Polarization analyzing power $A(\theta)$ in pp elastic scattering at 796 MeV

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High precision data have been obtained for the polarization analyzing power $A(\theta)$ in pp elastic scattering from 12 to 43° c.m. at 796 MeV. These data extend the angular range of data previously published by this group. Data at 428 MeV have also been obtained and are in agreement with recent double scattering data.

[NUCLEAR REACTIONS $^1H(p,p)^1H$, $E=428$, 796 MeV; measured $A(\theta)$; $\theta=12$ to 43° c.m.]

I. INTRODUCTION

In a previous paper,[1] we reported measurements of the analyzing power A in pp elastic scattering from 30 to 85° c.m. at 643, 787, and 796 MeV. This final paper includes complete experimental details in addition to further analyzing power data to extend the angular coverage at 796 MeV, and to cross calibrate with data from the TRIUMF accelerator near 428 MeV.[2-4]

These data are part of our continuing program to determine the isovector nucleon-nucleon amplitudes at medium energies. It is well known that at least nine independent spin parameters must be measured above pion production thresholds for a complete determination of these amplitudes. At this time, preliminary data, near 800 MeV, exist for 10 such parameters. These are cross section,[5] analyzing power (this paper and Ref. 1), the spin correlation parameters A_{NN} (Ref. 6) and A_{LL},[7] and the spin depolarization and transfer parameters D_{NN}, D_{SS}, D_{LS}, K_{NN}, K_{SS}, and K_{LS}.[8,9]

Determination of these amplitudes is urgently needed both to clarify the interpretation of the resonancelike structure observed near 800 MeV,[10] and for use in microscopic models of nucleon-nucleus interactions.[11]

In a recent LAMPF workshop[12] on program options, it was stated that "the imprecise (nucleon-nucleon) data have become the principal obstruction to analysis of the new LAMPF and Saclay (proton-nucleus) data." In this respect, the present forward angle data are especially important since the major part of the nucleon-nucleus data are concentrated at forward angles. The disagreement with the phase shift predictions (Fig. 1) indicates that the new data will significantly improve the phase shift predictions.

The quench ratio calibration described in Sec. III provides the absolute standard to which all the LAMPF polarization data are normalized.[13] The beam line polarimeters[14] and the pp elastic analyzing power are secondary standards of po-

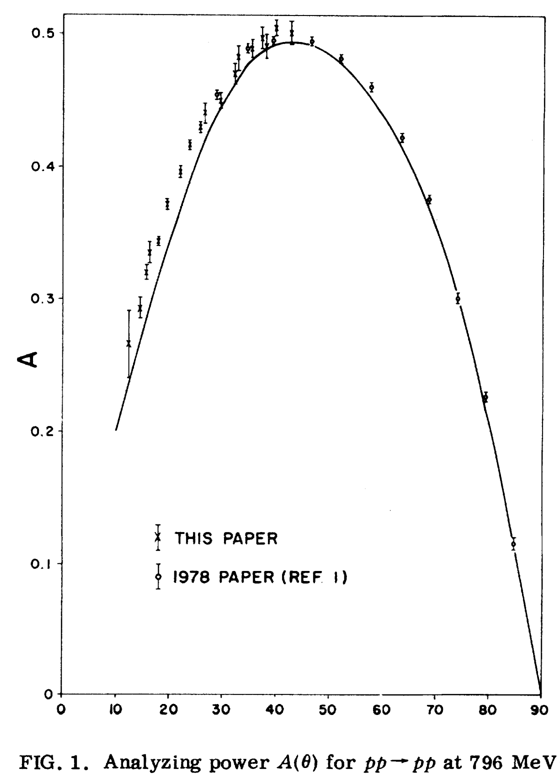

FIG. 1. Analyzing power $A(\theta)$ for $pp \to pp$ at 796 MeV: present and previous (Ref. 1) data compared with a recent phase shift fit (Ref. 24).

larization which were calibrated as part of the work described here.

The 428 MeV data provide an important cross calibration with measurements at TRIUMF. The work of Ref. 4 is underdetermined and requires a single absolute point for an exact solution. In Ref. 4, the underdetermination was resolved by reference to phase shift solutions. More recent work from TRIUMF[2] gives an absolute calibration independent of the phase shift analysis at three nearby energies (225, 327, and 520 MeV). The agreement (Fig. 2) of Ref. 4 with both Ref. 2 and the present data is reassuring.

II. EXPERIMENTAL DETAILS

The experimental techniques used to obtain the present data are essentially similar to those used previously.[1] In this paper, we expand our description of the techniques utilized in the measurements.

The experimental layout is shown in Fig. 3. A beam of protons with polarization up to 0.92 from the LAMPF accelerator was focused onto a small (few mm diameter) spot on a CH_2 target. Events were detected in four multiwire proportional chamber (MWPC) (Refs. 15,16) arms distinguishing pp elastic scattering from background by the precise angular correlation between the two final state protons that is characteristic of the two-body final state. The typical angular correlation spectrum of Fig. 4 shows that the background of random coincidences and $C(p, 2p)$ quasifree events is about 0.5% of the elastic events. Background spectra generated by a Monte Carlo technique were normalized to the wings of the spectra and subtracted. The estimated uncertainty due to background subtraction was about 0.02%.

Protons scattered to both left and right were

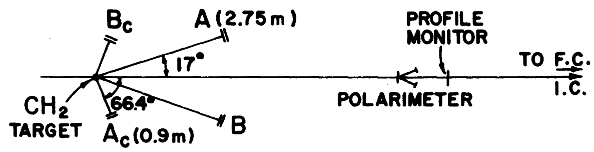

FIG. 3. Experimental layout: $(A \cdot A_c)$, $(B \cdot B_c)$ are MWPC arms in coincidence for left and right scattering.

detected simultaneously while flipping the beam spin (up and down) every three minutes. The left-right asymmetry ϵ is defined as $\epsilon = (L - R)/(L + R)$, where L is the geometric mean of events that scatter left while the beam spin is up, $L\uparrow$, and right while beam is down, $R\downarrow$; similarly $R = [(R\uparrow)(L\downarrow)]^{1/2}$ It is well known[17] that use of this technique cancels instrumental asymmetries to a high order. Careful examination of dead time effects and of multiple tracks in the MWPC's convinced us that false asymmetries from these were less than 10^{-4}. Dead time was monitored by sampling the MWPC busy signal with a beam related monitor (the polarimeter up signal). Cancellation of instrumental asymmetries was helped by the fact that the busy signals of the left and right pairs of arms were tied together so that to first order the dead time was only a function of beam intensity.

Events with more than one track in a chamber were rejected in the first analysis. A second pass was made for many runs, selecting the alternative MWPC address if this gave a better angular correlation. This was found to make a difference of $(1 \pm 2) \times 10^{-4}$ to the asymmetry. Comparison with calculations of δ ray distributions[18] convinced us that $\geq 90\%$ of the multiple tracks were from δ rays which would be a constant fraction of all events and therefore make no change to the asymmetry.

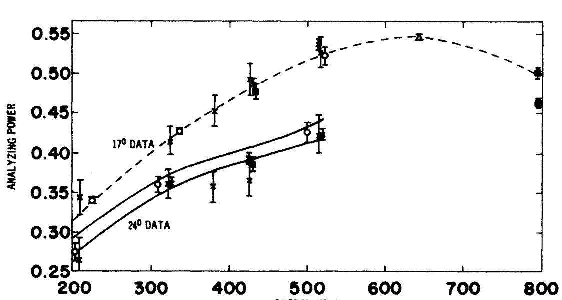

FIG. 2. Analyzing power A at $\theta = 17°$ and 24° lab for $pp \to pp$ as a function of energy. The 428 and 796 MeV data (squares) are from this paper, the open triangles from Ref. 1, open circles from Ref. 2, crosses from Ref. 3, and the band through the 24° data from Ref. 4. The dashed line is to guide the eye.

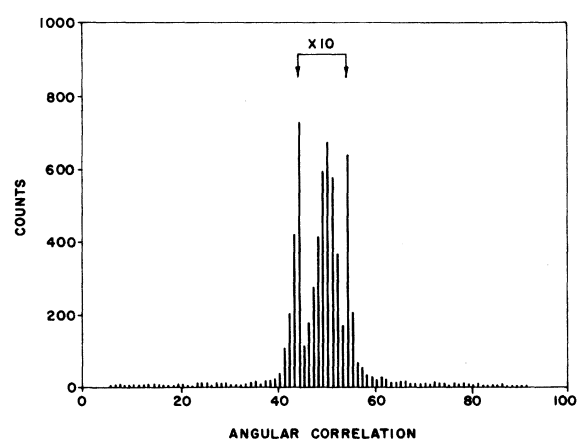

FIG. 4. Angular correlation between primary and conjugate scattered protons in $pp \to pp$. Note the ×10 scale change at the peak.

No corrections were made to the final data for either dead time or multiple tracks.

At the most forward angles, the conjugate detectors were moved close to the evacuated scattering chamber and the target (0.25 mm CH_2) set at 45° so that the low energy recoil particles had to pass through from 30 to 65 mg/cm^2 of CH_2, Mylar, and air. Since energy loss, multiple scattering, etc. were identical for beam spin up and down, these had no effect on the data other than a slight weighting of the bins toward backward angles. This has been taken account of in calculating the effective mean angle of each bin (see below).

The standard error of the mean of the 23 runs taken at 17° lab under a variety of conditions is in good agreement with the uncertainty predicted from counting statistics. The uncertainties in the tables are from counting statistics alone.

At small angles, the finite vertical acceptance of the detectors included events for which the scattering plane was not perpendicular to the spin vector. A correction was included for the average value of $\cos\phi$ where $\cos\phi$ is the angle between the scattering plane and the horizontal. In no case did this correction exceed either 0.75% or 0.4 standard deviations.

The earlier data[1] included a correction to A of up to 0.0015 for the finite horizontal angular acceptance. The present data from a single MWPC setting have been binned to give angular acceptances corresponding to $\frac{1}{4}$ to $\frac{1}{2}$ of the width of the MWPC. This together with the increased distance from the target to the forward MWPC (generally 4.2 m compared with 2.8 m previously) have reduced the finite angle corrections to between $\frac{1}{4}$ and $\frac{1}{32}$ of the previous values. No finite angle corrections have been applied to the present data.

The total angular acceptance of each MWPC bin ranged from 0.6 to 1.7° lab. The mean angle was calculated from the centroid of the distribution of events across the bin. The uncertainty in the mean angle is estimated to be about ±0.1° c.m.

The energy of the LAMPF accelerator was estimated as before to be 796 ± 2 MeV. This figure was obtained from the bend in the magnetic field of the LAMPF high resolution spectrometer (HRS). In a subsequent comparison, the energy obtained from the HRS bend was found to agree to better than 1 MeV with a simultaneous determination made by laser dissociation of H^- ions.[19]

The analyzing power A as presented in the tables is the ratio of the left-right asymmetry ϵ and the beam polarization P: $A = \epsilon/P$. The beam polarization was monitored by a polarimeter[14] consisting of four pairs of scintillation detectors placed to detect both primary and conjugate protons in coincidence elastically scattered from the hydrogen in CH_2, near 40° c.m., where the analyzing power has a broad maximum. Detectors were placed to detect scattering left, right, up, and down in order to monitor the polarization components in both the x and y directions. A constant $\simeq 5\%$ background from $C(p, 2p)$ quasifree scattering ($A = 0.275 \pm 0.015$ near 800 MeV) gave a calibrated total analyzing power $A = 0.481 \pm 0.002$ at 796 MeV. After subtraction of random coincidences ($\leq 10^{-3}$), it was found that the polarimeter readings were reproducible to better than 0.5%, the uncertainty in all cases being consistent with counting statistics. Further details of the LAMPF beam line polarimeters are contained in a Los Alamos report.[14]

The overall uncertainty quoted in the tables is the combined uncertainty from counting statistics in the MWPC's and the polarimeter. The polarimeter rate was typically twice that of the MWPC's.

III. POLARIZED BEAM CALIBRATION

In previous data at medium energies, absolute calibration has been obtained by one of two methods, either double scattering with nearly identical first and second scatters (measured asymmetry $= P_1 P_2 \simeq P_1^2$ if $P_1 \simeq P_2$) or by the NMR calibration of a polarized target.

LAMPF possesses an independent capability unique above Van de Graaff energies, of absolute calibration based on the atomic physics of the source. This method, known as the "quench ratio," was developed at the Los Alamos Van de Graaff accelerator[20] where it has been used and cross checked against p-^{4}He scattering[21] to obtain a calibration to ±0.4%.

The principle of the method, as it applies to the Los Alamos Van de Graaff accelerator, has been described previously[20] and so will only be described briefly here. The LAMPF ion source consists of three major components: cesium cell, spin filter, and argon cell. The cesium cell provides a beam rich in hydrogen atoms in the 2s excited state. The spin filter "quenches" to the ground state all but those in one electron-proton spin configuration. The argon cell preferentially ionizes the 2s-state atoms, giving a beam consisting primarily of polarized particles from the 2s state, but with some unpolarized background from ionization of ground-state atoms.

When the spin filter is detuned, all 2s atoms are quenched so that only this unpolarized background remains. The ratio of beam intensities for these two cases, known as the "quench ratio" Q, yields the beam polarization $P = 1 - 1/Q + P_q/Q$.

[The term p_q/Q is generally a small (0.3%) correction for the slight polarization P_q of the quenched beam.] Figure 5 shows the effect on both polarization and intensity of detuning the spin filter by changing the magnetic field B (known as "ΔB quench").

The major assumptions behind this measurement of the beam polarization are as follows:

(1) The unpolarized component must be unperturbed by the quenching. We have compared the ΔB quench with a ΔE quench obtained by changing the spin filter electric field, expecting any perturbation to be different in these two cases. Comparison of the two results shows a 0.2% to 0.5% difference. We believe this to be a perturbation caused by the changing electric field and have made this correction accordingly.

(2) There must be no depolarization between spin filter and experimental target. The quench ratio measures the polarization as it existed in the spin filter. Subsequent depolarization would not affect the measured quench ratio and would therefore lead to error.

The possibility of depolarization is difficult to check definitively. A calculation[22] indicates that depolarization in the accelerator should be of the order of 0.1%. Our direct empirical checks of depolarization have been limited to a comparison of different beam phase-space components measuring in each case the ratio of polarization measured by the quench ratio and the polarimeter (described above). This "effective analyzing power" should not change.

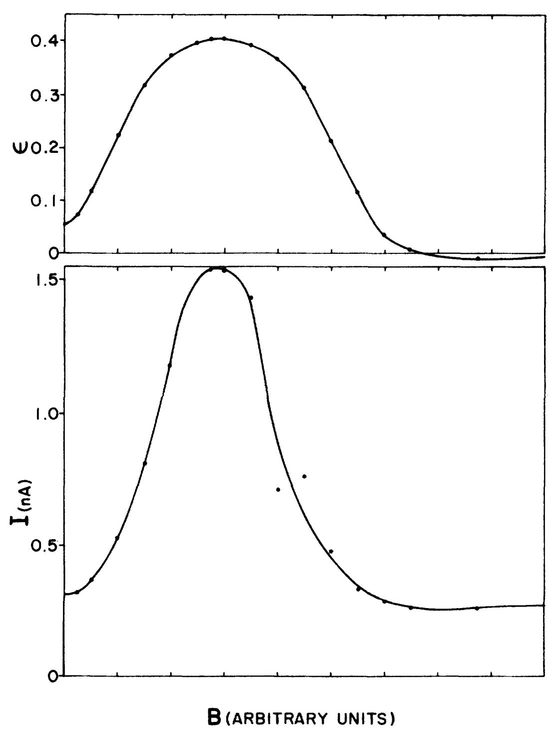

FIG. 5. Asymmetry ϵ and intensity I as a function of the spin filter solenoid current, illustrating a ΔB quench.

Depolarization is a function of the electromagnetic fields in the accelerator. These fields most nearly approach the design values (assumed in Ref. 22) along the axis of the linear accelerator. Toward the fringes of the beam phase space, the beam might be influenced by different fields, most obviously horizontal components of magnetic field which will precess the spin vectors of the fringe particles differently from the central particles, resulting in depolarization. Since the beam is fairly coherent along the length of the accelerator, then the comparison of good with full phase space should measure the difference between the ideal and actual depolarization while the comparison between good and bad should be a worst case measurement. We have measured the effective analyzing powers for these cases (constraining the phase space both at the beginning and end of the accelerator) and find ratios of 1.002 ± 0.005 for good/full phase space, and 1.008 ± 0.009 for good/bad phase space.

Furthermore, since it is common for the centroid of the beam to be off axis by one or two beam radii (rms), these depolarizing effects should precess the average spin vector by an amount equal to or greater than the random precession that causes depolarization. We have measured this average precession many times and never found it to be greater than 6°. Since cos 6° is 0.995, this indicates $\leq 0.5\%$ depolarization.

Within the ion source we have attempted to check depolarization by varying the fields and measuring the effective analyzing power in each case. Approximately doubling the field in the argon cell (and transition region) made a change of $(0.0 \pm 0.4)\%$, while reducing the field by a factor of 4 made a change of $(0.4 \pm 0.9)\%$. Similarly, a 30% increase in the ion source rf field gave a change of $(0.0 \pm 0.5)\%$.

We have repeated these 800 MeV calibrations on four separate occasions spread over two years. Internal consistency has ranged from 0.4 to 0.6%, while the four calibrations have a spread of ±0.5%. We assign a random error of ±0.5%. Depolarization can affect the result in only one direction. Adding in quadrature the 0.5% random error, 0.5% for ion source depolarization, and 0.5% for accelerator depolarization gives 0.9%, which is consistent with the 1% estimate in our earlier letter.[1]

It has been observed[14,20] that the polarized and unpolarized components of the beam have different phase space so that phase-space selection by beam stripping can change the average polarization. It is therefore essential to measure the quench ratio at the scattering target. We obtained good agreement between three intensity monitors: the sums of left plus right and up plus down polarimeter counts, and an adjacent ion chamber.

An independent check of the quench ratio calibrations using a polarized target at LAMPF is reported in our recently published paper[6] "Measurement of the Spin Correlation Parameter A_{nn} in *pp* Elastic Scattering at 796 MeV." The ratio of the polarization calibrations from the independent quench ratio and NMR techniques is reported as

$$\frac{P(\text{quench})}{P(\text{NMR})} = 1.002 \pm 0.005$$

(differing slightly from the preliminary figure quoted previously).[1] The half percent uncertainty represents internal fluctuations and does not include overall systematic errors in either technique. These are difficult to determine reliably, but we estimate ±2% for the NMR calibration. The cross calibration with the TRIUMF data reported below provides a further independent check at the ±2% level.

We conclude, therefore, that our best estimate of the normalization uncertainty for the 796 MeV analyzing power measurements is $(^{+1}_{-0.5})$%. This uncertainty has not been included in Table I and should be applied equally to all data (present and previous[1]) at 796 MeV.

Measurements at 428 MeV. The 428 MeV data (Table II) were taken to compare with the double-scattering measurements from TRIUMF.[2,4] Unfortunately, the behavior of the LAMPF ion source was unusual during this cross calibration, casting some doubt on the 428 MeV calibration. On this occasion, the residual polarization of the quenched beam P_q was ten times large than usual and had the opposite sign. Since we do not understand the origin of this anomaly, the resulting 3% correction term P_q/Q (Sec. III) is of doubtful validity. Two calibrations at 796 MeV made at this time were 0.6% and 1.5% lower than usual. Consequently, we have multiplied the 428 MeV data by a correction factor of 1.01 and increased the uncertainty. An overall normalization uncertainty of ±2% should therefore be applied equally to all data at 428 MeV. The results compare well with TRIUMF results (Fig. 2).

IV. CONCLUSIONS

We have obtained high precision analyzing power data at 796 MeV. The uncertainties are roughly an order of magnitude less than previous data[23] in this energy region. This precision is possible due to the high beam quality resulting in low backgrounds as well as the unique opportunities for beam polarization calibration utilizing the quench ratio method. Such precise data is important in constraining phase parameter searches, and models of the resonancelike structure observed near 800 MeV.

The 796 MeV data are shown in Fig. 1 in comparison with our previous data and a recent phase shift solution (CD79) from the program NNSCAT of Arndt *et al.*[24] The discrepancy at forward angles

TABLE I. Analyzing power A of *pp* elastic scattering at 796 MeV. The overall normalization error of $(^{+1}_{-0.5})$% has not been included.

θ_{lab}	$\theta_{c.m.}$	A	ΔA
5.22	12.44	0.2652	0.0259
6.12	14.58	0.2930	0.0084
6.67	15.89	0.3210	0.0050
6.81	16.22	0.3338	0.0085
7.50	17.86	0.3433	0.0031
8.32	19.80	0.3711	0.0042
9.21	21.90	0.3959	0.0046
9.99	23.74	0.4155	0.0031
10.81	25.67	0.4294	0.0043
11.30	26.82	0.4397	0.0080
12.47	29.57	0.4491	0.0059
13.70	32.44	0.4695	0.0081
13.79	32.65	0.4809	0.0096
14.98	35.42	0.4882	0.0071
15.82	37.37	0.4956	0.0080
16.20	38.24	0.4888	0.0102
16.97	40.02	0.5043	0.0059
18.17	42.78	0.4990	0.0090

TABLE II. Analyzing power A of *pp* elastic scattering at 428 MeV. The overall normalization error of ±2% has not been included.

θ_{lab}	$\theta_{c.m.}$	A	ΔA
15.76	34.73	0.4744	0.0053
17.00	37.43	0.4757	0.0038
18.22	40.08	0.4772	0.0053
22.76	49.87	0.4062	0.0035
24.00	52.52	0.3868	0.0025
25.23	55.15	0.3629	0.0035

indicates that these new data will significantly constrain the phase shift analysis at 800 MeV.

Two of our 428 MeV data points are shown in Fig. 2 superimposed on a graph adapted from a recent TRIUMF paper.[2] The agreement is good. This agreement indicates that both the quench ratio method used at Los Alamos and the double-scattering experiments at TRIUMF are correct within the stated uncertainties.

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