Physics in a Mirror:  
The TRIUMF 221 MeV $pp$ Parity 
Violation Experiment

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Abstract

We measure the difference in the scattering probability when an experiment scattering longitudinally polarized 221 MeV protons from liquid hydrogen is replaced by its mirror image. The result depends on the interplay between the weak and strong interactions in the Interesting region near the surface of the proton. The experiment is technically very challenging and requires elaborate precautions to measure and correct for various sources of systematic error.
1 INTRODUCTION

Fig. 1. The parity operation flips all three axes, which is equivalent to a mirror reflection plus a $180^\circ$ rotation. In this example, it would be a reflection in the $yz$-plane and a rotation about the $x$-axis. Because we can assume rotational invariance, parity inversion is often thought of as a mirror reflection.

Measuring the effects of the Weak Interaction between two protons in the presence of the Strong Interaction, some ten million times stronger, presents a unique set of difficulties. The measurement is only made possible by the fact that the strong force treats right-handed (spin aligned along the direction of motion like a right-handed screw) and left-handed particles equally, while the weak force favours left-handed particles. In fact, of the $W$ and $Z$ bosons which carry the weak force, the $W$s act only on left-handed particles, and the $Z$ acts much more strongly on left-handed particles. In the jargon of the field, the strong interaction is said to “conserve parity” or to be “invariant under the parity transformation”, a transformation that reflects each coordinate through the origin ($\vec{r} \rightarrow -\vec{r}$, see figure 1). The weak interaction, on the other hand, is not invariant under such a transformation, and is said to “violate parity”. In an experiment now underway at TRIUMF, a beam of protons with their spins aligned along the direction of motion is passed through a proton target (liquid hydrogen), and the fraction scattered when
the protons in the beam have their spins aligned along the beam direction is compared with the fraction scattered when the spin is opposite to the beam direction. Because these two cases differ only in that they are mirror images of each other, any difference will be an indication of the “parity violating” weak interaction. The difference is expressed as the parity violating longitudinal analyzing power $A_z = (\sigma^+ - \sigma^-)/(\sigma^+ + \sigma^-)$ where $\sigma^+$ and $\sigma^-$ are the scattering probabilities for positive (right-handed) and negative (left-handed) helicity respectively. The TRIUMF experiment expects to measure $A_z$ with a statistical uncertainty of $\pm 0.2 \times 10^{-7}$ and a systematic error of $\pm 0.2 \times 10^{-7}$. The major technical difficulty to be overcome in such an experiment is to be sure that when the proton spin is “flipped” from right handed to left handed, that the change in all other beam properties is either zero, or small and measured accurately enough that its effects can be corrected. The TRIUMF experiment measures, and corrects for the effects of, beam current, position, direction, size, and transverse polarization. Most of the time in such an experiment is spent understanding and controlling all the sources of systematic error. The current measurement is being made at 221 MeV, where the theoretical interpretation of the result is simplified as explained in the next section.

### 1.1 Choice Of Energy

In describing the scattering of an incident parallel beam of particles, it is common in nuclear physics to express the incident quantum mechanical “plane wave” in terms of a sum of “partial waves”, each with a specific angular momentum which is conserved in the scattering. The effect of a scattering interaction can then be described in terms of the phase shift it gives to each partial wave. Figure 2 shows the analyzing power, $A_z$, which we are measuring, broken down into contributions from the lowest three partial wave mixings. At low energies, $A_z$ arises almost completely from the $^1S_0 - ^3P_0$ parity-mixed partial wave\footnote{For historical reasons, the archaic notation $^{2S+1}J_{\ell}$ is normally used, where $\ell$ is the orbital angular momentum, with $\ell = S, P, D, F...$ denoting $\ell = 0, 1, 2, 3...$ respectively, $J$ is the total angular momentum, and $S$ is the total spin. Since parity is given by $(-1)^\ell$, $S$ and $P$ have opposite parity as do $P$ and $D$.}, while at the energy of the TRIUMF measurement, this contribution vanishes and $A_z$ arises essentially exclusively from the $^3P_2 - ^1D_2$ parity-mixed partial wave.
Fig. 2. Contributions to the parity violating longitudinal analyzing power, $A_z$, as calculated by Driscoll and Miller [1] for the first three parity mixed partial waves. The energy of the TRIUMF experiment is chosen so that only the PD wave contributes. Data taken at Bonn [2], PSI [3], and LANL [4] are also shown. The TRIUMF point is preliminary, from Hamian’s [8] analysis of one data set. The experiment is designed to obtain a final uncertainty similar to Bonn and PSI.

Because it is impossible to tell whether a given proton was scattered by the strong or the weak interaction, the rules of quantum mechanics dictate that we add the complex “scattering amplitudes” rather than the cross-sections (scattering probabilities). In the expression for $A_z$, all that remains are the “interference terms” involving the product of strong and weak interactions. The nature of the two interactions is such that the shape of the $A_z$ curve is set by the strong interaction while the sign and absolute scale is set by the weak interaction. Since the strong proton-proton interaction is already very well measured, it is possible, without knowing the weak interaction, to accurately determine the energy at which the $SP$ contribution crosses zero.

Just as the electromagnetic force between two electrons is interpreted as due to the exchange of photons between them, the strong force between two protons can be described by the exchange of mesons between them. The analyzing powers in figure 2 were calculated by Driscoll and Miller[1] using such a meson exchange model. In this calculation, the $SP$ contribution arises roughly equally from $\rho$ and $\omega$ meson exchange, whereas the $PD$ contribution
arises almost exclusively from $\rho$-meson exchange. By measuring at an energy where the $SP$ contribution integrates to zero over the acceptance of our apparatus, the TRIUMF experiment will be able to determine the value of the weak $\rho$ meson-nucleon-nucleon coupling constant $h_\rho$, a number that is now known only very poorly. Figure 3 shows the $PD$ contribution for a range of $h_\rho$ considered “reasonable” by Desplanques, Donoghue, and Holstein \cite{5}. The TRIUMF measurement will constrain this range significantly.

Also significant is the fact that at 221 MeV, the $^3P_2 - ^1D_2$ wave corresponds to an interaction near the surface of the proton. This probes an intermediate region between the long range interaction which can be considered strictly meson exchange and the very short range part where the interaction takes place between the quarks of the proton. The extent to which quark degrees of freedom are important here is an interesting question. For example, taking explicit account of quark degrees of freedom, Grach and Shmatikov \cite{6} calculate $A_z = 2.4 \times 10^{-7}$ at 230 MeV compared to the $A_z = 0.6 \times 10^{-7}$ from the meson exchange calculation of Driscoll and Miller \cite{1} referred to earlier. Adding an intermediate $\Delta$ to the meson exchange calculation, Iqbal and Niskanen \cite{7} calculate $A_z = 1.1 \times 10^{-7}$ at the same energy. Clearly a good measurement is needed.

Fig. 3. Contribution to $A_z$ from the parity mixed partial wave (PD) to which the TRIUMF experiment is sensitive. The solid curve shows the result of Driscoll and Miller’s [1] calculation using the DDH [5] “best guess” value for $h_\rho$, and the dotted curves show what would be expected if $h_\rho$ varied over the DDH “reasonable range”. The fictitious data point shows the error bar expected from the TRIUMF measurement and illustrates how such a measurement will significantly constrain the range of $h_\rho$. 

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2 THE EXPERIMENT

Fig. 4. Heart of the experiment, showing the target and main detectors. TRIC1 and TRIC2 are ion chambers containing hydrogen gas at approximately 1/5 atmosphere pressure. The target is 40 cm of liquid hydrogen.

Figure 4 shows the principle of the experiment. A 200 nA beam of protons with energy 221 MeV passes through the first detector (Transverse Ion Chamber 1, or TRIC1), then 40 cm of liquid hydrogen, and finally through the second detector (TRIC2). The first detector measures the beam current before the target, the second detector measures the beam current after the target, and a precision subtractor takes the difference between the two signals. The detector and electronic gains are adjusted to make the output of the subtractor zero with unpolarized beam.\(^2\) If there is a parity violating analyzing power for \(pp\) scattering at this energy, then the scattered fraction (\(\sim 4\%\)) will be slightly more or slightly less than the unpolarized case.

\(^2\)For those interested in technical details, I point out that we are interested in the AC part of the signals, and that the fine gain adjustment is made for best common-mode rejection at the spin flip frequency. This reduces both shot noise and the sensitivity to helicity correlated changes in beam current.
pending on the helicity of the beam. A signal synchronized with the helicity
and whose magnitude is proportional to $A_z$, will appear at the output of the
subtractor. This signal is very small. For example, if $A_z = 0.6 \times 10^{-7}$ and the
longitudinal polarization is 80%, we must measure a difference signal only
$2 \times 10^{-9}$ of the TRIC signal, a feat comparable to measuring the thickness
of a piece of paper in a 40 km measurement.

Upstream of TRIC1 are Intensity Profile Monitors and Polarization Prof-
file Monitors (IPMs and PPMs in figure 7) which measure the distribution
of intensity and transverse polarization across the beam.

2.1 Data Acquisition

To recover such a small signal, we use synchronous detection, the same prin-
ciple used by lock-in amplifiers. The data are binned according to spin state
and differences which are uncorrelated with spin state average out with time,
whereas helicity correlated differences do not.

The data are taken in $\frac{1}{60}$ second (200 ms) cycles, each cycle consisting of
eight $\frac{1}{40}$ second (25 ms) spin states arranged in the pattern $(+\ -\ -\ -\ +\ +\ +\ -$)
or its complement. The cycles are further arranged in a “super-cycle” with
the starting spin state of each cycle following the same eight state pattern.
The starting spin state of each supercycle is chosen at random. This data
taking pattern cancels both linear and quadratic drifts.

Each 25 ms spin state is divided into polarization measuring and asym-
metry measuring intervals as shown in figure 5. The main integration period
is set for exactly $\frac{1}{60}$ second to reject 60 Hz line frequency noise and all its
harmonics.

Fig. 5. Intervals during each spin state. First the PPM (Polarization Profile Mon-
itor) scans a $CH_2$ blade through the beam to measure the polarization distribution
across the beam, then the beam currents and profiles are measured by the TRICs
(Transverse Ion Chambers) and IPMs (Intensity Profile Monitors).
2.2 Sources Of Error

Sources of error can be divided into those which are related to the beam helicity and those which are not. Beam property changes which are synchronized with spin flip (“coherent” or “helicity correlated” changes) can, and usually do, produce a false signal of parity violation. Things which are not helicity correlated, such as detector noise and random variation in beam properties, do not bias the result, but only increase the run time required to reach a given precision.

2.2.1 RANDOM CHANGES

The ultimate limit to the statistical precision of the experiment is that determined by the counting statistics of the scattered protons, a limit which could be reached if we were able to count individual scattered protons. Then $A_z$ could be measured to $\pm 0.2 \times 10^{-7}$ in 20 hours. In practice, the count rate of the scattered protons is too high ($\sim 50$ GHz) for direct counting and the experiment measures currents instead. With our existing detector configuration, the running time for a $\pm 0.2 \times 10^{-7}$ precision rises to approximately 300 hours, largely because of detector noise.\(^3\)

In addition to detector noise, random variations in beam properties such as intensity or position contribute to noise in the signal and increase the required run time.

2.2.2 HELICITY CORRELATED CHANGES

Helicity correlated changes in beam properties can produce a false $A_z$ signal. This false signal is dealt with in different ways:

- Careful design and operation of the TRIUMF polarized ion source and cyclotron makes it possible to change the spin direction with the absolute minimum of effect on other beam properties.

- The parity equipment and operating conditions are carefully chosen to minimize the sensitivity to helicity correlated changes.

\(^3\)We could match this with a counting experiment by reducing the beam current to count at $\sim 1.5$ GHz. This rate is still impractically high and it is easier to use the higher beam current and put up with detector noise.
- The beam properties are accurately measured during data taking so the actual helicity correlated changes are known for each data set.

- Calibration runs determine the sensitivity to helicity correlated modulations so that corrections can be made.

Transverse polarization, beam intensity, position, and size are all measured and the resultant false effects are corrected for.

Fig. 6. The effect of transverse components of polarization. The two diagrams use a pencil beam with vertical polarization to illustrate the mechanism. In both cases, because the strong interaction analyzing power is positive in this example, the scatterer causes more beam to be scattered to the left in the positive spin state and more to the right in the negative spin state. In the left-hand diagram, since the beam passes through the center of the detector, there is no difference in the detector response for the two spin states. In the right-hand diagram, however, the beam is left of center at the detector, so the signal is larger in the negative spin state, causing a false signal of parity violation. The false signal is proportional to the size of the transverse component multiplied by the distance off center – a quantity called the \textit{first moment} of transverse polarization. A real beam of finite extent is made of a bundle of such pencil beams, and can have a first moment of transverse polarization even if its average transverse polarization is zero. For example, spin could be up on one side of the beam and down on the other.

**Transverse Polarization** If the proton spin is not perfectly longitudinal, the small transverse component will reverse with helicity. As explained in the caption to figure 6, the false signal is proportional to the product of the

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transverse component and the distance that the beam is off center. This product is referred to as the \textit{first moment} of transverse polarization. First moments of transverse polarization are the most difficult property for us to measure and are the main source of systematic error.

To determine first moment sensitivities, test runs are made with pure vertical and pure horizontal polarization. By scanning the vertically polarized beam horizontally and the horizontally polarized beam vertically, we are able to determine our sensitivities to the first moments $xP_y$ and $yP_x$, and to find the beam position at which there is no sensitivity to average transverse polarization. This axis, where transverse polarization components cause no false effect, is called the \textit{polarization neutral axis}.

In analyzing the effect of first moments, we separate \textit{extrinsic} first moments caused by a beam whose centroid is displaced from the neutral axis and which has some average transverse polarization, and \textit{intrinsic} first moments which do not depend on the position of the beam centroid but rather arise from the distribution of transverse components within the beam. By using fast ferrite-cored steering magnets servoed to the intensity profile monitors (IPMs in figure 7), we are able to hold the beam on the polarization neutral axis and virtually eliminate corrections for \textit{extrinsic} first moments. \textit{Intrinsic} first moments, on the other hand are independent of beam centroid position, arise in the cyclotron and beamline, and are very hard to control. Corrections for intrinsic first moments are typically the only corrections which are not consistent with zero when averaged over a one month running period.

By measuring the distribution of transverse components of polarization at the two Polarization Profile Monitors (PPMs in figure 7) we are able to use our measured first moment sensitivities to correct the data for the effects of first moments. The PPMs are able to determine first moments to $\pm 5\mu m$ in a one hour run. For a one month data taking period, the final correction to the raw $A_z$ is substantial, of the order $10^{-7}$, and uncertainty in the correction increases the uncertainty in the final $A_z$. For example, in the Hamian's\textsuperscript{8} analysis of the February, 1997 data set, the statistical uncertainty of $\pm 0.58 \times 10^{-7}$ was increased to $\pm 0.65 \times 10^{-7}$, primarily by uncertainty in the first moment corrections.
Fig. 7. Schematic of the whole Parity Experiment. Every item, from the ion source (OPPIS) to the end of the beamline, must be optimized to reduce systematic errors.

**Beam Intensity** If the gains are properly set, the beam currents before and after the target subtract perfectly and we are blind to beam current changes. In practice this “common mode rejection” is good\(^4\), but is not perfect, and it drifts slightly with time.

During normal operation, the coherent intensity modulation which accompanies spin flip ranges from approximately \(2 \times 10^{-5}\) to \(8 \times 10^{-5}\) of the 200 nA beam current. To determine what effect this has on the measured \(A_z\), 1.6 seconds out of every 16 are devoted to running with the ion source unpolarized and the beam intensity artificially modulated by a laser (“photodetachment laser” in figure 7) which co-propagates with about 30 m of the \(H^-\) beam prior to injection into the cyclotron. When this laser is on, electrons are removed from some of the \(H^-\) ions and these are then not accelerated. This gives us data with large (\(\sim 0.2\%\)) pure intensity modulation interleaved with the primary data. The false \(A_z\) produced by the photodetachment laser is then scaled using the measured value of intensity modulation recorded during the real data, and a correction can be made.

\(^4\)Of the order 80 to 90 db.
**Beam Position Modulation** The beam profiles are measured during each spin state using two $x-y$ Intensity Profile Monitors (IPM1 and IPM2 on figure 7). From this the beam centroid, size, and skewness are calculated and the mean and helicity correlated values are extracted. The false $A_z$ arising from helicity correlated motion is proportional to the size of the motion and the distance the beam is off the “neutral axis” of the experiment. To calibrate the sensitivity to coherent position modulation, a series of test runs are made in which fast ferrite-cored steering magnets are used to intentionally introduce a series of large coherent position changes. Enough different beam positions and modulations are recorded to describe our sensitivity to position motion. During real data taking we find that the actual beam position modulation with spin flip is at the limit of our detection ability (0.1$\mu$m in a one-hour run) and overall corrections for position modulation are insignificant.

**Beam Size Modulation** The same Intensity Profile Monitors which determine the beam position for each spin state also determine the beam size. If the beam size changes on spin flip, more or less of the beam tails will be clipped by the finite detector aperture and a false signal will appear. To calibrate our sensitivity to size modulation, large, intentional size modulation is introduced using two fast ferrite-cored quadrupole magnets. We find that our apparatus is very sensitive to size modulation. Fortunately the actual coherent size modulation with spin flip is very small ($< 0.1\mu$m on a 5mm beam) and its effect on our final $A_z$ averages to near zero.

**Energy Modulation** The gain of the hydrogen-filled ion chambers used as our main detectors is given by the number of electron-ion pairs produced by a proton going through the active region. As the beam energy is lowered, the energy loss per unit length ($\frac{dE}{dx}$) goes up and the gain increases. Because the proton beam loses approximately 27 MeV in the liquid hydrogen target, the gas gain in the downstream chamber rises more rapidly with a drop in beam energy than does the gain in the upstream chamber. The result is that a coherent beam energy modulation produces a false $A_z$ signal. In fact, the experiment is very sensitive to coherent energy modulation with $\frac{\partial A_z}{\partial E} = 2.8 \times 10^{-8}$ per eV.

It is normally possible to keep energy modulation at the ion source at the few milli-eV level, and it is known that the injection system and cyclotron
will multiply this by a factor of about 100, so we believe that coherent energy modulation does not bias our $A_z$ significantly. Nevertheless, the amplification factor can vary quite a bit and we are not able to measure the coherent energy modulation directly to the required precision during running, so another approach is adopted to minimize such effects.

It is possible to tune our beamline so that spin-up from the cyclotron becomes either positive or negative helicity at the parity apparatus. If the spin-up state always has, say, a slightly higher energy than the negative state, then when we switch the beamline helicity, asymmetry arising from true $A_z$ will reverse, but that from energy modulation will not. By averaging the apparent $A_z$ from the two different beamline helicities, effects of energy modulation should cancel out.

2.3 State Of The Data

In experiments such as this, most of the time is spent doing development and control measurements to understand and minimize sources of systematic error. Following some years of developing detectors and diagnostic equipment, the experiment was finally mounted on a new beamline 4A2 at TRIUMF in late 1994. 1995 and much of 1996 were spent improving the performance of the TRIUMF cyclotron and ion source, and refining our systematic error controls. A major data taking run was made in February and March of 1997. This data has been analyzed and a preliminary result reported by Hamian[8]. She obtained an overall uncertainty of $\pm 0.65 \times 10^{-7}$. Another major run from July and August of 1998 is now being analyzed. With the addition of a run planned for the summer of 1999, we should have enough data to determine $A_z$ with an uncertainty of $\pm 0.3 \times 10^{-7}$, adequate to significantly improve our knowledge of the weak meson-nucleon-nucleon coupling constant, $h_\rho$.

3 CONCLUSION

Proton-proton parity violation experiments are technically demanding, but provide a unique window on the interplay of strong and weak interactions. The TRIUMF 221 MeV measurement probes a very interesting region near the surface of the proton, between the quarks inside the proton and the pion exchange of more distant interactions. In terms of meson exchange, it is sensitive only to the $\rho$-meson exchange. The experiment is expected to finish
data taking in 1999 and a final result should be available in 2000.

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