Polarizing Helium-3 for down quark spin enrichment

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Abstract. The successful acceleration of an unpolarized Helium-3 beam by the AGS at BNL heralds the possibility of achieving polarized He-3 ions at RHIC. Assessing the level of polarization will be a challenge at high energy as the inelastic channels associated with He-3 scattering off a carbon target in the electromagnetic hadronic interference region may dilute expectations by comparison with the successful use of this method for proton polarimetry. The large anomalous magnetic moment of He-3 is helpful however, though the greater hadronic elastic cross section reduces the optimal analyzing power. Encouragement may be drawn from measurements indicating little high energy hadronic spin dependence.

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INTRODUCTION

Polarized proton beams have been available at the Relativistic Heavy Ion Collider (RHIC) of Brookhaven National Laboratory (BNL) for some years [1] particularly at the energies 100 GeV and 250 GeV. In a continuing study of the spin structure of a nucleon, the identification of contributions from an up quark and a down quark will require collisions of polarized neutrons in some form. The acceleration of polarized beams of light ions involving deuterons, tritium or helium-3 could provide a source of such polarized neutrons suitable for high-lighting the rôle of polarized down quarks [2]. Constraints on leptophobic gauge bosons follow from the use of polarized neutrons [3].

It is difficult to accelerate polarized deuterons to any energy above 30 GeV at RHIC due to the unsuitably low magnetic moment of the deuteron [4]. The acceleration of polarized helium-3 to high energy, on the other hand, is facilitated by a magnetic moment $\mu_{\rm h} = -2.1275$ that is much larger in size, particularly its anomalous moment. Preliminary studies indicate that two Siberian snakes may be sufficient to provide a high energy polarized helium-3 beam at RHIC [4].

Polarimetry for helium-3 may be not unlike that for a polarized proton beam [5] and could use the electromagnetic hadronic interference that survives at high energies in the diffractive elastic spin asymmetry [6]. In general, a spin half hadron of mass m with charge Ze and magnetic moment μ nuclear magnetons scattering elastically off a charge $Z'e$ ion of any spin has an asymmetry $A_{\rm N}$ that involves an interference of helicity nonflip and flip amplitudes each with electromagnetic and hadronic elements [7] as follows

$$-2\,\mathrm{Im}\left[\frac{ZZ'\alpha}{t} + (i+\rho)\,\frac{\sigma_{\rm tot}}{8\pi}\right]\left[\left(\frac{Z}{m} - \frac{\mu}{m_{\rm p}}\right)\frac{Z'\,\alpha}{2\sqrt{-t}} + \frac{\sqrt{-t}}{m_{\rm p}}\,r_{\rm s}\,\frac{\sigma_{\rm tot}}{8\pi}\right]^* \qquad (1)$$

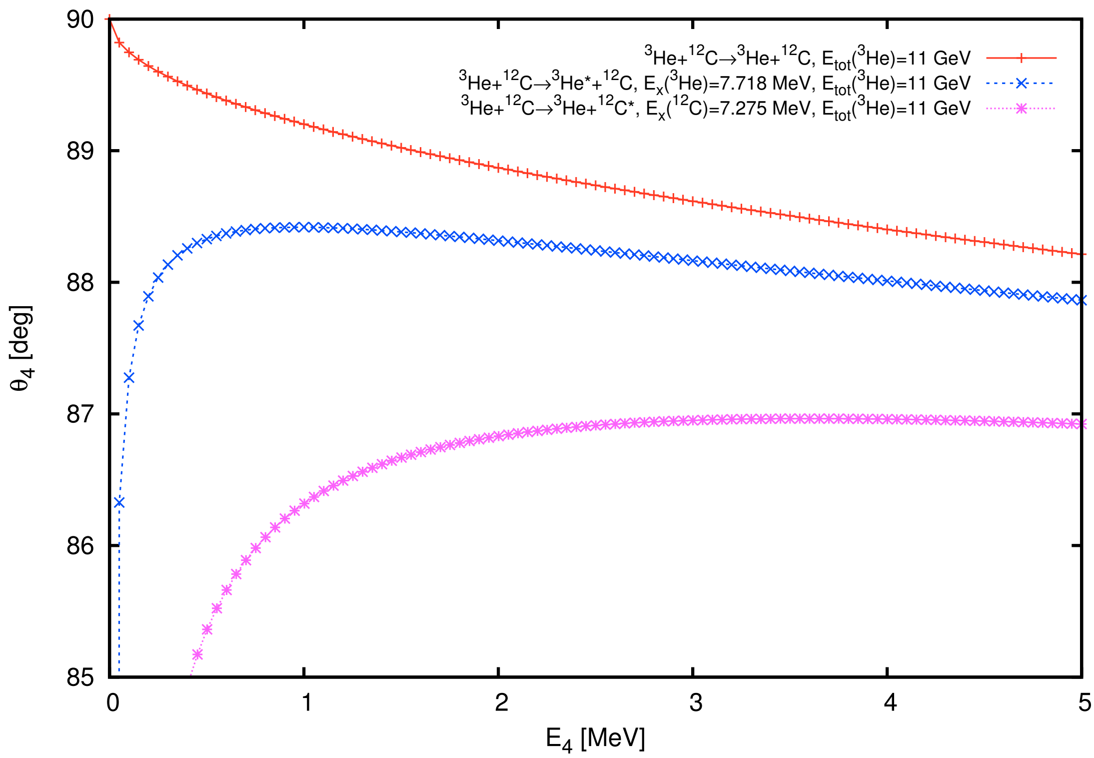

FIGURE 1. Carbon-12 laboratory recoil angle versus its recoil kinetic energy for an incident helium-3 beam scattering (in)elastically to helium-3 (break-up) or recoil carbon-12 (break-up).

ASSESSING HELIUM-3 POLARIZATION

The total hadronic cross section is $\sigma_{\rm tot}$ for the incoming particles of charge Ze and $Z'e$. Ignored in the above expression for the asymmetry are effects due to two photon exchange Coulomb phases, hadronic slope and form factors; they have been treated in detail in [8]. Also neglected are terms related to the real part parameter ρ, hadronic double spin dependence [9] [10] and single spin parameter $r_{\rm s}$ [11] in order to provide approximate expectations for a polarimeter. Eq. 1 with the spin averaged denominator included indicates that the normal single spin asymmetry is proportional to

$$A_{\rm N} \propto \left(t_{\rm opt}/t\right)^{1/2} \Big/ \left[\left(t_{\rm opt}/t\right)^2 + 3\right], \quad \text{where } t_{\rm opt} = -8\sqrt{3}\,\pi\alpha \left|ZZ'\right| / \sigma_{\rm tot}\,, \tag{2}$$

the optimum value of which varies slowly with energy s as $1/\sqrt{\sigma_{\rm tot}(s)}$ and occurs at momentum transfer $t = t_{\rm opt}$. Helions with magnetic moment $\mu_{\rm h} = -2.1275$ scattering on ions have a minimum analyzing power of about -3% in the interference region. In general, the optimum value is either a maximum or minimum depending on the sign of the anomalous magnetic moment term in

$$A_{\rm N}^{\rm opt} = \frac{1}{4Z}\left(\frac{\mu}{m_{\rm p}} - \frac{Z}{m}\right)\left(-3\,t_{\rm opt}\right)^{1/2}. \tag{3}$$

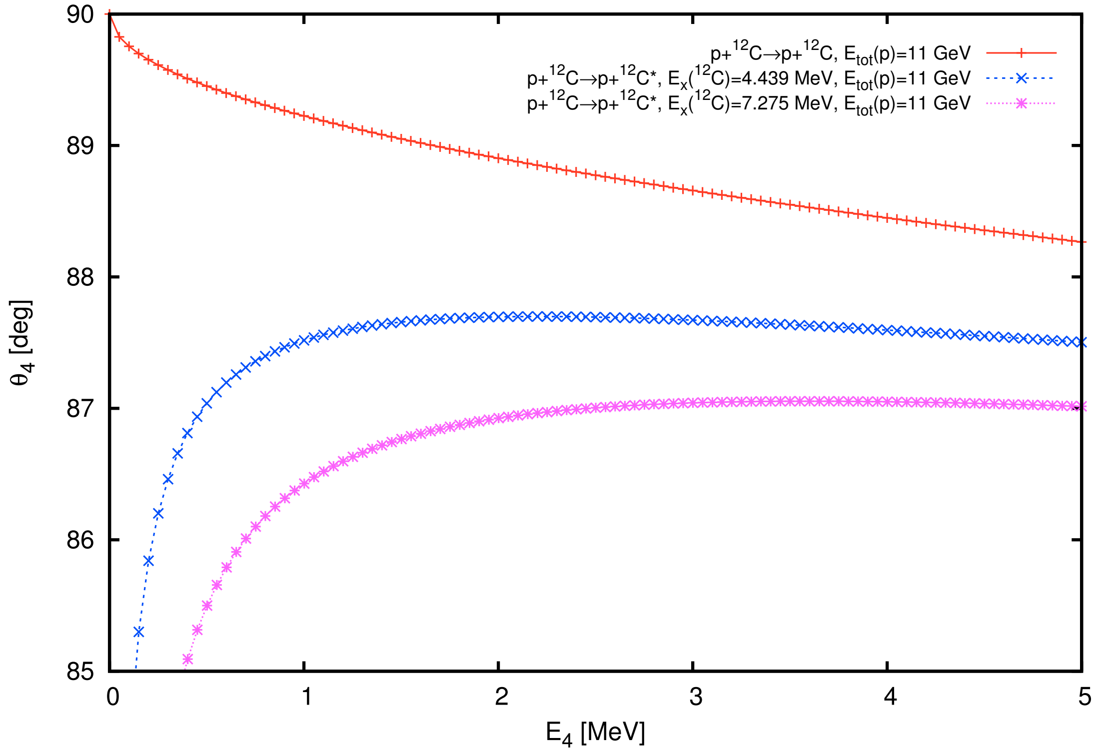

FIGURE 2. Carbon-12 laboratory recoil angle versus its recoil kinetic energy for an incident proton beam scattering (in)elastically to carbon-12 (or an excited nuclear state or break-up).

DIFFRACTIVE SCATTERING

The above asymmetry that arises from exploiting the spin dependence of the electromagnetic interaction offers a method of evaluating the level of polarization of a high energy helium-3 beam [12]. A purely hadronic analyzing power fails as a polarimeter since it tends to vanish at high energies in many cases. From Eqs. (2) and (3) the ratio of the analyzing power extrema for polarized helions and protons is

$$A_{\mathrm{N}}^{\mathrm{opt}}(\mathrm{hC})/A_{\mathrm{N}}^{\mathrm{opt}}(\mathrm{pC}) \;=\; -0.78\sqrt{t_{\mathrm{opt}}^{\mathrm{hC}}\Big/t_{\mathrm{opt}}^{\mathrm{pC}}}\,, \quad \text{where} \;\; t_{\mathrm{opt}}^{\mathrm{hC}}\Big/t_{\mathrm{opt}}^{\mathrm{pC}} \;=\; 2\,\sigma_{\mathrm{tot}}^{\mathrm{pC}}\Big/\sigma_{\mathrm{tot}}^{\mathrm{hC}} \qquad (4)$$

and the negative magnetic moment of the helion indicates that the optimum asymmetry corresponds to a negative minimum in contrast to the positive maximum for a proton.

The above relative polarimeter needs to be calibrated by a He-3 jet of known polarization to offset the unknown effects of hadronic spin dependence in helion carbon collisions. The STAR Collaboration at BNL has shown that the elastic proton proton hadronic helicity flip amplitude is negligible at $\sqrt{s} = 200$ GeV [11] though one cannot assume that this is also true for elastic helion collisions. Helions have recently been accelerated to 11 GeV in the AGS at BNL [13] where it appears that the helion carbon total cross section is twice that of the proton carbon one, so that from Eq. 4, $t_{\mathrm{opt}}(hC) \approx t_{\mathrm{opt}}(pC)$.

KINEMATIC LIMITS

For momentum transfers outside the interference region it would be important to include the effects of a finite nuclear size and of a hadronic real part [14]. When a helion scatters from a carbon target it may be desirable to ensure that it does so elastically, with the carbon recoiling at kinetic energy $E_4 = -t/2m_{\mathrm{C}}$, in order to maximize the spin asymmetry observed in the interference region. Inelastic events could dilute the asymmetry and render the polarimeter less effective.

One way to achieve elastic scattering is to introduce a kinematic cut on the laboratory recoil angle of the emerging carbon ion. For incident helions of energy 11 GeV, Fig. 1 indicates that elastic events are preferred if recoiling carbon nuclei with angles confined to above about 88.4 degrees are selected. By way of comparison, Fig. 2 shows the limiting angle for incident protons of the same energy.

SUMMARY

The spin structure of the nucleon probes QCD and the Electroweak interaction in interesting ways. Spin structure functions of the neutron are within reach given that the acceleration of polarized Helium-3 beams may be forthcoming. There is great potential for studies involving polarized down quarks that the advent of a polarimeter for He-3 beams makes possible. Spin contributions are significant in the investigation of detailed low momentum transfer processes that play a rôle in the understanding of diffraction.

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