PROCEEDINGS OF SCIENCE

A Helium-3 polarimeter using electromagnetic interference

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A source of polarized helium-3 ions is under development for high energy acceleration. Measuring polarization levels of a high energy beam of polarized He-3 ions will be required for a more complete study of many spin dependent processes. In particular, this will facilitate investigations involving the spin of a down quark as the spin properties of helium-3 are not unlike those of a neutron. The successful use of electromagnetic hadronic interference in high energy proton polarimetry is examined in the context of a forthcoming polarized helium-3 beam that is planned to be accelerated in the AGS and in RHIC at Brookhaven National Laboratory. Its possible use in an electron ion collider eRHIC is also being considered. The copious carbon nuclei recoiling both left and right from scattering off a very thin carbon target provide a rapid and sensitive indication of the polarization of incident fermions apart from a scaling factor arising from unknown hadronic spin dependent effects. As in the proton case, a polarized helium-3 jet would fully calibrate a helium polarimeter. Though the greater hadronic total cross section of helium-3 carbon scattering reduces the optimal analyzing power by comparison with the proton case, the larger size of the anomalous magnetic moment of He-3 nuclei and the doubling of the electric charge compensate to some extent. Kinematic cuts will be necessary in the case of helium-3 to ensure that a sufficient proportion of elastic collisions have taken place when assessing the level of polarization. While some of the inelastic collisions involving helium-3 break-up and carbon nuclear excitation events may contribute usefully to an asymmetry measurement it is not expected that the majority will do so. Detailed study is required. Progress in developing sources and in the acceleration to high energies of both polarized down and up quarks will continue to advance the understanding of the fundamental interactions of quarks since their introduction fifty years ago.

XVth International Workshop on Polarized Sources, Targets, and Polarimetry
September 9 - 13, 2013
Charlottesville, Virginia, USA

*Speaker.

PoS(PSTP 2013)057

1. Introduction

It has been accepted that an enriched source of polarized down quarks is needed to more completely probe the spin structure of ions and nucleons [1]. Among the possible sources are polarized deuterons and helions. Deuterons are difficult to accelerate at high energies while maintaining their polarization due to the small size of the magnetic moment. Helium-3 nuclei on the other hand are much more suitable as the G factor is large, though negative. The spin of the paired protons does not contribute and the magnetic moment of a helion is close to that of its embedded neutron.

In anticipation of the advent of polarized He-3 ions there will be a need for a polarimeter at the high energies beyond the region where low energy polarimetry methods work well [2]. The spin program at RHIC requires that polarimeters should achieve 5% accuracy and operate over a wide energy range, that is, from 24 to 250 GeV for protons and from 16 to 160 GeV/nucleon for helions. Polarimeter calibration is frequently required at each energy as are beam polarization profiles and decay lifetimes during store. Measurements of polarization on the ramp and of bunch to bunch emittances are also needed.

The level of high energy helium-3 beam polarization may well be evaluated in a way similar to that used for high energy protons [3]. The more prominent Coulomb phase arising from two photon exchange effects serves to enhance the analyzing power. It is also altered by the finite nuclear size of helium-3, particularly for momentum transfers outside the interference region [4]. A polarized helium-3 source for the beams at RHIC is currently under development [5].

Hadronic spin-flip effects need to be known as they influence the accuracy of interference polarimetry [6]. A 100 GeV/c RHIC proton beam incident upon a polarized atomic hydrogen gas jet target for 4-momentum transfer squared $0.001 < -t < 0.032$ (GeV/c)^2 did not see any substantial hadronic elastic spin-flip amplitude [7]. The pp2pp experiment at STAR (BNL) has also shown that the elastic proton proton hadronic single helicity-flip amplitude is small at $\sqrt{s} = 200$ GeV [8] though one cannot assume that this is also true for elastic helium-3 collisions.

2. Proton polarimeters at high energy

The proton polarimeter at RHIC uses an ultra thin carbon ribbon with a 2 MHz event rate taken for a few minutes every few hours. It provides an online monitor, a fill by fill beam polarization measurement, polarization profiles, and requires calibration from H-jet data.

A polarized atomic hydrogen gas jet target self-calibrates the polarized proton beam by measuring a precise analyzing power $A_{\rm N}$ at each energy and angle. The H-jet polarimeter operates continuously with around a 20 Hz event rate providing better than 5% statisitics in a 6-hour fill at 250 GeV. It secures an absolute proton beam polarization measurement and additionally calibrates the faster proton carbon polarimeter.

Elastic strong interaction spin averaged and spin dependent amplitudes tend to be imaginary at high energy resulting in low polarizations. Electromagnetic ampiltudes are largely real suggesting that the use of a Primakoff or a Coulomb effect might be suitable for high energy polarimetry. Coulomb nuclear interference has proved more reliable in tests of the method at large energies [9].

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3. Optimum analyzing power of polarimeter

A spin half hadron of mass m, charge Ze, magnetic moment μ nuclear magnetons (based upon the proton mass m_p) scattering elastically off a charge $Z'e$ ion of any spin has an analyzing power A_N that has in its numerator an interference between helicity nonflip and flip amplitudes each with electromagnetic and hadronic elements involving a Coulomb phase δ, a hadronic non-flip real part ratio ρ and a hadronic helicity-flip ratio $R_\mathrm{S} + iI_\mathrm{S}$

$$2\,\mathrm{Im}\left[\frac{ZZ'}{137t}e^{i\delta} + (\rho+i)\frac{\sigma_\mathrm{tot}}{8\pi}\right]^* \frac{\kappa\sqrt{-t}}{2m_\mathrm{p}}\left[\frac{ZZ'}{137t}e^{i\delta} + (R_\mathrm{S}+iI_\mathrm{S})\frac{\sigma_\mathrm{tot}}{8\pi}\right]. \tag{3.1}$$

Omitted from the above amplitudes are electromagnetic form factors and a hadronic diffractive t dependence that introduce very small changes in the low $-t$ region here. The total hadronic cross section of the particles with charge Ze and $Z'e$ is σ_tot. Including the spin averaged denominator, the analyzing power as a function of t is proportional to

$$A_\mathrm{N} \propto \frac{\sqrt{x}}{x^2+3}, \qquad \text{where } x = \frac{t_\mathrm{e}}{t} \qquad \text{and } t_\mathrm{e} = -\frac{8\pi\sqrt{3}\,ZZ'}{137\,\sigma_\mathrm{tot}}, \tag{3.2}$$

the extremum value of which occurs at $x = 1$, that is, at momentum transfer $t = t_\mathrm{e}$. The optimum value is typically from 3 % to 4 % in size and varies slowly with energy s as $1/\sqrt{\sigma_\mathrm{tot}(s)}$. It is either a maximum or a minimum depending on the sign of a quantity κ where

$$A_\mathrm{N}^\mathrm{opt} = \frac{\kappa}{4m_\mathrm{p}}\sqrt{-3t_\mathrm{e}}, \qquad \kappa = \frac{\mu}{Z} - \frac{m_\mathrm{p}}{m}. \tag{3.3}$$

The value of κ for protons is $\kappa_\mathrm{p} = 1.793$, its anomalous magnetic moment in nuclear magnetons, and is $\kappa_\mathrm{h} = -1.398$ for helions, again in nuclear magnetons [11]. Hadronic helicity amplitude ratios and two photon exchange δ are ignored here. Quantities related to proton carbon collisions may be compared to those of the more familiar proton proton case with the same incident fermion

$$t_\mathrm{e}^\mathrm{pC}\Big/t_\mathrm{e}^\mathrm{pp} = 6\,\sigma_\mathrm{tot}^\mathrm{pp}\Big/\sigma_\mathrm{tot}^\mathrm{pC} \approx 0.74, \qquad A_\mathrm{N}^\mathrm{pC}\Big/A_\mathrm{N}^\mathrm{pp} = \left(t_\mathrm{e}^\mathrm{pC}\Big/t_\mathrm{e}^\mathrm{pp}\right)^{1/2} \approx 0.86 \tag{3.4}$$

and with distinct incident fermions, by contrast, helion carbon and proton carbon scattering have extremum momentum transfer and asymmetry ratios

$$t_\mathrm{e}^\mathrm{hC}\Big/t_\mathrm{e}^\mathrm{pC} = 2\,\sigma_\mathrm{tot}^\mathrm{pC}\Big/\sigma_\mathrm{tot}^\mathrm{hC} \approx 1.0, \qquad A_\mathrm{N}^\mathrm{hC}\Big/A_\mathrm{N}^\mathrm{pC} = \frac{\kappa_\mathrm{h}}{\kappa_\mathrm{p}}\left(t_\mathrm{e}^\mathrm{hC}\Big/t_\mathrm{e}^\mathrm{pC}\right)^{1/2} \approx -0.78 \tag{3.5}$$

the same being approximately true if the target carbon particle C in Eq. (3.5) were replaced throughout by another ion such as a proton p or a helion h. The extremum value t_e has first order corrections in the Bethe phase δ and the hadronic ratios ρ, R_S and I_S and would more accurately be

$$t_\mathrm{e}\left[1 - (\rho+\delta)/\sqrt{3} - (R_\mathrm{S} - \rho I_\mathrm{S})4/\sqrt{3} + \cdots\right]. \tag{3.6}$$

Another factor with small terms ρ, δ, R_S and I_S, multiplies the extremum of the analyzing power

$$A_\mathrm{N}^\mathrm{opt}\left[1 + (\rho+\delta)\sqrt{3}/2 - (\sqrt{3}R_\mathrm{S} + I_\mathrm{S}) + \cdots\right]. \tag{3.7}$$

Glauber finite size corrections provide a further factor [4] that appears to be unity for values of $-t$ below extremum at $-t_\mathrm{e}$ and increases approximately as $1 + 0.01\,(t - t_\mathrm{e})/t_\mathrm{e}$ for values of $-t$ above extremum at $-t_\mathrm{e}$ in the case of both helion and carbon targets.

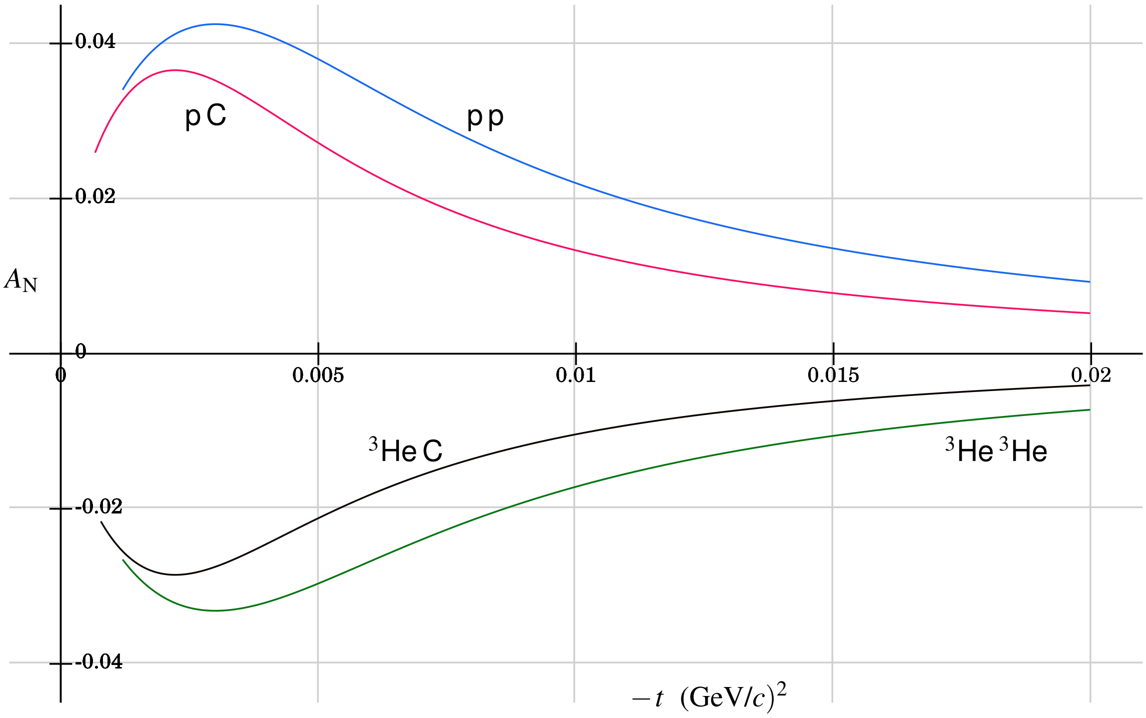

Figure 1: Analyzing power A_N versus the squared momentum transfer variable (-t) for the elastic scattering processes (from the top): (1) proton proton, (2) proton carbon, (3) helium-3 carbon, (4) helium-3 helium-3, assuming that $\sigma_{tot}(hC) = 2\,\sigma_{tot}(pC)$, that $\sigma_{tot}(hh) = 4\,\sigma_{tot}(pp)$, and that ρ, δ, R_S, I_S, and finite nuclear size effects are negligible.

4. Helium-3 jet polarimetry

Unpolarized helium-3 ions have been accelerated in the AGS at BNL (H. Huang *et al.*) [2]. The helion carbon cross section appears to be twice that for proton carbon scattering as expected from the factor $A^{2/3} = 3^{2/3} = 2.08$ and assuming that the helion carbon total cross section is twice the proton carbon total cross section it permits an estimate of the analyzing power for h-C scattering in the interference region. A_N is negative there due to the negative magnetic moment of the helion. Figure 1 shows the expected analyzing power for h-C scattering and h-h scattering in the absence of hadronic spin flip, Coulomb phase and nuclear finite size effects which have been discussed [6]. The kinematics of h-h collisions will be useful in studies of helium-3 jet polarimetry.

5. Kinematics and recoil angle

The analyzing power of elastic scattering in the interference region is reasobly well understood but inelastic channels are of concern as they have the potential to dilute measurements of the asymmetry. It may be important to arrange detectors so that elastic events are accepted while those inelastic events that make little contribution to the analyzing power are not counted. A study of inelastic kinematics may address the concern.

For an incident particle of mass m with laboratory energy E and laboratory momentum P producing an excited state of mass $m+\Delta m$ when scattering on a target of mass M, the laboratory recoil angle θ_4 of an excited state with mass $M+\Delta M$ and recoil kinetic energy T is given by the following expression, where $\varphi = \pi/2 - \theta_4$ is an angle measured from a perpendicular direction

$$\sin\varphi = \left[(E+M)(T+\Delta M) + \left(m+\tfrac{1}{2}\Delta m\right)\Delta m - \left(M+\tfrac{1}{2}\Delta M\right)\Delta M\right]\{T\,[T+2(M+\Delta M)]\}^{-1/2}/P.$$

In the case of inelastic collisions where Δm^2 and ΔM^2 may be neglected, the angle $\phi(T)$ has a minimum at recoil energy $T_\mathrm{m} \approx (m\Delta m + E\,\Delta M)\,/\,(E+M)$ to first order in excitation energies. The smallest value of T_m occurs when only the incident particle of mass m is excited for laboratory energies E such that $E > m\Delta m\,/\,\Delta M$ and this is almost always the case. With no target excitation, therefore, $T_\mathrm{m} \approx m\Delta m\,/\,(E+M)$. The acceptance of a detector could be arranged to avoid counting too many of the inelastic events that would correspond to a reduced asymmetry.

For example, production of $\mathrm{p}\pi^0$ from p-C scattering with $\Delta m = 135$ MeV occurs at smaller recoil angles than those corresponding to the break-up of carbon nuclei at $\Delta M = 7.3$ MeV for proton laboratory energies of $E > 17$ GeV. The break-up of ^{3}He from h-C scattering with $\Delta m = 7.7$ MeV is similarly more important than carbon excitation for incident helion energies of $E >$ 3 GeV. The recoil angle φ_el for elastic collisions and the approximate angle φ_inel for inelastic scattering with small T, small Δm, and no target excitation $\Delta M = 0$, are given by

$$\sin\varphi_\mathrm{el} = (E+M)\,(1+2M/T)^{-1/2}/P, \qquad \varphi_\mathrm{inel} \approx [\,(E+M)\,T + m\Delta m\,]\,[\,T(T+2M)\,]^{-1/2}/P$$

though multiple scattering of carbon nuclei as they exit the thin carbon ribbon target means that the formulæ are only approximate in practice. Figure 2 illustrates the recoil angles for elastic and inelastic proton carbon and helion carbon scattering at an energy of 150 GeV as a function of the recoil kinetic energy T in MeV. The helion energy would be 50 GeV/nucleon. Note that the gap in recoil angle between elastic and inelastic scattering decreases with increasing T according to

$$\varphi_\mathrm{inel} - \varphi_\mathrm{el} \approx m\Delta m\,[\,T(T+2M)\,]^{-1/2}/P, \qquad \varphi_\mathrm{inel}(T_\mathrm{m}) \approx [\,2\,(1+M/E)\,m\Delta m\,]^{1/2}/P, \qquad (5.1)$$

and that the minimum value of the recoil angle for inelastic collisions is as given here also. Inelastic collisions occuring beyond the angle $\varphi_\mathrm{inel}(T)$, a function of the recoil kinetic energy T above, may have a reduced analyzing power A_N that should be studied in detail for its effectiveness.

6. Conclusions

The availability of polarized down quarks facilitates study of hadronic spin structure. The ^{3}He–C analyzing power is $\approx -78\%$ of A_N for p-C in the high energy CNI region. The carbon recoil angle for h-C inelastic scattering is much less than that for protons though some inelastic collisions may contribute to the asymmetry of a relative polarimeter. A polarized helium-3 jet target permits helium-3 beam calibration. An enriched source of polarized down quarks is forthcoming.

Acknowledgments

N.H.B. is grateful to the organizers of PSTP2013 for their hospitality and for the invitation to speak at the Workshop. This work and presentation were part supported by the Research Executive Agency (REA) of the European Union (ITN STRONGnet).

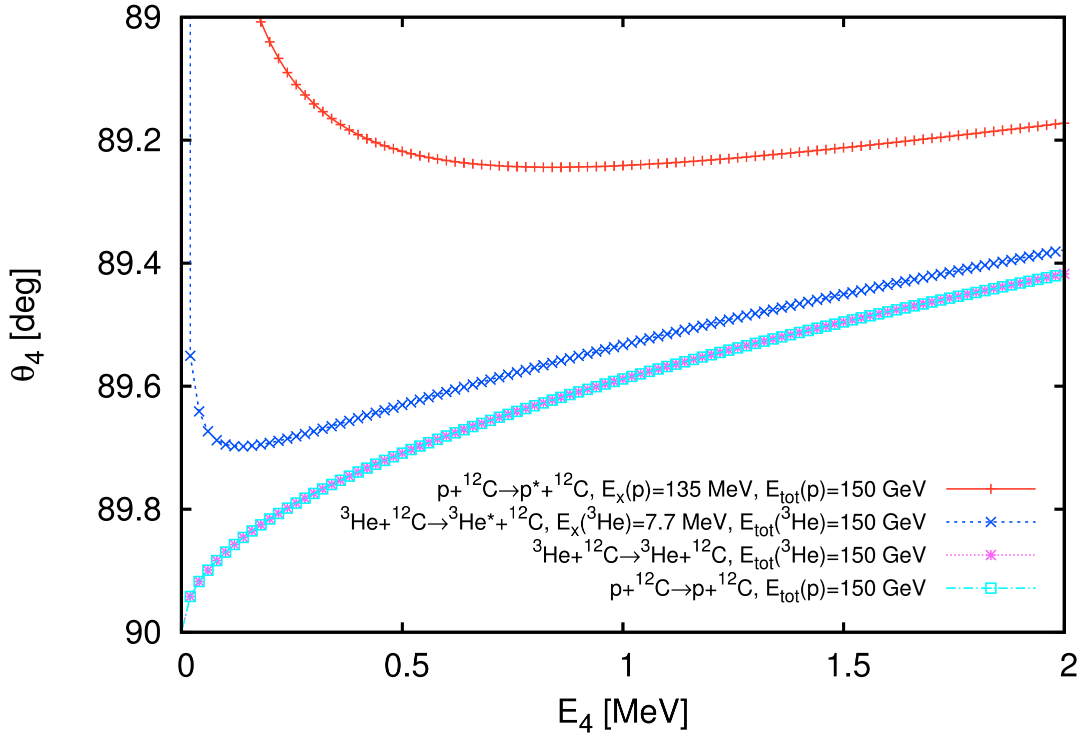

Figure 2: The laboratory angle θ_4 of a recoiling carbon nucleus versus its recoil kinetic energy E_4 for (from top) (1) a 150 GeV proton scattering to p π^0, (2) a helion of energy 50 GeV/nucleon scattering to break-up, (3) a helion of energy 50 GeV/nucleon scattering elastically, (4) a 150 GeV proton scattering elastically. Curves for the elastic scattering of helions and protons with the same energies are almost indistinguishable.

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