High Energy Light Ion Polarimetry

Nigel Buttimore

Trinity College Dublin

Ireland

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OUTLINE

- Understanding the spin structure of nuclei needs polarized up and down quarks
- Polarized down quarks are embedded in the polarized light ions ^{1}H, ^{2}H and ^{3}He

- Anomalous magnetic moment parameters for protons, deuterons, and helions
- Absolute and relative polarimetry from nuclei and light ion beams and targets

MAGNETIC MOMENTS

Introduce a parameter κ of an incident ion of mass m, charge Ze, spin J, and magnetic moment μ (in nuclear magneton units of $e/2m_p$) in terms of its G factor (with m_p as proton mass): W W MacKay, AIP Conference Proceedings 980, 191 (2008)

$$\frac{\kappa}{2m_p} = \frac{GJ}{m}, \qquad \text{that is,} \qquad \kappa = \frac{\mu}{Z} - \frac{2Jm_p}{m}.$$

For a proton where $m = m_p$, the anomalous magnetic moment will be $\kappa_p = \mu_p - 1$. An explanation of the more general expression for κ in the case of a spin half hadron is provided in Diffraction 2008: NB, AIP Conf Proc 1105, 189 (2009)

$$\kappa' = \kappa - 4Jm_p\frac{m}{s}, \qquad \text{that is,} \qquad \kappa' = \frac{\mu}{Z} - 2Jm_p\left(\frac{1}{m} + \frac{2m}{s}\right).$$

A study of the single helicity flip amplitude for spin-$\frac{1}{2}$ spin-$\frac{1}{2}$ elastic scattering due to one photon exchange indicates that κ' should replace κ because of the accuracy of new asymmetry measurements: NB, E Gotsman, E Leader, Phys Rev D 18, 694 (1978)

In the correction term, it is sufficiently accurate to approximate the flux factor $\sqrt{[\,s^2 - 2\,(m^2 + \widetilde{m}^2)\,s + (m^2 - \widetilde{m}^2)^2\,]}$ by s for the collision of particles of mass m & $\widetilde{m}$: AA Poblaguev et al, Phys Rev Lett 123, 162001 (2019), Phys Rev D 100, 116017 (2019)

For proton (p) and helion (h) scattering the values of κ_p and κ_h, from above, are:

$$\kappa'_p + \frac{2m_p^2}{s} = \mu_p - 1 = 1.793\,, \qquad \kappa'_h + \frac{2m_p\,m_h}{s} = \frac{\mu_h}{2} - \frac{m_p}{m_h} = -1.398$$

For deuterons of mass m_d scattering off a spin 0 nucleus, the single helicity flip electromagnetic amplitude for spin-1 spin-0 elastic collisions due to one photon exchange indicates that NB and TL Trueman, World Scientific (SPIN 2004) 706

$$\kappa'_d = \kappa_d - \frac{4m_p\,m_d}{s} \quad \text{where} \quad \kappa_d = \mu_d - \frac{2m_p}{m_d} = -0.143$$

In the case of deuterons scattering on a spin half hadron, the single helicity flip one photon exchange amplitude for spin-1 spin-1/2 elastic collisions also confirms the above expression for κ'_d NB, SPIN 2002, AIP Conf Proc 675, 841 (2003)

POLARIMETERS AT EIC

- Any nuclear target, of charge Z say, can act as a relative polarized light ion beam polarimeter. G Igo and I Tanihata, SPIN 2002, AIP Conf Proc 675, 836 (2003)

$$[\sigma_{\rm tot}(s)]^{1/2} A_{\rm N}^{\rm m} \propto Z^{1/2}$$

  Given the above error, using a nuclear target of higher charge Z has benefits. The mass M of the recoiling nucleus, however, should be such that its kinetic energy $-t_c\,/\,2\,M$ remains above the 20 keV sensitivity threshold of a detector.

- If a beam of the above target nuclei is also available then absolute polarimetry is possible via separate measurement of scattering on polarized light ion jets. Comparison with the time-reversed collision of a polarized light ion beam on the nuclear target provides absolute ion polarization up to $E = 275\,Z/A$ (GeV/n).

- For a $^{12}_{6}$C beam and target, absolute polarimetry would be possible up to 137 GeV/n, while for $^{40}_{18}$Ar, energies per nucleon of 123 GeV/n could be reached. Inelastic nuclear states of ^{12}C and of ^{40}Ar require study to ensure accuracy here.

- For a ^{1}H beam and target, absolute polarimetry is available up to 275 GeV. Inelastic scattering should be more manageable using (unpolarized) hydrogen. For a ^{2}H beam and target, absolute polarimetry is measurable up to 137 GeV/n.

- In the case of a polarized ^{3}He beam scattering on an unpolarized ^{3}He jet, absolute polarimetry is possible by comparison with the time-reversed process of an unpolarized ^{3}He beam colliding with a polarized ^{3}He jet of known polarization.

A polarized atomic He-3 jet target would self-calibrate a polarized He-3 beam by measuring a precise analyzing power A_{N} at each energy and momentum transfer. The same would be true for an (un)polarized deuteron beam and ^{2}H($\uparrow$) jet target

- Alternatives to the use of carbon as a relative polarimeter (with its possible thermal difficulties) could be a jet of atomic Hydrogen, Neon, or Argon, for which the rate per atom would change by a factor $(Z/6)^{1/2}$, about 29% better for ^{20}Ne and around 73% for ^{40}Ar. Recoil energies are acceptable for detection.

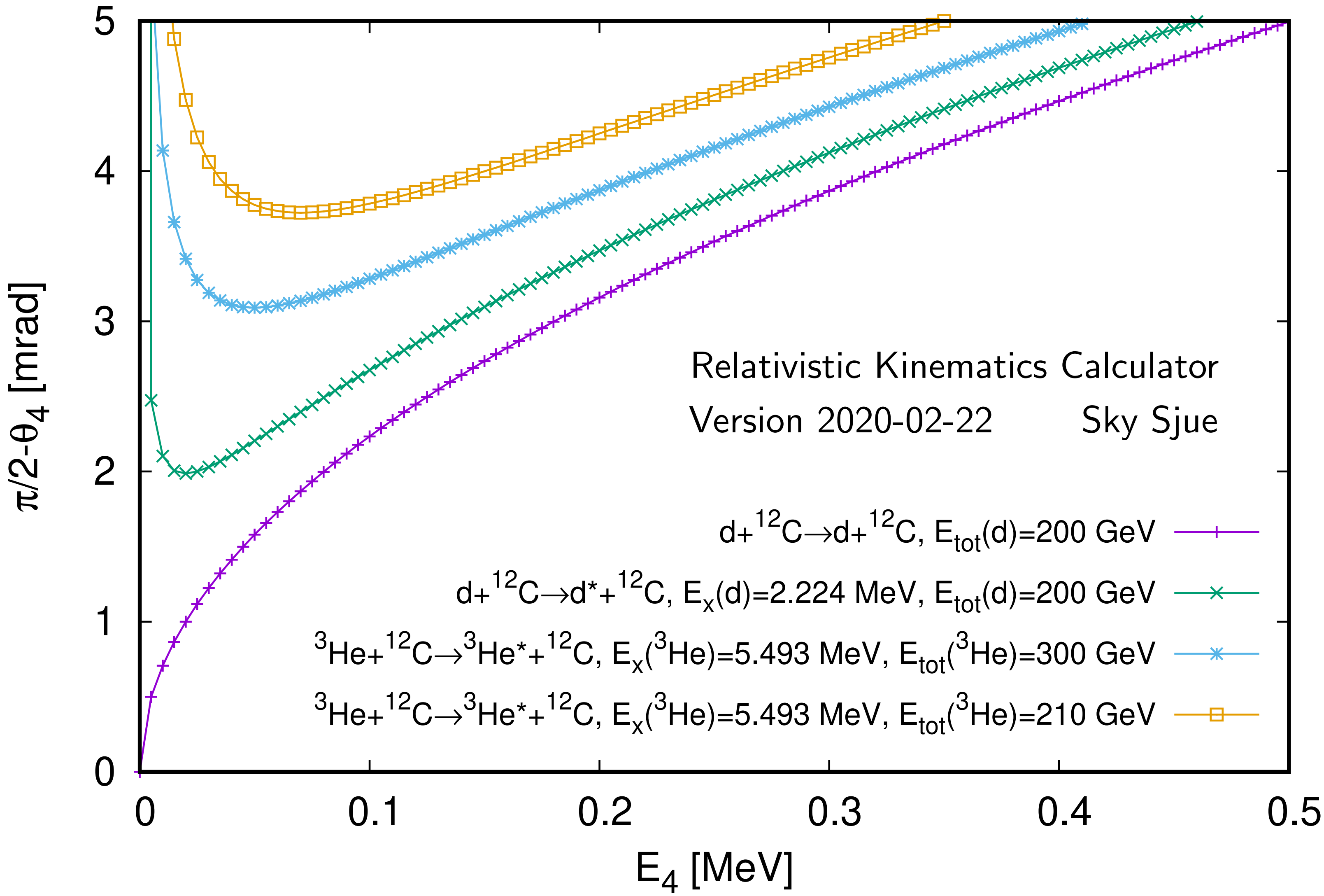

Figure 1: Complementary recoil angle versus recoil kinetic energy $T_R = E_4$ for, from top, (below legend), (1) h–C $\rightarrow$ [p+d]–C at 70 GeV/n, (2) h–C $\rightarrow$ [p+d]–C at 100 GeV/n, (3) d–C $\rightarrow$ [p+n]–C at 100 GeV/n, (4) d–C and h–C elastic ($\approx$ same) at 100 GeV/n.

INELASTIC KINEMATICS

Excited states of the incident mass m, $(+\Delta m)$, are more important than those of the target mass M, $(+\Delta M)$, for laboratory energies per nucleon, E, such that

$$E \quad > \quad \Delta m \, / \, \Delta M$$

For pC scattering with $\Delta m = 135$ MeV $(+\pi^0)$ and $\Delta M = 7.3$ MeV, $E > 19$ GeV

For hC scattering with $\Delta m = 5.5$ MeV (p+d) and $\Delta M = 7.3$ MeV, $E > 0.8$ GeV

For high energy per nucleon, E, of the incident particle on a target of mass M, the recoil angle $\phi_{\rm el} \approx v/2c$ for elastic scattering, measured from $90^{\rm o}$, is in radians

$$\phi_{\rm el} \;\approx\; \sqrt{\frac{T}{2\,M}}\,, \qquad \Delta\phi \;\approx\; \frac{\Delta m}{E\,\sqrt{2\,M\,T}}$$

Inelastic collisions occur beyond the angle $\phi_{\rm el} + \Delta\phi$, a function of the recoil kinetic energy $T = -t\,/\,2M$ above, where the analyzing power $A_{\rm N}$ may become diluted.

CONCLUSIONS

Studying the spin structure of hadrons with polarized leptons and polarized ions greatly increases the understanding of QCD interactions involving quarks & gluons

- The anomalous magnetic moment parameters of protons, deuterons, and helions need small energy dependent corrections when considering light ion polarimetry

  –> A nucleus available as beam and target is useful for absolute polarimetry.
  –> The nuclei could be protons, deuterons, helions, carbon, neon, argon, . . .
  –> Nuclei should be light enough to facilitate detection above the noise level.

- The ^{3}He–C analyzing power is $\approx -70\%$ of the A_{N} for p–C in the CNI region .

  –> A_{N} for vector polarized d–C is $\approx 10\%$ of A_{N} for CNI ^{3}He–C scattering

There is great potential for QCD studies employing polarized quarks and leptons.

BACKUP

References

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[3] NB and T. L. Trueman, "Deuteron polarization determination at high energies," 16th International Spin Physics Symposium (SPIN 2004), 706-709

[4] NB, "Forward helion scattering and neutron polarization," AIP Conf. Proc. **1105**, no.1, 189-192 (2009) doi:10.1063/1.3122170