Forward Helion Scattering and Neutron Polarization

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Abstract. The elastic scattering of spin half helium-3 nuclei at small angles can show a sufficiently large analyzing power to enable the level of helion polarization to be evaluated. As the helion to a large extent inherits the polarization of its unpaired neutron the asymmetry observed in helion collisions can be transformed into a measurement of the polarization of its constituent neutron. Neutron polarimetry therefore relies upon understanding the spin dependence of the electromagnetic and hadronic interactions in the region of interference where there is an optimal analyzing power.

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INTRODUCTION

The spin polarized neutrons available from a polarized helium-3 beam would be very suitable for the study of polarized down quarks in various QCD processes particularly relating to transversity [1], nucleon spin structure [2], multi Pomeron exchange [3], gluon distributions [4], and additional dimensions [5]. Measuring the analyzing power in small angle elastic scattering of hadrons with spin provides an opportunity for evaluating the level of polarisation of incident helium-3 nuclei (helions) [6] thereby providing an effective neutron polarimeter [7].

Such a method relies upon an understanding of high energy spin dependence in diffractive processes [8]. Here, the interference of elastic hadronic and electromagnetic interactions in a suitable peripheral region enhances the size of the transverse spin asymmetry sufficiently to offer a tangible polarimeter for high energy helions. Polarimetry has been studied [7] in an approximation which emphasises the rôle of the neutron and the Glauber corrections that are required for a light nucleus such as helium-3.

The approach of this article assumes that the helion is a spin half fermion and expects that the polarization of the neutron may be inferred from that of the helion via an understanding of compositeness. Outside the interference domain of collision angles, hadronic analyzing powers tend to zero at high energies but the large anomalous magnetic moment of the helion induces a substantial peak in the asymmetry at interference.

The polarized proton programme at RHIC [9] has provided information on the energy dependence [10] of hadronic helicity flip amplitudes for protons scattering off hydrogen and carbon nuclei, particularly for single spin flip amplitudes [11]. Helium-4 targets have also been suggested for proton polarimetry [12]. Here the task relates to a study of the asymmetry induced by the low momentum transfer scattering of helium-3 collisions off proton, carbon or helion targets.

SINGLE SPIN ASYMMETRY

We discuss polarimetry for a beam of spin half helium-3 nuclei and draw comparisons with the similar proton case [13]. The normal single spin asymmetry $A_{\rm N}$ of a spin half hadron of mass m, charge Ze and magnetic moment μ nuclear magnetons (based upon the proton mass m_p) scattering elastically off a charge $Z'e$ ion of any spin has as numerator (β being the incident laboratory velocity)

$$-2\,\mathrm{Im}\left[\frac{ZZ'\alpha}{t}+i\,\frac{\beta\sigma_{\rm tot}}{8\pi}\right]\left[\left(\frac{Z}{m}-\frac{\mu}{m_p}\right)\frac{Z'\alpha}{2\sqrt{-t}}+\text{hadronic spin-flip term}\right]^*, \qquad (1)$$

that is, interference of helicity nonflip and flip amplitudes each with electromagnetic and hadronic elements. The total hadronic cross section of the particles of charge Ze and $Z'e$ is $\sigma_{\rm tot}$. An explanation of the factor $(\mu/m_{\rm p}-Z/m)$ appears in the next section. Including the spin averaged denominator, the asymmetry is approximately given by

$$A_{\rm N} \;=\; \frac{Z'}{|ZZ'|}\left(\frac{\mu}{m_{\rm p}}-\frac{Z}{m}\right)\left(-3t_{\rm opt}\right)^{1/2}\frac{\sqrt{x}}{x^2+3} \qquad (2)$$

where contributions from the following have been neglected for simplicity, namely, hadronic helicity flip amplitudes, the nonflip real part at high energy, a Coulomb-Bethe phase shift, hadronic diffractive and form factor t dependences. Observe also that the ratio of purely electromagnetic flip to nonflip amplitudes is about 3%, that is, approximately 0.1% for the squared amplitudes that appear in the spin averaged denominator. Inclusion of such neglected terms has been detailed elsewhere [8]. Given

$$x \;=\; t_{\rm opt}/t\,, \qquad t_{\rm opt} \;=\; -8\sqrt{3}\pi\alpha\left|ZZ'\right|/\beta\sigma_{\rm tot}\,, \qquad (3)$$

the extremum of Eq. 1 occurs at $x=1$, that is, at $t=t_{\rm opt}$. The transverse asymmetry thus has an optimum value, either a maximum or minimum depending on its overall sign, at invariant momentum transfer $t_{\rm opt}$. To incude the possibility of an incident (or target) antiproton [14], or other hadronic antiparticle, the signs of Z and Z' have not been assumed to be positive in the following expression for an optimum analysing power

$$A_{\rm N}^{\rm opt} \;=\; \frac{Z'}{4|ZZ'|}\left(\frac{\mu}{m_{\rm p}}-\frac{Z}{m}\right)\sqrt{-3t_{\rm opt}}\,. \qquad (4)$$

The ratio of the asymmetry extrema for helions with $Z=2$ (magnetic moment $\mu_{\rm h}$) and protons with $Z=1$ (magnetic moment $\mu_{\rm p}$) scattering off the same nucleus with charge $Z'e$ is

$$\frac{A_{\rm h}^{\rm opt}}{A_{\rm p}^{\rm opt}} \;=\; \frac{\mu_{\rm h}/Z-m_{\rm p}/m_{\rm h}}{\mu_{\rm p}-1}\sqrt{\frac{Z\,\sigma_{\rm tot}^{\rm p}}{\sigma_{\rm tot}^{\rm h}}} \;=\; -1.1026\sqrt{\frac{\sigma_{\rm tot}^{\rm p}}{\sigma_{\rm tot}^{\rm h}}} \qquad (5)$$

for high energy polarized helions or protons scattering elastically. The helion proton mass ratio is $m_{\rm h}/m_{\rm p}=2.99315$; the magnetic moments $\mu_{\rm p}=2.79285$ and $\mu_{\rm h}=-2.1275$ of the proton and helion are in nuclear magnetons.

HELION ANOMALOUS MAGNETIC MOMENT

The negative magnetic moment of the helion indicates that the optimum asymmetry corresponds to a minimum in contrast to the maximum observed in the case of protons. Given that the total cross section for helion scattering is approximately three times that for proton collisions, with a small reduction for nuclear shadowing, it may be concluded that, but for sign, the size of the helion analyzing power is a substantial fraction of the proton asymmetry seen in the electromagnetic hadronic interference region.

The anomalous magnetic moment factor appearing in Eq. 1, $(\mu/m_{\rm p} - Z/m)$, arises from a study of the electromagnetic current for a fermion of mass m, charge $q = Ze$ and spin half. The current matrix element with initial and final four momenta p_μ and p'_μ can be written

$$\bar{u}' \left\{ \left(p' + p \right)^\mu F_1 \; - \; \tfrac{1}{2} \left[\gamma^\mu , \gamma^\nu \right] \left(p' - p \right)_\nu G_{\rm M} \right\} u / 2m \tag{6}$$

where the electromagnetic form factors $F_1(t)$ and $G_{\rm M}(t)/(2m)$, with metric tensor diag $(1, -1, -1, -1)$ and invariant momentum transfer variable $t = (p' - p)_\mu (p' - p)^\mu$, have static values equal to the charge and magnetic moment of the fermion

$$F_1(0) = q \, , \qquad G_{\rm M}(0)/2m = \mu' = \mu \, e/2m_{\rm p} \tag{7}$$

noting here that the magnetic moment μ' is normally quoted as μ in nuclear magnetons involving the mass $m_{\rm p}$ of the proton. Another expression for the current uses $F_1(t)$ and $F_2(t)$

$$\bar{u}' \left\{ \gamma^\mu F_1 - \tfrac{1}{4m} \left[\gamma^\mu , \gamma^\nu \right] (p' - p)_\nu F_2 \right\} u \tag{8}$$

where the Sachs magnetic form factor is expressed as $G_{\rm M}(t) = F_1(t) + F_2(t)$ so that the fermion with charge $q = Ze$ has the anomalous magnetic moment that occurs in Eq. 1

$$\frac{F_2(0)}{2m} \; = \; \mu' - \frac{q}{2m} \; = \; \frac{e}{2} \left(\frac{\mu}{m_p} - \frac{Z}{m} \right) . \tag{9}$$

In the absence of anomaly, the Dirac magnetic moment is $q/2m$, or Zm_p/m magnetons. For the case of the proton with $m = m_{\rm p}$ and $\mu = \mu_{\rm p}$, the anomalous magnetic moment reverts to a form $(\mu - 1) \, e/2m_{\rm p}$ involving the nuclear magneton as a factor.

It appears then that helium-3 scattering on, for example, carbon nuclei can provide a relative helion polarimeter. The inelastic channels for helion carbon collisions require study as there are many more such processes in contrast with the case of proton carbon scattering that has been successfully employed [15]. The cross sections for inelastic helion carbon collisions are not expected, however, to dilute the analyzing power to any great extent and would appear as a factor in a relative polarimetry measurement.

Calibration of the relative polarimeter could use a polarized helion beam scattering on a helion jet target and its time reversed process involving a polarized helion jet. The scattering could also be off a proton jet target with the time reversed process involving a proton beam and a polarized helion jet target. Non-identical spin half fermion fermion elastic scattering has been well studied [13] and cross sections [16] and helicity amplitudes [17] for single photon exchange processes are available.

CONCLUSIONS

Spin dependent collisions involving polarized down quarks are expected to provide increasingly stringent tests of QCD. The polarized neutrons embedded in a beam of spin polarized helium-3 nuclei offer a way of arranging a polarized down quark probe. The optimal analyzing power for helions scattering elastically off appropriate charged nuclei in the electromagnetic hadronic interference region of momentum transfer is sufficient to act as a method of polarimetry for a helion beam. The polarization of the unpaired neutron, and hence of the constituent down quark, can then be evaluated using techniques of the kind introduced by Glauber and others.

Absolute calibration of the helion polarimeter requires study of the time reversed collisions involving a polarized helion jet target, similar in many ways to the proton case but for the possible complication of a greater number of helion nucleus inelastic channels. Further theoretical insights may follow from studying the analytic structure of forward spin dependent amplitudes for helion processes [18], including sum rules involving magnetic moments [19]. A programme utilising polarized helions and neutrons will hopefully lead to a deeper understanding of diffractive spin dynamics.

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