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The polarimetry chain for the P2 experiment

K. Aulenbacher, I. Alexander and V. Tioukine
Institut für Kernphysik der Universität Mainz - Mainz, Germany

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Summary. — We plan to equip the P2 experiment at Mainz with two different types of polarimeters, a so-called double scattering Mott polarimeter and a Møller polarimeter with trapped polarized hydrogen atoms (Hydro-Møller polarimeter). We believe that both polarimeters have the potential to achieve an accuracy in the determination of the effective analyzing power of less than 0.5%.

PACS 29.20.Ej – Linear accelerators.
PACS 29.27.Hj – Polarized beams.

1. – Introduction

The P2 Collaboration at the Institut für Kernphysik (IKP) in Mainz is proposing a precision measurement of the electroweak mixing angle, θ_W. This is to be achieved by elastic electron scattering off the proton at low momentum transfer and at a low beam energy of 150–200 MeV [1]. The observed parity violating scattering asymmetry A_{PV} is $\propto P_B$, the beam polarization. The task for polarimetry is to achieve $\Delta P_B/P_B \leq 0.5\%$, since the accuracy of polarimetry should not compromise the overall accuracy of the A_{PV}-determination with a goal $\Delta A_{PV}/A_{PV} = 1.6\%$. An experiment aiming at the determination of P_B performs an asymmetry measurement, observing

$$A_{exp} = DS_0P_B = S_{eff}P_B. \tag{1}$$

S_0 is the analyzing power of the process in question and D is a dilution factor which is defined by the experimental conditions. The product of both is called the effective analyzing power, S_{eff}. If both factors are known with sufficient accuracy —and if A_{exp} can be determined with reasonable effort— the measurement of P_B is accomplished.

The present state of the art in high accuracy electron beam polarimetry is represented by two different types of polarimeters, namely the Laser-Compton [2] and the Møller polarimeter [3]. In both scattering processes, QED allows to calculate S_0 with sufficient

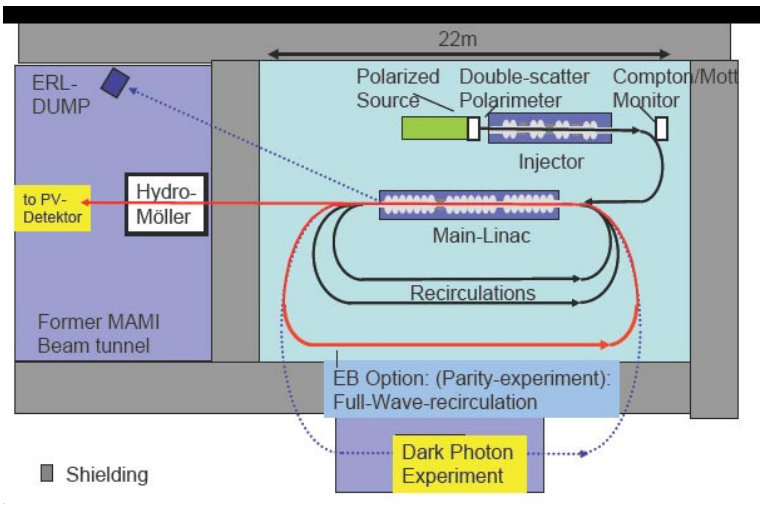

Fig. 1. – Scheme of the MESA accelerator with planned polarimetry chain.

accuracy, hence D is the critical factor. The Compton as well as the Møller process require a polarization of both reaction partners, therefore

$$D = P_{target} D'. \tag{2}$$

The error of D is the combined effect of the errors in P_{target} and in the other factor D' which contains contributions from experimental parameters such as finite acceptance, backgrounds or detector properties as energy calibration or nonlinearity. Presently, target polarization relative errors range between 0.5 and 1%, whereas $\Delta D'/D' \approx 0.5\%$. This means that despite long efforts both methods are presently restricted to accuracies of $\approx 1\%$ which prompts investigation of different approaches. Furthermore, in addition to accurate calibration, polarimeters must meet some more practical demands: Laser-Compton polarimeters may be considered as "non-invasive", and therefore qualify for an online polarisation measurement. On the other hand, Møller-polarimeters which have to use magnetized solid targets are not suitable for online measurements. Unfortunately, in our experiment, the low beam energy imposes too small analyzing power and gamma energy to allow for sufficient accuracy with a Laser-Compton device [4].

Facing this challenge we want to realize a recent proposal by Chudakov *et al.* [5] which could overcome most problems of the existing Møller devices and hence allow for online measurements. This so-called "Hydro-Møller polarimeter" is therefore favorable for the P2 experiment. However, to make the result unimpeachable an independent method must provide a cross check. This alternative method does not have to provide all advantages of the method of choice, for instance it does not have necessarily to be non-invasive. We have identified such a device by the so-called double scattering Mott polarimeter (DSMP). After a general introduction of the P2 experiment we describe the two different polarimeters and discuss their potential of improving the polarimeter accuracy.

2. – Layout of the P2 experiment

Figure 1 shows the schematic layout of the P2 experiment which requires about 10000 hours of data taking. We have proposed the MESA accelerator [6] as an optimum solution

in order to provide this enormous beamtime in addition to the ongoing research program at the MAMI-C accelerator in our institute. MESA is planned as a compact c.w. superconducting accelerator which serves for about one third of its time for experiments in the energy recovery linac (ERL) mode. One of these experiments is to search for possible new heavy gauge bosons (dark photon).

The majority of the available runtime would however be devoted to the P2 experiment in which MESA is operated as a conventional c.w. accelerator. This does not only offer to achieve the desired beam time within 2–3 years, but also gives more flexibility to optimize the accelerator concept with respect to the specific needs of such a high precision parity experiment. The experiment will consist of a large solid angle detector, background suppression may be achieved by using a solenoid-spectrometer. A $150\,\mu$A longitudinally polarized beam will hit a 60 cm long liquid hydrogen target. Due to the huge scattering rate of several hundred GHz the detector will be used in integrating mode. More details concerning the experiment can be found in [1]. The Hydro-Møller polarimeter will be installed upstream of the experiment. The areal density of stored hydrogen atoms will be of the order $10^{16}\,\mathrm{cm}^{-2}$. The DSMP will be integrated in the injection system of MESA. It operates at the source energy (0.1–0.2 MeV), since the event rate in the double scattering process scales like E^{-4}. Polarization losses between the DSMP and the Hydro-Møller should be negligible since the sojourn time of particles in the system is only of the order of a microsecond and no depolarizing resonances have to be crossed. However, the two polarimeters will operate at current levels which differ by 2-3 orders of magnitude. It is necessary to connect the results obtained under such large differences in intensity by an auxiliary measurement. We have demonstrated that conventional Mott- or Compton-absorption polarimeters can be employed for this task due to the very good reproducibility and the high dynamic range of such devices [7, 8]. The polarimeter chain will therefore also contain polarimeters of this type as polarization monitors.

3. – Hydro-Møller working principle

Atomic hydrogen atoms are generated by a dissociator and enter the fringe field of a solenoid. The gradient force is attracting for one single spin species. This species is trapped in the solenoid field whereas atoms with the opposite spin direction are repelled and are pumped away. This allows to achieve areal densities of more than $10^{16}\,\mathrm{cm}^{-2}$ inside the trap.

The amount of electronic polarization is expected to be of the order $1 - \epsilon(B)$ with $\epsilon(B) \approx 10^{-5}$ at $B = 8\,\mathrm{T}$. Chudakov and Luppov discuss in their paper [5] that dilutions by ions and molecules can be controlled, so that the almost complete polarization —free of systematic errors much below the desired level— can be ensured. Whereas the target is thin enough to allow online operation, the scattering rate in our high beam intensity experiment is large enough to allow for sufficient statistics.

The promise of significant advantages comes at the price of high technical complexity. Since there are no radial forces acting on the atoms in the solenoid they will eventually hit the inside surfaces of the trap. In order to avoid long sojourn time and to minimize molecular formation at the surface the trap has therefore to be covered with a thin film of suprafluid Helium at 0.3 K [9]. This requires cooling by a ^{3}He/^{4}He dilution refrigerator. Concerning detection at the low energies foreseen for our experiment, one must take into account cyclotron motion in the strong magnetic field. A specific detection system has yet to be designed. A suitable atomic trap is presently available at University of

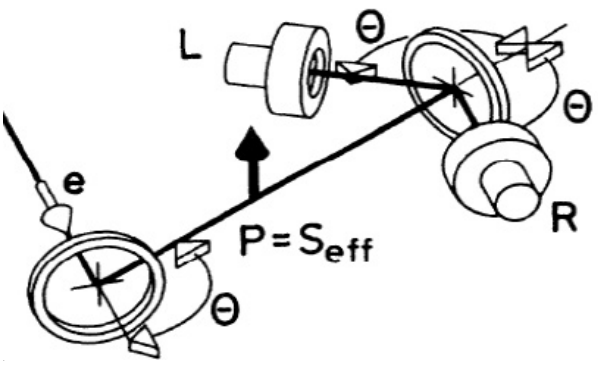

Fig. 2. – Scheme of a double scattering process for determination of S_{eff} (taken from [10]).

Virgina. It will be transported to Mainz with the goal to establish atomic trapping and to provide measurements of hydrogen electronic polarization and, furthermore, of its behaviour under excitation with the high intensity 180 MeV beam of MAMI-A. We consider these preparatory experiments as necessary input for the construction of an operational Hydro-Møller polarimeter which would become available before the start of the P2 data taking.

4. – Double scattering Mott polarimeter, DSMP

In double elastic scattering the problem of determination of S_{eff} (eq. (1)) is attacked from a radically different viewpoint. Assuming symmetry of the process under time reversal one finds that in elastic scattering the analyzing and the polarizing power are identical. If an elastic scattering process is characterized by an effective analyzing power S_{eff} we therefore find that the initially unpolarized particles get polarized to a degree $P = S_{eff}$ (see fig. 2). Under the assumption of parity conservation (very well justified at the low energies of the DSMP) and for an unpolarized target the polarization direction will be normal to the scattering plane. If we perform a second scattering with these particles under the same conditions we find an experimental asymmetry

$$A_{exp} = S_{eff} * P = S_{eff}^2. \tag{3}$$

The measurement of A_{exp} therefore directly determines the effective analyzing power except for the sign. After calibration a subsequent measurement may be done with a polarized beam and the polarization may be obtained according to eq. (1). Several pitfalls threaten this seemingly simple concept, especially one may question how to guarantee the equality of both scatterings, *i.e.* the target thicknesses, the solid angles and so on. In a series of experiments at the University of Münster [10-12] it was demonstrated that such factors can be controlled at the sub-percent level. The quoted uncertainty in the calibration of S_{eff} is 0.3%.

A further advantage of the double scattering method is that independent cross checks are possible if a polarized beam is available. It is then also possible to give up the condition of identical targets. Whereas one target has an analyzing power S_{eff}, the

other (first) target may be considered as an "auxiliary" one. The auxiliary target is characterized by its individual effective analyzing power S_{aux} and a depolarizing factor α. The initial beam is assumed to have a polarization direction vertical to the scattering plane and that its direction can be reversed ($\pm P_0$).

Application of reflection symmetry [12] yields, that the polarization of a beam with initial polarization $\pm P_0$ perpendicular to the scattering plane is changed behind the auxiliary target to $P^{\pm}_{aux} = (S_{aux} \pm \alpha P_0)/(1 \pm S_{aux} P_0)$. As suggested by Hopster and Abraham [13] and demonstrated by the Münster group [12] it is then possible to measure additional asymmetries:

1) Rotate the target characterized by S_{eff} directly into the polarized primary beam. Measure the asymmetry by switching the beam polarization ($\pm P_0$):

$$A_1 = S_{eff} P_0. \tag{4}$$

2) In the double scattering configuration one performs a scattering with a beam of fixed polarization direction $+P_0$:

$$A_2 = P^{+}_{aux} S_{eff} = \frac{S_{aux} + \alpha P_0}{1 + S_{aux} P_0} S_{eff}. \tag{5}$$

3) The same with $-P_0$:

$$A_3 = P^{-}_{aux} S_{eff} = \frac{S_{aux} - \alpha P_0}{1 - S_{aux} P_0} S_{eff}. \tag{6}$$

4) The same with unpolarized beam:

$$A_4 = S_{aux} S_{eff}. \tag{7}$$

5) Measure the asymmetry created by switching the initial polarization ($\pm P_0$) for the particles scattered into the direction of the S_{eff}-target:

$$A_5 = S_{aux} P_0. \tag{8}$$

These five equations contain four unknowns: P_0, S_{aux}, S_{eff}, α. From the five experiments one may therefore extract the parameters in different ways. The consistency of results for S_{eff} was proven in the work of Mayer *et al.* [12] at the level of 0.4%.

5. – Outlook/Conclusion

In order to set up the polarimeter chain until the beginning of the P2 experiment we have started to acquire equipment. In the case of Hydro-Møller we will receive a solenoid with dilution cooler from the University of Virginia which can serve as a prototype for the atomic trap of such an innovative polarimeter. In the case of the DSMP we were able to recuperate the apparatus used at Münster University. This is currently being installed at one of our polarized test sources where we first want to reproduce the results which were achieved almost 20 years ago. After getting the necessary experience with

the Hydro-Møller prototype and the DSMP we will define the modifications needed for the polarimeters in order to be integrated into the P2 experiment. In the case of Hydro-Møller we will also explore how to adapt the system for the much higher energies foreseen at experiments with the JLab 12 GeV beam.

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