πNN Coupling from High Precision np Charge Exchange at 162 MeV

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Differential np cross sections for unpolarized neutrons of 162 MeV have been measured to high precision with particular attention to the absolute normalization. These data can be extrapolated precisely and model independently to the pion pole and give a πNN coupling constant $g^2 = 14.62 \pm 0.06 \pm 0.29$ or $f^2 = 0.0808 \pm 0.0003 \pm 0.0017$. This is higher than recently suggested values.

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The precise value of the πNN coupling constant is of crucial importance for the quantitative discussion of a large number of phenomena in hadron and nuclear physics, as well as for the predictions by low-energy theorems of pion photoproduction and leptonproduction, for the Goldberger-Treiman relation, etc. Its strength governs the properties of the deuteron to such an extent that only a few percent difference in its value is sufficient to either unbind the deuteron or to produce a bound diproton, in both cases with major consequences for the world as we know it. The textbook value is $g^2 = 14.3$ to 14.5 deduced from πN scattering data in the resonance region and from forward dispersion relations in pp scattering as the principal sources of information. In the last few years the Nijmegen group [1,2] has proposed a substantially smaller value for the charged pseudoscalar coupling constant, $g^2 = 13.58(5)$ [or $f^2 = 0.0748(3)$] on the basis of their extensive and global analysis of NN scattering data, which has an excellent overall fit to the huge database. While their result is controversial, it has forced a critical reappraisal of the entire reasoning on which the previous value has been based. Reviewing this issue, it has become evident that the basis for the standard value in the literature is weaker than previously thought. It has therefore become urgent to determine g^2 to high precision, convincingly, and model independently [3].

To remedy this lack of precision data we present here a new generation of accurate np charge exchange cross sections at 162 MeV. The choice of beam energy is almost irrelevant, since the laboratory np cross sections above 100 MeV have a nearly universal shape as a function of momentum transfer. It is, however, easier to achieve the desired normalization accuracy below the pion production threshold. Since a reliable detection of recoil protons is easier to perform at higher energies, we have for this measurement chosen the highest neutron beam energy

available at the The Svedberg Laboratory. We use this angular distribution to determine the corresponding πNN coupling constant. The major difficulties are to achieve a correct normalization of the data, and to control the systematic pole extrapolation error. It is the unpolarized cross section and not the other observables that constrains the coupling constant. Additional observables would not improve the present analysis.

The neutron facility in Uppsala has been presented in detail recently [4], and only a brief description will be given here. The 162 ± 0.5 MeV (1.2 MeV FWHM) neutrons were produced with the ${}^7\text{Li}(p,n){}^7\text{Be}$ reaction by bombarding a 427 mg/cm² thick disk of ${}^7\text{Li}$ with protons from the cyclotron. The low-energy tail in the source neutron spectrum was suppressed using time-of-flight techniques. After the target, the proton beam was bent into a well-shielded beam dump. A system of collimators defined a 7 cm diameter neutron beam at the (n,p) target position. The proton count rate was maximized by using a sandwiched multitarget system, in which four 100 mg/cm² CH₂ targets were mounted. The protons were detected with a magnetic spectrometer, consisting of a dipole magnet and four drift chambers, two in front of and two behind the magnet. The momentum and emission angle of the protons were determined by reconstructing their trajectories through the magnetic field. A trigger signal for the data acquisition system was generated by a triple coincidence between a thin scintillator, positioned immediately after the multitarget box, and two large plastic scintillators, located behind the last drift chamber. Measurements of the ${}^1\text{H}(n,p)$ cross section were performed in the angular range $\theta_{\text{c.m.}} = 0^\circ - 62^\circ$, which corresponds to np scattering from 118° to 180° . The data were taken with the spectrometer magnet in three positions, covering different angular ranges. The c.m. angular resolution was better than 1° (FWHM).

The data were analyzed on an event-by-event basis, using $\pm 1^\circ$ software gates on vertical angles to avoid angle-dependent acceptance corrections. After background subtraction, the proton peak contents were determined for each 2° c.m.-angular bin. The statistical accuracy in the individual points varies between 1.0% and 2.8%, while the total systematic uncertainty in the relative cross section is less than 2% for each magnet setting. The three individual data sets were normalized to each other using the angular overlap regions.

Absolute np scattering cross sections were obtained by normalization to the total np cross section, experimentally determined to 48.83 mb by Lisowski *et al.* [5]. Hence, the angular distribution of the differential data was integrated over all angles, using the shape of the phenomenological phase-shift solution VZ40 [6] in the angular range not covered in the experiment. The total uncertainty in the cross section scale is estimated to be less than 4%, based on the differences between different phase-shift solutions. The final data are shown as filled circles in Fig. 1. The errors given are the combined statistical and systematic uncertainties in the relative cross sections. Previous measurements [7–9] close to the energy of the present experiment as well as the results for the Nijmegen potential [10] and for the one-pion exchange (OPE), as defined below, are shown for comparison. These previous data do not significantly constrain the πNN coupling constant at the present level of precision.

The differential cross section is made up of the incoherent squares of five amplitudes a , b , c , d , and e [11]. Their relative importance is shown in Fig. 2. The term $|e|^2$ is negligible, while $|a|^2$ and $|c|^2$ give a slowly varying background. The pion pole terms contribute to the amplitudes b and d . In the Born approximation, b has contributions from central, spin-spin, and tensor interactions, while d has pure tensor character [12]. These amplitudes are crucial to the extrapolation. The model-independent determination of the coupling constant g^2 requires accurate single-energy data with absolute normalization N of the unpolarized differential cross section. Since g^2 is al-

FIG. 1. Differential cross sections for elastic np scattering at 162 MeV in the angular range $\theta_{c.m.} = 118^\circ$ – 180° .

FIG. 2. Contributions of the a , b , c , d , and e amplitudes to the differential np charge exchange cross section using the Paris model. The pion pole contributions appear in $|b|^2$ and $|d|^2$.

ways proportional to $\sqrt{N}$, polarization information is of no particular use in the present context.

We extract the charged πNN coupling constant from the experimental data by extrapolation to the pion pole using three different procedures: the Chew method [13,14], the Ashmore method [15], and a difference method. The standard procedure in the past has been the Chew method [16–18], which extrapolates the function $y(x)$ defined from the c.m. differential cross section:

$$y(x) = \frac{sx^2}{m_\pi^4 g_R^4} \frac{d\sigma}{d\Omega}(x) = \sum_{i=0}^{n-1} a_i x^i. \quad (1)$$

Here s is the square of the total energy, $x = \mathbf{q}^2 + m_\pi^2$, m_π is the charged pion mass, $\mathbf{q}^2 = 2k^2(1 + \cos\theta)$ with $k^2 = MT_{lab}/2$ in terms of the nucleon mass M , and g_R^2 is a reference scale for the coupling. At the pion pole $x = 0$ the Chew function gives

$$y(0) \equiv a_0 \equiv g^4/g_R^4. \quad (2)$$

The Ashmore method parametrizes $d\sigma/d\Omega(x)$ in terms of a pion Born amplitude with a phenomenological background term. Since the pure pion Born term fails to give a qualitatively correct angular distribution, it is convenient to use the regularized pion Born amplitudes, a_π , b_π , c_π , and d_π , as given in Eqs. (12)–(16) of Ref. [12], to ensure a nonzero cross section at 180° . In these amplitudes, the r -space δ function has been subtracted, a procedure which is routinely used for many years in many-body applications of pion physics [19]. Since one expects also an important contribution to the np backward scattering from the ρ -meson exchange, we model the background amplitude to include such a contribution with adjustable strength. The extrapolation gives model-independent results as before, but fewer parameters should be needed.

The difference method is based on the Chew function, but it recognizes that a major part in the cross section behavior is described by models with exactly known values for the coupling constant. Hence, it applies the Chew

method to the difference between the value of the function $y(x)$ for a model and the experimental values, i.e.,

$$y_M(x) - y_{\text{exp}}(x) = \sum_{i=0}^{n-1} d_i x^i, \quad (3)$$

with g_R replaced by the model value g_M . At the pole

$$y_M(0) - y_{\text{exp}}(0) \equiv d_0 \equiv \frac{g_M^4 - g^4}{g_M^4}. \quad (4)$$

Thus one now determines the *difference* between the model coupling constant and experimental value, which should diminish systematic extrapolation errors.

In Table I we give the results for the three different methods applied to the present data. We have also generated pseudodata with uncertainties corresponding to the present experiment from 10 000 computer simulations using exact data points from the Nijmegen [10] and the Paris [20] potentials with a Gaussian, random error distribution [21]. The coupling constant was determined for each of these “experiments” using the different methods. The average g^2 , its rms uncertainty, and the associated average χ^2 per degrees of freedom (χ^2/N_{DOF}) as well as the systematic deviation δg^2 from the true model value are given in Table I. Thus we have a check on extrapolation errors and can control the systematic corrections. For the Chew model a perfect fit is achieved with a fourth order polynomial in x , but with a small systematic downward shift of 0.21 (Nijmegen) and 0.22 (Paris) as compared to the original model values. With a third order polynomial fit the error becomes smaller, but the systematic shift is considerably larger (2.08 for Nijmegen and 2.39 for Paris). The Chew method gives a large extrapolation uncertainty (0.93). It is not ideal for a precision determination of the coupling constant, although it gives reliable results with perfect data.

The Ashmore method permits one to fine-tune the parametrization of the tensor interaction, which is important for larger momentum transfers. A good description is obtained already with four terms, and the extrapolation error is smaller than with the Chew method. The pseudodata indicate that this method gives a small underestimate

of the deduced coupling constant by 0.15 (Nijmegen) and 0.33 (Paris). The value $g^2 = 14.09$ directly deduced from the data must therefore be increased by approximately 0.24 (the average of the two model corrections) and gives $g_{\text{Ashmore}}^2 = 14.34 \pm 0.55$. The Ashmore extrapolation gives a substantially reduced, but still not optimal, error.

The difference method requires only a few terms in the polynomial expansion in favorable cases, which gives a small extrapolation error. The similarity between the angular distributions from models and the experimental data is exploited, particularly for larger q^2 . This incorporates substantial additional physical information without introducing any model dependence. For the Nijmegen-Uppsala difference (Fig. 3) the very good χ^2/N_{DOF} minimum is obtained with a linear ($n = 2$) expansion with $g^2 = 14.62 \pm 0.06$. The difference method using the Paris potential requires at least four terms and has then an upward systematic shift of 0.41 for the Nijmegen potential and an error of 0.36, corresponding to $g^2 = 14.21 \pm 0.36$, consistent with but smaller than the value from the difference with the Nijmegen potential. (In order to apply the difference method with the Paris potential one has to take into account the fact that an average pion mass $\overline{m}_\pi = 138.038$ MeV has been used for the pion pole. This introduces minor modifications.) The Paris-Uppsala results for $n = 2, 3$, and 5 also give values for g^2 close to those of the Nijmegen-Uppsala difference, when we apply the systematic shifts obtained from the Paris-“Nijmegen” differences. The major uncertainty (0.29) in the analysis of the present experiment comes from the 4% experimental uncertainty in the overall normalization, which can be improved. The extrapolation error is very small and does not reflect systematics.

As a check on our procedure we have also applied our method to the recent precision data on antiproton charge exchange [22]. The authors of Refs. [17,18] have used the Chew method to analyze these data and find with $n = 6$ a value $g^2 = 12.80$ for the charged coupling constant, well below even the Nijmegen values ($g^2 = 13.58$). We can indeed reproduce this analysis ($g^2 = 12.76$), but we

TABLE I. Results applying different methods to our 31 data points and to the corresponding Nijmegen and Paris potential “pseudodata” (see text). The model coupling constants are $g_{\text{Nijmegen}}^2 = 13.58$ and $g_{\text{Paris}}^2 = 14.43$ with δg^2 the systematic shift from the true model value. Optimal values are given in bold.

Method	n	χ^2/N_{DOF}	g^2	χ^2/N_{DOF}	g^2	δg^2	χ^2/N_{DOF}	g^2	δg^2
			Uppsala		“Nijmegen”			“Paris”	
Chew	4	1.314	12.31 ± 0.43	1.129	11.50 ± 0.46	2.08	1.203	12.04 ± 0.43	2.39
	5	1.074	14.88 ± 0.93	1.000	13.37 ± 1.03	0.21	1.001	14.21 ± 0.94	0.22
Ashmore	4	1.094	14.09 ± 0.55	1.003	13.43 ± 0.57	0.15	1.011	14.10 ± 0.53	0.33
	5	1.067	15.43 ± 1.08	0.999	13.73 ± 1.22	-0.15	0.999	14.63 ± 1.11	-0.20
			Nijmegen-Uppsala		Paris-Uppsala			Paris-“Nijmegen”	
Difference	2	1.023	14.62 ± 0.06	1.286	15.56 ± 0.06		1.136	14.58 ± 0.06	-1.00
	3	1.038	14.52 ± 0.15	1.126	15.26 ± 0.14		1.049	14.37 ± 0.15	-0.79
	4	1.054	14.26 ± 0.37	1.036	14.65 ± 0.36		1.006	13.99 ± 0.37	-0.41
	5	1.065	15.02 ± 0.92	1.068	15.04 ± 0.92		0.999	13.56 ± 1.02	0.02

FIG. 3. Extrapolation to the pion pole of the difference between the $y(x)$ of Eq. (1) for the Nijmegen potential at 162 MeV and the $y(x)$ for our data. The model coupling constant is $g_M^2 = 13.58$.

also find that systematic errors favor a higher value, closer to the Nijmegen one, but well below our results for the np data. We do not know the origin of this difference. We note, however, that the pronounced minimum in the antiproton cross section makes it nearly mandatory to use a relatively large number of parameters for the extrapolation, even in the case of the difference method, and this increases the uncertainties. Also the shape of the extrapolation function tends to enhance extrapolation uncertainties in the antiproton case.

Our analysis of the present precise experiment on np charge exchange demonstrates that such data can be used for a direct and precise determination of the πNN coupling constant (for a contrary opinion, see Ref. [2]). We reproduce the original coupling constant for pseudodata from the Nijmegen and Paris potentials. The extrapolation error varies considerably, however, and it goes up with the number of parameters. The most accurate determination from the present data results from the comparison with the Nijmegen potential using the difference method. This gives $g^2 = \sqrt{N} g_{\text{exp}}^2 \approx 14.62(6)$ or $f^2 = \sqrt{N} f_{\text{exp}}^2 \approx 0.0808(3)$, where the normalization introduces an additional 2% uncertainty. The reason for this precision is probably that the Nijmegen potential describes well the tensor interaction but only partly the central one, which dominates at small momentum transfers. Our value is larger than the Nijmegen result $g^2 = 13.58(5)$, but it is consistent with values given in earlier data compilations based on the analysis of πN and NN scattering data [23]. Our earlier scattering data at

96 MeV [24] give a consistent, although lower, value for the coupling constant. Experiments with higher statistics and better systematics would improve the determination, which would be further clarified by similar experiments at other energies. A later version of the present experiment will have a more complete range of angles, which will decrease the error in the overall normalization and give an improved value for the coupling constant. A more extensive analysis will be published elsewhere.

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