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Absolute *np* and *pp* Cross Section Determinations Aimed at Improving the Standard for Cross Section Measurements

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Abstract. Purpose of present research is a keeping improvement of the standard for cross section measurements of neutron-induced reactions. The 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 the most recent ENDF/B-VII.0 and JENDL-4.0 data files, and the Nijmegen PWA. Also a comparison of evaluated data with recent experimental data was made to check a quality of evaluation. Excellent agreement was found between the new experimental data and our PWA predictions.

Keywords: Partial-wave analysis, cross section, *np* and *pp* interactions.

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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. The *np* scattering is also used as a *primary* standard in measurements of neutron-induced nuclear reactions [1]. Its cross section is used in determining the flux of incoming neutrons.

‡ Deceased

This information is important in many applications, such as astrophysics, the transmutation of nuclear waste, energy generation, and the conceptual design of an innovative nuclear reactor being carried out in the course of the Generation IV initiative [2]. 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 [1] and [3]. The need for neutron data above 20 MeV up to hundreds of mega-electron-volts with accuracy better than 10% [3] 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 the *np* cross sections below 20 MeV. Perhaps most widely known are the ENDF/B [4] and JENDL nuclear data files. The JENDL database has low energy evaluation, below 20 MeV, and high energy data file JENDL/HE [5], up to 3 GeV. Recently the new version of low energy database, JENDL-4.0, was released [6]. For case of *np* cross section data the JENDL-4.0 accepted evaluation from ENDF/B-VII.0 [4]. An R-matrix analysis of the nucleon-nucleon system [7] was used in the course of the ENDF/B-VII.0 (JENDL-4.0) evaluation of *np* cross sections, whereas in the JENDL/HE *np* cross section evaluation, a method based on phase-shift data [8,9] was used.

Here, we will concentrate on total *np* and *pp* cross sections determined on the basis of recent energy dependent (global) fits SP07 [10], LE08 [11] and associated single- energy solutions (SESs) [11] from the George Washington (GW) Data Analysis Center [12]. 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.

DATABASE

The GW fit to nucleon-nucleon elastic scattering data covers an energy range up to 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 [12].

The latest evolution of the SAID database is summarized in [10]. At present it contains 12,693 (24,916) data points for *np* (*pp*) interactions.

Not all of the available data have been used in each fit. Some data with very large χ^2 contributions have been excluded. Redundant data are also excluded. Polarized measurements with uncertainties >0.2 are not included as they have little influence on GW fits. A complete description of the database, and those data not included in GW fits, is available from the authors [12].

PARTIAL-WAVE ANALYSIS

Simultaneous fits to the full database are possible within the formalism used and described in seven previous GW analyses, which are regularly updated online; the full bibliography can be found in [11]. 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 up 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.

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,ε_X): a normalization constant (X) and its uncertainty (ε_X). The quantity ε_X is generally associated with the systematic uncertainty (if known). The modified χ^2 function, to be minimized, is then given by

$$\chi^2 = \sum_i \left(\frac{X\theta_i - \theta_i^{\exp}}{\varepsilon_i} \right)^2 + \left(\frac{X-1}{\varepsilon_X} \right)^2 . \qquad (1)$$

Here the subscript i labels data points within the distribution, θ_i^{exp} is an individual measurement, θ_i is the calculated value, and ε_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. In the global solution SP07 [10] χ^2/data is 21,496/12,693 for *np* and 44,463/24,916 for *pp*.

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 values ranging from 5 to 2830 MeV and bin widths varying from 2 to 75 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 can be 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. Further details on the global and SES fit results are given in [10] and [11].

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. Also generated was a low-energy fit to 25 MeV, LE08, 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. LEO8 results in a χ^2/data = 696/391 for *pp* and 627/631 for *np*. The numerical data for LE08 can be found in [10] or retrieved from the SAID [12]. 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.

For the region above 25 MeV, the SES errors give a more accurate estimate of the 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. Sufficient observables exist for a direct amplitude reconstruction at many energies, and we have compared GW amplitudes to those found in this way in [10].

As cross sections change rapidly with energy, 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 determinations of the *np* cross section. As expected, this band more closely reproduces the *np* SES, plotted as single points with error bars, than the 3000-MeV fit SP07. Deviations are within 1% for the *np* determinations and within 2% for *pp*.

In Fig. 1b, we plot ratios of SP07 and SES, for both *np* and *pp* cases, to the Nijmegen PWA predictions [13]. 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-VII.0 [4] and JENDL/HE [5] nuclear data files. A slightly better agreement is found with JENDL/HE than with ENDF/B-VII.0, though the wiggles seen in Fig. 2b reflect a lack of smoothness in JENDL/HE (SP07 and LE08 are a smooth function of energy). Apparently those wiggles resulted from linear interpolation between some reper points (points de repere) (reference points) in the JENDL/HE evaluation. The ENDF/B-VII.0 result is systematically below SP07 and the Nijmegen fit [13], but the maximal deviation is only 1%. SP07 and JENDL/HE 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 [5] by up to 5% (Fig. 3b).

COMPARISON WITH RECENT DATA

To evaluate a quality of data predictions of obtained PWA solutions, a comparison was done with new data, which were not included in the analysed database to the moment of the last analysis. Fig. 4a presents our global solution SP07 [10] and SES predictions for the *np* total cross section in the energy range from 8 to 500 MeV along with experimental data measured at the LANL [14]. Fig. 4b displays a ratio of experimental cross section [14] to those from the SP07 solution. One can see an excellent agreement of PWA prediction and experimental observable. Maximal discrepancy is nearly 1%. The χ^2 per data point calculated including experimental systematic errors is about 0.4 for dataset [14].

Another example of PWA prediction capabilities came from very recent data for angular distribution in *np* scattering obtained at Ohio University at a neutron energy of 14.9 MeV [14]. These data also were not used in our analysis. Fig. 5 shows result of the low-energy fit LE08 for *np* elastic scattering angular distribution at E_n = 14.9 MeV in comparison with the two normalization versions (details can be found in [14]) of experimental data [14]. Also results of the ENDF/B-VII.0 [4] and JENDL-3.3 [5] evaluations are plotted. Again one can see an excellent agreement of PWA predicted and experimental angular distribution within stated experimental errors. The JENDL-3.3 evaluation does not describe well the backward scattering angle data.

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 <1%. The agreement between SP07, JENDL/HE, and the Nijmegen analysis suggests an uncertainty of 0.5% or less. A comparison with ENDF/B-VII.0 shows deviations of 1% or less. Errors on the LE08 solution, 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 (e.g. Fig. 1), 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 PWA prediction capabilities checked by comparison with recent experimental data, which were not used in our analysis. Excellent agreement was found.

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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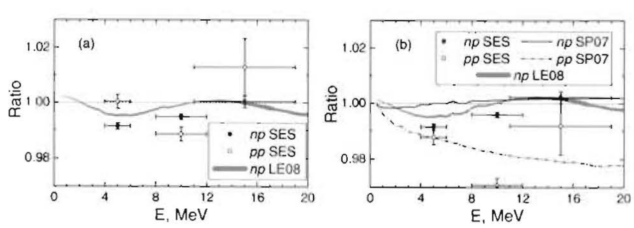

FIGURE 1. Ratios of total *np* and *pp* cross sections below 20 MeV. Horizontal bars give the energy binning of SES. (a) Single-energy to energy-dependent SP07 [10] ratios are plotted. The band represents the ratio of LE08 [11]

to SP07 for the *np* case. (b) SES [11] and SP07 divided by Nijmegen PWA predictions [13] are plotted. The band represents the ratio of LE08 to Nijmegen PWA for the *np* case.

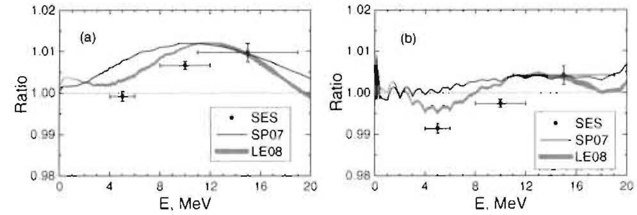

FIGURE 2. Ratio of total np cross sections below 20 MeV. Horizontal bars give the energy binning of SES. (a) Single-energy and SP07 [10] fits divided by the ENDF/B-VII.0 [4] results are plotted. The band gives a ratio of LE08 to ENDF/B-VII.0. (b) The same for JENDL/HE [5] evaluated data.

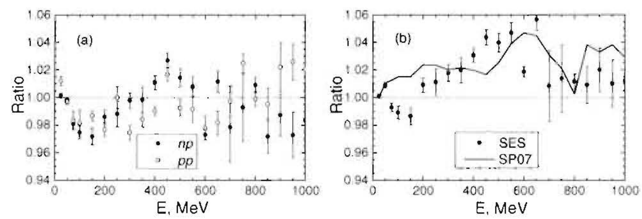

FIGURE 3. Ratios of total *np* and *pp* cross sections between 20 and 1000 MeV. (a) SES [11] to SP07 [10] ratios are plotted. (b) *np* SES and SP07 divided by JENDL/HE [5] results are plotted.

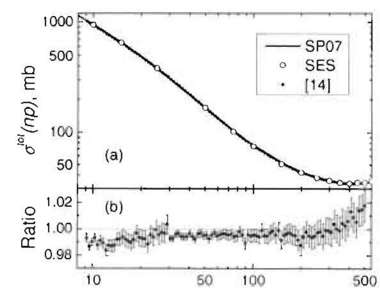

FIGURE 4. Total *np* cross sections in the energy range from 8 to 500 MeV. (a) SP07 [10] and SES [11] predictions are plotted along with experimental data [14]. (b) Data [14] divided by the SP07 fit are plotted.