Polarized Antiprotons
Form Factors and Transverse Spin

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Summary

- Bodega Bay Workshop 18–21 April 1985 in California
- Spin frontier for the partonic structure of the nucleon
- Channelling in a bent crystal inducing polarisation
- Spin observables for fermion fermion elastic collisions
- Conclusions and outlook

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Twelve Ideas at the Bodega Bay Workshop

- Decay in flight of produced antihyperons
- Spin filtering: polarised hydrogen target in storage ring
- Stochastic techniques à la stochastic cooling
- Dynamic polarisation: polarised electrons and microwaves
- Spontaneous spin-flip synchrotron radiation
- Spin-flip synchrotron radiation induced by X-ray laser

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More Ideas from the Bodega Bay Workshop

- Directly produced polarised antiprotons by scattering
- Repeated Stern-Gerlach deflection through quadrupoles
- Formation of antihydrogen: use of atomic beam methods
- Polarisation during storage in a Penning trap
- Polarising by channelling through a thin metallic foil
- Interaction with polarised photons from diamond crystal

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Channelling

Bent crystals have readily channelled many types of particle.

- CERN, Scandale et al., PRL 98 (2007) 154801
- RHIC, Fliller et al., PRSTAB 9 (2006) 013501
- IHEP, Afonin et al., Frascati Workshop (2004)
- FERMILAB-CONF-06-309-AD, Carrigan et al.

Ukhanov has suggested that bent crystals may polarise fermions through repeated interaction with nuclei (Kyoto Spin06 p 940).

The critical angle for axial channelling in a crystal derived by Lindhard in the first reference of NIM B 207 (2003) 402 (Uggerhøj et al.) corresponds to squared momentum transfer

$$t_a \;=\; -\,4\,Z\,\alpha\,p\,/\,\beta\,d$$

in the case of a particle of unit charge with momentum p and velocity β moving in the potential well around strings of nuclei of charge Ze spaced a distance d apart. From BK, LL (1974)

$$t_c \;=\; -\,8\,\pi\,Z\,\alpha\,/\,\beta\,\sigma_{\mathrm{tot}}$$

is where electromagnetic and hadronic effects are comparable.

Such collision of fermions may polarise them (Ukhanov Spin06). Consider the interference of helicty flip and nonflip amplitudes

$$M_+(s,t) \;\; \propto \;\; \sigma_{\rm tot} \left(i + \rho - \frac{t_c}{t} \right)$$

$$M_-(s,t) \;\; \propto \;\; \sigma_{\rm tot} \left(iI + R - \frac{\kappa_p \, t_c}{2\, t} \right) \frac{\sqrt{-t}}{m_p}$$

ρ and R being relative real parts and I an imaginary flip part. In the interference region of momentum transfer

$$0.009 < -t < 0.041 \;\; (\text{GeV}/c)^2$$

measurements of the analyzing power for proton carbon elastic scattering indicate that at 21.7 GeV$/c$ (Tojo 2002)

$$R = 0.088 \pm 0.058 \quad \text{and} \quad I = -0.161 \pm 0.226$$

and, similarly, in the region of momentum transfer

$$0.001 < -t < 0.032 \ \ (\text{GeV}/c)^2$$

single spin asymmetries for proton proton elastic scattering at laboratory momenta 24 and 100 GeV$/c$ provide similar constraints that restrict the sizes of hadronic helicity-flip amplitudes at these energies (Okada 2007).

A report on an analysis relating to the polarized proton programme at RHIC involving the elastic scattering of protons on protons in collider or fixed target mode and of proton beams on carbon targets provides a recent summary of the spin dependence of high energy hadron elastic scattering (Trueman 2007).

An extremum of the single spin asymmetry A_N normal to the scattering plane occurs near $t_m = \sqrt{3}\,t_c$ (PR D59 114010)

$$A_{\mathrm{N}}^{\mathrm{max}} = \frac{\kappa_p - 2\,I}{4\,m_p}\sqrt{-3\,t_m}$$

where κ_p is the anomalous magnetic moment of the hadron. For particle channelling close to $t = 0$ the normal single spin asymmetry behaves as a cubic in the momentum transfer $\sqrt{-t}$

$$A_{\mathrm{N}} \approx \frac{\kappa_p - 2\,I}{m_p}\,\frac{t}{t_c}\sqrt{-\,t}\;.$$

Some double spin asymmetries A_{ij}, K_{ij}, and D_{ij} also have singular terms in t arising from photon exchange (PR D18 694) that may alter the dynamics of the build-up of polarisation.

Channelling Summary

- Successive collisions in a crystal may amplify polarisation
- A significant hadronic analyzing power may be sufficient
- An analyzing power has an extremum in interference region
- The helicity flip hadronic amplitude may be important
- Spin transfer and depolarisation observables need study

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Polarisation Transfer

- Selective attenuation of particles circulating in a storage ring due to their spin dependent interaction with a polarised target was suggested by Csonka in 1968 as a way of polarising a beam.

- Such a method has polarised protons via their passage through a polarised hydrogen storage cell (PRL 71 13799).

- Hadronic and electromagnetic interactions induce differing losses for distinct orientations of the spin of a proton.

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Antiproton Polarisation

- Proton proton spin observables are known at low energy
- Antiproton proton spin cross sections are not well known
- Models of the antiproton proton interaction have appeared
- Haidenbauer, Klempt, Contalbrigo have reviews of models
- Antiproton polarisation may be transferred from leptons

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Polarisation Evolution

For particles circulating at frequency ν through a polarised target of areal density n and polarisation P, a coupled system

$$\frac{d}{d\tau}\begin{bmatrix} N \\ J \end{bmatrix} = -n\,\nu \begin{bmatrix} a & b \\ c & d \end{bmatrix}\begin{bmatrix} N \\ J \end{bmatrix}$$

describes the rate of change of the number of beam particles $N(\tau)$ and their total spin $J(\tau)$, (WM, CM, PRE 2006). Loss of particles involves integration beyond an acceptance angle, θ_{a}

$$a = 2\,\pi \int_{\theta_{\mathrm{a}}}^{\pi} \frac{d\,\sigma}{d\,\Omega}\,\sin\theta\,d\theta$$

Beam loss is induced by scattering over all angles beyond θ_{a} the acceptance angle of the storage ring (NN, FP, Spin06). The spin averaged differential cross section in a above, for antiproton electron elastic scattering to leading order in $1/t$, is

$$s\,\frac{d\sigma}{d\Omega} \;=\; \frac{\left(2\,\alpha\,m_e\,E_l\right)^2}{t^2}\,.$$

Changes in the total spin J due to matrix element c involve spin transfer, K_{ii} and asymmetry A_{ii} parameters integrated over particular angular ranges and multiplied by the target polarisation P. Depolarisation involves the matrix element d.

Spin transfer and asymmetry parameters for polarisations normal to the scattering plane have $1/t$ terms

$$s\,\frac{d\sigma}{d\Omega}\,K_{NN} \;=\; s\,\frac{d\sigma}{d\Omega}\,A_{NN} \;\approx\; \frac{2\alpha^2}{t}\,\mu_p\,m_e\,m_p$$

as do those with longitudinal directions of the spin if E_l and μ_p are the laboratory energy and magnetic moment of the hadron

$$s\,\frac{d\sigma}{d\Omega}\,K_{LL} \;=\; s\,\frac{d\sigma}{d\Omega}\,A_{LL} \;\approx\; \frac{2\alpha^2}{t}\,\mu_p\,m_e\,E_l$$

Electromagnetic spin transfer observables $K_{SS} = A_{SS}$ and the depolarisation parameter $1 - D_{NN}$ are not singular in t. Some baryon depolarisation does occur due to the singular terms

$$(1 - D_{LL})\, s\, \frac{d\sigma}{d\Omega} \;=\; (1 - D_{SS})\, s\, \frac{d\sigma}{d\Omega} \;\approx\; \frac{2\alpha^2}{t} \left(\frac{m_p\, m_e\, E_l}{k} \right)^2$$

A change in the total spin J results from the matrix element c which has a contribution involving a product of P with the spin transfer observable integrated over angles θ above a minimum angle θ_0 linked to the average distance between charges, an impact parameter beyond which scattering is inhibited.

$$P\,\pi \int_{\theta_0}^{\theta_{\mathrm{a}}} (2\, K_{\mathrm{LL}} \;\; \text{or} \;\; K_{\mathrm{NN}} + K_{\mathrm{SS}})\, \frac{d\,\sigma}{d\,\Omega}\; \sin\theta\, d\theta$$

In the transverse case, an azimuthal average leads to the appearance of both asymmetries K_{NN} and K_{SS}. A contribution to the matrix element d results from a similar integral over the azimuthally averaged depolarisation observable, below acceptance. In the short term, the rate of increase of hadron polarisation J/N is given approximately by

$$d\,J\,/\,d\tau \;\approx\; -\,n\,\nu\,c\,N$$

where c relates to integrals over double spin asymmetries that have singular behaviour in t and are enhanced by such factors as

$$\ln(t_a\,/\,t_0) \;= \ln(t_a\,/\,n).$$

Transfer at Low Energy

In a distorted wave approximation involving Coulomb effects, the Mainz group find that the angle integrated polarisation transfer cross section for proton electron elastic scattering is some nine orders of magnitude greater than that expected

$$|\,\langle\, A_{LL}\, d\sigma/d\Omega\,\rangle\,| \quad \text{is } 10^9 \text{ times larger}$$

from a plane wave one photon exchange calculation at an incident proton laboratory kinetic energy of 1.2 keV. The same would apply for antiproton positron collisions. It would be interesting to know if the double spin asymmetry and depolarization observables show a similar dramatic change.

Studies incorporating cooling mechanisms may be concerned with the value at low energies of

- the integrated depolarization cross section over angle
- the elastic spin averaged differential cross section

The large increase with energies decreasing to about 1 keV, a lower limit to the distorted wave approximation, compensates for the low lepton areal density when comparison is made with a method using storage cells.

Conclusions

It is clear that the availability of a polarized antiproton beam would probe the detailed spin dependence of antimatter collisions and would facilitate unprecedented tests of QCD transversity. A number of methods have been suggested in seeking to achieve polarization, among them the technique of channelling. Another method considers the use of spin transfer from polarized atoms and their constituents, and a third, the notion of transferring polarization from a beam of leptons, electrons or positrons, or, conceivably, muons.

The efficiency with which antiprotons enter a well prepared crystal is a concern when evaluating a method of channelling that endeavours to induce polarization by encouraging passage through a curved lattice of nuclei, necessarily of considerable length. Moreover, the size of the analyzing power deep within the electromagnetic hadronic interference region is limited by the requirement that the crystal can only be bent to a certain degree, not to mention the risk of failing to keep the projectile close to an attracting row of lattice nuclei due to an uncontrolled centrifugal force resulting from too enthusiastic a curvature.

The use of the spin dependence of hadronic and electromagnetic cross sections in selectively attenuating an antiproton beam as it collides with a polarized hydrogen target offers the most persuasive technique for achieving polarization.

Though the spin observables need more refined measurement for antiproton proton elastic scattering, the hope is that the success of the proton proton programme will serve as a guide as to what may be forthcoming in the antiparticle case.

Transferring spin from a polarized beam of leptons has the attractive feature that the appropriate cross sections may be calculated with confidence, in principle, by using our detailed understanding of quantum electrodynamics. The subtleties of the evaluation at lower energy, however, are being drawn to the surface due to the pressure of attempting to achieve an estimate of the overall effect. The rate of transfer of polarization does seem to be in need of enhancement. Nevertheless, nothing should be left undone on the margin of the impossible particularly when more intense electron or positron beams may appear as a result of requirements in another sphere.

- Spin dependent antiproton collisions test QCD transversity
- Maximum analyzing power at interference probes spin effects
- Significant double spin asymmetries near forward direction
- Important for stored antiproton polarisation build-up

Charles Lutwidge Dodgson born in Daresbury 1832

- “There’s no use trying, one can’t believe impossible things.”
- “I daresay you haven’t had much practice,” said the Queen.
- “When I was younger, I always did it for half an hour a day.”
- “Why, sometimes I’ve believed as many as six impossible
- things before breakfast.”

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Six Impossible Things

- Increase the target lepton density by using positronium
- Muons in muonium increase the maximum scattering angle
- Intense compressed magnetic field to polarise antiprotons
- Arrange back scattered hadrons to join preceding bunch
- Hadrons scattered forward largely of one spin state
- Successive bunches with alternate spin orientations