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POLARIZATION IN INCLUSIVE PRODUCTION AT BROOKHAVEN*

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MASTER

ABSTRACT

At Brookhaven, Λ 's are produced polarized in p-p interactions perpendicular to a horizontal production plane defined by $\hat{p} \times \hat{\Lambda}$, with their spins pointing down roughly twice as often as up, for a 1 GeV/c transverse Λ momentum. Such a large effect must indicate a simplicity in the underlying dynamics of particle production, even at low transverse momentum. This paper discusses four BNL experiments in the context of experiments done at other energies and discusses our present (lack of) understanding of the origin of the effect.

INTRODUCTION

Polarization of Λ 's was observed in the inclusive reaction $p + Be \rightarrow \Lambda + X$ at NAL in 1976.¹ With an incident proton momentum of 300 GeV/c, a Λ transverse momentum of 1.5 GeV/c and a Λ polarization of 25%, it was clear that spin effects were important at high energy. Relative to a normal to the production plane defined by $(\hat{p} \times \hat{\Lambda})$, 60% more Λ 's produced with a transverse momentum of 1.5 GeV/c had their spins oriented down as up. This result contradicted two widely-held views:

1. that polarization is a low energy complication that disappears at high energy and
2. that high energy particle production, particularly at low transverse momentum, is a very complicated process that is reasonably described--and, perhaps, will only be described--by thermodynamic models; i.e., quark dynamics will only appear at large transverse momentum.

I believe that these two views are still popular. In fact, the two views have been combined into a statement that physics is well-understood by SU(5) and that phenomena which have not been explained such as polarization are small "details". I disagree. To quote a colleague, "To believe that high energy physics is now understood with our present theoretical understanding of strong interactions is just plain foolish."²

By 1980, the 1976 result has been confirmed and there are interesting new results from NAL, the CERN PS, the ISR, Serpukhov and Brookhaven. M. Sheaff gave a talk on the subject at the Argonne polarization conference in 1976,³ K. Heller and R. Polvado described the results at the polarization conference in 1978^{4,5} and O.E. Overseth gave the new NAL results here.⁶

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In this paper I will describe the Brookhaven experiments in the context of the variety of experiments done so far and give my opinions on the state of the field.

INCLUSIVE POLARIZATION EXPERIMENTS

Despite the lack of theoretical insight about the origin of inclusive polarization (for some of us, of course, the fact that theorists ~~are~~ ^{try to} make an explanation makes this field very attractive), there are a number of experimental questions that can be and should be asked: Confirmation? Energy dependence? Target dependence? Kinematic dependence? Incident particle dependence? Produced particle dependence?

Heller gave answers to several of these questions at this conference in 1978. An analysis of a PS experiment showed the same Λ polarization for 24 GeV incident protons, $p + Pt \rightarrow \Lambda + X$ as the NAL 300 GeV experiment. This both confirmed the original result and indicated remarkable energy-independence. Another result presented then came from a preliminary analysis of an NAL experiment for $p + p \rightarrow \Lambda + X$ which gave a large Λ polarization. The fact that these Λ 's were also polarized was not a surprise (indeed, if these Λ 's had not been polarized--whereas Λ 's from a metal target were polarized, it would have been very startling), but it closed a possible escape-hatch for theorists that the polarization might have been some nuclear effect. Other results presented in 1978, also from NAL, were that $\bar{\Lambda}$'s are not produced polarized, and that Ξ^0 's are. Polvado⁵ presented evidence that protons are not polarized in $p + p \rightarrow p + p + X$. These results showed clearly that polarization is characteristic of particle production at high energy, and that understanding polarization might lead to a description of how quarks rearrange themselves in high energy collisions.

The results also showed that the effect could be studied at other energies and with other particles. Results since the last conference come from the ISR,⁷ Serpukov,⁸ Brookhaven⁹⁻¹² and NAL. Overseth has shown the NAL results. To summarize these, Λ 's, Ξ^+ 's and Ξ^- 's are polarized, and Ξ^+ are produced polarized with the opposite sign. The final Λ polarization results from hydrogen show a clear dependence on Feynman-x, as well as p_t . The ISR experiment found a very large Λ polarization for $p + p \rightarrow \Lambda + X$ at an equivalent lab energy of 1500 GeV for protons incident on a stationary target, a striking result.

There have been a number of Serpukov experiments over many years which have looked at $K^-p \rightarrow \Lambda + X$ in a bubble chamber with K^- energies from 4 to 32 GeV. These results have not previously been discussed in the context of the other inclusive polarization experiments. Their results, in Figure 1, are integrated over transverse momentum. In the fragmentation region of the K^- they see very large polarization, independent of energy. In the fragmentation region of the proton they see no significant polarization. The possible significance of these results will be discussed later.

BROOKHAVEN EXPERIMENTS

There have been four BNL experiments. Two have been published since 1978 and two are in an early stage of analysis. Three of the experiments have used the University of Massachusetts spectrometer in a neutral hyperon beam. The first experiment, published last winter,⁸ observed Λ polarization from a metal target. The importance of the result was that it was a high statistics confirmation of the polarization effect--most previous results were from NAL, the PS results had been analyzed by a subset of the NAL group, and the ISR experiment had limited statistics. The first BNL experiment, however, did not have the possibility of changing the spin direction to eliminate biases so, I believe, it is difficult to compare their results quantitatively with others.

Results from a second BNL experiment were published this February.⁹ A Massachusetts/BNL/Michigan/Minnesota collaboration changed the orientation of the sweeping magnet so that the field would be perpendicular to the Λ spin direction and would precess the spin about 45° . By reversing the polarity of the field, we reversed one component of the polarization, and could confidently eliminate biases in the polarization measurement. The purpose of the experiment was to study Λ polarization--to run a bias-controlled experiment at Brookhaven energy with hydrogen, deuterium, and beryllium production targets. We found no significant dependence on a proton versus a neutron target and a hint of A -dependence. Basically, the polarization was slightly reduced as A increased, just what one would expect--that a nucleus would have a smearing effect on p-nucleon results. The most curious effect seen was in the energy dependence. See Figure 2. We compared the BNL beryllium data to the NAL beryllium data and we can now compare $p + p \rightarrow \Lambda + X$ for BNL, NAL (presented here⁶), and ISR. I have shown the NAL fit to the polarization¹⁵, matching the BNL x and p_T . (The hydrogen fit at NAL was found to agree very well with the NAL beryllium data.) The NAL and Brookhaven results are remarkably similar. Note that the beryllium figure includes NAL data which is not matched to the BNL data for (x, p_T) . They look very different. A clear conclusion of this is that there is little or no energy dependence between 28 and 400 GeV. The difference we remarked on in our February paper was due to differences in the (x, p_T) of the data. The ISR results have a still steeper p_T dependence than either BNL or NAL, but with $\bar{x} = .7$, compared to the BNL $\bar{x} = .5$. The NAL fit indicates that the ISR experiment would see half its observed polarization if it were matched in x and p_T to the BNL data. The result of this adjustment, shown in Fig. 2, is that Λ polarization appears to be independent of energy from BNL to the ISR.

The same group¹¹ has just completed data-taking for a $p + n \rightarrow \Sigma^+ + X$ experiment. We do not yet have results. The experiment is particularly interesting for several reasons: the Λ polarization observed by everyone is diluted by $\Sigma^+ \rightarrow \Lambda \gamma$ events, seen at the same time as prompt Λ 's. It is surely diluted, rather than enhanced, because of the low integrated analyzing power of the daughter Λ from

Σ^0 decay: 100% Σ^0 's with 100% polarization would give only -33% Λ polarization. Measuring the Σ^0 polarization and the (Σ^0 /all Λ) production ratio gives at once three results: the Σ^0 /prompt Λ ratio, Λ polarization, and Σ^0 polarization, all of which will yield clues to solving the puzzle of particle production. It will also be interesting to compare Σ^0 polarization with Σ^+ , since NAL has found that Σ^+ polarization is opposite from Λ . We should have over 10^4 Σ^0 's with $p_T > 1$ GeV/c.

The fourth Brookhaven experiment¹¹ also does not yet have results. It used the multiparticle spectrometer where they observed $\pi^- p \rightarrow \Lambda^+ X$, while searching for hadronic charm production. The π^- momentum was 16 GeV/c and they fired the spark chambers of the MPS on a high momentum proton 8-12 GeV/c. They could not reverse the spin direction, but their apparatus and trigger were left-right and up-down symmetric about the beam, neglecting second-order left-right asymmetries due to the MPS magnetic field direction. Λ 's produced to the left should have the opposite polarization direction from Λ 's produced to the right, so they will have the ability to check for biases (the ISR experiment checked for biases this way). They will have 10^4 Λ 's with $p_T > .8$ GeV/c. These results will test models in a very different way from proton beam results: if the added quarks from the transformation $\pi^- \rightarrow \Lambda$ carry the polarization information independent from the absorbed quarks, the π^- beam should yield polarized Λ 's in the same way that a proton beam yields polarized Σ^0 's. If the Λ 's are polarized, their acceptance will allow them to study the low- p_T and x-dependence of the effect.

The Brookhaven experiments use the advantages of lower energy-- there are, of course, serious disadvantages in lifetime compared to NAL. Brookhaven also spans the energy regions of low energy resonance physics and high energy behavior. A very attractive MPS experiment would trace the $p + p \rightarrow \Lambda^+ X$ energy dependence down to a few GeV, study x and p_T dependence over the Peyrou plot, and break the inclusive cross-section for Λ production into exclusive channels, isolating the contributors to the polarization.

Clearly we are now discussing a second generation of inclusive polarization experiments where we no longer search for, but study the effect.

MODELS OF POLARIZATION

One clear result of the large polarizations is to eliminate several popular models. I would eliminate three of them: the thermodynamic model which, by its nature, predicts no polarization; triple-Regge and resonance models which, although they can describe Λ production (perhaps with polarization), cannot describe exotic production such as Σ^0 in the same framework (the fact that both Λ 's and Σ 's are produced with similar large polarizations implies strongly that their production processes are similar). There is another model close to the precipice--QCD. There is a clear prediction¹⁶ that there should be no polarization at high $p_T \rightarrow 5$ GeV/c. This is to be tested in an experiment at NAL. Furthermore, QCD does not predict

polarization at low p_T --its view that low- p_T particle production is complicated with many graphs seems, to me, to be a prediction of no polarization there.

There are no comprehensive models which predict both the polarizations and the cross sections. Quark models of the polarization^{13,14} are based on the observation that the s-quark of the Λ carries the polarization of the Λ --that the (u,d)-quark pair are in a spin-0 state. Thus, in the conversion $p \rightarrow \Lambda$ (see Figure 3) if the s-quark from the sea for some reason remembers the orientation of the production plane, the Λ will be polarized. This conjecture is more interesting now with the NAL result that Σ^+ 's are polarized in the opposite direction. For Σ 's, the non-strange quark pairs (which are spectators) are in a spin-1 state, so that the added s-quark spin is opposite to the Σ -spin--the polarization flips compared to Λ . Now, the spin-1 state has a probability of having $S_z = 0$, when the s-quark spin is in the same direction as the Σ -spin. Therefore, one expects, ignoring a Z^0 dilution of the Λ polarization, that due to this admixture the Σ 's should be less polarized than the Λ 's. The NAL experiment finds that the Σ^+ 's are as polarized. It is possible to adjust the predicted polarization ratio Λ/Σ^+ . This results in a firm prediction for the production ratio Λ/Σ^+ which will be measured at BNL.

Σ polarization also gives mixed results for the quark models. For Σ 's the two new s-quarks are in a spin-1 state, so the polarization should be in the same direction as for Λ 's (it is) and less due to the $\text{spin}_z = 0$ admixture of the spin-1 s-diquark in the Σ (Σ polarization is the same as Λ). There is, of course, the Σ^0 caveat. But there are additional problems. In these models the memory of the added quark spin direction for the orientation of the production plane presumably occurs through the transverse momentum of the added quark which gives its p_T to the produced particle.¹⁵ When two quarks of the produced particle come from the sea, the contribution of each quark to the transverse momentum of the particle (such as the Σ) is less. With this coupling reduced, one would expect at the least a less steep p_T -dependence of the polarization for Σ 's than for Λ 's. In fact, the p_T -dependence of Λ 's and Σ 's is identical.

Presumably, there is nothing special about the target material about the s-quark, or about the incident particle type. Brookhaven and NAL results agree with quark models that the target material should not matter. It can be argued that $p + p \rightarrow p + X$ should not be polarized because the produced proton need not have picked up quarks from the sea--that $p \rightarrow p$ has very different processes involved than $p \rightarrow \Lambda$, which is borne out by the several times larger proton cross section. It is difficult to see, however, why the Indiana group⁵ did not see polarization at $p_T = 1.5 \text{ GeV}/c$ for $p + C \rightarrow p + X$. This reaction is half $p + p$ and half $n + p$ (the observed proton was in the target fragmentation region). The polarization could have been masked by the reduced coupling of the sea u-quark spin to the produced proton spin.

The results from Serpukov⁸ on $K^- + p \rightarrow \Lambda + X$ are curious and seem to cause problems for quark models. For the reaction $K^- p \rightarrow \Lambda$ in the K^- fragmentation region, the s-quark is a spectator. The two new quarks in the Λ are in a spin-0 state and do not contribute to the polarization. Quark models would predict no polarization. A very large polarization is seen which is independent of energy from 4 to 32 GeV (Figure 1). The experiment also measured the Λ polarization in the proton fragmentation region. There, one would expect $p \rightarrow \Lambda$ to be polarized. They saw no polarization at 32 GeV. Caveats: the results were integrated over p_T and the statistics were limited for the proton fragmentation region. The BNL experiment $\pi^- + p \rightarrow \Lambda + X$ will test the model. Since an s-quark is picked up from the sea, along with a u, the Λ 's should be polarized with the same sign as $p \rightarrow \Lambda$, but less due to the reduced coupling between the s-quark transverse momentum and the Λ p_T .

This quark model for polarization, as it now stands, is very slippery. Production processes which do not agree with the model can be ignored because of the possibility of different mechanisms dominating the interaction. The fact that protons and $\bar{\Lambda}$'s are not polarized is attributed to their different production mechanisms. In fact, with these models, the $\bar{\Lambda}$ should be polarized since there should be nothing special about quarks (versus antiquarks). The p_T coupling of the $\bar{s}$ to the $\bar{\Lambda}$ is less, so one might expect the $\bar{\Lambda}$ to be polarized at higher p_T than the Λ . However, the Ξ case lies in between the Λ and $\bar{\Lambda}$ cases, and we see the same p_T dependence of the polarization for Λ and Ξ , but no $\bar{\Lambda}$ polarization. To quote Yousef Makdisi: "Perhaps s-quarks come from the Red Sea and $\bar{s}$ -quarks come from the Dead Sea."

Polarization models appealing to quark pictures are both attractive and murky. Models must begin to describe both polarizations and cross sections.¹⁷

CONCLUSIONS

The field needs a theory. Results from the Brookhaven Σ^+ and $\pi^- \rightarrow \Lambda$ experiments are eagerly awaited. There are still a large number of experiments to do: a very high p_T experiment at NAL, a dedicated ISR experiment with more events and a large kinematic range--these are approved experiments; an experiment at the Brookhaven MPS looking at exclusive pieces of $p + p \rightarrow \Lambda + X$, and studying energy dependence down to low energy; an experiment looking at $n \rightarrow p + \pi^+$ plus experiments with other incident particles such as leptons; polarized proton work at the AGS looking at the spin transfer $p \uparrow \rightarrow \Lambda \uparrow$. An experiment studying $n \rightarrow \Sigma^+ + \pi^-$ where the Σ^+ has received both u and s-quarks from the sea would be attractive, compared with $p \rightarrow \Sigma^+$. (A similar comparison can be made for $p \rightarrow \Sigma^- + \pi^+$, but the Σ^- has a very low analyzing power.) Another interesting question: what is the linkage between inclusive polarization and inclusive π -production using either a polarized beam or a polarized target?

G. Preparata stated at this conference that, as a graduate student, he was taught that polarization was not an interesting subject. The times may be changing: Craig Dukes--a graduate student of Oliver Overseth's--stated "Of course particles are produced polarized at high energy. High energy interactions are quark interactions and the quarks have spin. At low energy one expects less polarization due to multi-quark screening."

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References

1. G. Bunce, R. Handler, R. March, P. Martin, L. Pondrom, M. Sheaff, K. Heller, O.E. Overseth, P. Skubic, T. Devlin, B. Edelman, R. Edwards, J. Norem, L. Schachinger and P. Yamin, Phys. Rev. Letters 35, 1113 (1975).
2. A. Krisch, in a letter to Dr. P.K. Williams of the High Energy Physics Advisory Panel, April 1980.
3. M. Sheaff, 1976 Conference on High Energy Physics with Polarized Beams and Polarized Targets (HEPPBPT).
4. K. Heller, 1978 Conference HEPPBPT.
5. R. Polvado, 1978 Conference HEPPBPT.
6. O.E. Overseth, this conference. References to NAL results can be found there.
7. S. Erhan, W. Lockman, M. Medinnis, T. Meyer, J. Rander, P. Schlein, R. Webb, A. Boehm, H. Foeth, A. Staude, R. Ellis, B. Naroska, P. Strolin and J. Zsembery, Phys. Letters 82B, 331 (1979).
8. M.L. Faccini-Turluer, R. Barloutaud, C. Cochet, A. Givernaud, L. Mosca, J. Saudraix, P. Sixel, L. Becker, U. Gensch, E. deVelt, F.A. Triantis, R. Windmolders, H. Blumenfeld, Yu. I. Arastov, P.V. Chiapnikov, A.A. Minaenko, A.M. Rybin, U.S. Uvarov and J. MacNaughton, Z. Phy. C. Part. and Fields 1, 19 (1979).
9. F. Lomanno, D. Jensen, M.N. Kreisler, R. Poster, M.S. Z. Rabin, M. Way, J. Wise and J. Humphrey, Phys. Rev. Letters 43, 1905 (1979).
10. K. Raychaudhuri, D. Jensen, F. Lomanno, D. McIntyre, M. Rabin, G. Bunce, P. Yamin, P.T. Cox, J. Dworkin, O.E. Overseth, K. Heller, and Y. Makdisi, Phys. Letters 90B, 319 (1980).

11. ENL E^+ experiment. M. Sullivan, D. Jensen, M.N. Kreisler, Lomanno, M. Marsden, K. Raychaudhuri, C. Dukes, O.E. Overseth, G. Bunce, Y. Makdisi, P. Yamin, K. Heller and M. Shupe.
12. BNL MPS experiment. S.U. Chung, A. Etkin, R. Fernow, K. Foley, J.H. Goldman, H. Kirk, J. Kopp, A. Lesnik, W. Love, T.W. Morris, S. Ozaki, E. Platner, S.D. Protopopescu, A. Saulys, D.P. Weygand, C.D. Wheller, E. Willen, J. Bensinger, W. Morris, S.J. Lindenbaum, M.A. Kramer, U. Mallik, Z. Bar-Yam, J. Dowd, W. Kern, M. Winik, J. Button-Shafer, S. Ohar and R. Lichti.
13. K. Heller's model in K. Heller, et al., Phys. Rev. Letters 41, 607 (1978).
14. B. Andersson, G. Gustafson and G. Ingelman, Phys. Letters 85B, 417 (1979).
15. R. Grobel discusses this in his Ph.D. thesis, University of Wisconsin (1980).
16. G.L. Kane, J. Pumplin, and W. Repko, Phys. Rev. Letters 41, 1689 (1978).
17. See G. Preparata, this conference.

Figure 1. Λ polarization from K^- beam at Serpukov. Ref. 8.

Figure 2. Λ polarization from $p + \begin{pmatrix} \text{Be} \\ \text{H}_2/\text{D}_2 \end{pmatrix} \rightarrow \Lambda + X$, ref. 10

(labeled THIS EXP. and 28.5 GeV/c), compared to 400 GeV/c (ref. 4 and see ref. 6). The x-points represent an NAL fit¹⁵ to their hydrogen data at the corresponding BNL (x, p_T). The open triangles are ISR points which matches the ISR data (ref. 7) to the BNL (x, p_T), following the observed NAL x-dependence.

Figure 3. Quark diagrams for different experiments.