Nucleon-nucleon elastic scattering to 3 GeV

Richard A. Arndt*, Igor I. Strakovsky†, and Ron L. Workman‡

Center for Nuclear Studies and Department of Physics
The George Washington University Washington, DC 20052
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Abstract

A partial-wave analysis (PWA) of $NN$ elastic scattering data has been completed. This analysis covers an expanded energy range, from threshold to a laboratory kinetic energy of 3 GeV, in order to include recent elastic $pp$ polarized scattering measurements performed at SATURNE II. Results of the energy-dependent fit are compared with single-energy solutions and Saclay amplitudes obtained via the direct-reconstruction approach. We also comment on the status of $\epsilon_1$ in the low-energy region.

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* arndtra@enterprise.phys.vt.edu
† igor@gwu.edu
‡ rworkman@gwu.edu
I. INTRODUCTION

This analysis of elastic nucleon-nucleon scattering data updates our previous analyses to 1.6 GeV [1] and 2.5 GeV [2] in the laboratory kinetic energy. The present analysis has been extended to 3 GeV in order to include both the elastic $pp$ polarized measurements $[3] - [12]$ from SATURNE II at Saclay, and $pp$ differential cross sections measured $[13]$ by the EDDA collaboration using the cooler synchrotron at COSY. A detailed description of our database is given in Section II.

As discussed in Ref. [2], the region beyond 2 GeV is interesting for several reasons. These include the suggestion of a narrow dibaryon resonance, corresponding to a center-of-mass energy of 2.7 GeV. Near this energy, a sharp structure was found in preliminary $A_{yy}$ measurements $[14]$ and this was taken as support for such a resonance. The authors of Ref. $[13]$ considered this possibility but found no evidence in their differential cross section measurements. No significant anomaly was seen in the angular and energy dependence of detailed analyzing power $[10]$ and correlated spin measurement at Saclay $[8]$.

The possible onset of behavior suggested by dimensional counting at high energy and fixed center-of-mass angle is also intriguing $[15,16]$. In Ref. [2], we noted that $d\sigma/dt$ appeared to be approaching $s^{-10}$, as expected within perturbative QCD. Thus, an extended energy range is needed to verify this trend. An extension of the $np$ analysis beyond 1.3 GeV would also benefit those studying the two-body photodisintegration of the deuteron at Jefferson Lab, which shows an interesting scaling behavior at some scattering angles $[17,18]$. Unfortunately, the $np$ data base remains too sparse to support a reliable analysis beyond 1.3 GeV.

In the present work, we have focused mainly on the influence of new polarization data at higher energies, and on the behavior of $\epsilon_1$ at low energies. The Saclay group has recently performed a single-energy phase-shift analysis of elastic $pp$ scattering data to 2.7 GeV and $np$ elastic scattering data to 1.1 GeV $[19]$. In this study, a second set of amplitudes $[13,20]$ was obtained through a direct reconstruction of the scattering amplitudes at fixed energies and angles. We have compared our results to these and, in some cases, find evidence (complimentary to that given by the Saclay group) for non-uniqueness at higher energies. At lower energies, where the behavior of $\epsilon_1$ has been a source of controversy, we compare our results to those of several other groups and suggest there is little evidence for an anomalously large tensor interaction. Results of our analyses are displayed in Section III. In Section IV, we summarize our findings and conclusions.

II. DATABASE

Our two previous $pp$ scattering analyses $[1,2]$ extended to 1.6 and 2.5 GeV, respectively. In both cases, the associated $np$ analysis was restricted to 1.3 GeV. The present data base $[21]$ is considerably larger due both to an expanded energy range for the $pp$ system and the addition of new data at lower energies. The full data base has increased by 30% since the publication of Ref. [2], and is about 70% larger than the set available for the analysis of Ref. [1]. (The total data base has doubled over the last decade (see Table I).) The distribution of recent (post-1997) $pp$ and $np$ data is given in Fig. 1.
In the full database, one will occasionally find experiments which give conflicting results. Some of these have been excluded from our fits. We have, however, retained all available data sets so that comparisons can be made through our on-line facility [21]. Below, we list recent additions to our data base. Some of the data listed as new were available, in unpublished form, at the time of our previous analysis [2]. A complete description of the data base and those data not included in our analyses is available from the authors.

Two thirds of the 4802 new pp polarization data were produced at Saclay using the SATURNE II accelerator [3] – [12]. These measurements of 9 spin-dependent quantities have increased our data base by a factor of two over the energy range from 1.6 to 2.5 GeV and accounted for a third of the data from 2.5 to 3.0 GeV. Many of the new pp polarization measurements below 450 MeV were made at the Indiana cooler (A_y, A_yy, A_xx, A_zz, and A_zx) [25] – [29]. Also, in this energy range are 11 new unpolarized cross sections (at 398 MeV) measured at the Osaka facility [30].

The np data base has not increased significantly. As a result, we have not extended the range of our analyses for the I = 0 system beyond 1.3 GeV. The Geneva group [31], working at PSI, has provided 247 new np spin measurements. From this source, we have also added spin observables A_y, A_t, D_t, and R_t from 260 to 538 MeV [31]. About 60% of the recent SATURN II np polarized measurements fall within our energy range; the full range extends from about 1.1 to 2.4 GeV (182 data points) [32]. A few measurements of Δσ_L and Δσ_T were produced by TUNL [33] and Charles University at Prague [34]. A single measurement of D_t, at 16 MeV, was provided [35] by the ISKP cyclotron at Bonn. We have added 12 unpolarized measurements, between 29 and 73 MeV, from the Louvain-la-Neuve Cyclotron [36]. Finally, we have retained in the analysis a set of 82 total cross section measurements, between 4 and 231 MeV [37], which had earlier been removed in order to have a low-energy data base identical to that used by the Nijmegen group [38].

### III. PARTIAL-WAVE ANALYSES

Fits to the expanded database and extended energy range were found to be possible within the formalism used and described in our previous analyses [11]. Both energy-dependent and single-energy solutions were obtained from fits to the combined pp and np data bases to 1.3 GeV, and from fits to the pp data base alone from 1.3 to 3 GeV. In Table II, we compare the energy-dependent and single-energy results 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 147 parameters were varied in the energy-dependent analysis (SP00).

Our single-energy and energy-dependent results for the isovector and isoscalar partial-wave amplitudes are displayed in Figs. 2 and 3. Here, we also compare with our previous fit (SM97) [2] and a much older fit (FA91) [22]. Partial waves with J < 6 are displayed, whereas the analysis fitted waves up to J = 7. In most cases, SP00 and SM97 are in good agreement. Somewhat larger changes are seen in comparisons with FA91. Differences are generally largest, as one would expect, near the energy upper limits for the various solutions and in the smaller partial waves. Figs. 2 and 3 therefore show that a doubling of the data base has led to a refinement of the amplitudes, but has not required a dramatic change in their behavior.
Single-energy solutions were produced up to 2825 MeV (for \(pp\) scattering). In these fits, initial values for the partial-wave amplitudes and their (fixed) energy derivatives were obtained from the energy-dependent solution. A comparison of global and single-energy solutions then serves as a check for structures that could have been “smoothed over” in the energy-dependent analysis. However, structures with widths less than 10 MeV would be very difficult to detect.

In order to ascertain that the extension to 3 GeV (1.3 GeV for \(np\)) did not seriously degrade our low-energy results, a 0 − 400 MeV fit was also developed. The resultant solution, SP40, used 30 \(I = 1\) and 27 \(I = 0\) variable parameters to give a \(\chi^2/\text{datum}\) of 4398/3454 (pp), and 5415/3831 (np). The global fit, SP00, produced, for the same energy range, a \(\chi^2/\text{datum}\) of 4593/3454 (pp) and 5371/3831 (np). We consider this quite reasonable given that the number of variable parameters per datum is nearly three times larger for SP40 than for SP00.

In Figs. 4 and 5, we compare our results with the Saclay single-energy analyses [19] for isovector waves below 2.7 GeV and isoscalar waves below 1.1 GeV. In the isoscalar case, the agreement is quite good, given the overall scatter of single-energy fits around the global result. More substantial differences are seen in the Saclay results for \(I = 1\) partial waves above 1 GeV.

A possible explanation for this discrepancy is given in the recent Saclay amplitude-reconstruction analysis [19,20]. In Fig. 6, we compare the Saclay results to curves generated from our single-energy and energy-dependent solutions. (A similar comparison was made in the \(I = 0\) case, with good overall agreement between the three solutions.) Here, we are using the notation of Ref. [19] and write the scattering matrix, \(M\), as

\[
M(\vec{k}_f, \vec{k}_i) = \frac{1}{2} \left[ (a + b) + (a - b) \left( \vec{\sigma}_1 \cdot \vec{n} \right) \left( \vec{\sigma}_2 \cdot \vec{n} \right) + (c + d) \left( \vec{\sigma}_1 \cdot \vec{m} \right) \left( \vec{\sigma}_2 \cdot \vec{m} \right) + (c - d) \left( \vec{\sigma}_1 \cdot \vec{l} \right) \left( \vec{\sigma}_2 \cdot \vec{l} \right) + e \left( \vec{\sigma}_1 + \vec{\sigma}_2 \right) \cdot \vec{n} \right],
\]

where \(\vec{k}_f\) and \(\vec{k}_i\) are the scattered and incident momenta in the center-of-mass system, and

\[
\vec{n} = \frac{\vec{k}_i \times \vec{k}_f}{|\vec{k}_i \times \vec{k}_f|}, \quad \vec{l} = \frac{\vec{k}_i + \vec{k}_f}{|\vec{k}_i + \vec{k}_f|}, \quad \vec{m} = \frac{\vec{k}_f - \vec{k}_i}{|\vec{k}_f - \vec{k}_i|}.
\]

In Refs. [19,20], multiple solutions were found at most energy-angle points. The \(pp\) amplitudes are plotted together in Fig. 6 where we can see that, in some cases, our single-energy results favor one branch, while the energy-dependent fit follows another. This feature was also evident in Ref. [19], where it was shown that the Saclay partial-wave analyses followed a branch different from our preliminary energy-dependent fits.

Finally, in Fig. 7, we return to the low-energy region which has been controversial mainly due to recent determinations of \(\epsilon_1\). In Ref. [33], the trend of recent determinations was used to argue for an \(NN\) tensor interaction stronger than predicted by all meson-exchange-based potential models, and in conflict with values found in both the Nijmegen and VPI partial-wave analyses. This trend is absent in our figure, where we have compared two of our energy-dependent fits, SP00 and SP40, and the Nijmegen potential, to a selection of recent single-energy fits. Clearly there is considerable scatter in the single-energy results. However, given this variation, the overall agreement with energy-dependent fits is quite good.
IV. CONCLUSIONS AND FUTURE PROSPECTS

In our previous analysis [2], an extension of the energy range for \( pp \) elastic scattering, from 1.6 to 2.5 GeV, was mainly motivated by the addition of precise new (unpolarized) cross section measurements from the EDDA collaboration [13]. Given the sparse polarization data in this region, the fit was expected to change significantly with the addition of Saclay [3] – [12] and future COSY (polarized) measurements. It is therefore somewhat surprising how little our new solution (SP00) has changed from SM97 [2].

We have seen that the \( I = 0 \) amplitudes are generally in good agreement with the Saclay results. This holds true in the low-energy region as well, the Saclay value for \( \epsilon_1 \) being consistent with our result. However, the agreement for \( pp \) (\( I = 1 \)) amplitudes above 1 GeV is less impressive.

As mentioned above, this difference in partial-wave solutions may be a reflection of the non-uniqueness seen in the Saclay amplitude reconstruction. The selection of data included in these analyses could also be a factor. Clearly, this serves as further motivation for the polarization measurements being performed at COSY [15] and JINR [16].

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FIGURE CAPTIONS

Figure 1. Energy-angle distribution of recent (post-1997) (a) \(pp\) and (b) \(np\) data. The \(pp\) data contribution below 3000 MeV is 30% and most new data are \(A_y\) (47%) or \(A_{yy}\) (29%). The \(np\) data contribution below 1300 MeV is 6% and most new data are \(A_y\) (24%). Total cross sections are plotted at zero degrees.

Figure 2. Isovector partial-wave amplitudes from 0 to 3 GeV in the proton kinetic energy. Solid (dashed) curves give the real (imaginary) parts of amplitudes corresponding to the SP00 solution. The real (imaginary) parts of single-energy solutions are plotted as filled (open) circles. The SM97 solution \[2\] is plotted with long dash-dotted (real part) and short dash-dotted (imaginary part) lines. FA91 solution \[22\] is shown by dashed lines. The dotted curve gives the unitarity limit \(\text{Im} T - T^2 - T_{sf}^2\) from SP00, where \(T_{sf}\) is the spin-flip amplitude. All amplitudes are dimensionless.

Figure 3. Isoscalar partial-wave amplitudes from 0 to 1.2 GeV. Notation as in Fig. 2.

Figure 4. Phase-shift parameters for isovector partial-wave amplitudes from 0 to 3000 MeV. The SP00 and SM97 \[2\] solutions are plotted as solid and dash-dotted curves, respectively. Our single-energy solutions and those from Saclay \[19,20\] are given by filled and open circles, respectively.

Figure 5. Phase-shift parameters for isoscalar partial-wave amplitudes from 0 to 1200 MeV. Notation as in Fig. 6.

Figure 6. Direct-reconstruction scattering amplitudes at (a) 1.80 GeV, (b) 2.10 GeV, (c) 2.40 GeV, and (d) 2.70 GeV. The real (imaginary) parts of amplitudes \(a\) to \(e\) \[19\] are shown in \(\sqrt{mb/sr}\) as a function of the c.m. scattering angle and plotted as filled (open) circles. Our SP00 (single-energy) solution is plotted with solid (dashed) lines.

Figure 7. Summary of analyses giving \(\epsilon_1\) in the energy range up to 80 MeV. The solid (dashed) curve gives our SP00 (SP40) PWA results. Nijmegen potential results \[39\] are plotted as a dash-dotted line. Filled circles (diamonds) give GW (Saclay \[19\]) single-energy PWA results. Open squares denote the single-energy PWA from PSI \[40\]. Other results are from TUNL (star) \[33\], Bonn (filled box) \[41,35\], Prague (open diamond) \[34\], Erlangen (open circle) \[42\], PSI (filled triangle) \[43\], and Karlsruhe (open triangle) \[44\].
Table I. Comparison of present (SP00 and SP40) and previous (SM97, SM94, VZ40, FA91, SM86, and SP82) energy-dependent partial-wave analyses. The $\chi^2$ values for the previous solutions correspond to our published results ([1], [2], and [22] – [24]).

| Solution | Range (MeV) | $\chi^2/ pp$ data | Range (MeV) | $\chi^2/ np$ data | Ref. |
|----------|-------------|-------------------|-------------|-------------------|-----|
| SP00     | 0 – 3000    | 3661/21796        | 0 – 1300    | 1869/11472        | Present |
| SP00     | (0 – 2500)  | 3427/20947        | 0 – 1300    | 1769/11330        | Present |
| SP00     | (0 – 1600)  | 2392/15766        | 0 – 1300    | 1769/11330        | Present |
| SP00     | (0 – 400)   | 4593/3454         | (0 – 400)   | 5371/3831         | Present |
| SP40     | 0 – 400     | 4398/3454         | 0 – 400     | 5415/3831         | Present |
| SM97     | 0 – 2500    | 2868/16994        | 0 – 1300    | 1743/10854        | [2]  |
| SM94     | 0 – 1600    | 2237/12838        | 0 – 1300    | 1751/10918        | [1]  |
| VZ40     | 0 – 400     | 3098/2170         | 0 – 400     | 4595/3367         | [1]  |
| FA91     | 0 – 1600    | 2060/11880        | 0 – 1100    | 1371/7572         | [22] |
| SM86     | 0 – 1200    | 1190/7223         | 0 – 1100    | 887/5474          | [23] |
| SP82     | 0 – 1200    | 919/5207          | 0 – 1100    | 9103/5283         | [24] |
Table II. Comparison of the single-energy (SES) and energy-dependent (SP00) fits to \( pp \) and \( np \) data. Values of \( \chi^2 \) are given for the single-energy and SP00 fits (evaluated over the same energy bins). Also listed is the number of parameters varied in each single-energy solution.

| Energy Range (MeV) | \( \chi^2 \) SES(SP00)/\( pp \) data | \( \chi^2 \) SES(SP00)/\( np \) data | Parameters |
|-------------------|-----------------------------------|-----------------------------------|------------|
| 4-6               | 22(39)/28                         | 78(83)/63                         | 6          |
| 7-12              | 84(134)/88                        | 254(333)/101                      | 6          |
| 11-19             | 17(47)/27                         | 205(455)/247                      | 8          |
| 19-30             | 123(268)/114                      | 292(321)/316                      | 8          |
| 32-67             | 282(354)/224                      | 809(879)/548                      | 10         |
| 60-90             | 48(63)/72                         | 514(629)/355                      | 10         |
| 80-120            | 152(156)/154                      | 465(453)/382                      | 10         |
| 125-174           | 313(336)/287                      | 603(653)/333                      | 11         |
| 175-225           | 494(542)/435                      | 701(734)/504                      | 13         |
| 225-270           | 222(246)/228                      | 299(345)/278                      | 13         |
| 276-325           | 771(802)/740                      | 628(680)/564                      | 17         |
| 325-375           | 460(474)/406                      | 416(460)/353                      | 17         |
| 375-425           | 738(758)/607                      | 804(870)/599                      | 17         |
| 425-475           | 1055(1156)/803                    | 828(870)/682                      | 18         |
| 475-525           | 1311(1565)/1081                   | 1248(1404)/787                    | 30         |
| 525-575           | 858(956)/754                      | 672(694)/488                      | 31         |
| 575-625           | 1039(1112)/760                    | 423(484)/367                      | 34         |
| 625-675           | 908(842)/773                      | 1270(1611)/873                    | 36         |
| 675-725           | 860(923)/797                      | 404(468)/386                      | 37         |
| 725-775           | 1007(1311)/827                    | 518(556)/381                      | 37         |
| 775-824           | 1690(1840)/1301                   | 1550(1861)/948                    | 38         |
| 827-874           | 1155(1330)/914                    | 388(467)/365                      | 39         |
| 876-924           | 342(475)/389                      | 752(905)/625                      | 41         |
| 926-974           | 762(992)/679                      | 363(512)/353                      | 43         |
| Energy Range (MeV) | $\chi^2$ SES(SP00)/$pp$ data | $\chi^2$ SES(SM97)/$np$ data | Parameters |
|-------------------|-----------------------------|-----------------------------|------------|
| 976-1020          | 917(1177)/708               | 284(425)/328                | 43         |
| 1078-1125         | 815(1128)/573               | 519(846)/427                | 47         |
| 1261-1299         | 691(1006)/505               | − − −                       | 30         |
| 1481-1521         | 140(307)/149                | − − −                       | 30         |
| 1590-1656         | 505(892)/460                | − − −                       | 31         |
| 1685-1724         | 174(309)/116                | − − −                       | 31         |
| 1778-1818         | 625(1097)/506               | − − −                       | 33         |
| 1929-1975         | 377(463)/366                | − − −                       | 33         |
| 2065-2120         | 1173(1938)/829              | − − −                       | 33         |
| 2175-2225         | 1476(2046)/758              | − − −                       | 33         |
| 2330-2470         | 1013(1808)/713              | − − −                       | 33         |
| 2500-2600         | 250(523)/311                | − − −                       | 33         |
| 2642-2714         | 302(1016)/307               | − − −                       | 33         |
| 2792-2869         | 148(405)/153                | − − −                       | 33         |
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