Polarizing Helium-3 for down quark spin enrichment

Nigel Buttimore

Trinity College Dublin

12 September 2012

OUTLINE

Introduction to the spin structure of polarized protons and neutrons

- Asymmetry from spin dependence in diffractive elastic scattering
  - offers a method of evaluating the level of hadronic polarization
- Intense beam of polarized neutrons from polarized helium-3 nuclei
  - provides a richer source of polarized down quarks for a spin study

Outlook for measuring helium-3 beam and neutron polarization levels.

NUCLEON HELICTY IN QCD

A stationary nucleon comprising various partons has angular momentum

$$\sum_{\text{flavour}} \langle\, P,\, S_3 = \tfrac{1}{2}\,|\, J_{\rm f}^3 \,|\, P,\, S_3 = \tfrac{1}{2}\,\rangle \quad = \quad \frac{1}{2}$$

with quark, antiquark, gluon and orbital angular momentum elements.

- The ith component of quark angular momentum operator is (Qiu 2009)

$$J_q^i \quad = \quad \int d^3x\, \psi_q^\dagger \left[\gamma^i\gamma_5 \,-\, i\,\epsilon^{ijk} x^j D^k\right] \psi_q$$

- The ith gluon angular momentum operator in QCD has element (Ji)

$$J_g^i \quad = \quad \int d^3x \, \epsilon^{ijk} \, \epsilon^{klm} \, T^{0l} \, x^m$$

with a cross product of a $\nu = 0$ momentum tensor $T^{\nu\lambda}$ and location x^μ

A positive helicity state nucleon is described by helicity PDFs at scale Q

$$\Delta f_j(x, Q^2) \; = \; f_j^{\rightarrow}(x, Q^2) \, - \, f_j^{\leftarrow}(x, Q^2)$$

involving partons of type j with positive ($\rightarrow$) and negative ($\leftarrow$) helicity.

- The contribution of valence and sea quarks to the nucleon helicity is

$$\Delta\Sigma \quad = \quad \int_0^1 dx \sum_{\text{flavour}} \left[\, \Delta q_f(x) \;+\; \Delta\bar{q}_f(x) \,\right]$$

  the quark having light-cone momentum fraction x of the nucleon's.

Such integrals may be found from measured double spin asymmetries

$$A_{\mathrm{LL}} \quad = \quad \frac{d\Delta\sigma}{d\sigma} \quad = \quad \frac{d\sigma_{\rightrightarrows} \;-\; d\sigma_{\rightleftarrows}}{d\sigma_{\rightrightarrows} \;+\; d\sigma_{\rightleftarrows}}$$

A sum over initial partons yields the polarised cross section difference

$$d\,\Delta\sigma \;=\; \int dx\,\Delta q(x) \int dx'\,\Delta g(x')\; d\,\Delta\hat{\sigma}_{qg} \;+\; \mathcal{O}(\alpha_S^2) \;+\; \mathcal{O}(p_T^{-1})$$

EMC, SMC, COMPASS, E1 . ., HERMES, HALL-A, CLAS, PHENIX, STAR

- Flavour distributions result from Semi-Inclusive DIS, $l\,N \;\to l\,h\,X$

A next to leading order QCD global analysis of asymmetry data reveals

$$\begin{aligned} \Delta u \,+\, \Delta\bar{u} &= 81\,\% \\ \Delta d \,+\, \Delta\bar{d} &= -46\,\% \\ \Delta g &= -\;8\,\% \end{aligned} \qquad\qquad \begin{aligned} \Delta\bar{u} &= 4\,\% \\ \Delta\bar{d} &= -11\,\% \\ \Delta\bar{s} &= -\;6\,\% \end{aligned}$$

Surprisingly, quarks and antiquarks only contribute 24 % to proton spin and gluons only $-8\,\%$

de Florian, Sassot, Stratmann, Vogelsang (Phys Rev Lett, 2008)

Evaluating levels of helium-3 beam polarisation at high energy is needed.

Hadronic polarisations tend to vanish at higher collision energies making the measurement of the level of nucleon polarization a challenging problem.

A source of neutrons with oriented spin may be available for eRHIC in the form of polarized helium-3 nuclei which, being charged, are candidates for electromagnetic hadronic interference polarimetry

T L Trueman, AIP Conf Proc 980 (2008) 403

- Spin asymmetries have provided spin dependent couplings of the Pomeron

  T L Trueman, Phys Rev D77 (2008) 054005

- Constraints on leptophobic gauge bosons can follow from using polarized neutrons at RHIC

  P Taxil et al, Eur Phys J C **24** (2002) 149

Polarimetry for a high energy helium-3 beam is not unlike that for protons.

INCIDENT HADRON POLARISATION ?

The RHIC accelerator is opening up a new frontier in hadronic spin studies

- its polarized beams provide a new range of tests of the Standard Model
- the detailed partonic structure of the nucleon and of ions will emerge

The polarized reaction $\mathrm{h\,h}\!\uparrow \rightarrow \mathrm{h\,h}$ provides the h absolute analyzing power

- a helion jet of known polarization will calibrate the analyzing power
- a very thin carbon fixed target serves as a relative helion polarimeter

A relative polarimeter acts promptly having been calibrated by a He-3 jet

A polarimeter requires a process with nonvanishing high energy polarization

- Spin one photon exchange suggests the Primakoff or a Coulomb effect
- Electromagnetic hadronic interference has proved more reliable in tests
- Helion ion scattering has about -3% asymmetry in the interference region

A spin half hadron of mass m, charge Ze, magnetic moment μ scattering elastically off a charge $Z'e$ has an asymmetry that involves an interference

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

of helicity nonflip & flip amplitudes with electromagnetic & hadronic parts.

Including the spin averaged denominator, the asymmetry is proportional to

$$A_{\mathrm{N}} \;\propto\; \frac{\sqrt{x}}{x^2+3}\,, \qquad x \;=\; \frac{t_{\mathrm{opt}}}{t}\,, \qquad t_{\mathrm{opt}} \;=\; -\,\frac{8\sqrt{3}}{\sigma_{\mathrm{tot}}}\,\pi\alpha\,|Z\,Z'|$$

the optimum value of which occurs at $x = 1$, that is, at transfer $t = t_{\mathrm{opt}}$.

- The optimum value varies slowly with squared energy s as $1/\sqrt{\sigma_{\mathrm{tot}}(s)}$
- It is either a maximum or minimum depending on the sign of a term in

$$A_{\mathrm{N}}^{\mathrm{opt}} \;=\; \frac{1}{4Z}\left(\frac{\mu}{m_{\mathrm{p}}} - \frac{Z}{m}\right)\sqrt{-3\,t_{\mathrm{opt}}}$$

Hadronic helicity flip amplitudes and two photon exchange are ignored here.

Hadronic spin flip and Coulomb phase effects have been treated in detail in

NB, Kopeliovich, Leader, Soffer, Trueman, Phys Rev D59 (1999) 114010

W Guryn and the STAR Collaboration at BNL have recently shown that the

- elastic pp hadronic helicity flip amplitude is negligible at $\sqrt{s} = 200$ GeV

  L. Adamczyk *et al.* [STAR Collaboration], arXiv:1206.1928 [nucl-ex]

- one cannot assume that this is also true for elastic helium-3 collisions.

W W MacKay discusses helium-3 acceleration in C-A/AP/# 296 (2007)

`http://www.rhichome.bnl.gov/AP/ap_notes/ap_note_296.pdf`

Helium-3 ions have recently been accelerated to 11 GeV in the AGS at BNL
It appears that the helion Carbon cross section is twice that of proton C.

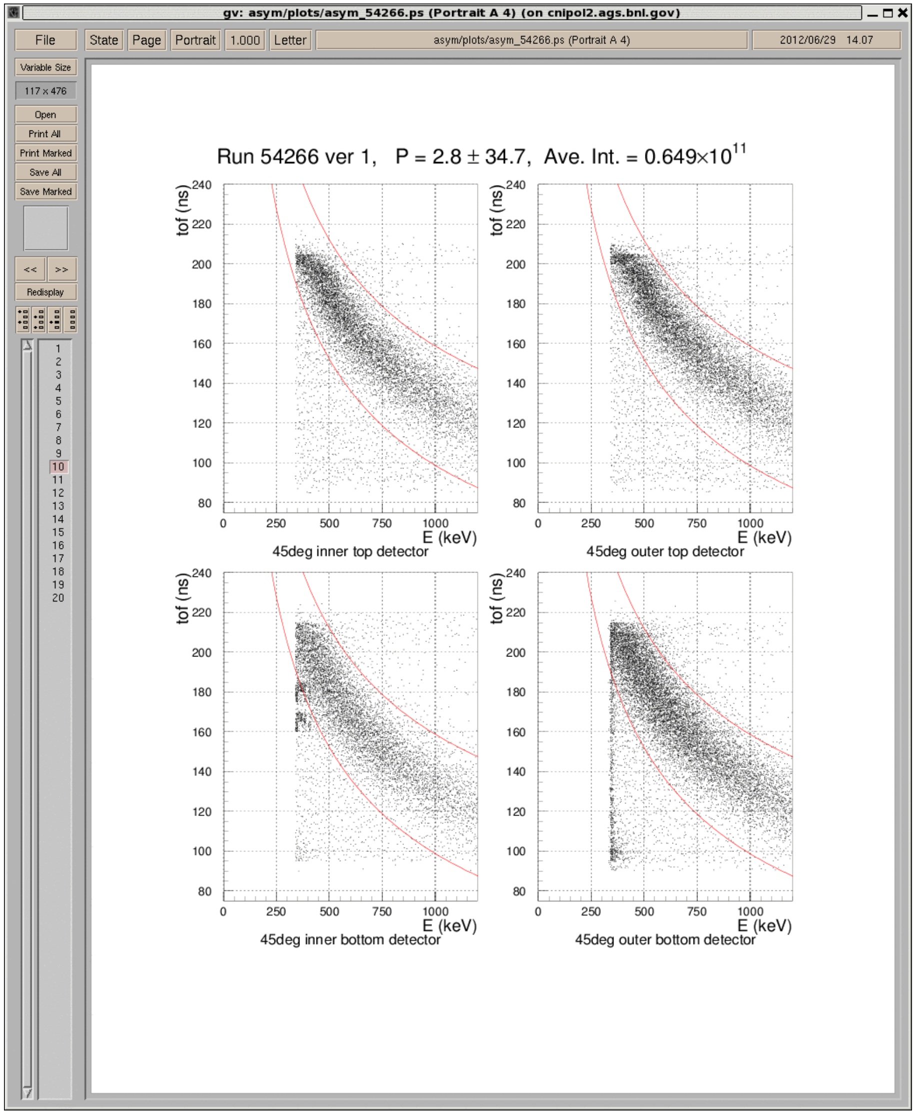

Figure 1: Time of flight of carbon recoiling from helium-3 versus its recoil kinetic energy.

The ratio of the asymmetry extrema for polarised helions and protons is

$$\frac{A_{\rm h}^{\rm opt}}{A_{\rm p}^{\rm opt}} \quad = \quad \frac{\mu_{\rm h}/Z - m_{\rm p}/m_{\rm h}}{\mu_{\rm p} - 1}\sqrt{\frac{Z\sigma_{\rm tot}^{\rm p}}{\sigma_{\rm tot}^{\rm h}}} \quad = \quad -\,0.780\,\sqrt{\frac{2\,\sigma_{\rm tot}^{\rm p}}{\sigma_{\rm tot}^{\rm h}}}$$

when a spin half proton or helion scatters elastically on a carbon ribbon.

The mass ratio & magnetic moments of the proton and helium-3 nuclei are

$$m_{\rm h}/m_{\rm p} = 2.99315, \qquad \mu_{\rm p} = 2.79285, \qquad \mu_{\rm h} = -2.1275$$

so the negative magnetic moment of the helion indicates that the optimum asymmetry corresponds to a minimum in contrast to the proton's maximum

A study that includes finite size nuclear effects and hadronic real parts is

B Z Kopeliovich and T L Trueman, Phys Rev D **64** (2001) 034004

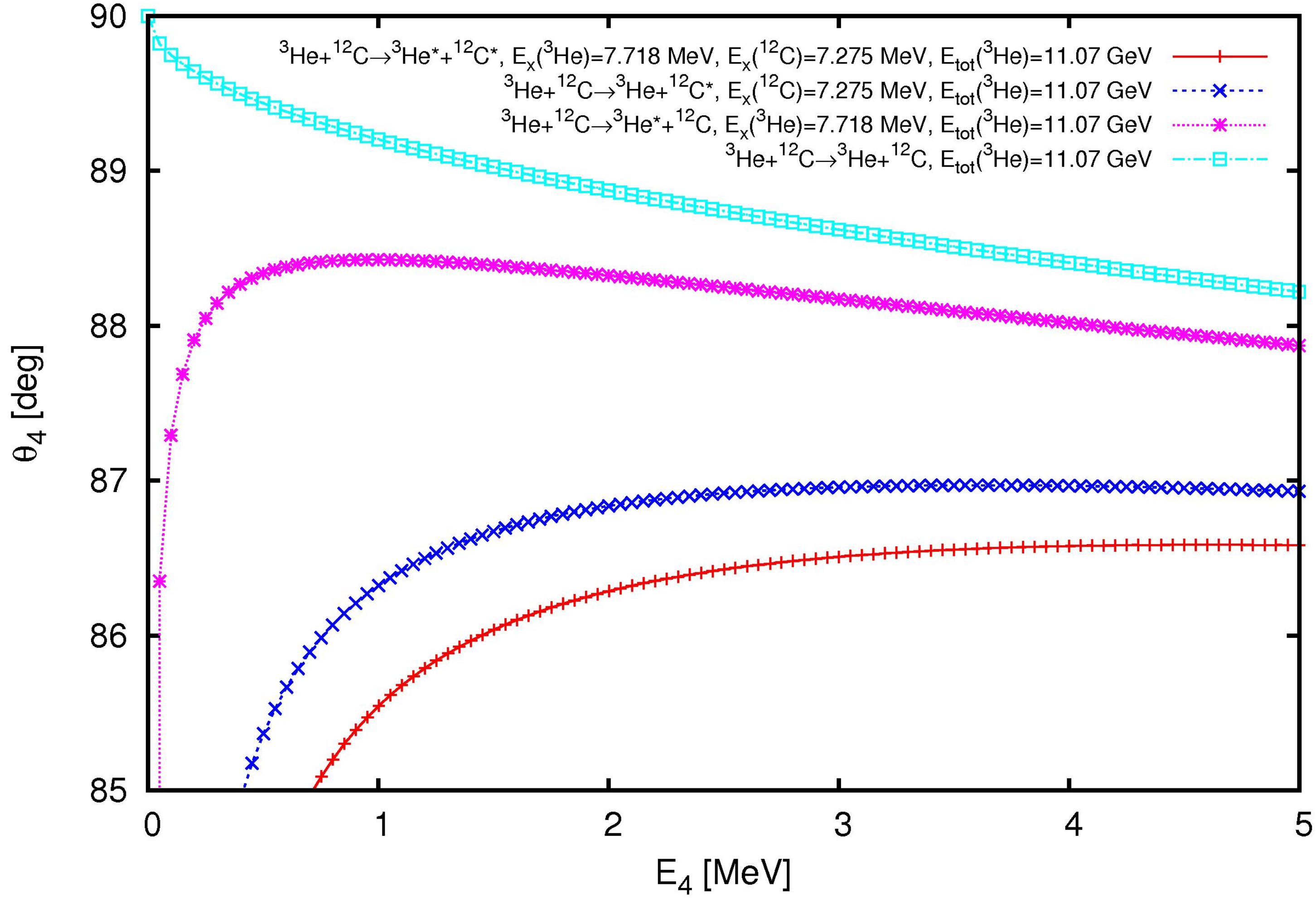

Figure 2: Carbon laboratory recoil angle versus its recoil kinetic energy for an incident helium-3 beam scattering (in)elastically to helion (break-up) or carbon (break-up) or both.

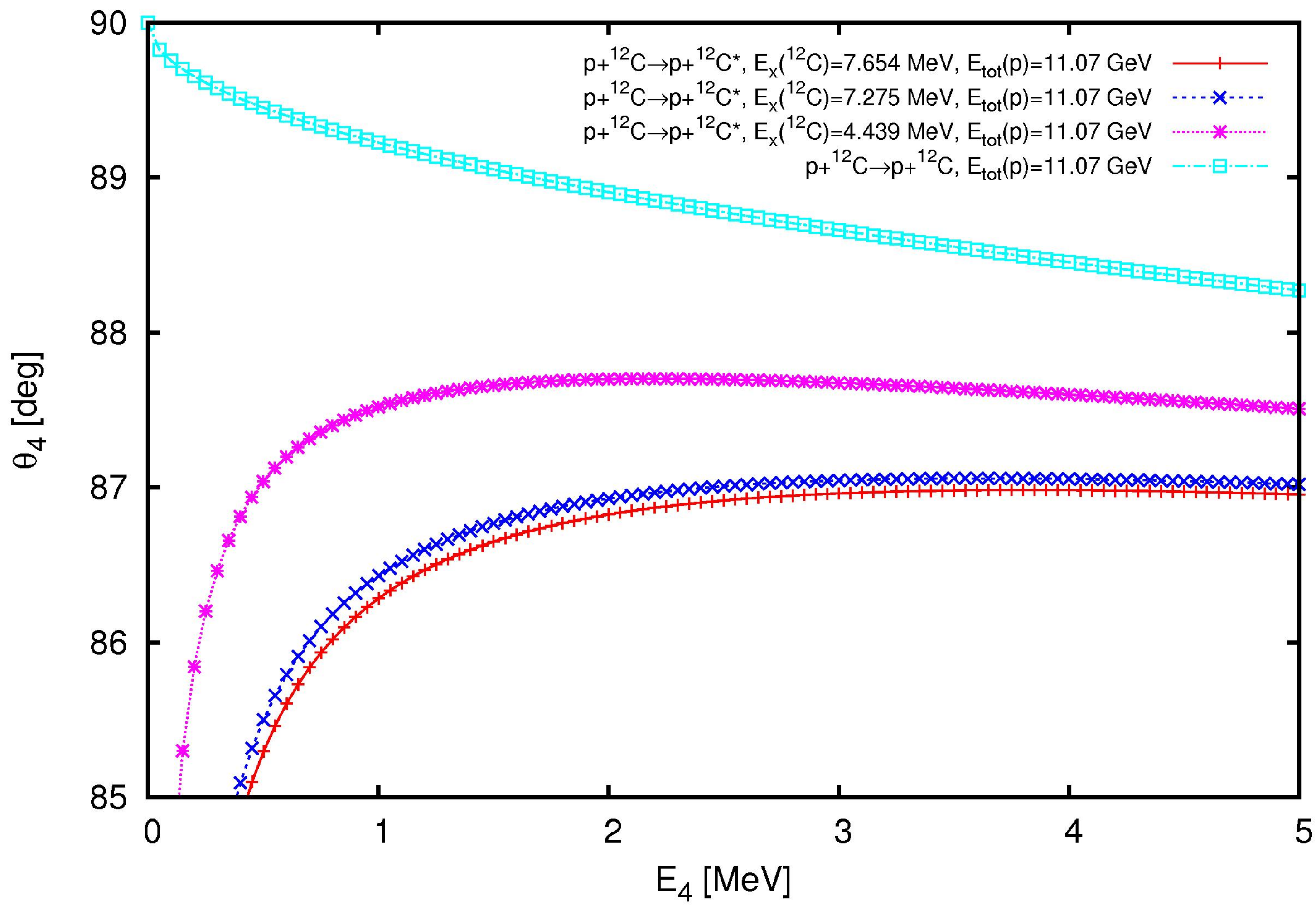

Figure 3: Carbon laboratory recoil angle versus its recoil kinetic energy for an incident proton beam scattering (in)elastically to a carbon ground state (and excited nuclear states).

CONCLUSIONS

The spin structure of the nucleon probes QCD in interesting ways

- Spin structure functions of the neutron are set to improve
  - measuring proton polarization levels is gaining ground
- Helium-3 (and neutron) polarization levels may be forthcoming
  - finding a beam containing polarized down quarks is challenging

There is great potential for studies requiring polarized down quarks.