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SPIN-ORBIT AND SPIN-SPIN INTERACTIONS IN ΛN AND NN SCATTERING

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ABSTRACT

Nonvanishing values of the spin-polarization experimental observables clearly derive from the different spin-dependent interactions, i. e., spin-orbit, spin-spin, and spin-tensor. The explicit dependence of selected observables on these interactions is discussed for scattering with the spin-structure $1/2 + 1/2 \rightarrow 1/2 + 1/2$.

Recent papers have remarked on the role of specific spin-dependent interactions in baryon-baryon scattering, as revealed by selected spin-polarization experimental observables. It has been suggested that both the spin-orbit and spin-spin interactions contribute to the polarization transfer (depolarization) coefficient $D_{yy'}$ in ΛN scattering [1]; and that the spin-spin interaction alone is responsible for a nonzero value of the spin-correlation coefficient A_{yy} in NN scattering [2]. In fact, as will be shown, just the opposite is true: $D_{yy'}$ differs from its spin-independent value, $D_{yy'} = 1$, due only to the spin-spin force, and both the spin-orbit and spin-spin forces contribute to A_{yy} [3].

Reference 1 has described the determinations of the polarizations of Λ hyperons produced by the quasifree (π^+,K^+) reaction on ^{12}C at a pion momentum of 1.05 GeV/c. These polarizations were deduced from measurements of the asymmetries, with respect to the reaction plane, of the pions from the weak decay $\Lambda \rightarrow \pi^- p$. In the region of the peak in the kaon spectrum, which corresponds to the quasifree Λ production, the polarizations are in very good agreement with those calculated from the elementary Λ production reaction $n(\pi^+,K^+)\Lambda$, The firm conclusion, that the Λ production in the ^{12}C target is characterized by the quasifree process in this region, is supported by the fact, as pointed out by the authors, that the Λ depolarization due to final-state interactions (ΛN rescattering) is expected to be small. This follows, according to them, because the depolarizing "spin-orbit and/or spin-spin interactions" are known to be small for Λ hypernuclei.

Before establishing more formally that the spin-orbit interaction does not contribute to the depolarization, the essential point is that the constraint of parity conservation, which limits the polarization produced in a reaction to be along the normal $(\mathbf{y} = \mathbf{k}_\pi \times \mathbf{k}_\Lambda)$ to the production plane, also prohibits the spin flip of this component by the spin-orbit force. Thus, the spin-orbit interaction simply scatters transverse spin-up and spin-down states differently without any spin flip. Then, since depolarization requires some spin flip, the spin-orbit interaction does not contribute to it. On the other hand, both non-flip (spin-orbit) and spin-flip (spin-spin) terms contribute to A_{yy}.

More specifically, the polarization after scattering of an initially polarized spin-1/2 particle is given by

$$p_{y'} = (P_y + p_y D_{yy'})/(1 + p_y A_y) , \qquad (1)$$

where p_y is the initial polarization, P_y and A_y are, respectively, the polarizing and analyzing powers of the scattering, and $D_{yy'}$ is the polarization transfer (depolarization) coefficient [4]. Since A_y and P_y are zero in forward scattering, the polarization after a small-angle rescattering due to a final-state interaction is essentially

$$p_{y'} = p_y D_{yy'} . \qquad (2)$$

Then, the spin $1/2 + 1/2 \rightarrow 1/2 + 1/2$ matrix of scattering amplitudes, appropriate for both ΛN and NN scattering, is [6]

$$M = a_{oo} + a_{yo}\, \sigma_{yo} + a_{oy}\, \sigma_{oy} + a_{xx}\, \sigma_{xx} + a_{yy}\, \sigma_{yy} + a_{zz}\, \sigma_{zz} , \qquad (3)$$

where $\sigma_{jk} \equiv \sigma_j \otimes \sigma_k$ is the 4 X 4 direct-product matrix of the 2 X 2 projectile and target Pauli spin-matrices [7]. The projectile (target) spin-orbit amplitude is a_{yo} (a_{oy}), the a_{jj} $(j = x, y, z)$ are spin-spin amplitudes, and a_{oo} is the spin-independent amplitude. From

$$D_{yy'} = Tr\, M\sigma_{yo}M^{\dagger}\sigma_{yo} / Tr\, MM^{\dagger} \qquad (4)$$

and (3) one obtains

$$D_{yy'} = \frac{|a_{oo}|^2 + |a_{yo}|^2 + |a_{oy}|^2 - |a_{xx}|^2 + |a_{yy}|^2 - |a_{zz}|^2}{|a_{oo}|^2 + |a_{yo}|^2 + |a_{oy}|^2 + |a_{xx}|^2 + |a_{yy}|^2 + |a_{zz}|^2} . \qquad (5)$$

Thus, $D_{yy'}$ differs from unity, thereby signaling some depolarization, only because of the spin-spin amplitudes which provide the required spin flip.

The experimental results [1] also show a substantial reduction of the Λ polarization in the higher excitation region of the spectrum, i.e., the lower kaon energy region. The authors suggest that depolarization might occur, after the Λ production, in a (subsequent) ΛN interaction at these higher Λ energies, for which the nucleon could be knocked out of the nucleus. In view of the remarks above, this would require that both the ΛN scattering probability and the spin-spin interaction strength increase substantially with the increase in Λ energy. There is, however, a simpler explanation for a decrease in the p_y *component* of the Λ polarization in the production process itself. In the quasifree kinematics, $\boldsymbol{y}$, as defined above, is also the normal to the (π^+,K^+) reaction plane since $\boldsymbol{k}_\Lambda$ and $\boldsymbol{k}_K$ are colinear in the c.m. frame. This is not the case at the higher excitation energies where quasifree production no longer applies, since then, with the three- (or more) body final state $K\Lambda X$, the Λ production plane is no longer the same as the (π^+, K^+) reaction plane and, so, is not defined. Thus, in the limit of vanishing quasifree production, the component of Λ polarization along $\boldsymbol{y} = \boldsymbol{k}_\pi \times \boldsymbol{k}_K$, averaged over all possible production orientations, also goes to zero. This result might then be useful in a quantitative distinction among the quasifree and other Λ-production processes.

With respect to the observable A_{yy}, its substantial values at the highest energies and momentum transfers achieved in pp scattering have shown little respect for the predictions of perturbative QCD, as has been emphasized on several occasions [2]. With

$$A_{yy} = Tr\, M\, \sigma_{yy}\, M^\dagger \,/\, Tr\, MM^\dagger, \tag{6}$$

from (3), and the fact that $a_{yo} = a_{oy}$ in this identical-particle scattering, one finds

$$A_{yy} = \frac{2\,|a_{yo}|^2 + 2\,Re(a_{oo}\,a_{yy}^* - a_{xx}\,a_{zz}^*)}{|a_{oo}|^2 + 2\,|a_{yo}|^2 + |a_{xx}|^2 + |a_{yy}|^2 + |a_{zz}|^2}, \tag{7}$$

and one sees the explicit dependence of A_{yy} on both the spin-orbit term, a_{yo}, and the spin-spin terms, a_{xx}, a_{yy}, and a_{zz}.

Finally, although the (projectile) analyzing power A_{yo} is rightfully considered to be a spin-orbit observable, in the sense that it is directly proportional to the spin-orbit amplitude, it still can have a contribution from a spin-spin term. That is, with

$$A_{yo} = Tr\, M\, \sigma_{yo}\, M^{\dagger} / Tr\, MM^{\dagger}, \tag{8}$$

and the differential cross section $I = \frac{1}{4}\, Tr\, MM^{\dagger}$, we have

$$IA_{yo} = 2\, Re(a_{oo}\, a_{yo}^{*} + a_{oy}\, a_{yy}^{*}), \tag{9}$$

and for identical-particle scattering

$$IA_{yo} = 2\, Re\, [a_{yo}(a_{oo}^{*} + a_{yy}^{*})]. \tag{10}$$

Both (9) and (10) show that a nonvanishing analyzing power has a contribution from the spin-spin amplitude a_{yy}.

Although nothing has been said concerning the tensor interaction, its effect is implicitly included by the nonequality of a_{xx}, a_{yy}, and a_{zz}. That is, a spin-spin term in the M-matrix has the form $a_{ss}\,(\sigma_1 \cdot \sigma_2) = a_{ss}\,(\sigma_{xx} + \sigma_{yy} + \sigma_{zz})$, so it is the tensor interaction that destroys the equality among those three amplitudes.

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[3] I follow the terminology and notation of the Madison convention, *Proc. Third Int. Symp. on Polarization Phenomena in Nuclear Reactions*, eds. H. H. Barschall and W. Haeberli (University of Wisconsin Press, Madison, 1971), p. xxv; and its extensions [4,5]. The y direction is taken normal to the reaction plane, $\boldsymbol{y} = \boldsymbol{k_i} \times \boldsymbol{k_f}$. The comparable convention often used in intermediate and high energy physics replaces the (x, y, z) triad with (S, N, L).

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