Λ⁰ polarization as function of target density

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Abstract. Λ⁰ polarization (P) depends on x_f and p_t; it depends also on the density of the target material: P(x_f, p_t, ρ) = (κ₀/(λ₀ + ρ/ρ_w))x_f p_t, with κ₀ = −0.423 ± 0.065 (GeV/c)^−1 and λ₀ = 1.191 ± 0.200 in the range 0 < p_t < 1.2 GeV. Here ρ is the target material density and ρ_w is the Tungsten density. From this equation, it follows that Λ⁰ polarization is reduced by target density.

1. Introduction

The role that spin plays in hadron interactions isn't completely understood yet. Analysis of hyperon’s polarization can help to understand the spin dependence of hadron interactions. Hyperons such as Λ⁰, Ξ, Σ and Ω are created polarized[1]-[5] in pNucleus interactions. There are many experimental hyperon polarization reports, however a theoretical model explaining all of the data doesn’t exist yet [6]-[11]. In the present work, a phenomenological analysis of experimental data of polarization of Λ⁰’s inclusively created from unpolarized pNucleus collisions is carried out.

2. Definition of polarization and kinematical variables

Λ⁰ polarization along some quantization axis ˆn is defined by

P = ⟨⃗σ · ˆn⟩. (1)

Kinematical variables used to describe Λ⁰ polarization are p_t, defined as the component of Λ⁰ momentum transverse to the incoming beam direction; x_f, defined as the component of Λ⁰ momentum in center-of-mass collision frame (CMF) parallel to the incoming beam direction scaled by its possible maximum value (x_f ≃ 2p_∥/√s); √s, the total energy of the reaction in CMF; A, target atomic mass; and M_x, mass of particles diffractively created[1].

Experimentally, Λ⁰ polarization is obtained by measuring the distribution of the proton from the decay Λ⁰ → pπ⁻[12], in the frame where Λ⁰ is at rest, which is given by [6]

\[ \frac{dN}{d\Omega} = N_0(1 + \alpha P \cos \theta), \] (2)
where $dN/dΩ$ is the angular distribution of the proton from $Λ^0$, $N_0$ is a normalization constant, $\alpha$ is the asymmetry parameter decay ($\alpha = 0.642 \pm 0.013$) \cite{13}, $P$ is the polarization of $Λ^0$ and $\theta$ is the angle between momentum direction of proton and the normal to the production plane, $\hat{n}$, which is defined in agreement with the next coordinate system:

$$\hat{n}_y = \frac{\vec{P}_\text{beam} \times \vec{P}_Λ}{\left| \vec{P}_\text{beam} \times \vec{P}_Λ \right|}, \hat{n}_z = \frac{\vec{P}_Λ}{\left| \vec{P}_Λ \right|}, \hat{n}_x = \hat{n}_y \times \hat{n}_z.$$ (3)

### 3. $Λ^0$ polarization analysis

#### 3.1. Kinematical regions

In order to understand polarization dependences on $x_f$ and $p_t$ it’s necessary to compare data from the same covered kinematical regions, which depend on the particular characteristics of the experiments. Fig. 1 shows kinematical regions covered by some experiments. Berilium was the most common target used in experiments with unpolarized beams and targets\cite{16, 19, 29, 30}.

#### 3.2. $Λ^0$ polarization dependence on beam energy

Beam energy has been varied from $\sim 6$\cite{15} to $\sim 2000 GeV$\cite{20} (energy equivalent in laboratory system) in different experiments\cite{33}. Fig. 2 shows comparisons between polarization data inside similar kinematical regions with same target from different experiments. The only free variable was the beam energy. Inside statistical margins, the $Λ^0$ polarization is constant; $Λ^0$ polarization doesn’t depend on beam energy.

#### 3.3. $Λ^0$ polarization dependence on type of nucleus

Targets most used in experiments have been metals: Be\cite{16, 19, 29, 30}, Cu\cite{24, 27}, W\cite{28, 27}, Ir\cite{21}, Pt\cite{18}, Pb\cite{24}, in addition to H and p\cite{14, 16, 20, 22, 31}, D\cite{22} and $\bar{p}$\cite{32} (H and D in liquid state). Measurements of polarization with neutron beams on carbon targets\cite{33} and carbon-nucleus beams on Tantalus and Carbon targets\cite{26} have been reported too. A weak dependence of polarization on target atomic mass ($A$) was predicted\cite{34}: It was suggested that
as atomic mass increases, polarization in same kinematic region should weakly increase (decreases in absolute value). That suggestion is based on a parton hard scattering model. Experimental data show a feeble dependence on type of target but, as it is shown below, the available data do not support Ref. 34 proposal. However, data suggest a $\Lambda^0$ polarization dependence on target material density. Two mechanisms can explain possible dependences on type of target:

a) Isospin channel effect: In $pp$ reactions, $\Lambda^0$ is produced through a pure channel of isospin ($I=1$), but in $pn$ reactions, $\Lambda^0$ can be produced through two channels of isospin ($I=0,1$). The mechanism responsible for $\Lambda^0$ polarization in inclusive $pNucleus$ reactions can produce different magnitude for $\Lambda^0$ polarization if $\Lambda^0$ is created through one pure channel of isospin (that is to say, if one isospin amplitude dominates the reaction). This phenomenon implies a dependence on the number of protons or neutrons from nuclei. It is necessary to make comparisons between polarization data of $\Lambda^0$’s from $pn$ interactions and $\Lambda^0$’s from $pp$ interactions in order to search for isospin effect in $\Lambda^0$ polarization. We assume in this work that this effect contributes equally for all analyzed cases.

b) Target density effect: When $\Lambda^0$ is produced with certain polarization, in subsequent interactions with another nuclei, it changes its motion direction (without changing its spin direction). The $\Lambda$ polarization in $pp \rightarrow \Lambda + X$ could differ from that in $pNucleus \rightarrow \Lambda + X$ reactions because in the latter case the production of the $\Lambda$ takes place ‘inside’ the nucleus. This implies a dependence of polarization on target material density.

3.4. Kinematical dependence of $\Lambda^0$ polarization

Eq. (4) was proposed[35] to describe $\Lambda^0$ polarization in exclusive reactions $pp \rightarrow p\Lambda K^+(\pi^+\pi^-)^N$ ($N=1,2,3,4$). It is valid in $-1 < x_f < 1$, $0 < p_t < 2.0$ GeV/c, for $a_1 = -0.443 \pm 0.037$ (GeV/c)$^{-1}$. It is the most simple function. Eq. (4) was used in order to make phenomenological fits to polarization data. This analysis was performed target by target in order to search for dependence on nucleus kind.

\[ P_1(x_f, p_t) = a_1 x_f p_t, \]  

In order to check the suggestion mentioned in section 3.3 about the dependence of $\Lambda^0$ polarization on type of target, Eq. (4) was used in the range $0 < p_t < 1.2$ GeV/c. Table (I) gives the final results for the fitted parameters from Eq. (4). The values of the parameter

![Figure 2. $\Lambda^0$ polarization as function of beam energy, with Be target.](image-url)
Table 1. Results for the parameters in Eq. (4) from the fit to data. Target material density values are given too.

| Target | $a_1 x_f p_t$ | $\rho/\rho_w$ |
|--------|----------------|----------------|
| $p$    | $-0.364 \pm 0.008$ | $2.7$ | $0$ |
| $H$    | $-0.426 \pm 0.048$ | $3.4$ | $0.00366$ |
| $p+H$  | $-0.366 \pm 0.008$ | $2.8$ | $-$ |
| $D$    | $-0.218 \pm 0.044$ | $0.6$ | $0.00875$ |
| $Be$   | $-0.325 \pm 0.004$ | $3.1$ | $0.09575$ |
| $Cu$   | $-0.265 \pm 0.004$ | $1.8$ | $0.46424$ |
| $W$    | $-0.282 \pm 0.100$ | $2.4$ | $1$ |
| $Pb$   | $-0.223 \pm 0.051$ | $0.04$ | $0.58808$ |

$a_1$ as function of the material density $\rho/\rho_w$ (scaled by Tungsten’s density in order to normalize the scale) are given in Fig. 3. The parameterization

$$a_1 = \frac{-\kappa_0}{\lambda_0 + \rho/\rho_w}$$

(5)
gives a good fit to the values of $a_1$ in Table I, according to $\chi^2/dof$ minimal criterion, with $\kappa_0 = 0.423 \pm 0.065 \text{ (GeV/c)}^{-1}$ and $\lambda_0 = 1.191 \pm 0.200$ with $\chi^2/dof = 1.48$. The $a_1$-value analysis was performed using different functions (polynomials and exponentials), but the above simple parameterization proved to be more effective to describe $\Lambda^0$ polarization. The form of Eq. (5) indicates that $\Lambda^0$ polarization dependence on target density is a multiplicative term of the $x_f-p_t$ dependence, and hence, it suggests that (independently of the $\kappa$ and $\lambda$ parameters values) the target material density plays an important role in the measured $\Lambda^0$ polarization from inclusive reactions.

For $0 < p_t < 1.2 \text{ GeV/c}$, $\Lambda^0$ polarization as function of $x_f$, $p_t$ and $\rho$ is described by

$$P(x_f, p_t, \rho) = f(x_f p_t) = \left(\frac{1}{\lambda_0 + \rho/\rho_w}\right)(-\kappa_0 x_f p_t).$$

(6)

4. Conclusions

General features of $\Lambda$ polarization from $pNucleus$, are well known: It strongly depends on $x_f$ and $p_t$ and weakly on target nature. The $\Lambda^0$ polarization doesn’t depend on beam energy (even though in the definition of the scaling variable $x_f$ the reaction total energy is involved). The simplest parameterization of polarization is proportional to $x_f p_t$ (See Eq. 4). The $\Lambda^0$ polarization produced in inclusive $pNucleus$ reactions is described by the Eq. (6), where $\rho/\rho_w$ is the material density divided by Tungsten’s density, $\kappa_0 = 0.423 \pm 0.065 \text{ (GeV/c)}^{-1}$, and $\lambda_0 = 1.191 \pm 0.200$ for $0 < x_f < 1$, and $0 < p_t < 1.2 \text{ GeV/c}$. Equation (6) shows that the dependence on target nature can be written as a multiplicative function and this dependence is well described by the target density effect: The absolute value of $\Lambda^0$ polarization decreases as the density of the target increases. This may be understood physically because after being produced in the target nucleus $\Lambda^0$ can be scattered inside the nuclei (thus reducing its polarization) before it escapes. Greater the target material density the more likely that $\Lambda$ will undergo such a
Figure 3. Parameter $a_1$ as function of target material density (in units of tungsten’s density).

collision. Despite all accumulated knowledge, the explanation of $\Lambda^0$ polarization from first principles remains as an open problem.

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