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Design concepts and detectors for parity violation experiments

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Summary. — Throughout the last fifteen years, a number of experiments on parity violation in elastic electron nucleon scattering have been carried out, especially at Jefferson Lab and at the Mainzer Mikrotron facility MAMI. While the main challenge —the precise measurement of tiny cross-section asymmetries of order 10^{-6}— was the same for all those experiments, quite different approaches were employed by the experimentalists. The diversity in the used techniques will be pointed out to give an overview of the achieved experience with such high-precision measurements.

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1. – Introduction

The techniques developed in the course of recent parity violation experiments at particle accelerators paved the road for a number of future experiments aiming for even higher sensitivity and precision as was almost unimaginable fifteen years ago. The diversity of concepts will be depicted by reviewing some of those experiments. Finally a short outlook on future experiments is given.

2. – General requirements for accelerator PV experiments

The cross-section asymmetries in parity violation experiments are typically of order 10^{-6} (ppm) or even smaller. Therefore new experimental techniques had to be invented and existing methods needed to be further developed and refined. Sources for electron beams with high degree of polarization of order 80% and capable of delivering high currents (order 100 μA) have been developed. To understand and control the systematics of the experiments the accelerator beams need to be stabilized and the beam helicity to be rapidly switched to take advantage of the short term stability of the corresponding particle detectors and data acquisition systems. Helicity correlated as well as non-helicity correlated beam properties have to be measured and recorded and fed back into the stabilization systems of the accelerators to provide the experimentators with what is known as "parity beam" today. To detect or exclude more subtle systematic effects, addititonal checks are state of the art in today's parity violation experiments, such as flipping the meaning of the signs of the beam helicity signals in the experiment electronics by inserting an additional half-waveplate in the polarized source laser optics.

When all these measures are applied, it is possible to measure asymmetries on the level of 10^{-6} routinely as for example in the A4 experiment at MAMI. Other experiments as for example Q_{weak} at Jefferson Lab measure physics asymmetries of only $0.2 \cdot 10^{-6}$ already, and even more sensitive experiments are planned for the next decades.

To measure an asymmetry of 10^{-6} with an uncertainty of 1% from counting statistics means one has to detect 10^{16} scattered particles.

At a rate of $10^{9}\,\text{s}^{-1}$ this would still take 115 days of measuring time (live time!). Therefore parity violation experiments need to run at very high luminosity and particle detection rates to produce results in a reasonable amount of time. High power cryotargets had to be newly developed, like the 250 W 10 cm liquid hydrogen target used in the A4 experiment at MAMI. Today the power range has been significantly extended by more than one order of magnitude by the Q_{weak} target that needs to be provided with 2500 W of cooling power to handle the heat load of the electron beam.

3. – Experimental concepts

The following section gives an overview of the main concepts and features of selected recent parity violation experiments at accelerators. There are two main groups of experiments: counting and integrating experiments. In integrating experiments detectors are read out using analog integrators to integrate the electrical current from the detector. In a counting experiment the signals caused by individual detected particles are counted. Data (integrated current or number of events) are recorded separately for both beam helicities.

For counting experiments the granularity of the detector are chosen so that count rates of individual detector modules can still be handeled without excessive dead-time and pile-up correction.

Especially in integrating experiments the response of the detector and possible background contributions need to be studied carefully and are therefore determined in special runs using additional tracking detectors that are turned off during normal data taking. In contrast the data from a counting experiment can still contain explicit information about the background situation as for example in the A4 experiment, where it is used in the offline analysis to minimize and control systematic contributions from background processes.

The helicity of the beam is switched rapidly, for example at the frequency of the power line, to cancel out humming in the beam parameters and detector properties at the power line frequency and higher harmonics. Luminosity and beam properties like position, energy and beam current are recorded for each beam helicity window in order to apply corrections to the measured main detector data.

Both methods, counting and integrating, have different advantages and challenges that are addressed in different ways by the following experiments.

3˙1. *HAPPEX*. – The HAPPEX experiment at Jefferson Lab was designed to measure the parity violation asymmetry A_{PV} on hydrogen at $Q^2 \approx 0.47\,\text{GeV}^2$. In order to detect the required number of elastic scattering events total absorbing Cherenkov detectors were employed and the signals from the detectors were integrated rather than counting single events. The elastic events were separated from the inelastic background by the Hall A high resolution spectrometers (HRS). A 20 cm long liquid hydrogen target was required to reach the design luminosity at a beam current of 100 μA causing a 600 W heat load on the target.

The beam helicity was switched at a frequency of 30 Hz to cancel out possible humming from the power line frequency of 60 Hz and quadruple helicity patterns ("$- + + -$" and "$+ - - +$" were chosen to have the same number of switchings from "–" to "+" as from "+" to "–".

To verify and quantify the signal/background separation, special runs in counting mode (*i.e.* non-integrating, single event readout of the detectors) at low beam intensities were taken.

3·2. *A4*. – Around the same time as the HAPPEX experiment, the A4 collaboration was installing another parity violation experiment at the Mainzer Mikrotron (MAMI) in Mainz that is still running today (2012). In contrast to the combination of the integrating technique with the use of magnetic spectrometers for the background suppression of HAPPEX, the concept of A4 is based on the idea of counting every single elastic scattering event. The separation of the background is achieved by an calorimetric energy measurement of the detected particles. Only in the offline analysis the background is then separated from the signal counts by cuts on the energy spectra.

A4 uses a very fast homogenous Cherenkov calorimeter consisting of 1022 lead flouride (PbF_2) crystals covering a range in the scattering angle of $30 < \theta < 40$. PbF_2 was chosen after investigations about components of slow scintillation light in other possible Cherenkov radiators that proved that PbF_2 showed only pure Cherenkov light. It was therefore suitable to build the experiment with an per-channel deadtime of only 20 ns throughout the complete system from crytstal and photomultiplier up to the custom analog and digital histogramming electronics. Thus, running the experiment with count rates of up to $10^8\,s^{-1}$ on the whole calorimeter with typically 90% background and 10% signal contribution is feasible and allowed for the required statistics to measure A_{PV} at $Q^2 = 0.23\,\mathrm{GeV}^2$. The energy resolution of the calorimeter of 3.9% at 1 GeV allows to keep the correction of the measured asymmetry due to π^0 contamination as low as 0.00 ± 0.06 ppm.

Another interesting detail is the 250 W sub-cooled, high flow liquid hydrogen target that is routinely operated without beam rastering. The luminosity is monitored by water Cherenkov monitors (readout integrating over helicity windows) to adjust the target temperature, position and flow and the beam diameter to avoid boiling of the liquid hydrogen.

The helicity pattern is similar to that of HAPPEX, quadruples of 20 ms helicity windows, with the 20 ms PLL-locked to the local power line frequency.

The detector of the A4 experiment was upgraded in 2005 with 72 plastic scintillators to suppress photons from π^0 decay when carrying out measurements under backward angles. It ran sucessfully at six different beam energies ranging from 315 to 1508 MeV with hydrogen and deuterium targets and longitudinal as well as transverse beam spin orientation.

3·3. *G0*. – The G0 experiment was designed as another counting experiment, detecting the scattered protons (instead of electrons as the other experiments do), to measure A_{PV} for $0.1 < Q^2 < 1.0\,\mathrm{GeV}^2$. For the backward runs later in the course of the experiment the electrons were then detected. The separation of the elastic signal from the background was achieved by time-of-flight measurements with a custom TDC readout. A superconducting toroid magnet focussed the particles onto plastic scintillators at rates of order of $10^6\,\mathrm{s}^{-1}$, read out by dedicated histogramming electronics. It needs to be emphasized at this point that due to its special design G0 could cover a large range (one order of magnitude) in Q^2 in a single measurement with the asymmetries on the detectors ranging from 1 to almost 40 ppm. In contrast to that the other experiments discussed here could only measure one (small, integrated-out range of) Q^2 at a time. The high luminosity of G0 required a 1000 W liquid hydrogen target.

In addition to this already very interesting concept, the instrumentation of the eight detector sectors used two different, complementary systems (4 "north-american" and 4 "french" sectors). This approach provided the possibility of further cross checks of the systematics of the measurement.

For the helicity pattern the established 30 Hz quadruples were used, but also special runs with 120 Hz to check for 60 Hz and harmonics noise were carried out.

3˙4. *PREX*. – The PREX experiment measured the parity violation asymmetry in elastic electron scattering off ^{208}Pb to determine the neutron distribution in the lead nucleus.

As target a 0.5 mm lead foil, backed with diamond layers to ensure sufficient heat conductivity and cooled with liquid helium at 30 W, was used. To achieve the goal to measure the RMS neutron radius of lead to 1% a double Wien filter with solenoid was used for the first time to avoid spin flip correlated beam movements for better cancellation of systematics.

Separation of the elastic signal from background was achieved by use of the Hall A high resolution spectrometers (HRS). The first excited state of ^{208}Pb is separated from the ground state by 2.6 MeV. The high count rates of $500 \cdot 10^6\,\mathrm{s}^{-1}$ and therefore the need for radiation-hard detectors was accounted for by using small quartz detectors.

The experiment succeeded to control all systematics on the level of 0.02 ppm.

3˙5. Q_{weak}. – The Q_{weak} experiment pushed all experimental parameters even further to the frontiers of state-of-the-art parity violation measurements to precisely measure the weak charge of the proton. To measure the expected physics asymmetry of only 0.2 ppm with a small uncertainty, a total counting rate of $6.5 \cdot 10^9\,\mathrm{s}^{-1}$ on the eight fused silica (quartz) bar Cherenkov detectors needs to be sustained. A normal-conduction toroidal magnet together with a system of apertures is employed to separate elastic from inelastic events that come from a 35 cm long liquid hydrogen target. At a beam current of 180 μA a cooling power of 2500 W needs to be provided to the target.

The tiny physics asymmetry requires an even faster helicity flip rate. Octuple helicity patterns at a flip rate of 960 Hz (16 times the 60 Hz power line frequency) are used.

In order to determine the Q^2 range and check for background contaminations of the signal, special counting runs are taken. Two sets of drift chambers and a plastic scintillator that can scan along one of the main detector quartz bars are used to track the particles from the target to the main detector.

3˙6. *Outlook on future experiments*. – Among the next parity violation experiments to be carried out will be the MOLLER experiment at Jefferson Lab and the P2 experiment in Mainz.

The P2 experiment [6] in Mainz will measure the weak mixing angle, repeating the measurement of the Q_{weak} experiment, mentioned above. P2 will take advantage of the

TABLE I. – *Overview of the discussed parity violation experiments according to* [1-4]. *Some experiments ran under a number of different conditions as well, depending on the needs of the physics program.*

	HAPPEX	A4	G0	PREX	Q_{weak}
$A_{PV}/10^{-6}$	10	6	1–38	0.5	0.2
P_{target}/W	1000	250	1000	30 (lead)	2500
rate / 1/s	$2 \cdot 10^6$	$100 \cdot 10^6$	10^6	$500 \cdot 10^6$	$6.5 \cdot 10^9$
meas. mode	integrating	counting	counting	integrating	integrating
s/b separation	magnetic	calorimetric	magnetic	magnetic	magnetic
helicity flipping / Hz	30	25	30 (120)	30	960

lower systematic effects at lower beam energy compared to Q_{weak}, but it has to cope with a tiny physics asymmetry of only 0.01 to 0.02 ppm (depending on the beam energy that will finally be chosen). The design phase is still ongoing, but rates on the detector are expected to be of order 200 to 1000 GHz. Although the experiment could be carried out with the beam from the first stage of the existing MAMI facility (MAMI A), there are plans to build an new compact accelerator (MESA).

After this the MOLLER experiment [5] at Jefferson Lab will determine the electroweak mixing angle with 0.1% relative precision at a mean Q^2 of 0.056 GeV^2. The experiment will use the 11 GeV beam that will be available at Jefferson Lab after the machine upgrade to 12 GeV. The physics asymmetry of only $36 \cdot 10^{-9}$ asks for a very high luminosity design that will comprise a 5000 W liquid hydrogen target and a total count rate of about 150 GHz on the integrating quartz Cherenkov detector. A spectrometer consisting of two normal-conducting toroids and a aperture system will separate signal and background events.

4. – Conclusions

Throughout the last decade a number of parity violation experiments have been carried out at Jefferson Lab and MAMI. To measure the tiny parity violating asymmetries precisely, a number of new techniques have been developed, experimental parameters have been pushed to their limits, and the connection between the accelerators has become part of the experiment in order to be able to provide the necessary "parity quality" beam. Table I shows an overview of the experiments discussed above.

Only the experience gained during those ten years will make the future experiments of the next generation possible. Among the planned measurements are another measurement of the weak charge of the proton by the P2 experiment at MAMI that will improve the Q_{weak} result by a factor of three and the Møller scattering parity experiment (MOLLER) that will run after the Jefferson Lab upgrade to 12 GeV. As the parity violating asymmetries in these experiments will be even smaller than in any of the preceeding measurements the corners of the designs are already determined: They will have high power liquid hydrogen targets, magnetic spectrometers for signal/background separation and Cherenkov main detectors with integrating readout. The important aspect of stabilizing the beams to fulfill the needs of these experiments will only be possible based on the valuable experience gained in the earlier parity violation experiments.

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