Λ^0 polarization and its relation with nucleonic resonances

Victor M. Castillo-Vallejo[a]* Julián Félix [b] and Virendra Gupta[a]

[a]Departamento de Física Aplicada, CINVESTAV-IPN, Unidad Mérida
Ant. Carr. Progreso Km 6, A.P. 73 Cordemex 97310, Mérida, Yucatán, México

[b] Instituto de Física, Universidad de Guanajuato,
Loma del Bosque 103, Lomas del Campestre León, Guanajuato, 37150, México

In the sequential reactions $pp \to pN^*$ and $N^* \to \Lambda^0 K^+$ Λ^0 polarization vector is proportional to N^* polarization vector. This result is valid whatever the value of the spin of N^* and for both, conserving-parity decays and non-conserving-parity decays. Besides, for the particular case of N^* having spin 1/2, N^* and Λ^0 production planes coincide each other. Based on these results, a technique to evidence nucleonic resonances in $pp \to p\Lambda^0 K^+$ is established, which is independent of the mechanism responsible of this reaction.

1. Introduction

Hyperons polarization studies contribute to understand the spin dependence of hadronic interactions. From all the hyperons, Λ^0 is the most studied in both theoretical and experimental analysis and, in spite of Λ^0 polarization problem is not completely solved yet, some clues have been established about the origin of its polarization; for instance, in exclusive pp reactions, Λ^0 polarization seems to be related to its production mechanism[1]. In order to completely solve the problem of Λ^0 polarization in pp reactions, it is necessary to discriminate the contributions to Λ^0 polarization from Λ^0 produced directly from those produced indirectly. In this work it is analyzed the case when Λ^0 is created through the decay of one nucleonic resonance from unpolarized $pp \to p\Lambda^0 K^+$ reactions. The problem is analyzed using only kinematical information of the reaction and, hence, the conclusions are independent of any dynamical model which could explain the interaction of the initial protons. The reaction is split out in two sequential reactions: $pp \to pN^*$ and $N^* \to \Lambda^0 K^+$. A relation between polarization vectors of the resonance N^* and baryon Λ^0 is derived. From this relation, a graphic method to detect the presence of nucleonic resonances in $pp \to p\Lambda^0 K^+$ is established.

*Present address: Centro de Investigaciones en Optica (CIO), Loma del Bosque 115, Lomas del Campestre, León Guanajuato, 37150, México, Email: victorcv@cio.mx

2. POLARIZATION VECTOR IN STRONG INTERACTIONS

It is known that polarization vector is a pseudovector and it changes its sign under time reversal operation. If the reaction of interest follows parity and time reversal symmetries, any component of polarization vector with properties diferent to the above exposed should be suppressed. A first assertion coming as a consequence of the above arguments is the next:

Statement 1 *In $pp \to pN^*$, N^* spin should point along its production-plane normal. In the decay $N^* \to \Lambda^0 K^+$, Λ^0 is created with its spin pointing along the normal to its own production plane.*

We use this basic result (which is valid due to both the parity and the time reversal symmetries) to demonstrate in Section 4 a technique to detect resonances.

3. RELATION BETWEEN Λ^0 AND N^* POLARIZATION VECTORS

Statement 1, in spite of its simplicity, allow to establish restrictions over angular distributions and over the relation between polarization vectors of N^* and Λ^0, such as it is shown in the following sections.

3.1. Case 1. N^* spin equals $\frac{1}{2}$

In $N^* \rightarrow \Lambda^0 K^+$, Λ^0 polarization is related to N^* polarization through the following equations:

$$\vec{\mathcal{P}}_{\Lambda^0} = (\vec{\mathcal{P}}_{N^*} \cdot \hat{p})\hat{p} + \hat{p} \times (\vec{\mathcal{P}}_{N^*} \times \hat{p}). \quad (1)$$

$$\vec{\mathcal{P}}_{\Lambda^0} = (\vec{\mathcal{P}}_{N^*} \cdot \hat{p})\hat{p} - \hat{p} \times (\vec{\mathcal{P}}_{N^*} \times \hat{p}). \quad (2)$$

where $\hat{p}$ is a unit vector pointing along the motion of Λ^0 in the frame where N^* is at rest. Eqs. (1) and (2) are obtained from the most general formula relating polarization vector of daughter and parent baryons in the decay of a 1/2-spin baryon into a 1/2-spin baryon and a 0-spin meson due to Lee and Yang[2,3], by requiring the parity to be conserved

In the decay $N^* \rightarrow \Lambda^0 K^+$, if the component of Λ^0 polarization along its motion direction is restricted to be zero, according to Statement 1, then in Eqs. (1) and (2) the term $\vec{\mathcal{P}}_{N^*} \cdot \hat{p}$ should be zero and hence Λ^0 momentum and N^* polarization are perpendicular each other. Therefore, for the particular case of a 1/2-spin particle strongly decaying into one 1/2-spin baryon and a 0-spin meson, the production planes of the parent and daughter particles are the same. This shows the validity of the next statement:

Statement 2 *In $pp \rightarrow pN^*$, $N^* \rightarrow \Lambda^0 K^+$, when N^* has $S = 1/2$, the production plane of Λ^0 and the production plane of N^* are the same.*

3.2. Case 2. N^* spin higher that 1/2

Since strong decays conserve parity, when the spin and parity of N^* are fixed, its decay occurs through one channel of parity. In order to separately study the cases for both values of N^* parity, two channels are defined as follows:

Channel 1. $l = S - 1/2$ and then, parity of N^* can be expressed as $\wp(N^*) = (-1)^{S+1/2}$.

Channel 2. $l = S + 1/2$ and then, parity of N^* can be expressed as $\wp(N^*) = (-1)^{S+3/2}$.

where l is the orbital angular momentum of Λ^0 and K^+ measured in the N^* rest frame and which takes the values $l = S \pm 1/2$. The following relations between N^* and Λ^0 polarization vectors are obtained when Λ^0 polarization vector is integrated over Λ^0 angular distribution measured in N^* rest frame.

Channel 1

$$\vec{\mathcal{P}}(\Lambda^0) = \vec{\mathcal{P}}(N^*). \quad (3)$$

Channel 2

$$\vec{\mathcal{P}}(\Lambda^0) = \left(-\frac{S}{S+1}\right)\vec{\mathcal{P}}(N^*). \quad (4)$$

These results allow to establish the next statement:

Statement 3 *Polarization vector of Λ^0, when it is integrated over the angular distribution of Λ^0 measured in the N^* rest frame, is proportional to polarization vector of N^*.*

Eqs. (4) and (3) are valid when the decay conserves parity. In a more general situation, the decay of one resonance could violate parity, i.e., it could have interference between both of the channels above defined. In this case, the more general relation between the polarization vector of N^* and that of Λ^0 is as follows:

$$\vec{\mathcal{P}}(\Lambda^0) = \left(\frac{1 + (2S+1)\gamma}{2(S+1)}\right)\vec{\mathcal{P}}(N^*). \quad (5)$$

The parameter γ is related to the parity violation of the decay and it is defined in Ref. [2]. This equation reduces to Eq. 4 (3) when $\gamma = -1(+1)$. When the decaying particle has $S = 3/2$, the above expression coincides with that reported in literature for the decay $\Omega^- \rightarrow \Lambda^0 K^-$[4–6].

4. NUCLEONIC RESONANCES IN $pp \rightarrow p\Lambda^0 K^+$

Known nucleonic resonances decaying in $\Lambda^0 K^+$ channel are broad (typical widths are $100 - 200$ MeV) and they are located inside of a short range of masses (from 1650 until 2200 MeV). This causes they overlap, making difficult the characterization of them, i. e., it is hard a clear identification of each resonance. A different graphical method to detect the presence of nucleonic resonances in the above reaction, based in the validity of Statement 3, can be established as follows.

Assuming that parity is conserved in $pp \to pN^*$, $N^* \to \Lambda^0 K^+$, the angle between Λ^0 and N^* production planes can be calculated, on one hand, with the next equation

$$\hat{n}_{N^*} \cdot \hat{n}_{\Lambda^0} = \frac{\vec{\mathcal{P}}_{N^*} \cdot \vec{\mathcal{P}}_{\Lambda^0}}{|\vec{\mathcal{P}}_{N^*} \cdot \vec{\mathcal{P}}_{\Lambda^0}|}, \qquad (6)$$

where $\hat{n}_{N^*}$ and $\hat{n}_{\Lambda^0}$ are the normal to N^* and Λ^0 production planes respectively, $\vec{\mathcal{P}}_{N^*}$ and $\vec{\mathcal{P}}_{\Lambda^0}$ are the polarization vectors. Due to Statement 3, that expression is restricted to be

$$\hat{n}_{N^*} \cdot \hat{n}_{\Lambda^0} = \pm 1, \qquad (7)$$

independently of N^* spin and when Λ^0 polarization vector is integrated over its angular distribution in N^* rest frame . On the other hand, for fixed direction of N^* and independently of its energy, $\hat{n}_{N^*} \cdot \hat{n}_{\Lambda^0}$ can be measured by taking into account that

$$\begin{aligned} \hat{n}_{N^*} &= \frac{(\vec{p}_{beam} \times \vec{p}_{N^*})}{|\vec{p}_{beam} \times \vec{p}_{N^*})|}, \\ \hat{n}_{\Lambda^0} &= \int \mathrm{d}\Omega_{\Lambda^0} \frac{(\vec{p}_{N^*} \times \vec{p}_{\Lambda^0})}{|\vec{p}_{N^*} \times \vec{p}_{\Lambda^0})|}, \end{aligned} \qquad (8)$$

where $\vec{p}_{beam}$, $\vec{p}_{N^*}$, and $\vec{p}_{\Lambda^0}$ are the momenta of beam, N^* and Λ^0 measured in a fixed reference frame (CMF for instance), $\hat{n}^{'}$ is the normal to Λ^0 production plane for each event and the integration is done over the angular distribution of Λ^0 in any, the fixed reference frame (CMF) or the N^* rest frame. Experimentally, $\vec{p}_{N^*}$ is defined by $\vec{p}_{N^*} = \vec{p}_{\Lambda^0} + \vec{p}_{K^+}$. The analysis is performed in bins of momenta of N^*.

Using the above considerations, a plot of $\hat{n}_{N^*} \cdot \hat{n}_{\Lambda^0}$ vs $M(\Lambda^0 K^+)$, where $M(\Lambda^0 K^+)$ is the invariant mass of $\Lambda^0 K^+$ system, would reveal the presence of resonant states of the proton decaying through that channel. Those resonances would show a particular shape in that plot: It should have a concentration of events near of $\hat{n}_{N^*} \cdot \hat{n}_{\Lambda^0} = \pm 1$, in contrast to non-resonant states, which would be uniformly distributed along all the values of $\hat{n}_{N^*} \cdot \hat{n}_{\Lambda^0}$ because non-resonant states don't have definite spin nor parity. This method can be implemented in an analysis of the above reaction in a more practical way by imposing a cut in the variable $\hat{n}_{N^*} \cdot \hat{n}_{\Lambda^0}$ as follows:

$$\begin{aligned} &\text{Resonant events (principally).} \\ a)\ \ &\hat{n}_{N^*} \cdot \hat{n}_{\Lambda^0} \geq 0.999, \text{ or } \hat{n}_{N^*} \cdot \hat{n}_{\Lambda^0} \leq -0.999. \\ &\text{Non-resonant events.} \\ &b) - 0.999 < \hat{n}_{N^*} \cdot \hat{n}_{\Lambda^0} < 0.999. \end{aligned} \qquad (9)$$

The above cut would isolate events with Λ^0 coming from the decay of one resonance and hence, it would allow to measure the properties of one resonance directly from the spectrum of $M(\Lambda^0 K^+)$ after the events of non-resonant contribution (background) are separated from the rest. This technique can be considered as one complementary to a partial wave analysis. This method can not be used if $\vec{\mathcal{P}}_{N^*} = 0$, i.e., if N^* is created unpolarized, because in this particular case $\hat{n}_{N^*} \cdot \hat{n}_{\Lambda^0} = 0$ and hence, there is not criterium to isolate the resonant events.

5. CONCLUSIONS

In the sequential reactions $pp \to pN^*$, $N^* \to \Lambda^0 K^+$, restrictions from symmetries on the resonances and Λ^0 spins become to establish a relation between the production planes and the polarization vectors $\vec{\mathcal{P}}$ of N^* and Λ^0 allowing isolate resonant events from those non-resonant such as Statements 1-3 establish.

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