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Can the Thomas-Precession Mechanism Produce Hyperon Polarization?

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ABSTRACT

We show that the Thomas-precession model for polarization asymmetry in inclusive hadron production fails to explain the experimental data when hyperons are produced at small momentum fraction of the incident particles due to the strong dependence of the model on the masses of sea quarks and x_F, the fraction of momentum carried by the outgoing hyperon.

Key-words: Hyperon polarization; Semiclassical models..

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1 Introduction

The fact that hyperons are produced with significant polarization in inclusive reactions is known from about twenty years ago, when was observed the production of polarized Λ_0 from a proton beam interacting with an unpolarized target[1].

Subsequent experiments have shown this fact for a variety of hyperons and anti-hyperons produced in several inclusive reactions[2][3].

From the theoretical point of view, this fact has stimulated the production of several models trying to explain the polarization of hyperons in inclusive reactions. Among them we can mention the semiclassical models by De Grand and Miettinen[4][5], which has been applied to explain polarization in other reactions than $p+p \rightarrow \Lambda_0 + X$ [6]; the Lund model[7] in which the mechanism that produces the hyperon polarization is basically a soft process where sea $q\bar{q}$ pairs are produced by a tunneling process through a classically forbidden region in the color field before entering the outgoing hyperon's wave function and the s-quark scattering model[8] in which the s-quark originating from the incident proton sea or produced during the collision in the subprocess $g \rightarrow s\bar{s}$ became polarized due to its non-zero mass by multiple scattering on quark-gluon matter.

An extensive review on models and experimental results can be found in ref.[9].

Among these semiclassical models, one of the most popular and apparently successful seems to be the De Grand and Miettinen model, known as Thomas-precession model, which will be critically revised in this work.

The paper is organized as follows: in section 2 we briefly describe the model by De Grand and Miettinen, in section 3 we point out some inherent contradictions of the model and finally, section 4 is devoted to conclusions.

2 De Grand and Miettinen model

De Grand and Miettinen proposed a simple model in which the polarization of the outgoing hyperon is produced by a Thomas- precession effect in the quark recombination process[4]. As a result of the Thomas-precession effect they obtained the simple but successful rule to explain polarization in a variety of VVS (Valence-Valence-Sea) and VSS (Valence-Sea-Sea) reactions

fast partons recombine preferentially with spin up
slow partons recombine preferentially with spin down

in the production plane defined by $\hat{n} = \frac{\vec{p}\times\vec{p}_{hyp}}{\left|\vec{p}\times\vec{p}_{hyp}\right|}$, where $\vec{p}$ is the beam momentum and $\vec{p}_{hyp}$ is the momentum of the outgoing hyperon. This rule seems to take qualitatively into account all the available experimental data on the $SU(3)$ octect hyperon production. It must be mentioned that the model predicts zero polarization for all SSS (Sea-Sea-Sea) recombination process.

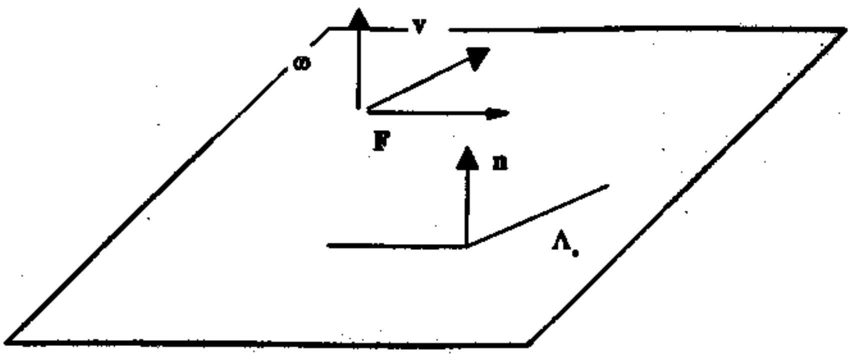

Figure 1: Thomas precession for s-quarks in the reaction $p + p \rightarrow \Lambda_0 + X$

We will restrict the analysis of the model to the reaction $p + p \rightarrow \Lambda_0 + X$ because of the particularly simple spin structure of the Λ_0. In it, since the u and d quark must couple to the spin-singlet state, the spin must be carried by the s-quark and so, the polarization of the Λ_0 is that of the s-quark. Obviously, all results can be extended without difficulty to other reactions.

The fundamental observation underlying the model is that the s-quark involved in the recombination process resides in the sea of the proton and carries a very small fraction of its momentum. However, it is a valence quark in the Λ_0, so it must carry a large fraction ($\sim \frac{1}{3}$) of the Λ_0's momentum.

Since the Λ_0 also carries a large fraction x_F of the proton's momentum, recombination induces a large increase in the longitudinal momentum of the s-quark, from $x_s \overrightarrow{p}$ to $\frac{1}{3} x_F \overrightarrow{p}$ as it passes from the sea of the proton to the Λ_0.

At the same time, the s-quark carries transverse momentum: on the average p_T(s in p) $\sim p_T$(s in Λ) $\sim \frac{1}{2} p_T(\Lambda)$. Therefore, the velocity vector of the s-quark is not parallel to the change in momentum induced by recombination and the s-quark must feel the effect of Thomas-precession.

Assuming that we are able to describe the recombination process with a Hamiltonian, it must contain the term

$$U = \overrightarrow{s} \cdot \overrightarrow{\omega}_T \tag{1}$$

with the Thomas frequency

$$\overrightarrow{\omega}_T = \frac{\gamma}{1+\gamma} \frac{\overrightarrow{F}}{m_s} \times \overrightarrow{v} \tag{2}$$

where $\overrightarrow{v}$ is the strange quark velocity, $\overrightarrow{F}$ the force, m_s the strange quark mass and $\gamma = (1 - v^2)^{-1}$. For sea quarks $\overrightarrow{\omega}_T$ points up and out of the production plane so, in order that the recombination potential be the more attractive as possible, $\overrightarrow{s} \cdot \overrightarrow{\omega}_T < 0$ what imply the following rule *slow (sea) partons recombine preferentially with spin down*

in the scattering plane as it is shown in fig. 1.

For a leading parton, since it is decelerated in the recombination process, $\vec{\omega}_T$ points down and out of the production plane and a similar argument shows that $\vec{s} \cdot \vec{\omega}_T < 0$ when

fast (leading) partons recombine preferentially with spin up

in the scattering plane.

This is basically the model by De Grand and Miettinen.

3 On the validity of the model

We will show here that the argument presented by De Grand and Miettinen [4] is strongly dependent on the sea quark masses and x_F . It generates doubts on the ability of the Thomas-precession mechanism to be the origin of the rule because of, depending on the value assigned to the s-quark mass and on the value of x_F, the model can predicts results that are opposite to that observed experimentally as we will show.

As in the preceding section, our analysis will be restricted to the $p + p \to \Lambda_0 + X$ reaction, but can be easily extended to other reactions involving heavy sea quarks.

To start with some comments about the sea of the proton are in order. We will assume that the sea of the proton and the proton travel together. This assumption implies that the longitudinal velocity of the sea quarks are of the order of the proton's velocity. Since the longitudinal direction is defined to be that of the proton beam, the transversal velocity of sea-quarks must be zero in average. This assumption is equivalent to consider that the sea of the proton is constrained to a box with periodic boundary conditions and that this box travels with the same velocity than protons. Then, our definition of sea is the following:

$$\begin{gathered} \left\langle v_{\|}^{sea} \right\rangle = v_{\|}\left(proton\right) \\ \left\langle v_{T}^{sea} \right\rangle = 0 \end{gathered} \tag{3}$$

It seems to be very reasonable, in other way, after some time, the sea and the proton will be independent one from the other.

But if $\left\langle v_{\|}^{sea} \right\rangle = v_{\|}\left(proton\right)$ then the ratio of the sea-quarks momentum to the proton momentum must be the ratio of the masses of the sea-quark under consideration and the proton:

$$\frac{\left\langle p_{\|}\left(q/p\right)\right\rangle}{p} = \frac{m_q}{m_p} \tag{4}$$

with the obvious notation $p_{\|}\left(q/p\right)$ the longitudinal momentum of the quark q in the sea of the proton and p the momentum of the proton.

Since the s-quark mass is

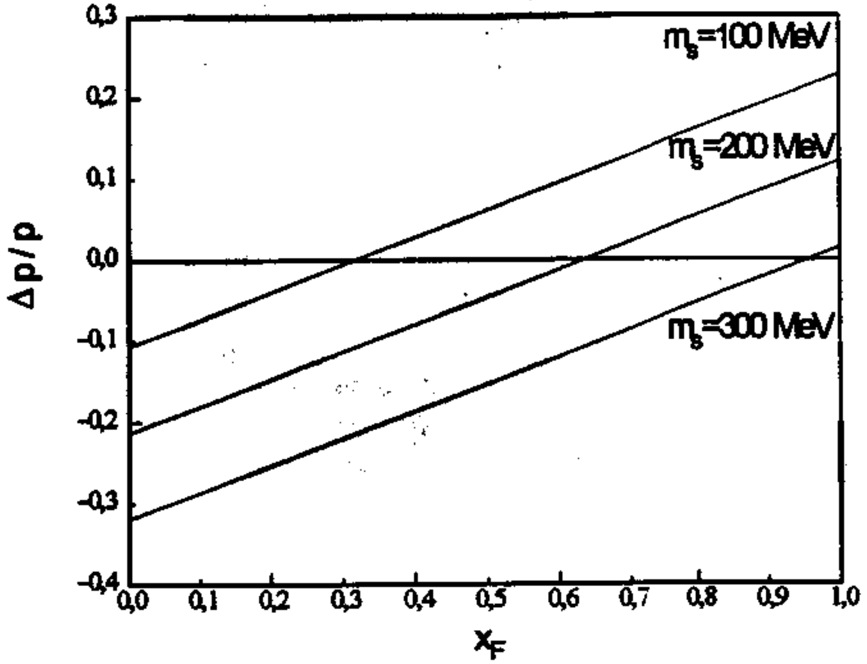

Figure 2: $\Delta p/p$ for s-quarks at various m_s values in the reaction $p+p \rightarrow \Lambda_0 + X$

$$100MeV \leq m_s \leq 300MeV \tag{5}$$

as quoted in ref.[10] we expect that

$$0.106p \leq \langle p_{\|}(q/p) \rangle \leq 0.318p \tag{6}$$

that is a very different value for $p_{\|}(q/p)$ from that taken in ref.[4].

Since the Λ_0 is produced with momentum equal to $x_F p$, we can assume that the s-quark in the Λ_0 carries approximately $\frac{1}{3}$ of the Λ_0's momentum and if we are considering Λ_0 production at small p_T, then approximately

$$p_{\|}(s/\Lambda_0) \sim \frac{1}{3} x_F p \tag{7}$$

where $p_{\|}(s/\Lambda_0)$ is the momentum of the s-quark in the Λ_0.Then, from eqs. 6 and 7 the variation of the s-quark momentum in passing from the sea of the proton to the Λ_0 is

$$\Delta p(s) = \left(\frac{1}{3} x_F - \frac{m_s}{m_p}\right) p \tag{8}$$

It is obvious from eq. 8 that $\Delta p(s)$ is not necessarily a positive quantity as it is shown in fig. 2. It depends strongly on the values of x_F and m_s, so the De Grand and Miettinen affirmation that "there is a large increment in the longitudinal momentum of the s-quark when it passes from the sea of the proton to the Λ_0 "is of relative value if not false.

If we call x_{F0} the value of x_F in which $\Delta p(s) = 0$, it is obvious from eq. 8 that for $x_F < x_{F0}$, $\Delta p(s) < 0$ and the s-quark is decelerated when it passes from the sea of the proton to the Λ_0.

In this case, the argument of ref. [4] based on the Thomas-precession mechanism gives us the opposite result, i.e. the s-quark recombines preferentially with spin up in the production plane and, since the polarization of the Λ_0 is the polarization of the s-quark,

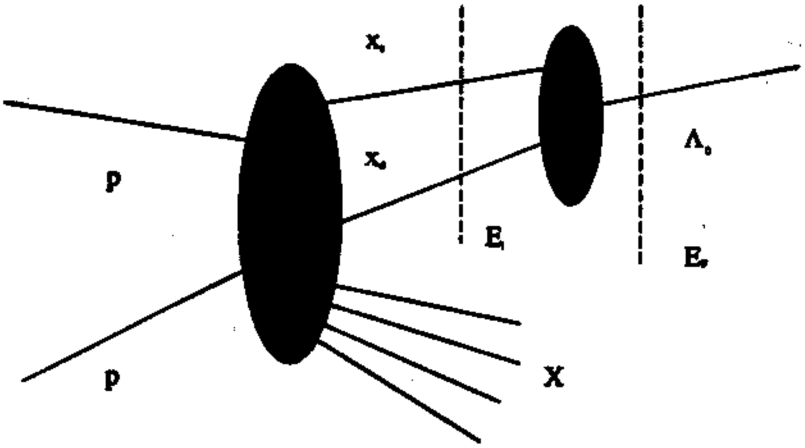

Figure 3: Amplitude for the reaction $p + p \rightarrow \Lambda_0 + X$

then we might see that, for $x_F < x_{F0}$, the Λ_0 is polarized in the opposite way to that shown by experiments.

Indeed, assuming $m_s = 100 MeV$, the smallest possible value, we might see an appreciable amount of experimental data showing the opposite result whenever $x_F < 0.318$ if the Thomas-precession mechanism is valid.

We can make a quantitative evaluation of our arguments along the lines of De Grand and Miettinen[4].

If we represent schematically the reaction $p + p \rightarrow \Lambda_0 + X$ as in the diagram of fig. 3 then the scattering amplitude is inversely proportional to the energy difference between intermediate and final states

$$A_s \propto \frac{1}{\Delta E + \overrightarrow{\omega} \cdot \overrightarrow{s}} \tag{9}$$

where ΔE is the energy difference in absence of spin effects and must be a positive quantity in order that recombination be possible.

Choosing our axis of quantization along the normal to the scattering plane we have

$$A_\uparrow \propto \frac{1}{\Delta E + \overrightarrow{\omega} \cdot \overrightarrow{s}}$$
$$A_\downarrow \propto \frac{1}{\Delta E - \overrightarrow{\omega} \cdot \overrightarrow{s}}$$

then, to a leading order in ω_T , the polarization asymmetry defined as

$$P\left(p \rightarrow \Lambda_0\right) = \left(|A_\uparrow|^2 - |A_\downarrow|^2\right) / \left(|A_\uparrow|^2 + |A_\downarrow|^2\right)$$

is

$$P\left(p \rightarrow \Lambda_0\right) = -\frac{\omega_T}{\Delta E} \tag{10}$$

Now we parametrize, as in ref. [4]

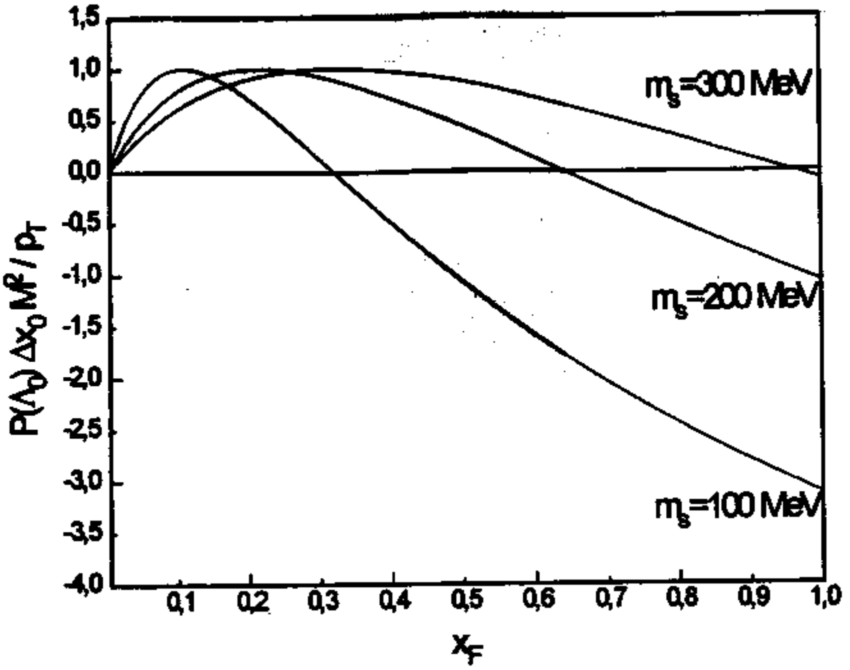

Figure 4: Λ_0 polarization at fixed p_T for various m_s values as given by the Thomas precession mechanism in the reaction $p + p \rightarrow \Lambda_0 + X$

$$\Delta E \equiv \frac{M^2}{2x_F p} \tag{11}$$

with M^2 a positive parameter and evaluate ω_T by taking a time average

$$\begin{aligned}\overrightarrow{\omega_T} &= \tfrac{1}{\Delta t}\int dt\,\frac{\overrightarrow{F}\times\overrightarrow{v}}{m}\\ &\simeq \frac{\langle\sin\theta\rangle}{\Delta t}\frac{\Delta p}{m}\widehat{n}\end{aligned} \tag{12}$$

where Δp is the change in momentum of the s-quark given by eq. 8, $\langle\sin\theta\rangle = \frac{p_T^s}{p_\parallel^{ave}}$ with $p_\parallel^{ave} \sim \frac{1}{2}\left(\frac{1}{3}x_F + \frac{m_s}{m_p}\right)p$ and $p_T^s \sim \frac{1}{3}p_{T\Lambda}$. Δt is a characteristic recombination time of the order of $\Delta t \sim \left(\frac{p_\parallel^{ave}}{m}\right)\Delta x_0$ with Δx_0 approximately the radius of the proton.

Therefore

$$\omega_T = \frac{4\,(1-3\xi)}{\Delta x_0\,(1+3\xi)^2\,x_F p}\,p_{T\Lambda} \tag{13}$$

where $\xi = \frac{x_s}{x_F} = \frac{m_s}{x_F m_p}$. Replacing eqs. 11 and 13 in eq. 10 we obtain for the polarization asymmetry

$$P\,(p \rightarrow \Lambda_0) = \frac{8\,(1-3\xi)}{\Delta x_0 M^2\,(1+3\xi)^2}\,p_{T\Lambda} \tag{14}$$

As Δx_0 and M^2 are positive parameters, in figs. 4 and 5 we show the plots for $P\,(p \rightarrow \Lambda_0)\,\Delta x_0 M^2$ at fixed $p_{T\Lambda}$ and x_F respectively.

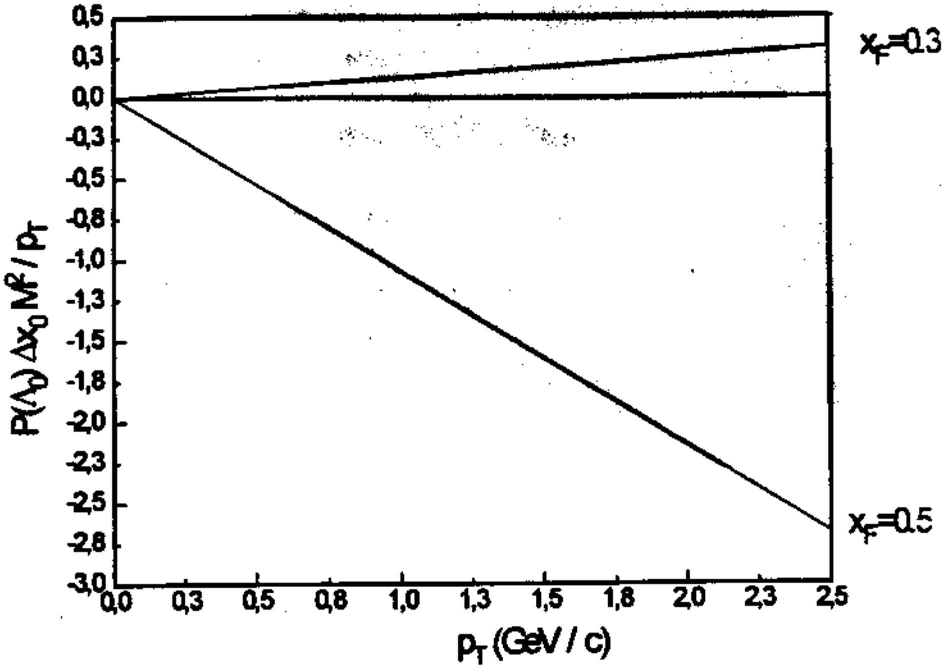

Figure 5: Λ_0 polarization at fixed x_F for $m_s = 100\ MeV$ as given by Thomas precession mechanism in the reaction $p + p \to \Lambda_0 + X$

It must be noted that in order to obtain the plots of figures 4 and 5 we have not assumed any ξ-parametrization unlike in ref. [4], but simply calculated its value. Obviously, when $x_F \to 0$, $\xi \to \infty$ so that the point $x_F = 0$ is singular, but this is not important because we can not observe the Λ_0 for $x_F = 0$ therefore it is sufficient to know the behavior of $P\,(p \to \Lambda_0)$ as given by eq. 14 for small and positive x_F.

From these two plots it becomes clear that there is a change in sign of the polarization whenever x_F passes through x_{F0}. This behavior is entirely due to the Thomas-precession mechanism and is not seen experimentally.

4 Conclusions

We have shown that the Thomas-precession model for polarization asymmetry in inclusive hadron production is strongly dependent on x_F, the momentum fraction of the incident particle at which the hadron is produced, and on the sea quark masses. The problems above mentioned are evident when the sea quarks involved in the recombination process are as heavy as the s-quark whose mass is between 100 MeV and 300 MeV. The model is very sensible to the s-quark mass, as we shown in the particular case of the $p+p \to \Lambda_0+X$ reaction. It is evident that for m_s = 300 MeV the model is not able to describe the experimental results while for smaller values of m_s there is an appreciable amount of experimental data which contradicts the model.

As the rule

fast partons recombine prefenrentially with spin up
slow partons recombine preferentially with spin down

proposed by De Grand and Miettinen seems to be qualitatively valid, at least for the experimental data on hyperon production within the $SU(3)$ octect, it becomes clear that its origin is not the Thomas-precession mechanism, since the rule is valid on the whole range of x_F, $0 < x_F < 1$, and it is independent of the sea-quarks masses.

In addition, we wish to remark that the De Grand and Miettinen 's model does not applyto SSS recombination process [4], therefore it can not describe polarization for hyperons and anti-hyperons which have no common quarks with the beam particles [3], and the origin of polarization in inclusive hadron production continues to be obscure.

5 Acknowledgments

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