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Simulation of proton–proton elastic scattering for the KOALA recoil detector ☆

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ABSTRACT

Proton–proton elastic scattering at 3.2 GeV/c is simulated for the newly constructed KOALA recoil detector. The integrated luminosity (L), total cross section (σ_{tot}), slope parameter (b) and ratio of the real to imaginary part of the elastic scattering amplitude (ρ) are extracted from the spectrum of the squared 4-momentum transfer, and their corresponding systematic errors are evaluated to be 5.40%, 1.79%, 1.80% and 0.0200, respectively. Based on the simulation results, the precision of the luminosity is estimated to be better than 4%. It indicates that the KOALA recoil detector is a good candidate to determine σ_{tot}, b andρ with high precision and thus can be implemented for the $\bar{\text{P}}$ANDA luminosity calibration.

1. Introduction

Measurement of absolute cross section is one of the important quantities for the upcoming $\bar{\text{P}}$ANDA experiment at the HESR of FAIR in the beam momentum range from 1.5 GeV/c to 15 GeV/c [1]. In order to achieve the goal of the $\bar{\text{P}}$ANDA experiment, the absolute time-integrated luminosity for a physics run should be determined within a systematic uncertainty better than 5% [2]. However, the existing luminosity measurement methods which have been implemented for the internal target experiments, such as E760 and E835 at Fermilab [3,4], ANKE at COSY [5] and the colliding hadron beam experiments at LHC [6], are not suitable for the $\bar{\text{P}}$ANDA experiment due to the limitations in the setup of target surrounded by the magnetic spectrometer.

The $\bar{\text{P}}$ANDA luminosity will be determined by using a newly designed luminosity detector (LMD) to measure the $\bar{p}p$ elastic scattering rate in the polar angular range from 3 to 9 mrad [2]. To achieve the desired luminosity (L), the total cross section (σ_{tot}), the slope parameter (b) and the ratio of the real to imaginary part of the elastic scattering amplitude (ρ) are necessary for the luminosity calibration before performing the $\bar{\text{P}}$ANDA experiment. However, the existing data of these parameters in the HESR beam momentum region are not sufficient for the luminosity calibration.

In order to obtain sufficient data for the luminosity calibration, the KOALA (Key experiment fOr the pAnda Luminosity cAlibration) has been proposed [7]. The measurement is based on the detection of recoil protons which correspond to antiproton scattering at extremely forward angles. The KOALA experiment will be carried out at the HESR by measuring the squared 4-momentum transfer ($|t|$) of antiproton–proton elastic scattering in the region of $[0.0008, 0.1000]$ (GeV/c)^2.

The laboratory kinetic energy, E_p, of the recoil protons and the recoil angle, α, are related to $|t|$ as following:

$$|t| = 2m_p E_p \tag{1}$$

$$|t| = \frac{4m_p^2 \sin^2\alpha}{(1/\beta_{cm}^2) - \sin^2\alpha} \tag{2}$$

where m_p is the proton's mass and $1/\beta_{cm}^2 = \frac{E_{beam}+m_p}{E_{beam}-m_p}$. Here, E_{beam} is the beam energy.

The recoil measurement technique has been used in previous experiments [3,8,9]. It has some important advantages over measurements

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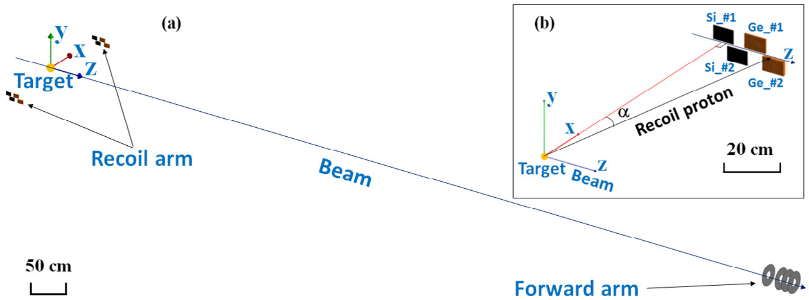

Fig. 1. (a) Sketch of the designed KOALA experimental setup. The target is at the origin of the coordinates and the beam line is along the z axis. Two recoil arms are placed at $x = \pm 1$ m. The forward arm is located at $z = 10$ m. (b) Sketch of the commissioning experimental setup. α is the recoil angle. From left to right are the detector Si_#1, Si_#2 (shown in black color), Ge_#1 and Ge_#2 (shown in brown color). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of scattered antiprotons at small forward angles. The most important is that the problem of distinguishing elastically scattered antiprotons from non-interacting, or transmitted can be avoided. In addition, recoil protons have small energies and they can be measured with excellent energy resolution and signal to noise ratio in solid state detectors. Finally, corresponding to antiprotons in a small cone at forward angles, the recoil protons can be spread over a much larger azimuthal ring. A detector with a small extension in azimuthal angle can reduce problems associated with large count rates, which are present at forward angles.

The sketch of the KOALA experimental setup is shown in Fig. 1(a). The target is at the origin of the coordinates and the beam line is along the z axis. Two recoil arms are placed at $x = \pm 1$ m and the forward arm is located at 10 m downstream the beam [2,10,11]. The scattered antiprotons will be detected by the forward arm and the recoil protons measured by the two recoil arms. The parameters σ_{tot}, ρ and b are determined from the characteristic shape of the $|t|$-spectrum and they will be used as an input for the $\bar{\text{P}}$ANDA luminosity calibration [7,10].

Fig. 1(b) shows the built recoil arm and the commissioning experimental setup at COSY-ANKE [12]. Proton–proton elastic scattering is measured in the 2.5–3.2 GeV/c region, since the antiproton beam is not available and the recoil protons have similar dynamic characteristics in both $\bar{p}p$ and pp elastic scattering. Excellent energy resolution and proper working performance are achieved [11].

In this work, simulations of proton–proton elastic scattering for the newly built KOALA recoil arm are performed to study the systematic uncertainty for the experiment at COSY-ANKE [10]. The present simulations are carried out with Pythia8 [13] and Geant4 [14–16].

2. Simulation settings

2.1. Elastic scattering

Pythia8 is chosen as the event generator since it is capable to describe the data of the previous experiments reasonably down to the Coulomb-nuclear interference region [17–20], once the empirical description of the $|t|$-spectrum is implemented [21]. In Pythia8, the differential cross section of proton–proton elastic scattering is given by

$$\begin{aligned}\frac{d\sigma}{dt} &= \frac{1}{L}\frac{dN_{el}}{dt}\\ &= 4\pi(\alpha\hbar c)^2\frac{G^4(t)}{t^2}\\ &\quad -\sigma_{tot}\alpha\frac{G^2(t)}{t}\exp\left(\frac{-bt}{2}\right)(\rho\cos(\alpha\phi(t))+\sin(\alpha\phi(t)))\\ &\quad +\frac{1+\rho^2}{16\pi(\hbar c)^2}\sigma_{tot}^2\exp(-bt).\end{aligned} \tag{3}$$

$$\phi(t) = ln\left(\frac{2}{bt}\right) - \phi_0 \tag{4}$$

where L is the integrated luminosity, $\frac{dN_{el}}{dt}$ the elastic scattering differential counts, α the fine structure constant, $\phi(t)$ the relative phase, and

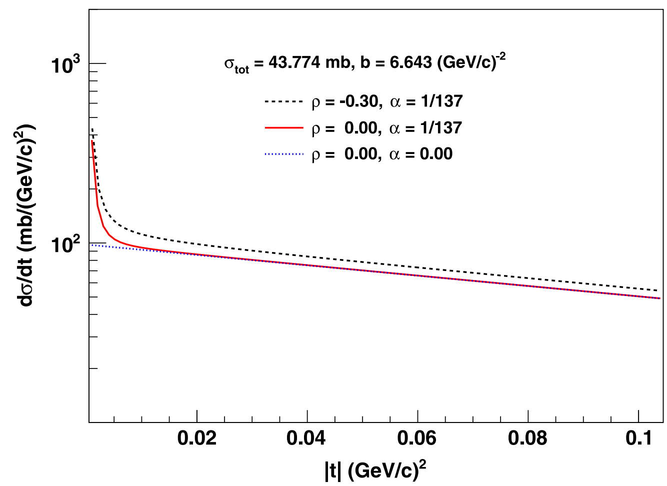

Fig. 2. (Color Online) The prediction of elastic differential cross section as a function of $|t|$ at 3.2 GeV/c, from Eq. (3).

$\phi_0 = 0.577$ the Euler's Constant. $G(t)$ is the electromagnetic form factor, which is given as $G(t) = \frac{\lambda^2}{(\lambda+t)^2}$, where $\lambda = 0.72$ (GeV/c)^2.

Proton–proton elastic scattering at 3.2 GeV/c, which was used in the commissioning experiment, is chosen for the simulation study. The predicted elastic differential cross sections from Eq. (3) for different impact parameter contributions are shown in Fig. 2 as a function of $|t|$ at 3.2 GeV/c. The settings of σ_{tot} = 43.774 mb [11], b = 6.643 (GeV/c)$^{-2}$ [11] keep the same for all cases. As it can be seen, for $\alpha = 1/137$, as increasing ρ from −0.30 [22] to 0, the contribution from the Coulomb-nuclear interference becomes smaller, and the differential cross section goes down faster above the interference region. While $\rho = 0$ and $\alpha = 0$, there is only strong interaction.

2.2. Beam and target

In order to resemble the experimental conditions as much as possible, the designed target size and the beam properties are used, which are the main sources of the systematic uncertainty. In the simulations, the diameter and thickness of the target are set to be 3.0 mm and 2.0 mm, respectively. The beam momentum spread of $\Delta p/p = 2.5 \times 10^{-4}$ and the angular divergence of σ'_x = 0.8910 mrad and σ'_y = 1.1964 mrad at the ANKE target position are taken.

2.3. Detector setup

The sketch of the commissioning KOALA experimental setup is shown in Fig. 1(b). The detector layout of the recoil arm as well as