Spin Filtering in Storage Rings

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Outline:

- Tons of top class QCD: FAIR as a unique successor of DIS physics
- H.O. Meyer's problem: Spin filtering & scattering within the ring acceptance angle
- Why does the spin-filtering on polarized electrons cancel out?
- Understanding the FILTEX result
- Spin-exchange vs. spin-flip
- Testing filtering mechanisms by depolarization
- Implications for spin-filtering of antiprotons in PAX FAIR
- Longitudinal vs. transverse filtering
- Deuterium vs. hydrogen polarized internal target?

The transmission and scattering

- Why is the sky blue? It is exclusively the scattered light!
- Why is the setting sun red? It is exclusively the transmitted light!
- Transmission $\equiv$ propagation at exactly zero angle
- Why does the sun change its color? Transmission changes the un-scattered light!
- Optical filtering: with rare exceptions the transmitted light.
- Unique feature of storage rings: a mixing of the transmitted and scattered beam
- Transmission: the polarization dependent refraction index

$$n = 1 + \frac{2\pi}{p^2} N \hat{f}(o)$$

- The forward NN scattering amplitude $\hat{f}(o)$ depends on the beam and target spins
- Polarized target is an optically active medium (Baryshevsky & Podgoretsky, 1964)

Kinematics of p-atom scattering in storage rings

- FILTEX ring acceptance $\theta_{acc} = 4.4$ mrad.
- p-Atom $\equiv$ incoherent quasielastic (QE) scattering off atomic protons and electrons at

$$\theta \gtrsim \theta_{min} = 1/pa_{Bohr} = \alpha_{em} m_e/\sqrt{2m_p T_p} \Longrightarrow d\sigma_{QE} = d\sigma_{el}^{pp} + d\sigma_{el}^{ep}$$

- Light electrons do not deflect protons (Horowitz& Meyer): $\theta \leq \theta_e = m_e/m_p$
  pe scattering goes entirely within the ring acceptance!
- Coulomb dominated pp scattering up to CNI region

$$\theta \lesssim \theta_{CNI} \approx \sqrt{2\pi\alpha_{em}/m_p T_p \sigma_{tot,nucl}^{pp}} \sim 100\text{mrad}$$

  Storage rings are uniquely sensitive to deep-under-CNI scattering.
- Strong inequality

$$\theta_{min} \ll \theta_e \ll \theta_{acc} \ll \theta_{CNI}$$

  .
- Beam losses are dominated by Coulomb pp scattering.

Electrons in hydrogen: are they visible?

- Beam attenuation:

$$\hat{\sigma}_{tot}(p - atom) \equiv \hat{\sigma}_{QE} = \hat{\sigma}^{pp}_{tot} + +\hat{\sigma}^{pe}_{tot}.$$

- Gigantic

$$\hat{\sigma}^{pe}_{tot} = \hat{\sigma}^{e}_{el}(> \theta_{\min}) \sim 4\pi\alpha^2_{em}a^2_{Bhor} \sim 10^4 Barn$$

  is invisible, as $\theta \leq \theta_e \ll$ angular divergence of any beam and pe scattering does not cause any attenuation!

- Skrinsky (2004): shall spin filtering by $e\uparrow$ be observable?
- Milstein & Strakhovenko (2005), kinetic equation for spin population numbers: electrons are invisible also polarization-wise
- Independent & simultaneous observation by NNN & F.Pavlov within a different and more generic formalism: the quantum evolution equation for the spin-density matrix of the stored beam with allowance for scattering within the ring acceptance angle

Polarization of Transmitted Beam

- Time = distance z traversed in the medium.

$$\text{The Fermi Hamiltonian} = \hat{H} = \frac{1}{2}N\hat{F}(0) = \frac{1}{2}N[\hat{R}(0) + i\hat{\sigma}_{tot}]$$

$N =$ density of atoms in the target.

- The density matrix of the stored beam ($\sigma_b =$ beam spin operator)

$$\hat{\rho}(\boldsymbol{p}) = \frac{1}{2}[I_0(\boldsymbol{p}) + \sigma_b \boldsymbol{s}(\boldsymbol{p})]$$

- Textbook quantum-mechanical evolution for pure transmission ($\theta_{acc} \to 0$)

$$\frac{d}{dz}\hat{\rho}(\boldsymbol{p}) = i\left(\hat{H}\hat{\rho}(\boldsymbol{p}) - \hat{\rho}(\boldsymbol{p})\hat{H}^{\dagger}\right) = \underbrace{i\frac{1}{2}N\left(\hat{R}(0)\hat{\rho}(\boldsymbol{p}) - \hat{\rho}(\boldsymbol{p})\hat{R}(0)\right)}_{\text{Real potential=Pure refraction}} - \underbrace{\frac{1}{2}N\left(\hat{\sigma}_{tot}\hat{\rho}(\boldsymbol{p}) + \hat{\rho}(\boldsymbol{p})\hat{\sigma}_{tot}\right)}_{\text{(Imaginary potential=Pure attenuation)}}$$

Polarization of Transmitted Beam Cont'd

- $$\begin{aligned}\hat{\sigma}_{tot} &= \sigma_0 + \underbrace{\sigma_1(\sigma_b \cdot Q) + \sigma_2(\sigma_b \cdot k)(Q \cdot k)}_{spin-sensitive\ loss}, \\ \hat{R}(0) &= R_0 + \underbrace{R_1(\sigma_b \cdot Q) + R_2(\sigma_b \cdot k)(Q \cdot k)}_{\sigma_b \cdot \text{Pseudomagnetic field}}\end{aligned}$$

  k = beam axis, Q = target polarization.

- Evolution of the beam polarization $P = s/I_0$

$$\begin{aligned}dP/dz &= \underbrace{-N\sigma_1(Q - (P \cdot Q)P) - N\sigma_2(Q \cdot k)(k - (P \cdot k)P)}_{\text{Polarization buildup by spin-sensitive transmission loss}} \\ &+ \underbrace{NR_1(P \times Q) + NR_2(Pk)(Q \times k)}_{\text{Spin precession in pseudomagnetic field}}\end{aligned}$$

- Precession: prime observable in neutron optics
- After the precession is averaged out, a full equivalence to the Milstein-Strakhovenko kinetic equation.

Transmission: Transverse Polarization Buildup

- Coupled evolution for pure transmission

$$\frac{d}{dz}\begin{pmatrix} I_0 \\ s \end{pmatrix} = -N \begin{pmatrix} \sigma_0(>\theta_{\rm min}) & Q\sigma_{1,T}(>\theta_{\rm min}) \\ Q\sigma_{1,T}(>\theta_{\rm min}) & \sigma_0(>\theta_{\rm acc}) \end{pmatrix} \cdot \begin{pmatrix} I_0 \\ s \end{pmatrix},$$

- Solutions

$$\propto \exp(-\lambda_{1,2} N z)$$

with eigenvalues

$$\lambda_{1,2} = \sigma_0 \pm Q\sigma_{1,T}$$

- Reduction to Meyer's equation for pure transverse polarizations:

$$\frac{dP}{dz} = -N\sigma_{1,T} Q(1 - P^2)$$

$$P(z) = -\tanh(Q\sigma_{1,T} N z)$$

- Any spin-dependent loss filters spin of the stored beam.

Add Scattering within the Ring Acceptance

- Quasielastic (QE) $p + atom \equiv$ scattering off quasifree protons & electrons:

$$\frac{d\hat{\sigma}_{QE}}{d^2\boldsymbol{q}} = \frac{1}{(4\pi)^2}\hat{\mathfrak{F}}_e(\boldsymbol{q})\hat{\rho}\hat{\mathfrak{F}}_e{}^{\dagger}(\boldsymbol{q}) + \frac{1}{(4\pi)^2}\hat{\mathfrak{F}}_p(\boldsymbol{q})\hat{\rho}\hat{\mathfrak{F}}_p{}^{\dagger}(\boldsymbol{q})$$

- What is lost in transmission is partly recovered by scattering within the ring acceptance $\theta \leq \theta_{acc}$
- Loss-recovery balance: rigorous derivation from multiple-scattering theory

$$\frac{d}{dz}\hat{\rho} = \underbrace{i\frac{1}{2}N\left(\hat{R}\hat{\rho}(\boldsymbol{p}) - \hat{\rho}(\boldsymbol{p})\hat{R}\right)}_{Ignore\ this\ precession} - \underbrace{\frac{1}{2}N\left(\hat{\sigma}_{tot}\hat{\rho}(\boldsymbol{p}) + \hat{\rho}(\boldsymbol{p})\hat{\sigma}_{tot}\right)}_{Evolution\ by\ transmission\ loss}$$

$$+ \underbrace{N\int^{\Omega_{acc}}\frac{d^2\boldsymbol{q}}{(4\pi)^2}\hat{\mathfrak{F}}(\boldsymbol{q})\hat{\rho}(\boldsymbol{p}-\boldsymbol{q})\hat{\mathfrak{F}}^{\dagger}(\boldsymbol{q})}_{Lost\ and\ recovered\ by\ scattering\ within\ the\ ring\ acceptance}$$

Elastic NN scattering

- Three -spin problem: Q, P, S — the target, beam and scattered particle polarizations.
- Menagerie of spin observables (Bystricky et al):

$$
\begin{aligned}
d\sigma &= \frac{1}{2} d\sigma_0 \Big\{ 1 + \underbrace{A_{00i0} P_i + A_{000j} Q_j}_{beam\&target\ analyzing\ powers} \\
&+ \underbrace{S_l P_{l000}}_{normal\ polarization\ of\ scattered\ p's} \\
&+ \underbrace{A_{00ij} P_i Q_j}_{beam-target\ double\ spin\ asymmetry} + \underbrace{S_l P_i Q_j M_{l0ij}}_{triple-spin\ correlation} \\
&+ \underbrace{S_l P_i D_{l0i0}}_{beam-to-scattered\ spin\ transfer} \\
&+ \underbrace{S_l Q_j K_{l00j}}_{target-to-scattered\ spin\ transfer} \Big\}
\end{aligned}
$$

Stationary polarizations in the storage ring

- Standard basis vectors rotate with the azimuthal scattering angle
- Fixed basis:

  normal to the ring (transverse): $Q = Q\mathbf{N}$

  tangential to the ring (longitudinal) with the Siberian Snake: $Q = Q\boldsymbol{k}$.

- Cooling and beam optics etc. mix azimuthal angles of oscillations around the equilibrium orbit after each pass through PIT
- Average $d\sigma$ over the azimuthal angle
- Precession in the transmission averages out for left-right and up-down symmetric scattering in the PIT.

Transverse Spin: Azimuthal Averaging

- Azimuthal averaging:

$$A_{OOOj}Q_j = Q(A_{OOOn}\cos\phi + A_{OOOs}\sin\phi) \Longrightarrow 0$$

- Double spin asymmetry:

$$A_{OOij}P_iQ_j \Rightarrow= \frac{1}{2}PQ(A_{OOnn} + A_{OOss}).$$

- Depolarization (beam-to-scattered spin transfer)

$$S_lP_iD_{l0i0} \Rightarrow \frac{1}{2}SP\Big(D_{s'0s0}\cos\theta + D_{k'0s0}\sin\theta + D_{n0n0}\Big),$$

- Target-to-beam spin transfer (spin exchange):

$$S_lQ_jK_{l00j} \Rightarrow \frac{1}{2}SQ\Big(K_{s'00s}\cos\theta + K_{k'00s}\sin\theta + D_{n00n}\Big),$$

Transverse Spin: Spin-Transfer vs. Spin-Flip

$$
\begin{aligned}
d\sigma = d\sigma_0 \frac{1}{2}\Big\{ 1 \quad &+ \quad \frac{1}{2} \underbrace{PQ\Big(A_{OOnn} + A_{OOss}\Big)}_{beam-target\ spin\ asymmetry} \\
&+ \quad \frac{1}{2} \underbrace{SP\Big(D_{s'0s0}\cos\theta + D_{k'0s0}\sin\theta + D_{n0n0}\Big)}_{beam-to-scattered\quad spin\quad transfer} \\
&+ \quad \frac{1}{2} \underbrace{SQ\Big(K_{s'00s}\cos\theta + K_{k'00s}\sin\theta + K_{n00n}\Big)}_{target-to-scattered\quad spin\quad transfer} \Big\} \\
&\equiv \quad \frac{1}{2} \underbrace{\Big(1 + SP\Big) d\Sigma_{0,T}}_{unpolarized\ non-flip} + \frac{1}{2} \underbrace{\Big(1 - SP\Big) 2d\Delta\Sigma_{0,T}}_{unpolarized\ spin-flip} \\
&+ \quad \frac{1}{2} \underbrace{Q\Big(P + S\Big) d\Sigma_{1,T}}_{polarized\ non-flip} + \frac{1}{2} \underbrace{dQ\Big(P - S\Big) \Delta\Sigma_{1,T}}_{polarized\ spin-flip} .
\end{aligned}
$$

- Don't confuse the Target-to-Scattered-Spin-Transfer with the Beam-Spin-Flip which vanishes for $S = P = \pm 1$! (Walcher et al.)

Spin-Flip: Transverse Polarization

- Beam-Target Spin Asymmetry:

$$d\sigma_{1,T} = \frac{1}{2} d\sigma_0 PQ \Big(A_{OOnn} + A_{OOss} \Big)$$

- Non-Flip X-sections

$$\begin{aligned} d\Sigma_{0,T} &= \; = d\sigma_0 \frac{1}{2} \Big[1 + \frac{1}{2} \Big(D_{s'0s0} \cos\theta + D_{k'0s0} \sin\theta + D_{n0n0} \Big) \Big] \\ d\Sigma_{1,T} &= \; \frac{1}{2} d\sigma_0 \Big[\Big(A_{OOnn} + A_{OOss} \Big) + \Big(K_{s'00s} \cos\theta + K_{k'00s} \sin\theta + K_{n00n} \Big) \Big] \end{aligned}$$

- Spin-Flip off unpolarized target

$$2d\Delta\Sigma_{0,T} = \frac{1}{2} \Big[1 - \frac{1}{2} \Big(D_{s'0s0} \cos\theta + D_{k'0s0} \sin\theta + D_{n0n0} \Big) \Big]$$

- Spin-Flip off polarized target

$$d\Delta\Sigma_{1,T} = \frac{1}{2} d\sigma_0 \Big[\Big(A_{OOnn} + A_{OOss} \Big) - \Big(K_{s'00s} \cos\theta + K_{k'00s} \sin\theta + K_{n00n} \Big) \Big].$$

Longitudinal Spin: Spin-Transfer vs. Spin-Flip

- Elastic scattering

$$
\begin{aligned}
d\sigma &= \frac{1}{2} d\sigma_0 \Big\{ 1 + PQ A_{OOkk}, \\
&+ SP\Big(- D_{s'0k0} \sin\theta + D_{k'0k0} \cos\theta \Big) + SQ\Big(- K_{s'0k0} \sin\theta + K_{k'0k0} \cos\theta \Big) \Big\} \\
&\equiv \underbrace{\frac{1}{2}\Big(1 + SP\Big) d\Sigma_{0,L}}_{non-flip} + \underbrace{\frac{1}{2}\Big(1 - SP\Big) d\Delta\Sigma_{0,L}}_{spin-flip} \Big\} \\
&+ \underbrace{\frac{1}{2} Q\Big(P + S) d\Sigma_{2,L}}_{polarized\ non-flip} + \underbrace{\frac{1}{2} Q\Big(P - S) d\Delta\Sigma_{2,L}}_{polarized\ spin-flip}
\end{aligned}
$$

- Total X-section: $d\sigma_{tot} = d\sigma_0 \Big\{ 1 + PQ A_{OOkk} \Big\} = d\sigma_0 + PQ d\sigma_{2,L}$.
- Spin-flip, unpolarized target $d\Delta\Sigma_{0,L} = \frac{1}{2}\Big[1 + D_{s'0k0} \sin\theta - D_{k'0k0} \cos\theta \Big]$
- Spin-flip, polarized target $d\Delta\Sigma_{2,L} = \frac{1}{2}\Big[A_{OOkk} + K_{s'0k0} \sin\theta - K_{k'0k0} \cos\theta \Big]$

Transmission vs. Scattering within the Ring Accept

- Decompose total transmission losses

$$\frac{d}{dz}\hat{\rho} = -\underbrace{\frac{1}{2}N\Big(\hat{\sigma}_{tot}(>\theta_{\rm acc})\hat{\rho}(\boldsymbol{p}) + \hat{\rho}(\boldsymbol{p})\hat{\sigma}_{tot}(>\theta_{\rm acc})\Big)}_{Unrecoverable\ transmission\ loss}$$

$$-\quad \frac{1}{2}NI_0(\boldsymbol{p})\Big[\underbrace{\sigma_0^{el}(<\theta_{\rm acc}) + \sigma_1^{el}(<\theta_{\rm acc})PQ}_{Potentially\ recoverable\ beam\ loss} + \sigma_b\underbrace{\Big(\sigma_0^{el}(<\theta_{\rm acc})P + \sigma_1^{el}(<\theta_{\rm acc})Q\Big)}_{Potentially\ recoverable\ spin\ loss}\Big]$$

- Recovery from SWRA (angular divergence of the beam at target $\ll \theta_{acc}$):

$$\int d^2\boldsymbol{p}\int^{\Omega_{\rm acc}}\frac{d^2\boldsymbol{q}}{(4\pi)^2}\hat{\mathfrak{F}}(\boldsymbol{q})\hat{\rho}(\boldsymbol{p}-\boldsymbol{q})\hat{\mathfrak{F}}^{\dagger}(\boldsymbol{q}) = \hat{\sigma}^E(\leq\theta_{\rm acc})\cdot\int d^2\boldsymbol{p}I_0(\boldsymbol{p})$$

- The mismatch of the loss and recovery

$$\Delta\hat{\sigma} = \frac{1}{4}\Big(\hat{\sigma}_{el}(<\theta_{\rm acc})(1+\sigma_b P) + (1+\sigma_b P)\hat{\sigma}_{el}(<\theta_{\rm acc})\Big) - \hat{\sigma}_{QE}(\leq\theta_{\rm acc})$$

is a pure spin-flip effect for both transverse and longitudinal polarizations!

Needle-Sharp Scattering off Electrons: $\theta_e \ll \theta_{acc}$

- Breit pe interaction (1929): Coulomb + hyperfine + tensor + negligible proton spin-orbit

$$\hat{\sigma}^{ep}_{tot} = \underbrace{\sigma^{ep}_0}_{Coulomb} + \underbrace{\sigma^{ep}_1(\sigma_p \cdot Q_e) + \sigma^{ep}_2(\sigma_p \cdot \mathbf{k})(Q_e \cdot \mathbf{k})}_{Coulomb \times (Hyperfine + Tensor)} + spin - flip$$

- Spin-flip from the proton spin-orbit is negligible compared to spin-exchange:

$$\Delta\Sigma_{0,T} \sim \frac{m_e}{m_p} \cdot \frac{T_{kin}}{m_p} \sigma^{ep}_1$$

- Polarization of scattered protons S (transverse case):

$$\mathrm{S} = P + Q_e \sigma^{ep}_1 / \sigma^{ep}_0$$

- clearcut electron-to-proton spin transfer (Akhiezer (57),...,Horowitz-Meyer)
- Polarization by transmission losses is exactly canceled by recovery from SWRA: Skrinsky was right in his suspicions.

Polarization Buildup

- Coupled evolution equations after into-the-beam scattering

$$\frac{d}{dz}\begin{pmatrix} I_0 \\ s \end{pmatrix} = -N \begin{pmatrix} \sigma_0(>\theta_{\rm acc}) & Q\sigma_{1,T}(>\theta_{\rm acc}) \\ Q(\sigma_{1,T}(>\theta_{\rm acc}) + \Delta\Sigma_{1,T}) & \sigma_0(>\theta_{\rm acc}) + 2\Delta\Sigma_{0,T} \end{pmatrix} \cdot \begin{pmatrix} I_0 \\ s \end{pmatrix},$$

- Solutions $\propto \exp(-\lambda_{1,2}Nz)$ with eigenvalues $\lambda_{1,2} = \sigma_0(>\theta_{\rm acc}) + \Delta\sigma_0 \pm Q\sigma_3$

$$Q\sigma_3 = \sqrt{Q^2\sigma_{1,T}(>\theta_{\rm acc})(\sigma_{1,T}(>\theta_{\rm acc}) + \Delta\Sigma_{1,T}) + \Delta\Sigma_{0,T}^2}$$

- The polarization buildup

$$P(z) = -\frac{Q(\sigma_{1,T}(>\theta_{\rm acc}) + \Delta\Sigma_{1,T})\tanh(Q\sigma_3 Nz)}{Q\sigma_3 + \Delta\Sigma_{0,T}\tanh(Q\sigma_3 Nz)}$$

- $\Delta\Sigma_{0,T} \ll \sigma_{1,T}(>\theta_{\rm acc})$: the effective small-time polarization cross section

$$\sigma_{P,T} \approx -Q(\sigma_{1,T}(>\theta_{\rm acc}) + \Delta\Sigma_{1,T})$$

Pure electron target with spin-flip

- Scattering is entirely within the ring acceptance:

$$\sigma_0(>\theta_{acc}) = 0, \quad \sigma_{1,T}(>\theta_{acc}) = 0, \quad Q\sigma_3 = \Delta\Sigma_{0,T}.$$

- Evolution of the spin-density matrix:

$$\frac{d}{dz}\begin{pmatrix} I_0 \\ s \end{pmatrix} = -N\begin{pmatrix} 0 & 0 \\ Q\Delta\Sigma_{1,T} & 2\Delta\Sigma_{0,T} \end{pmatrix}\cdot\begin{pmatrix} I_0 \\ s \end{pmatrix},$$

- M & S & Walcher : filtering without absorption: $I_0(z) = I_0(0)$
- Measure spin-flip $\Delta\Sigma_{0,T}$: filtering by spin-flip is the same as depolarization of stored polarized protons,

$$P(z) = P(0)\exp(-2N\Delta\Sigma_{0,T}z) + Q\frac{\Delta\Sigma_{1,T}}{2\Delta\Sigma_{0,T}}\left\{1 - \exp(-2N\Delta\Sigma_{0,T}z)\right\}$$

- Depolarization proof that $\Delta\Sigma_{0,T} \ll \sigma_1(Meyer - Horowitz - Walcher)$
- Pure hadronic spin-flip is negligible: $\Delta\Sigma_{0,T} \lesssim \sigma_{tot}\theta_{acc}^2 \lesssim 10^{-4}\sigma_{tot}$.

FILTEX according to Meyer-Horowitz:

- The FILTEX as published in 1993: $\sigma_{P,T} = 63 \pm 3(stat.)$ mb, a 20σ measurement!

- Better understanding of target density & polarization (F.Rathmann, PhD): $\sigma_{P,T} = 72.5 \pm 5.8(stat. + sys.)$ (stat.)
- Expected filtering by pure nuclear scattering: $\sigma_{P,T\ expected} = 122$ mb.
- H.O. Meyer: correct σ_P for scattering within the beam. Strong suppression by CNI, Meyer's reevaluation $\sigma_{1,T}(> \theta_{\rm acc}) = 83$ mb (SAID of 94) instead of 122 mb
- Add scattering within the beam off polarized electrons: $\delta\sigma^{ep}_{1,T} = -70$ mb
- Add scattering within the beam off polarized protons: $\delta\sigma^{ep}_{1,T} = +52$ mb
- Net result: $\sigma_{P,T} = 65$ mb. Good but accidental agreement with FILTEX!
- What went wrong: : Double counting, Meyer should have started with loss from $\theta > \theta_{min}$, and then add scattering within the beam.
- Still, Meyer asked right questions and was infinitesimally close to the correct answer!

FILTEX with scattering within the ring acceptance

- NNN-Pavlov: SAID-SP05 for filtering by transmission loss:

$$\sigma_{1,T}(> \theta_{\mathrm{acc}}) = -85.6 \text{ mb}$$

(only marginal changes from SAID to Nijmegen databases).

- Careful extrapolations under the CNI region
- Very small spin-flip (loss-recovery mismatch) X-section is found

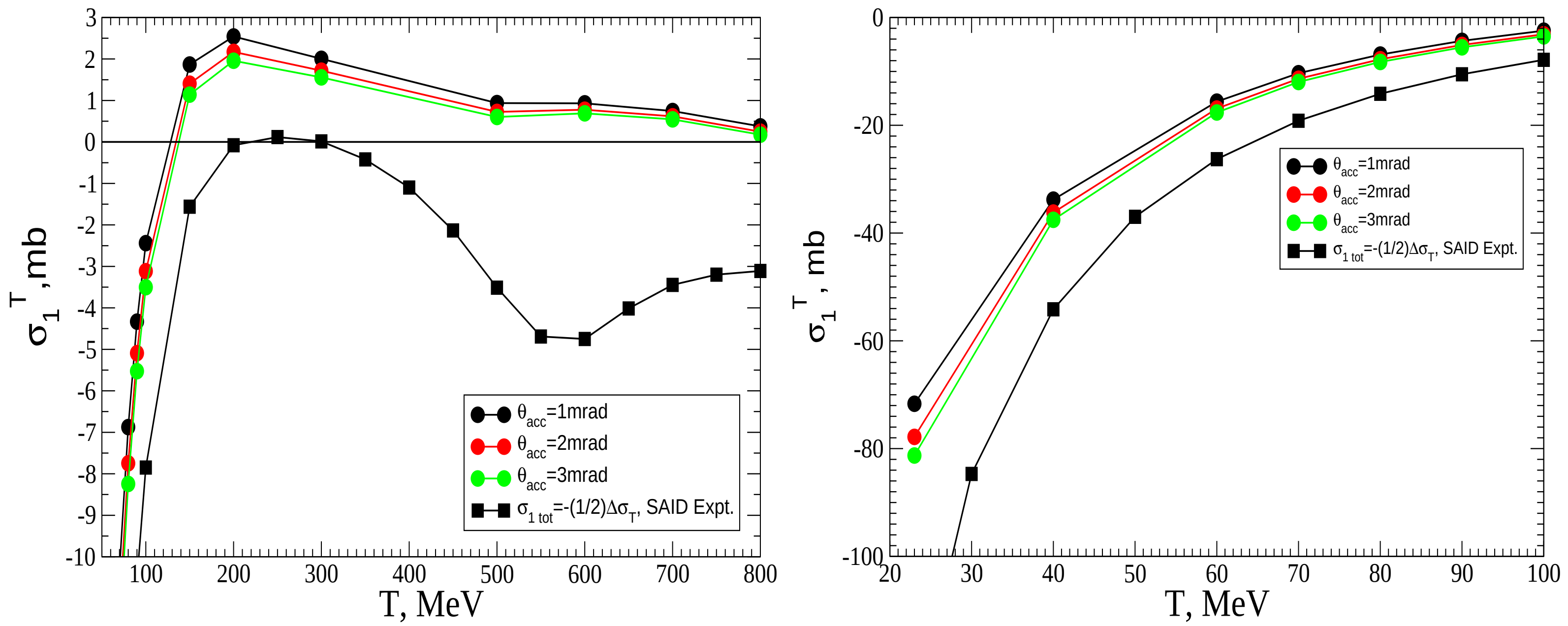
$$\Delta\Sigma_{1,T} \approx -6 \cdot 10^{-3} \text{ mb}$$

Nonrelativistic heavy particles love retaining their spin

Vanishing interference of the dominant non-flip Coulomb with spin-orbit in the azimuthal integrated cross section

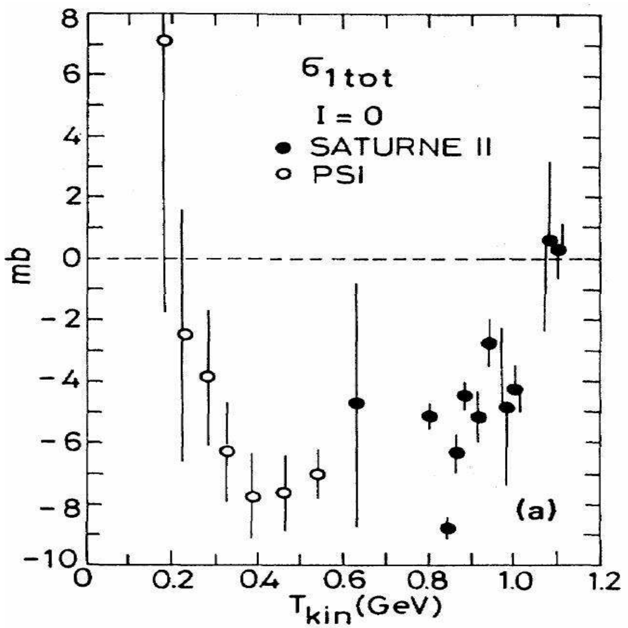
- Full agreement with Milstein-Strakhovenko evaluations
- The practical concluions: filtering magenta is dominated by losses for scattering beyond the ring acceptance angle.
- Add spin-dependent annihilation for antiprotons

COSY: energy dependence of transverse filtering



- SAID ≡ exp. data on transverse two-spin asymmetry $\Delta\sigma_T$
- Very strong CNI:
  strong suppression at low energy,
  changing the sign, of the filtering X-section vs. pure nuclear $\Delta\sigma_T$.
- Sizable dependence on the acceptance angle is a pure CNI effect

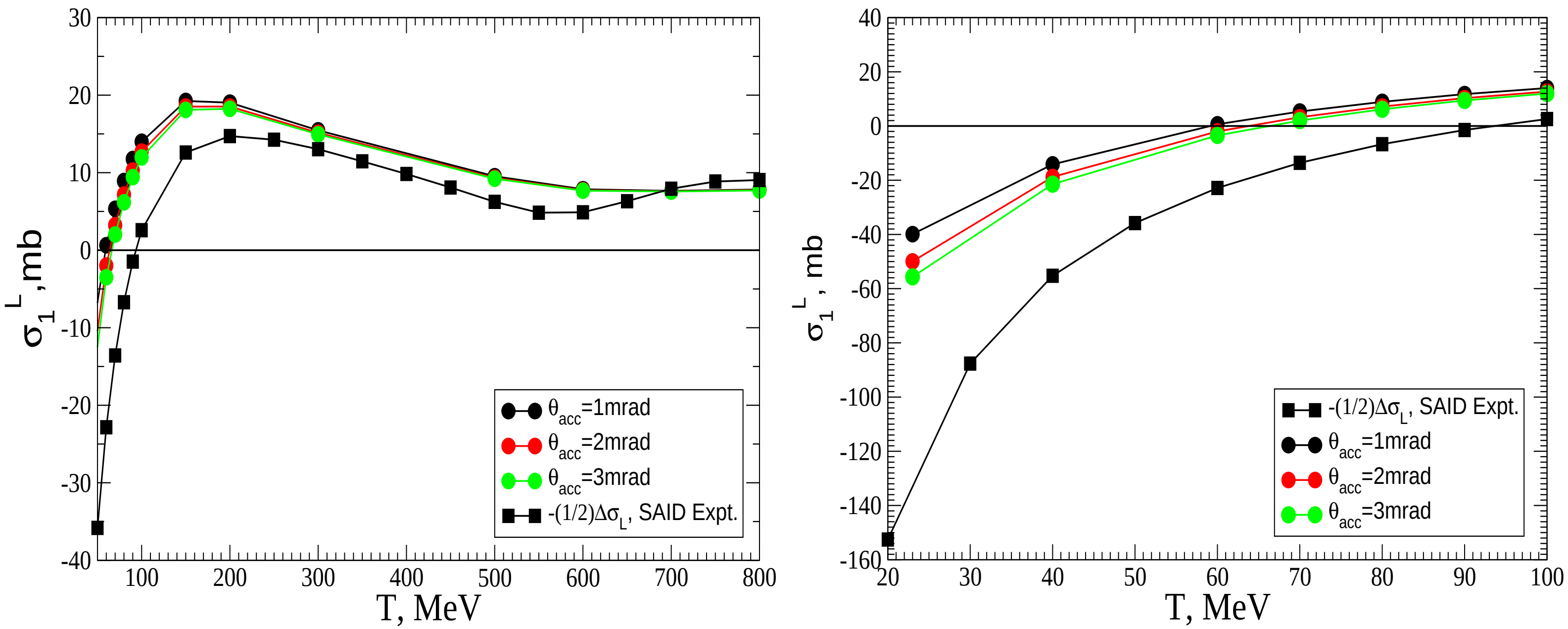
COSY: transverse filtering with deuterons



$\sigma_1(I=0) = -\frac{1}{2}\Delta\sigma_T(I=0)$ vs. energy in the isoscalar NN channel (deuteron).

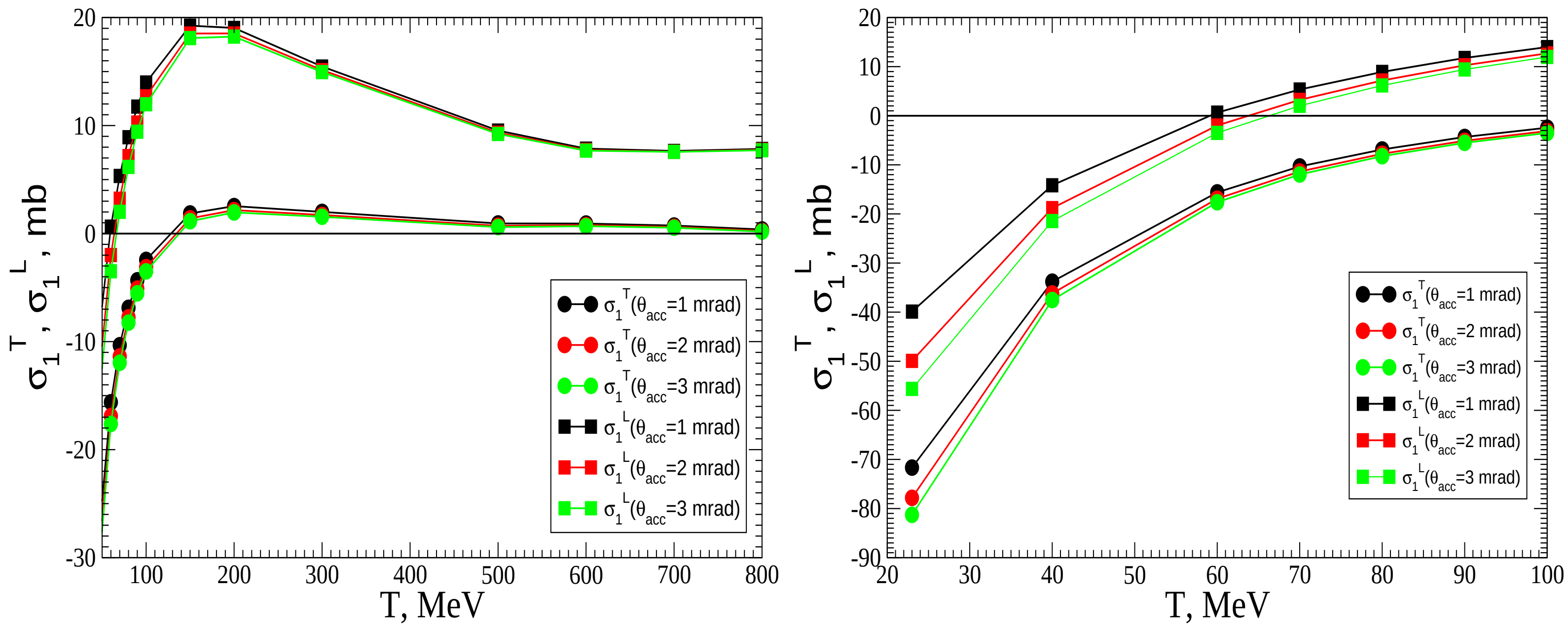
- The same electron effect but $\sigma_1(I=0)$ is much larger than $\sigma_1(pp)$.
- Disentangling the electron effect by hydrogen-deuterium comparison
- Relatively weaker CNI effect in deuterium is expected
- More detailed theoretical analysis is needed

COSY: longitudinal spin filtering



- Strong CNI suppression of filtering below $T_p \lesssim 60$ MeV
- Favorable CNI effects enhance filtering above $T_p \gtrsim 100$ MeV
- Deuterium target $T_p \lesssim 60$ MeV: theoretical scrutiny is needed.

Longitudinal vs. transverse filtering



- Filtering at $T_p \gtrsim 100$ MeV: Longitudinal $\gg$ Transverse.
- 100-150 MeV SNAKE at COSY would do a fantastic job
- COSY filtering at 40-50 MeV: nuclear inequality $\sigma_{1,T} > \sigma_{2,L}$ is opposite to the EM one.

Conclusions: what is the future for PAX?

- FILTEX: an important proof of the principle of spin filtering.
- A Budker-Juelich consensus on storage rings:
  Polarized atomic & free electrons wouldn't polarize antiprotons.
  Expect Spin-flip $\ll$ blue Electron-to-Proton spin transfer
- Walcher: loss-free filtering in a polarized electron "cooler".
  Strong enhancement of ep spin-exchange at special relative velocities.
  Sizable filtering if spin-flip is equated to spin-exchange.
- Depolarization test of spin-flip is possible at COSY.
- Still slight disagreement between experiment $\sigma_P = 72.5 \pm 5.8(stat. + sys.)$ (FILTEX) and theory, $\sigma_P = 85.6 mb$ (Meyer & Budker Institute & IKP FZJ).
- Solution for PAX: optimize filtering by pure nuclear antiproton-proton interaction with existing antiprotons. $N\bar{N}$ models are encouraging though not quite reliable.
- Disentangle Meyer-Horowitz vs. Budker-Jülich by energy dependence for $L\&T$ with both hydrogen and deuterium.