Light ion polarimetry at high energy

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OUTLINE

- Polarized up and down quarks are needed to probe nuclear spin structure
- The polarized quarks in neutrons are embedded within polarized light ions
- Coulomb interference polarizes neutrons — J Schwinger 1946 and 1948

  –> If $q_c = 4\pi\,\alpha\,\mu_n/m_p\,\sigma_{\rm tot}$ (μ_n is magnetic moment of neutron)

  –> $A_{\rm N} \approx 2\,\mathrm{Im}\,[\,(\,i+\rho\,)^*\,(-\,q_c\,/q\,)\,]\,/\,(\,|\,i+\rho\,|^2 + |-q_c\,/q\,|^2\,)$
- Maximum analyzing power is $1/\sqrt{1+\rho^2}$ at transfer $q = q_c\,/\sqrt{1+\rho^2}$
- Improved treatment of the Coulomb phase for higher charges, Z and $\widehat{Z}$
- Application to 3He-p, 3He-3He, p-12C, & 3He-12C CNI elastic scattering

HELICITY AMPLITUDES

A light ion of mass m, charge Ze, EM form factors $F_1(t)$, $F_2(t)$, total CM energy $\sqrt{s}$, scattering on a target $[\widetilde{m},\ \widetilde{Z}e,\ \widetilde{F}(t)]$, with hadronic real to imaginary ratio ρ and slope B, has amplitude Kopeliovich and Lapidus, Yad Fiz 19, 218 (1974)

$$(\rho + i)\, e^{Bt/2} \;-\; (t_c/t)\, F_1\, \widetilde{F}\, e^{i\delta_C}, \qquad\qquad F_1\, \widetilde{F} \approx \exp(B_e t/2)$$

A scale factor $\sqrt{[\, s^2 - 2\,(m^2 + \widetilde{m}^2)\, s + (m^2 - \widetilde{m}^2)^2\,]}\, \sigma_{\rm tot}/8\pi$ has been used. The Coulomb phase δ_C with $Z\widetilde{Z}\alpha = \mathcal{Z}/137$, and the momentum transfer t_c of the elastic process at Coulomb interference, are $[\,\gamma = 0.5772\cdots$ is Euler's constant$\,]$

$$\delta_C(t) \;=\; \mathcal{Z}\alpha \ln \left| 2e^{-\gamma}/(B + B_e)\, t \,\right|, \qquad t_c \;=\; -8\pi\mathcal{Z}\alpha/\sigma_{\rm tot}(s)$$

$$\delta_C(t_c) \;=\; \mathcal{Z}\alpha \ln(e\mathcal{Z}_m/\mathcal{Z}), \qquad \mathcal{Z}_m \approx 4e^{-\gamma}\sigma_{\rm el}/[\sigma_{\rm tot}(1+\rho^2)\alpha(1 + B_e/B)]$$

The phase δ_C, regarded as depending on $\mathcal{Z} = Z\widetilde{Z}$, has a maximum when $\mathcal{Z} = \mathcal{Z}_m$. Note $\delta_C \approx 7\%$ for $\mathcal{Z} = 4$ (hh $\to$ hh) and $\delta_C \approx 10\%$ for (hC $\to$ hC) or (hNe $\to$ hNe).

As δ_C can be larger than 10%, $\exp(i\delta_C)$ will be written $\cos\delta_C + i\sin\delta_C$. A_N remains unchanged when each amplitude is scaled by an additional factor $\exp(-B\,t/2)\,\exp(-i\,\delta_C)$. To first order in t, for $-t < 0.02\,\text{GeV}^2$, the nonflip amplitude is then NB, Kopeliovich, Leader, Soffer, Trueman, Phys Rev D59 (1999) 114010

$$(\rho + i)\,e^{-i\,\delta_C} - (\,t_c\,/\,t\,)\,F_1\,\widetilde{F}\,e^{-B\,t/2} = i\,\widehat{\sigma} + \widehat{\rho} - t_c\,/\,t$$

$$\widehat{\sigma} = \cos\delta_C - \rho\sin\delta_C$$

$$\widehat{\rho} = \rho\cos\delta_C + \sin\delta_C - t_c(B_e - B)/2$$

Similarly, the single helicity flip amplitude with scaled hadronic element $R_5 + i\,I_5$, including possibly a different hadronic slope and Coulomb phase, is $(\,q/m_p\,)$ multiplied by Kopeliovich, Krelina, Acta Phys Polon Supp 12, 747 (2019)

$$(R_5 + i\,I_5)\,e^{-i\,\delta'_C} - (\kappa' t_c/2t)\,F_2\,\widetilde{F}\,e^{-B' t/2} = i\,I' + R' - (\kappa' t_c/2t)$$

$$I' = I_5\cos\delta'_C - R_5\sin\delta'_C$$

$$R' = R_5\cos\delta'_C + I_5\sin\delta'_C - \kappa'\,t_c\,(B'_e - B')\,/\,4$$

The anomalous moment parameter of the incident ion κ relates to its G factor, its beam momentum P, and its magnetic moment μ in nuclear magnetons $e/2m_p$, with m_p as proton mass W W MacKay, AIP Conference Proceedings 980, 191 (2008)

$$\frac{\kappa'}{m_p} = \frac{G}{m} - \frac{m}{P\,\widetilde{m}}, \qquad \kappa' = \frac{\mu}{Z} - \frac{m_p}{m} - \frac{m_p^2}{E\,\widetilde{m}}.$$

The term involving P follows from a detailed study of the single helicity flip amplitude due to one photon exchange. NB, Gotsman, Leader, Phys Rev D 18, 694 (1978)

If the integer A is the mass number of an incident ion and E is its energy per nucleon, then $P \approx A\,E \approx mE/m_p \approx s/2\widetilde{m}$. Poblaguev, Phys Rev D 100, 116017 (2019)

The improved accuracy of recent asymmetry measurements requires such terms to be included in a number of analyses. Poblaguev et al, Phys Rev Lett 123, 162001 (2019)

Excluding the $1/E$ correction term, present also in d-C and p-d EM collisions, $\kappa_p = 1.973$, $\kappa_d = -0.143$, and $\kappa_h = -1.398$, for proton, deuteron, and He-3 ions.

ANALYZING POWER

For small values of the scaled helicity flip items R' and I', introduce the quantities

$$x = \frac{t_c}{t}, \qquad \widehat{r} = 8\,\frac{\widehat{\sigma}\,R' - \widehat{\rho}\,I'}{\hat{\sigma}\,\kappa' - 2\,I'}, \qquad \bar{\rho} = \widehat{\rho} - \left(\frac{\kappa'}{m_p}\right)^2 \frac{t_c}{2}$$

The items here are written in terms of helicity nonflip $\widehat{\rho}$ and $\widehat{\sigma}$, amended by δ_C. The analyzing power for the elastic reaction would then be expressed in the form

$$A_{\mathrm{N}} \;=\; \frac{q_c}{m_p}\,(\widehat{\sigma}\,\kappa' \;-\; 2\,I'\,)\,\frac{x^{1/2} \;-\; \widehat{r}\,x^{-1/2}/4}{x^2 \;-\; 2\,\bar{\rho}\,x \;+\; \eta}$$

where $\eta \;=\; 1 + \rho^2 + [\,\rho\cos\delta_C + \sin\delta_C + (B - B_e)\,t_c/4\,]\,(B - B_e)\,t_c\,.$ By neglecting $\widehat{r}^2$ terms, such as writing $(1 - \widehat{r}/x)^{-1} = 1 + \widehat{r}/x$, A_{N} has a maximum for $\kappa > 0$ (a minimum for $\kappa < 0$) at the positive root of the quadratic equation in $x = t_c/t$

$$3\,x^2 \;-\; 2\,(\widehat{\rho} + \widehat{r})\,x \;-\; \eta \;+\; 2\bar{\rho} \;=\; 0$$

The analyzing power for the elastic reaction, with $\bar{\eta} = (\eta + \bar{\rho}^{\,2}/3)^{1/2}$, has an extremum at t_m given, to first order in $\widehat{r}$, by

$$\sqrt{3}\, t_c/t_m = \bar{\eta} + \bar{\rho}/\sqrt{3}\; + (\sqrt{3} - 2\bar{\rho}/\bar{\eta}\,)\,\widehat{r}/3$$

and x may be substituted in A_N to obtain the maximum (or minimum) value of the analyzing power that occurs near the squared momentum transfer $t_m = \sqrt{3}\, t_c$.

$$A_{\mathrm{N}}^{\mathrm{m}} = \frac{\kappa'}{4m_{\mathrm{p}}} \sqrt{-3\, t_{\mathrm{m}}} \left[1 + \frac{\sqrt{3}}{2}(\bar{\rho} + \delta_C) - \sqrt{3}\, R' - I' \right]$$

The Figure of Merit has a maximum around the squared momentum transfer t_c.
Glauber corrections to the elastic amplitudes and the analyzing power have been studied. Kopeliovich and Trueman, Phys Rev D 64, 034004 (2001)
Absorption corrections could be incorporated as extra terms in the above analysis.
Hagiwara, Hatta, Pasechnik, Zhou, Eur Phys J C 80, 427 (2020)

POLARIMETERS AT EIC

- A light ion carbon polarimeter requires calibration from an experiment involving a beam of polarized ions scattering on a gas jet of the same polarized nuclei.

- It secures an absolute ion beam polarization measurement and additionally calibrates the carbon polarimeter (involving possibly another nucleus as target).

A polarized atomic He-3 gas jet target would self-calibrate a polarized He-3 beam by measuring a precise analyzing power A_{N} at each energy & momentum transfer.

- 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 ^{10}Ne and around 73% for ^{18}Ar. Recoil energies are acceptable for detection.

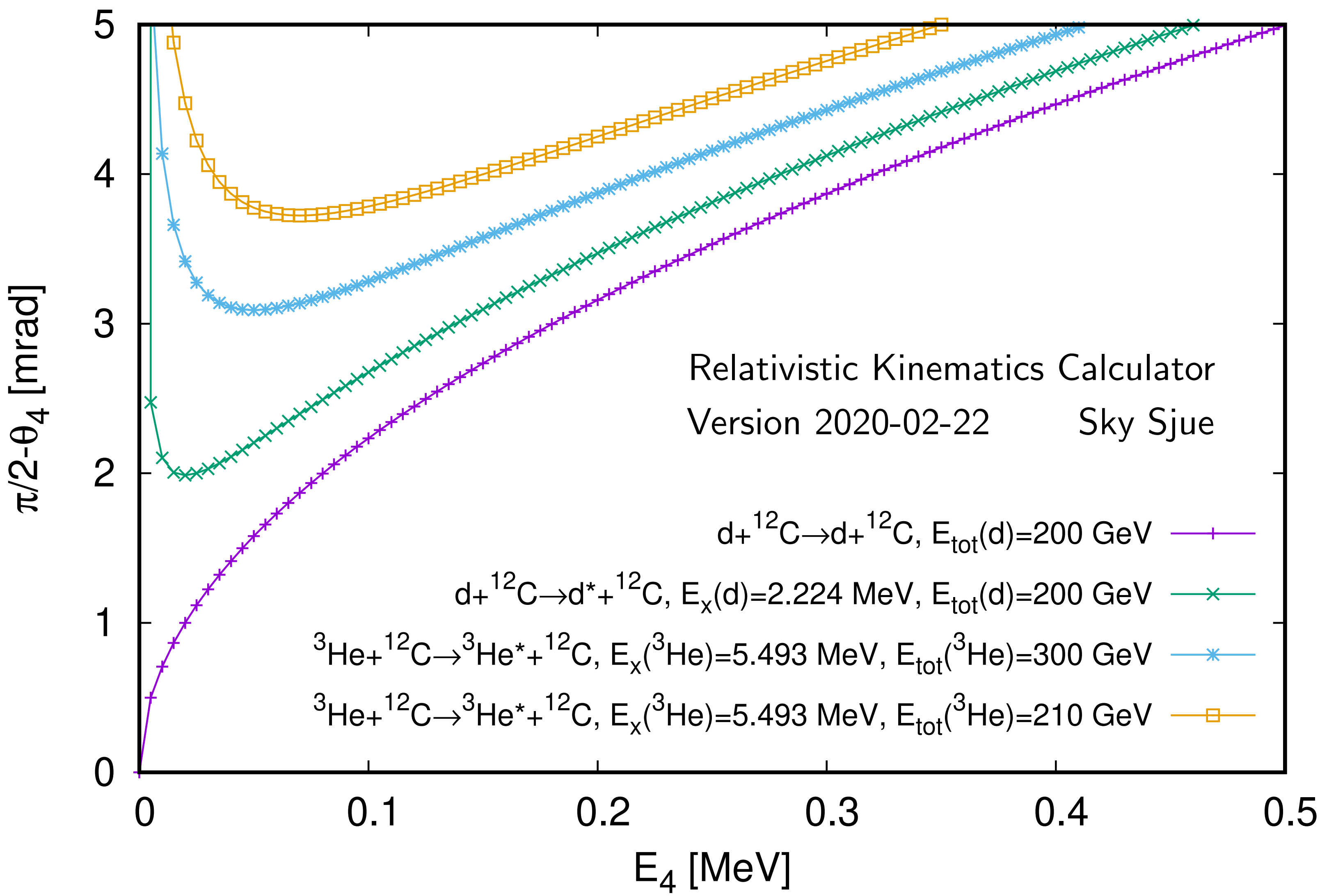

Figure 1: Complementary recoil angle versus recoil kinetic energy $T_R = E_4$ for, from top, (below legend), (1) h–C → [p+d]–C at 70 GeV/n, (2) h–C → [p+d]–C at 100 GeV/n, (3) d–C → [p+n]–C at 100 GeV/n, (4) d–C and h–C elastic (≈ same) at 100 GeV/n.

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 E such that

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

For pC scattering with $\Delta m = 135$ MeV $(+\pi^0)$ and $\Delta M = 7.3$ MeV, $E > 17$ GeV

For hC scattering with $\Delta m = 5.5$ MeV (p+d) and $\Delta M = 7.3$ MeV, $E > \; 2$ GeV

If P is the laboratory momentum of the incident particle of mass m, the recoil angle $\phi_{\rm el} \approx v/2c$ for elastic scattering, measured from a $90^{\,\rm o}$ location, is in radians

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

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

- Ions of a polarized beam and target nuclei of higher Z require improved treatment of Coulomb phases and of electromagnetic and hadronic form factors
  - The recoil kinematics for polarized inelastic scattering needs careful attention
- 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 the A_{N} for CNI ^{3}He–C scattering

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

BACKUP

References

[1] "Spin asymmetry for proton deuteron collisions at forward angles," AIP Conf. Proc. **675**, no.1, 841-845 (2003) doi:10.1063/1.1607252

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

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