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 ≡ 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

$$\theta \gtrsim \theta_{min} = 1/pa_{Bohr} = \alpha_em_e/\sqrt{2m_pT_p} \quad \Rightarrow \quad d\sigma_{QE} = d\sigma_{el}^{pp} + d\sigma_{el}^{ep}$$

- 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

$$\theta \leq \theta_{CNI} \approx \sqrt{2\pi\alpha_em_em_pT_p\sigma_{tot,nucl}^{pp}} \sim 100\text{ mrad}$$

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:

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

Gigantic

\[ \hat{\sigma}_{\text{tot}}^{pe} = \hat{\sigma}_{\text{el}}^{e}(> \theta_{\text{min}}) \sim 4\pi\alpha_{\text{em}}^2 a_{B\text{hor}}^2 \sim 10^4 \text{Bar} n \]

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)

\[
\hat{\rho}(\mathbf{p}) = \frac{1}{2} [\hat{l}_0(\mathbf{p}) + \sigma_b \mathbf{s}(\mathbf{p})]
\]

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

\[
\frac{d}{dz} \hat{\rho}(\mathbf{p}) = i \left( \hat{H} \hat{\rho}(\mathbf{p}) - \hat{\rho}(\mathbf{p}) \hat{H}^\dagger \right) = i \frac{1}{2} N \left( \hat{R}(0) \hat{\rho}(\mathbf{p}) - \hat{\rho}(\mathbf{p}) \hat{R}(0) \right)
\]

\[
\text{Real potential=} \text{Pure refraction}
\]

\[
- \frac{1}{2} N \left( \hat{\sigma}_{tot} \hat{\rho}(\mathbf{p}) + \hat{\rho}(\mathbf{p}) \hat{\sigma}_{tot} \right)
\]

(Imaginary potential=} Pure attenuation)
Polarization of Transmitted Beam Cont’d

\[ \hat{\sigma}_{\text{tot}} = \sigma_0 + \sigma_1(\mathbf{\sigma}_b \cdot Q) + \sigma_2(\mathbf{\sigma}_b \cdot k)(Q \cdot k), \]

\[ \hat{R}(0) = R_0 + R_1(\mathbf{\sigma}_b \cdot Q) + R_2(\mathbf{\sigma}_b \cdot k)(Q \cdot k) \]

\( k = \) beam axis, \( Q = \) target polarization.

Evolution of the beam polarization \( P = s/I_0 \)

\[ \frac{dP}{dz} = -N\sigma_1(Q - (P \cdot Q)P) - N\sigma_2(Q \cdot k)(k - (P \cdot k)P) \]

Polarization buildup by spin-sensitive transmission loss

\[ + \ N R_1(P \times Q) + N R_2(Pk)(Q \times k) \]

Spin precession in pseudomagnetic field

Precession: prime observable in neutron optics

After the precession is averaged out, a full equivalence to the Milstein-Strakhovenko kinetic equation.
Coupled evolution for pure transmission

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

Solutions

\[\alpha \exp(-\lambda_{1,2} Nz)\]

with eigenvalues

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

Reduction to Meyer's equation for pure transverse polarizations:

\[
\frac{dP}{dz} = -N\sigma_{1,T}Q\left(1 - P^2\right)
\]

\[P(z) = -\tanh(Q\sigma_{1,T}Nz)\]

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:

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

- 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

$$\frac{d}{dz}\hat{\rho} = \left[ i\frac{1}{2}N\left(\hat{R}\hat{\rho}(p) - \hat{\rho}(p)\hat{R}\right) - \frac{1}{2}N\left(\hat{\sigma}_{tot}\hat{\rho}(p) + \hat{\rho}(p)\hat{\sigma}_{tot}\right) \right] \text{ Ignore this precession} + \left[ \frac{d^2q}{(4\pi)^2} \hat{F}(q)\hat{\rho}(p - q)\hat{F}^\dagger(q) \right] \text{ Evolution by transmission loss}$$

Lost and recovered by scattering within the ring acceptance
Elastic NN scattering


Menagerie of spin observables (Bystricky et al):

\[
d\sigma = \frac{1}{2} d\sigma_0 \left\{ 1 + \left[ A_{00i0} P_i + A_{000j} Q_j \right] \right\}_{\text{beam & target analyzing powers}} \\
+ \left[ S_i P_{i000} \right]_{\text{normal polarization of scattered }} \\
+ \left[ A_{00ij} P_i Q_j \right]_{\text{beam-target double spin asymmetry}} + \left[ S_i P_i Q_j M_{10ij} \right]_{\text{triple-spin correlation}} \\
+ \left[ S_i P_i D_{i0j0} \right]_{\text{beam-to-scattered spin transfer}} \\
+ \left[ S_j Q_j K_{100j} \right]_{\text{target-to-scattered spin transfer}} \}
\]
Stationary polarizations in the storage ring

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

  normal to the ring \((\text{transverse})\): \(Q = QN\)

  tangential to the ring \((\text{longitudinal})\) with the Siberian Snake: \(Q = Qk\).

- 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:

\[ A_{OOQj}Q_j = Q(A_{OOon} \cos \phi + A_{OOOs} \sin \phi) \Rightarrow 0 \]

Double spin asymmetry:

\[ A_{OOij}P_iQ_j \Rightarrow \frac{1}{2}PQ(A_{OOon} + A_{OOss}). \]

Depolarization (beam-to-scattered spin transfer)

\[ S_lP_iD_{t0i0} \Rightarrow \frac{1}{2}SP\left(D_{s'0s0} \cos \theta + D_{k'0s0} \sin \theta + D_{n0n0}\right), \]

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

\[ S_lQ_jK_{l00j} \Rightarrow \frac{1}{2}SQ\left(K_{s'00s} \cos \theta + K_{k'00s} \sin \theta + D_{n00n}\right), \]
Transverse Spin: Spin-Transfer vs. Spin-Flip

\[
d\sigma = d\sigma_0 \frac{1}{2} \left\{ \begin{array}{c}
1 \\
\frac{1}{2} P Q \left( A_{0O_n n} + A_{0O_s s} \right) \\
+ \frac{1}{2} S P \left( D_{s'0s0} \cos \theta + D_{k'0s0} \sin \theta + D_{n0n0} \right) \\
+ \frac{1}{2} S Q \left( K_{s'00s} \cos \theta + K_{k'00s} \sin \theta + K_{n00n} \right) \end{array} \right\} \\
\text{beam–target spin asymmetry} + \text{beam–to–scattered spin transfer} + \text{target–to–scattered spin transfer}
\]

\[
\approx \frac{1}{2} \left( 1 + SP \right) d\Sigma_{0,T} + \frac{1}{2} \left( 1 - SP \right) 2d\Delta\Sigma_{0,T} + \frac{1}{2} Q \left( P + S \right) d\Sigma_{1,T} + \frac{1}{2} dQ \left( P - S \right) \Delta\Sigma_{1,T}.
\]

unpolarized non–flip  unpolarized spin–flip

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:

\[
   d\sigma_{1,T} = \frac{1}{2} d\sigma_0 \mathcal{P} \mathcal{Q} \left( A_{O0nn} + A_{O0ss} \right)
\]

Non-Flip X-sections

\[
   d\Sigma_{0,T} = d\sigma_0 \frac{1}{2} \left[ 1 + \frac{1}{2} \left( D_{s'0s0} \cos \theta + D_{k'0s0} \sin \theta + D_{n0n0} \right) \right]
\]

\[
   d\Sigma_{1,T} = \frac{1}{2} d\sigma_0 \left[ \left( A_{O0nn} + A_{O0ss} \right) + \left( K_{s'00s} \cos \theta + K_{k'00s} \sin \theta + K_{n00n} \right) \right]
\]

Spin-Flip off unpolarized target

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

Spin-Flip off polarized target

\[
   d\Delta \Sigma_{1,T} = \frac{1}{2} d\sigma_0 \left[ \left( A_{O0nn} + A_{O0ss} \right) - \left( K_{s'00s} \cos \theta + K_{k'00s} \sin \theta + K_{n00n} \right) \right].
\]
Longitudinal Spin: Spin-Transfer vs. Spin-Flip

Elastic scattering

\[ d\sigma = \frac{1}{2} d\sigma_0 \left\{ 1 + PQ A_{OOkk}, \right\} \]

\[ + SP \left( - D_{s'0k0} \sin \theta + D_{k'0k0} \cos \theta \right) + SQ \left( - K_{s'0k0} \sin \theta + K_{k'0k0} \cos \theta \right) \}

\[ \equiv \frac{1}{2} \left\{ \left( 1 + SP \right) d\Sigma_{0,L} \right\} + \frac{1}{2} \left\{ \left( 1 - SP \right) d\Delta\Sigma_{0,L} \right\} \]

\[ + \frac{1}{2} \left\{ \left( P + S \right) d\Sigma_{2,L} \right\} + \frac{1}{2} \left\{ \left( P - S \right) d\Delta\Sigma_{2,L} \right\} \]

Total X-section: \[ d\sigma_{tot} = d\sigma_0 \left\{ 1 + PQ A_{OOkk} \right\} = d\sigma_0 + PQ d\sigma_{2,L}. \]

Spin-flip, unpolarized target \[ d\Delta\Sigma_{0,L} = \frac{1}{2} \left[ 1 + D_{s'0k0} \sin \theta - D_{k'0k0} \cos \theta \right] \]

Spin-flip, polarized target \[ d\Delta\Sigma_{2,L} = \frac{1}{2} \left[ A_{OOkk} + K_{s'0k0} \sin \theta - K_{k'0k0} \cos \theta \right] \]
Decompose total transmission losses

\[
\frac{d}{dz} \hat{\rho} = -\frac{1}{2} N \left( \hat{\sigma}_{\text{tot}}(> \theta_{\text{acc}}) \hat{\rho}(p) + \hat{\rho}(p) \hat{\sigma}_{\text{tot}}(> \theta_{\text{acc}}) \right)
\]

Unrecoverable transmission loss

\[
-\frac{1}{2} N l_0(p) \left[ \sigma_0^{el}(< \theta_{\text{acc}}) + \sigma_1^{el}(< \theta_{\text{acc}}) P Q + \sigma_b \left( \sigma_0^{el}(< \theta_{\text{acc}}) P + \sigma_1^{el}(< \theta_{\text{acc}}) Q \right) \right]
\]

Potentially recoverable beam loss

Potentially recoverable spin loss

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

\[
\int d^2 p \int_{\Omega_{\text{acc}}} d^2 q \frac{d^2 q}{(4\pi)^2} \hat{F}(q) \hat{\rho}(p - q) \hat{F}^\dagger(q) = \hat{\sigma}^E (\leq \theta_{\text{acc}}) \cdot \int d^2 p l_0(p)
\]

The mismatch of the loss and recovery

\[
\Delta \hat{\sigma} = \frac{1}{4} \left( \hat{\sigma}_{el}(< \theta_{\text{acc}})(1 + \sigma_b P) + (1 + \sigma_b P) \hat{\sigma}_{el}(< \theta_{\text{acc}}) \right) - \hat{\sigma}_{Q\text{E}} (\leq \theta_{\text{acc}})
\]

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):

\[ \tilde{\sigma}_{tot}^{ep} = \sigma_0^{ep} + \sigma_1^{ep} (\sigma_p \cdot Q_e) + \sigma_2^{ep} (\sigma_p \cdot k)(Q_e \cdot k) + \text{spin-\textit{flip}} \]

\[ \text{Coulomb} \quad \text{Coulomb} \times (\text{Hyperfine+Tensor}) \]

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

\[ \Delta \Sigma_{0,T} \sim \frac{m_e}{m_p} \cdot \frac{T_{kin}}{m_p} \sigma_1^{ep} \]

Polarization of scattered protons $S$ (transverse case):

\[ S = P + Q_e \sigma_1^{ep} / \sigma_0^{ep} \]

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

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

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

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

The polarization buildup

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

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

\[
\sigma_{P,T} \approx -Q(\sigma_{1,T}(>\theta_{acc}) + \Delta \Sigma_{1,T})
\]
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:

\[
\frac{d}{dz} \begin{pmatrix} l_0 \\ s \end{pmatrix} = -N \begin{pmatrix} 0 & 0 \\ Q\Delta\Sigma_{1,T} & 2\Delta\Sigma_{0,T} \end{pmatrix} \begin{pmatrix} l_0 \\ s \end{pmatrix}.
\]

- M & S & Walcher: filtering without absorption: \( l_0(z) = l_0(0) \)

- 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: \( \Delta\Sigma_{0,T} \lesssim \sigma_{tot}\theta^2_{acc} \lesssim 10^{-4}\sigma_{tot}. \)
FILTEX according to Meyer-Horowitz:

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

Better understanding of target density & polarization (F.Rathmann, PhD):
$$\sigma_{p,T} = 72.5 \pm 5.8 (\text{stat.} + \text{sys.}) \text{ (stat.)}$$

Expected filtering by pure nuclear scattering: $\sigma_{p,T \text{ expected}} = 122 \text{ mb}$. 

H.O. Meyer: correct $\sigma_p$ for scattering within the beam. Strong suppression by CNI, Meyer’s reevaluation $\sigma_{1,T} (> \theta_{acc}) = 83 \text{ mb}$ (SAID of 94) instead of 122 mb

Add scattering within the beam off polarized electrons: $\delta \sigma_{1,T}^{ep} = -70 \text{ mb}$

Add scattering within the beam off polarized protons: $\delta \sigma_{1,T}^{ep} = +52 \text{ mb}$

Net result: $\sigma_{p,T} = 65 \text{ mb}$. 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:

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

(only marginal changes from SAID to Nijmegen databases).

Careful extrapolations under the CNI region

Very small spin-flip (loss-recovery mismatch) \( \times \)-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 conclusions: filtering magenta is dominated by losses for scattering beyond the ring acceptance angle.

Add spin-dependent annihilation for antiprotons
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

\[
\sigma_1(l = 0) = -\frac{1}{2} \Delta \sigma_T(l = 0) \text{ vs. energy in the isoscalar } NN \text{ channel (deuteron).}
\]

- The same electron effect but \( \sigma_1(l = 0) \) 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.
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 ≪ blue Electron-to-Proton spin transfer

• Walcher: loss-free filtering in a polarized electron “cooler”.
  Strong enhancement of $e_p$ 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 $\sigma_p = 72.5 \pm 5.8 \text{(stat. + sys.)}$ (FILTEX) and theory, $\sigma_p = 85.6 \text{mb}$ (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.