NUCLEON-NUCLEON SCATTERING AT LAMPF AND KEK*

CONF-880983--39

DE89 017803

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ABSTRACT

A review of current measurements of spin-dependent observables in p-p and n-p scattering is given for experiments done at two laboratories, Clinton P. Anderson Meson Physics Facility at Los Alamos (LAMPF) and the National Laboratory for High Energy Physics in Japan (KEK).

INTRODUCTION

The nucleon-nucleon interaction has been pursued at many different laboratories in the past 30 years. However, it wasn't until the last 12 years that interest was aroused by the possibility of the existence of dibaryon resonances as results from measurements¹ of $\Delta\sigma$ and $\Delta\sigma_T$, done at the ZGS (Argonne), exhibited structure in the incident momentum region 1-3 GeV/c. By including these data in his phase shift analysis Hoshizaki² was prompted to predict the existence of several dibaryon resonances. Further accumulation of data and other phase shift analyses (PSAs) have since diminished the likelihood that these resonances exist, but, as a result of this effort, the importance of measuring spin-dependence in nucleon-nucleon scattering had been emphasized, especially in the search for resonant structures. Of course, to fix the phase shifts, the connecting link between theory and experiment, knowledge of spin-dependent observables is essential. The p-p experiments have established the I=1 phase shifts uniquely up to 600 MeV, but above this energy there is disagreement between the Arndt³ PSA and that of the Saclay group.⁴ The different approaches used in these PSAs combined with the lack of accuracy in the data and the different data-bases may account for the substantial differences in the 1S_0 , 3P_0 , 3P_2 , 3F_2 , 3F_3 and 1G_4 phase shifts for these two PSAs.

In the n-p sector, which is the source of the I=0 phases, the situation is much worse, as was recently highlighted by Arndt.⁵ In the present paper some of what has been done at LAMPF and KEK to further improve the data-bases for both p-p and n-p scattering will be presented.

Much work has been done in the π -d channel but the lack of time does not permit its presentation here. The 3-body inelastic channels will be covered by P. J. Riley in a later contribution to this conference.

* For the 8th International Symposium on High Energy Spin Physics, Minneapolis, 1988

FG05-88ER40399

MASTER

THE EXPERIMENTS

In order to grasp the extent of the progress made to date one, can observe in Table I a list of all the elastic p-p spin-dependent experiments done at LAMPF, and in Table II the n-p experiments. Only one spin dependent n-p quasi-free elastic experiment has been done at KEK, Sakuda et al.,⁶ which was an analyzing power measurement at four energies between 665 and 1100 MeV. In the elastic p-p sector the only published data are from the measurements of the differential cross section by R. Shimizu et al.⁷

The only elastic spin-dependent p-p experiment (also an analyzing power measurement) at KEK has just recently finished the data taking stage.⁸ Its purpose was to search for narrow energy structures. The effort was a collaboration of Texas A&M, Tokyo Institute of Technology, Kyoto University, Tohoku University, and KEK to attempt a measurement at very fine energy intervals (3-17 MeV) between 1.5 and 3.5 GeV. The technique made use of the beam during the ramp phase. A very thin target (30 μ thread of polyethylene) was inserted while the beam energy was increasing at selected points along the ramp. The p-p elastic measurements were made with four sets of hodoscopes arranged to detect both left and right scattering of both conjugate pairs of protons (see Fig. 1). All combinations of hodoscope hits from each pair were fed redundantly into two banks of scalers. These banks were alternately enabled and read every 1 ms into a computer, thereby providing a scaler experiment. On the other hand a π -d measurement was attempted with two MWPC and hodoscope arrays placed to detect the deuteron and pion at their conjugate angles. The deuteron arm also contained a scintillator bank made up of three counters at a long flight path (8.5 m) in order to separate the slower deuterons from the preponderance of faster particles that contributed to the large background rates. The angles chosen for these arrays were also compatible for elastic p-p scattering, which showed up immediately in contrast to π -d, the presence of which has yet to be ascertained. The experiment is now in the analysis stage and should provide the elastic results in the near future, whereas the π -d results will take significantly more effort to produce if they are at all forthcoming. A difficulty common to both these reactions is the beam polarization value. Because of the depolarizing resonances in the accelerator the polarization is changing as the energy is being ramped up. One will have to rely on knowledge of the location of these resonances and thus account for the discontinuities in the energy dependence of the analyzing power. A beam polarization measurement at 500 MeV was made continuously during the experiment and the deterioration of the polarization above this energy has been studied by the KEK group up to 3.5 GeV.

Recent experiments have been conducted at LAMPF to explore the n-p sector. A large effort⁹ was mounted to measure the spin observables C_{LL} , C_{SL} , and C_{SS} at several energies between 480 and 800 MeV. Some 484 and 634 MeV results have already been reported in Ref. 9, while preliminary results for 484, 634, and 790 MeV have been presented by T. Shima at the PANIC conference in Kyoto (1987). These results have been revised and will appear along

TABLE I PP ELASTIC Spin Observables

compiled by McNaughton

Obs.	Exp.	pts	Δ	Θ_{cm}	Energy	Status
A	15	35	.01	1-14	800	PRC27(83)282
	27	29	.002	12-90	800	PRL41(78)384, PRC23(81)1128
	27	15	.003	30-90	643	PRC25(82)2107, PRL41(78)384
	385	13	.005	10-47	800	PRC27(83)682
	392	6	.01	7-55	500	PRC34(86)1433
	492	13	.002	40	318-800	PRC24(81)1778
	631	28	.01	7-15	800	PRC25(82)373
	636	25	.01	34-90	600-750	PRC30(84)1251
	27	14	.01	30-90	800	PRC23(81)838
	27	11	.01	35-90	643	PRC25(82)2107
C_{NN}	517	6	.003	90	500-800	PRL49(82)1135
	505	12		90	318-800	analyzing
	512	15	.05	15-35	5, 6, 800	analyzing
	517	90		35-90	500-800	prelim
	709	40	.01	4-36	650, 800	PRL58(87)1084
	2GS	68	.01	70-90	433-806	PRL41(78)1436
	498	130	.02	80-90	303-800	NPB213(83)365, PRD29(84)2435
C_{LL}	516	15	.02	30-90	500-800	analyzing
	583	50	.02	4-36	650, 800	prelim
	2GS	30	.02	30-50	570-823	PRL51(83)1411
C_{LS}	518	15	.02	50-90	500-800	analyzing
	512	22	.02	23-90	5, 6, 800	PRD29(84)2137
C_{SS}	709			3-40	650, 800	approved
	194	7	.03	27-90	800	PRC25(82)1967
D_{NN}	194	5	.03	27-78	647	PRC26(82)249
	392	4	.02	5-24	800	PRC30(84)279, PRC32(85)239
	392	5	.04	7-55	500	PRC34(86)1433
	492	12	.03	90	400-800	PL143B(84)343
	194	8	.03	21-90	800	PRC25(82)1967
D_{SS}	194	7	.03	27-90	647	PRC26(82)249
	392	4	.01	5-24	800	PRC30(84)279, PRC32(85)239
	392	6	.03	7-55	500	PRC34(86)1433
	636	12	.02	41-90	600-750	PRC30(84)1251
	194	8	.03	21-90	800	PRC25(82)1967
D_{LS}	194	7	.03	27-90	647	PRC26(82)249
	392	3	.01	7-24	800	PRC30(84)279, PRC32(85)239
	392	7	.02	7-55	500	PRC34(86)1433
	636	14	.02	40-90	600-750	PRC30(84)1251
	392	4	.01	5-24	800	PRC30(84)279, PRC32(85)239
D_{SL}	392	6	.02	7-55	500	PRC34(86)1433
	636	14	.02	18-90	650, 800	PRC30(84)1251
	392	3	.01	7-24	800	PRC30(84)279, PRC32(85)239
D_{LL}	392	7	.03	7-55	500	PRC34(86)1433
	636	29	.02	18-90	600-800	PRC30(84)1251
	194	4	.03	46-90	800	PRC25(82)1967
K_{NN}	194	3	.06	56-78	647	PRC26(82)249
	194	4	.03	46-90	800	PRC25(82)1967
K_{SS}	194	3	.05	56-90	647	PRC26(82)249
	636	7	.02	45-90	600-750	PRC30(84)1251
	194	4	.03	46-90	800	PRC25(82)1967
K_{LS}	194	3	.04	56-90	647	PRC26(82)249
	636	8	.02	46-90	600-750	PRC30(84)1251
	194	4	.03	46-90	800	PRC25(82)1967
K_{SL}	636	7	.02	47-90	650, 800	PRC30(84)1251
	636	13	.02	47-90	650-800	PRC30(84)1251

TABLE II NP ELASTIC SPIN OBSERVABLES

compiled by McNaughton

Includes quasi-elastic p-p and n-p experiments in parentheses.

Obs.	Exp.	pts	Δ	Θ_{cm}	Energy	Status
A	65	100	.01	60-170	300-775	prelim
	360	20	.03	100-178	800	prelim
	(385)	18	.03	14-75	800	prelim
	(392)	3	.005	22-45	500	PRC27(83)682
	(457)	14	.01	20-90	650, 800	prelim
	589	2		6-18	800	prelim
	(KEK)	30	.08-.2	26-130	670-1100	PRD25(82)2004
	66	60	.06	70-170	390-665	prelim
	961			80-165	800	prelim
	665	75		40-160	500-800	prelim+PRL59(87)1645
C_{SS}	770	75		40-160	500-800	prelim
C_{LS}	770	75		40-160	500-800	prelim
D_{NN}	(392)	4	.06	14-69	800	PRC32(85)239
	(392)	3	.06	22-45	500	PRC34(86)1433
	590	4	.05	20-90	800	analyzing
	589	1		6-18	800	analyzing
	(928)	4		70-100	800	analyzing
D_{SS}	(392)	9	.06	14-58	800	PRC32(85)239
	(392)	4	.04	22-55	500	PRC34(86)1433
	(928)	4		70-100	800	analyzing
D_{LS}	(392)	7	.04	14-58	800	PRC32(85)239
	(392)	3	.05	22-45	500	PRC34(86)1433
	(928)	4		70-100	800	analyzing
D_{SL}	(392)	9	.05	14-58	800	PRC32(85)239
	(392)	4	.05	22-55	500	PRC34(86)1433
	(928)	4		70, 80	800	analyzing
D_{LL}	(392)	7	.05	14-58	800	PRC32(85)239
	(392)	3	.06	22-45	500	PRC34(86)1433
	(928)	4		70, 80	800	analyzing
K_{NN}	(360)	1	.03	180	800	PL103B(81)313
	403	3	.1	168-177	800	PRL48(82)781
	(664)	3	.01	180	500-800	FL153B(85)235
K_{SS}	876			50-180	650, 800	approved
	403	3	.1	168-177	800	PRL48(82)781
	876			50-180	650, 800	approved
K_{LS}	876			50-180	650, 800	approved
K_{SL}	403	3	.1	168-177	800	PRL48(82)781
	876			50-180	650, 800	approved
K_{LL}	(360)	1	.03	180	800	PL103B(81)313
	(664)	3	.01	180	5-800	FL153B(85)235
	876			50-180	650, 800	approved

with the rest of the results from the experiment in a comprehensive paper. In another experiment C_{NN} was measured at 790 MeV in order to extend previous measurements¹⁰ between 390 and 665 MeV.

The n-p spin-correlation observables using L and S type beam and target were measured in two phases over a period of three years. During that time various improvements were made through the addition of two detector planes, P0 and P3. The setup in Fig. 2 shows where the additional detectors were placed within the single-arm spectrometer that was used to measure the angle and momentum of the outgoing charged particles from the polarized proton target. The polarized neutron beam was provided by the $^2\text{H}(\vec{p}, \vec{n})$ reaction with a longitudinally polarized proton beam. The large drift chamber P4, along with the front chambers P1 and P2, gave sufficient resolution to be able to pick out a missing-mass peak that corresponded to elastic n-p scattering. A fit to this peak and a carbon target subtraction were used to remove the unwanted background coming from pion production and quasi-free scattering in the nonhydrogenous materials in the polarized target.

The data labeled E665 in Figs. 3 and 4 refer to the original setup, while that labeled E770 was obtained with the addition of P0 and P3. The C_{LL} and C_{SL} results at 634 MeV from these different stages are compared with various PSAs²⁻⁴ and the Bonn meson exchange model.¹¹ The Hoshizaki prediction appears to do remarkably well for both C_{LL} and C_{SL} in fitting the E770 results. The Arndt and BASQUE predictions are not much different, but just don't seem to follow the E770 data as well. The Bonn calculation also is not way out of line, but it too isn't going to give a very good χ^2 for these data. These measurements should be a guide for refinements to the theory. In Fig. 5 the C_{SS} results are shown. However, rather than compare these to PSAs the results of the direct measurement of the combined observables C_{SL} and C_{SS} are compared to PSAs in Fig. 6. Here, in contrast to the C_{SL} and C_{LL} results, the Arndt PSA does much better than the Hoshizaki PSA. It is difficult at this point to give reasons for these discrepancies, but, perhaps when the data are included in the data-bases, these differences will vanish.

The setup for the recent C_{NN} measurement¹², which used the same neutron beam described above, is shown in Fig. 7. In order to have a large solid angular acceptance a magnet was not used. Instead time-of-flight (TOF) measurements were utilized to give the energy separation that was necessary for extraction of the elastic signal. One of these TOF measurements was with respect to the rf of the accelerator, which allowed the separation of elastic events caused by the peak incident energy neutrons from those in the lower part of the neutron beam energy spectrum. This separation was enhanced by the capability of LAMPF to provide a bunched beam in short bursts (< 1 ns) 100 ns apart. Normally the bursts were separated by only 5 ns, that caused ~500 MeV neutron events to overlap with the ~800 MeV events in the rf-TOF spectrum. The 100 ns bunched beam gave very clean separation for all neutron energies. Further event selection was accomplished with the opening angle and coplanarity in the two arms, together with the TOF measurements also within each of the two arms.

The C_{NN} results are shown in Fig. 8 where they are compared to the PSA predictions^{3,4} of Arndt, Hoshizaki, BASQUE, and Saclay. It is clear that both Hoshizaki and Saclay do not fit these data, whereas Arndt and BASQUE do much better with Arndt being the closer of the two. Although the errors on these data are considerably larger than what had been hoped for, it is still important to have made this measurement at this level of precision. Taken alone, this measurement's impact on the phase shifts may not be significant, but, when combined with other measurements¹³ of similar precision and values, a substantial improvement should be observed in the determination of the n-p phase shifts.

Analyzing power results from the same experiment were also obtained, and these are shown in Fig. 9. They were measured in two ways, extraction of asymmetries with target polarized as opposed to beam polarized, which is indicated by the full and open circles respectively. The third set of points (crossed circles) are from an earlier experiment¹⁴ that was done with an unpolarized neutron beam and a polarized proton target, and are for energies distributed over a 50 MeV bin centered at 775 MeV. They represent the highest energy bin for data that were taken with a broad neutron spectrum, which was produced by a Be(p,n) reaction, where the energy range was 350-800 MeV. The entire results of this experiment are compared to PSAs in Fig. 10 and to other experiments in Fig. 11. The Arndt and Saclay predictions do considerably better than the BASQUE and Hoshizaki ones, as might be expected, since the latter two do not contain these data in their data-bases whereas the former two do. Still there is disagreement with Arndt and Saclay, especially at 525, 475, and 425 MeV with Arndt, and at 775 and 725 MeV with Saclay. All the discrepancies lie in the region centered around 100° where the minimum occurs. The systematic error associated with these data is 7% (relative) and it would not account for the 10-20% differences evident in Fig. 10. In Fig. 11 the departures from other data are even larger, reaching as much as 35% at 425 MeV when compared to the TRIUMF measurements.¹⁵ From these comparisons there is no reason to choose one set of data over another. However, the agreement of these data with a recent Saclay measurement¹³ at 794 MeV increases their credibility, especially since the energy dependence is devoid of much of the systematic error that the angular distribution is subject to. That is, if the normalization can be established at one energy, it is good for all energies, since the data were taken at all energies simultaneously; the different angular settings were separated in time and were subject to drift effects in the NMR electronics used to measure the target polarization.

Forward scattering experiments in the p-p sector have been done at LAMPF for the observables $d\sigma/d\Omega$, Analyzing power, C_{NN} , and C_{LL} . Since these relate to forward dispersion relations (FDR) (which predict forward scattering amplitudes) in conjunction with measurements of σ_{tot} , $\Delta\sigma_L$, and $\Delta\sigma_T$, they are of considerable interest. One of the latest of these experiments was a C_{LL} (A_{LL}) measurement by Pauletta et al.,¹⁶ which along with previous measurements of the above mentioned observables enabled them to obtain experimental values of the forward scattering amplitudes.

Their results disagree with the FDR of Grein and Kroll¹⁷ at 650 MeV, but agree at 800 MeV. Should this discrepancy hold it is suggestive of energy structure in the amplitudes that could be a manifestation of the disputed dibaryon resonances.

The last results to be presented are analyzing power measurements for forward n-p elastic scattering. Data were obtained with a slightly modified version of the spectrometer used to get the $C_{LL}(np)$ data mentioned earlier. These data are compared in Fig. 12 to the quasi-free results that used the High Resolution Spectrometer at LAMPF to look at the ${}^2\text{H}(\vec{p},pn)$ reaction.¹⁸ The free scattering data are in good agreement with these quasi-free results, but disagree with points from Saclay¹⁹ that are low with respect to the LAMPF data. The PSA prediction³ is dominated by the very precise quasi-free data and fits them very well, as one might expect.

Some current experiments at LAMPF, for which no results are available as yet, are two and three spin measurements for p-p elastic at 733 MeV, an accurate (1%) p-p $d\sigma/d\Omega$ measurement, and an n-p $\Delta\sigma_L$ experiment. The latter two are presently still in the data taking stage.

Finally, future projects at LAMPF will entail a whole slate of spin transfer parameters for n-p elastic scattering. An improved measurement of $C_{NN}(np)$ is anticipated, and if all goes well a measurement of $\Delta\sigma_T(np)$ may get done. A substantial improvement of these experiments will become possible through several upgrades of the facilities at LAMPF. An increase in the polarized beam intensity will be obtained through the installation of an Optically Pumped Polarized Ion Source (OPPIS); a Medium Resolution Spectrometer (MRS) will be constructed by 1989; and a Neutron Time Of Flight facility is now being commissioned. The next few years should see a major increase in our understanding of the nucleon-nucleon interaction as a result of these investigations and those pursued in the inelastic channels.

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FIGURE CAPTIONS

- Fig. 1. Setup of p-p analyzing power experiment at KEK using an internal target.
- Fig. 2. Setup of n-p spin correlation experiment at LAMPP.
- Fig. 3. The 634 MeV C_{LL} data compared to PSAs, which can be found through the interactive program SAID of Ref. 3, and the calculation from Ref. 11.
- Fig. 4. The 634 MeV C_{SL} n-p data compared as in Fig. 3.
- Fig. 5. The 484 MeV C_{SS} n-p data.
- Fig. 6. The directly measured observable, the combination $(0.5)C_{SS} - (0.8)C_{SL}$, compared to the PSAs, which can be found through the interactive program SAID of Ref. 3.
- Fig. 7. Setup for the C_{NN} 790 MeV n-p experiment at LAMPP.
- Fig. 8. The C_{NN} results compared to PSAs, which can be found through the interactive program SAID of Ref. 3.
- Fig. 9. Analyzing power n-p results from the recent 790 MeV experiment compared to results given in Ref. 14 as follows: Ba - Bagaturia *et al.*, 600 MeV (Ref. 12); Bl - Ball *et al.*, 544 and 719 MeV (Ref. 13); Bt - Barlett *et al.*, 800 MeV (Ref. 14); Bi - Bilenkaya *et al.*, 605 MeV (Ref. 15); By - Bystricky *et al.*, 725 and 800 MeV (Ref. 16); Ch - Cheng *et al.*, 400, 500, 600, and 700 MeV (Ref. 2); Cl - Clough *et al.*, 425 and 495 MeV (Ref. 17); Dz - Dzhelepov *et al.*, 635 MeV (Ref. 18); Ko - Korolev *et al.*, 633 and 784 MeV (Ref. 19); Le - Leung, 600 MeV (Ref. 20); Ma - Marshall *et al.*, 500 MeV (Ref. 21); Ra - Ransome *et al.*, 790 MeV (Ref. 22); Si - Siegel *et al.*, 350 MeV (Ref. 23); Wr - Wright *et al.*, 425 MeV (Ref. 24); Zu - Zulkarneev *et al.*, 635 MeV (Ref. 25), where the references are given in the paper to be

published. These data were taken from the SAID data-base of Ref. 3.

Fig. 10. The complete results of the earlier analyzing power n-p experiment compared to PSAs, which can be found through the interactive program SAID of Ref. 3.

Fig. 11. The same data as in Fig. 10 compared to other experiments. The symbols for these experiments are defined in Ref. 14.

Fig. 12. Analyzing power measurements near 800 MeV for n-p elastic forward scattering. The down triangles are the from Ref. 18, the up triangles are from Ref. 19, and the solid circles are the free n-p LAMPF data.

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Fig. 1

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Fig. 9

Fig. 10

Fig. 11

Fig. 12