POLARIZED PROTONS AT THE 200-GeV ACCELERATOR

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ABSTRACT

We investigate the possibilities of providing beams of polarized protons at the 200-GeV accelerator. Three possibilities are considered: 1) direct acceleration of polarized protons, 2) polarization from elastic scattering, and 3) polarized protons from hyperon decay. In particular, the problem of polarization resulting from hyperon decay is treated in some detail. Beams of high-energy protons with intensities $\sim 10^5$ per pulse and 50% polarization appear feasible from Λ^0 decay. With machine modifications direct acceleration of polarized protons appears possible resulting in intensities 10^2 higher than in beams from hyperon decay.

I. INTRODUCTION

It will be of considerable interest to study the spin dependence of proton interactions at high energies. Prevailing theoretical opinion anticipates vanishing of the spin dependence at very high energies. It is important to check this prediction and to examine how and where this asymptotic region is reached, if indeed it is.

Spin dependence may be studied by the use of polarized targets, by double and triple scattering, and by the use of polarized beams, and, of course, by combinations of these three basic techniques. The possibilities of using the first two of these techniques at the 200- GeV accelerator have been the subjects of previous studies. C. Schultz has discussed the use of polarized targets[1] at NAL and H. Neal has argued[2] that double scattering experiments will continue to be useful at the higher energies in studying polarization phenomena. In this note, we wish to investigate the possibilities of providing beams of polarized protons at the 200-GeV accelerator. We consider three possibilities: 1) acceleration of polarized protons, 2) polarization from elastic scattering and 3) polarized protons and neutrons from hyperon decay.

II. DIRECT ACCELERATION OF POLARIZED PROTONS

The most direct way to produce intense beams of polarized protons is to polarize the protons in the ion source and to accelerate them directly in the accelerator.

L. Teng has studied this problem of acceleration of polarized protons in the 200-GeV machine. There is no problem in accelerating the polarized protons in the Cockcroft-Walton or Linac. However, in both the booster and main ring there occur resonances between the precession frequency of the polarized protons and the vertical betatron oscillation. At each of these resonances complete depolarization will occur for the beam if nothing is done. During the acceleration cycle there are about a dozen such resonance points to cross, about 6 in the booster and 6 in the main ring.

It appears quite feasible to jump the vertical betatron oscillation as each resonance point is reached by using pulsed quads in the ring. These quads would have to be added, but there is room in the straight sections for them. The timing and amplitude of the pulse on the quads is crucial, but in this way one would attempt to jump across the resonances and to avoid the depolarization of the beam during the acceleration cycle.

At the present stage of the art, typical intensities from a polarized ion source are of the order of a few microamperes. Since the source intensity anticipated for the 200-GeV accelerator is 200 mA, the polarized proton beam accelerated directly in the accelerator would yield a 10^5 decrease in intensity from that of the regular proton beam, resulting in intensities of the order of 10^7-10^8 polarized protons per pulse.

III. POLARIZED BEAMS FROM ELASTIC SCATTERING

The traditional method of producing (and analyzing) polarized proton beams by elastic scattering will not be available at high energies if indeed spin effects become unimportant as energy increases. Present evidence on p - p scattering shows polarization decreasing with increasing energy, but rather slowly. The maximum polarization observed in p - p scattering is 25% for 3 GeV,[3] 18% at 6 GeV,[4] and 6% at 14 GeV.[5] Unless this monotonic decline reverses with increasing energy, elastic scattering does not look very encouraging as a means to produce proton beams with high polarization.

IV. POLARIZED NUCLEONS FROM HYPERON DECAY

It has often been suggested to use hyperon decay as a source of polarized protons and neutrons but the details have not been presented. We shall discuss here in some detail the polarization that results from hyperon decay and indicate how useful beams of polarized particles could be produced.

There have been two general schemes proposed for production of hyperon beams. First of all, in any neutral beam resulting from protons interacting in a target, Λ^o and Ξ^o hyperons will be constituents of the beam along with neutrons, neutral kaons, and gamma rays. From the Hagedorn-Ranft curves the maximum in the hyperon momentum distribution occurs at about 2/3 of the bombarding energy, corresponding to mean decay lengths of about 9 meters (for 130 GeV/c) for both Λ^o and Ξ^o hyperons.

This will result in intense beams of the order of 10^8 Λ^0 and Ξ^0 hyperons per pulse. Upon decay, 2/3 of these hyperons lead to protons and 1/3 to neutrons. Because the Q value for the decay is small, the nucleons largely preserve the momentum and direction of the parent hyperon.

The second hyperon beam that has been proposed in various forms[6] is a well-collimated, high-intensity beam of the negatively charged hyperons, Ω^-, Ξ^-, and Σ^-. Such a beam can be expected to have a Σ^- intensity of ~10^8 per pulse and assuming that production of hyperons decreases by a factor of 10^2 with each increment in strangeness, results in fluxes of $\Sigma^- : \Xi^- : \Omega^- = 10^8 : 10^6 : 10^4$ particles per pulse. The Σ^- decays all lead to neutrons, and 2/3 of the Ξ^- and Ω^- result in protons and 1/3 in neutrons. Thus, normalizing to 10^8 Σ^- in the beam, after decay we have 6.7×10^5 protons/pulse, almost all from Ξ^- decay, and 10^8 neutrons/pulse from Σ^- decay. Now to examine what can be said about the polarization of these decay protons and neutrons.

The polarization in the center-of-mass (c.m.) of the decay baryon in hyperon decay is given by

$$\langle\sigma\rangle = \frac{1}{(1 + \alpha \vec{P}\cdot \hat{q})} \left[(\alpha + \vec{P}\cdot \hat{q})\, \hat{q} + \gamma\, \hat{q} \times (\vec{P} \times \hat{q})\right],$$

where $\vec{P}$ is the polarization of hyperon, $\hat{q}$ specifies the direction of the decay baryon in the center-of-mass, and α, γ are the parameters characterizing the hyperon decay. We have assumed time-reversal invariance, ignored small final-state interactions, and set the decay parameter β equal to zero in the expression for the polarization.

In transforming the polarization vector from the c.m. to the laboratory there is a relativistic effect which rotates the spin vector toward the laboratory direction of the decay baryon. Even at these high energies this effect turns out to be small, but since that is not obvious let us consider the details. Classically, the spin vector remains fixed in transforming from the c.m. to laboratory. In Fig. 1 is illustrated the case of how the baryon helicity component α in the c.m. transforms in the laboratory to be inclined at an angle ϵ with respect to the laboratory momentum vector. Classically $\epsilon = \Phi - \theta$ where Φ is the c.m. decay angle and θ is the decay angle in the laboratory. Relativistically this angle ϵ is given by

$$\tan \epsilon = \frac{\sin \Phi}{\gamma_0\left(\cos \Phi + \frac{\beta_0}{\beta_{cm}}\right)}$$

where β_0, γ_0 refer to the baryon in the c.m. system, and β_{cm} is the velocity of the c.m. In Table 1 the angle ϵ has been evaluated for angle of maximum deviation from the classical case $\Phi = 90°$ for various hyperon decays. The velocity of the decaying hyperon has been taken as $\beta_{cm} = 1$.

Table I. Comparison of Relativistic Angle ϵ With Classical Angle Φ for $\Phi = 90°$

	ϵ
Λ	84°
Σ	78°
Ξ	83°

Thus we see that the maximum discrepancy is 12°, so for our purposes we will ignore the relativistic rotation of spin vectors in this treatment. The effect of this transformation of spin is to cause a component of the longitudinal polarization α in the c.m. to become transverse $\alpha \sin \epsilon$ in the laboratory system.

We will also assume unless otherwise stated that in the laboratory the decay baryon is emitted at 0° with respect to the hyperon. At hyperon momenta greater than 100 GeV/c this decay angle is always less than 0.07° for Λ^o decay and is less than 0.2° for Ω^- decay, the largest case.

Consider now the decay of a beam of hyperons of polarization $\vec{P}$. After decay this gives rise to a beam of protons and/or neutrons. If we take the expression for the polarization of the decay baryon, weight it with the decay distribution and integrate over all decay angles we find the resultant polarization of the decay baryon is $(1 + 2\gamma/3)\,\vec{P}$, where γ is a parameter characterizing the decay. In Table II is presented a summary of the decay parameters for various hyperons.

Table II. Hyperon Decay Parameters.

	α	γ
Λ^o	0.65	0.75
Σ^-	-0.08	+1.0
Ξ^-	-0.38	0.925
Ξ^o	-0.36	0.93

Thus, in the neutral beam, protons and neutrons from Λ^o decay will have a transverse polarization equal to 0.84 P_{Λ^o} and the protons and neutrons that eventually result from Ξ^o decay have a polarization equal to 0.80 P_{Ξ^o}. For the negative hyperon beam, neutrons from Σ^- decay will have the same polarization as the Σ^- hyperons and the protons in the beam will have a polarization equal to 0.80 P_{Ξ^-}.

If the hyperons are not produced with polarization, there will be no net polarization for decay baryons downstream. This is simply a statement that polarization will not result from an unpolarized beam if you do not discriminate in angle. Whether the hyperons will be produced polarized at these high energies is an open question. Of course polarization can only occur for non-zero degree production, a factor which should be considered when designing the hyperon beams. Moreover, in the intense beams proposed the production processes are complicated and varied, and it is difficult to be optimistic that high polarization will occur.

In order to have polarized nucleons from unpolarized hyperons it must be contrived to select the nucleons from a certain limited interval of decay angles. For example, calculation shows that nucleons that decay to the left of the hyperon beam will have a transverse polarization in that direction equal to $\alpha/2$. This is true for nucleons that decay into any hemisphere. Those that decay above the hyperon beam will have transverse polarization upward equal to $\alpha/2$. Selecting those that decay only forward in the center-of-mass will result in nucleons with a longitudinal polarization of $\alpha/2$. The latter can be done, for example, by preferentially selecting the faster nucleons. Similarly the faster Λ^o's from Ξ decay can be preferentially selected because they have a longer mean decay length, and they will be longitudinally polarized. However the neutrons from Σ^- decay can have no polarization if the Σ^- are unpolarized, regardless of how selected in angle and momentum, since the α for Σ^- decay is zero.

In the decay of unpolarized hyperons, the decay proton or neutron can have a polarization which is transverse if we selectively measure decays left vs right (or up vs down) with respect to the hyperon beam line, and it can have longitudinal polarization if one can discriminate decays forward from decays backward in the c.m. These polarization components will be proportional to the decay parameter α, the proportionality coefficient depending on angle interval selected. Fortunately Λ^o has a large α and is an excellent candidate to produce polarized proton beams. If protons can be selected from limited intervals of momentum and decay angle, intense beams of protons can be produced with transverse and longitudinal polarization components which can be varied by changing the choice of the central momentum and mean decay angle.

In a separate paper[7] J. Sandweiss and the author show how in practice to exploit this to produce an intense beam of polarized protons from Λ^o decay in a neutral beam at the 200-GeV accelerator. Such a beam could have an intensity the order of 10^5

protons per pulse with transverse and longitudinal polarization components each as high as 50%. With care in design, moreover, the polarization would be known, and one would not depend on the unknown analyzing power of a second scatterer to measure this. The neutral beam will also contain anti-Λ^0 hyperons which in the same way can produce beams of polarized anti-protons.

V. CONCLUSIONS

It will be of considerable interest to investigate spin dependence at high energies exceeding those now available. Theoretical opinion expects spin dependence effects to vanish at high energies. If this turns out to be true,polarization will not result from p - p scattering. Also analyzing powers will vanish in elastic scattering, and it would be difficult to determine whether an elastically scattered beam is indeed polarized or not. To study these effects it would be desirable to produce a polarized proton beam whose polarization is known. This is possible utilizing the protons from hyperon decay. If hyperons can be produced polarized, the decay protons and neutrons retain most or all of this polarization which will appear as a transverse polarization. If the hyperons are not produced polarized, selection of the decay protons for limited decay angles and momenta will result in both transverse and longitudinally polarized proton beams. The best case appears to be protons from Λ^0 hyperons present in a neutral beam. Beams of high-energy protons with intensity $\sim 10^5$ per pulse and 50% polarization appear feasible. Beams of similarly polarized anti-protons can also be made. If demand warrants it, it appears possible, with machine alterations, to accelerate polarized protons directly in the accelerator resulting in intensities $\sim 10^2$ higher than in beams from hyperon decay. Investigation of spin dependence in high-energy interactions should be possible at the 200-GeV accelerator using relatively high-intensity beams of polarized protons.

VI. ACKNOWLEDGMENTS

It is a pleasure to acknowledge conversations with L. Teng regarding direct acceleration of polarized protons in the 200-GeV accelerator.

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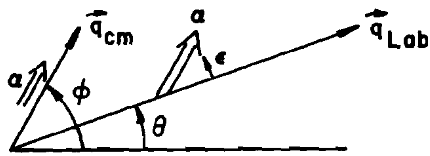

Fig. 1. Transformation of direction of spin vector in going from center-of-mass to laboratory system.