THE NUCLEON-NUCLEON INTERACTION AT MEDIUM ENERGIES

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ABSTRACT

A summary of the medium energy nucleon-nucleon elastic and inelastic scattering data is presented from an experimenter's viewpoint. Motivation for additional measurements is given. Experiments which rely on the unique capabilities of the Indiana Cooler are emphasized.

Introduction

The nucleon-nucleon (NN) interaction has been studied for many years. Recently there has been great progress in this field due to the wealth of new results from the meson factories at laboratory kinetic energies between about 300 and 800 MeV. As a result, phase shift solutions obtained by various groups have been converging toward unique results.

This paper addresses the question, "Are additional nucleon-nucleon measurements needed in the Indiana Cooler energy range?" In order to answer this question, some general comments on elastic scattering amplitudes are given in Section A and an overview of the existing data base is presented in Section B. This is followed by an extended discussion of pp elastic scattering in Section C. The types of spin observable measurements, tests for basic symmetries or for systematic errors, and the special case of experiments at small angles are all covered. The np elastic scattering situation is presented in Section D, and the nucleon-nucleon inelastic reactions $NN \rightarrow d\pi$, $NN\pi$ and $d\gamma$ are discussed in Section E. Finally, a summary of these remarks is given in Section F.

A) NN $\rightarrow$ NN Amplitudes

Under the assumptions of parity and time-reversal invariance, there are five complex $I=1$ (isospin-1 or pp) elastic scattering amplitudes at each angle $\theta = \theta_{c.m.}$ ($0 < \theta < 90^\circ$) and beam kinetic energy T . An overall phase cannot be directly measured except near 0° , where it can be obtained relative to the Coulomb phase. The reason is that all elastic scattering spin observables are bilinear in the amplitudes, that is

$$\begin{aligned} \text{Spin observable} &\sim \text{Re}(Ampl_2^* \cdot Ampl_1) & (1) \\ &\quad \text{or} \\ &\text{Im}(Ampl_2^* \cdot Ampl_1) . \end{aligned}$$

There have been several analyses and suggested schemes to determine the $I=1$ amplitudes in a model independent fashion for beam momenta up to 6 GeV/c.¹⁻⁸ These schemes involve measurement at each angle and energy of at least 9 different pp elastic scattering spin parameters.

With the additional assumption of isospin invariance, there are also five amplitudes for the $I=0$ nucleon-nucleon system. Again, the

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$I=0$ amplitudes at $180^\circ - \theta$ are determined by the amplitudes at θ , just as in the pp case. Some schemes to use np elastic scattering spin observable data to obtain the $I=0$ amplitudes, assuming the $I=1$ amplitudes are known, are given in Refs. 2,9.

At energies $T \lesssim 1000$ MeV, the nucleon-nucleon amplitudes are usually determined using a phase shift analysis.¹⁰⁻¹⁵ The amplitudes are decomposed into partial waves $^{2S+1}L_J$, where $\vec{S} = \vec{s}_1 + \vec{s}_2$ is the sum of the intrinsic nucleon spins, $\vec{L}$ is the orbital angular momentum, and $\vec{J} = \vec{L} + \vec{S}$ is the total angular momentum. A fit is made to the experimental data in some energy range to obtain the partial wave amplitudes. In order to make the problem tractable, some theoretical inputs and constraints are used. These often differ among the various phase shift analyses, reflecting to some extent the philosophies, styles, or judgement of the physicists doing the analysis.

There are several types of theoretical inputs and constraints which are used. For example, partial waves with J larger than some cutoff are generally determined from meson exchange calculations, which are used to obtain the long-range part of the NN interaction. At a given energy, the cutoff value of J has sometimes grown with time as the total amount of spin parameter data has increased near that energy. Also, at energies below the threshold for π production ($T \lesssim 300$ MeV), the amplitudes are required to be purely elastic. Finally, continuity constraints are applied to the phase shift parameters to require a smooth variation with beam energy. Various phase shift analyses perform these continuity conditions in different ways, and there is some evidence that structure in the amplitudes at $\theta_{c.m.} = 90^\circ$ may have been smoothed too much at higher energies (Ref. 16 and Fig. 1). A particular problem has involved the inelasticities,¹⁷ which are also related to a number of total cross sections (the optical theorem relates total cross sections to elastic scattering amplitudes at 0°).

Another way to look at the problem concerns the connection between the amplitudes and the phase shift parameters.¹⁸ Schematically,

$$\left(\begin{array}{c} \text{Partial Wave} \\ \text{Amplitude} \end{array} \right) \sim \left(\begin{array}{c} \text{Kinematic} + \\ \text{Spin Factors} \end{array} \right) \cdot \int_1^1 (\text{Ampl.}) \cdot \left(\begin{array}{c} \text{Legendre} \\ \text{Polynomial} \end{array} \right) \cdot d(\cos \theta) \quad (2)$$

The five full amplitudes (Ampl.) can be determined in a model independent way only to an overall angle dependent phase (Phase (θ)), as mentioned before. It is the various theoretical inputs and constraints noted above that permits the evaluation of the overall phase in the phase shift analyses. Furthermore, as described in the next section, a model independent amplitude analysis cannot even be performed for $T \lesssim 400$ MeV because of a lack of sufficient spin parameter data.

It should be noted in Eq. (2) that if J is the total angular momentum for the partial wave, then the order of the Legendre polynomial is J or $J \pm 1$. Therefore, at least J angles must be measured to find the partial wave amplitude with angular momentum J .

Similar considerations also apply to the inelastic reactions such as $NN + \pi d$, πNN , etc. In those cases the number of amplitudes is larger than for nucleon-nucleon elastic scattering, making the experimental job of determining the amplitudes more difficult.

Figure 1 a) The pp elastic scattering amplitudes at $\theta_{\text{c.m.}} = 90^\circ$ as a function of lab kinetic energy. The definition of the amplitudes and the data used in the determination are from Ref. 16. The solid curves are Arndt's predictions (Refs. 10, 19). a) The magnitudes of the amplitudes. b) The relative phases.

B) Existing NN + NN Data

In order to properly evaluate the quality and quantity of the nucleon-nucleon elastic scattering spin parameter data, a variety of factors must be considered. Some of these factors are the number of points and of different spin parameters, the angles and energies covered, and the quoted errors. The large number of parameters makes it difficult to give a detailed characterization of the data base. Instead, a number of different ways of displaying the data in terms of the parameters above will be presented. In this way, some general features of the data base will be exhibited.

Figure 2 shows one way of presenting the pp and np points measured.¹⁰ Only spin parameters other than differential cross sections and polarization are shown; similar plots of the other two quantities can be found in Ref. 10. The location of the measured data as a function of θ and T is indicated by a box for "old" data (pre-1978) and by an N for "new" data (post-1977). Each symbol plotted may represent more than one spin parameter or point at the same angle and energy.

Figure 2 Representation of the nucleon-nucleon elastic scattering data base in terms of $\theta_{c.m.}$ and T_{lab} from Ref. 10. Only spin observables other than cross sections and polarizations are included. a) $pp + pp$. b) $np + np$.

Concentrating on the pp results, it is apparent that they are rather sparse between about 150 and 300 MeV. The same is true for the differential cross section and polarization results. Near 140 MeV, the data are from Harvard, Harwell and Orsay. Above about 300 MeV, many laboratories have contributed, including the meson factories. In between, with the exception of some polarization results from Berkeley and TRIUMF, all the other data are from Rochester. These results were published in the early and mid-1960's, with most of the data at an energy of 210 MeV. Some independent checks of these results and some measurements of other spin parameters and other energies seem appropriate.

Using only pp elastic scattering spin parameter data other than differential cross section and polarization, the results from the data base of Ref. 19 were binned into three energy ranges (100-250, 250-400, 400-550 MeV) for Figs. 3-5. In Fig. 3, the pp data were grouped into five year classes (1970-1974, etc.) to illustrate the age of the measurements. The recent results from the meson factories are apparent, especially in the range $T = 400-550$ MeV. On the other hand, the lack of recent activity for the $T = 100-250$ MeV class can be clearly seen.

Figure 3 Number of pp elastic scattering points as a function of the year of publication. The data are from Ref. 19 and include only spin parameters other than cross sections and polarizations.

The integrated number of experimental points with errors less than some size is shown in Fig. 4. The shapes of the $T = 100-250$ and $400-550$ MeV curves are quite similar, whereas the data between 250-400 MeV has a larger fraction of points with poorer statistical precision. With the increasing importance of inelastic channels at higher energies, as well as the larger number of partial waves significantly affected by short-range forces, the larger data base at higher energies is certainly justified.

Figure 4 The integrated number of pp elastic scattering points as a function of the size of the quoted statistical errors. The data are from Ref. 19 and include only spin parameters other than cross sections and polarizations.

Finally, in Fig. 5 both the number of points and of different spin parameters for the pp data are shown as a function of angle. A lack of data at small angles is apparent in the range $T = 100-250$ MeV. For Fig. 5b, the polarization data were included in the count of the different spin parameters. It is clear that there are too few different spin parameters measured to perform a model independent amplitude analysis at any angle (other than 0° and 90°) below 400 MeV.

Figures 5 The number of points a) and different spin observables b) for pp elastic scattering as a function of c.m. angle. The data are from Ref. 19 and include only spin parameters other than cross sections for b) and other than polarizations and cross sections for a).

The situation for the np data base is generally poorer than for the pp case. With the exception of the more extensive np differential cross section data, the total of the other spin parameter measurements is less for np than for pp elastic scattering. This is true even though the relevant angular range is $0-180^\circ$ for np, but only $0-90^\circ$ for pp scattering. In addition, the statistical precision of the np results is generally poorer than for pp results, and there are indications of significant systematic errors for some of the np data. The lack of np data between about 150 and 300 MeV is similar to the pp situation noted earlier; this can be seen in Fig. 2b and the corresponding plot for np polarization in Ref. 10.

In conclusion, much of the pp data between 100 and 400 MeV is fairly old, with fewer parameters measured than at higher energies. The statistical precision, on the average, is somewhat poorer between 250-400 MeV, but is comparable to recent data from meson factories for $T = 100-250$ MeV. There is almost no data between 150 and 300 MeV with the exception of the Rochester results near 210 MeV, and forward angle measurements are lacking at the lower energies. A reasonable experimental case could be made to recheck some of the Rochester data, even though there may be no reason to suspect any problems. Measurements of additional spin parameters, energies and angles in the 150-300 MeV range would probably be useful to more accurately determine the phase shifts (and to test the theoretical inputs and continuity conditions). Finally, the np data base is even less complete than the pp case, and more data are justified.

For the remainder of this paper, the notation (beam, target; forward scattered, recoil) will be used to express the elastic scattering spin observables. The spin directions in the laboratory frame are defined in Fig. 6, and Table 1 gives symbols for the observables. In the table, * indicates the spin direction is known, and 0 means the spin direction is not measured. The subscripts i,j,k refer to one of the three spin directions in Fig. 6. For example, the correlation tensors such as C_{LL} , C_{SS} , etc. involve both a polarized beam and a polarized target.

Figure 6 Definition of $\vec{N}$, $\vec{S}$ and $\vec{L}$ spin directions in the lab frame.

Table 1

Observable	Description	Symbol
(0,0;0,0)	Differential Cross Section	$d\sigma/d\Omega$
(*,0;0,0) or (0,*,0,0)	Polarization	P
(*,*,0,0)	Correlation Tensor	$C_{jk} = A_{jk}$
(*,0;0,*) or (0,*,*,0)	Polarization Transfer Tensor	K_{jk}
(0,*,0,*) or (*,0;*,0)	Depolarization Tensor	D_{jk}
(*,*,0,*)	Triple Spin Tensor	H_{ijk}
(*,*,*,0)	Triple Spin Tensor	J_{ijk}

Assuming the usual conservation laws, there are three independent total cross sections for the nucleon-nucleon system. These three are

$$\begin{aligned}
 \sigma^{\text{Tot}} &= [\sigma^{\text{Tot}}(\uparrow\uparrow) + \sigma^{\text{Tot}}(\downarrow\downarrow)]/2 \\
 &= [\sigma^{\text{Tot}}(\uparrow\uparrow) + \sigma^{\text{Tot}}(\downarrow\downarrow)]/2 \quad (3) \\
 \Delta\sigma_T &= \sigma^{\text{Tot}}(\uparrow\uparrow) - \sigma^{\text{Tot}}(\downarrow\downarrow) \\
 \Delta\sigma_L &= \sigma^{\text{Tot}}(\uparrow\downarrow) - \sigma^{\text{Tot}}(\downarrow\uparrow)
 \end{aligned}$$

The spin averaged total cross section is σ^{Tot} . The quantity $\Delta\sigma_T$ is the difference in total cross sections for beam and target transverse polarized. The quantity $\Delta\sigma_L$ is the difference in total cross sections for beam and target longitudinally polarized (the arrows denote the spin directions in the laboratory frame).

C) pp Elastic Measurements

This section will focus on spin parameters other than differential cross sections. Cross sections are also important, but the experimental techniques and problems are different. For example, absolute solid angles, efficiencies and luminosities are needed for differential cross sections, but only relative values for "spin-up" and "spin-down" are required for the other spin observables. Three

types of apparatus are employed for these measurements: polarized beams, polarized targets, and polarimeters to measure the spin of an outgoing proton. (This will be referred to as a "carbon" polarimeter, even though under some conditions an analyzer other than carbon may be used. In addition, a magnet may be included to precess L-type to S- or N- type spin.) In order to reduce systematic errors, it is quite important to reverse the beam and target spins frequently. Similarly, if the beam and target are both unpolarized, then the carbon polarimeter should be rotated often for the same reason. (See, for example, the high energy experiment with a gas jet target performed at Fermilab by an Indiana group.²⁰)

There are several classes of spin parameter measurements, depending on the type of apparatus used. These are given below, along with some comments on each class. The relation of these spin observables to the amplitudes and relations between various sets of amplitudes are given in the comprehensive paper by Bystricky, Lehar and Winternitz.²¹

1) Polarization = P

The polarization parameter can be measured with either the beam or the target or the outgoing proton polarized. In these cases, the spin observable is (N,0;0,0) or (0,N;0,0) or (0,0;N,0) or (0,0;0,N). Comparison between various of the observables can be used to cross-calibrate the polarization or analyzing power of two types of apparatus (polarized target and carbon polarimeter, for example), or to search for systematic effects in the hardware. If the apparatus can be independently calibrated in some way, then a test of time reversal invariance can be performed by comparing (N,0;0,0) and (0,0;N,0).

2) Polarized Target and Carbon Polarimeter

As given in Table 1, the parameters that can be obtained are

$$\begin{aligned} D_{jk} &= (0,j;0,k) \\ K_{jk} &= (0,j;k,0) \end{aligned} \quad (4)$$

and the observables that are allowed to be different from zero are D_{NN} , K_{NN} , D_{SS} , K_{SS} , D_{SL} , K_{SL} , D_{LS} , K_{LS} , D_{LL} and K_{LL} . Parity conservation requires that only observables with an even number of L and S subscripts are nonzero. Therefore, a measurement of D_{NS} , K_{LN} , etc. can be viewed as a test of parity conservation or of systematic errors in the experiment. There are relations between the D's and K's from time reversal invariance and from the conservation of spin directions in the c.m. frame to the laboratory system

$$\begin{aligned} \frac{D_{LS} + D_{SL}}{D_{SS} - D_{LL}} &= \tan \theta_R \\ \frac{K_{LS} + K_{SL}}{K_{SS} - K_{LL}} &= -\tan \theta_F \end{aligned} \quad (5)$$

In Eq. (5), θ_F and θ_R are the laboratory angles of the forward and recoil protons respectively.

3) Polarized Beam and Carbon Polarimeter
The spin parameters in this case are

$$\begin{aligned} D'_{jk} &= (j, 0; k, 0) \\ K'_{jk} &= (j, 0; 0, k). \end{aligned} \quad (6)$$

Relations analogous to Eq. (5) can also be derived. The D_{jk} and D'_{jk} are linearly related, and the K_{jk} and K'_{jk} are also linearly related. Hence, if these parameters need to be measured, the choice of D_{jk} or D'_{jk} , etc. can be made on the basis of experimental problems with one technique or another. For example, at high energies, the D_{jk} and K'_{jk} are usually measured because the carbon analyzing power and the scattering cross section in the carbon for the lower energy recoil proton is higher than for the forward proton.

4) Polarized Beam and Polarized Target

From Table 1, the spin parameters are $C_{jk} = (j, k; 0, 0)$ and the nonzero quantities are C_{NN} , C_{SS} , $C_{SL} = C_{LS}$ and C_{LL} . As above, parity conservation requires $C_{NS} = 0 = C_{LN}$ etc. These measurements are good for low count rate situations, since the outgoing proton spin is not measured. A polarized gas target in the Cooler has several advantages over the conventional polarized target technique. One is the lower energy loss for the recoil proton, which permits coincidence measurements to smaller scattering angles. A second advantage is the lack of background nuclei in the target. In the past, good precision small angle polarized target data have only been obtained using a very high resolution magnetic spectrometer (HRS at LAMPF) to separate pp and p + Nucleus elastic scattering. A third advantage is the lack of high magnetic fields at the interaction point, which complicate the tracking and precess the beam spin direction in the case of $C_{SL} = C_{LS}$. A final advantage is the larger angular region without obstruction from polarized target magnet coils; such freedom is presently available only for "frozen spin" targets using dilution refrigerators. Few such experiments have been performed to date using this technique.²²

5. Polarized Beam, Polarized Target and Carbon Polarimeter

The lower statistical precision of these difficult "triple-spin" experiments has limited them to a few special cases. All of the advantages of using polarized gas targets apply here as well, and there is an added advantage that the lack of magnetic field at the interaction point means there is no spin precession of the outgoing protons. In the notation of Table 1,

$$\begin{aligned} H_{ijk} &= (i, j; 0, k) \\ J_{ijk} &= (i, j; k, 0), \end{aligned} \quad (7)$$

then there are constraints analogous to Eq. (5),

$$\frac{H_{NSS} - H_{NLL}}{H_{NLS} + H_{NSL}} = -\tan \theta_R$$

$$\frac{J_{NSS} - J_{NLL}}{J_{NLS} + J_{NSL}} = \tan \theta_F.$$
(8)

From the information on the different classes, several patterns emerge. First, there are constraints between various spin observables within each of the classes. Also, the types of spin parameters D_{ij} or D'_{ij} , K_{ij} or K'_{ij} , and C_{ij} each contain four independent quantities. Experiments with fewer spins measured will in general be easier and have higher statistical precision. Finally, there are significant advantages for the use of polarized gas targets over conventional polarized targets.

Before ending the discussion on pp elastic scattering, the special case of 0° results will be mentioned. There are only three independent amplitudes at 0° . Their real parts can be found from small angle elastic scattering measurements in the Coulomb-nuclear interference region (see Fig. 7 and Ref. 23). The imaginary parts of the same amplitudes can be related to the three total cross sections σ^{Tot} , $\Delta\sigma_T$ and $\Delta\sigma_L$ by the optical theorem. Dispersion relation calculations²⁴ connect the real and imaginary parts. A variety of theoretical input is used to perform these calculations. The small angle polarized target measurements using HRS at LAMPF were performed specifically to test these dispersion relation predictions at 650 and 800 MeV. Data at lower energies do not exist, and such small angle experiments are ideally suited to the Indiana Cooler, where the costs would be significantly less than the present LAMPF experiments.

Figure 7 The polarization parameter as a function of c.m. angle for pp elastic scattering at 800 MeV. The data at the smallest angles are from an HRS experiment at LAMPF (Ref. 23).

The $\Delta\sigma_L$ and $\Delta\sigma_T$ measurements were the source of intense investigation at energies above about 400 MeV (Figs. 8, 9 and Refs. 16, 17,

25-31) in the past few years. However, there are few data at lower energies, and the errors are not particularly small. Up to now, various technical problems with the transmission technique, energy losses and nuclear interactions in the target and detectors, etc. have limited the precision of the low energy data. The experimental method in the past has attempted to obtain the amount of transmitted, noninteracting beam for parallel and antiparallel beam and target spins. The technique with a polarized gas target would have to be different, relying instead on detecting all interactions, since detectors cannot be placed in the direct beam. In both cases, only the relative amount of "spin-up" and "spin-down" beam is required, but the absolute target density is important since a total cross section is being measured. It should also be noted that below π -production threshold, $\Delta\sigma_T$ and $\Delta\sigma_L$ must be purely elastic.

$$\Delta\sigma_T = \Delta\sigma_T (\text{elastic}) = - \int (C_{NN} + C_{SS}) \frac{d\sigma}{d\Omega_{el}} d\Omega \quad (9)$$

$$\Delta\sigma_L = \Delta\sigma_L (\text{elastic}) = -2 \int C_{LL} \frac{d\sigma}{d\Omega_{el}} d\Omega .$$

These relations can be used as a consistency check on the $\Delta\sigma$, C_{jj} and $d\sigma/d\Omega$ data.

Figure 9 The difference in pp total cross sections for beam and target longitudinally polarized as a function of lab kinetic energy. The data are from Refs. 16, 17, 29, 30.

Figure 8 The difference in pp total cross sections for beam and target transversely polarized as a function of lab kinetic energy. The data are from Refs. 17, 25-28.

Given the preceding information on the different classes of experiments and on the amplitudes, the natural question arises as to the number of experiments to perform. For instance, it has been claimed that the pp phase shifts are accurately known up to 650 MeV.¹² On the other hand, past experience at energies above 500 MeV has indicated that when a new type of spin parameter was measured, the data seldom agreed well with the phase shift predictions until sufficient data existed to perform a model independent amplitude analysis.

There are several possible approaches to the problem of how many experiments to perform. Certainly one would be to measure sufficient parameters at several energies in the 100-400 MeV range to do a model independent amplitude analysis. If the statistical precision were good enough and systematic errors could be kept small, then significant tests of the theoretical inputs to the phase shift analyses could be performed. Similarly, the data could be used to search for a time-reversal-invariance violation in the $I=1$ nucleon-nucleon amplitudes.³² A major problem is the long-term commitment needed to complete the program, such as that exhibited by the U. Geneva group at SIN^{7,33}. Insofar as possible, measurements in classes 1-4 should be used, although under certain circumstances, some spin parameters from class 5 might be measured at the same time. For example, the limitation to N-type polarized beam would still permit a model independent amplitude determination if there was fair use of data from class 5.

An alternate approach would be to measure a few spin parameters at a few energies and compare the results to existing phase shift predictions. It would seem prudent to measure some new type of spin parameters in this energy region, since they would be sensitive to different combinations of the amplitudes than the existing data. If there was a significant disagreement, then further measurements could be done; otherwise the effort would be terminated. Still another approach would be to perform experiments with much higher precision than the existing data. The goal would be to significantly reduce the uncertainties on the phase shifts, not necessarily to collect a full set of measurements to perform a model independent amplitude analysis. This approach requires considerable effort to understand and control systematic errors. In my opinion, any of these approaches could be reasonably justified, with the choice dependent on the experimenters and the constraints imposed by the hardware (and funding).

D) np Elastic Scattering

A secondary beam of neutrons from the Indiana Cooler could be very useful for np elastic scattering studies. Neutrons could be tagged using the associated particle technique to select the energy and direction. The tagging would be especially useful for total cross section or absolute differential cross section measurements, where a knowledge of the number of incident particles is essential.

The present np data base is generally smaller than the pp data base near the same energy, especially for spin parameters other than differential cross sections. The statistical precision is also poorer on the average, but systematic differences between various

sets of measurements of the same spin observable are even more serious.

To illustrate these problems, Fig. 10 contains the np total cross sections at medium energies.³⁴⁻³⁸ The recent LAMPF results³⁸ have a different shape and normalization from much of the older data. Another example of serious discrepancies is the backward ($\theta_{c.m.} = 180^\circ$) charge exchange differential cross section data (Refs. 37, 39-40 and Fig. 11). Precision measurements in the Cooler energy region could help clarify the experimental situation.

Figure 10 The np total cross section as a function of lab kinetic energy from Refs. 34-38. Note the upper curve corresponds to the energy and cross section scales at the top, etc.

There are numerous np polarization data and these can also be used to demonstrate problems with systematic errors in the np data base. In Fig. 12 is shown the np polarization at two neutron c.m. angles as a function of laboratory kinetic energy.^{2, 41-47} In some cases, when data were not obtained at exactly 90° or 120° , the results of a single set of measurements were interpolated to the proper angles. There is a sizeable variation, outside the quoted statistical errors, evident in some cases. The np elastic scattering situation is significantly worse than the pp case in this regard (for example, see Ref. 48).

It is evident from Fig. 2 that additional spin parameter measurements are needed before the np and pp data bases are comparable. Since the np results are mixtures of $I=0$ and $I=1$ amplitudes,

$$\text{Ampl}_{np} = (\text{Ampl}_{I=1} + \text{Ampl}_{I=0})/2, \quad (10)$$

and since systematic errors are present in the np data base, the need for further experiments is strengthened. Note that the lack of np data between 150 and 300 MeV, except near 210 MeV, is reminiscent of

the pp situation discussed before. Also, note that $\Delta\sigma_T$ and $\Delta\sigma_L$ for free np interactions do not exist at any energy and there are discrepancies between various dispersion relation predictions.^{12,24}

Figure 11 The np backward differential cross section as a function of lab momentum from Ref. 39. Other data are given in Refs. 37, 40.

Figure 12 Experimental np elastic scattering polarization as a function of lab kinetic energy at two neutron c.m. angles from Refs. 2, 41-47. Smooth curves have been drawn by eye through the data and error bands of $\pm 10\%$ are also shown.

Performing sufficient measurements to permit a model independent amplitude analysis may seem a monumental task, but the job may not be as bad as it first seems. Measurements of one spin parameter at both $\theta = \theta_{c.m.}$ and $180^\circ - \theta$ generally gives two independent bits of information on $I=0$ amplitudes at θ .^{2,9} For example, if the neutron polarized beam intensity is not very high, making extensive measurements with a carbon polarimeter prohibitive, there is a lot of information that can still be obtained on these amplitudes. If np spin observables $d\sigma/d\Omega$, P , C_{NN} , C_{SS} , C_{LS} , C_{LL} are measured at θ and $180^\circ - \theta$, and if the $I=1$ amplitudes are known, then Ref. 9 shows that the $I=0$ amplitudes can be obtained in a model independent manner with discrete ambiguities. Some additional carbon polarimeter data could resolve the discrete ambiguities and allow checks for systematic errors as well.

E) NN + Inelastics

This section will be split into three parts on the three inelastic reactions $NN + \pi d$, $NN + NN\pi$ and $np + d\gamma$. The experimental and theoretical situation in all three cases is far from satisfactory. Interest in these reactions at energies above 450 MeV has been increasing recently, as large amounts of new nucleon-nucleon elastic scattering data have become available from the meson factories and other accelerators. In one sense, these reactions are the "logical next step" after the elastic scattering studies. The interest in the first two inelastic reactions has also been driven by the presence of resonance-like behavior in some $I=1$ elastic scattering phase shifts. The problem with inelasticities alluded to before¹⁷ also impacts the understanding of this behavior.

1. NN + πd

In this reaction, many new data have recently become available (for a summary, see Refs. 49, 50). Most of the new results are at energies above about 450 MeV, and they include cross sections, polarizations of the proton and of the deuteron (it_{11}), and polarized beam - polarized target spin parameters C_{NN} , C_{SS} , C_{LS} , C_{LL} . One reason that polarized target experiments have contributed heavily to the data base is that this is a two-body final state, which is relatively easy to separate from reactions on background nuclei in conventional polarized targets. An example of such data is shown in Fig. 13 from Refs. 51, 52. Various theoretical predictions⁵³⁻⁵⁶ are also shown which are qualitatively similar to the data, but which are quite different quantitatively in some cases.

Phase shift analyses have been attempted up to 800 MeV (proton laboratory kinetic energy) and are given in Refs. 49, 50. There are insufficient data at any energy to perform a model independent amplitude analysis for the six complex amplitudes in this reaction. Below about 450 MeV, only differential cross section and polarization results exist. As a consequence, the phase shift analyses have used a considerable amount of theoretical input, restrictions on the number of partial waves considered, and/or reliance on continuity conditions to arrive at a solution. Additional experiments at lower energies would be beneficial. On the other hand, this reaction can

be studied with conventional techniques not requiring the unique characteristics of the Cooler. Furthermore, the most important measurements at this time may involve pions incident on polarized deuterium targets and the use of a carbon polarimeter to determine the spin of an outgoing proton. Such experiments are more appropriate for the meson factories.

Figure 13 Experimental results on the $pp + \pi^-$ reaction from SIN (Refs. 51,52). The solid lines represent a phenomenological fit, while the other curves correspond to various theoretical predictions. a) C_{SS} as a function of $\cos^2 \theta_\pi$. b) C_{SL} as a function of $\cos \theta_\pi$.

One type of measurement on this reaction that may be ideally suited to the Cooler involves a high precision test of charge independence. Using the associated particle technique to produce tagged beams of protons and neutrons at the same time, then the ratio of cross sections for

$$\begin{aligned} p + p &\rightarrow d + \pi^+ \\ n + p &\rightarrow d + \pi^0 \end{aligned} \quad (11)$$

can be measured by detecting the deuteron. Various experimental problems related to deadtimes and other rate effects, solid angles, target thickness, detection efficiencies, absolute beam intensity, etc. could cancel in the ratio.

2. $NN + NN\pi$

Below 500 MeV, recent experiments at TRIUMF⁵⁷ have measured a number of spin observables for the $pp + pn\pi^+$ reaction. In general,

the statistical errors are rather large, and there are few additional data besides cross sections on this channel (see Fig. 14 and Ref. 57). Spin information for $pp \rightarrow pp\pi^0$, $np \rightarrow np\pi^0$, $np \rightarrow pp\pi^-$ is basically absent in this energy range. There are many complex amplitudes for each channel, and hence many possible spin parameters that can be measured. However, it does not appear that an adequate number of spin observables will be measured to perform a model independent analysis below 500 MeV in the foreseeable future.

Figure 14 Experimental measurements of C_{NN} , C_{LL} and C_{SS} for the reaction $pp + pn\pi^+$ at 420, 465 and 510 MeV from TRIUMF (Ref. 57). The data are plotted against the invariant mass of the $p\pi^+$ system, and the curves are theoretical predictions (Ref. 58).

The standard theoretical model used to predict spin observables in the $NN \rightarrow NN\pi$ reaction is the coupled channels approach of Silbar, Kloeet, Dubach and Cass.⁵⁸ Some of the predictions at low energy are shown in Fig. 14, where significant discrepancies are observed. In general, the model has had mixed success, doing quite well for some spin observables and some kinematic regions and quite poorly in others.

The Indiana Cooler could make an important contribution to the understanding of which elastic scattering partial waves feed the inelastic channel $NN \rightarrow NN\pi$. Experiments with a polarized proton beam and a polarized gas target could measure spin observables much more easily than is possible with a conventional polarized target. A larger fraction of phase space could be detected because of the lower

energy losses in the target. Magnetic fields that cause the precession of proton spins near conventional polarized targets would also be minimized. The lack of background nuclei in the gas targets would permit simplifications in the detection apparatus; angular measurements alone are adequate to discriminate between events from hydrogen and from nuclei for two-body final states, but they are inadequate for three-body final states. Finally, the lack of polarized target magnet coils near the interaction region allows a more complete coverage of phase space with the gas target.

Another important measurement would be good precision cross section data for the $I=0$ inelastic reactions. These are often quite difficult because both pp and np experiments are required and systematic errors are frequently dominant (Refs. 59, 60). The use of tagged beams of protons and neutrons at the same time could permit accurate determination of the $I=0$ inelastic cross sections where many sources of systematic errors would cancel (as in the discussion of the $pp + \pi d$ and $np + \pi d$ reactions). There are indications that this inelastic cross section may be very small below 500 MeV, so such measurements may be more appropriate for higher energy coolers.

3 $np + d\gamma$

This reaction is quite basic, and should be calculable (in principle) from knowledge of the nucleon-nucleon interaction and electromagnetism. With high precision experimental data, tests of various corrections, such as meson exchange currents, off-shell effects, relativity, etc., should also be possible.

However, in the past there have been many measurements of cross sections and sizeable inconsistencies among different experiments. There have also been lots of calculations which were quite different from each other. Recently, some progress has been made in obtaining agreement between different experiments (see Ref. 61) and this should assist in constraining the theoretical predictions (Fig. 15). Tagged beams of neutrons should be of considerable help in obtaining precise cross section normalizations.

Figure 15 Differential cross section for the reaction $np \rightarrow d\gamma$ at a γ -ray lab energy of 95 MeV from Ref. 61. Three theoretical calculations are also shown.

Few spin observables have been measured in this reaction. Asymmetries for linearly polarized photons⁶² or for polarized neutrons⁶³ (Fig. 16), or protons at higher energies⁶⁴ have been obtained. Many additional measurements of these spin parameters and others will probably be required before the $np + d\gamma$ process is completely understood.⁶⁵

Figure 16 Polarization or analyzing power for the reaction $np + d\gamma$ using polarized neutrons as a function of the γ -ray angle in the c.m. frame from Ref. 63. The curves are theoretical predictions.

CONCLUSIONS

Various aspects of the nucleon-nucleon interaction were discussed. A summary of the gaps in our knowledge below 500 MeV is given below:

- 1) Some pp elastic scattering spin parameters should be measured in the energy range from 150 to 300 MeV, especially at small angles. The Cooler and a polarized gas target offer distinct experimental advantages for some of these measurements.
- 2) There are significant systematic differences in much of the np elastic scattering data base. Measurements with a tagged neutron beam should permit high precision determinations of differential and total cross sections. Other spin parameters should also be measured in the energy range from 150 to at least 300 MeV.
- 3) The goal of understanding the spin structure of pion production near threshold (up to 500 MeV) has not been achieved. There are few experimental results except differential cross sections and a few spin observables in any of the inelastic channels in this energy range. Measurements of spin parameters in any of these channels, and in particular for $pp + NN\pi$ where the Cooler offers special advantages, would be quite useful.

In conclusion, the Cooler has the potential to make unique contributions to the study of the nucleon-nucleon interaction.

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