Λ^0 Polarization in exclusive and inclusive p-Nucleus reactions

J. Félix[a]*

[a]Instituto de Física, Universidad de Guanajuato. Lomas del Bosque 103, Frac. Lomas del Campestre, León GTO. 37150, México. felix@fisica.ugto.mx

Among all properties of baryons, the polarization they acquire when created from unpolarized p-Nucleus collisions is the most recent discovered one; so far, the origin of baryon polarization remains unexplained in spite of the experimental evidences accumulated in the past thirty years. Up to these days, Λ^0 is the most studied baryon for polarization, because it is very easy to produce at the energies of the principal high energy physics accelerators of the world. This paper is a review of the experimental information accumulated on the polarization of Λ^0 in unpolarized exclusive and inclusive p-Nucleus collisions as function of x_F, P_T, and diffractive mass of the $\Lambda^0 K^+$ system in the past thirty years.

1. INTRODUCTION

It is an experimental evidence that baryons in general are created polarized, when they are produced from unpolarized *particle-Nucleus* collisions. For instance Ξ, Σ, Λ^0, etc., are produced polarized in exclusive as well as in inclusive reactions at different energies[1–3]. In the same experimental circumstances, it appears that Ω^-[1](K.B. Luk et al) and $\overline{\Lambda}^0$[1] [17](K. Heller et al) do not appear polarized. However, it appears that $\overline{\Lambda}^0$ is created polarized in $K^- p$ reactions[18]. The origin of baryon polarization is not known up to these days.

From the above mentioned baryons, Λ^0 is the most studied one for polarization, because it is very easy to produce and analyze for polarization. In many experiments Λ^0's from unpolarized pp inclusive and exclusive collisions, at different energies, are produced polarized[2]. This polarization depends on x_F, P_T, and $\Lambda^0 K^+$ invariant mass[3].

Based on the above experimental evidences, some authors have proposed many theoretical ideas -in the context of the Lund model, parton recombination, multiple scattering of the strange quark, gluon fusion, Regge theory, coherent scattering, low and high order QCD calculations, valence quark effects, and quark condensates- trying to understand Λ^0 polarization[4]. See reference [5] for a review of the theoretical ideas proposed to explain Λ^0 polarization. To date, there is no a satisfactory explanation for baryon polarization in general.

This paper is a summary of the experimental results on Λ^0 polarization, as function of x_F, P_T, and $M_{\Lambda^0 K^+}$, in the specific final states

$$pp \rightarrow p\Lambda^0 K^+(\pi^+\pi^-)^N; N = 1, 2, 3, 4, 5, \quad (1)$$

at 27.5 GeV, from the BNL e766 collaboration. And in the specific final state

$$pp \rightarrow p\Lambda^0 K^+, \quad (2)$$

at 800 GeV, from the FNAL e690 collaboration.

FNAL e690 and BNL e766 collaborations are described in detail elsewhere[6].

2. TECHNIQUE TO MEASURE Λ^0 POLARIZATION

The polarization of Λ^0 is measured with respect to the normal vector to the Λ^0 production plane defined as

$$\hat{n} \equiv \frac{\vec{P}_{beam} \times \vec{P}_{\Lambda^0}}{\mid \vec{P}_{beam} \times \vec{P}_{\Lambda^0} \mid}, \quad (3)$$

*Thanks to the BNL e766 and FNAL e690 collaborations (http://www-e690.fnal.gov). This research was supported in part by CONACYT, México, under grant No. 2002-C01-39941, CONCYTEG 06-16-K117-99, and Apoyo a la investigación científica UGTO 2006.

where $\vec{P}_{beam}$ and $\vec{P}_{\Lambda^0}$ are the momentum vectors of the incident beam proton and of the Λ^0, respectively.

The angular distribution of the proton from Λ^0, in the Λ^0 rest frame, is described by this expression[19]:

$$\frac{dN}{d\Omega} = N_0(1 + \alpha \mathcal{P} cos\theta), \tag{4}$$

where α is the Λ^0 decay asymmetry parameter (0.642 ± 0.013[7]) and $\mathcal{P}$ is the Λ^0 polarization. The polarization is determined by a linear fit of a function of the above form to the $cos\theta$ distribution of the proton -after Monte Carlo detector acceptance corrections- for two free parameters: Intercepts (N_0), and slope $N_0\alpha\mathcal{P}$. From these parameters the Λ^0 polarization and its statistical error are measured. The systematic errors are obtained simulating the detector acceptance and efficiency using the Monte Carlo technique.

3. Λ^0 POLARIZATION AS FUNCTION OF x_F AND P_T

The discovery of Λ^0 polarization in inclusive pp reactions showed that it depends linearly on P_T and that it is negative with respect to the Λ^0 production plane[8]: At $P_T = 0.0$, $\mathcal{P} = 0.0$, and it decreases as P_T increases up to close $\mathcal{P} = -0.25$ at $P_T = 1.2$ GeV. Also it was determined in inclusive pp reactions that Λ^0 polarization depends on x_F. See Reference [9] for a review of the experimental results on Λ^0 polarization.

In the reaction $pp \rightarrow p\Lambda^0 K^+(\pi^+\pi^-)^2$ at 27.5 GeV, Λ^0 polarization in a function of P_T and x_F[10]. Reference[10] was the first report on Λ^0 polarization in exclusive reactions at high energies.

Λ^0 polarization as function of P_T is given by $\mathcal{P} = (-0.250 \pm 0.067)P_T + (0.063 \pm 0.041)$ -$\frac{\chi^2}{N_{DOF}} = 1.04$, for $x_F > 0.0$-; by $\mathcal{P} = (0.147 \pm 0.056)P_T + (-0.007 \pm 0.033)$ -$\frac{\chi^2}{N_{DOF}} = 1.04$, for $x_F < 0.0$-; and by $\mathcal{P} = (-0.189 \pm 0.042)P_T + (0.029 \pm 0.025)$ -$\frac{\chi^2}{N_{DOF}} = 1.68$, for $x_F > 0.0$ and $x_F < 0.0$- combined.

The average Λ^0 polarization is roughly linear as function of x_F. This is given by $\mathcal{P} = (-0.20 \pm 0.06)x_F + (-0.032 \pm 0.018)$ -$\frac{\chi^2}{N_{DOF}} = 0.247$, for $x_F > 0.0$ and $x_F < 0.0$ combined-. The average Λ^0 polarization changes sign at $x_F \simeq 0.0$.

A complete analysis of Λ^0 polarization in the particular reactions described by Eq. 1, with $N = 1, 2, 3, 4$, was performed at high statistics, searching for Λ^0 polarization as function of x_F and P_T[11] together. To analyze the data, $\mathcal{P}$ is parameterized as a function of x_F and P_T simultaneously: $\mathcal{P} = \mathcal{P}(x_F, P_T)$. The parameters of this function are determined using the maximum likelihood method[12] with Eq. 4 as the probability distribution for having dN protons in a solid angle $d\Omega$. For the maximum likelihood analysis, the chosen function that represents the simplest bilinear combination of x_F and P_T is as follows:

$$\mathcal{P}(x_F, P_T) = (-0.443 \pm 0.037)x_F P_T, \tag{5}$$

for -1.0 $\leq x_F \leq$ 1.0 and 0.0 $\leq P_T \leq$ 1.8 GeV/c-.

The conclusion from this result is as follows: The mechanism responsible for Λ^0 polarization is independent of the Λ^0 production mechanism, at least for the examined final state reactions.

Furthermore, in general, equation

$$\mathcal{P}(x_F, P_T) = (-a)x_F P_T, \tag{6}$$

for $-1.0 \leq x_F \leq 1.0$ and $0.0 \leq P_T \leq 1.8$ GeV/c, is valid for Λ^0 polarization from exclusive and inclusive $p - Nucleus$ reactions[14] with the proper a value that depends on the particular beam and target reaction.

Both Λ^0 polarization from inclusive and exclusive $p - nucleus$ reactions follow the same trend as function of x_F and P_T: $\mathcal{P}(x_F, P_T) = (a)x_F P_T$. This equation is valid for $-1.0 < x_F < +1.0$ and $0.0 < P_T < 2.0$ GeV/c and for $nucleus = p, Be, Cu, W$ and Pb. The value of a depends on the target nature: For instance it is $-(0.443 \pm 0.037)$, in exclusive pp reactions; $-(0.376 \pm 0.024)$, in inclusive pp reactions; -there is no statistical difference between Λ^0 polarization from inclusive and exclusive reactions-. This equation is independent of the beam energy and is the most simple bilinear form that describes Λ^0 polarization in $-1.0 < x_F < +1.0$ and $0.0 < P_T < 2.0$ GeV/c kinematical region.

From Eq. 2, Λ^0 polarization at 800 GeV as function of x_F and P_T is shown in Table II of the Reference[3] (J. Félix et al). This functionality of Λ^0 polarization in terms of x_F and P_T is not observed in the reactions described by Eq. 1. This was the first time that large Λ^0 polarization is reported at low P_T. At large P_T -greater than 0.6 GeV/c- Λ^0 polarization agrees with previous reported measurements.

From Eq. 1, with $N = 5$, the polarization of 1973 Λ^0's from the specific reaction $pp \rightarrow p\Lambda^0 K^+(\pi^+\pi^-)^5$ created from 27.5 GeV incident protons on a liquid Hydrogen target, as function of x_F, P_T, and $M_{\Lambda^0 K^+}$, is, inside statistics, consistent with the polarization of Λ^0's from $pp \rightarrow p_{fast}\Lambda^0 K^+$ at 800 GeV[15,16].

4. Λ^0 POLARIZATION AS FUNCTION OF M_X

Λ^0 polarization depends on x_F, P_T -parameters associated with Λ^0- as well as on $M_{\Lambda^0 K^+}$ -the diffractive mass of the system $X = \Lambda^0 K^+$-. In general Λ^0 polarization depends on the diffractive mass of the system $\{\Lambda^0 K^+(\pi^+\pi^-)^N\}$, with $N = 0, 1, 2, 3, 4, 5$.

From Eq. 1, for $N = 2$, Λ^0 polarization depends on $(\Lambda^0 K^+)$, $(\Lambda^0 K^+\pi^+\pi^-)$, $(\Lambda^0 K^+\pi^+\pi^-\pi^+\pi^-)$ diffracted mass systems[10]. This is a novel result indicating that Λ^0 polarization could be related with the polarization of some resonances from where Λ^0's are created. These results are as follows:

Λ^0 polarization is roughly linear with $M_{(\Lambda^0 K^+)}$, decreasing from zero at $M_{(\Lambda^0 K^+)} = 1.63$ GeV to -0.16 at $M_{(\Lambda^0 K^+)} = 2.47$ GeV. The linear fit is $\mathcal{P} = (-0.185 \pm 0.068)M_{(\Lambda^0 K^+)} + (0.30 \pm 0.14)$, with $\chi^2/N_{dof} = 0.002$. These results agree with those reported in Reference[3](T. Henkes *et al*) in the reaction $pp \rightarrow p\Lambda^0 K^+$ at higher energies and for masses from 1.6 to 2.4 GeV/c^2. To boot, Λ^0 polarization is roughly linear with $M_{(\Lambda^0 K^+\pi^+\pi^-)}$, decreasing from zero at $M_{(\Lambda^0 K^+\pi^+\pi^-)} = 2.75$ GeV to -0.16 at $M_{(\Lambda^0 K^+\pi^+\pi^-)} = 3.75$ GeV; the linear fit is $\mathcal{P} = (-0.170 \pm 0.057)M_{(\Lambda^0 K^+\pi^+\pi^-)} + (0.475 \pm 0.187)$, with $\chi^2/N_{dof} = 0.073$. And additionally, Λ^0 polarization is roughly linear with $M_{(\Lambda^0 K^+\pi^+\pi^-\pi^+\pi^-)}$, decreasing from zero at $M_{(\Lambda^0 K^+\pi^+\pi^-\pi^+\pi^-)} = 3.9$ GeV to -0.14 at $M_{(\Lambda^0 K^+\pi^+\pi^-\pi^+\pi^-)} = 5.1$ GeV; the linear fit is $\mathcal{P} = (-0.154 \pm 0.048)M_{(\Lambda^0 K^+\pi^+\pi^-\pi^+\pi^-)} + (0.63 \pm 0.22)$, with $\chi^2/N_{dof} = 0.55$.

Furthermore, from Eq. 1, for $N = 1, 2, 3, 4, 5$, Λ^0 polarization depends on $M_{(\Lambda^0 K^+)}$. From Eq. 2, Λ^0 polarization also is a function of $M_{(\Lambda^0 K^+)}$.

There is some relation between $\Lambda^0 K^+$ mass distribution and Λ^0 polarization. That relation evidences the connection between Λ^0 polarization and $\Lambda^0 K^+$ resonance structure -where the variations in $M_{(\Lambda^0 K^+)}$, from Eq. 2, are bigger, the variations of Λ^0 polarization are bigger; see, and compare, Fig. 6 and Fig. 4 from Reference[3] (J. Félix *et al*). Maybe both polarizations, Λ^0 polarization and $\Lambda^0 K^+$ system polarization, could be related. In this case the origin of Λ^0 polarization -and in general of all baryons- could be due to parity conservation in strong interactions.

5. CONCLUSIONS

Λ^0 polarization is a function of x_F, P_T, and the diffractive mass of $\Lambda^0 K^+$ system. This functionality is not unique; it seems that it depends on the production mechanism.

For exclusive $pp \rightarrow p\Lambda^0 K^+(\pi^+\pi^-)^N$, with $N = 1, 2, 3, 4$ at 27.5 GeV, Λ^0 polarization depends on the diffractive mass of the $\Lambda^0 K^+$ system and on the diffractive mass of $(\Lambda^0 K^+(\pi^+\pi^-)^N, N = 1, 2, 3, 4)$, differing from that from $pp \rightarrow p\Lambda^0 K^+$ at 800 GeV and from $pp \rightarrow p\Lambda^0 K^+(\pi^+\pi^-)^5$ at 27.5 GeV.

The production mechanism of Λ^0 is very important and plays a fundamental role in the Λ^0 polarization. It appears that different production mechanisms of Λ^0 produce different Λ^0 polarization functionality.

It appears that Λ^0 polarization does not depend on the *beam* energy but on the nature -quark content- of the beam, on the energy of the effective beam -this is, the beam that really produces Λ^0- and on the isospin channel via Λ^0 is produced.

To reach a complete knowledge about Λ^0 polarization more studies and measurements must be performed in all possible experimental circumstances. For instance, a very important example is the measurement of Λ^0 polarization in exclusive $pp \to pp\Lambda^0\overline{\Lambda}^0$ at different energies and $pp \to p\Lambda^0 K_s^0 \pi^+$ at different energies.

In spite of all the above experimental efforts, it seems that the explanation of Λ^0 polarization is still faraway.

REFERENCES

1. J. Duryea *et al*, Phys. Rev. Lett. 67, 1193(1991). R. Rameika *et al*, Phys. Rev. **D33**, 3172(1986). C. Wilkinson *et al*, Phys. Rev. Lett. 58, 855(1987). B. Lundberg *et al*, Phys. Rev. **D40**, 39(1989). F. Lomanno *et al*, Phys. Rev. Lett. 43, 1905(1979). S. Erhan *et al*, Phys. Lett. **B82**, 301(1979). F. Abe *et al*, Phys. Rev. Lett. 50, 1102(1983). K. Raychaudhuri *et al*, Phys. Lett. **B90**, 319(1980). K. Heller *et al*, Phys. Rev. Lett. 41, 607(1978). F. Abe *et al*, J. of the Phys. S. of Japan. 52, 4107(1983). P. Aahlin *et al*, Lettere al Nuovo Cimento 21, 236(1978). A. M. Smith *et al*, Phys. Lett. **B185**, 209(1987). V. Blobel *et al*, Nuclear Physics **B122**, 429(1977). G. Zapalac *et al*, Phys. Rev. Lett. 57, 1526(1986). A. Morelos *et al*, Phys. Rev. Lett. 71 2172(1993). Y. W. Wah *et al*, Phys. Rev. Lett. 55 2551(1985). L. Deck *et al*, Phys. Rev. **D28**, 1(1983). E. C. Dukes *et al*, Phys. Lett. **B193** 135(1987). K. B. Luk *et al*, Phys. Rev. Lett. 70, 900(1993).
2. K. Heller *et al*, Phys. Lett. **B68**, 480(1977). G. Bunce *et al*, Phys. Lett. **B86**, 386(1979).
3. T. Henkes *et al*, Phys. Lett. B283, 155(1992). J. Félix *et al*, Phys. Rev. Lett. 88, 061801-4(2002).
4. T. A. DeGrand *et al*, Phys. Rev. **D24**, 2419(1981). B. Andersson *et al*, Phys. Lett. **B85**, 417(1979). J. Szweed *et al*, Phys. Lett. **B105**, 403(1981). K. J. M. Moriarty *et al*, Lett. Nuovo Cimento 17, 366(1976). S. M. Troshin and N. E. Tyurin, Sov. J. Nucl. Phys. 38, 4(1983). J. Soffer and N.E. Törnqvist, Phys. Rev. Lett. 68, 907(1992). Y. Hama and T. Kodama, Phys. Rev. **D48**, 3116(1993). R. Barni *et al*, Phys. Lett. **B296**, 251(1992). W. G. D. Dharmaratna and G. R. Goldstein, Phys. Rev. **D53**, 1073(1996). W. G. D. Dharmaratna and G. R. Goldstein, Phys. Rev. **D41**, 1731(1990). S. M. Troshin and N. E. Tyurin, Phys. Rev. **D55**, 1265(1997). L. Zuo-Tang and C. Boros, Phys. Rev. Lett. 79, 3608(1997).
5. J. Félix, Mod. Phys. Lett. **A14**, 827(1999).
6. J. Uribe *et al*, Phys. Rev. D49, 4373(1994). E. P. Hartouni *et al*, Nucl. Inst. Meth. A317, 161(1992). E. P. Hartouni *et al*, Phys. Rev. Lett. 72, 1322(1994). E. E. Gottschalk *et al*, Phys. Rev. D53, 4756(1996). D. C. Christian *et al*, Nucl. Instr. and Meth. A345, 62(1994). B. C. Knapp and W. Sippach, IEEE Trans. on Nucl. Sci. NS 27, 578(1980). E. P. Hartouni *et al*, IEEE Trans. on Nucl. Sci. NS 36, 1480(1989). B. C. Knapp, Nucl. Instrum. Methods **A289**, 561(1980).
7. S. Eidelman *et al*, Phys. Lett. **B592**, 1(2004).
8. G. Bunce *et al*, Phys. Rev. Lett. 36, 1113(1976).
9. J. Félix, Mod. Phys. Lett. **A12**, 363(1997).
10. J. Félix *et al*, Phys. Rev. Lett. 76, 22(1996).
11. J. Félix *et al*, Phys. Rev. Lett. 82, 5213(1999).
12. L. Montanet *et al*, Phys. Rev. D **50**, 1173(1994).
13. J. Félix, Rev. Mex. de Fís. 45(4) 421(1999).
14. J. Félix, Mod. Phys. Lett. **A16**, 1741(2001).
15. J. Félix *et al*, Λ^0 Polarization in $pp \to p\Lambda^0 K^+(\pi^+\pi^-)^5$ at 27.5 GeV. SPIN2004, proceedings. The 16^{th} International Spin Physics Symposium. Trieste, IT. 10-16 October 2004.
16. J. Félix *et al*, Λ^0 Polarization in $pp \to p\Lambda^0 K^+(\pi^+\pi^-)^5$ at 27.5 GeV. HEPP-EPS 2005, proceedings. International Europhysics Conference on High Energy Physics. Lisboa, Portugal July 21-27, 2005.
17. E. J. Ramberg *et al*, Phys. Lett. B 338, 403(1994).
18. S. A. Gourlay *et al*, Phys. Rev. Lett. 56, 2244(1986).
19. J. Félix, Ph. D. Thesis, Universidad de Guanajuato-Universidad de Massachusetts, México (1994).