Spin Filtering of Stored (Anti)Protons: from FILTEX to COSY to AD to FAIR

Kolya Nikolaev and Fedya Pavlov

Institut f. Kernphysik, Forschungszentrum Jülich, 52425 Jülich, Germany
L.D.Landau Institute for Theoretical Physics, 142432 Chernogolovka, Russia

17th International Spin Physics Symposium (SPIN2006)
Kyoto, Japan, 2 - 7 October 2006.

Outline:

- Tons of top class QCD: Transversity from Drell-Yan with polarized antiprotons makes FAIR a unique successor of DIS physics
- Spin filtering in storage ring: a unique way of polarizing intense beam of antiprotons to high degree of polarization
- H.O. Meyer's problem: Spin filtering & scattering within the ring acceptance angle (SWRA)
- Undestanding the FILTEX experiment at TSR (23 MeV)
- Why the spin-filtering on polarized electrons cancels out?
- Implications for spin-filtering of antiprotons in PAX FAIR
- Longitudinal vs. transverse filtering
- Deuterium vs. hydrogen polarized internal target?

The transmission and scattering

- Optical filtering: with rare exceptions one only deals with the transmitted light.
- Transmission: Polarized target is an optically active medium with the polarization dependent refraction index

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

- Unique feature of storage rings: a mixing of the transmitted and scattered beam
- FILTEX ring acceptance $\theta_{acc} = 4.4$ mrad.
- Light electrons do not deflect heavy protons (Horowitz& Meyer): $\theta \leq \theta_e = m_e/m_p$
- Scattering within the ring acceptance angle (SWRA) does not absorb the beam:
- intensity-wise SWRA is entirely invisible
- Central issue: is SWRA invisible also polarization-wise?

The In-Medium Evolution of Transmitted Beam

- Time = distance z traversed in the medium.

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

N = density of atoms in the target.

- The density matrix of the stored beam

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

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

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

Evolution of Transmitted Beam Cont'd

- Spin dependence:

$$\hat{\sigma}_{tot} = \sigma_0 + \underbrace{\sigma_1(\boldsymbol{\sigma} \cdot Q) + \sigma_2(\boldsymbol{\sigma} \cdot \boldsymbol{k})(Q \cdot \boldsymbol{k})}_{spin-sensitive\ transmission\ loss},$$

$$\hat{R} = R_0 + \underbrace{R_1(\boldsymbol{\sigma} \cdot Q) + R_2(\boldsymbol{\sigma} \cdot \boldsymbol{k})(Q \cdot \boldsymbol{k})}_{\boldsymbol{\sigma}\cdot\text{Pseudomagnetic field}}$$

$\boldsymbol{k}$ = beam axis, Q = target polarization.

- Evolution of the beam polarization $P = \boldsymbol{s}/I_0$

$$dP/dz = \underbrace{-N\sigma_1(Q - (P \cdot Q)P) - N\sigma_2(Q\boldsymbol{k})(\boldsymbol{k} - (P \cdot \boldsymbol{k})P)}_{\text{Polarization buildup by spin-sensitive transmission}}$$

$$+ \underbrace{NR_1(P \times Q) + nR_2(Q\boldsymbol{k})(P \times \boldsymbol{k})}_{\text{Spin precession in pseudomagnetic field}}$$

- Aaverage out the precession: equivalence of the quantum evolution eqn. to the kinetic eqn. for spin population numbers.

The polarization buildup

- Coupled evolution equations for pure transmission

$$\frac{d}{dz}\begin{pmatrix} I_0 \\ s \end{pmatrix} = -N \begin{pmatrix} \sigma_0(>\theta_{\rm min}) & Q\sigma_1(>\theta_{\rm min}) \\ Q\sigma_1(>\theta_{\rm min}) & \sigma_0(>\theta_{\rm acc}) \end{pmatrix} \cdot \begin{pmatrix} I_0 \\ s \end{pmatrix},$$

- Solutions

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

with eigenvalues

$$\lambda_{1,2} = \sigma_0 \pm Q\sigma_1$$

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

$$\frac{dP}{dz} = -N\sigma_1 Q(1 - P^2)$$

$$P(z) = -\tanh(Q\sigma_1 N z)$$

- Any spin-dependent loss filters spin of the stored beam, 100 % limiting polarization

FILTEX: SWRA according to Meyer-Horowitz

- FILTEX at 23 MeV TSR (1993): proof of the principle with transverse polarization: $\sigma_P = 63 \pm 3(stat.)mb$
- Pure transmission by pure nuclear scattering: $\sigma_{P,expected}(SAID) = 122$ mb.
- H.O. Meyer: only scattering beyond θ_{acc} must be included. Correct for CNI, Meyer's reevaluation $\sigma_1(CNI; > \theta_{\rm acc}) = 83$ mb vs. 122 mb
- EM tensor and hyperfine int's: electron-to-proton polarization transfer. Scattered electrons bring 100 per cent of their polarization back into the stored beam: $\delta\sigma_1^{ep} = -70$ mb
- Add polarization of protons from SWRA : $\delta\sigma_1^{pp} = +52$ mb
- Net result: $\sigma_P = \sigma_1(CNI; > \theta_{\rm acc}) + \delta\sigma_1^{pp} + \delta\sigma_1^{ep} = 135 \quad {\rm mb} + \delta\sigma_1^{ep} = 65 \quad {\rm mb}.$
- Good but accidental agreement with FILTEX: double counting of SWRA.
- Better understanding of target density & polarization (F.Rathmann, PhD): $\sigma_P = 72.5 \pm 5.8(stat. + sys.)$ (stat.)

SWRA and Spin Filtering

- Quasielastic (E) $p + atom \rightarrow p'_{scatt} + e + p_{recoil}$, $\boldsymbol{q}$ = momentum transfer:

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

- Unitarity of recovery of lost beam from SWRA: $\theta \leq \theta_{acc}$
- SWRA from multiple-scattering theory:

$$\frac{d}{dz}\hat{\rho} = i[\hat{H},\hat{\rho}] = \underbrace{i\frac{1}{2}N\Big(\hat{R}\hat{\rho}(\boldsymbol{p}) - \hat{\rho}(\boldsymbol{p})\hat{R}\Big)}_{Ignore\ this\ precession} - \underbrace{\frac{1}{2}N\Big(\hat{\sigma}_{tot}\hat{\rho}(\boldsymbol{p}) + \hat{\rho}(\boldsymbol{p})\hat{\sigma}_{tot}\Big)}_{\text{Transmission}}$$

$$+ \underbrace{N\int^{\Omega_{acc}} \frac{d^2\boldsymbol{q}}{(4\pi)^2}\hat{\mathfrak{F}}(\boldsymbol{q})\hat{\rho}(\boldsymbol{p}-\boldsymbol{q})\hat{\mathfrak{F}}^\dagger(\boldsymbol{q})}_{\text{Recovery from SWRA}}$$

Pure SWRA off Atomic Electrons: $\theta_e \ll \theta_{acc}$

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

$$U(\boldsymbol{q}) = \alpha_{em}\left\{\frac{1}{\boldsymbol{q}^2} + \mu_p \frac{(\sigma_p \boldsymbol{q})(\sigma_e \boldsymbol{q}) - (\sigma_p \sigma_e)\boldsymbol{q}^2}{4 m_p m_e \boldsymbol{q}^2}\right\}$$

$$\hat{\sigma}^e_{tot} = \underbrace{\sigma^e_0}_{Coulomb} + \underbrace{\sigma^e_1(\sigma_p \cdot Q_e) + \sigma^e_2(\sigma_p \cdot \boldsymbol{k})(Q_e \cdot \boldsymbol{k})}_{Coluomb\times(Hyperfine+Tensor)}$$

- Polarization of scattered protons P_f (transverse case):

$$\sigma^e_0 P_f = \sigma^e_0 P + \sigma^e_1 Q_e$$

- clearcut electron-to-proton spin transfer (Akhiezer,...,Horowitz-Meyer): used at MAMI/Bates/Jlab for precision measurements of G_E/G_M
- negligible spin-flip form proton spin-orbit int. (Milstein-Strakhovenko)
- Don't confuse the spin transfer (spin exchange) with the spin-flip

Skrinsky: do electrons polarize (anti)protons?

- Electron contribution to the tranmission losses

$$\frac{1}{2}\frac{d}{dz}I_0(\boldsymbol{p})(1+\sigma\cdot P(\boldsymbol{p})) = -\frac{1}{2}NI_0(\boldsymbol{p})\Big[\underbrace{\sigma_0^e+\sigma_1^e PQ_e}_{\text{particle number loss}} + \sigma\underbrace{\left(\sigma_0^e P+\sigma_1^e Q_e\right)}_{\text{selective spin loss}}\Big]$$

- What is recovered from scattering within the ring acceptance :

$$N\int\frac{d^2\boldsymbol{q}}{(4\pi)^2}\hat{\mathfrak{F}}_e(\boldsymbol{q})\hat{\rho}(\boldsymbol{p}-\boldsymbol{q})\hat{\mathfrak{F}}_e^\dagger(\boldsymbol{q})$$

$$= \underbrace{\frac{1}{2}NI_0(\boldsymbol{p})\left[\sigma_0^e+\sigma_1^e(P\cdot Q)\right]}_{\text{Particles recovered from SWRA}} + \underbrace{\frac{1}{2}NI_0(\boldsymbol{p})\sigma\left[\sigma_0^e P+\sigma_1^e Q_e\right]}_{\text{Spin recovered from SWRA}}$$

- Transmission losses are exactly canceled by scattering within the ring acceptance.
- Polarization-wise atomic electrons are invisible

Nuclear *pp* Scattering within the Ring Acceptance

- Decompose pure transmission losses (transverse polarization)

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

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

- Feedback from SWRA (angular divergence of the beam at target $\ll \theta_{acc}$: integrate over $\boldsymbol{p}$)

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

- The mismatch of transmission loss and feedback from SWRA

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

What SWRA Does to Polarization

$$\underbrace{\hat{\sigma}^E(\leq \theta_{\rm acc})}_{SWRA} = \underbrace{\sigma_0^{el}(\leq \theta_{\rm acc}) + \sigma_1^{el}(\leq \theta_{\rm acc})(P \cdot Q)}_{Feedback\ of\ particles\ from\ SWRA}$$

$$+ \underbrace{\sigma \cdot \left(\sigma_0^E(\leq \theta_{\rm acc})P + \sigma_1^E(\leq \theta_{\rm acc})Q\right)}_{Feedback\ of\ spin\ from\ SWRA}$$

The mismatch X-section operator is a beam proton spin-flip:

$$\Delta\hat{\sigma} = \underbrace{\sigma_0^{el}(< \theta_{\rm acc}) + \sigma_1^{el}(< \theta_{\rm acc})PQ_e}_{Potentially\ recoverable\ particle\ loss} + \sigma \underbrace{\left(\sigma_0^{el}(< \theta_{\rm acc})P + \sigma_1^{el}(< \theta_{\rm acc})Q_e\right)}_{Potentially\ recoverable\ spin\ loss}$$

$$- \underbrace{\sigma_0^{el}(\leq \theta_{\rm acc}) + \sigma_1^{el}(\leq \theta_{\rm acc})(P \cdot Q)}_{Particles\ from\ SWRA} - \underbrace{\sigma \cdot \left(\sigma_0^E(\leq \theta_{\rm acc})P + \sigma_1^E(\leq \theta_{\rm acc})Q\right)}_{Spin\ from\ SWRA}$$

$$= \sigma\left(\Delta\sigma_0 P + \Delta\sigma_1 Q\right)$$

Mismatch cont'd

- $\Delta\sigma_{0,1}$: a mismatch between the spin of the beam taken away by the scattered particle and put back by after the SWRA (=spin-flip)

$$\sigma_1^{el}(>\theta_{\rm acc}) = \frac{1}{2}\int_{\theta_{\rm acc}} d\Omega\Big(d\sigma/d\Omega\Big)\Big(A_{00nn}+A_{00ss}\Big)$$

$$\Delta\sigma_0 = [\sigma_0^{el}(\leq\theta_{\rm acc}) - \sigma_0^{E}(\leq\theta_{\rm acc})]$$

$$= \int_{\theta_{\rm min}}^{\theta_{\rm acc}} d\Omega\frac{d\sigma}{d\Omega}\Big(1-\frac{1}{2}D_{n0n0}-\frac{1}{2}D_{s'0s0}\cos(\theta_{lab})\Big)$$

$$\Delta\sigma_1 = \sigma_1^{el}(\leq\theta_{\rm acc}) - \sigma_1^{E}(\leq\theta_{\rm acc})$$

$$= \frac{1}{2}\int_{\theta_{\rm min}}^{\theta_{\rm acc}} d\Omega\frac{d\sigma}{d\Omega}\Big(A_{00nn}+A_{00ss}-K_{n00n}-K_{s'00s}\cos(\theta_{lab})\Big)$$

- The SAID menagerie:
  $A_{00nn}=A_{yy}$, $A_{00ss}=A_{xx}$, $K_{n00n}=D_t$, $D_{s'0s0}=R$, $D_{n0n0}=D$, $K_{s'00s}=-R'_t$.
- $\Delta\sigma_0$ = spin-flip on unpolarized target, $\Delta\sigma_1$= spin-flip on polarized target,
  $|\Delta\sigma_1|\leq|\Delta\sigma_0|$

Polarization Buildup

- Coupled evolution equations after into-the-beam scattering

$$\frac{d}{dz}\begin{pmatrix} I_0 \\ s \end{pmatrix} = -N \begin{pmatrix} \sigma_0(>\theta_{\rm acc}) & Q\sigma_1(>\theta_{\rm acc}) \\ Q(\sigma_1(>\theta_{\rm acc}) + \Delta\sigma_1) & \sigma_0(>\theta_{\rm acc}) + \Delta\sigma_0 \end{pmatrix} \cdot \begin{pmatrix} I_0 \\ s \end{pmatrix},$$

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

$$\lambda_{1,2} = \sigma_0 + \frac{1}{2}\Delta\sigma_0 \pm Q\sigma_3, \quad Q\sigma_3 = \sqrt{Q^2\sigma_1(\sigma_1 + \Delta\sigma_1) + \frac{1}{4}\Delta\sigma_0{}^2},$$

- The polarization buildup (also Milstein&Strakhovenko)

$$P(z) = -\frac{Q(\sigma_1 + \Delta\sigma_1)\tanh(Q\sigma_3 N z)}{Q\sigma_3 + 0.5\Delta\sigma_0 \tanh(Q\sigma_3 N z)}$$

- The effective small-time polarization cross section

$$\sigma_P \approx -Q(\sigma_1 + \Delta\sigma_1) = 85.6 \text{ mb} \qquad vs.\ M-H \qquad \sigma_P \approx -Q(\sigma_1 + \delta\sigma_1^{ep+pp})$$

Delta sigma_1 =
-6*10^-3 mb

Pure electron target

- Pure SWRA: $\sigma_0(>\theta_{acc}) = 0, \quad \sigma_1(>\theta_{acc}) = 0, \quad Q\sigma_3 = \Delta\sigma_0.$
- Evolution of the spin-density matrix:

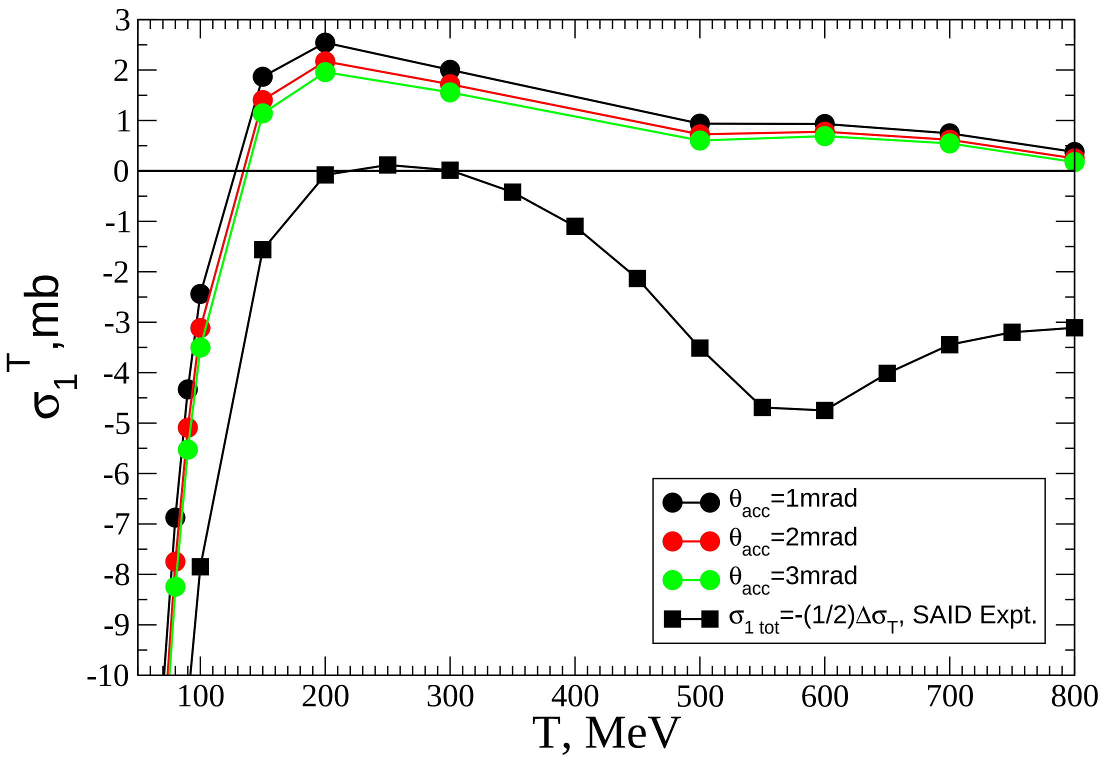
$$\frac{d}{dz}\begin{pmatrix} I_0 \\ s \end{pmatrix} = -N\begin{pmatrix} 0 & 0 \\ Q\sigma_1(>\theta_{acc}) & \Delta\sigma_0 \end{pmatrix}\cdot\begin{pmatrix} I_0 \\ s \end{pmatrix},$$

- The number of stored particles is conserved: $I_0(z) = I_0(0)$
- Evolution of the polarization:

$$P(z) = P(0)\exp(-N\Delta\sigma_0 z) + Q\frac{\Delta\sigma_1}{\Delta\sigma_0}\left\{1 - \exp(-N\Delta\sigma_0 z)\right\}$$

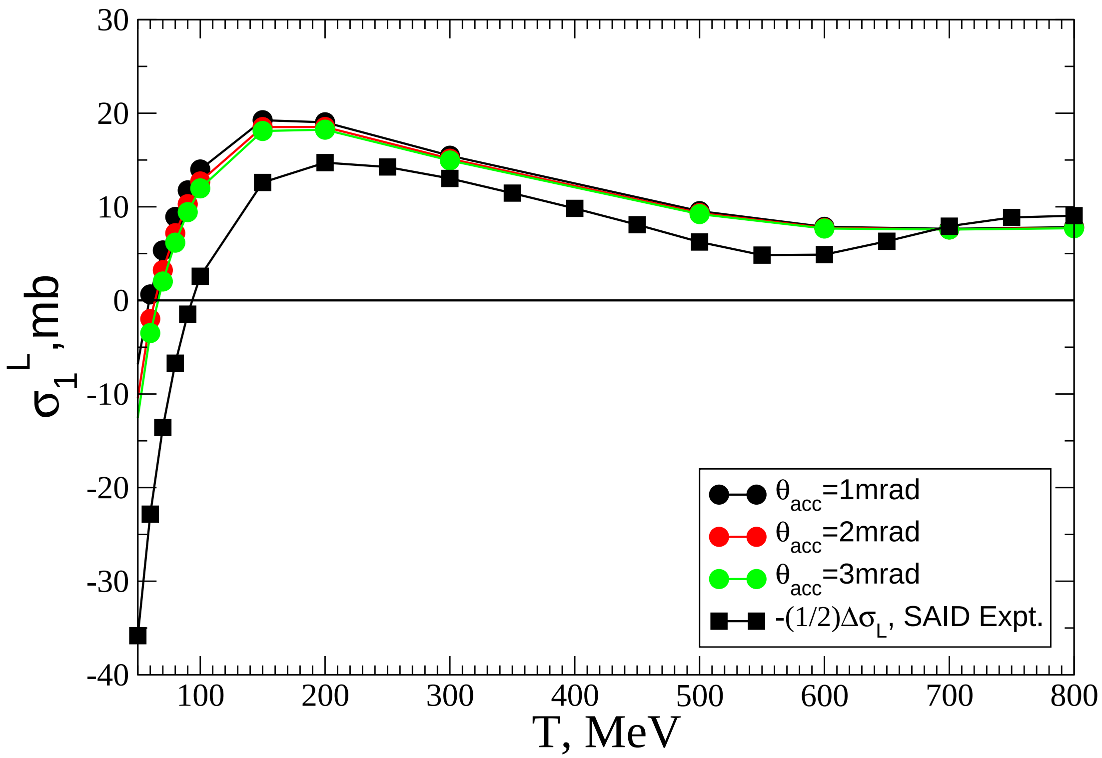
- Depolarization of stored protons in unpolarized ^{4}He: $\Delta\sigma_0$ and $|\Delta\sigma_1| \leq |\Delta\sigma_0|$.
- Depolarization proof that $\Delta\sigma_0 \ll \sigma_1(>\theta_{acc})$
- Pure hadronic mechanism: $\Delta\sigma_0 \lesssim \sigma_{tot}\theta^2_{acc} \lesssim 10^-4\sigma_{tot}.$

COSY: energy dependence of transverse filtering



Two strong CNI effects:
Substantial departure from pure nuclear $\Delta\sigma_T$.
Sensitivity to acceptance angle.

COSY: longitudinal filtering



Strong CNI effect at low energy, much weaker at high energy

Conclusions: what is the future for PAX?

- FILTEX: an important proof of the principle of spin filtering.
- A consensus between theorists (Budker Institute & IKP FZJ): Polarized electrons in polarized atoms wouldn't polarize antiprotons in storage rings.
- Still slight disagreement between experiment $\sigma_P = 72.5 \pm 5.8(stat. + sys.)$ (FILTEX) and theory, $\sigma_P = 85.6mb$ (Meyer & Budker Institute & IKP FZJ).
- Solution for PAX: spin filtering by nuclear antiproton-proton interaction . Must be optimized with existing antiprotons.
- $N\bar{N}$ models are encouraging, but unreliable.
- Meyer-Horowitz vs. Budker-Juelich: go longitudinal & transverse with both hydrogen and deuterium. The distinct energy dependence will be a solid proof of the pure hadronic mechanism.