MEASUREMENTS OF THE TOTAL CROSS SECTION DIFFERENCE $\Delta\sigma_T$
IN np TRANSMISSION BETWEEN 0.86 AND 0.94 GeV

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ABSTRACT

We present results of the total cross section difference $\Delta\sigma_T(np)$ obtained in transmission measurements at the energies 0.86, 0.88, 0.91 and 0.94 GeV. The SATURNE II polarized beam of free neutrons obtained from the break-up of polarized deuterons was transmitted through the polarized Saclay frozen-spin proton target. The beam and target polarizations were oriented in the vertical direction. The present results agree with previous SATURNE measurements and improve the amplitude analysis in the forward direction.

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1. INTRODUCTION

We present measurements of the total cross section difference $\Delta\sigma_T$ in np elastic scattering at 0.86, 0.88, 0.91 and 0.94 GeV. Results were obtained with the SATURNE II polarized beam of free quasi-monochromatic neutrons scattered in the Saclay frozen spin proton target. The beam and target polarizations were oriented vertically. Present data complete the previous results given in ref.[1]. The experiment was carried out simultaneously with the measurements of the analyzing powers A_{ocno} and A_{oonn} , the spin correlation parameter A_{oonn} , and the rescattering observables D_{onon} and K_{onno} . The experiment is part of a systematic study of the nucleon-nucleon system at SATURNE II.

Throughout this paper we use the nucleon-nucleon formalism and the four-spin notation of observables developed in ref.[2].

2. Determination of $\Delta\sigma_T$

The general expression of the total cross section for a polarized nucleon beam transmitted through a polarized proton target (PPT), with arbitrary directions of beam and target polarizations, was first written in refs[3,4] as

$$\sigma_{tot} = \sigma_{0tot} + \sigma_{1tot}(\vec{P}_B, \vec{P}_T) + \sigma_{2tot}(\vec{P}_B, \vec{k})(\vec{P}_T, \vec{k}) \quad (2.1)$$

where $\vec{P}_B$ and $\vec{P}_T$ are the beam and target polarization vectors, $\vec{k}$ is the unit vector in the incident beam direction. The terms σ_{0tot} (spin-independent total cross section), σ_{1tot} and σ_{2tot} (spin dependent contributions) are related to the forward scattering amplitudes via the optical theorem :

$$\sigma_{0tot} = \frac{2\pi}{k} \text{Im}[a(0) + b(0)] \quad (2.2)$$

$$\sigma_{1tot} = \frac{2\pi}{k} \text{Im}[c(0) + d(0)] \quad (2.3)$$

$$\sigma_{2tot} = -\frac{4\pi}{k} \text{Im} d(0) \quad (2.4)$$

where k is the wave number,

The difference of the total cross section measurements with either parallel or antiparallel beam and target polarization directions, orientated perpendicularly ($\uparrow$) with respect to k , yields

$$\{\sigma_{\text{tot}}(\uparrow\uparrow) - \sigma_{\text{tot}}(\downarrow\uparrow)\}/P_B P_T = 2\sigma_{1\text{tot}} = -\Delta\sigma_T \quad (2.5)$$

The measurement with longitudinally polarized beam and target provides :

$$\{\sigma_{\text{tot}}(\Rightarrow) - \sigma_{\text{tot}}(\Leftarrow)\}/P_B P_T = 2(\sigma_{1\text{tot}} + \sigma_{2\text{tot}}) = -\Delta\sigma_L \quad (2.6)$$

The negative sign for $\Delta\sigma_T$ and $\Delta\sigma_L$ corresponds to an usual, although unjustified convention in the past literature. The relations (2.5) and (2.6) have been treated in detail in ref.[5].

3. POLARIZED BEAM AND TARGET

Polarized neutrons were produced by break-up of vector-polarized deuterons on a Be target. The production target was 20 cm thick and the beam spot at the transmission target was 20 mm in diameter. The beam extraction is described in ref.[7]. The neutron beam momentum spread of about ± 20 MeV is due to deuteron absorption in the production target and to the Fermi motion of the neutrons in the deuterons. The deuteron beam polarization was flipped every burst of the accelerator by a change of the RF transitions in the ion source. The polarization of the break-up neutrons was determined by a dedicated experiment, as explained in refs[6,7]. It is $P_B = 0.59$, independent of energy. The polarization of the protons in the accelerated deuterons was also checked by the beam polarimeter[8].

The neutron beam interacted with the 35 mm thick, 40 mm wide and 49 mm high polarized proton target(PPT)[9,10]. The target material was pentanol, with a typical proton polarization of 95%. The target polarization was held in a magnetic field of ~ 0.33 T produced by a vertical superconducting holding coil. The target polarization was inverted every few hours. The polarization direction was changed by a PPT repolarization at a different microfrequency.

4. EXPERIMENTAL SET-UP AND ANALYSIS

The experimental set-up and its electronics are shown in Figs 1a and 1b, respectively. They were described in detail in ref.[1] Here we give only the most important items. The setup consisted of a beam monitor (S) and the transmission counter (T). Both detectors were of similar design. Each consisted of a CH_2 converter placed immediately behind a large veto scintillation counter S3A (T3A). Charged particles emitted forward were detected by two counters S1 and S2 (T1 and T2) in coincidence.

The following rates were recorded on a magnetic tape for each spill of the accelerator (Fig. 1b):

- $S13 = (S1.S3A).(S2.S3A)$, $T13 = (T1.T3A).(T2.T3A)$
- $S1A = (S1.S3A)$, $S2A = (S2.S3A)$, $T1A = (T1.T3A)$, $T2A = (T2.T3A)$
- Accidental coincidences: $S13F = S1A.(S2A \text{ delayed})$, $T13F = T1A.(T2A \text{ delayed})$
- single counts in each of the six counters.

If N_{in} is the number of neutrons incident on the target and N_{out} the number of neutrons transmitted in a counter of solid angle Ω , then the total cross section is :

$$N_{out} = N_{in} \exp[-\sigma(\Omega)n_H x] \quad (4.1)$$

where n_H is the number of hydrogen atoms in 1 cm^3 and x is the target thickness. $\sigma(\Omega)$ depends on the polarizations P_B and P_T . If one sums over the events taken with fixed target polarization and using eq.(2.5) or (2.6), the ratio of the measurements with beam polarization $+P_B$ and $-P_B$ (the absolute values are assumed equal) becomes :

$$R = \frac{(N_{out}/N_{in})^-}{(N_{out}/N_{in})^+} = \exp[\Delta\sigma(\Omega)P_B P_T n_H x] \quad (4.2)$$

Because $N_{out} = T/\epsilon_T$ and $N_{in} = S/\epsilon_S$ where $T = T13 - T13F$ ($S = S13 - S13F$) is the number of neutrons seen in the T (S) detector and ϵ_T (ϵ_S) its efficiency. We get:

$$R = \frac{(T/S)^-}{(T/S)^+} \quad \text{and} \quad \Delta\sigma(\Omega) = \frac{1}{P_B P_T n_H x} \ln \frac{(T/S)^-}{(T/S)^+} \quad (4.3)$$

The extrapolation of $\Delta\sigma(\Omega)$ towards the zero solid angle gives $\Delta\sigma_{\text{tot}}$. The solid angle subtended by the T detector from the center of the target was $\Omega = 2.5 \text{ msr}$ ($0 \leq \theta_{\text{lab}} \leq 1.6^\circ$). The angle is small enough that the extrapolation of results towards $\Omega = 0$ is not necessary. In our energy range the difference between the measured value and the value extrapolated to $\Omega = 0$ is less than 0.05 mb. This is much smaller than the experimental error in the present experiment.

The counts in the beam monitor and transmission detector are independent. The neutron detection efficiencies ϵ_S and ϵ_T were about 1.3% for S and 1.8% for T. This array provides very good stability of the detection efficiency. Note that the results depend neither on the absolute efficiencies of S and T, nor on their ratio (eqs(4.3)). The small detection efficiencies decrease the probability for a converted neutron to be accompanied by another quasi-simultaneous converted neutron. This probability is estimated from results obtained with different neutron beam intensities[1]. It represents a main source of systematic errors. We have found it always smaller than 10^{-4} corresponding to a maximum systematic error of 0.5 mb.

The efficiencies of the detectors S and T will depend on the transverse beam polarization if the detector components or the entire detectors are displaced perpendicular to the beam direction. The efficiency ϵ_T is practically independent on the target polarization. The effects due to displacement and transverse beam polarization cancel when taking the simple average of results measured with two opposite beam and target polarizations. We have also studied the distribution of results from independent measurements for the same sign of the target polarization. Since the fluctuations were about 1.15 times larger than expected from statistics alone we have added quadratically an error of ± 0.15 for random-like instrumental effects.

5. RESULTS AND DISCUSSION

The preliminary results for $\sigma_{1\text{tot}} = -\Delta\sigma_T/2$ were reported in ref.[10], the final results are listed in Table 1. The same table gives the averages from this experiment and from ref.[1]. The total error is the quadratic sum of the statistical and systematic errors. The present results are shown in Fig. 2, where also the previous SATURNE II data from ref.[1] and the PSI data[11] are plotted. The $\Delta\sigma_T(\text{np})$ observable has been measured at SATURNE II and PSI only, whereas $\Delta\sigma_L(\text{np})$ was measured at these two laboratories and at LAMPF[12].

Using relations (2.2) to (2.6) and taking into account the $\Delta\sigma_L(I=0)$ data, calculated in ref.[1], we may deduce two of the three imaginary parts of amplitudes for np forward scattering i.e. $\text{Im } c(0^\circ, \text{np})$ and $\text{Im } d(0^\circ, \text{np})$, as defined in ref.[2]. The amplitudes could not be calculated at 0.86 and 0.91 GeV since the $\Delta\sigma_L(\text{np})$ observable has not been measured at these energies. Fig. 3 shows the energy dependence of $\text{Im } c(0^\circ, \text{np})$ and $\text{Im } d(0^\circ, \text{np})$ for all existing data.

Observable $\sigma_{1\text{tot}}$ for the isospin $I=0$ state was deduced using the averages in Table 1 and the corresponding pp quantities from the phase shift analysis of ref.[13]. It holds :

$$\sigma_{1\text{tot}}(I=0) = 2\sigma_{1\text{tot}}(\text{np}) - \sigma_{1\text{tot}}(\text{pp}) = (2\pi/k)\text{Im}[c(0^\circ, I=0) + d(0^\circ, I=0)] \quad (5.1)$$

$$\Delta\sigma_L(I=0) = 2\Delta\sigma_L(\text{np}) - \Delta\sigma_L(\text{pp}) = (4\pi/k)\text{Im}[c(0^\circ, I=0) - d(0^\circ, I=0)] \quad (5.2)$$

The $I=0$ results are listed in Table 2 at four energies. Fig. 4 shows the existing $\sigma_{1\text{tot}}(I=0)$ data. The shape of $\sigma_{1\text{tot}}(I=0)$ is similar to that for np transmission (Fig. 2). Figs 5a,b illustrate the energy dependence of $\text{Im } c(0)$ and $\text{Im } d(0)$ for $I=0$. The same amplitudes for $I = 1$, calculated from the phase shift analyses [13,14,15], are plotted in Figs 5,b for comparison. For $I = 0$ and $I = 1$ the amplitudes $c(0^\circ)$ are different in the entire energy range, the amplitudes $d(0^\circ)$ are close one to the other below 0.6 GeV.

6. CONCLUSIONS

The present results improve at four energies the previously measured $\sigma_{1\text{tot}}(\text{np})$ values. The Saclay results connect smoothly with the PSI ones. The existing mea-

surements of the total cross section differences provide, via the optical theorem, two imaginary parts of the nucleon-nucleon amplitudes between 0.18 and 1.1 GeV. Our results will improve dispersion-relation predictions as well as PSA calculations, especially when all new np elastic scattering data from PSI, LAMPF and SATURNE II, recently published or in print, will have been included in those analyses.

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TABLE CAPTIONS

TABLE 1 Results of the present $\sigma_{1\text{tot}} = -\Delta\sigma_T(\text{np})/2$ transmission measurement. Average values from this experiment and from ref.[1] are also listed.

TABLE 2

$\sigma_{1\text{tot}}$ and invariant amplitudes $\text{Im } c(0^\circ)$ and $\text{Im } d(0^\circ)$ for the isospin state $I = 0$. Average values of $\sigma_{1\text{tot}}(\text{np})$ from the present experiment and from ref.[1] were used. From the same reference were taken the $\Delta\sigma_L(\text{np})$ data. The corresponding pp data were taken from ref.[13].

FIGURE CAPTIONS

- Fig. 1 Experimental set-up for $\Delta\sigma_T(np)$ measurements (Fig. 1a) and electronic scheme of the monitor detectors (Fig. 1b).
S1, S2, S3A, T1, T2 and T3A are scintillation counters, CH_2 are radiators, CFD are constant-fraction discriminators, MEM are memory registers and arrows denote the scalers.
- Fig. 2 Energy dependence of $\sigma_{1tot}(np)$. Meaning of the symbols :
triangles ... present experiment
• SATURNE II, ref.[1]
o PSI, ref.[11].
- Fig. 3 Energy dependence of the forward scattering amplitudes c and d for np scattering. Meaning of the symbols :
• averages from the present experiment and SATURNE II data of ref.[1]
+ PSI, ref.[11].
- Fig. 4 Energy dependence of $\sigma_{1tot}(I=0)$. The pp data were calculated from the Saclay-Geneva PSA[13]. Meaning of the symbols :
• averages from the present experiment and SATURNE II data of ref.[1]
+ PSI, ref.[11].
- Fig. 5 Energy dependence of the forward scattering amplitudes c (Fig. 5a) and d (Fig. 5b) for the isospin states $I = 0$ and $I = 1$. Meaning of the symbols :
triangles ... averages from the present experiment and SATURNE II data of ref.[1] ($I = 0$).
• previous SATURNE II data of ref.[1] ($I = 0$).
o PSI, ref.[11] ($I = 0$).
solid line .. results from the energy dependent phase shift analyses (refs[14,15] for $I = 1$.
+ results from the energy-fixed PSA (ref.[13]) for $I = 1$.

Table 1

Present experiment					Averages from this exp. and from ref.[1]		
T_{kin} (GeV)	P_{lab} (GeV/c)	Experi- mental value (mb)	Statis- tical error (mb)	Total error (mb)	Experi- mental value (mb)	Statis- tical error (mb)	Total error (mb)
0.860	1.535	-4.481	0.260	0.300	-4.480	0.200	0.244
0.880	1.558	-4.701	0.327	0.430	-3.879	0.166	0.267
0.910	1.593	-4.019	0.347	0.530	-3.990	0.258	0.385
0.940	1.628	-3.377	0.364	0.470	-3.097	0.270	0.342

Table 2

T_{kin} (GeV)	P_{lab} (GeV/c)	σ_{tot} $I = 0$ (mb)	$\text{Im } c(0)$ $I = 0$ $\sqrt{\text{mb/sr}}$	$\text{Im } d(0)$ $I = 0$ $\sqrt{\text{mb/sr}}$
0.860	1.535	-6.28 ± 0.40		
0.880	1.558	-5.03 ± 0.33	-0.27 ± 0.12	-0.56 ± 0.12
0.910	1.593	-5.22 ± 0.52		
0.940	1.628	-3.41 ± 0.54	-0.13 ± 0.03	-0.45 ± 0.03

a)

b)

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5