Corrections for the polarization-dependent efficiency and new neutron-proton analyzing power data at 7.6 MeV

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(Received 21 June 2010; published 10 August 2010)

We present new corrections for the polarization-dependent efficiency (PDE), which introduces a false asymmetry into measurements of *n-p* analyzing power $A_y(\theta)$ caused by double scattering in the neutron side detectors. To accomplish this, we created a new database of $^{12}\mathrm{C}(\vec{n},n)$ $A_y(\theta)$ by using a combination of fits to data, phase-shift analysis, and *R*-matrix analysis. Our recorrection for PDE of previously reported *n-p* $A_y(\theta)$ data at 7.6 and 12.0 MeV and new data at 7.6 MeV indicate that we have achieved a superior representation of $^{12}\mathrm{C}(\vec{n},n)$. Our results continue to suggest a possible charge dependence of the pion-nucleon coupling constant.

DOI: 10.1103/PhysRevC.82.027001 PACS number(s): 13.75.Cs, 24.70.+s, 29.85.−c

The motivation for collecting high-precision neutron-proton (*n-p*) analyzing power $A_y(\theta)$ data is to test the accuracy of nucleon-nucleon (NN) phase-shift analysis (PSA) predictions for this observable. At low energy, *n-p* $A_y(\theta)$ depends greatly on the $^3P_0$, $^3P_1$, and $^3P_2$ phase shifts and good-quality data can be useful in constraining these parameters. Nearly two decades ago, Triangle Universities Nuclear Laboratory (TUNL) collected *n-p* $A_y(\theta)$ data at $E_n = 7.6$, 12.0, 14.0, 16.0, and 18.0 MeV [1]. In terms of uncertainties, these data were of similar quality as earlier measurements by Holslin and co-workers [2] at $E_n = 10.03$ MeV. None of these data were of adequate precision to show clear discrepancies with the Nijmegen PSA predictions [3]. Reference [1] also found that data from 14 to 20 MeV probably would not be able to demonstrate discrepancies with NN predictions, since there is less difference between the various theoretical models in this energy range.

The work of Braun [4], therefore, concentrated on the lower energies and achieved smaller uncertainties than Refs. [1,2]. All three experiments used the neutron production reaction $^2\mathrm{H}(\vec{d},\vec{n})^3\mathrm{He}$, but Ref. [4] used TUNL's atomic beam polarized ion source, which produced large deuteron beam currents (about 1200 nA as compared to 300 nA for Ref. [1] and 150 nA for Ref. [2]). This increase in beam flux was reflected in a reduction of the final absolute uncertainties in the data, from about ±0.0010 to about ±0.0006. The first published data from Ref. [4] were the 12.0 MeV data of Ref. [5]. Comparison of these data to a model study favored a larger value for the charged pion-nucleon coupling constant than for the neutral pion-nucleon coupling constant. This conclusion was questioned in a later review of all available *n-p* $A_y(\theta)$ data below 20.0 MeV [6]. Although Ref. [6] is correct to point out that strong conclusions should not be made on the basis of one data set, it should also be remembered that the data of Ref. [4] attained smaller uncertainties and cover a broader angular range than any other *n-p* $A_y(\theta)$ data set.

It might prove to be impractical to take enough high-precision *n-p* $A_y(\theta)$ data to settle the question of charge dependence in the low-energy NN interaction. However, even if experimentalists are willing to commit to the long counting times required to collect such data, the information will not be useful without careful analysis and correction. Many of these concerns are familiar, especially the removal of backgrounds caused by accidental counts, edge effects in the scatterer, double scattering in the scatterer, and the possibility of remaining polarized backgrounds.

One correction, however, is unique to *n-p* $A_y(\theta)$ data and of great importance. This is because of the polarization-dependent efficiency (PDE), which is endemic to the organic-scintillator side detectors used in the measurements. In each side detector, polarized neutrons can scatter first from a carbon nucleus and then from a proton. As known from the work of Ref. [7], the $A_y(\theta)$ of $^{12}\mathrm{C}(\vec{n},n)$ shows large fluctuations with energy in the range between 3.0 and 7.0 MeV. Because of the kinematic variation of the neutron energies over the face of the side detectors, the $^{12}\mathrm{C}$-p double-scattering events can introduce a false asymmetry into the *n-p* $A_y(\theta)$ measurement [8]. This false asymmetry does not cancel with the usual spin-flip techniques used in $A_y(\theta)$ measurements. The only way that the PDE effect can be accounted for is by using Monte Carlo (MC) techniques.

There are two ways of addressing the PDE problem. The approach of Holslin and co-workers was to minimize the size of the PDE corrections. After they found a large PDE effect by using 4.0-cm-wide neutron side detectors and flight paths of about 55 cm (as reported in Ref. [8]), they switched to 1.3-cm side detectors to collect their final data (as reported in Ref. [2]). The use of narrow detectors reduced the variation of neutron energy at the side detectors, and, therefore, the variation in $^{12}\mathrm{C}(\vec{n},n)$ $A_y(\theta)$. Of course, the price one must pay for small PDE corrections is lower *n-p* count rates.

TUNL has taken the other horn of the dilemma by using relatively large scattering elements (similar to Ref. [8]) and seeks to achieve accurate PDE corrections. One of the most

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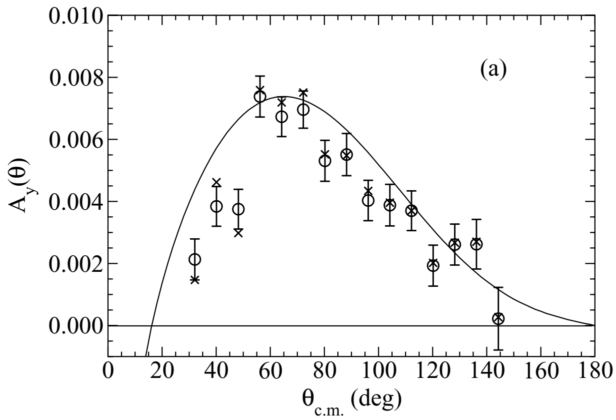

FIG. 1. The *n-p* $A_y(\theta)$ data at 7.6 MeV from (a) Ref. [4] and (b) Ref. [1]. The crosses use the original PDE corrections, while the circles use the PDE corrections of the present paper. The final data for (a) are listed in Table I. The solid curves are the PSA predictions of Ref. [3].

important things needed in this approach is a good MC library for ^{12}C($\vec{n}$,n). To improve this database, Roper and co-workers [9] gathered 33 distributions of ^{12}C($\vec{n}$,n) $A_y(\theta)$ data from 2.2 to 8.5 MeV.

We broke up the ^{12}C library into three energy regimes. For the low-energy regime, we used the *R*-matrix analysis of Hale [10], which produced an excellent representation of ^{12}C($\vec{n}$,n) for energies up to 6.4 MeV. However, this analysis missed the values of $A_y(\theta)$ for values of $\theta_{\text{c.m.}}$ smaller than 40° and E_n between 3.5 and 4.5 MeV. Therefore, we substituted Legendre polynomial fits to the ^{12}C $A_y(\theta)$ data of Ref. [9] for this regime. This change resulted in small but significant improvements to the PDE corrections. (For the 12.0-MeV *n-p* $A_y(\theta)$ distributions, an E_n of about 4.0 MeV corresponds to a $\theta_{\text{c.m.}}$ of about 109°.) For the intermediate-energy regime, from 6.4 to 8.5 MeV, we first used only the data of Ref. [9] and interpolated between the energies of each distribution linearly. However, because Ref. [9] left a gap between 7.0 and 7.5 MeV, we supplemented the database with distributions taken from the PSA of Chen and Tornow [11]. This modification also made small but significant changes to the PDE corrections. (For the 12.0-MeV distributions, an E_n of about 7.25 MeV corresponds to a $\theta_{\text{c.m.}}$ of about 78°.) For the highest-energy regime, from 8.5 to 12.0 MeV, the $A_y(\theta)$ of ^{12}C is relatively smooth, and we used the PSA of Ref. [11] exclusively.

Because the lowest- and intermediate-energy regions proved to be particularly sensitive, we attempted a new and highly detailed PSA for ^{12}C($\vec{n}$,n) up to 8.5 MeV. It proved difficult to achieve a better representation than the *R*-matrix analysis of Ref. [10]. Following the detailed activity of the $n + {}^{12}$C total cross section led to overly noisy predictions of the differential quantities which varied too quickly with energy and which we often rejected as unphysical.We found that any representation of $n + {}^{12}$C that fit the data and was not noisy did not produce significant changes to the PDE corrections. This suggested that our established library was reliable.

Results for *n-p* $A_y(\theta)$ after the PDE corrections are displayed in Figs. 1 and 2 for incident neutron energies of 7.6 and 12.0 MeV, respectively. For each figure, panel (a) shows the data of Ref. [4], while panel (b) displays the data of Ref. [1]. In both cases, the crosses display the data with the original PDE corrections, and the open circles display the data with the present PDE corrections. The 12.0-MeV data shown as the open circles in Fig. 2(a) are identical to the

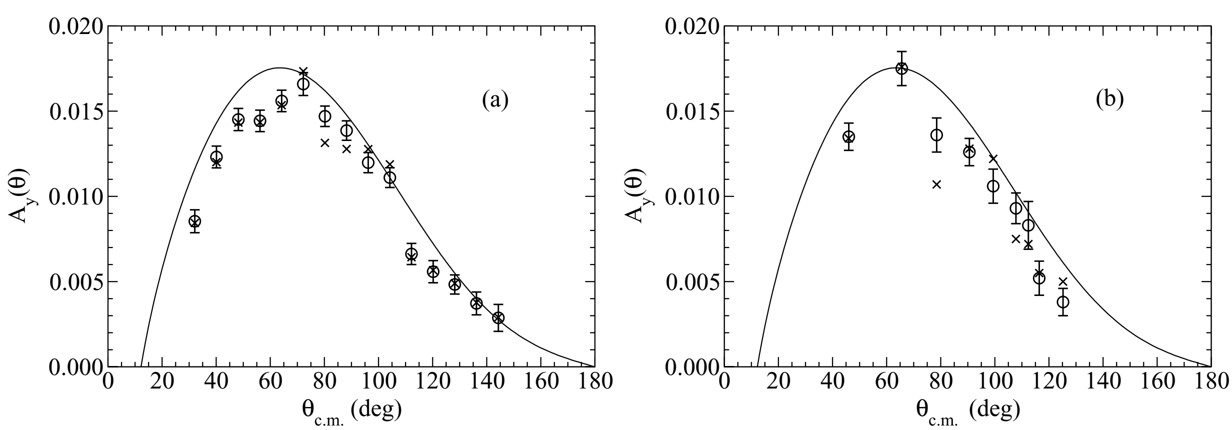

FIG. 2. The *n-p* $A_y(\theta)$ data at 12.0 MeV from (a) Ref. [4] and (b) Ref. [1]. The crosses use the original PDE corrections, while the circles use the PDE corrections of the present paper. The circles in (a) are the same data that appear in Ref. [5]. The solid curves are the PSA predictions of Ref. [3].

TABLE I. Results of n-p $A_y(\theta)$ at $E_n = 7.6$ MeV.

$\theta_{\text{c.m.}}$	PDE correction	Final results
32.1	$-0.000\,80 \pm 0.000\,15$	$0.002\,13 \pm 0.000\,66$
40.1	$-0.000\,71 \pm 0.000\,14$	$0.003\,84 \pm 0.000\,64$
48.2	$0.000\,47 \pm 0.000\,15$	$0.003\,75 \pm 0.000\,64$
56.2	$-0.000\,41 \pm 0.000\,16$	$0.007\,38 \pm 0.000\,66$
64.2	$0.000\,69 \pm 0.000\,16$	$0.006\,73 \pm 0.000\,64$
72.2	$0.000\,06 \pm 0.000\,13$	$0.006\,96 \pm 0.000\,60$
80.2	$-0.001\,19 \pm 0.000\,24$	$0.005\,31 \pm 0.000\,66$
88.2	$-0.001\,60 \pm 0.000\,28$	$0.005\,51 \pm 0.000\,68$
96.2	$0.001\,27 \pm 0.000\,26$	$0.004\,03 \pm 0.000\,65$
104.2	$0.000\,24 \pm 0.000\,27$	$0.003\,88 \pm 0.000\,67$
112.2	$0.000\,85 \pm 0.000\,26$	$0.003\,70 \pm 0.000\,64$
120.2	$-0.000\,05 \pm 0.000\,22$	$0.001\,93 \pm 0.000\,66$
128.2	$-0.000\,13 \pm 0.000\,28$	$0.002\,61 \pm 0.000\,66$
136.2	$-0.000\,20 \pm 0.000\,45$	$0.002\,62 \pm 0.000\,80$
144.3	$-0.000\,21 \pm 0.000\,50$	$0.000\,22 \pm 0.001\,01$

data that appear in Ref. [5]. The 7.6-MeV data shown as the open circles in Fig. 1(a) and listed in Table I, are based on the same experimental procedure as Ref. [5]. All four of these data sets show small systematic improvements in their overall smoothness, which offer further confirmation that our new ^{12}C library is an improvement over those used in Refs. [1,4].

The uncertainty of the PDE correction has three potential sources. The first, and the only one included in the results listed in Table I, are the purely statistical uncertainties associated with the MC calculation. We determined this by running 20 simulations, each starting with a different random number for each n-p scattering angle. A second uncertainty can arise because of the choice of the $^{12}\text{C}(\vec{n},n)$ MC library. This is less like a random uncertainty and more like a systematic uncertainty that can be corrected for. Because our current ^{12}C library is a significant improvement over previous attempts and uses the new data of Ref. [9], we do not believe that all of the variations seen in Figs. 1 and 2 reflect uncertainties in the PDE correction.

A third uncertainty in the PDE correction is related to the simulation of the experimental center-detector pulse height (CDPH) spectra and to the yield gates used in these spectra. In Ref. [1], the nominal CDPH gate was set at 20% of the peak height and, in Ref. [4], the nominal gate was set at 30%. Although the gain settings used in the MC simulation for the center detector are not of great importance, the energy resolution factor can affect the PDE result. An increase in the MC resolution factor above the actual experimental level results in an increase in the CDPH peak width. Although this makes the PDE correction less sensitive to the yield gates, it sometimes produces a small change to the PDE correction that uses the nominal gate.

The CDPH-gate uncertainty is highest for values of E_n at the side detectors where there is large activity in the $^{12}\text{C}(\vec{n},n)$ system. (The general sensitivity of the PDE to E_n may be observed in Fig. 4 of Ref. [1].) To estimate this uncertainty, we calculated the PDE with three different CDPH gates: 10%, 20%, and 30% of the CDPH peak height in the simulations for Ref. [1], and 20%, 30%, and 40% for Ref. [4]. Usually, the PDE corrections did not change significantly. For nine out of ten of the n-p measurements, the variation in the PDE by using the lowest and highest gates was less than one-fourth of the PDE statistical uncertainty. Some measurements were sensitive to changes in the ^{12}C library but were not particularly sensitive to the CDPH gate. For example, the datum at $\theta_{\text{c.m.}} = 78.6^\circ$ in Fig. 2(b) has a PDE correction of $-0.000\,22$, a purely statistical uncertainty of $\pm0.000\,24$, and a variation over the CDPH gates of $\pm0.000\,05$. (This datum was left out of Ref. [1].) A small number of measurements was sensitive to both the ^{12}C library and to the CDPH gate. The gate sensitivity was especially noticeable when the MC resolution factor had to be set low to reproduce narrow experimental spectra. For example, the datum at $\theta_{\text{c.m.}} = 112.2^\circ$ of Fig. 2(a) has a PDE correction of $0.001\,14$, a statistical uncertainty of $\pm0.000\,28$, and a variation caused by the CDPH gates of $\pm0.000\,20$.

We also used our MC simulation to recorrect the 10.03-MeV data of Refs. [2,12]. These references analyzed the n-p $A_y(\theta)$ data by sorting two-dimensional (2D) spectra [time of flight (TOF) vs CDPH]. In our MC simulation, we made a reasonable approximation to this by setting one-dimensional gates, first on the TOF spectra and then on the CDPH spectra. While much of the experimental information was available, certain details were missing. For example, Ref. [12] displays samples of 2D spectra at only two scattering angles. However, because the whole purpose of taking data with the narrow side detectors was to minimize the PDE corrections, the 10.03 MeV data set was not sensitive to these issues, as can be seen in Fig. 3. Again, the crosses use the original PDE corrections [2], and the open circles use the PDE corrections of the present paper. As expected, the changes caused by the new PDE correction are quite small. It would have been interesting to attempt a recorrection of the data taken with the 4-cm-wide side detectors of Refs. [8,12]. Unfortunately, the references do not contain sufficient experimental details.

Any future n-p $A_y(\theta)$ data that are taken with the purpose of testing NN potential models probably will have to achieve statistics at least as good as the 12.0-MeV data of Ref. [5] and the new 7.6-MeV data presented here. To achieve

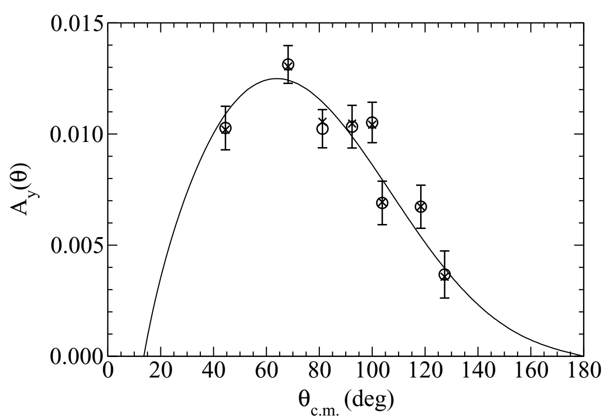

FIG. 3. The n-p $A_y(\theta)$ data at 10.03 MeV [2]. The crosses use the PDE corrections of Ref. [2], while the open circles use the PDE corrections of the present paper. The solid curve is the PSA prediction of Ref. [3].

this will probably require the use of relatively large side detectors, which will necessitate a careful treatment of the PDE correction. While it is sometimes possible to measure n-p $A_y(\theta)$ for experimental conditions in which the PDE effect is small, this is not possible for many important regions of E_n and $\theta_{\mathrm{c.m.}}$. As the present paper has stressed, to correct for the PDE requires assembling a complete and accurate database for $^{12}\mathrm{C}(\vec{n},n)$. Our revision of our MC library led to significant improvements in the PDE corrections.

The data of Figs. 1(a) and 2(a) are two of the most detailed n-p $A_y(\theta)$ distributions available, which offer high-precision data over a broad range of angles. Although the less-complete data set of Fig. 3 is in agreement with the Nijmegen PSA predictions [3], the data of Figs. 1 and 2 generally have lower values than the PSA, especially at the forward angles. This is in agreement with the model study of Ref. [5], which suggested a charge dependence of the pion-nucleon coupling constant.

This work was supported in part by the US Department of Energy, Office of Nuclear Physics, under Grant No. DE-FG02-97ER41033. We thank Isaac D. Gerg for his work at Penn State Altoona, G. M. Hale of LANL for his R-matrix analysis, and Z. P. Chen of Tsinghua University for his help with the PSA.

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