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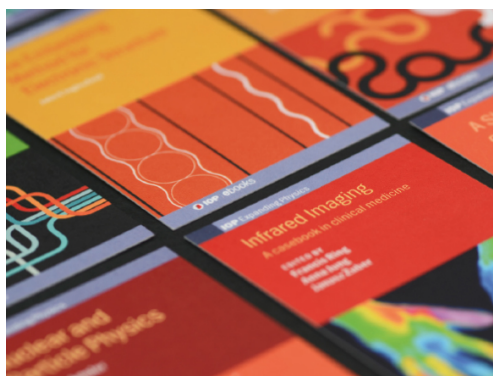
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Polarizing a stored proton beam by spin flip? - A high statistic reanalysis

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Abstract. Prompted by recent, conflicting calculations, we have carried out a measurement of the spin flip cross section in low-energy electron-proton scattering. The experiment uses the cooling electron beam at COSY as an electron target. A reanalysis of the data leeds to a reduced statistical errors resulting in a factor of 4 reduced upper limit for the spin flip cross section. The measured cross sections are too small for making spin flip a viable tool in polarizing a stored beam.

1. Introduction

A polarized antiproton beam is a vital tool for several important topics in particle physics, including a first measurement of the transversity distribution of the valence quarks in the proton, a test of the predicted opposite sign of the Sivers–function, related to the quark distribution inside a transversely polarized nucleon, and a first measurement of the moduli and the relative phase of the time-like electric and magnetic form factors of the proton [1].

The experiment, which is making use, for the first time, of the electron cooler as an electron target, has been carried out to resolve the discrepancy between two recently published calculations [2, 3], and to settle the question whether in the future spin flip will play a role in polarizing stored beams. More recently, Arenhövel [2] predicted that the spin-flip cross section in electron-proton scattering at low energy (a few eV in the center-of-mass system) is very large because of the mutual attraction of the two oppositely charged particles. Walcher and co-workers adopted this idea for a proposal to polarize stored antiprotons with a co-moving beam of polarized positrons [4]. The proper low interaction energy would be achieved by making the two beam velocities almost the same. Even though the achievable positron beam intensities are quite low, the predicted spin flip cross sections are so large that the scheme would still be feasible. For instance, at a center-of-mass energy of $0.93\,\mathrm{eV}$ (corresponding to a proton energy in the lepton rest frame of $T_h = 1.7\,\mathrm{keV}$) Arenhövel predicts a spin flip cross section of $\sigma_S = 4 \cdot 10^{13}\,\mathrm{b}$. However, a calculation of the same quantity by Milstein and co-workers [3] resulted in $\sigma_S = 0.75\,\mathrm{mb}$. The goal of the experiment described in the following is to resolve this discrepancy of 16 orders of magnitude.

The time evolution equations for the beam polarization P_B and the number of stored particles N have been discussed repeatedly, e.g. [5]. Here only two special cases are discussed. The first case deals with polarizing an initially unpolarized beam ($P_B = 0$). As long as P_B is still small,

the rate of change of polarization is constant and given by

$$\frac{dP_B}{dt} = f_R d_T P_T \left[2\Delta\sigma_S + \Delta\sigma_R\right]. \tag{1}$$

We define the "polarizing cross section", σ_{pol}, as the sum of the two terms in the bracket.

The second special case describes the effect of an unpolarized target ($P_T = 0$) on an already polarized beam,

$$\frac{dP_B}{dt} = -2f_R d_T \sigma_S P_B, \tag{2}$$

which shows that the "de-polarizing cross section" is equivalent to twice the spin flip cross section σ_S. Since it is always true that $\sigma_S \geq \Delta\sigma_S$, it follows from eqs. (1) and (2) that if a polarized target is capable of polarizing an unpolarized beam by spin flip, an unpolarized target will de-polarize an already polarized beam. The experiment described in this paper makes use of this principle.

2. Experiment

The goal of this experiment is to determine the depolarization of a polarized proton beam by its interaction with the electrons of the cooler beam. The measurement is carried out with a proton beam in the COSY ring [6], using the detector setup in the target chamber of the ANKE spectrometer [7]. The proton energy is $T_p = (49.3 \pm 0.1)\,\text{MeV}$, corresponding to a velocity of $v_p = 0.312 \cdot c$, and the usual relativistic parameter $\gamma_p = 1.053$.

2.1. Cooler beam as an electron target

In this experiment the COSY electron cooler [8] serves two functions. On one hand, as usual, it provides the phase-space cooling of the stored proton beam, while on the other hand it plays the role of an electron target for the actual measurement of the low-energy spin-flip cross section in ep scattering.

In the cooling mode, the electron velocity is adjusted to the velocity v_p of the stored protons. When the cooler is used as a target, a relative motion between the proton and the electron beam is achieved by "detuning" the accelerating voltage by ΔU, changing the electron velocity by Δv_e, and inducing an average relative "detune" velocity u_0.

Besides this induced velocity, there are additional contributions to the relative motion between protons and electrons. The dominant effect arises from the transverse thermal motion of the electrons. Other contributions include the betatron motion of the protons, the velocity spread of both beams, and the ripple on the electron high-voltage supply.

2.2. Cycle scenario

The scenario of our experimental cycle is shown in fig. 1. At the beginning of the cycle, the ring is filled with vertically polarized protons (typically, the beam polarization is $P_B \approx 0.5$). During the first half of the cycle, the coasting beam is interacting with the electrons in the cooler. During the second half, while cooling the beam, the internal deuteron target is turned on to measure the beam polarization.

The first half of the cycle contains 49 sub-cycles of 10 s length. During such a sub-cycle the electron velocity is first tuned to the beam velocity to cool the beam for 5 s, then the electron beam velocity is detuned for another 5 s. This is the time when the actual experiment takes place with a total "interaction" time in the detuned mode of $t_{\text{int}} = 245\,\text{s}$ per cycle. The scenario just described shall be called "E-cycle". To reduce systematic uncertainties, E-cycle polarization measurements are compared to those observed in a reference cycle, or "0-cycle". Reference cycles are identical in every respect, except that during the interaction time (in the second half
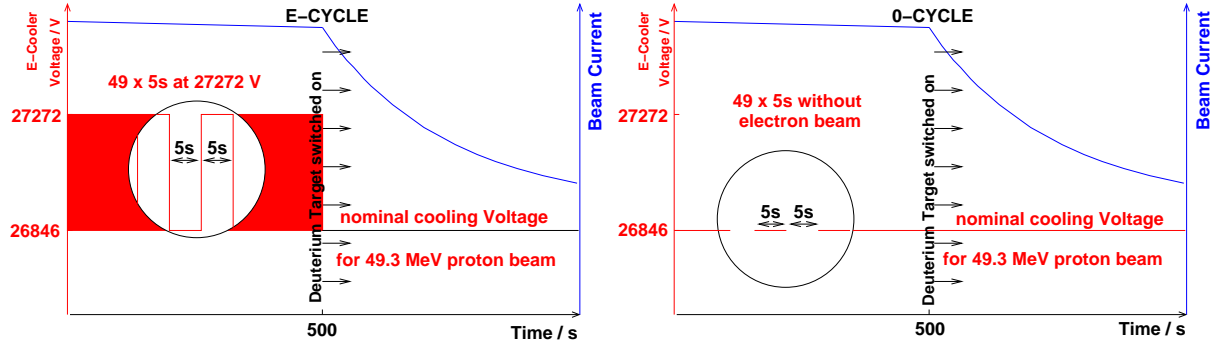
Figure 1. Time sequence of the experimental "E-" and "0-cycles". Both electron accelerating voltage ($\Delta U = 320.42\,\text{V}$) and number of protons orbiting in the ring are plotted.

of the sub-cycles, for a total time t_int in each cycle) the cooler beam is *turned off*. During the experiment, E-cycles and 0-cycles are alternated, first with beam polarization up ($\uparrow$), then with an unpolarized beam and finally with polarization down ($\downarrow$). The deduced polarization ratio $R \equiv P_E/P_0$ (see sect. 3.3.3) reflects the effect of an electron target on the beam polarization.

2.3. Polarimetry

The beam polarization is measured using pd elastic scattering. Precise analyzing power data are available at $T_p = 49.3\,\text{MeV}$ [9] and cross sections have been measured at a nearby energy ($T_p = 46.3\,\text{MeV}$) [10]. The beam energy for this experiment was chosen partly because of this. The target consists of a deuterium cluster jet with about $5 \cdot 10^{14}$ deuterons per cm^2 [11]. The detector system consists of two silicon tracking telescopes [12] placed symmetrically to the left and right of the beam, as shown in fig. 2. Each telescope features three position-sensitive detectors, oriented parallel to the beam direction. The first two layers are $300\,\mu\text{m}$ thick with an active area of $51\,\text{mm}$ by $66\,mm$. They are located $28\,\text{mm}$ and $48\,\text{mm}$ from the beam axis. The third, $5\,\text{mm}$ thick detector, $68\,\text{mm}$ from the beam axis is not used in this experiment. Within the mechanical constraints of the detector support, the telescope positions with respect to the interaction region are chosen to optimize the figure of merit for the pd analyzing reaction. The position resolution of the detectors is about $200\,\mu\text{m}$, both, vertically (y axis) and along the beam direction (z axis).

A first analysis described in [13], is based on clearly identified pd elastic scattering events. Additionally, two different samples have been extracted from the data. A minimum bias sample "MB" was selected by choosing the complete deuteron region in the energy loss spectra and applying an additional cut on the scattering angle (fig. 3). In case no deuteron was found by "MB", the event was analyzed for events with exactly one track and in case this track stored in the "OT" sample. By this the "MB" and the "OT" samples are completely disjunct and therefore statistical independent.

Making use of the cross ratio method, we calculate the asymmetry for bins in the deuteron scattering angle (a detailed description can be found in ref [13]).

$$\epsilon_n = \frac{1}{\langle\cos\phi\rangle} \frac{\delta_n - 1}{\delta_n + 1}, \text{ where } \delta_\text{n} = \sqrt{\frac{Y_{L\uparrow}(\text{n}) \cdot Y_{R\downarrow}(\text{n})}{Y_{L\downarrow}(\text{n}) \cdot Y_{R\uparrow}(\text{n})}}. \tag{3}$$

Taking the weighted average for all bins, one arrives at the beam polarization. This procedure is carried out separately for E-cycles and 0-cycles, resulting in the respective polarizations P_E
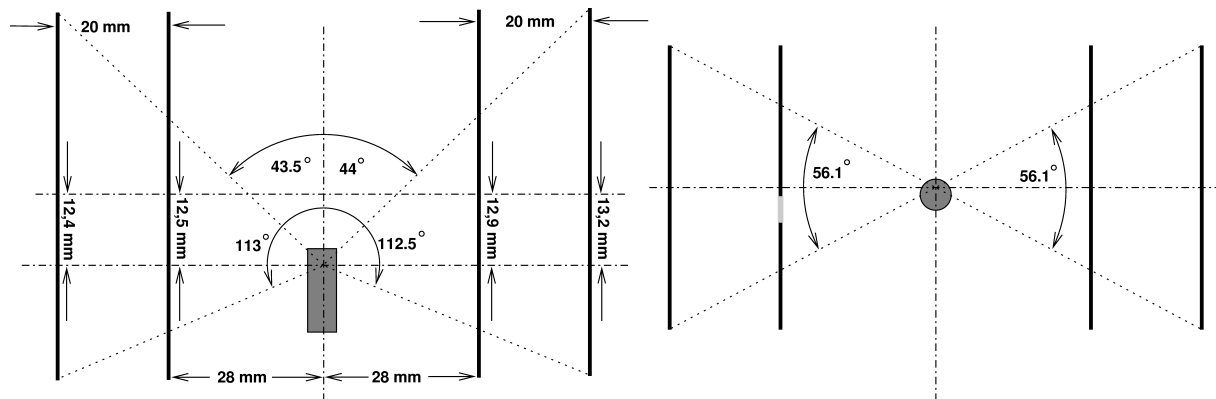
Figure 2. Detector setup in the target chamber of the ANKE spectrometer, seen from the top(left) and in beam direction (right). The detector telescopes are mounted to the left and right of the interaction region. The beam target overlap is as well indicated as a region in the left detector, which due to radiation damage gives no data.

and P_0, with or without electron beam during the 'interaction' part of the cycle. The ratio $R \equiv P_E/P_0$ then constitutes the final result of the polarization measurement. The systematic errors of this measurement can be neglected. Similar to the polarization, the asymmetries ϵ_E and ϵ_0 of the "MB" and "OT" samples have been individually used to evaluate the ratio R of the polarizations as it is independent of the analyzing powers.

$$R = \frac{P_E}{P_0} = \frac{\epsilon_E \cdot A_y}{\epsilon_0 \cdot A_y} = \frac{\epsilon_E}{\epsilon_0} \tag{4}$$

The solid curve in fig. 4 is a polynomial fit to that part of the data from the E-cycle with $426\,\mathrm{V}$ detuning potential, scaled to fit the individual datasets. The fitted functions follows the shown data points with a detuning potential $\Delta U = 246\,\mathrm{V}$. This is true for the asymmetries ϵ_0 and ϵ_E for all data points and therefore a prove of the stability of the event selection. The scaling factors α_0 and α_E are directly proportional to the measured asymmetries and their ratio gives R.
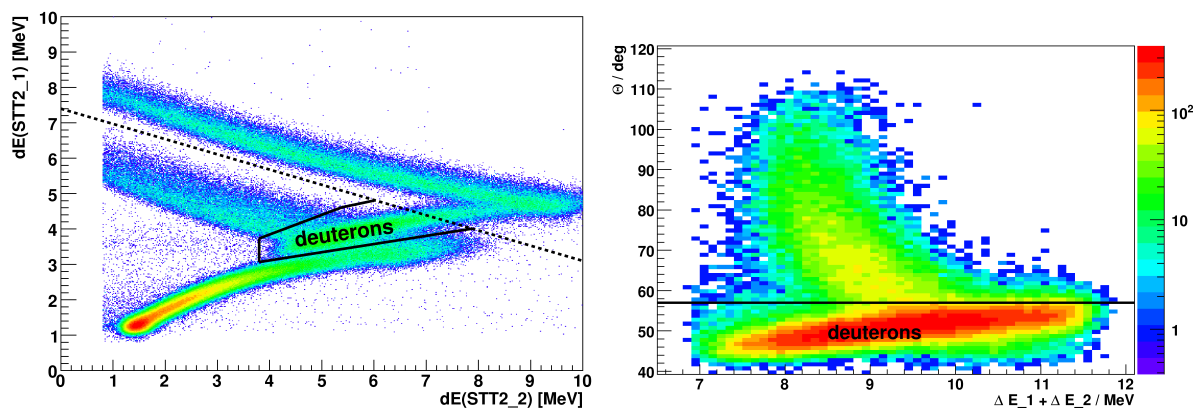

Figure 3. Left: This energy loss spectrum for STT2 (Right STT) indicates the minimum bias cuts, which are used to reconstruct deuterons. Right: The additional cut $\theta < 57°$ strongly reduces the background from breakup protons.
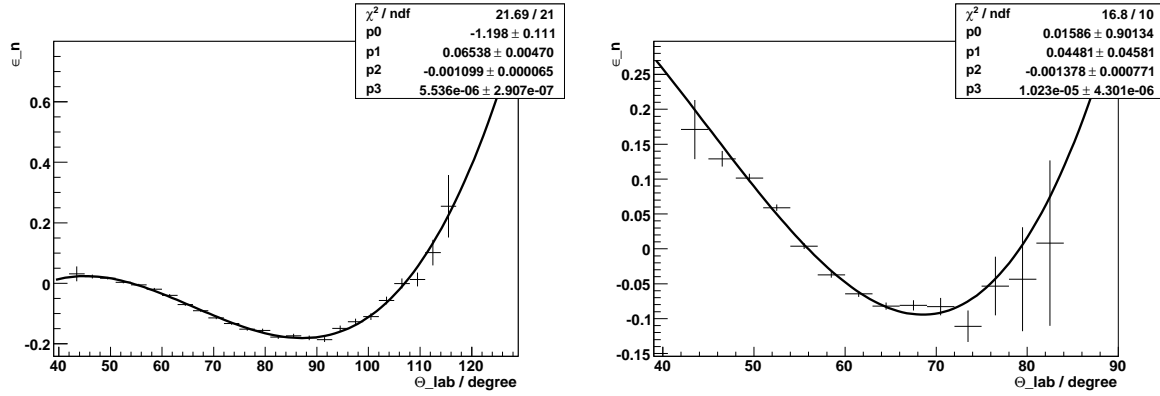
Figure 4. Left(Right): Figure for the "OT"("MB") sample. The asymmetries ϵ_n with its statistical errors *vs* the scattering angle in laboratory θ. The horizontal bars indicate the bin width of 3°. The solid curve represents a polynomial fit to the measured asymmetry.

2.4. Result

For each of the six detune potentials $\Delta k (k = 1 \ldots 6)$, the result of the measurement consists of the ratios $R_k \equiv \left(\frac{P_E}{P_0} \right)_k$ as described in the previous section. Due to the random thermal movement of the electrons two cross sections with spin along (transverse) σ_λ $(\sigma\tau)$ the relative motion contribute and one obtains[13]

$$y_k \equiv \frac{-\ln R_k}{2ct_{\text{int}} n_{e,k} u^{\star 2} (L_C/L_R)} = \sigma^\star_{S,\tau} I_{\tau,k} + \sigma^\star_{S,\lambda} I_{\lambda,k}. \tag{5}$$

The denominator contains the speed of light, the interaction time $t_{\text{int}} = 245\,\text{s}$, the electron density n_e, a reference velocity, arbitrarily set to $u^\star = 0.002$, the active length $L_C = (1.75 \pm 0.25)\,\text{m}$ of the cooler, and the ring circumference $L_R = 183.47\,\text{m}$. The cooler length is uncertain because of details of inflection and extraction of the electron beam, and the electron density is affected by uncertainties of the electron beam current $I_e = 170\,\text{mA}$ and its area $A_e = 5\,\text{cm}^2$. We estimate that the overall systematic uncertainty of the denominator is $\pm 20\,\%$.

The asymmetry ratios R_k (fig. 5) are consistent with unity, i.e., the polarization differences between E-cycles and 0-cycles are of the order of their statistical errors.

The depolarizing cross sections, $\sigma^\star_{S,\tau}$ and $\sigma^\star_{S,\lambda}$ (at the reference velocity $u^\star$) appear as unknowns in eq. (5). Since our experiment fails to find a depolarization effect, we instead derive an upper limit for the two cross sections that is compatible with our data. Following the usual treatment, we define the likelihood function and use the Bayesian approach to calculate the posterior probability density function.

The probability p is evaluated numerically. The upper cross section limits, shown in fig. 5, are contours of constant p.

As mentioned earlier, the spin flip cross sections are proportional to the inverse square of the relative velocity $u^\star$. The values shown in fig. 5 are for $u^\star = 0.002$, corresponding to a center-of mass energy of about $1\,\text{eV}$, or to a proton kinetic energy in the electron rest system of $T_h = 1.2\,\text{keV}$.

The present result is in agreement with the calculation of Milstein et al. [3], but clearly rules out the validity of the prediction of $\sigma_{S,\lambda} = 4 \cdot 10^{13}\,\text{b}$ claimed in refs. [2, 4]. Since the completion of this experiment, the calculation presented in these two references has been withdrawn [14, 15]).

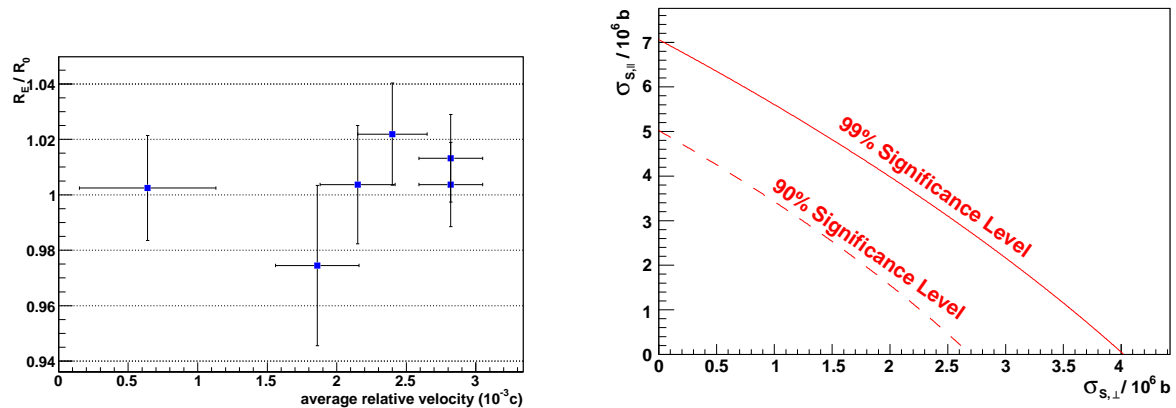**Figure 5.** Left: Ratio R of Polarizations with and without electron beam. Right: Upper limit allowed by the data of this experiment for transverse and longitudinal spin flip cross sections at a relative velocity of $u^\star = 0.002$.

Acknowledgments

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