PRODUCTION DYNAMICS OF HYPERON POLARIZATION

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Abstract

I briefly review the experimental and theoretical situation of polarization of inclusively produced hyperons in small transverse momentum reactions and describe simple phenomenological approaches to its outstanding problems: the dynamical origin of the effect, its relation to flavor SU(6), and the ratio of hyperon polarization produced by proton and meson fragmentation.

Introduction and Experimental Results

The polarization of baryons produced inclusively in low transverse momentum processes is a striking yet poorly understood phenomena. Baryon polarization increases roughly linearly with increasing baryon transverse momentum and with increasing fraction x_F of the incident hadron's longitudinal momentum carried off by the baryon.[1] The magnitude of the polarization of all baryons produced in the fragmentation of a proton beam is roughly equal, although the sign of the polarization varies dramatically from baryon to baryon, while the asymmetry of Λ's produced in the fragmentation of a K^- is much larger.[2] A summary of polarization data, and its comparison with the model of Ref. 3, is shown in Table I. The sign of the polarization is positive if the polarization lies along the direction $\vec{p}_{beam} \times \vec{p}_{final}$.

Unfortunately all theoretical studies of polarization are difficult. Lipkin's[14] catch-22 is not really a joke:

1. All polarization predictions are trivially simple at high energy and teach us nothing.
2. All polarization phenomena are hopelessly complicated at high energy and teach us nothing.

There is considerable interest in the recent EMC results[15] for polarized structure functions. These results may or may not be relevant to small p_T physics. If they are relevant, then they show that a lot of the spin of the proton is carried by the fast components of the proton's wave function. However, structure functions measure single quark distributions at short distances (high Q^2). It is not obvious that these distributions have anything to do with small p_T reactions since the length scales are very different. Even if one were to evolve

TABLE 1. Comparison of model with polarization data.

Transition	Predicted	Observed	Energy (GeV)	Reference
$p \to \Lambda$	$-\epsilon$	-0.1 to -0.2	24-2000	4
$p \to \bar{\Lambda}$	0	0	24-2000	4
$p \to \Sigma^+$	ϵ	0.1 to 0.2	400	5
$p \to \Sigma^-$	$\epsilon/2$	0.15, 0.3	400	6,7
$p \to \Sigma^0$	ϵ			
$p \to \Xi^0$	$-\epsilon$	-0.1 to -0.2	400	8
$p \to \Xi^-$	$-\epsilon$	-0.1 to -0.2	400	9
$K^+ \to \bar{\Lambda}$	ϵ	> 0.4, $x_F > 0.3$	32, 70	10
$K^- \to \Lambda$	ϵ	0.4	176, 14	2,11
$\pi^- \to \Lambda$	$-\epsilon/2$	-0.05	18	12
$\gamma \to \Lambda$	$-\epsilon/2$	-0.1	20	13

the quark distributions back in Q^2 to $Q^2 = (300)^2$ MeV^2, soft physics involves multiquark, not single quark, distributions. (One cannot fit inclusive small p_T data by assuming that quarks in the proton with the distribution measured in deep inelastic scattering fragment hadrons with the fragmentation functions measured in e^+e^- annihilation.)

All of the predictions of Ref. 3 assume SU(6) symmetry for the valence quarks of the beam and produced particle. This assumption is almost certainly incorrect. The infinite-momentum-frame wave function of the beam contains sea partons in addition to the valence partons and it is unreasonable to assume that the sea partons all couple to zero total angular momentum. Unfortunately, relaxing the assumption of SU(6) symmetry opens up so many possibilities that little work has been done to explore them.

Models of Polarization Asymmetry

The model for baryon polarization in low transverse momentum processes which was proposed by Miettinen and me[3] had several key ingredients. We began with the parton model. We assumed that there is some ordering of flavor quantum numbers in the infinite momentum frame wave function of the beam and target particles, so that the quarks which carry the valence quantum numbers of the hadrons also carry most of their momenta while the quarks and antiquarks which have no quantum numbers in common with the hadrons (the so-called "sea partons") carry very little of the hadron's momentum. This is a standard parton model assumption. Next, we assumed that during the formation process the outgoing baryon was formed from the coalescence of three quarks which carry its valence quantum numbers, and that the three quarks each carried out about one third of the baryon's momentum. With these assumptions we were able to formulate a simple rule which continues to account for all the observed regularities in hyperon polarization: Quarks which gained longitudinal momentum during the baryon formation process have a greater probability of recombining with their spins down while quarks which lose longitudinal momentum during the reaction tend to have a greater probability of recombining with their spins up. All the observed regularities in $p \rightarrow B + X$ arise solely from this rule plus Clebsch-Gordon coefficients.

In all processes which show a non-zero polarization asymmetry there is an exchange of one or two valence quarks from the beam to the produced baryon. A convenient way we found to parameterize the polarization asymmetry is to represent the baryon as a combination of a quark and a diquark:

$$|Bb\rangle = \sum (DSMqm|Bb)|DSM\rangle|qm\rangle$$

Here b is the third component of the spin of B, S and M the spin and third component of the spin of the diquark, and M the third component of the spin of the quark. We assume standard SU(6) wave functions.

Now suppose B and B' have two valence quarks in common. In that case the reaction can proceed by the replacement of one quark in the wave function by a new quark from the sea. We will call this VVS recombination. We compute relative magnitudes for the cross section by assuming the existance of a T-matrix amplitude which factorizes into a sea-quark term A and a valence-diquark term B. We add all the amplitudes incoherently so that

$$|T|^2 = \sum_{s=0,1} \sum_{M} |(SM, \frac{1}{2}b - M|\frac{1}{2}b)(SM, \frac{1}{2}b' - M|\frac{1}{2}b')B_{b'-M}A_{SM}|^2 \qquad (1)$$

All the signs and all the relative magnitudes for the proton-induced data can be fit by taking

$$|B_s|^2 = B(1 - s\epsilon') \tag{2}$$

$$|A_{SM}|^2 = A_S(1 + \delta M) \tag{3}$$

with $A_1 = A_0$ and $\epsilon = \epsilon'/2 \simeq \delta$ roughly linear in x_F and p_T. Note that the polarization asymmetry of the quark is equal to the asymmetry of the diquark even though the diquark has twice the spin of the quark. The case of one common quark and two sea quarks (VSS recombination) is similar except that the signs of ϵ and δ are reversed since the diquark is slowed by the recombination process.

Finding a dynamical explanation of this rule has proven to be very difficult. The problem is that the process is a long distance effect of QCD, where QCD is strongly interacting. The only reliable nonperturbative calculational scheme for QCD which exists at present, lattice gauge theory, has been so far restricted to static observables. Thus one is reduced to phenomenological model-building.

I am aware of several approaches to the problem. The one I prefer is our semiclassical explanation.[3] One expects a spin-momentum relation for fermions similar to the one required by our rule whenever their direction of motion is not parallel to any forces (in this case the ones causing them to bind into the outgoing baryon) acting on them. In this case the amount of spin precession is proportional to the cross product of the force with the quark's velocity; for the kinematics appropriate to fragmentation this amounts to an asymmetry proportional to the product of the quark's transverse momentum times its change in x_F during recombination. We constructed a crude but explicit model for the x_F and p_T dependence of Λ polarization; it qualitatively resembles the data but fails in detail.[16] What I believe to be a similar explanation, couched in the language of the Lund string model, has been given by Sköld.[17]

Recently, Fujitsu and Matsuyama[18] have argued that this picture is not possible because of the nature of the boound state spectrum of Dirac particles bound in a linear potential. However it is not obvious to me that the quarks whose spins are responsible for a polarization asymmetry are ever in energy eigenstates of some potential until after the whole production process is complete. More recently, Dharmaratna, Goldstein and Ringland[19] have proposed interference effects between various orders of perturbative QCD scattering diagrams as the origin of the polarization asymmetry. However, they have not yet extended their calculations sufficiently for a comparison with data. Their model is inspired by the earlier work of Szwed,[20] in which the polarization arised from the scattering of a quark with the hadronic medium.

Problems with Models

These models have several problems. First of all, parton models for small -p_T reactions are models with a lot of freedom. It is not clear what the connection is between the quark distributions measured in deep inelastic scattering and the ones inferred in small-p_T reactions. It is not obvious how to parameterize the quarks-to-hadrons transformation. We know resonances are important; how should they be included? We know that the $\bar{B}/B$ ratio is not 1 even at $x_F = 0.$, even for Ω's. How should that be modelled? Is it overcounting to consider both quark recombination and resonances?

Next, predictions for polarizations employ SU(6) symmetry, which amounts to the assumption that valence quarks carry all the spin of the proton. We know that SU(6) works rather poorly for ratios of cross sections; it predicts, for example, that $(p \to \Sigma^0)/(p \to \Lambda) = 1/9$ while the real ratio is about 0.24. How much of the model predictions survive the relaxation of SU(6) symmetry? For Λ production all results are independent of SU(6) since all of the Λ's spin comes from the sea quark. For other particles the variation is not too severe (under reasonable modifications of the model) because the asymmetry is a function of ratios of cross sections.

Unfortunately, relaxing the assumption of SU(6) symmetry opens up an enormous parameter space. Let us consider the Σ^0 as an example. Let us write the (ud) part of the proton wave function in the most arbitrary form:

$$|p_\uparrow\rangle = A(ud)_{11} + B(ud)_{10} + C(ud)_{1-1} + D(ud)_{00} \qquad (4)$$

If we assume that the Σ^0 has its usual SU(6) wave function we can compute

$$\langle\Sigma_\uparrow|p_\uparrow\rangle = \frac{2}{3}|A|^2 b_\downarrow + \frac{1}{3}|B|^2 b_\uparrow$$

$$\langle\Sigma_\downarrow|p_\uparrow\rangle = \frac{2}{3}|C|^2 b_\uparrow + \frac{1}{3}|B|^2 b_\downarrow$$

If we write $|A|^2/|B|^2 = x$ and neglect the C terms (so at least the diquark's spin is not too dissimilar from the proton's spin) then the asymmetry is

$$P = \frac{x\delta + (x-1)\epsilon}{1+x}$$

or if $\delta \simeq \epsilon$

$$P = \epsilon(\frac{2x-1}{1+x}).$$

The SU(6) limit is $x = 2$. (Notice that one could still have $x = 2$ even if SU(6) were violasted.)

With the advent of polarized beams and targets other observables can be measured. Two other observables are the polarization transfer

$$D = \frac{1}{2\sigma_0}(\sigma(i=f) - \sigma(i \neq f)) \tag{5}$$

and the analyzing power

$$A = \frac{1}{2\sigma_0}(\sigma(i=\uparrow) - \sigma(i=\downarrow)). \tag{6}$$

Like P, A depends on ϵ and δ and should show x_F and p_T dependence. D, however, is a pure (SU(6)) number. It is thus most susceptable to the effects of SU(6) breaking.

Brookhaven experiment E817 has measured several of these quantities.[21] They find that A for $p \to \pi^0$ is in good agreement with the model of Ref. 3, but for the Σ^0 they have some puzzling results which, if true, pose a serious challenge to the model. We can quantify these results in Table 2: Since $\epsilon \simeq 0.1$ there is a clear inconsistency with the model.

TABLE 2. Comparison of Σ^0 observables with data.

Reaction	Predicted	SU(6)	Observed
P	$\epsilon(\frac{2x-1}{1+x})$	ϵ	
A	$\frac{x}{1+x}$	2/3	0.38 ± 0.18
D	$\epsilon(\frac{2x}{1+x})$	$\frac{4}{3}\epsilon$	$-0.013 \pm .024$

Next there are two specific problems of dynamics. First, why is $\epsilon = \delta$ or why should the asymmetry of a spin-1 diquark be nearly the same as the asymmetry of a spin-1/2 quark? Secondly, why is the asymmetry for $K^- \to \Lambda$ much greater than the asymmetry for $p \to \Lambda$? Surprisingly, both these questions can be addressed in the same recombination model framework.

Simple Recombination Models and Polarization Asymmetry

Recombination Models In order to model polarization asymmetry, we must first begin by modelling inclusive hadron production. A simple way to describe inclusive hadron production is via recombination models. In these class of models the inclusive baryon differential cross section is given by

$$x_F \frac{d\sigma}{dx_F} = \int \frac{dx_1}{x_1} \int \frac{dx_2}{x_2} \int \frac{dx_3}{x_3} F_{123}(x_1, x_2, x_3) R(x_1, x_2, x_3, x_F) \delta(x_1 + x_2 + x_3 - x_F) \quad (7)$$

where F_{123} is a combined probability function for three quarks to be found in the fragmenting hadron's wave function at x_1, x_2 and x_3 and R is a "recombination function" which weights the relative probability that the three quarks will coalesce into a baryon at x_F. Neither F nor R can be measured directly, so a complete model must assume (or fit them to) some functional form. I have neglected transverse momentum but that can easily be added; for the moment assume that one is working at some nonzero transverse momentum.

Variatons of this model which have been employed include the Kuti-Weisskopf model[22] and Hwa's valon model.[23]

Typically, F has the generic form

$$F(x_1, x_2, x_3) = f_1(x_1) f_2(x_2) f_3(x_3) g(x_1 + x_2 + x_3) \quad (8)$$

where the f_i's represent some sort of "intrinsic" distribution of the ith quark in the wave function and $g(x)$ represents the effects of all the spectators; to get agreement with counting rules, one needs $g(x) \simeq (1-x)^f$ at large x. At smaller x $g(x)$ can be much more model dependent.

A constraint on R is that it should peak when each quark carries one third of the

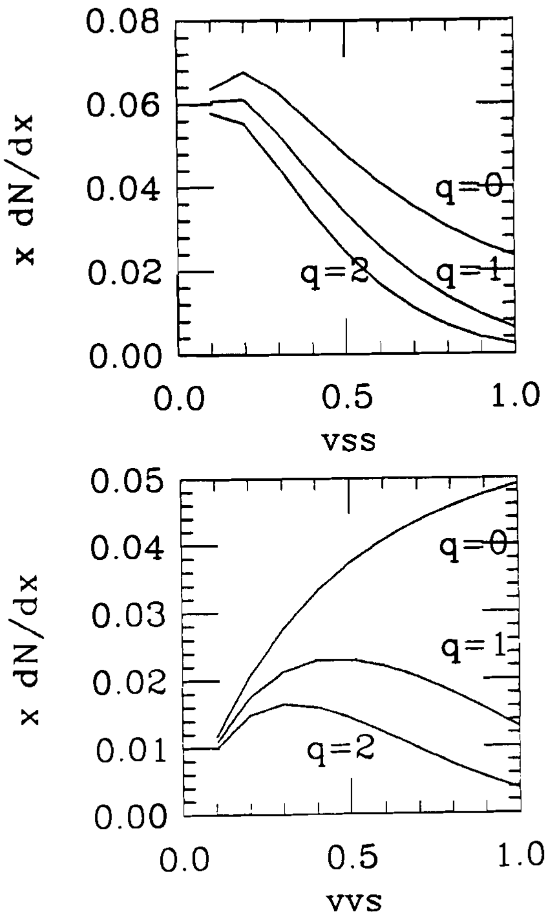

Fig. 1 VVS and VSS recombination spectra for the model of (7) vs. q.

outgoing baryon's momentum. A simple form of R which does that is

$$R = \frac{x_1 x_2 x_3}{x_F^2}\left(1 + C\left(x_1 - \frac{x_F}{3}\right)\right). \tag{9}$$

The second term is the piece responsible for polarization asymmetry of quark 1. It has an arbitrary but universal normalization (which rises linearly with p_T) and implements the phenomenology of the model of Ref. 3 so that the recombination of quark 1 is affected.

It is now straightforward to integrate (7) and show that the asymmetry is (approximately) linear in x_F with a modulation which depends on the choice of f and g.

Modelling Meson and Baryon Induced Reactions Let us try to model polarization asymmetry arising from valence and sea quarks in VVS or VSS recombination. We will parameterize the valence distribution as $f_v(x) = x^p(1-x)^q$ and the sea distribution as $f_s(x) = (1-x)^{q_s}$. The specific form of g is unimportant since it will cancel in the ratio.

Now we can calculate the four different possibilities of V or S polarization with VVS or VSS recombination. We fix $p = \frac{1}{2}$, $q_s = 5$ and vary q_v from 0 to 2. The resulting VVS and VSS rates (or rather, the rates divided by $g(x)$) are shown in Fig. 1. We see that the shapes of cross sections are rather q_v independent for large x_F. The absolute magnitude can be hidden in the function $g(x)$ which carries the bulk of the x_F dependence. On the other hand, the polarization asymmetry itself (shown in Fig. 2) varies rather dramatically with q_v. As q_v rises (or the valence quark spectrum steepens) the polarization asymmetry arising from the valence quark falls.

We see that when two quarks with identical distributions are involved in recombination with one odd quark, the polarization asymmetry arising from either one of them is about half as big as the asymmetry arising from the odd quark. This is a justification of the $\epsilon = \delta$ rule of DeGrand and Miettinen (the diquark has the same asymmetry as the quark). When all three quarks have the same intrinsic distribution, the polarization asymmetry arising from any one quark is zero (so $p \to \bar{\Lambda}$ has no polarization).

Thus the difference of polarization between meson and baryon induced reactions seems in this model to be due to the much flatter "intrinsic" distribution of valence quarks in the meson wave function.

Implications for Polarized Beams

The model of Ref. 3 is in good shape except for the Brookhaven E817 Σ^0 results. There are many other tests of the model which can easily be carried out as part of any program involving polarized beams. It is important to continue to probe the P, A, and D observables for a variety of beam and outgiong particles to try to elucidate the dynamics of polarization. We still need a convincing explanation of the origin of polarization at the quark level.

The recent Ω^- magnetic moment experiment[24] has produced results in agrement with the predictions of Ref. 3. The direct process $p \to \bar{\Omega}$ does not produce polarized Ω^-'s while those Ω^-'s produced from a neutral secondary beam are polarized. (The model predicts that 5/6 of the neutral beam polarization is transferred to the Ω^-.) The measurement of the magnetic moment of the Ω^- is an extremely important task. Not only is it the last "stable" particle whose magnetic moment can be measured, it is the particle whose magnetic moment is the easiest to calculate nonperturbatively (via lattice Monte Carlo.) This is because it is composed of heavy quarks. On the lattice one cannot yet compute

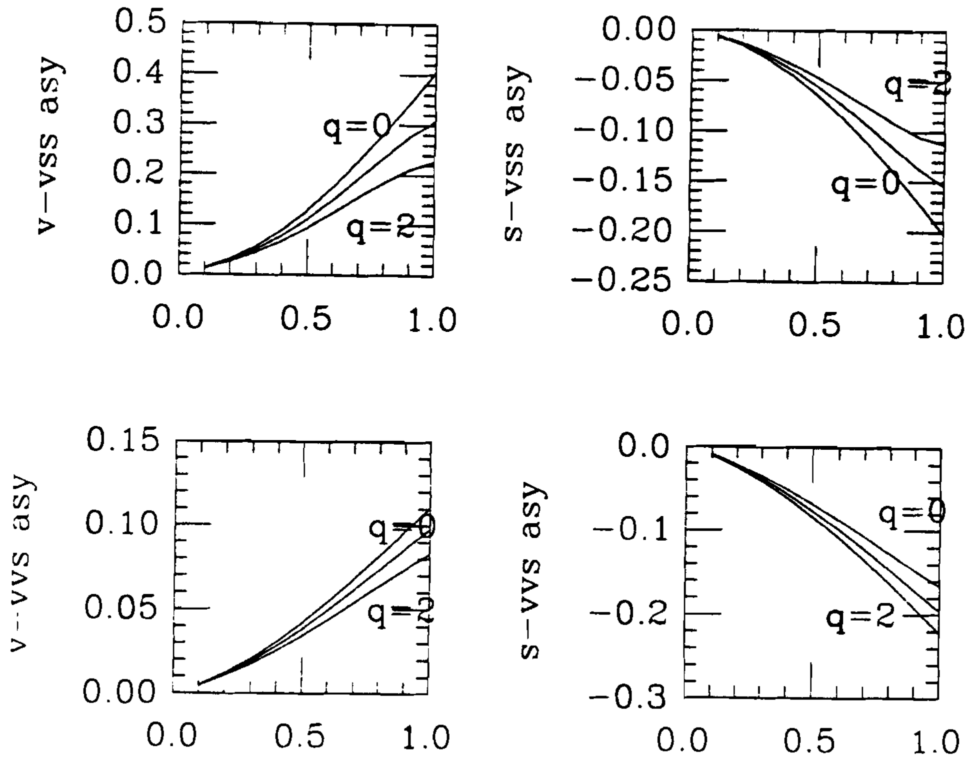

Fig. 2 The four kinds of polarization asymmetry vs. q.

quantities involving light quarks directly; one must carry out the calculation for heavy quarks and extrapolate. This is because as the quark mass goes to zero the quark propagator becomes more and more ill-behaved (it gets a zero eigenvalue) and standard matrix inversion techniques become very slow.

Surprisingly, only two lattice calculations of the Ω magnetic moment[25,26] have been performed and both were done with very small lattices. It seems that the subject is ripe for a revisit. The goal of experiment and lattice gauge theory should be to measure the magnetic moment with sufficient accuracy to see violations of naive SU(6); that is, to see $\mu(\Omega) \neq 3\mu(\Lambda)$.

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