Absolute Total \( np \) and \( pp \) Cross-Section Determinations

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Abstract—Absolute total cross sections for \( np \) and \( pp \) scattering below 1000 MeV are determined based on partial-wave analyses (PWAs) of nucleon-nucleon scattering data. These cross sections are compared with most recent ENDF/B and JENDL data files, and the Nijmegen PWA. Systematic deviations from the ENDF/B and JENDL evaluations are found to exist in the low-energy region.

I. INTRODUCTION

Nucleon-nucleon scattering is the simplest two-body reaction that allows an examination of different nuclear interaction models. Progress in the development of nuclear models is linked to the availability of high-quality data. \( np \) scattering is also used as a primary standard in measurements of neutron-induced nuclear reactions.\(^1\)\(^,\)\(^2\) Its cross section is used in determining the flux of incoming neutrons.

This information is important in many applications, such as astrophysics \([(n, γ), (n, α), \text{and others}]\), the transmutation of nuclear waste \([(n, f), (n, y), \text{and others}]\), energy generation, and the conceptual design of an innovative nuclear reactor being carried out in the course of the Generation IV initiative\(^3\) \([(n, f), \text{and neutron-actinoid elastic and inelastic scattering and others}]\). The increasing quality of neutron-induced nuclear reaction measurements requires a high-quality standard for \( np \) cross sections, reproducing total \( np \) cross sections with an accuracy of 1% or better for energies below 20 MeV (Refs. 1 and 4). The need for neutron data above 20 MeV up to hundreds of mega-electron-volts with accuracy better than 10% (Ref. 4) leads to the requirement of cross-section data for the \( np \) reference reaction with uncertainties at the few percent level.

An extensive database exists for nucleon-nucleon scattering, with measurements from laboratories worldwide. These data sets, from the various laboratories, have different statistical and systematic uncertainties that must be taken into account when combined into a single fit. At present, there are several evaluations of total \( np \) cross sections below 20 MeV. Perhaps most widely known are the ENDF/B (Ref. 5)\(^a\) and JENDL (Ref. 6)\(^b\) nuclear data files.

\(^a\)Numerical data are available via National Nuclear Data Center; http://www.nndc.bnl.gov/endf, release ENDF/B-VII.0.

\(^b\)Numerical data are available via Japan Atomic Energy Agency Nuclear Data Center; http://wwwndc.jaea.go.jp/jendl/j33/j33.html, release JENDL-3.3.
An R-matrix analysis of the nucleon-nucleon system was used in the course of the ENDF/B evaluation of np cross sections, whereas in the JENDL np total cross-section evaluation, a method based on phase-shift data was used.

Here, we will concentrate on total np and pp cross sections determined on the basis of recent energy-dependent (global) fits and associated single-energy solutions (SESs) from the George Washington (GW) Data Analysis Center. Precise measurements collected over many years have helped to isolate discrepancies between different experiments and have contributed to a good description of nucleon-nucleon scattering at the level of both observables and amplitudes.

In Sec. II, we comment on the np and pp data that are available in the GW database and that have been used in this analysis. In Sec. III, we give a brief overview of the method used to fit data and extract amplitudes. Then, in Sec. IV, we present total np and pp cross sections determined on the basis of both global and SES results. Finally, in Sec. V, we summarize our findings.

II. DATABASE

The GW fit to nucleon-nucleon elastic scattering data covers an energy range from threshold up to a laboratory kinetic energy of 1300 MeV (for np data) and 3000 MeV (for pp data). The np analysis was restricted to 1300 MeV because of a lack of high-energy data. The full database includes all available unpolarized and polarized measurements. A number of fits, from the GW group and others, are available through the online SAID facility.

The evolution of the SAID database is summarized in Table I. Over the course of seven previous GW nucleon-nucleon partial-wave analyses (PWAs), the upper energy limit has been extended from 1200 (1100) to 3000 (1300) MeV in the laboratory proton (neutron) kinetic energy. (These fits are regularly updated online, and the designation SM97, for example, denotes the time of update: summer 1997.)

Not all of the available data have been used in each fit. Some data with very large \( \chi^2 \) contributions have been excluded. Redundant data are also excluded. These include total elastic cross sections based on differential cross sections already contained in the database. Polarized measurements with uncertainties >0.2 are not included as they have little influence on GW fits. However, all available data have been retained in the database (the excluded data labeled as “flagged”) so that comparisons can be made through the GW online facility. A complete description of the database, and those data not included in GW fits, is available from the authors.

III. PARTIAL-WAVE ANALYSIS

Simultaneous fits to the full database are possible within the formalism used and described in previous GW analyses. The observables are represented in terms of partial-wave amplitudes, using a Chew-Mandelstam K-matrix approach, which incorporates the effect of an N\( \Delta \) channel on the nucleon-nucleon scattering process. By parameterizing the K-matrix elements as functions of energy, data from threshold to 3000 MeV can be fitted simultaneously (both pp and np, with a 1300-MeV limit for np). In general, GW PWAs have attempted to remain as model-independent as possible. The present (SP07) and previous energy-dependent solutions are compared in Table I.

In fitting the data, systematic uncertainty has been used as an overall normalization factor for angular distributions. With each angular distribution, we associate the pair \((X, \epsilon_X)\): a normalization constant \(X\) and its uncertainty \(\epsilon_X\). The quantity \(\epsilon_X\) is generally associated with the systematic uncertainty (if known). The modified \(\chi^2\) function, to be minimized, is then given by

\[
\chi^2 = \sum_i \left( \frac{X \theta_i - \theta_i^{\text{exp}}}{\epsilon_i} \right)^2 + \frac{(X - 1)^2}{\epsilon_X^2},
\]

where the subscript \(i\) labels data points within the distribution, \(\theta_i^{\text{exp}}\) is an individual measurement, \(\theta_i\) is the calculated value, and \(\epsilon_i\) is the statistical uncertainty. For total cross sections and excitation data, we have combined statistical and systematic uncertainties in quadrature. Renormalization freedom significantly improves GW best-fit results, as shown in Table II.

Starting from this global fit, we have also generated a series of SES results. Each SES is based on a “bin” of scattering data spanning a narrow energy range. A total of 43 SESs have been generated, with central energy

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*The full database and numerous PWAs with potential models can be accessed via ssh call to the SAID facility: gwdac.phys.gwu.edu, with userid: said (no password), or a link to the Web site: http://gwdac.phys.gwu.edu.
values ranging from 5 to 2830 MeV and bin widths varying from 2 to 75 MeV. For example, solution c5 is a fit to data between 4 and 6 MeV. In generating the SES, a linearized energy dependence is taken over the energy range, reducing the number of searched parameters. A systematic deviation between the SES and global fits is an indication of missing structure in the global fit (or possibly problems with a particular data set). An error matrix is generated in the SES fits, which can be used to estimate the overall uncertainty in the global fit. The global and SES fit results, up to 1000 MeV, are summarized in Table III (further details are given in Ref. 10).

| Range   | SP07 Norm/Unnorm | SP00 Norm/Unnorm | SM97 Norm/Unnorm | Nijmegen93 Norm/Unnorm | Data np | Data pp |
|---------|------------------|------------------|------------------|------------------------|--------|--------|
| 0 to 4  | 2.5/28.0         | 2.5/28.0         | 2.5/27.9         | 3.3/26.7               | 63     | 193    |
| 0 to 20 | 1.8/13.2         | 1.9/13.3         | 2.3/13.8         | 2.9/10.1               | 468    | 389    |
| 0 to 200| 1.5/7.2          | 1.5/7.1          | 1.7/6.8          | 1.7/5.9                | 2381   | 1491   |
| 200 to 400| 1.3/3.3        | 1.4/3.3          | 1.4/3.3          | 1.3/2.5                | 2208   | 2172   |
| 400 to 600| 1.5/8.7         | 1.4/8.0          | 1.5/10.6         | 1.3/2.5                | 2779   | 3655   |
| 600 to 800| 1.5/8.4         | 1.5/7.7          | 1.4/10.6         | 1.4/3.1                | 2529   | 3974   |
| 800 to 1000| 1.4/3.4         | 1.4/3.4          | 1.4/3.1          | 1.4/3.1                | 2112   | 3274   |

*The Nijmegen solution is valid up to 350 MeV; the final tabulated energy range is 200 to 350 MeV. Last two columns list numbers of np and pp data included in fit SP07 and its associated SES.

IV. TOTAL np AND pp CROSS SECTIONS

Isovector and isoscalar partial-wave amplitudes, determined through the PWA, have been used to generate total np and pp cross sections presented in Tables IV and V. In Table IV, we compare results from two global fits, SP07 (with an energy limit of 3000 MeV) and LE08 (a low-energy fit to 25 MeV, which searches 19 parameters, scattering length $a$, and effective range $r$ for three S waves and 13 leading parameters for S, P, and D waves). LE08 results in a $\chi^2$/data = 696/391 for pp and 627/631 for np. The SP07, LE08, and SES results below 20 MeV are summarized in Table VI. Errors for LE08 have been generated from the error matrix and require some comments.

In the region below 25 MeV, there are numerous total cross-section measurements for np but not for pp, which is hindered by large Coulomb effects. As a result, the np error estimates are more reasonable. Those quoted for pp are far too small (lower limits) in the threshold region. In two cases (c5 and c150 of Table III), the $\chi^2$ from the energy-dependent fit was actually lower than that from the SES fit. There is a possibility that this can indicate that the energy bin for the SES fit is too broad.

But, a rather narrow bin will not allow a stable result because of the lack of data to constrain the solution.

For the region above 25 MeV, in Table V, we compare the global fit SP07 with the grid of SES fits. Here, the SES errors give a more accurate estimate of the

TABLE III

| Solution | Range (MeV) | pp $x^2$ | np $x^2$ | $\chi^2$/Data |
|----------|-------------|----------|----------|---------------|
| c5       | 4 to 6      | 37       | 22/28    | 74            |
| c10      | 7 to 12     | 128      | 81/88    | 255           |
| c15      | 11 to 19    | 55       | 16/27    | 366           |
| c25      | 19 to 30    | 251      | 120/114  | 319           |
| c50      | 32 to 67    | 331      | 283/224  | 721           |
| c75      | 60 to 90    | 61       | 48/72    | 652           |
| c100     | 80 to 120   | 155      | 149/154  | 521           |
| c150     | 125 to 174  | 352      | 311/287  | 533           |
| c200     | 175 to 225  | 570      | 528/435  | 870           |
| c250     | 225 to 270  | 289      | 266/263  | 601           |
| c300     | 276 to 325  | 853      | 815/805  | 1163          |
| c350     | 325 to 375  | 522      | 503/474  | 509           |
| c400     | 375 to 425  | 819      | 771/680  | 1295          |
| c450     | 425 to 475  | 1307     | 1186/877 | 1216          |
| c500     | 475 to 525  | 1811     | 1556/1215| 1386          |
| c550     | 525 to 575  | 1075     | 938/817  | 1192          |
| c600     | 575 to 625  | 1196     | 1045/838 | 517           |
| c650     | 625 to 675  | 980      | 959/807  | 1502          |
| c700     | 675 to 725  | 982      | 956/887  | 460           |
| c750     | 725 to 775  | 1474     | 1085/926 | 545           |
| c800     | 775 to 824  | 2056     | 1833/1385| 1777          |
| c850     | 827 to 874  | 1296     | 1142/980 | 500            |
| c900     | 876 to 924  | 542      | 406/444  | 936           |
| c950     | 926 to 974  | 961      | 769/728  | 528           |
| c999     | 976 to 1020 | 1206     | 1010/776 | 421           |

* $\chi^2$ is given by the energy-dependent fit, SP07 (Ref. 10), over the same energy intervals.
### TABLE IV
Comparison of SP07 (Ref. 10) and LE08 Results for Total \( \sigma^p \) and \( \sigma^p \) Cross Sections Below 25 MeV*

| \( T \) (MeV) | LE08 \( \sigma^p \) (mb) | SP07 \( \sigma^p \) (mb) | LE08 \( \sigma^p \) (mb) | SP07 \( \sigma^p \) (mb) | LE08 \( \sigma^p \) (mb) | SP07 \( \sigma^p \) (mb) |
|-------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0.5         | 1100.00 ± 0.01  | 1098.00         | 6148.00 ± 0.07  | 6135.00         | 6148.00 ± 0.07  | 6135.00         |
| 1.0         | 1513.00         | 1513.00         | 4261.00 ± 0.19  | 4253.00         | 4261.00 ± 0.19  | 4253.00         |
| 1.5         | 1469.00 ± 0.11  | 1471.00         | 3421.00 ± 0.32  | 3417.00         | 3421.00 ± 0.32  | 3417.00         |
| 2.0         | 1325.00 ± 0.17  | 1325.00         | 2911.00 ± 0.44  | 2911.00         | 2911.00 ± 0.44  | 2911.00         |
| 2.5         | 1175.00         | 1175.00         | 2555.00 ± 0.52  | 2558.00         | 2555.00 ± 0.52  | 2558.00         |
| 3.0         | 1042.00 ± 0.01  | 1042.00         | 2266.00 ± 0.57  | 2291.00         | 2266.00 ± 0.57  | 2291.00         |
| 3.5         | 930.60 ± 0.30   | 930.60          | 2073.00 ± 0.61  | 2079.00         | 2073.00 ± 0.61  | 2079.00         |
| 4.0         | 836.70 ± 0.30   | 836.70          | 1989.00 ± 0.61  | 1990.00         | 1989.00 ± 0.61  | 1990.00         |
| 4.5         | 757.70 ± 0.11   | 757.70          | 1752.00 ± 0.61  | 1760.00         | 1752.00 ± 0.61  | 1760.00         |
| 5.0         | 690.60 ± 0.12   | 690.60          | 1627.00 ± 0.59  | 1635.00         | 1627.00 ± 0.59  | 1635.00         |
| 5.5         | 633.30 ± 0.02   | 633.30          | 1519.00 ± 0.55  | 1526.00         | 1519.00 ± 0.55  | 1526.00         |
| 6.0         | 583.80 ± 0.02   | 583.80          | 1424.00 ± 0.52  | 1431.00         | 1424.00 ± 0.52  | 1431.00         |
| 6.5         | 538.70 ± 0.02   | 540.80          | 1341.00 ± 0.47  | 1347.00         | 1341.00 ± 0.47  | 1347.00         |
| 7.0         | 503.10 ± 0.02   | 503.10          | 1266.00 ± 0.43  | 1271.00         | 1266.00 ± 0.43  | 1271.00         |
| 7.5         | 469.90 ± 0.03   | 469.90          | 1199.00 ± 0.37  | 1203.00         | 1199.00 ± 0.37  | 1203.00         |
| 8.0         | 430.40 ± 0.03   | 440.40          | 1139.00 ± 0.33  | 1142.00         | 1139.00 ± 0.33  | 1142.00         |
| 8.5         | 414.00 ± 0.04   | 414.00          | 1084.00 ± 0.29  | 1086.00         | 1084.00 ± 0.29  | 1086.00         |
| 9.0         | 390.30 ± 0.04   | 390.30          | 1033.00 ± 0.25  | 1035.00         | 1033.00 ± 0.25  | 1035.00         |
| 9.5         | 369.00 ± 0.05   | 369.00          | 987.10 ± 0.21   | 988.60          | 987.10 ± 0.21   | 988.60          |
| 10.0        | 349.60 ± 0.06   | 349.60          | 944.60 ± 0.18   | 945.50          | 944.60 ± 0.18   | 945.50          |
| 10.5        | 332.00 ± 0.06   | 332.00          | 905.30 ± 0.15   | 905.70          | 905.30 ± 0.15   | 905.70          |
| 11.0        | 316.00 ± 0.07   | 316.00          | 868.80 ± 0.13   | 868.90          | 868.80 ± 0.13   | 868.90          |
| 11.5        | 301.20 ± 0.08   | 301.20          | 834.80 ± 0.12   | 834.60          | 834.80 ± 0.12   | 834.60          |
| 12.0        | 287.00 ± 0.09   | 287.00          | 803.00 ± 0.12   | 802.70          | 803.00 ± 0.12   | 802.70          |
| 12.5        | 275.20 ± 0.10   | 275.20          | 773.30 ± 0.12   | 772.90          | 773.30 ± 0.12   | 772.90          |

*See text for a discussion of uncertainties.

### TABLE V
Comparison of SES and SP07 (Ref. 10) Results for Total \( \sigma^p \) and \( \sigma^p \) Cross Sections Between 25 and 1000 MeV

### TABLE VI
Single-Energy (Binned) Fits (Ref. 10) of Combined Elastic \( np \) and \( pp \) Scattering Data Below 20 MeV*

| Solution | Range (MeV) | SP07 \( \chi^2 \) | LE08 \( \chi^2 \) | SES \( \chi^2 \) | N913 \( \chi^2 \)/Data |
|----------|-------------|-----------------|-----------------|-----------------|-----------------|
| \( c5 \)  | 4 to 6 (6)  | 37              | 30              | 22              | 51/28           |
| \( c10 \) | 7 to 12 (6) | 129             | 98              | 81              | 107/88          |
| \( c15 \) | 11 to 19 (8)| 55              | 37              | 17              | 15/27           |
| \( c5 \)  | 4 to 6 (6)  | 75              | 58              | 78              | 78/62           |
| \( c10 \) | 7 to 12 (6) | 256             | 138             | 222             | 132/106         |
| \( c15 \) | 11 to 19 (8)| 366             | 231             | 219             | 246/247         |

*\( \chi^2 \) are given by the energy-dependent SP07 (Ref. 10), LE08, and N913 (Ref. 15) fits, over the same energy intervals. Number of searched parameters in SES is given in the second column in parentheses.

uncertainty in our cross sections. The amplitudes found in GW fits to 1000 MeV have remained stable for many years against the addition of new measurements. Suffi- cient observables exist for a direct amplitude reconstruc- tion at many energies, and we have compared GW amplitudes to those found in this way in Ref. 10.
As cross sections change rapidly near threshold, we have chosen to display the agreement between various fits in terms of ratios. This gives a clear picture of the overall consistency and reveals cases where systematic deviations are present. The ratios of SES values to the global fit SP07, below 20 MeV, are displayed in Fig. 1a. Also plotted is a band showing the ratio of LE08 to SP07 for the np case. (b) SES (solid circles for np and open circles for pp) and SP07 (solid line for np and dash-dotted line for pp) divided by Nijmegen PWA predictions\(^{15}\) are plotted. The band represents the ratio of LE08 to Nijmegen PWA for the np case.

In Fig. 1b, we plot ratios of SP07 and SES, for both np and pp cases, to the Nijmegen PWA predictions\(^{15}\). The low-energy Nijmegen total pp cross sections are systematically above SP07 (~2% or less) while np cross sections agree with SP07 at better than the 0.3% level.

In Fig. 2, we plot ratios of the GW np fits with the ENDF/B and JENDL nuclear data files\(^{5,6}\). A slightly better agreement is found with JENDL (Ref. 6) than with ENDF/B (Ref. 5), though the wiggles seen in Fig. 2b reflect a lack of smoothness in JENDL (SP07 and LE08 are a smooth function of energy). The ENDF/B result is systematically below SP07 and the Nijmegen fit\(^{15}\), but the maximal deviation is only 1%. SP07 and JENDL agree at the 0.5% level over most of the region below 20 MeV.

At higher energies (up to 1000 MeV), ratios of the grid of SES to SP07 differ from unity by <3% (Fig. 3a). Above 180 MeV, SAID np cross sections are larger than JENDL/HE (Ref. 6) by up to 5% (Fig. 3b).
V. SUMMARY AND CONCLUSIONS

We have generated fits to describe the total \( np \) and \( pp \) scattering cross sections below 1000 MeV. These fits have been both energy dependent (SP07, LE08) and single energy (analyzing narrow bins of data). The uncertainties associated with our total \( np \) cross sections below 20 MeV are clearly \( \pm 1\% \). The agreement between SP07, JENDL, and the Nijmegen analysis suggests an uncertainty of \( \pm 0.5\% \) or less. A comparison with ENDF0 shows deviations of \( \pm 1\% \) or less. Errors on the LE08 solution in Table IV, while obtained using a well-defined method, are lower bounds as they do not account for systematics effects.

For the \( pp \) cross sections, uncertainties are larger, and systematic disagreements are evident in comparisons with the Nijmegen PWA. The main problem stems from a lack of relevant \( pp \) data at low energies. Here also, at low energies, the various determinations agree at the few-percent level.

The advantage of the GW parameterization is its smooth energy dependence and coverage from threshold to high energies. We also have the capability to modify the GW fits to either generate SES centered on a particular energy or produce lower-energy fits when a specific energy region is of interest. We will continue to update both GW energy-dependent solutions and SESs as the new measurements become available.

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