Production data acquisition for the experimental test of charge symmetry in 183-MeV $n-p$ scattering occurred during the period from August, 1987 to September, 1988. By summer 1989, the analysis of the data had progressed far enough to reveal clear charge-symmetry-breaking (CSB) effects. These preliminary results are shown in Figs. 1 and 2 and discussed below (see also Refs. 1,2). A final replay of all the data, incorporating a number of refinements aimed primarily at a better quantitative assessment of the magnitude of some systematic errors in the results, is now nearly completed. We hope to submit papers reporting the final result for publication in Summer, 1990.

We have measured the difference $\Delta A(\theta) = A_n(\theta) - A_p(\theta)$ between the analyzing powers associated with flipping the neutron spin ($A_n$) and the proton spin ($A_p$) in $n-p$ scattering. This difference would vanish in the absence of Class IV CSB potentials, which have isovector terms antisymmetric under interchange of the two nucleons. The most important direct electromagnetic source of such potentials is the spin-orbit interaction between the neutron’s magnetic moment and the proton current; its effects are generally smaller in magnitude than those expected to arise from strong-interaction CSB (e.g., associated with the inferred mass difference between up and down quarks). This situation represents a great advantage in interpretability for the $n-p$ experiment, in comparison with more traditional searches for $n-n$ vs. $p-p$ potential differences (Class III CSB potentials), where one must rely on a very accurate evaluation and subtraction of Coulomb effects that account for $\lesssim 90\%$ of any observed differences.

In comparing experimental results to calculations for $\Delta A(\theta)$, one must be aware of an inherent ambiguity in the measurements, which arises because there are not known methods for sufficiently accurate ($< 0.1\%$) absolute determination of the beam ($P_b$) and target ($P_t$) polarizations. Since strictly we measure the asymmetries $P_b A_n(\theta)$ and $P_t A_p(\theta)$, our experimental uncertainty (a few %) in the ratio $P_b/P_t$ renders us insensitive to contributions to $\Delta A(\theta)$ whose sole effect would be a small normalization difference between $A_n(\theta)$
and $A_p(\Theta)$. Such would be the effect of any term in $\Delta A(\Theta)$ proportional to the average analyzing power $A_n(\Theta) \equiv [A_n(\Theta) + A_p(\Theta)]/2$. In other words, the best we can do strictly is to determine a quantity

$$\Delta A(\Theta) = \Delta A_{\text{true}}(\Theta) + C \cdot A(\Theta),$$

where $C$ is a constant whose value depends on the (unknown) deviation of our best estimate for $P_b/P_t$ from the true value of this ratio.

There are several possible approaches to circumventing the ambiguity in "$\Delta A(\Theta)$". The one followed in a previous measurement at a bombarding energy of 477 MeV was to confine attention to the single angle ($\Theta_o = 71^\circ$ c.m.) where $A(\Theta)$ crosses zero, via precise independent measurements of the zero-crossing angles for $A_n(\Theta)$ and $A_p(\Theta)$. The TRIUMF result "$\Delta A(\Theta_o) = \Delta A_{\text{true}}(\Theta_o) = (47 \pm 22 \pm 8) \times 10^{-4}$ (the second quoted error is systematic) is shown in the right-hand frame of Fig. 1 for comparison to the present result. Our approach has been to make measurements over a broad range of angles simultaneously, thereby ensuring that $P_b/P_t$ at least does not change from angle to angle. We can then reduce our measurements to a single unambiguous result, analogous to the TRIUMF datum, by averaging "$\Delta A(\Theta)$" over any ("magic") angle range for which the average value of $A(\Theta)$ happens to vanish:

$$<\Delta A(\Theta)>_{\text{magic angle range}} = <\Delta A_{\text{true}}(\Theta)>_{\text{magic angle range}}.$$

In Fig. 1 we present our preliminary result for one specific "magic" range, $82.2^\circ \leq \Theta_{\text{cm}} \leq 116.1^\circ$ (straddling the $A(\Theta)$ zero-crossing at $\Theta_o = 96^\circ$):

$$<\Delta A(\Theta)>_{82.2^\circ - 116.1^\circ} = (32.1 \pm 6.1 \pm 6) \times 10^{-4}.$$

If we combine statistical and systematic errors in quadrature, the latter result differs from zero by 4 standard deviations and, more significantly, from the value expected (averaged over the same angle range) from the electromagnetic spin-orbit interaction (labeled $\gamma$ in Fig. 1) by 3 standard deviations. This difference represents the strongest experimental evidence to date of CSB in the nuclear force.

Despite the ambiguity embodied in eq. (1), we can furthermore extract useful information on the angular dependence of $\Delta A$ from our measurements. One technique for comparing the measured and calculated angular distributions yields the results shown in Fig. 2. The experimental points here have been extracted from the measured asymmetries by adjusting $P_b/P_t$ (and, hence, the constant $C$ in eq. (1)) until the resulting "$\Delta A$" data set (specifically, the data in the range $68^\circ \leq \Theta_{\text{cm}} \leq 121^\circ$) has the minimum possible variance. In so doing, we effectively select that component of $\Delta A_{\text{true}}(\Theta)$ that is uncorrelated with $A(\Theta)$, in the sense that

$$<A(\Theta) \cdot \Delta A(\Theta)>_{68^\circ - 121^\circ} = <A(\Theta)>_{68^\circ - 121^\circ} \cdot <\Delta A(\Theta)>_{68^\circ - 121^\circ}.$$

For any theoretical calculation of $\Delta A(\Theta)$, we can select out the analogous component for comparison to experiment by following the same procedure, i.e., taking $\Delta A_{\text{true}}(\Theta) + C \cdot A(\Theta)$ and adjusting $C$ to minimize the variance of the result over the same angle range ($68^\circ - 121^\circ$). Had we chosen an alternative prescription for optimizing $C$, both the experimental and theoretical results in Fig. 2 would be modified slightly, but the comparison of theory to experiment (e.g., as measured by $\chi^2$) would be unaffected.
Figure 1. Measured and calculated values of the charge-symmetry-breaking observable $\Delta A$ for n-p scattering at $T_n = 183$ MeV (present preliminary result) and $T_n = 477$ MeV (from Ref. 7.) The solid error bars are purely statistical, while the dotted extensions indicate the effect of adding systematic errors in quadrature. The solid and broken horizontal lines represent theoretical predictions based on the Bonn NN potential for various contributing diagrams, as described in the text.

Calculations of CSB effects arising in meson-exchange potentials for the n-p system have been made by a number of groups. The ones represented by solid and dashed lines in Fig. 1 are based on results obtained by Holzenkamp, Holinde and Thomas (HHT) using the momentum space Bonn N-N potential. The dashed lines in Fig. 1 include, in addition to the electromagnetic contribution, the isovector potential term arising from single-$\pi$ and single-$\rho$ exchange when the n-p mass difference is taken into account. With the inclusion of these effects, the calculated value agrees with the TRIUMF measurement at 477 MeV but still falls significantly ($\sim 2\sigma$) short of our result at 183 MeV. Good agreement is obtained at 183 MeV when the calculations include also the mixing of $\rho^0$ and $\omega^0$ mesons, using a mixing matrix element determined empirically from $e^+e^- \rightarrow \pi^+\pi^-$ measurements in the mass region of the $\omega^0$. Despite the short range of the $\rho - \omega$ mixing Class IV potential, it produces much more readily measurable effects at 183 than at 477 MeV. This occurs because at 477 MeV the $\rho - \omega$ contribution to $\Delta A(\Theta_0)$ happens to cross zero at very nearly the same angle ($\Theta_0$) as does $A(\Theta)$. It then not only contributes negligibly to $\Delta A(\Theta_0)$ (as seen in the right-hand frame of Fig. 1), but also its effect on the angular distribution in
Figure 2. Comparison of the measured angular distribution for $\Delta A$ with calculations from Refs. 4 and 5, which employ different distorting potentials and quite different $\rho NN$ and $\omega NN$ coupling constants. Both the experimental results and the theoretical curves have been subjected to the "$\Delta A$" variance minimization procedure described in the text. The error bars shown are statistical; systematic errors are typically about one-third as large as the statistical uncertainties for each individual angle bin. The total $\chi^2$ values specified first are for inclusion of statistical errors only, with the values in parentheses reflecting the effect of adding systematic errors in quadrature. The arrow marks the angle at which the average analyzing power $A(\theta)$ crosses zero.

The full Bonn potential calculation, including the $\rho - \omega$ mixing, is represented by the solid curve in Fig. 2, where one can see that it also provides excellent agreement with our measured angular distribution ($\chi^2$/point = 0.6 when statistical and systematic measurement errors are included). The largest uncertainty in the calculations arises from the poorly known values of the $\rho NN$ and $\omega NN$ coupling constants, and is reflected by the difference between the solid and dot-dashed calculations in Fig. 2. The HHT calculation uses the relatively large coupling constants ($g^2_\rho/4\pi \approx 0.77, g^2_\omega/4\pi \approx 23$) characteristic of the Bonn potential. The Beyer-Williams$^5$ calculation employs smaller values ($g^2_\rho/4\pi = 0.55, g^2_\omega/4\pi = 8.1$), based on dispersion analyses of low-energy NN and $\pi N$ scattering data, together with the Reid soft-core potential for evaluating distortion effects. The agreement
between the latter calculation and our measured angular distribution is also reasonable, but about 3 standard deviations worse than in the HHT case. Thus, our experimental results favor the stronger vector meson coupling constants, although they do not rule out the smaller values.

The importance of $\rho - \omega$ mixing has also been suggested by recent theoretical explanations of other manifestations of CSB: the apparent difference between $nn$ and $pp$ scattering lengths, the $^3H-^3He$ binding energy difference, and the $A$-dependence of the Nolen-Schiffer anomaly. It now appears possible to account for all of these observations reasonably quantitatively, with consistent calculations, when the strong $g_\rho$ and $g_\omega$ values are used. This represents a great advance in our understanding of both charge symmetry violations in nuclear physics and the NN interaction at separations $\lesssim 1$ fm.