CHARACTERIZATION OF THE ANALYZING TARGET OF THE PEPPo EXPERIMENT

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Abstract

The purpose of the PEPPo experiment is to demonstrate, for the first time, the production of polarized positrons from a polarized electron beam. The experiment was performed in Spring 2012 at the CEBAF injector of Jefferson Laboratory (JLab) using a highly spin polarized electron beam. The positron polarization was measured by means of a Compton transmission polarimeter. This work discuss the experimental set up with a special emphasis on the analyzing magnet constituting the polarization filter of the experiment. The knowledge of the analyzing target polarization is discussed on the basis of simulations and calibrated to experimental data.

INTRODUCTION

Polarized positron beams are essential tools for the understanding of numerous physics phenomena ranging from high energy physics to solid state physics [1]. Various methods have been investigated over the past decades for the production of polarized positrons. The aim of the PEPPo (Polarized Electrons for Polarized Positrons) experiment [2] is to demonstrate and characterize, for the first time, the longitudinal polarization transfer from electrons to positrons via polarized bremsstrahlung and pair creation. The positron polarimeter uses an iron target polarized by a solenoidal magnetic field and followed by a calorimeter. Measurement of the Compton transmisson asymmetry, when the polarization of the incident electron beam and/or the polarity of the magnet is reversed, is the key data of the PEPPo experiment. The expected experimental asymmetries are $0.01 - 0.1\%$ and may be accurately measured taking advantage of the JLab practices for the control of helicity correlated systematics.

POLARIZED POSITRON PRODUCTION AND MEASUREMENT AT PEPPO

Polarized Positron Production

Polarized positron production is actually a two step process which involves the production of circularly polarized photons in a target via the bremsstrahlung reaction followed, within the same target, by the conversion of polarized photons into polarized $\mathrm{e^+e^-}$ pairs through the pair creation process:

$$\overrightarrow{\mathrm{e}^-} \rightarrow \overset{\circlearrowleft}{\gamma} \rightarrow \overrightarrow{\mathrm{e}^+} (\overrightarrow{\mathrm{e}^-})\,. \tag{1}$$

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Positrons with energies close to the energy of the incoming electrons get $\sim$ 100% of initial electron polarization while positrons with lower energies have lower polarization [3, 4]. In this energy range, the magnitude of the polarization transfer is depending on the production target thickness. The PEPPo experiment used a continuous highly polarized electron beam (85%) of $8.25\ \mathrm{MeV/c}$ with intensities up to $600\ \mathrm{nA}$ to measure the polarization transfer to positrons in the momentum range $3.2 - 6.3\ \mathrm{MeV/c}$ from a thin (0.1 mm) and a thick (1 mm) tungsten production target ($\mathrm{T_1}$). Positrons produced at $\mathrm{T_1}$ are collected with a solenoid lens and selected in momentum via a two dipole spectrometer. The measurement of positron polarization follows a two steps process: the polarization is first transferred to photons produced from positron interactions within a 2.0 mm tungsten conversion target ($\mathrm{T_2}$); the photon polarization is then analyzed with a Compton transmission polarimeter. The PEPPo setup is adapted from the SLAC E-166 experimental apparatus [5] that was used to demonstrate helical undulator induced polarized positrons production [6]. A detailed discussion of the PEPPo experiment can be found in [7].

Positron Polarimetry

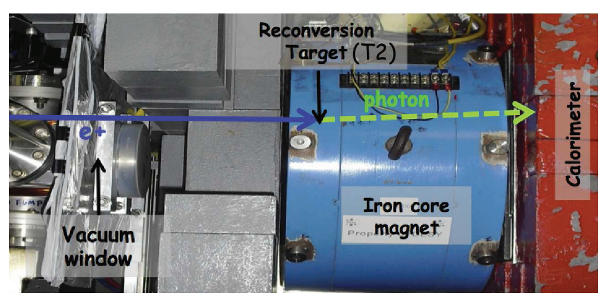

Figure 1: The Compton transmission polarimeter arrangement featuring the analyzing magnet and the calorimeter enclosed in a lead shielding hut. Positrons enter from the left and convert to photons in the reconversion target $\mathrm{T_2}$. The transmitted photon flux is measured in the calorimeter on the right.

Polarized photons created in $\mathrm{T_2}$ interact with a polarized iron target 50 mm in diameter and 75 mm in length. This takes advantage of the sensitivity of Compton scattering of circularly polarized photons in a polarized target. A solenoidal field magnetizes the iron target with polarization up to 8.36% at saturation. The target polarization $\mathrm{P_T}$ depends on the magnetic field intensity B, the magnetic field $\mathrm{B_0}$ generated by energizing coils, the electron density of the target ρ_e, the Bohr magneton μ_b, and the vacuum permeability μ_0,

$$\mathrm{P_T} = 2\,\frac{g'-1}{g'}\,\frac{\mathrm{B}-\mathrm{B_0}}{\rho_e \mu_b \mu_0} = 0.03727\,(\mathrm{B[\,T]}-\mathrm{B_0[\,T]}) \quad (2)$$

with g'= 1.919. Photons transmitted through the absorber are detected in a 3×3 CsI crystal array coupled to 9 photomultipliers. The total energy of photons is measured with a 4% resolution at 511 keV. The experimental asymmetry A_T is obtained from comparison of the number of transmitted photons between opposite beam polarizations ($\mathrm{N}^{\pm}_{\gamma}$) for a given target polarization orientation

$$\mathrm{A_T} = \frac{\mathrm{N}^{+}_{\gamma} - \mathrm{N}^{-}_{\gamma}}{\mathrm{N}^{+}_{\gamma} + \mathrm{N}^{-}_{\gamma}} = \mathrm{P_{e^+}}\,\mathrm{P_T}\,\mathrm{A_{e^+}}, \quad (3)$$

where $\mathrm{P_{e^+}}$ is the positron polarization to determine and $\mathrm{A_{e^+}}$ is the analyzing power of the polarimeter [8].

THE ANALYZING MAGNET

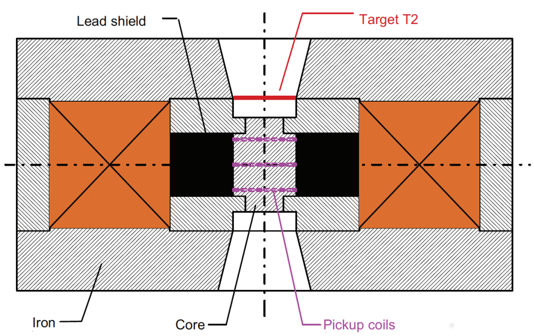

Figure 2: Schematic of the analyzing magnet horizontal section [5].

The PEPPo analyzing magnet operate at ±60 A and provides a magnetic field close to saturation [5]. The different elements of the magnet are shown in Fig. 2, particularly the reconversion target $\mathrm{T_2}$ and the iron target (core). The core is instrumented with 3 pick-up coils monitoring the magnetic field from the measurement of the magnetic flux variation when the magnet current is varied. It is further surrounded by a lead shielding cylinder that defines the effective active region of the target.

The magnetic field is modeled with OPERA 2d [9]. Considering the cylindrical symmetry of the magnet, the geometry given to OPERA represents a quadrant of the solenoid with a symmetry axis along z. The magnetic permeability of the material is described by steel 1010 properties yielding a maximum field at center of 2.497 T at 60 A. As a consequence of the magnet geometry, the magnetic field is not constant. The field decreases along z and with a partial longitudinal orientation at the edge of the iron core. The net effect of this variation can be represented by an effective length smaller than the physical length of the polarized target, as the ratio between the longitudinal magnetic field averaged over the iron core volume and the maximum longitudinal field. However, such a prescription introduces a significant systematic error in the knowledge of the target polarization as seen on Fig. 3 where the relative variation of the target polarization averaged over z varies along the target radius between +5% and −8% of the 7.54% volume averaged polarization deduced from simulations using Eq. 2. The goal of our efforts is to remove this uncertainty by calibrating the OPERA model of the analyzing magnet with experimental measurements and to implement into GEANT4 a model of the target polarization. This will allow for a precise determination of the product $\mathrm{P_T A_{e^+}}$ which enters the measurement of positrons polarization (Eq. 3).

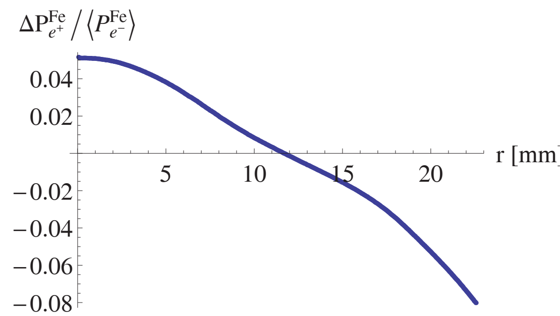

Figure 3: Relative variation along the radius axis of the target polarization averaged over z.

EXPERIMENTAL CHARACTERIZATION OF THE ANALYZING TARGET

The first source of experimental information consists of the fringe field measurements at 60 A performed prior installation, spanning a 15 mm radius region and extending from 40 mm up to 450 mm in z. The agreement between data and simulation is better than 10% in the cone entrance of the magnet (40 − 100 mm) and degrades in the external region: $\mathrm{B}^{\mathrm{OP2d}}_{z}$= 43.3 mT as compared to $\mathrm{B}^{\mathrm{Mea.}}_{z}$= 43.8 mT at z= 52 mm ($\mathrm{T_2}$ location), and 0.922 mT as compared to 0.904 mT at z=100 mm. In the outer region, the field is so low that its variation is of the order of a few steps of the Hall probe resolution, leading to unreliable comparisons. One can also question the actual permeability of the magnet material which is known to be sensitive to the iron production process.

The second source of information is the magnetic field intensity provided by the pick-up coils. The orientation of the target polarization was regularly flipped during the experiment for systematics studies. A specific procedure has been implemented for the measurement of the magnetic field at the time of the polarity change. The signal from the pick-up coils generated from the current ramp (10 A/s) was supplied to a bi-polar voltage-to-frequency module read by a scaler. The scaler was sampled at 960 Hz allowing for a precise scan of the magnetic flux signal (Fig. 4) reaching about 1.9 V at maximum. The magnetic flux is related to the magnetic field from the expression

$$B = \frac{\Phi}{nS} = \frac{1}{nS}\int V(t)dt = \frac{2\pi}{nS}\int r\frac{dB(r)}{dt}\,drdt \quad (4)$$

ISBN 978-3-95450-122-9

where S is the pick-up coil area and n is the number of turns. Central coil yields $\mathrm{B} = 2.5163 \pm 0.0023$ T and edge coil $\mathrm{B} = 2.5226 \pm 0.0021$ T. A small field asymmetry between magnet polarities is also observed $\Delta\mathrm{B} = -0.0079 \pm 0.0016$, in systematic agreement with measured Compton asymmetries.

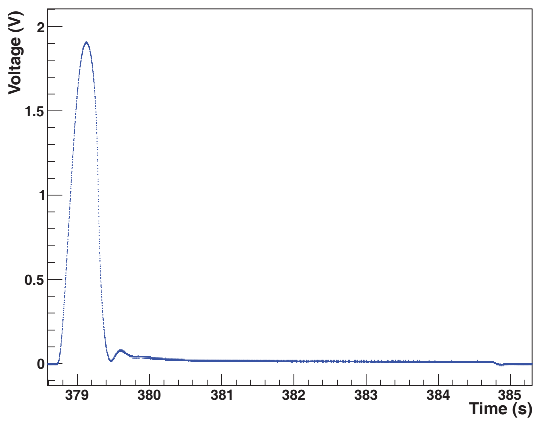

Figure 4: Voltage signal measured at the pick-up coils for a 10 A/s magnet current ramp.

The difference between the measured and calculated values of the field intensity come from the magnetic properties of the material. In addition, Foucault currents may also affect the measurements since the steel material is not laminated. The link between the data and the OPERA model of the magnet is currently developed on the basis of the second part of Eq. 4 which figures the effect of the current variation on the magnetic field. An approach neglecting the Foucault currents is used and is expected to be precise for the current ramp under consideration.

G4PEPPO

G4PEPPo is the simulation package of the experiment based on GEANT4 [10]. It has been constructed from the simulation package of the E-166 experiment [5] taking advantage of the GEANT4 upgrade for polarization effects in electromagnetic processes [11]. G4PEPPo is divided in 3 segments: the electron beam transport to the positron production target including optical elements of the line and particle production at target; the positron collection and transport up to the termination of the vacuum line and featuring the solenoid lenses and the spectrometer; the polarimeter section starting just before the vacuum window and comprising the analyzing magnet and the CsI calorimeter. Each segment is independent in order to address efficiently different experimental concerns. The last section is of interest for the present work. It allows to address multiple scattering and depolarization effects of the incident beam through the vacuum window and the air gap up to T_2 where the polarized physics package of GEANT4 is used to describe polarized photon creation and absorption inside the polarized iron core. The energy deposition of transmitted photons inside the CsI crystal array is simulated. Simulations for opposite positron polarization or opposite polarized target orientation allows to extract the polarimeter analyzing power. The original E-166 package has been modified for the PEPPo specific features and is now including the analyzing magnet field obtained from OPERA. A bilinear interpolation method is used to determine the field along a particle track. Introduction of the local target polarization (as opposed to the average one) based on Eq. 2 and OPERA field maps is progressing.

CONCLUSION

A comprehensive scheme has been developed to take into account the variation of the polarization of the target of the Compton transmission polarimeter of the PEPPo experiment. It relies on OPERA magnetic field simulations calibrated to experimental data and modifications of the G4PEPPo package to consider the local target polarization. The full procedure is intended to resolve significant systematic uncertainties.

ACKNOWLEDGMENT

We are deeply grateful to the SLAC E-166 Collaboration, particularly K. Laihem, K. McDonald, S. Riemann, A. Schälicke, P. Schüler, J. Sheppard and A. Stahl for loan of fundamental equipment parts and support in GEANT4 modeling. We also thank N. Smirnov for coordinating delivery of critical hardware. This work was supported in part by the U.S. Department of Energy, the French Centre National de la Recherche Scientifique and the International Linear Collider project. Jefferson Science Associates operates the Thomas Jefferson National Accelerator Facility under DOE contract DE-AC05- 06OR23177.

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