from our fit. This verifies that the set of total, total elastic (deduced from differential cross sections), and reaction cross sections are self-consistent.

The present analysis actually gives an improved fit to the data below 1.6 GeV. This is due to the altered basis set, found necessary to fit the higher energy data. Numerical comparisons are given in Table II. Here we see that the COSY data [2] comprise a large fraction of the total set above 1.6 GeV. The results of analyses with (SM97) and without (NM97) this data set show how influential these measurements have been in determining the amplitudes. (The fits SM97 and NM97 used identical parametrization schemes. Only the data base was changed.) The COSY data contribute a χ^2/datum of 1.07 when included in the fit. This jumps to 5.6 when we attempt a prediction based on the remaining data.

IV. CONCLUSIONS AND FUTURE PROSPECTS

We have extended our pp partial-wave analyses nearly 1 GeV beyond the limit quoted in our previously published

TABLE II. Comparison of present and previous solutions. Data set A was used in the SM94 analysis [1]. Data set B contains all data (apart from the EDDA data [2]) used in generating solution SM97. See the text for details regarding the SM97 and NM97 fits.

PWA	Data	χ^2/pp data (0–1600 MeV)	χ^2/np data (0–1300 MeV)
SM94 [1]	(data set A)	22375/12838	17516/10918
SM94 [1]	(data set B	2230-12990	1949-1-943
SM97	(data set B)	20910/12889	17400/10843
		(0–2520 MeV)	(0–2000 MeV)
SM97	(data set B)	26460/14873	17440/10854
SM97	(EDDA data set [2])	2278/2121	–
NM97	(data set B)	25240/14873	17280/10854
NM97	(EDDA data set [2])	11964/2121	–

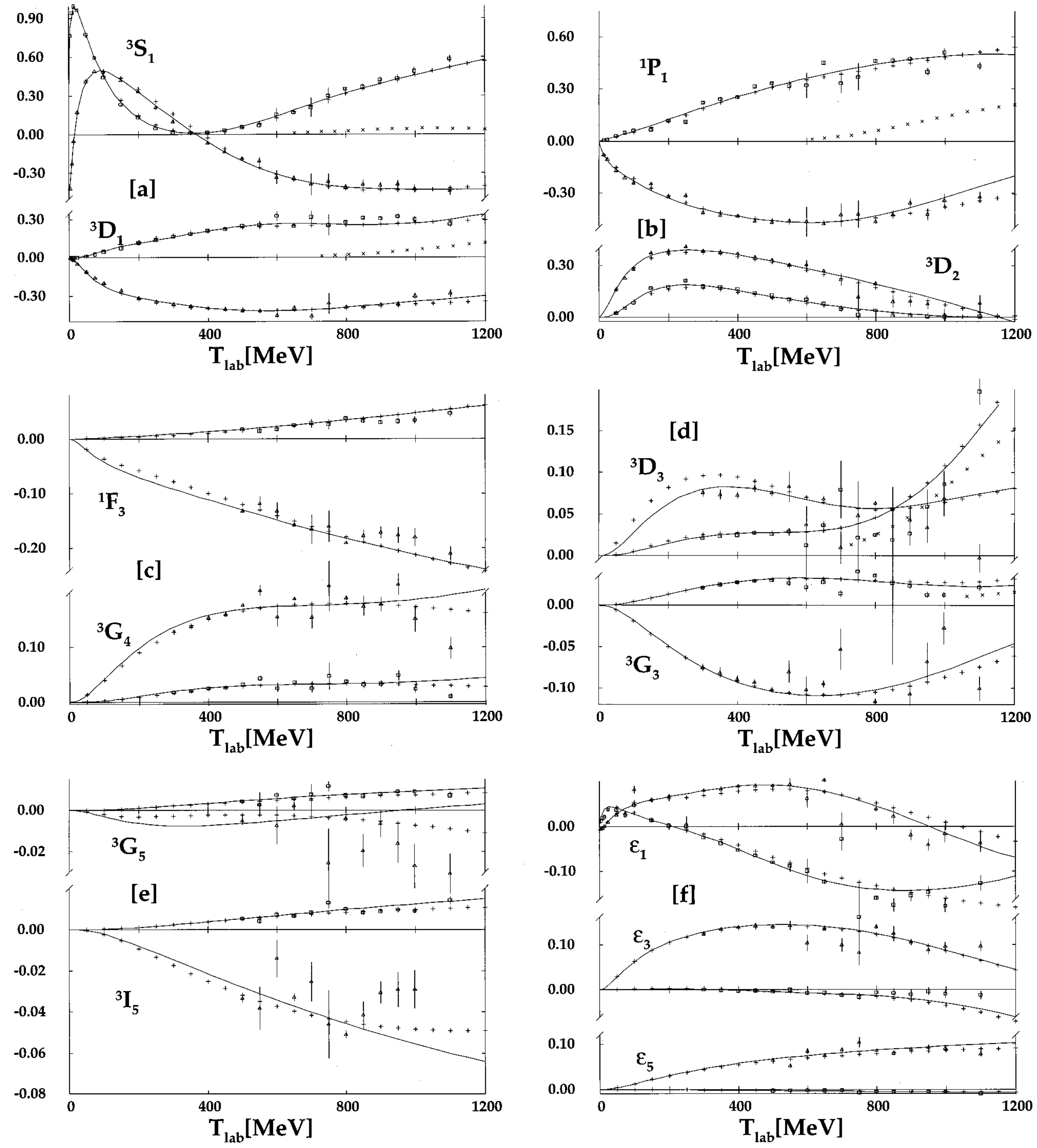

FIG. 2. Isoscalar partial-wave amplitudes from 0 to 1.2 GeV. Notation as in Fig. 1.

results [1]. The present range has been selected to include all of the recent elastic *pp* cross section data measured by the EDDA group [2]. We found that it was possible to simultaneously fit the *pp* total cross section data, in particular the precise data of Ref. [22], along with differential cross sections from the EDDA Collaboration [2]. The resulting reaction cross sections, which were not included in the fit, are quite well reproduced. The predicted reaction cross sections are consistent with the results of Ref. [70] at lower energies, but deviate from these and follow the results of Ref. [71] above 1 GeV.

While we find that the partial-wave amplitudes above 1.6 GeV are smooth and structureless, reflecting the behavior seen in the total and elastic cross section data, we have also considered the effect of more localized structures reported in polarization measurements [3,5]. We can add resonancelike structures in individual partial waves to see their effect on any observable. This will be utilized as more polarization data become available.

As the high energy region was constrained mainly by cross section data, the present solution should be considered as a guide to the expected amplitudes. The EDDA Collaboration is planning to measure P, A_{yy}, A_{xx}, and A_{xz} in the near future. This will be crucial to any future analyses.

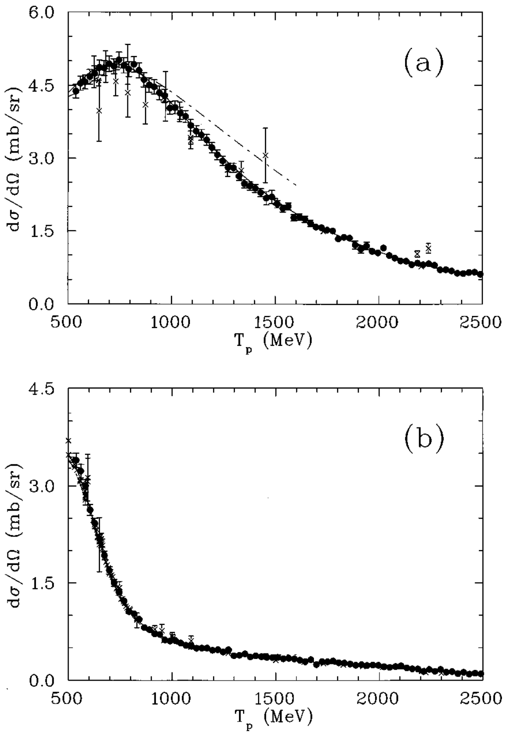

FIG. 3. Comparison between SM97 (solid curve) and differential cross sections at (a) $\theta^* = 45° \pm 1°$ and (b) $\theta^* = 90° \pm 1°$. Recent COSY measurements [2] are plotted as solid circles. Other data from the SAID database [7] are plotted as crosses. Our previous solution (SM94) is plotted to 1.6 GeV (dot-dashed line).

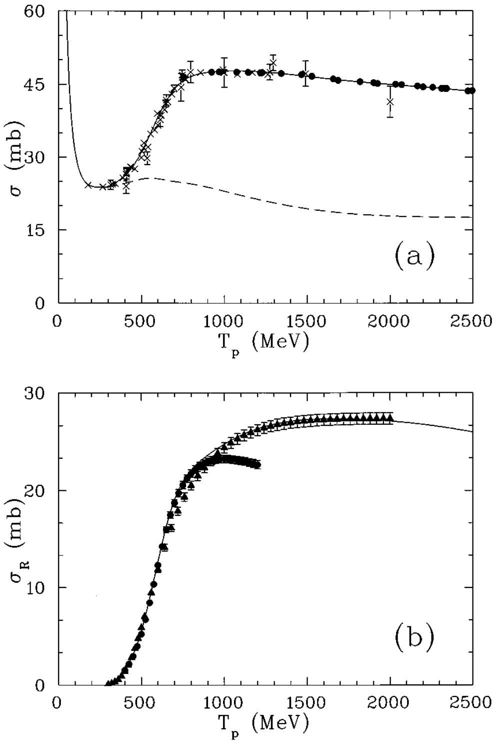

FIG. 4. Total cross section comparisons. (a) The solid (dashed) curves give the predictions of solution SM97 for the total (total elastic) cross section. Experimental points are from the SAID database [7]; solid circles are from Ref. [22]. (b) The solid curve gives the total reaction cross section of SM97. Solid circles are estimates from Ref. [70]. Solid triangles are estimates from Ref. [71].

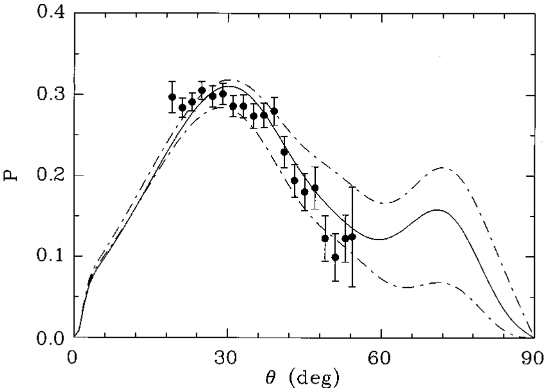

FIG. 5. Angular dependence of recent SATURNE II analyzing power (P) data [73]. This measurement, at 2.16 GeV, was not included in the SM97 analysis. The solid line gives the SM97 prediction. The dashed lines are generated from a single-energy solution and its associated error estimate.

Further data are also expected from a number of other laboratories. About 2000 polarized pp measurements are expected above 1000 MeV [72] as the nucleon-nucleon program at SATURNE II is completed. While not included in the present fit, preliminary data [73] from SATURNE II is in reasonable agreement with our predictions. A representative fit to P data, at 2.16 GeV, is given in Fig. 5.

A similar number of polarized quantities from np elastic scattering are expected (between 250 and 560 MeV [74]) from PSI. Other np sources include an extension of $\Delta\sigma_L$ measurements [75] at JINR [61], TRIUMF analyzing power measurements at 350 MeV [76], and TUNL measurements [77] of the P parameter and $\Delta\sigma_L$ at 7 and 15 MeV. We will continue to update our energy-dependent and single-energy solutions as the new measurements become available.

Finally we note that by extending our analysis to 2.5 GeV, we may be bridging the gap between the low and high energy regions. This is suggested if we plot $d\sigma/dt$ versus s, as is shown in Fig. 6. The result expected from dimensional counting at high energy and fixed c.m. angle [78,79] is

$$\frac{d\sigma}{dt} \sim \frac{1}{s^{N-2}} = s^{-10}, \tag{7}$$

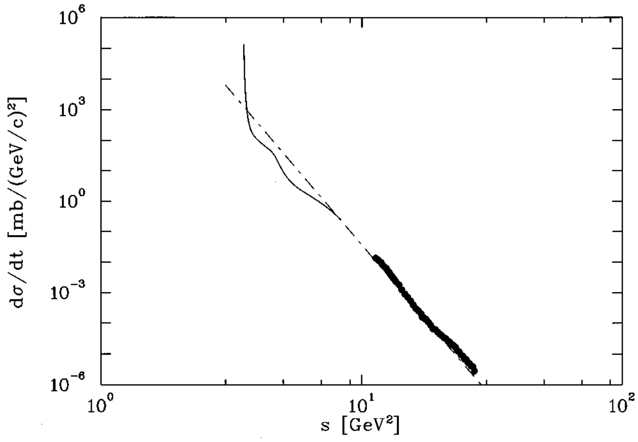

FIG. 6. $d\sigma/dt$ plotted as a function of s at $\theta^* = 90°$. The SM97 solution is plotted as a solid curve. The dash-dotted line gives $d\sigma/dt \sim s^{-10}$. The plotted data are from Ref. [80].

where N is the minimum number of fundamental constituents (quarks). While a slightly extended energy range would be more definitive, our results do appear to be consistent with this limit.

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[1] R. A. Arndt, I. I. Strakovsky, and R. L. Workman, Phys. Rev. C **50**, 2731 (1994).

[2] EDDA Collaboration, D. Albers, J. Bisplinghoff, R. Bollmann, K. Büsser, P. Cloth, R. Daniel, O. Diehl, F. Dohrmann, H. P. Engelhardt, J. Ernst, P. D. Eversheim, M. Gasthuber, R. Gebel, J. Greiff, A. Gross, R. Gross-Hardt, S. Heider, A. Heine, F. Hinterberger, M. Igelbrink, R. Jahn, M. Jeske, U. Lahr, R. Langkau, J. Lindlein, R. Maier, R. Maschuw, T. Mayer-Kuckuk, F. Mosel, M. Müller, M. Münstermann, D. Prasuhn, H. Rohdjess, D. Rosendaal, U. Ross, P. von Rossen, H. Scheid, N. Schirm, M. Schulz-Rojahn, F. Schwandt, V. Schwarz, W. Scobel, G. Sterzenbach, H. J. Trelle, A. Wellinghausen, W. Wiedmann, K. Woller, and R. Ziegler, Phys. Rev. Lett. **78**, 1652 (1997).

[3] A recent study was made by E. L. Lomon, Few-Body Syst., Suppl. **7**, 213 (1994). For a different approach to this problem see B. Z. Kopeliovich and F. Niedermayer, Phys. Lett. B **117B**, 101 (1982); S. J. Brodsky and G. F. de Teramond, Phys. Rev. Lett. **60**, 1924 (1988). A review is given by I. I. Strakovsky, Fiz. Elem. Chastits At. Yadra **22**, 615 (1991) [Sov. J. Part. Nucl. **22**, 296 (1991)].

[4] This should not be confused with the d' dibaryon, which is predicted to have a much lower mass ($m_{d'} \approx 2.06$ GeV) and a narrow width ($\Gamma \leqslant 10$ MeV) [see, for example, R. Bilger, πN Newslett. No. 10, 47 (1995); M. Schepkin, R. Bilger, H. Clement, K. Föhl, and G. J. Wagner, *ibid.* Newsletter No. 10, 54 (1995)].

[5] J. Ball, P. A. Chamouard, M. Combet, J. M. Fontaine, R. Kunne, J. M. Lagniel, J. L. Lemaire, G. Milleret, J. L. Sans, J. Bystricky, F. Lehar, A. de Lesquen, M. de Mali, Ph. Demierre, R. Hess, Z. F. Janout, E. L. Lomon, D. Rapin, B. Vuaridel, L. S. Barabash, Z. Janout, V. A. Kalinnikov, Yu. M. Kazarinov, B. A. Khachaturov, V. N. Matafonov, I. L. Pisarev, A. A. Popov, Yu. A. Yusov, M. Beddo, D. Grosnick, T. Kasprzyk, D. Lopiano, H. Spinka, A. Boutefnouchet, V. Ghazikhanian, and C. A. Whytten, Phys. Lett. B **320**, 206 (1994).

[6] N. Hoshizaki, in Proceedings of the Workshop on the Experiments by Polarized Proton and Electron Beams, Tsukuba, Japan, 1988, p. 201.

[7] The full database and our partial-wave analyses can be accessed through the SAID program. This is available via a telnet call to clsaid.phys.vt.edu with the userid: said (no password required). Another choice is the URL http://clsaid.phys.vt.edu.

[8] W. Haeberli, B. Lorentz, F. Rathmann, M. A. Ross, T. Wise, W. A. Dezarn, J. Doskow, J. G. Hardie, H. O. Meyer, R. E. Pollock, B. von Przewoski, T. Rinckel, F. Sperisen, and P. V. Pancella, Phys. Rev. C **55**, 597 (1997).

[9] A. J. Simon, G. Glass, M. W. McNaughton, T. Noro, K. H. McNaughton, P. J. Riley, E. Gülmiz, C. A. Whitten, V. R. Gupps, R. D. Ransome, and D. L. Adams, Phys. Rev. C **53**, 30 (1996).

[10] G. Pauletta, M. Gazzaly, N. Tanaka, B. Aas, D. Adams, H. Fujisawa, S. Greene, H. Hasai, G. Igo, S. Ishimoto, K. Jones, D. Lopiano, A. Masaike, K. Iwatani, Y. Ohashi, S. Okumi, L. Santi, F. Sperisen, and C. Whitten, Phys. Lett. B **211**, 19 (1988).

[11] G. W. Abshire, G. W. Bryant, M. Corcoran, R. R. Crittenden, S. W. Gray, R. M. Heinz, A. W. Hendry, H. A. Neal, and D. R. Rust, Phys. Rev. D **12**, 3393 (1975).

[12] M. G. Albrow, S. Andersson/Almehed, B. Bošnjaković, C. Daum, F. C. Erné, J. P. Lagnaux, J. C. Sens, and F. Udo, Nucl. Phys. **B23**, 445 (1970).

[13] I. Ambats, D. S. Ayres, R. Diebold, A. F. Greene, S. L. Kramer, A. Lesnik, D. R. Rust, C. E. W. Ward, A. B. Wicklund, and D. D. Yovanovitch, Phys. Rev. D **9**, 1179 (1974).

[14] C. M. Ankenbrandt, A. R. Clark, B. Cork, T. Elioff, L. T. Kerth, and W. A. Wenzel, Phys. Rev. **170**, 1223 (1968).

[15] I. P. Auer, A. Beretvas, E. Colton, H. Halpern, D. Hill, K. Nield, B. Sandler, H. Spinka, G. Theodosiou, D. Underwood, Y. Watanabe, and A. Yokosawa, Phys. Rev. Lett. **41**, 1436 (1978).

[16] I. P. Auer, E. Colton, H. Halpern, D. Hill, H. Spinka, G. Theodosiou, D. Underwood, Y. Watanabe, and A. Yokosawa, Phys. Rev. Lett. **41**, 354 (1978).

[17] I. P. Auer, C. Chang-Fang, E. Colton, H. Halpern, D. Hill, H. Kanada, H. Spinka, N. Tamura, G. Theodosiou, K. Toshioka, D. Underwood, R. Wagner, and A. Yokosawa, Phys. Rev. Lett. **48**, 1150 (1982).

[18] I. P. Auer, E. Colton, W. R. Ditzler, D. Hill, R. Miller, H. Spinka, G. Theodosiou, J.-J. Tavernier, N. Tamura, K. Toshioka, D. Underwood, R. Wagner, A. Yokosawa, P. Kroll, and W. Jauch, Phys. Rev. Lett. **51**, 1411 (1983).

[19] P. Bareyre, J. F. Detoeuf, L. W. Smith, R. D. Trip, and L. van Rossum, Nuovo Cimento **20**, 1049 (1961).

[20] G. G. Beznogikh, A. Bujak, V. A. Nikitin, M. G. Shafranova, V. A. Sviridov, Truong Bien, L. V. Vikhlyantseva, V. I. Zayachki, and L. S. Zolin, Phys. Lett. **43B**, 85 (1973).

[21] D. A. Bell, J. A. Buchanam, M. M. Calkin, J. M. Clement, W. H. Dragoset, M. Furić, K. A. Johns, J. D. Lesikar, H. E. Mietinen, T. A. Mulera, G. S. Mutchler, G. C. Philips, J. B. Roberts, and S. E. Turpin, Phys. Lett. **94B**, 310 (1980).

[22] D. V. Bugg, D. C. Salter, G. H. Stafford, R. F. George, K. F.

Riley, and R. J. Tapper, Phys. Rev. **146**, 980 (1966); D. V. Bugg (private communication).

[23] W. C. Carithers, R. K. Adair, C. J. B. Hawkins, H. Kasha, R. C. Larsen, L. B. Leipuner, L. W. Smith, and T. P. Wangler, Phys. Rev. **179**, 1304 (1969), not included in this analysis.

[24] F. F. Chen, C. P. Leavitt, and A. M. Shapiro, Phys. Rev. **103**, 211 (1956).

[25] B. Cork, W. A. Wenzel, and C. W. Causey, Phys. Rev. **107**, 859 (1957).

[26] A. R. Clyde, Ph.D. thesis, UCRL-16275, Berkeley, 1966 (unpublished).

[27] L. Dalkhazav, P. A. Devinski, V. I. Zayachki, Z. M. Zlatanov, L. S. Zolin, L. F. Kirillova, Z. Korbel, P. K. Markov, Ngo Kuang Zui, Nguen Din Ty, V. A. Nikitin, L. Rob, V. A. Sviridov, D. Tuvtendorzh, L. G. Khristov, Kh. M. Chernev, Chyong Byen, and M. G. Shafranova, Sov. J. Nucl. Phys. **8**, 196 (1969).

[28] S. Dalla Torre-Colautti, R. Birsa, F. Bradamante, M. Giorgi, L. Lanceri, A. Martin, A. Penzo, P. Schavon, V. Sossi, A. Villari, H. Azaier, K. Kuroda, A. Michalowicz, and F. Lehar, Nucl. Phys. **A505**, 561 (1989).

[29] R. Diebold, D. S. Ayres, S. L. Kramer, A. J. Pawlicki, and A. B. Wicklund, Phys. Rev. Lett. **35**, 632 (1975).

[30] J. M. Fontaine, F. Perrot, J. Bystricky, J. Derégel, F. Lehar, A. de Lesquen, L. van Rossum, J. Ball, and C. D. Lac, Nucl. Phys. **B321**, 299 (1989).

[31] T. Fujii, G. B. Chadwick, G. B. Collins, P. J. Duke, N. C. Hien, M. A. R. Kemp, and F. Turkot, Phys. Rev. **128**, 1836 (1962).

[32] P. Grannis, J. Arens, F. Betz, O. Chamberlain, B. Dieterle, C. Schultz, G. Shapiro, H. Steiner, L. van Rossum, and D. Weldon, Phys. Rev. **148**, 1297 (1966).

[33] K. A. Jenkins, L. E. Price, R. Klem, R. J. Miller, P. Schreiner, M. L. Marshak, E. A. Peterson, and K. Ruddick, Phys. Rev. D **21**, 2445 (1980).

[34] R. C. Kammerud, B. B. Brabson, R. R. Crittenden, R. M. Heinz, H. A. Neal, H. W. Paik, and R. A. Sidwell, Phys. Rev. D **4**, 1309 (1971). Included 1092 MeV data absent in our previous analysis [1].

[35] C. D. Lac, J. Ball, J. Bystricky, F. Lehar, A. de Lesquen, L. van Rossum, F. Perrot, J. M. Fontane, P. Chaumette, J. Derégel, J. Fabre, V. Ghazikhanian, and A. Michalowicz, Nucl. Phys. **B321**, 269 (1989).

[36] C. D. Lac, J. Ball, J. Bystricky, F. Lehar, A. de Lesquen, L. van Rossum, F. Perrot, J. M. Fontane, P. Chaumette, J. Derégel, J. Fabre, V. Ghazikhanian, and A. Michalowicz, Nucl. Phys. **B321**, 284 (1989).

[37] C. D. Lac, J. Ball, J. Bystricky, F. Lehar, A. de Lesquen, L. van Rossum, F. Perrot, J. M. Fontane, P. Chaumette, J. Derégel, J. Fabre, V. Ghazikhanian, A. Michalowicz, Y. Onel, and A. Penzo, Nucl. Phys. **B315**, 269 (1989).

[38] C. D. Lac, J. Ball, J. Bystricky, F. Lehar, A. de Lesquen, L. van Rossum, F. Perrot, J. M. Fontane, P. Chaumette, J. Derégel, J. Fabre, V. Ghazikhanian, A. Michalowicz, Y. Onel, and A. Penzo, Nucl. Phys. **B315**, 284 (1989).

[39] F. Lehar, A. de Lesquen, J. P. Meyer, L. van Rossum, P. Chaumette, J. Derégel, J. Fabre, J. M. Fontane, F. Perrot, J. Ball, C. D. Lac, A. Michalowicz, Y. Onel, D. Adams, J. Bystricky, V. Ghazikhanian, C. A. Whitten, and A. Penzo, Nucl. Phys. **B294**, 1013 (1987).

[40] F. Lehar, A. de Lesquen, L. van Rossum, J. M. Fontane, F. Perrot, P. Chaumette, J. Derégel, J. Fabre, J. Ball, C. D. Lac, Y. Onel, A. Michalowicz, J. Bystricky, and V. Ghazikhanian, Nucl. Phys. **B296**, 535 (1988).

[41] A. Lin, J. R. O'Fallon, L. G. Ratner, P. F. Schultz, K. Abe, D. G. Crabb, R. C. Fernow, A. D. Krisch, A. J. Salthouse, B. Sandler, and K. M. Terwilliger, Phys. Lett. **74B**, 273 (1978); Report No. UM-HE 78-3, Ann Arbor, 1978.

[42] Y. Makdisi, M. L. Marshak, B. Mossberg, E. A. Peterson, K. Ruddick, J. B. Roberts, and R. D. Klemm, Phys. Rev. Lett. **45**, 1529 (1980).

[43] D. Miller, C. Wilson, R. Giese, D. Hill, K. Nield, P. Rynes, B. Sandler, and A. Yokosawa, Phys. Rev. D **16**, 2016 (1977).

[44] H. A. Neal and M. J. Longo, Phys. Rev. **161**, 1374 (1967).

[45] J. H. Parry, N. E. Booth, G. Conforto, R. J. Esterling, J. Scheid, D. J. Sherdin, and A. Yokosawa, Phys. Rev. D **8**, 45 (1973).

[46] F. Perrot, H. Azaiez, J. Ball, J. Bystricky, P. Chaumette, Ph. Chesny, J. Derégel, J. Fabre, J. M. Fontane, J. Gosset, F. Lehar, W. R. Leo, A. de Lesquen, C. R. Newsom, Y. Onel, A. Penzo, L. van Rossum, T. Siemiarczuk, J. Vrzal, C. A. Whitten, and J. Yonnet, Nucl. Phys. **B278**, 881 (1986).

[47] F. Perrot, J. M. Fontane, F. Lehar, A. de Lesquen, J. P. Meyer, L. van Rossum, P. Chaumette, J. Derégel, J. Fabre, J. Ball, C. D. Lac, A. Michalowicz, Y. Onel, B. Aas, D. Adams, J. Bystricky, V. Ghazikhanian, G. Igo, F. Sperisen, C. A. Whitten, and A. Penzo, Nucl. Phys. **B294**, 1001 (1987).

[48] F. Perrot, J. M. Fontane, F. Lehar, A. de Lesquen, L. van Rossum, P. Chaumette, J. Derégel, J. Fabre, J. Ball, C. D. Lac, Y. Onel, A. Michalowicz, J. Bystricky, and V. Ghazikhanian, Nucl. Phys. **B296**, 527 (1988).

[49] D. R. Rust, P. N. Kirk, R. A. Lundy, C. E. W. Ward, D. D. Yovanovitch, S. M. Pruss, C. W. Akerlof, K. S. Han, D. I. Meyer, and P. Schmuesser, Phys. Rev. Lett. **24**, 1361 (1970); private communication of A. N. Diddens to F. Lehar, 1978.

[50] D. T. Williams, I. J. Bloodworth, E. Eisenhandler, W. R. Gibson, P. I. P. Kalmus, L. C. Y. Lee Chi Kwong, G. T. J. Arnison, A. Astbury, S. Gjesdal, E. Lillethun, B. State, O. Ullaland, and I. L. Watkins, Nuovo Cimento A **8**, 447 (1972).

[51] C. A. Davis, R. Abegg, A. R. Berdoz, J. Birchall, J. R. Campbell, L. Gan, P. W. Green, L. G. Greeniaus, R. Helmer, E. Korkmaz, J. Li, C. A. Miller, A. K. Oper, S. A. Page, W. D. Ramsay, A. M. Sekulovich, V. Sum, W. T. H. van Oers, and J. Zhao, Phys. Rev. C **53**, 2052 (1996).

[52] M. G. Bachman, P. J. Riley, P. W. Green, E. Korkmaz, D. J. Margaziotis, B. W. Mayes, L. S. Pinsky, Y. Tzamouranis, A. Amer, A. R. Berdoz, J. Birchall, J. R. Campbell, C. A. Davis, N. E. Davison, W. R. Falk, S. A. Page, W. D. Ramsay, A. M. Sekulovich, W. T. H. van Oers, D. L. Adams, G. S. Mutchler, D. A Hutcheon, and C. A. Miller, Phys. Rev. C **52**, 495 (1995).

[53] S. Bowyer, Ph.D. thesis, 1994; S. Vigdor (private communications).

[54] M. W. McNaughton, K. H. McNaughton, G. Glass, P. J. Riley, K. H. Auer, C. A. Davis, E. Gülmez, J. C. Hiebert, R. H. Jeppeson, R. D. Ransome, H. Spinka, V. Sum, I. Supek, G. E. Tripard, and H. Woolverton, Phys. Rev. C **53**, 1092 (1996).

[55] V. Carlson, R. Garnett, D. Hill, K. F. Johnson, D. Lopiano, Y. Ohashi, T. Shima, H. Spinka, R. Stanek, D. Underwood, A. Yokosawa, M. Beddo, G. Burleson, J. A. Faucett, G. Kyle, M. Rawool-Sullivan, H. Shimizu, G. Glass, S. Nath, L. C. Northcliffe, J. J. Jarmer, R. H. Jeppesen, and G. E. Tripard, Phys. Rev. D **53**, 3506 (1996).

[56] R. Garnett, M. Rawool, V. Carlson, D. Hill, K. F. Johnson, D. Lopiano, Y. Ohashi, T. Shima, H. Spinka, R. Stanek, D. Underwood, A. Yokosawa, M. Beddo, G. Burleson, J. A. Faucett, G. Kyle, H. Shimizu, G. Glass, S. Nath, L. C. Northcliffe, J. J. Jarmer, R. H. Jeppesen, and G. E. Tripard, Phys. Rev. D **40**, 1708 (1989); W. R. Ditzler, D. Hill, J. Hoftiezer, K. F. Johnson, D. Lopiano, T. Shima, H. Shimizu, H. Spinka, R. Stanek, D. Underwood, R. G. Wagner, A. Yokosawa, G. R. Burleson, J. A. Faucett, C. A. Fontenla, R. W. Garnett, C. Luchini, M. W. Rawool-Sullivan, T. S. Bhatia, G. Glass, J. C. Hiebert, R. A. Kenefick, S. Nath, L. C. Northcliffe, R. Damjanovich, J. J. Jarmer, J. Vaninetti, R. H. Jeppesen, and G. E. Tripard, *ibid.* **46**, 2792 (1992); T. Shima, D. Hill, K. F. Johnson, H. Shimizu, H. Spinka, R. Stanek, D. Underwood, A. Yokosawa, G. Glass, J. C. Hiebert, R. A. Kenefick, S. Nath, L. C. Northcliffe, G. R. Burleson, R. Garnett, J. A. Faucett, M. Rawool-Sullivan, R. Damjanovich, J. J. Jarmer, R. H. Jeppesen, and G. E. Tripard, *ibid.* **47**, 29 (1993).

[57] W. S. Wilburn, C. R. Gould, D. G. Haase, P. R. Huffman, C. D. Keith, N. R. Roberson, and W. Tornow, Phys. Rev. C **52**, 2351 (1995).

[58] J. Broz, J. Cerny, Z. Dolezal, G. M. Gurevich, M. Jirasek, P. Kubik, A. A. Lukhanin, J. Svejda, I. Wilhelm, N. S. Borisov, Yu. M. Kazarinov, B. A. Khachaturov, E. S. Kuzmin, V. N. Matafonov, A. B. Neganov, I. L. Pisarev, Y. A. Plis, Y. A. Usov, M. Rotter, and B. Sedlak, Z. Phys. A **354**, 401 (1996).

[59] Z. Dolezal (private communication).

[60] M. Beddo, G. Burleson, J. A. Faucett, S. Gardiner, G. Kyle, R. Garnett, D. Grosnick, D. Hill, K. Johnson, D. Lopiano, Y. Ohashi, T. Shima, H. Spinka, R. Stanek, D. Underwood, A. Yokosawa, G. Glass, R. Kenefick, S. Nath, L. C. Northcliffe, J. J. Jarmer, S. Penttilä, R. Jeppesen, G. Tripard, M. Devereux, and P. Kroll, Phys. Rev. D **50**, 104 (1994).

[61] B. P. Adiasevich, V. G. Antonenko, S. A. Averichev, L. S. Azhgirey, J. Ball, N. A. Bazhanov, B. Benda, N. S. Borisov, Yu. T. Borzunov, E. I. Bunyatova, V. F. Burinov, E. V. Chernykh, S. A. Dolgii, G. Durand, A. P. Dzyubak, A. N. Fedorov, V. V. Fimushkin, J. M. Fontaine, V. V. Glagolev, L. B. Golovanov, D. P. Grosnick, G. M. Gurevich, D. A. Hill, A. V. Karpunin, T. E. Kasprzyk, B. A. Khachaturov, A. D. Kirillov, N. I. Kochelev, A. D. Kovalenko, A. I. Kovalev, M. V. Kulikov, V. P. Ladygin, A. B. Lazarev, F. Lehar, A. de Lesquen, M. Y. Liburg, D. Lopiano, A. A. Lukhanin, P. K. Maniakov, V. N. Matafonov, E. A. Matyushevsky, G. M. Mgebrishvili, S. V. Mironov, A. B. Neganov, G. P. Nikolaevsky, A. A. Nomofilov, Yu. K. Pilipenko, I. L. Pisarev, N. M. Piskunov, Yu. A. Plis, Yu. P. Polunin, V. V. Polyakov, A. N. Prokofiev, D. A. Ronzhin, P. A. Rukoyatkin, J. L. Sans, V. I. Sharov, S. N. Shilov, Y. A. Shishov, V. B. Shutov, P. V. Sorokin, H. M. Spinka, A. Yu. Starikov, G. D. Stoletov, E. A. Strokovsky, L. N. Strunov, A. L. Svetov, V. V. Teterin, S. V. Topalov, V. Yu. Trautman, A. P. Tsvinev, Yu. A. Usov, V. V. Vikhrov, V. I. Volkov, A. A. Yershov, V. P. Yershov, S. A. Zaporozhets, and A. A. Zhdanov, Z. Phys. C **71**, 65 (1996).

[62] J. Götz, G. Brogli-Gysin, M. Hammans, P. Haffter, R. Henneck, J. Jourdan, G. Masson, L. M. Qin, S. Robinson, I. Sick, and M. Tuccillo, Nucl. Phys. **A574**, 467 (1994).

[63] W. Bürkle and G. Mertens, Few-Body Syst. **22**, 11 (1997).

[64] M. Drosg, RePort No. LASL, LA-7269-MS, 1978 (unpublished).

[65] M. L. Perl, J. Cox, M. J. Longo, and M. N. Kreisler, Phys. Rev. D **1**, 1957 (1970).

[66] P. W. Lisowski *et al.*, in ‘‘Symposium on Neutron Cross Sections from 10 to 50 MeV,’’ edited by M. R. Bhat and S. Pearlstein, BNL Report No. BNL-NCS-51245, 1980, Vol. 1, p. 301; P. W. Lisowski (private communication) not included in this analysis.

[67] V. G. J. Stoks, R. A. M. M. Klomp, M. C. M. Rentmeester, and J. J. de Swart, Phys. Rev. C **48**, 792 (1993).

[68] R. A. Arndt, J. S. Hyslop, and L. D. Roper, Phys. Rev. D **35**, 128 (1987).

[69] M. H. MacGregor, R. A. Arndt, and R. M. Wright, Phys. Rev. **169**, 1128 (1968).

[70] B. J. VerWest and R. A. Arndt, Phys. Rev. C **25**, 1979 (1982).

[71] J. Bystricky, P. La France, F. Lehar, F. Perrot, T. Siemiarczuk, and P. Winternitz, J. Phys. (Paris) **48**, 1901 (1987).

[72] F. Lehar (private communication).

[73] J. Arvieux, J. Ball, J. Bystricky, J. M. Fontaine, G. Gaillard, J. P. Goudour, R. Hess, R. Kunne, F. Lehar, A. de Lesquen, D. Lopiano, M. de Mali, F. Perrot-Kunne, D. Rapin, L. van Rossum, J. L. Sans, and H. M. Spinka, Z. Phys. A (submitted).

[74] C. Lechanoine-LeLuc (private communication); A. Ahmidouch, Ph. Demierre, N. Goujon-Naff, R. Hess, C. Lechanoine-LeLuc, D. Rapin, A. Teglia, B. Vuaridel, J. Arnold, J. Franz, H. Lacker, E. Rössle, H. Schmitt, P. Sereni, B. van den Brandt, M. Daum, P. Hautle, J. A. Konter, S. Mango, P. A. Schmelzbach, R. Drevenak, M. Finger, A. Janata, M. Slunecka, and F. Lehar, in *Particles and Nuclei, PANIC96*, Williamsburg, VA, 1996, edited by C. E. Carlson and J. J. Domingo (World Scientific, Singapore, 1996), p. 343; A. Ahmidouch, J. Arnold, B. van den Brandt, M. Daum, Ph. Demierre, R. Drevenak, M. Finger, J. Franz, N. Goujon, P. Hautle, Z. Janout, W. Hajdas, E. Heer, R. Hess, R. Koger, J. A. Konter, H. Lacker, C. Lechanoine-LeLuc, F. Lehar, S. Mango, Ch. Mascarini, D. Rapin, E. Rössle, P. A. Schmelzbach, H. Schmitt, P. Sereni, M. Slunecka, R. Stachetzki, A. Teglia, and B. Vuaridel, in *Polarization Phenomena in Nuclear Physics*, edited by E. J. Stephenson and S. E. Vigdor, AIP Conf. Proc. 339 (AIP, New York, 1994), p. 308.

[75] F. Lehar (private communication).

[76] C. A. Davis and L.G. Greeniaus (private communication).

[77] W. Tornow (private communication).

[78] S. J. Brodsky and G. R. Farrar, Phys. Rev. Lett. **31**, 1153 (1973).

[79] G. R. Farrar, S. Gottlieb, D. Sivers, and G. H. Thomas, Phys. Rev. D **20**, 202 (1979).

[80] C. W. Akerlof, R. H. Hieber, A. D. Krisch, K. W. Edwards, L. G. Ratner, and K. Ruddick, Phys. Rev. **159**, 1138 (1967).