New experimental upper limit of the electron-proton spin-flip cross section

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Abstract

In a previous publication, measurements of the depolarization of a stored proton beam by interaction with a co-propagating unpolarized electron beam at low relative energy have been presented and an upper limit of about $3 \cdot 10^7$ b for the electron-proton spin-flip cross section was determined. A refined analysis presented in this paper reduces the previous upper limit by a factor of three by the introduction of a new procedure that makes use also of non-identified particles.

Keywords: Polarized beams, Storage rings, Electron-proton scattering, Antiprotons

1. Introduction

In a recent paper, the PAX Collaboration has published the first experimental upper limit for the ep spin-flip cross section at center-of-mass energies between 100 meV and 2 eV [1]. The measurement was motivated by the proposal to use the spin-flip mechanism in the interaction with a polarized positron beam to polarize a stored antiproton beam [2]. The experiment was performed by searching for the depolarization in the inverse reaction, i.e., the depolarization of a stored beam by spin-flip in ep scattering [1]. The test was carried out at the COSY storage ring

of Jülich [3]. The experiment ruled out the use of spin-flip as a method to polarize a stored beam and led to a revised theoretical estimation of the ep spin-flip cross section [5–7]. It allowed for the first experimental determination of an upper limit for the ep spin-flip cross section in the region of interest.

In this paper we present a new analysis of the acquired data that allowed us to significantly increase the statistical accuracy of the measurement and thus to reduce the upper limit by a factor of three compared to our previous publication [1].

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2. Experiment

The goal of the experimental test was to detect the possible depolarization of a polarized proton beam interacting with an unpolarized co-propagating electron beam [1]. The task was accomplished by injecting a polarized proton beam into COSY and by making dedicated use of the electron cooler beam. The electron cooler was employed to provide the usual phase-space cooling of the stored proton beam and, in addition, to serve as an electron target for the measurement of the low-energy ep spin-flip cross section. The experimental cycle consisted of two parts. In the first part, a vertically polarized proton beam was injected into the ring and interacted with the electron cooler beam. During the second part, the residual polarization in the beam was measured. In order to identify the effect of the ep interaction on the polarization of the proton beam, two types of cycles were implemented, an E-cycle, where the electron target was present, and a 0-cycle without electron target. Data were taken at six different relative proton-electron velocities in the range 0 and $\pm 0.003 c$. The measured left-right asymmetry in pd elastic scattering at $T = 49.3 \text{ MeV}$ was used to determine the beam polarization from the known analyzing power A_y [4]. The scattered particles from the interaction of the polarized beam impinging with a D_2 -cluster target were detected by two telescopes symmetrically placed around the target, each consisting of three layers of double-sided silicon strip detectors. A complete description of the experimental setup can be found in [1].

3. Data analysis

In the previously published data, only clearly identified deuterons (D-sample) from elastic scattering were taken into account to determine the spin-flip cross section σ_S , which is related to the ratio $R = P_E/P_0$ between the beam polarizations measured with (E) and without (0) interaction with the electron beam. The ep spin-flip cross section is derived by integrating Eq. (4) of Ref. [1] over the duration t_E of the interaction,

$$\sigma_S = \frac{-\ln R}{2 \cdot d_t \cdot t_E \cdot f}, \quad (1)$$

where d_t is the electron target density and f the beam revolution frequency. The beam polarization was determined by dividing the measured asymmetry ϵ of the reconstructed events by the known analyzing power A_y (from [4]). In the evaluation of the asymmetries use was made of the so-called *Cross-Ratio* method [8].

In the new analysis, the ratio R was evaluated directly from the measured asymmetries in each angle bin, without introducing the analyzing power and the beam polarization. This procedure allowed us to increase the statistics

Figure 1: Energy loss in the first vs second layer in one of the Silicon Tracking Telescopes. The minimum bias cuts used to reconstruct deuterons are indicated. In addition to the stopped deuterons, the new analysis made use of the additional events in the overlap region.

by including non-identified particles¹. Two different event samples were utilized, a minimum-bias (MB) sample and a one-track (OT) sample. In addition to the D-sample, the MB-sample contains also events from the proton-deuteron overlapping region (see Fig. 1). Thus $4.4 \cdot 10^6$ events in the MB-sample were used in addition to the $3.2 \cdot 10^6$ events of the D-sample. The OT-sample contains all events with one track in the detection system and no identified deuteron using the MB cuts. These additional $10.9 \cdot 10^6$ events that exhibit asymmetries up to $|0.2|$, are primarily responsible for the gain in statistics.

The asymmetries ϵ_E and ϵ_0 for the E - and 0-cycles in each angular bin were separately evaluated for the six detune voltages. The angular binning of $\Delta\theta = 3^\circ$ is consistent with the precision of the track reconstruction. The data were fitted by a linear regression function with a single parameter ($R \cdot \epsilon_0 = \epsilon_E$), because for an unpolarized beam $\epsilon_0 = \epsilon_E = 0$. The coefficients were extracted by a χ^2 minimization accounting for the statistical errors of both ϵ_E and ϵ_0 . The procedure showed no significant deviations of the regression coefficient from unity and no systematic dependence on the scattering angle or the data sample. As an example, in Fig. 2 ϵ_E vs. ϵ_0 is shown for a detune voltage of $\Delta U = 426 \text{ V}$, corresponding to a relative velocity of $\bar{v} = 2.82 \cdot 10^{-3} c$. The systematic contribution is estimated to be smaller than the statistical uncertainty.

Table 1 shows the measured ratios R for the different relative proton-electron velocities for the two different analysis methods and the different data samples. R_{oo} indicates the old analysis method applied to the old data sample (D-sample), published in Ref. [1], R_{no} the new analysis applied to the old data sample, and R_{nn} the new analysis applied to the new data sample (OT and MB). The

¹It should be noted that, although the beam polarization does not directly appear in Eq. (1), it clearly affects the statistical errors since $\epsilon \propto A_y P$.

ΔU (V)	$\bar{v}$ (10^{-3} c)	R_{oo}	R_{no}	R_{nn}
-426	2.82	1.084 ± 0.051	1.091 ± 0.051	1.013 ± 0.016
0	0.64	1.022 ± 0.055	1.025 ± 0.055	1.002 ± 0.019
246	1.86	1.008 ± 0.096	1.012 ± 0.096	0.974 ± 0.029
301	2.15	1.094 ± 0.074	1.101 ± 0.074	1.004 ± 0.021
348	2.40	1.023 ± 0.055	1.029 ± 0.055	1.022 ± 0.018
426	2.82	1.027 ± 0.049	1.027 ± 0.049	1.004 ± 0.016
weighted average		1.044 ± 0.024	1.048 ± 0.024	1.007 ± 0.008

Table 1: Measured $R = \epsilon_E/\epsilon_0$ for different analysis methods and data samples for the six detune voltages ΔU used in this experiment, corresponding to relative electron-proton velocities $\bar{v}$ in the proton rest frame. R_{oo} indicates the results of the old analysis on the old data sample, R_{no} the results of the new analysis on the old data sample and R_{nn} the results of the new analysis on the new data sample. The weighted average $\bar{R}$ is given in the bottom row.

Figure 2: Correlation plot ϵ_E vs. ϵ_0 for the asymmetries measured with and without electron beam interaction for a detune voltage of $\Delta U = 426$ V. The OT-sample is indicated by black-open circles, while the MB-sample by red-filled circles. The error bars indicate the statistical errors. The fit to the combined data set yields $R_{nn} = \epsilon_E/\epsilon_0 = 1.004 \pm 0.016$ with $\chi^2/\text{ndf} = 0.792$.

comparison of column R_{oo} with R_{no} illustrates that the improvement in the result comes from the increased statistics of the new data sample and not from the application of the new analysis method.

In Fig. 3 the results of the old and new analysis are reported for comparison. The horizontal bars indicate the velocity distribution determined by the thermal motion of the co-propagating electrons (see Ref. [1] for a detailed discussion).

By introducing the velocity dependence of the cross section $\propto v^{-2}$ [9] the probability density function was calculated by using the likelihood method. The estimation of the systematic uncertainty of R is based on the deviation of its weighted average (see Table 1) from unity. Therefore, for the old data sample a systematic uncertainty of 0.05 was used, while for R_{nn} a systematic uncertainty of 0.01 was used. The confidence levels of 90 % and 99 % for the old and new result are shown in Fig. 4. The new upper limits for the transverse and longitudinal spin-flip cross sections $\sigma_{\perp}^*$ and $\sigma_{\parallel}^*$ at a relative velocity of $v^* = 0.002$ c

Figure 3: Measured R as a function of the average relative velocity $\bar{v}$ for the old (red triangles) and new (blue squares) analysis. The horizontal bars indicate the range $\Delta\bar{v}$ of velocities contributing to each measurement.

and a transverse electron temperature of $kT_e = 0.3$ eV are $5.5 \cdot 10^6$ b and $8.0 \cdot 10^6$ b, respectively, at 99 % confidence level, reducing the previous upper limits by a factor of three.

4. Conclusions

A refined analysis of previously published data on the ep spin-flip cross section was performed. The new analysis made use of the independence of the cross section extraction procedure from the exact knowledge of the analyzing power and the beam polarization. The new approach allowed us to decrease by a factor three the previously determined upper limit of the ep spin-flip cross section.

Based on the reachable intensities of present and future polarized positron beams, the suitable lower limits of the polarizing spin-flip cross section to be effective to polarize a stored antiproton beam in-situ, were estimated to be 10^{10} b for existing and 10^6 b for possible advanced developments [10]. We conclude that while already the experimentally determined upper limits of the spin-flip cross section presented here are insufficiently small, the revised

Figure 4: Upper limit allowed by the data of this experiment for the transverse and the longitudinal spin flip cross sections $\sigma_{\perp}^*$ and $\sigma_{\parallel}^*$ at a relative velocity of $v^* = 0.002 \text{ c}$, corresponding to a center-of-mass energy of about 1 eV. The confidence level expresses the probability for the actual cross sections to be smaller than the values on the contour line. The blue and red lines represent the results extracted from the new and old data analysis, respectively.

theoretical limits [5–7] are smaller by another eight orders of magnitude.

The present work is supported by the EU grants of the Projects I3HP2 and I3HP3 (Grant Agreements 227431 and 283286) and of the ERC Advanced Grant POLPBAR (Grant Agreement 246980).

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