Polarized Beams
a powerful tool for particle physics

Wolfgang Hillert

Electron Stretcher Accelerator

Physics Institute of Bonn University

Why?
→ Physics with polarized protons/deuterons and electrons

How?
→ a) Beam generation (sources of polarized protons and electrons)
→ b) Beam acceleration (crossing of depolarizing resonances)
→ c) Spin management, energy calibration

Coming?
→ Polarized antiparticles, new projects
Why?
Matter and Forces

Electromagnetic Interaction
- Crystal Lattice
- Atom

Strong Interaction
- Nucleus
- Hadron

10^{-9}m 10^{-10}m 10^{-14}m 10^{-15}m

“Nanometer“

“Femtometer“
Nucleons:

Made from quarks and gluons, bound by strong interaction.

Many open questions, e.g.:

- **What generates the mass of the nucleon** and its excitations (resonances)?
  - small contribution of the quark masses!

- **Spin-Structure of the nucleon?**
  contributions to the nucleon spin?
  - spin of the quarks
  - spin of the gluons
  - angular momentum (quarks, gluons)

**Polarized beams (and polarized targets) required!**
Baryon - Spectroscopy

**Atomic Physics**

Atom: $10^{-10}$ m

Excitation with Photons:
**Line Spectrum**

**Hadron Physics**

Hadron: $10^{-15}$ m

Excitation with Photons:
**Overlapping Resonances**

Linewidth from $\Delta E \cdot \Delta t \geq \hbar$

→ **Double Polarization Experiments**
a) Sources for polarized particles
Spin Filtering?

Stern-Gerlach Experiment:

\[ \vec{F} = (\hat{\mu} \cdot \nabla) \vec{B} \quad \rightarrow \quad F_z = \mu \cdot \frac{\partial B_z}{\partial z} \]

Split-up into different separated beams in case of neutral atoms

Charged particles (e\(^{-}\), p\(^{+}\)):

\[ \vec{F} = \frac{q}{m} \cdot (\vec{p} \times \vec{B}) \quad \text{and} \quad \Delta x \cdot \Delta p_x > \hbar \]

but:
Polarized Protons

Functional Principle:

**Atomic Beam**
- dissociator
- LN$_2$-cooled nozzle
- → thermalized H atoms

**Beam Separation**
- 6-pole fields & RF-transitions
- act as „Stern-Gerlach“-polarizer
- pol-enhancement by RF-pumping
- sextupole
- RF

**Ionization**
- Penning ionizer
- e-removal and acceleration

Haeberli (review), 1967
Polarization Scheme
slow (≈ 3 meV) atomic beams

Deuteron:

\[ F = J + I \]
\[ m_F = m_j + m_I \]
\[ |m_j, m_I> \]

F = 3/2
-1/2
-1/2
+1/2
+3/2
-3/2

F = 1/2
-1/2
+1/2

State No. | Unpolar. | Electron Polar. (1st 6-Pole) | RF-Trans. (3\&5) | 2nd 6-Pole | RF-Trans. (2\&6)
---|---|---|---|---|---
1 | | | | | |
2 | | | | | |
3 | | | | | |
4 | | | | | |
5 | | | | | |
6 | | | | | |

\[ P_{Z} \]
\[ P_{Z}^2 \cdot I_r \]
\[ P_{ZZ} \]
\[ P_{ZZ}^2 \cdot I_r \]

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Polarized $H^-$-Atoms

$H^+_\uparrow + Cs \rightarrow \overline{H}^+_\uparrow + Cs^+$
COSY CBS Source
High Intensities

Other types of sources in operation, e.g.:

- **OPPIS (BNL)**
  
  *Optically Pumped Polarized Ion Source*
  
  based on polarization transfer:
  
  $$\text{H}^+ + \text{Rb}^+ \rightarrow \text{H}^+ + \text{Rb}^+$$

- **CIPIOS (FZJ)**
  
  *Cooler Injector Polarized Ion Source*
  
  based on spin filtering and RF transitions
  
  ionization:
  
  $$\text{H}^+ + \text{D}^+ \rightarrow ^+\text{H}^+ + \text{D}$$
Polarized Electrons

Functional Principle:

- Semiconductor photocathode based on GaAs
- Circularly polarized laser light
- Photoelectron emission from GaAs
- Polarization transfer from laser photons to emitted electrons

Pierce & Meier, 1976
Polarized Electrons

Optical Pumping:

\[ P_{\text{max}} = \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}} = \frac{1 - 3}{1 + 3} = -0.5 \]
Polarized Electrons

Removal of the degeneracy:
- local distortions of the lattice (strain)
- multilayer structures (superlattice)
Operation, heat cleaning and activation in extreme UHV

Lifetime 1000 h $\leftrightarrow P (\text{H}_2\text{O}, \text{CO}_2) < 10^{-13}$ mbar
Polarized $e^-$-Sources Worldwide

- **CEBAF (Jefferson Lab, a)**
  \[ E = 100 \text{ keV}, \ P > 80\%, \ I = 200 \mu\text{A} \ (\text{cw}) \]

- **Bonn (ELSA, b)**
  \[ E = 48 \text{ keV}, \ P > 80\%, \ I = 100 \text{mA} \ (1\mu\text{s}) \]

- **Mainz (MAMI, c)**
  \[ E = 100 \text{ keV}, \ P > 80\%, \ I < 40 \mu\text{A} \ (\text{cw}) \]

- **Darmstadt (S-DALINAC, d)**
  \[ E = 100 \text{ keV}, \ P > 80\%, \ I = 60 \mu\text{A} \ (\text{cw}) \]

**Challenge:** long photocathode lifetime $\leftrightarrow$ ultimate vacuum required
b) Acceleration of polarized particles
## Facilities with Polarized Beams

### Protons:
- **COSY** / Jülich \((E < 2.4 \text{ GeV})\)
- **Saturne II** / Saclay \((E < 3 \text{ GeV})\)
- **KEK PS** / Tsukuba \((E < 7 \text{ GeV})\)
- **ZGS** / Argonne \((E < 12 \text{ GeV})\)
- **AGS** / Brookhaven \((E < 22 \text{ GeV})\)
- **RHIC** / Brookhaven \((E < 250 \text{ GeV})\)
- ... 

### Electrons:
- **SDALINAC** / Darmstadt \((E < 130 \text{ MeV})\)
- **AMPS** / Nikhef \((E < 0.9 \text{ GeV})\)
- **SHR** / MIT-Bates \((E < 1 \text{ GeV})\)
- **MAMI** / Mainz \((E < 1.6 \text{ GeV})\)
- **ELSA** / Bonn \((E < 3.2 \text{ GeV})\)
- **SPEAR** / SLAC \((E < 3.7 \text{ GeV})\)
- **DORIS** / DESY \((E < 5 \text{ GeV})\)
- **CEBAF** / Jlab \((E < 6 \text{ GeV})\)
- **PETRA** / DESY \((E < 18 \text{ GeV})\)
- **HERA** / DESY \((E = 27.5 \text{ GeV})\)
- **SLC** / SLAC \((E < 46 \text{ GeV})\)
- ...
Polarization

• Spin ½: Electrons, Protons, ...

\[ L = \frac{1}{2} \rightarrow m = \left\{ \begin{array}{c} + \frac{1}{2} \\ -\frac{1}{2} \end{array} \right\} \]

\[ m_z = 1/2 \rightarrow L = 3/4 \]

\[ L = 3/4 \rightarrow m_z = -1/2 \]

\[ P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} \]

Vector Polarization

• Spin 1: Deuterons, ...

\[ L = 1 \rightarrow m = \left\{ \begin{array}{c} +1 \\ 0 \\ -1 \end{array} \right\} \]

\[ m_z = 1 \rightarrow L = 2 \]

\[ m_z = 0 \rightarrow L = 2 \]

\[ m_z = -1 \rightarrow L = 2 \]

in addition:

\[ P = 1 - \frac{3N_0}{N_\uparrow + N_0 + N_\downarrow} \]

Tensor Polarization
Spin ↔ Magnetic Moment:
\[ \vec{\mu} = g \frac{e}{2m} \cdot \vec{S} \]

Spins in Magnetic Fields:
\[ \frac{d\vec{S}}{dt} = \vec{\mu} \times \vec{B} \]

Landé-Factor and Gyromagnetic Anomaly:
- Electrons: \( a = \frac{1}{2} (g - 2) = 1,15967 \cdot 10^{-3} \)
- Protons: \( a = \frac{1}{2} (g - 2) = 1,792843 \)
- Deuterons: \( a = \frac{1}{2} (g - 2) = -0,142987 \)
Spin-Precession

Spin-Tune: \( Q_{sp} = \gamma a, \quad a = \frac{g - 2}{2} \)

\[
\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} \\
\vec{\Omega}^* = -\frac{e}{m_0} (1 + a) \cdot \vec{B} \\
\vec{\Omega}_{BMT} = -\frac{e}{m_0 \gamma} \left\{ (1 + a\gamma) \cdot \vec{B}_\perp + (1 + a) \cdot \vec{B}_\parallel - \left( a + \frac{1}{\gamma + 1} \right) \cdot \gamma \vec{\beta} \times \frac{\vec{E}}{c} \right\}
\]
LINACs and Recirculators

Example: MAMI / Mainz

- RTM 2
  - 51 turns
  - 180 MeV
  - $B = 0.55 \, T$

- RTM 1
  - 18 turns
  - 14.9 MeV
  - $B = 0.10 \, T$

- Linac
  - 3.5 MeV
  - $\Delta E = 0.6 \, MeV$
  - $\varphi_z = -22^\circ$

- Wien filter

- RTM 3
  - $B = 1.28 \, T$

- Source of pol. e$^-$

$\vec{E} \perp \vec{B}$, \quad $E/B = \nu$

\[
\phi_{\text{Spin}} = \frac{eB_\perp}{\gamma^2 m_0 v} \cdot \frac{\beta c}{L}
\]

✓ for "moderate" energies!
Spin-Precession in Circular Acc.

\[ \frac{d \vec{S}}{dt} = \vec{\Omega} \times \vec{S} \]

\[ \vec{\Omega}^* = -\frac{e}{m_0} (1 + \alpha) \cdot \vec{B} \]

\[ \vec{\Omega}_{BM} = -\frac{e}{m_0 \gamma} \left\{ (1 + \alpha \gamma) \cdot \vec{B}_\perp + (1 + \alpha) \cdot \vec{B}_\parallel - \left( \alpha + \frac{1}{\gamma + 1} \right) \cdot \gamma \vec{\beta} \times \frac{\vec{E}}{c} \right\} \]
Spin-Precession in Circular Acc.

Spin-Tune: \[ Q_{sp} = \gamma a, \quad a = \frac{\gamma - 2}{2} \]

- **Electrons:** \[ \gamma = 862.31 \cdot n \leftrightarrow \Delta E_{\text{kin}} = 440.6 \text{ MeV} \]
- **Protons:** \[ \gamma = 0.5578 \cdot n \leftrightarrow \Delta E_{\text{kin}} = 523.3 \text{ MeV} \]
- **Deuterons:** \[ \gamma = 6.9936 \cdot n \leftrightarrow \Delta E_{\text{kin}} = 13.12 \text{ GeV} \]

**Magic Energies** \( (\gamma \cdot a = n) \)
Depolarizing Resonances

Magic Energies ($\gamma \cdot a = n$)

- **electrons:** $\gamma = 862.31 \cdot n \leftrightarrow \Delta E_{\text{kin}} = 440.6 \text{ MeV}$
- **protons:** $\gamma = 0.5578 \cdot n \leftrightarrow \Delta E_{\text{kin}} = 523.3 \text{ MeV}$
- **deuterons:** $\gamma = 6.9936 \cdot n \leftrightarrow \Delta E_{\text{kin}} = 13.12 \text{ GeV} !!!$
Imperfection Resonance: \( \gamma \cdot \alpha = n, \quad n \in \mathbb{Z} \)
Depolarizing Resonances

Strong Focusing: Betatron Oscillations!

Imperfection Resonance: \[ \gamma \cdot \alpha = n, \quad n \in \mathbb{Z} \]
Resonances of 1\textsuperscript{st} order

\begin{itemize}
  \item Electrons
    \begin{itemize}
      \item $\gamma a = 3$
      \item $\gamma a = 4$
      \item $\gamma a = 5$
      \item $\gamma a = 6$
      \item $\gamma a = 7$
    \end{itemize}
  \item Protons
    \begin{itemize}
      \item $\gamma a = 1$
      \item $\gamma a = 2$
      \item $\gamma a = 3$
      \item $\gamma a = 4$
      \item $\gamma a = 5$
    \end{itemize}
\end{itemize}

COSY Univ. Bonn ($P = 2$)

Optics with $P = 2$
Resonance Crossing

Crossing Speed: \( \alpha = \dot{\gamma} \alpha / \omega_{rev} \) → Resonance Strength \( \varepsilon \)
Resonance Crossing

Froissart-Stora-Formula

\[
\frac{P_f}{P_i} = 2 \cdot e^{-\frac{\pi |\sigma|^2}{2\alpha}} - 1
\]

\[
\frac{P_f}{P_i} = \frac{2}{\pi |\sigma|^2 + 1} - 1
\]
Vertical Orbit Excitations

Take care of the resonance-driving harmonics $\gamma \cdot a = n$!
Vertical Orbit Excitations

Take care of the resonance-driving harmonic $\gamma \cdot a = n$!

Advantages:
- Distortions have only to be sufficiently strong
- No detailed optimization required

Disadvantages:
- CO excursions may be too large for available aperture

\[ B(s) = a \cdot \sin(Q_{sp} \cdot \theta) + b \cdot \cos(Q_{sp} \cdot \theta) \]
Synchrotron Oscillations

Multiple crossing of depolarizing resonances due to energy oscillations

Oscillation frequency/tune:

- **electrons (ELSA):**
  \[ \Omega \approx 80 \text{ kHz} \leftrightarrow Q_s \approx 0.04 \]

- **protons (COSY):**
  \[ \Omega \approx 0.5 \text{ kHz} \leftrightarrow Q_s \approx 0.0006 \]

Crossing of (weaker) sidebands around imperfection resonance
Synchrotron Oscillations

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**Protons:** synchrotron satellites close by → „broader“ resonance → larger values required for full spin flip

Crossing of (weaker) sidebands around imperfection resonance

(figure taken from habil. A. Lehrach)
Synchrotron Oscillations

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- **Crossing of (weaker) sidebands around imperfection resonance**

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Crossing of Synchrotron-Sidebands

Beam excitation will only cause partial spin flip $\rightarrow$ depolarization!

- Reduce resonance strength by **proper centering in the quads**
- Compensate **resonance driving horizontal magnetic fields**

Full Spin-Flip no longer possible!

Experimental verification at ELSA:

```
\text{\textquoteleft\textquoteleft Modified	extquoteright\textquoteright\textquoteleft Froissart-Stora Formula:}

\frac{P_f}{P_i} = \left(2 \cdot e^{\frac{\beta^2}{2\alpha}} - 1\right) \cdot \left(2 \cdot e^{\frac{\beta^2}{2\alpha}} - 1\right)^2
```

\(\gamma_a = 5\)
CO Correction on the Ramp

vertical beam position / mm in stretcher during ramp $E_{\text{inj}} = 1.200\,\text{GeV}$, $E_{\text{extr}} = 2.350\,\text{GeV}$

- $\dot{B} = 1.2\,\text{Tesla/s}$
- $\Delta z_{\text{rms}} \leq 80\,\mu\text{m}$

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Harmonic Correction
(Imperfection-Resonances)

\[ B(s) = a \cdot \sin(Q_{sp} \cdot \theta) + b \cdot \cos(Q_{sp} \cdot \theta) \]
Spin-Orbit Response Technique

2 Contributions:

\[ \alpha_n = \sum_{j \in \text{Dip}_n} \alpha_{\text{corr},j} + l \cdot \sum_{j \in \text{Dip}_n} k_j \cdot \Delta z_j = \sum_{j \in \text{Dip}_n} \alpha_{\text{corr},j} + l \cdot \sum_{j \in \text{Dip}_n} k_j \cdot (\text{ORM} \cdot \tilde{\alpha}_{\text{corr}})_j \]

Spin-Orbit Response Matrix:

\[ \tilde{\alpha}_{\text{harm}} = HCM \cdot \tilde{\alpha}_{\text{corr}} \]

\[ HCM_{i,k} = \delta_{i,k}^{\text{VC}} + \sum_{m=1}^{32} \delta_{m,k}^O \cdot l_m \cdot k_m \cdot \text{ORM}_{m,i} \]
Spin-Orbit Response Technique

HCM

[Graph showing spin-orbit response technique with markers for wanted and achieved distributions and kick angles.]
Intrinsic Resonances

\[ \gamma \cdot a = n \cdot P \pm Q_z \]

Countermeasures:

- high superperiodicity \( P \) (lattice, machine optics)
- reduce vertical beam size (cooling, skew quads, optics)
- increase crossing speed (tune jumping)
Intrinsic Resonances

Countermeasures:
- high superperiodicity $P$ (lattice, machine optics)
- reduce vertical beam size (cooling, skew quads, optics)
- increase crossing speed (tune jumping)

Tune Jumping:
Tune-Jump Quadrupole

- Copper coil air core
- Length 0.6 m
- Max. current ±3100 A
- Max gradient 0.45 T/m
- Rise time 10 μs,
- Fall time 10 to 40 ms
Polarization during Acceleration

Intrinsic resonances $\rightarrow$ tune jumps
Imperfection resonances $\rightarrow$ vertical orbit excitation

$P > 75\%$ at $3.3$ GeV/c
Beam Energy: $E = 2.35$ GeV

$P_{av} \approx 63.89\%$

CBELSA/TAPS data taking Nov./Dec. 2009
Why not having a polarized beam in:

- LEP (@ 100 GeV)?
- HERA-p (920 GeV)?
- Tevraton (1 TeV)?
- LHC (7 TeV)?

Remember:

- Typically, at least every 500 MeV a depolarizing resonance is waiting for you!

Energy spread of the beam > 10^{-4} (↔ >100 MeV typ for machines above!)

- large number of resonances, no longer isolated from each other
- strong synchrotron sidebands
Siberian Snakes

Partial snake: \( 0 < \chi < 180^\circ \)

Full snake: \( \chi = 180^\circ \)

Invariant Spin Axis \( \vec{n} \)
**Siberian Snakes**

**Partial Snake:**
- Increase of the Resonance Strength by $|\varepsilon_x| = \chi / 2\pi$
- Adiabatic Crossing of Imperfection Resonances if $\chi \gg 2\pi |\varepsilon_r| + \sqrt{8\pi \alpha}$

**Full Snake:**
- Invariant Spin Axis lies in the Accelerator Plane
- Snake Resonances: $k + \frac{1}{2} = Q_{sp} = \pm l \cdot Q_x \pm m \cdot Q_z$
Relativistic Heavy-Ion Collider RHIC

Spin resonances:
AGS: two partial snakes (11° and 45° spin rotators)
RHIC: ~1000 spin resonances → two full Siberian snakes per ring

RHIC beam energy:
100 GeV/u gold
250 GeV polarized protons
Remember: \[ \hat{\Omega}_{BMT} = -\frac{e}{m_0 \gamma} \left\{ \left( 1 + a \gamma^2 \right) \cdot \vec{B}_\perp + (1 + a) \cdot \vec{B}_\parallel \right\} \]
Siberian Snakes

AGS snake magnets:
- twist helical dipoles 3 T superconducting (left), 1.5 T room temperature (right)

RHIC snake magnet:
- 4 superconducting 4 T helical dipoles, 2.4 m long with 360° twist
Synchrotron Radiation

Emission of $\gamma$-Quants:

- Perturbation of the Orbit (recoil, dispersion)
- Slightly tilted invariant spin axis

→ Spin Diffusion!

Simple model:

Phase-Space:

<table>
<thead>
<tr>
<th></th>
<th>longitudinal</th>
<th>horizontal</th>
<th>vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td>spin</td>
<td>n</td>
<td>s</td>
<td>n</td>
</tr>
</tbody>
</table>

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Siberian snakes will not work for high energy electron storage rings!

Polarization Lifetime

Horizontal Polarization:

\[ \tau_{pol} \sim \gamma^{-7} \]
Synchrotron Radiation

Transition Rates:
- no spin flip: \( w_{\uparrow\downarrow}, w_{\downarrow\downarrow} \)
- with spin flip: \( w_{\uparrow\downarrow}, w_{\downarrow\uparrow} \)

Probability of a spin-flip transition:
\[
\frac{w_{\uparrow\downarrow} + w_{\downarrow\uparrow}}{(w_{\uparrow\uparrow} + w_{\downarrow\downarrow}) + (w_{\uparrow\downarrow} + w_{\downarrow\uparrow})} = \frac{1}{3} \left( \frac{\hbar \omega}{E} \right)^2 < 10^{-10}
\]

= very small, but:

The beam will get polarized in a while due to \( w_{\uparrow\downarrow} > w_{\downarrow\uparrow} ! \)

Sokolov-Ternov-Effect: \( P(t) = P_{ST} \left( 1 - e^{-t/\tau_p} \right) \) with \( P_{ST} = \frac{w_{\uparrow\downarrow} - w_{\downarrow\uparrow}}{w_{\uparrow\downarrow} + w_{\downarrow\uparrow}} = \frac{8}{5\sqrt{3}} = 92.4\% \)

Rise time:
\( \tau_p = \left( \frac{8}{5\sqrt{3}} \frac{c\lambda_e r_e}{2\pi R^3} \gamma^3 \right)^{-1} \)

Depolarizing effects:
\( P_\infty = P_{ST} \frac{\tau_{\text{depol}}}{\tau_p + \tau_{\text{depol}}} \) and \( \frac{1}{\tau} = \frac{1}{\tau_p} + \frac{1}{\tau_{\text{depol}}} \)
Polarization Rise Times

Some Accelerator Facilities:

- **BESSY I / Berlin (0.8 GeV)**
  \[ \tau = 150 \text{ min}, \quad P > 75\% \]
- **SPEAR / SLAC (3.7 GeV)**
  \[ \tau = 15 \text{ min}, \quad P > 70\% \]
- **CESR / Cornell (4.7 GeV)**
  \[ \tau = 300 \text{ min}, \quad P > 75\% \]
- **DORIS / DESY (5.0 GeV)**
  \[ \tau = 4 \text{ min}, \quad P = 80\% \]
- **PETRA / DESY (16.5 GeV)**
  \[ \tau = 18 \text{ min}, \quad P > 80\% \]
- **HERA / DESY (27.5 GeV)**
  \[ \tau = 35 \text{ min}, \quad P = 70\% \]
- **LEP / CERN (46.5 GeV)**
  \[ \tau = 300 \text{ min}, \quad P = 57\% \]

Polarization comes „for free“, but that may take some time …
HERA with long. polarization

**HERA MiniRotator:**
56 meters „short“, no quadrupoles
27 – 39 GeV, both helicities
How?

c) Spin management, energy calibration
Spin Flip with RF Fields

Spin oscillation frequency:
\[ \omega_{sp} = \omega_{rev} \cdot \gamma \cdot a \]

Resonance condition:
\[ \omega_- = \omega_{rev} \cdot (k + \gamma \cdot a) \]
\[ \omega_+ = \omega_{rev} \cdot (k + 1 - \gamma \cdot a) \]

Generation of rotating B-field by linear oscillating horizontal B-field (superposition!)

Causes **depolarizing resonance**:

longitudinal: \[ \varepsilon_{B_\parallel dl} = \frac{e}{p} \cdot \frac{1 + a}{2\sqrt{2\pi}} \int B_{\parallel \text{rms}} \, dl \]

transverse: \[ \varepsilon_{B_\perp dl} = \frac{e}{p} \cdot \frac{1 + \gamma a}{2\sqrt{2\pi}} \int B_{\perp \text{rms}} \, dl \]

**Slow resonance crossing by slowly varying the oscillation frequency of the spin-flipper**
Spin Flip with RF Fields

Slow „Froissart-Stora“ Transition \((\Delta \nu \text{ over } \Delta t)\) causes spin flip:

Vector Polarization: \[
\frac{P_f}{P_i} = 2 \cdot e^{-\frac{(\pi \nu_0)^2}{\Delta \nu/\Delta t}} - 1
\]

Tensor Polarization: \[
\frac{P_f}{P_i} = \frac{3}{2} \left( 2 \cdot e^{-\frac{(\pi \nu_0)^2}{\Delta \nu/\Delta t}} - 1 \right)^2 - \frac{1}{2}
\]

![Graph showing polarization changes over time](image)
Results from COSY / FZJ

RF Solenoid

\[ \int B_{\text{rms}} dl = 0.69 \text{ T mm} \]
No influence on CO, but only useful at low Lorentz-\(\gamma\)

RF Dipole

\[ \int B_{\text{rms}} dl = 0.54 \text{ T mm} \]
Enhancement by Lorentz-\(\gamma\), causes CO distortions

© SPIN@COSY Collaboration
Results from COSY / FZJ

Spin flipping

Proton spin-flip efficiency: 99.92 ± 0.04%
Deuteron spin-flip efficiency: 97 ± 1%

Resonance strength

$p=1.85$ GeV/c (Deuterons)
$\Delta t=0.2s$, $\Delta f/2=100$ Hz
$\int B_{rms}dl=0.6$ T·mm

Q_y = Q_z - 4
Energy Calibration

Operation on top of an integer resonance → vertical polarization vanishes!

Beam energy from flipper oscillation frequency:

\[ \omega_{sf} = \omega_{rev} \cdot (k \pm \gamma \cdot a) \]

known
measured

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal beam momentum</td>
<td>3150.5 [MeV/c]</td>
</tr>
<tr>
<td>Revolution frequency</td>
<td>1403 832 ± 6 [Hz]</td>
</tr>
<tr>
<td>Spin-resonance frequency</td>
<td>1011 810 ± 15 [Hz]</td>
</tr>
<tr>
<td>Orbit length</td>
<td>183.4341 ± 0.0002 [m]</td>
</tr>
<tr>
<td>Relativistic ( \gamma ) factor</td>
<td>1.9530 ± 0.0001</td>
</tr>
<tr>
<td>Reconstructed beam momentum</td>
<td>3146.41 ± 0.17 [MeV/c]</td>
</tr>
</tbody>
</table>

\[ \Delta p < 10^{-4} ! \]

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Energy Calibration

Beam Depolarization when crossing the Imperfection Resonance $\gamma a = 4$

Transformation of the measured B-Field to Beam Energy

$10^{-4} < \Delta E/E < 10^{-3}$

$E/\text{MeV} = 3.3024 \text{ B/mT} - 0.34$
Coming?

Polarized anti-particles, new projects
New Projects

**e^+/e^- - Collider:**
- International Linear Collider (500 GeV)
- CERN Compact Linear Collider (3 TeV)
  → polarized positrons

**p/\bar{p}-Collider:**
→ polarized antiprotons @ HESR/GSI

**Electron-Ion-Collider:**
- ELIC @ CEBAF / Jefferson Lab!
- eRHIC @ RHIC / BNL?
- ENC @ HESR / GSI???
Conclusions: what should be remembered?

(Spin dynamics is complicated?! 😊)

**Generation of polarized beams:**
- Sources for polarized protons/deuterons and electrons
- Self polarization of electrons in storage rings

**Acceleration of polarized beams:**
- Depolarizing resonances ↔ compensation measures
- Spin management → precise energy calibration

There are new projects on the horizon …

Thank you for your attention!
International Linear Collider: ILC
The Next Generation?
The “Rivals”:

\[ \bar{e}^- \rightarrow \rightarrow e^+ \]
**Generation of Polarized Positrons**

**Idea:** Circularly polarized $\gamma \rightarrow$ longitudinally polarized $e^-$ and $e^+$

**Methods** to produce circularly polarized photons:

**Helical Undulator**
- Ribbon-wire wound in a double helix
- Current
- Circularly Polarized Photons
- $e^-$ beam

**Compton Backscattering**
- Laser beam
- $\gamma$-ray
- $e^-$
- $e^+$
Demonstration Experiments

E166 @ SLAC: 46.6 GeV e⁻ beam

Helical undulator:
(1m long, \(\lambda=2.25\)mm, \(K\approx0.17\), aperture 0.9mm)

KEK-ATF: 1.28 GeV e⁻ from ATF
2nd harmonic of TAG laser
\[\rightarrow \gamma \text{ with maximum energy of 56 MeV}\]

Compton scattering

Pair creation

1.28GeV e⁻ beam
Circularly Polarized Laser Light \(\lambda = 532\)nm

Polarized γ-ray \(E_{\text{max}} = 56\) MeV
Tungsten

Polarized e⁺
ILC Positron Source Layout

- 312 pulses
- ~5 ns
- ~2 m
- e\textsuperscript{−}γ e\textsuperscript{+}

CLIC Compton Linac

- Compton backscattering inside a CO\textsubscript{2} laser amplifier cavity
- Production of 1 photon per electron (demonstrated at BNL)

- 10 consecutive Compton IPs to accumulate γ flux
Compton Ring:

- $E = 1.06 \text{ GeV}$
- $C = 46.8 \text{ m}$
- $V_{RF} = 200 \text{ MV}$
- $f_{RF} = 2 \text{ GHz}$
- $\beta_{CP} = 0.05 \text{ m}$

$156 \text{ ns/turn, 312 bunches with } 6.2 \times 10^9 \text{ e}^-/\text{bunch}$

$1100 \text{ turns makes 312 bunches with } 4.4 \times 10^9 \text{ e}^+/\text{bunch}$

$2 \text{ GHz} \times 1100 \text{ turns} \rightarrow 170 \mu\text{s pulse length for both linacs}$
parallel spin rotation beam lines for randomly selecting e+ polarization; pair of kicker magnets is turned on between pulse-trains

“Compton source”: fast helicity reversal for e+ by reversing polarization of laser
FAIR @ GSI / Darmstadt

High Energy Storage Ring
Future HESR Upgrade Options

- Polarized Proton-Antiproton Collider
  - HESR 15 GeV/c – 3.5 GeV/c
  - Spin Filtering
  - Antiproton Polarizer (APR)
  - Asymmetric Collider

- Polarized Electron-Nucleon Collider ENC

Accelerator Working Group:

A. Lehrach, Polarized Beams at Jülich
Polarized Antiprotons

\[ \sigma_{\text{tot}} = \sigma_0 + \sigma_\perp \cdot \vec{P} \cdot \vec{Q} + \sigma_\parallel \cdot (\vec{P} \cdot \vec{k})(\vec{Q} \cdot \vec{k}) \]

- **P beam polarization**
- **Q target polarization**
- **k \parallel beam direction**

**For initially equally populated spin states:**

\[ \sigma_{\text{tot} \pm} = \sigma_0 \pm \sigma_\perp \cdot Q \]

- **Transverse case:**
- **Longitudinal case:**

**Figure of merit:**

\[ P^2 \cdot I \rightarrow \text{Two beam lifetime} \]

A. Lehrach, Polarized Beams at Jülich
Polarization of a Stored Beam by Spin-Filtering

Experiment with COSY / schematic

- Stacking injection at 45 MeV
- Electron cooling on
- Acceleration to 49.3 MeV
- Start of spin-filter cycle at PAX: 16 000 s
- PAX ABS off
- ANKE cluster target on
- Polarization measurement (2 500 s) at ANKE
- Spin flips with RF Solenoid
- New cycle with different direction of target polarization

COSY Cycle Results

A. Lehrach, Polarized Beams at Jülich
Conclusions: what should be remembered?

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