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MONTE CARLO SIMULATION OF POLARIZATION MEASUREMENTS IN KAON ELECTRO-PRODUCTION

T. ANGELESCU[a], O. K. BAKER[b,c], P. GUÈYE[b] and L. TEODORESCU[a]

[a] *University of Bucharest, Department of Physics, P.O. Box MG12,*
R-76900 Bucharest, Romania

[b] *Nuclear/High Energy Physics Research Center of Excellence, Department of Physics,*
Hampton, VA 23668, U. S. A.

[c] *Jefferson Lab, Physics Division, 12000 Jefferson Avenue, Newport News, VA 23606,*
U. S. A.

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Kaon electro-production experiments with polarized electron beam are planed at the Thomas Jefferson National Accelerator Facility (Virginia, USA) in order to complete the information on polarization response functions for the kaon electro-production reactions. The experiment uses the self analyzing property of the Λ recoil. The scattered electrons will be detected in coincidence with the kaons and the decay protons. This paper presents the simulation of this experiment which takes into account the spectrometer acceptances, multiple scattering and radiative corrections. The phase space distribution of the decay protons in the Λ center-of-mass system are generated in order to extract information on the polarization on the three directions. An experimental test with an unpolarized beam has been performed to estimate the efficiency of the method.

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1. Introduction

Meson production in electron-proton scattering can be investigated in unpolarized and polarized experiments using the reaction

$$\mathrm{e} + \mathrm{p} \longrightarrow \mathrm{e}' + \mathrm{K}^+ + Y \tag{1}$$

where Y could be Λ or Σ^0.

The complete characterization of the interaction can be obtained only if one can measure the whole set of response functions in the differential cross-section. The whole model-independent formalism is described in [1] . The center-of-mass (CM) differential cross-section can be written as

$$\begin{aligned}\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} &= \frac{\mid \vec{P}_K \mid}{k_\gamma^{\mathrm{CM}}} P_\alpha P_\beta \Big\{ R_T^{\beta\alpha} + \epsilon_L R_L^{\beta\alpha} + [2\epsilon_L(1+\epsilon)]^{1/2} ({}^c R_{TL}^{\beta\alpha} \cos\phi + {}^s R_{TL}^{\beta\alpha} \sin\phi) \\ &+ \epsilon({}^c R_{TT}^{\beta\alpha} \cos 2\phi + {}^s R_{TT}^{\beta\alpha} \sin 2\phi) + h[2\epsilon_L(1-\epsilon)]^{1/2} ({}^c R_{TL'}^{\beta\alpha} \cos\phi \\ &+ {}^s R_{TL'}^{\beta\alpha} \cos\phi + {}^s R_{TL'}^{\beta\alpha} \sin\phi) + h(1-\epsilon^2)^{1/2} R_{TT'}^{\beta\alpha} \Big\}\end{aligned}$$

where $R^{\alpha\beta}$ are the response functions depending on squared four-momentum transfers Q^2, W and t. $\vec{P}_K$ is the kaon momentum in the (γ_v,p) CM system. $P_\alpha = (1, \vec{P}), P_\beta = (1, \vec{P}')$, where $\vec{P}$ and $\vec{P}'$ are the target and recoil polarization unit vectors. $P_0 = 1$ leads to the unpolarized cross-section. h is the electron helicity ($h \neq 0$ for polarized beam). ε and ε_L are the transverse and longitudinal polarization parameters of the virtual photon exchanged between the leptonic and hadronic vertexes. ϕ is the azymuthal angle between the scattering and reaction plane. A complete experiment can determine 36 response functions. For unpolarized beam and target and integrating on recoil polarization, the cross-section depends only on four response functions: $R_T^{00}, R_L^{00}, {}^c R_{TL}^{00}, {}^c R_{TT}^{00}$. Measuring the recoil polarization, one can determine another 8 response functions: $R_T^{y'0}, R_L^{y'0}, {}^c R_{TL}^{y'0}, {}^s R_{TL}^{x'0}, {}^s R_{TL}^{z'0}, {}^c R_{TT}^{y'0}, {}^s R_{TT}^{x'0}, {}^s R_{TT}^{z'0}$. With a polarized beam, 6 other response functions can be found: ${}^s R_{TL'}^{00}, {}^c R_{TL'}^{x'0}, {}^c R_{TL'}^{z'0}, {}^s R_{TL'}^{y'0}, R_{TT'}^{x'0}, R_{TT'}^{z'0}$. Target polarization adds information on the other 18 remaining response functions.

Looking at the above relation for $\mathrm{d}\sigma/\mathrm{d}\Omega$, it is clear that the experimental determination of these response functions requires measurements at different ϵ_L and ϕ (at least for two angles).

The set of kaon electro-production experiments chose a simpler approach [2]. By detecting the K-meson along the γ_v direction and averaging over the whole range in ϕ, the R_T^{00} and R_L^{00} response functions can be determined with an unpolarized experiment and be separated by using three kinematic settings at different ϵ_L. ${}^c R_{TL}^{00}$ and ${}^c R_{TT}^{00}$ can be obtained out of a ϕ distribution of the differential cross-section [3]. By measuring the Λ transverse polarization in the same experiment one can obtain $R_T^{y'0} + \epsilon_L R_L^{y'0}$ [4].

A polarized beam experiment, E98-101 [2], is planed at Jefferson Lab and it will give information about $R_{TT'}^{z'0}$ by measuring the longitudinal polarization of the recoil (Λ) for positive and negative helicity of the electron.

In order to extract the dynamical information from the experimental data, an essential tool is a simulation program, which could give the phase-space distributions on all the kinematic quantities.

In this paper we describe the simulation program for polarization measurements in kaon electro-production, which permitted to establish the best conditions for extracting dynamic information out of the experimental data.

2. Program structure

The electro-production experiment with the two spectrometers in coincidence is simulated in the Monte Carlo program following the principles of the conceptual design [5], ray reconstruction [6] and radiative corrections [7] for Jefferson Lab Hall C spectrometers. The schematic view of the detector package is shown in Fig. 1. The program follows different steps of simulation for the interaction and the detection:

1) The vertex simulation in the reaction p(e,e'K$^+$)Y has been done using the Williams-Ji-Cotanch (WJC) model [8]. The cross-sections are used in the program as a weight associated to each event. We also used in the program a cross-section extrapolated in W, Q^2 and t with a fit on an extended range of experimental data [9]. A constant differential cross-section corresponds to phase space and has been used in computing the spectrometer acceptances.

2) The simulation of the charged particle trajectories in the two spectrometers, High Momentum Spectrometer (HMS) for scattered electrons and Short Orbit Spectrometer (SOS) for kaons and protons, takes into account the straggling, multiple Coulomb scattering and radiative losses in internal and external bremsstrahlung. This part of the program corresponds to the Monte

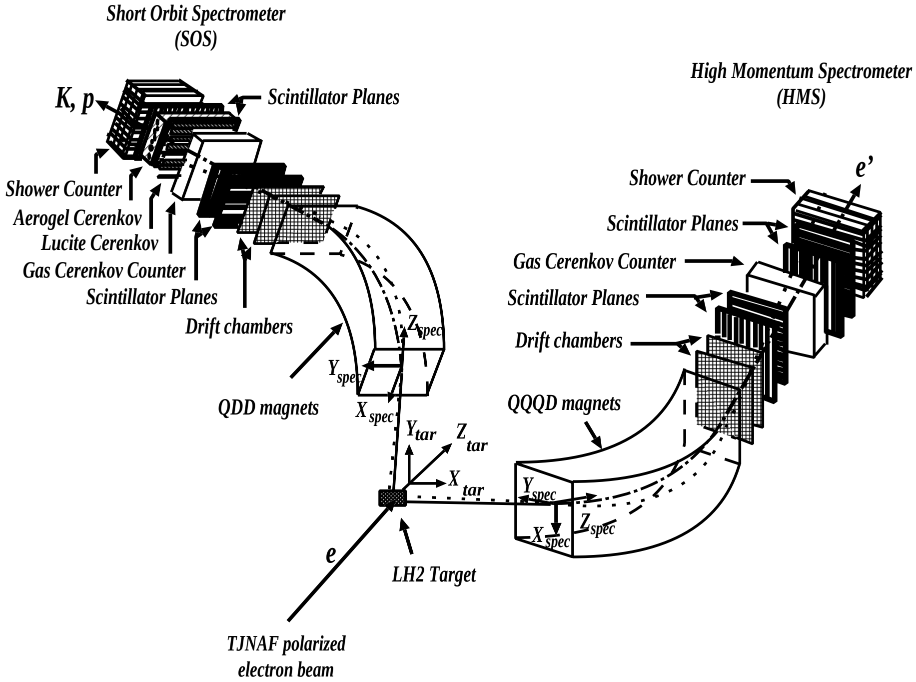

Fig. 1. View of the detector package of the Hall C spectrometer.

Carlo simulation SLAC program adapted for Hall C experiments at Jefferson Lab [10].

3) The simulation of the hyperon decay and the detection of the decay proton in the SOS spectrometer takes into account the momentum and angular distribution due to the hyperon decay in flight, and the multiple scattering and straggling of the proton when passing through the detector package, as well as the radiative corrections for the Λ decay. The simulation was destinated to the computation of the recoil polarization in different kinematic settings of kaon electro-production experiments with polarized and unpolarized beam (experiment E98-101 [2]). It answers the following questions:
    - what is the probability of simultaneous detection in SOS of the K^+ and the decay proton?
    - what is the phase space associated to the distributions in polarization angles and how one can extract the Λ polarization value out of these distributions?
    - what is the minimal statistics for measuring the polarization variables with different statistical uncertainties and the corresponding acquisition time?

In the following we will discuss the most important problems solved by the simulation program and the corresponding issues for the polarization measurements in kaon electro-production experiments.

3. *Simulation method*

3.1. (K^+, Λ) *electro-production simulation*

The simulated reaction is

$$e + p \longrightarrow e' + K^+ + \Lambda \,. \tag{2}$$

The scattered electron and the K^+ are detected by the two spectrometers, HMS and SOS, respectively. The angular and momentum acceptances of the two spectrometers are given in Table 1.

- The incident electron energy (E_e) has been randomly generated within a 10^{-3} resolution, corresponding to the actual beam energy uncertainty delivered into Hall C.
- The scattered electron momentum and angles ($P_{e'}, \theta_{e'}, \phi_{e'}$) are generated uniformly within the HMS angular and momentum acceptances.
- The electro-produced kaon angles (θ_K, ϕ_K) are generated uniformly within the SOS angular acceptance.

- In addition to these 6 quantities, the position of the vertex interaction point in the target for each event is also generated inside the liquid hydrogen target using at the same time different raster sizes to test the influence of the beam spot size on the reconstructed distributions.

TABLE 1. The typical angular and momentum acceptances and central pathlengths of the HMS and SOS Hall C magnetic spectrometers.

	HMS	SOS
ΔP	±7.5%	±15%
$\Delta\Theta$	±30 mrad	±58 mrad
Φ	±70 mrad	±38 mrad
L_0	7.5 m	25 m

From the momentum, position and angles of the particle at the target, the code transports the particle inside the detector hut using the COSY [6] forward matrix elements to give the corresponding parameters at the focal plane. Then, the COSY backward matrix elements are used to transport the particle back to the target and give the reconstructed parameters. We stress that this model assumes the production of a particle in a plane located in the middle point of the target. The calculations include the energy loss and multiple scattering correction of the particle while traveling through all materials from the target to the last element inside the detector hut, as well as radiative corrections which were applied to all charged particles involved in the reaction.

To test the validity of the Monte Carlo simulation in the reaction (2), we have compared the simulated Λ missing-mass distribution to the experimental one obtained in experiment E93-018 [2]. The result on Λ missing mass is shown in Fig. 2.

The experimental peak and radiative tail are well reproduced by the simulation program. In the simulation program, Σ has not been included which explains the discrepancy at higher missing mass. During this experiment, data taken at Q^2=1.5 (GeV/c)^2, W=1.69 GeV were analyzed in order to investigate the feasibility of Λ polarization experiment.

3.2. Λ decay simulation

In Λ polarization measurement the $\Lambda \to \mathrm{p} + \pi^-$ decay is used as a self polarization analyser. The angular distribution of the proton can be written as [11]

$$\mathrm{d}N(\theta^{\mathrm{CM}}) = \frac{1}{4\pi}[1 + \alpha P_\Lambda \cos\theta^{\mathrm{CM}}]\ \mathrm{d}\Omega^{\mathrm{CM}}\,, \tag{3}$$

where θ^{CM} is the polar angle between the proton momentum direction and the polarization vector of the Λ in the Λ rest system. α is the asymmetry parameter, $\alpha = 0.642 \pm 0.013$.

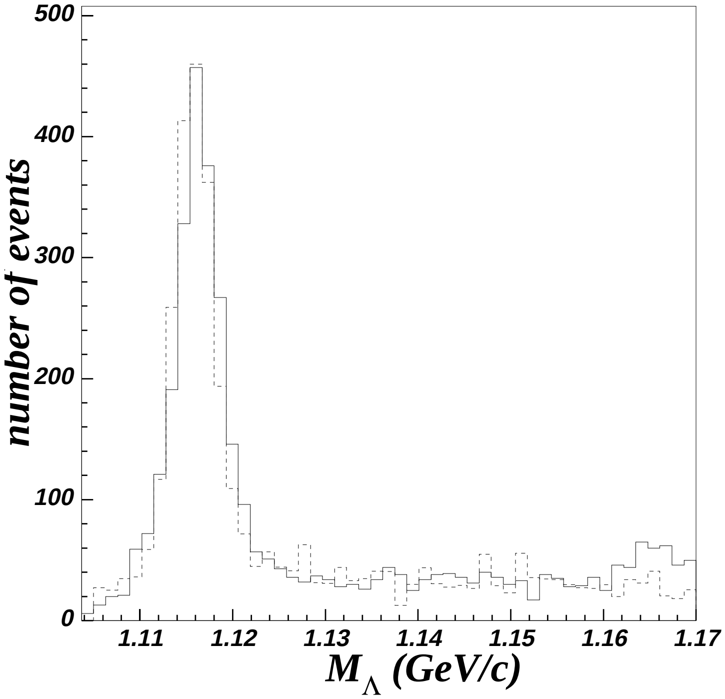

Fig. 2. The experimental Λ missing mass spectrum (solid line) compared with the Monte Carlo simulated one (dashed line).

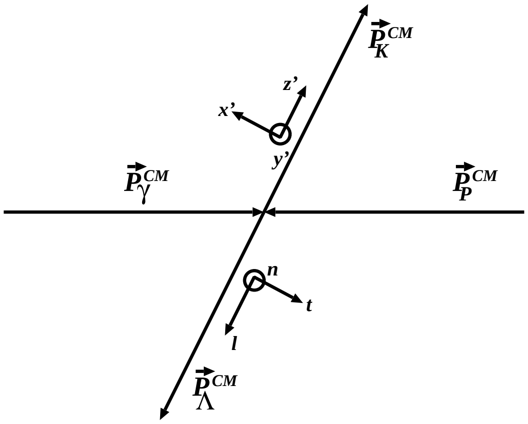

Fig. 3. The coordinate systems for the polarization vectors.

Since the vector polarization has three components, three polarization angles can be defined in the (γ_v,p) rest system: longitudinal (θ_l^{CM}), transverse (θ_t^{CM}) and normal (θ_n^{CM}), corresponding respectively to the $\vec{l}$, $\vec{t}$, $\vec{n}$ polarization directions shown in Fig. 3.

The longitudinal direction is taken along the $\vec{P_\gamma} \times \vec{P_{\mathrm{K}}}$ direction, perpendicular to the production plane. In the experiment, the decay protons will be detected along the K^+ direction in the acceptance limits of the SOS spectrometer. We expect a drastic limitation of the angular distributions due to the spectrometer acceptance and a small efficiency in detecting the decay protons. This justifies the importance of a correct simulation for the decay proton sample of the experiment.

The Λ decay proton has been generated uniformly in $\cos\theta_\Lambda$ and ϕ_Λ in the Λ rest system. The momentum of the proton is fixed in this system. Then, we applied a general Lorentz boost to compute the momentum and direction of the proton in the laboratory system (LS). In the same way as for the reaction (2), each proton is transported through the SOS spectrometer hut using the forward and backward COSY matrix elements. All protons reconstructed outside the angular and momentum SOS acceptance were rejected.

Since the Λ can decay anywhere from its production vertex in the target with a lifetime of about $2.63 \cdot 10^{-10}$ s, we have to consider its decay probability including the branching ratio of the decay channel (63.9%). The decay point was generated according to an exponential law. We cut events with a decay length bigger than 30 cm. At this distance, the probability that a Λ hyperon survived is less than 1%.

The proton momentum and direction are modified due to straggling, multiple scattering and radiative losses through the SOS detectors. Therefore, for computing the polarization angles we boosted these modified momenta to the Λ rest system. The angular distribution for each polar angle was recorded. They were used to eliminate the false asymmetry and obtain the three polarization values (P_l, P_t, P_n) of the Λ according to relation (3). In the same time, we introduced the theoretical model and used the weighted distributions to extract the polarization, modelling in this way the experiment. We could thus evaluate the polarization errors and their dependence on the number of events available in the Monte Carlo sample.

3.3. Polarization computation

We used different methods for extracting the value of P_Λ from the relation (3).

3.3.1. **Linear fit method**

After correcting for the spectrometer acceptance (that means dividing the distribution given by the model or the experiment with the corresponding phase space one), $\mathrm{d}N(\theta^{\mathrm{CM}})/\mathrm{d}\cos\theta^{\mathrm{CM}}$ has a linear dependence on $\cos\theta^{\mathrm{CM}}$

$$F(\theta^{\mathrm{CM}}) = B + A\cos\theta^{\mathrm{CM}} \,. \tag{4}$$

By fitting the final distribution with (4) using the minimum χ^2 method, we can find A and B and their corresponding errors ΔA and ΔB. Then $\alpha P_\Lambda = A/B$ and by propagating the errors on A and B we can extract the error on P_Λ. We used the MINUIT CERN Library package [12]. This metod is the most reliable if we know the spectrometer acceptance with small statistical errors.

3.3.2. Integral method

If one integrates over the positive and negative side of the $\cos\theta^{\rm CM}$ distribution, one obtains N_+ and N_- events, respectively. Then

$$\alpha P_\Lambda = \frac{1}{<\cos\theta^{\rm CM}>} \frac{N_+ - N_-}{N_+ + N_-} \,. \tag{5}$$

$$<\cos\theta^{\rm CM}> = \frac{|\cos\theta_+^{\rm CM}| + |\cos\theta_-^{\rm CM}|}{2} \,. \tag{6}$$

The average value of $<\cos\theta^{\rm CM}>$ is determined by using the Monte Carlo simulation.

The error on the polarization will be

$$\frac{\Delta(\alpha P_\Lambda)}{\alpha P_\Lambda} = \frac{2}{N_+ - N_-}\sqrt{\frac{N_+ - N_-}{N_+ + N_-}} \,. \tag{7}$$

Roughly, the error of the asymmetry is proportional to $1/\sqrt{N}$ for not too high asymmetries (N is the total number of events in the distribution). The method is reliable if the instrumental asymmetry is very small in comparison with the physical one and we determine $<\cos\theta^{\rm CM}>$ from the simulation program with a very small statistical error.

3.3.3. Multiple bin method

One can divide the $\cos\theta^{\rm CM}$ distribution into multiple bins on both positive and negative sides. For each corresponding bin, one can compute the asymmetry $(\alpha P_\Lambda)_j$

$$(\alpha P_\Lambda)_j = \frac{2A_j}{(|\cos\theta_-^{\rm CMj}| + |\cos\theta_-^{\rm CMj}|) - A_j(|\cos\theta_+^{\rm CMj}| - |\cos\theta_-^{\rm CMj}|)} \,, \tag{8}$$

where $A_j = (N_j^+ - N_j^-)/(N_j^+ + N_j^-)$. N_j^+, N_j^- are the numbers of events in the corresponding bins on the positive and negative side of the $\cos\theta^{\rm CM}$ distribution. Then, one finds the average weighted asymmetry

$$(\alpha P_\Lambda) = \frac{\Sigma w^j (\alpha P_\Lambda)_j}{\Sigma w^j} \tag{9}$$

$$w^j = 1/\sigma_j^2 \tag{10}$$

$$\sigma_j = \frac{2}{N_+^j + N_-^j}\sqrt{\frac{N_+^j N_-^j}{N_+^j + N_-^j}} \,. \tag{11}$$

3.3.4. **Maximum likelihood method**

For a large sample, maximum likelihood gives an unique, unbiased minimum variance estimate [13]. For the experimental distribution (3), the likelihood function has the form

$$\mathcal{L}(\alpha P_\Lambda) = \Pi(1 + \alpha P_\Lambda \cos\theta_i^{\mathrm{CM}})\,. \tag{12}$$

The product is extended over the number of events of the sample which could be binned for convenience. From the likelihood function dependence on αP_Λ, one finds the maximum value which gives the polarization. The error is given by the $(\alpha P_\Lambda)_1$ and $(\alpha P_\Lambda)_2$ values for which the likelihood function diminishes by 1/2 from the maximum value. The advantage of the method is that we can detect an asymmetric error on the polarization.

4. Results

4.1. Event selection

The events generated in reaction (3) were selected for the polarization measurement experiment in the following way:

- In order to accept protons in the SOS with a momentum close to the K^+ momentum, the (γ_v, p) center-of-mass energy has been chosen very close to the threshold of $\mathrm{K}^+\Lambda$ production. In that case, K^+ and Λ both move forwards with about the same momentum in the laboratory system and the decay proton along the hyperon direction has a momentum inside the SOS momentum acceptance (see Table 1).
- Reaction (2) has been selected by detecting electrons and kaons in coincidence. The decay protons have been detected in SOS with the kaons in the same coincidence window (≈ 30 ns). The delay due to the Λ life time (0.263 ns) is negligible. The selection of the decay protons is based on the missing mass spectrum in the decay process

$$\Lambda \longrightarrow \mathrm{p} + \mathrm{X}\,. \tag{13}$$

Figure 4 shows a decay–missing-mass spectrum from simulated events compared with an experimental spectrum [4]. The experimental spectrum attests the presence of accidental events e'K^+ in the coincidence window which do not correspond to reaction (2). One can use cuts given by the Monte Carlo simulation on the lower part of the spectrum but not on the higher part where both spectra show a radiative tail. After selecting events by using these criteria, we compared the polarization angular distribution of the Monte Carlo simulation with experimental data at Q^2=1.5 (the test experiment). Figure 5 shows the distribution in $\theta_l^{\rm CM}$, $\theta_t^{\rm CM}$, $\theta_n^{\rm CM}$.

Though the number of events in the experimental spectra is low, the agreement between the simulation and data is evident. We should stress that for this test experiment we increased the momentum acceptance in the SOS. In this way we obtained more protons, but in the same time the longitudinal angular distribution is distorted, and the kinematic limits are smeared out due to the spread in the Λ direction.

The phase space distributions in $\theta_l^{\rm CM}$, $\theta_t^{\rm CM}$, $\theta_n^{\rm CM}$ can be used for extracting the polarization as mentioned in Sec. 3.3. A test on the instrumental asymmetry in $\theta_n^{\rm CM}$ gave (-0.015 ± 0.002), which can be an indication on the limit in measuring the transverse polarization.

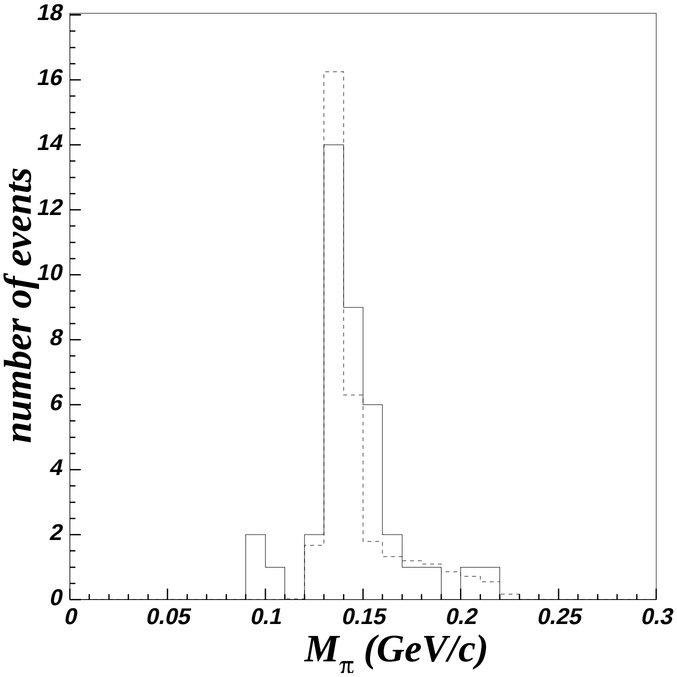

Fig. 4. The experimental $\Lambda \to \mathrm{p} + \pi^-$ *decay missing mass spectrum (solid line) compared with the Monte Carlo simulated one (dashed line).*

4.2. Proton detection efficiency

The simulation program has been applied to the kinematic settings proposed for measuring polarization in the experiment E98-101. The kinematic parameters are given in Table 2.

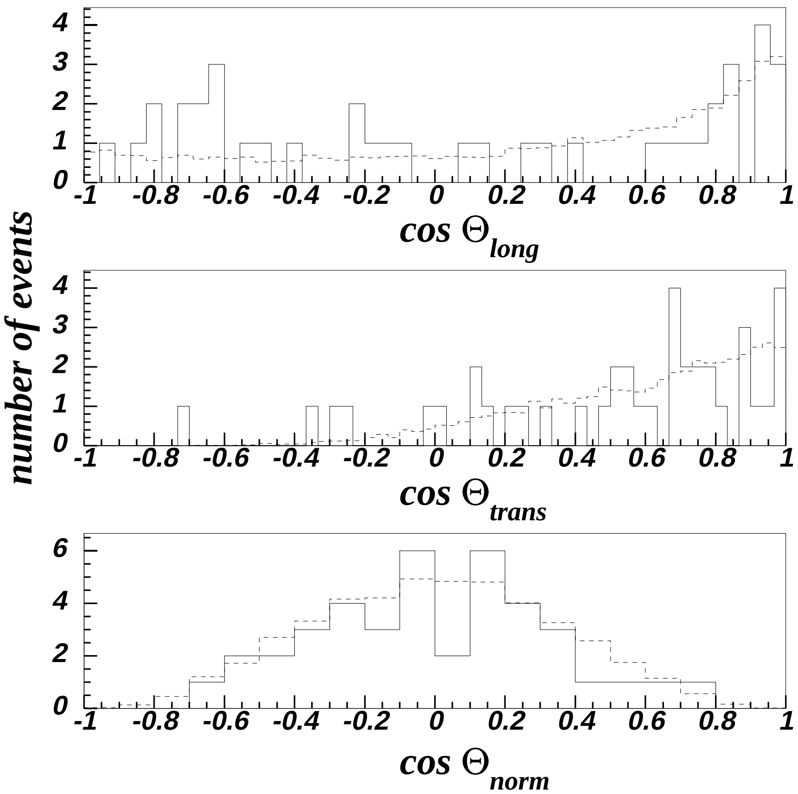

Fig. 5. Comparison of the Λ *polarized polar angles obtained from experiment E93018 and our Monte Carlo simulation at* $Q^2 = 1.5$ $(\mathrm{GeV/c})^2$. *The solid line represents the experimental data, the dashed-line is for our Monte Carlo simulation.*

TABLE 2. Kinematic settings of E98-101.

Q^2 $(\mathrm{GeV/c})^2$	E_e (GeV)	$P_{e'}$ (GeV/c)	$\theta_{e'}$ (Deg.)	P_K (GeV/c)	θ_K (Deg.)	P_P (GeV/c)
0.455	4.045	2.800	11.50	0.704	23.22	0.712
0.604	4.045	2.700	13.50	0.790	23.94	0.763
0.765	4.045	2.600	15.50	0.866	24.29	0.823
0.990	4.045	2.500	18.00	0.898	24.86	0.940
1.171	4.045	2.400	20.00	0.960	24.64	1.011
1.539	4.045	2.200	24.00	1.072	23.73	1.151
2.059	4.045	1.900	30.00	1.314	21.60	1.314

The number of events with a selected decay proton is given in Table 3 alongside with the estimated rates for a beam current of 30 μ A. Table 3 shows that about 5% of good reconstructed Λ's will give a decay proton fulfiling all selection criteria.

TABLE 3. Estimated rates of good $\Lambda - \pi^-$ reconstructed events for an incident beam current of 30 μA.

Q^2 setting $(\mathrm{GeV/c})^2$	Estimated Λ rates (events/s)	Percentage of good π^- (%)	Estimated π^- rates (events/s)
0.455	0.282	2.3	0.007
0.604	0.275	2.8	0.008
0.765	0.251	5.2	0.013
0.990	0.171	4.9	0.008
1.171	0.144	6.0	0.009
1.539	0.103	9.7	0.010
2.059	0.079	12.2	0.010

4.3. Minimal statistics for polarization measurements

As we have seen in Sec. 3.3, a rough evaluation of the statistical error of the asymmetry gives $\frac{1}{\sqrt{N}}$, where N is the total number of events in the distribution. For 1000 div 3000 events, the error on the asymmetry is 0.03 div 0.018. In our experimental conditions we can measure safely P_Λ in the range 0.3 div 0.5. Using the linear fit method and grouping events in bins of equal weight the error depends essentially on the spread of the points from the straight line, the $\sqrt{\chi^2/ND}$ value which decreases also as $\frac{1}{\sqrt{N}}$. The beam time request for E98-101 [2] is based on this evaluation assuming a polarization of 0.3 and 3000 events in the distribution.

5. Conclusion

A Monte Carlo simulation has been performed in order to support Λ polarization measurements in the reaction $\mathrm{e} + \mathrm{p} \longrightarrow \mathrm{e}' + \mathrm{K}^+ + \Lambda$ in the experimental Hall C at Jefferson Lab. The two spectrometer arms measure the scattered electron in coincidence with K^+ in addition with the proton from the Λ decay detected in the same arm as the kaon. This method imposes severe constraints on the proton acceptance, limiting the detection efficiency and the angular distributions. About 5% of the decay protons fulfill the selection conditions. The phase space angular distributions in the Λ hyperon rest system have been computed with high accuracy in order to obtain the Λ polarization out of the experimental data. Different models can be used to simulate the theoretical prediction on the polarization and find the minimal statistics for extracting the corresponding asymmetry.

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SIMULACIJA PORARIZACIJSKIH MJERENJA U ELEKTROTVORBI KAONA MONTE CARLO METODOM

U Thomas Jefferson National Accelerator Facility (Virginia, USA) predlažu se mjerenja elektrotvorbi s polariziranim elektronima radi cjelovitosti podataka o polarizacijskim funkcijama odziva u elektrotvorbi kaona. Mjerenje rabi samoanalizacijsko svojstvo odboja Λ čestice. Raspršeni elektroni opažat će se sudesno s kaonima i protonima. Ovaj rad predstavlja simulaciju tog eksperimenta u kojoj se uzimaju u obzir prihvati spektrometara, višestruko raspršenje i radijativne popravke. Izvodi se fazna raspodjela protona u centru mase Λ čestice radi dobivanja podataka o polarizaciji u trima smjerovima. Mjerenjem pomoću nepolariziranog snopa ocijenili smo učinkovitost metode.