Beam energy measurement by resonant depolarization method at VEPP-4M

Ivan Nikolaev

Budker Insitute of Nuclear Physics
Novosibirsk, Russia

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Outline

1. Introduction
2. The idea of the method
3. Radiative polarization
4. Polarization measurement
   - Touschek polarimeter
   - Compton backscattering polarimeter
   - Synchrotron Spin-light polarimeter
5. Conclusion

Introduction

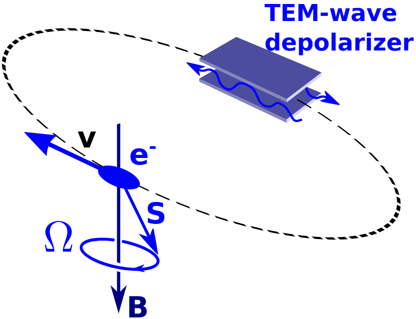
Resonant depolarization technique is the most precise method of beam energy measurement ($\Delta E/E \sim 10^{-6}$)

- Suggested and firstly applied in BINP (Novosibirsk) at 1974
- Used in experiments of precise mass measurement:
  - Φ, K^{+}, K^{-} at VEPP-2M with OLYA detector (1975-1979)
  - J/ψ, $\psi(2S)$ — VEPP-4 with OLYA (1980)
  - Υ, $\Upsilon(2S)$, $\Upsilon(3S)$ — VEPP-4 (MD-1), CESR (CUSB), DORIS-II(ARGUS, Crystal Ball) (1982-1986)
  - K^{0}, ω — VEPP-2M with CMD (1987)
  - Z bosons — LEP (OPAL, DELPHY, L3, ALEPH) (1993)
  - J/ψ, $\psi(2S)$, D^{+}, D^{0} mesons and τ lepton at VEPP-4M (2003-2012)
- Calibration of other technique of beam energy measurement (Compton backscattering edge, etc)

The idea of the method

Frenkel (1926),
Bargmann, Michel, Telegdi (1959)

$$\frac{ds^i}{d\tau} = 2\mu F^{ij} s_j - 2\mu' u^i F^{jk} u_j s_k$$



$$\frac{d\vec{s}}{dt} = \overbrace{2\mu \frac{\vec{s} \times \vec{B}'}{\gamma}}^{\text{dynamic}} + \overbrace{(\gamma - 1)\frac{\vec{s} \times [\vec{\mathrm{v}} \times \dot{\vec{\mathrm{v}}}]}{\mathrm{v}^2}}^{\text{kinematic (Thomas,1926)}}$$

$$\Omega = \omega_0\left(1 + \frac{E}{m_e}\frac{\mu'}{\mu_0}\right) = \omega_0 n \pm \omega_d, \quad n \in \mathbb{Z}$$

$$\delta(\mu'/\mu_0) \approx 2.3 \times 10^{-10} \quad \delta m_e \approx 2.2 \times 10^{-8}$$

$$E = (440.6484431 \pm 0.0000097)\,[\mathrm{MeV}] \times \left(n - 1 \pm \frac{\omega_d}{\omega_0}\right)$$

Radiative polarization

Main method of polarized beam obtaining

Sokolov-Ternov effect (1963)

Intensity of SR with spin flip

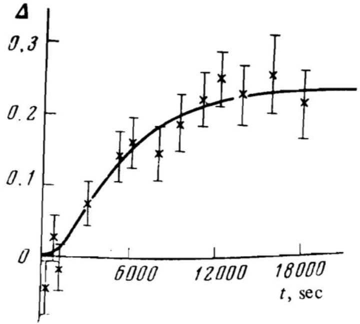
$$W^{\uparrow\downarrow} \approx W_0 \frac{4}{3}\left(\frac{\omega_c}{E}\right)^2$$

$$\tau_p = P_0 \frac{\lambda_C}{c} \frac{1}{\alpha\gamma^2}\left(\frac{H_0}{H}\right)^3; \quad P_0 = \frac{8\sqrt{3}}{15} \approx 92.4\%$$

First observation

- VEPP-2 (Novosibirsk) at 1970
- ACO storage ring (Orsay) at 1972

Radiative polarization at VEPP-2M observed with Touschek polarimeter, $\tau = 70$ min (1974)



$$P(t) = P\left(1 - e^{-t/\tau}\right); \quad \tau = \frac{\tau_d \tau_p}{\tau_p + \tau_d}$$

Depolarizing resonances

$$\nu = \frac{\Omega}{\omega_0} - 1 = l\nu_x + n\nu_y + m\nu_s \quad l,n,m \in \mathbb{Z}$$

- Stochastic depolarization

$$\tau_d \sim \left(\nu_0^2 \sum \frac{|w_k|^2}{(\nu_0 - \nu_k)^4}\right)^{-1}$$

- Difficult to accelerate polarized beam due to resonance cross
- Spin precession shift

$$\delta\nu \sim \frac{1}{2} \sum \frac{|w_k|^2}{\nu_0 - \nu_k}$$

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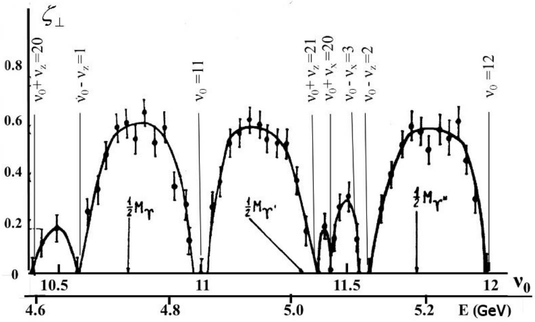


Equilibrium polarization degree measurement at VEPP-4 with laser polarimeter.

Polarization measurement

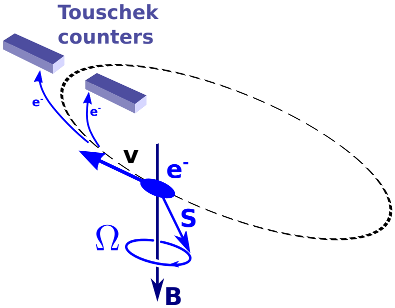
- Touschek (intrabeam scattering) polarimeter.
  Best for lower energies $E < 2$ GeV
- Compton backscattering polarimeter (high energies $E > 5GeV$)
  - Laser polarimeter
  - Compton backscattering of synchrotron light from clashing (positron) beam
- Synchrotron spin-light polarimeter

Touschek polarimeter

Møller $(e^-e^- \to e^-e^-)$ scattering

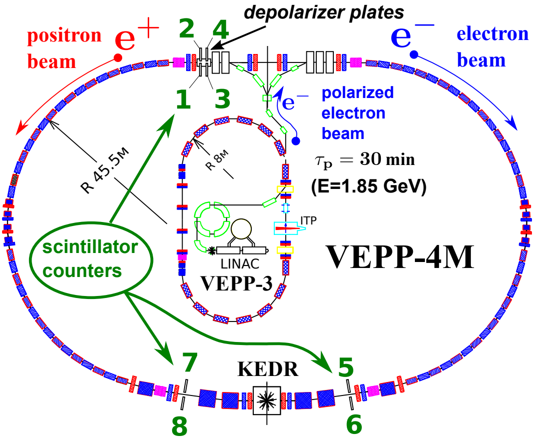
$$d\sigma = d\sigma_0 \left(1 - (\vec{s_1}\vec{s_2})\frac{\sin^2\theta}{1 + 3\cos^2\theta}\right)$$

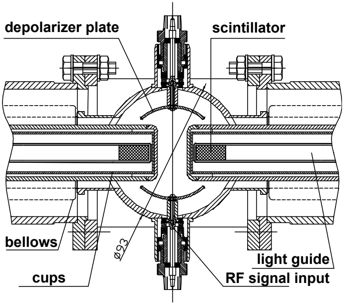
- Baier, Khoze (1968) calculation for flat beam in storage ring
  - proposal to use beam lifetime to detect polarization
- Tumaikin's (1970) proposal to use scintillator counter
- Serednyakov, Skrinsky, Tumaikin, Shatunov (1976) calculation for 2D beam

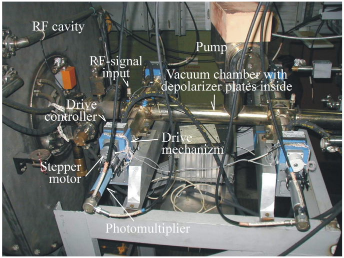


- Baier, Katkov, Strakhovenko (1978) Coulomb effects for flat beam and some relativistic correction for spin direction
- Strakhovenko (2011) Coulomb effects, 2D beam

Touschek polarimeter at VEPP-4M







8 movable scintillator counters located inside vacuum chamber at different places of VEPP-4M

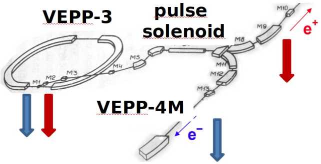
Obtaining polarization at VEPP-4M

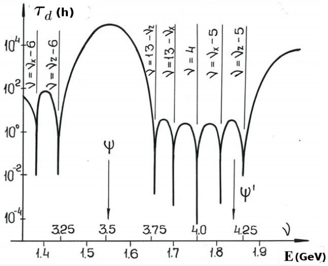
Sokolov-Ternov polarization time

Ring	VEPP-3	VEPP-4M
τ_p [h]	$\frac{12}{E[GeV]^5}$	$\frac{1540}{E[GeV]^5}$
τ_p @ 1.55 GeV	1.34 h	172 h
τ_p @ 1.85 GeV	0.56 h	70 h

- Good beam polarization for J/ψ, $\psi(2S)$
- Problem with τ lepton energy region (close to $\nu = 4$ resonance)
  - Injection of polarized beam at 1.85 GeV and deaccelerate to 1.78 GeV
  - Energy calibration after 30 min magnetic field relaxation
  - Compton edge energy measurement during data taking

Polarized beam injection into VEPP-4M ring

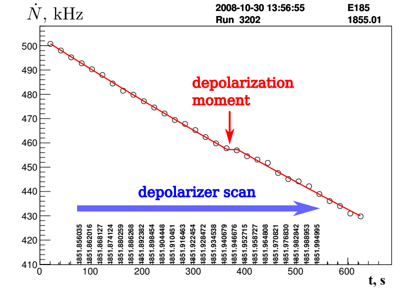


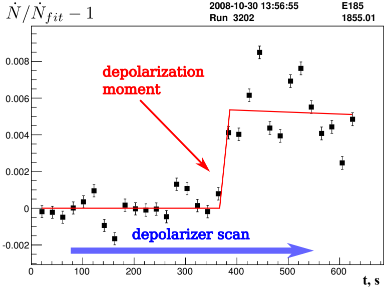


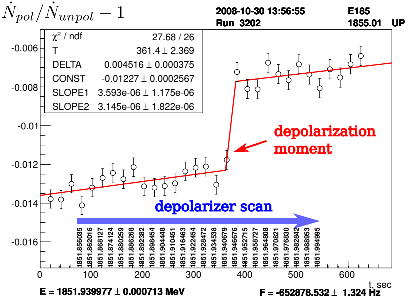
Performance characteristic of Touschek polarimeter at VEPP-4M

- Operation energy range 1.5 – 2.0 GeV
- Operation beam current > 0.1 mA
- Count rate up to 1 MHz (50 kHz/mA^2/counter)
- Work with up to 4 bunches (electron or positron)
- Compensation technique (polarized-unpolarized comparison)
- Depolarization jump $\Delta = 1 - 3$ %
- Accuracy 1 keV (10^{-6})
- Double calibration with up and down frequency scan
- Measurement time $\sim$ 2 hours
- 4000 energy calibrations from 2001 to 2016 for J/ψ, $\psi(2S)$, $D^{\pm}$, D^0, $\psi(3770)$ mesons and τ lepton masses measurement experiments with KEDR detector

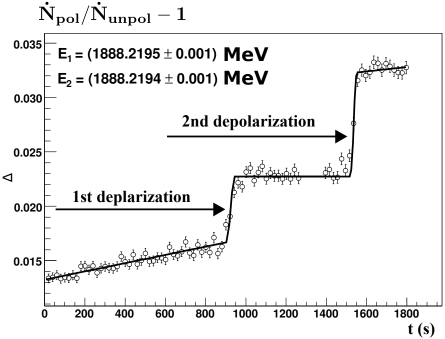
Compensation technique



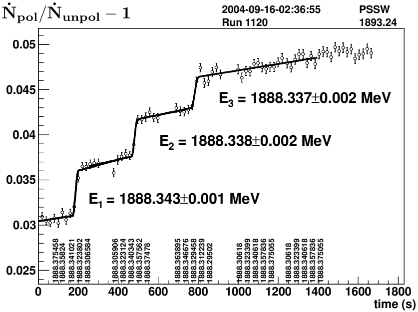




Double and triple beam energy measurement with same polarized bunch



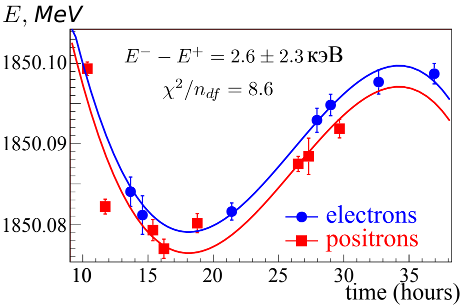
Double jump



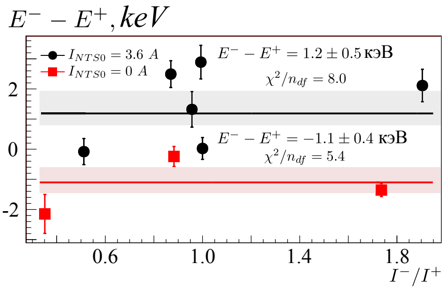
Triple jump

Double up-down scan increase reliability of energy calibration. Suppress cases of calibration at side 50 Hz spin resonances

Electron and positron energy comparison



serial interlaced e^-/e^+ energy calibrations



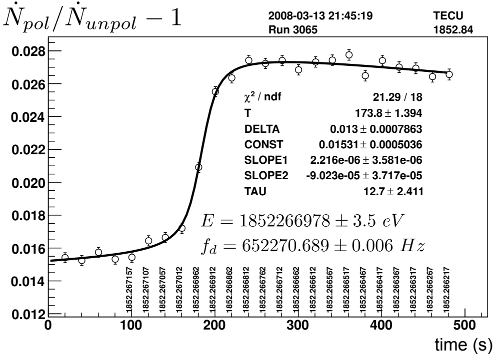
simultaneous e^-/e^+ energy calibrations

Investigating systematics of energy calibration for J/ψ, ψ' mass measurement experiment

Possibility of CPT-invariance test

- slow depolarizer scan speed 5 eV/sec ($\sim$ 10 mHz/sec)
- Slow NMR stabilization of the main field
- Fast magnetic field stabilization to shrink spin line width
- Cooling water stabilization
- Energy drift 1 keV/hour
- RF separation of the bunches

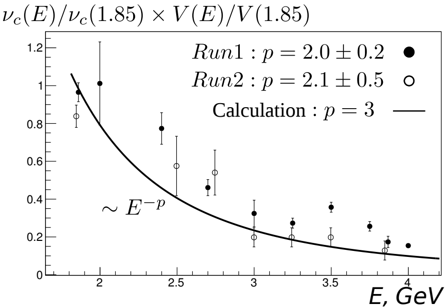
Spin precession frequency resolution 2×10^{-9}

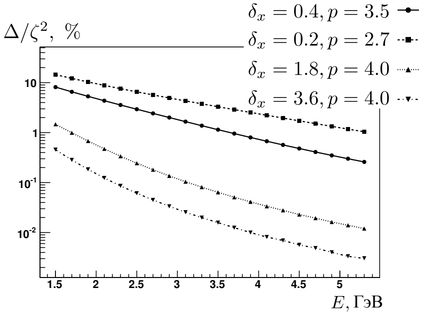


- Selective depolarizer

Investigating possibility of CPT-invariance test trough simultaneous comparison of electron and positron precession frequency.

$$\dot{N} \propto \frac{I_{beam}^2}{E^{2\div 3} V_{beam}} \propto \frac{1}{E^{5\div 6}} \qquad \Delta \approx \frac{0.5\%}{\delta q_x \delta q_y} \zeta^2 \propto \frac{1}{E^4}$$





Small polarization effect for $E = 5$ ГэВ

$\dot{N} \approx 10$кГц for $I = 10$ mA

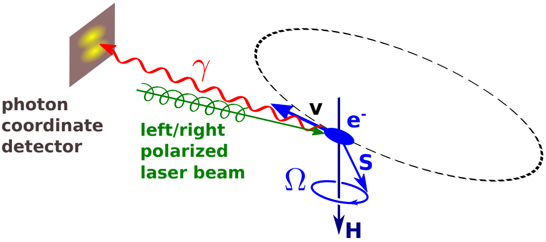
$\Delta \approx 0.1\%$

Need alternative method of polarization measurement

Compton backscattering polarimeter

- Suggested by Baier and Khoze (1969)
- Firstly implemented at SPEAR (1979)
- Then applied at VEPP-4 (1982)
- Tikhonov (1982): SR from clashing beam as source of circular polarized light
- at LEP for Z boson mass measurement (1993)

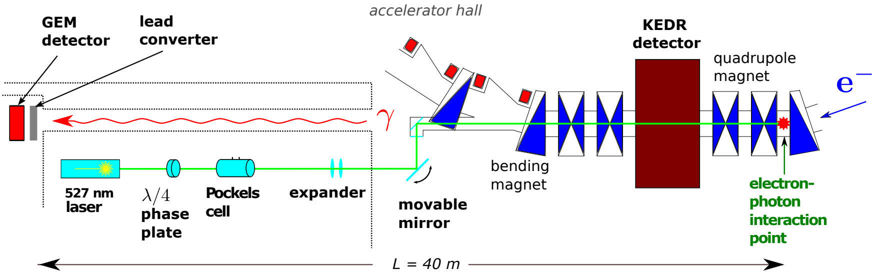
Up-down scattering asymmetry for left-right photon backscattering on vertically polarized electron beam

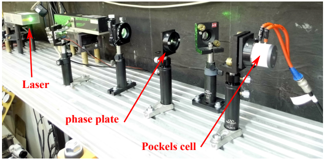


$$\frac{\sigma_{\text{up}} - \sigma_{\text{down}}}{\sigma_{\text{up}} + \sigma_{\text{down}}} \approx -\frac{3}{4}\frac{E\omega_0}{m_e^2} VP = 2.6\%$$

ω_0 is the initial photon energy, V is the Stokes parameter of circular polarization (± 1)

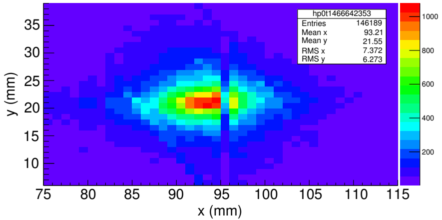
Laser polarimeter at VEPP-4M

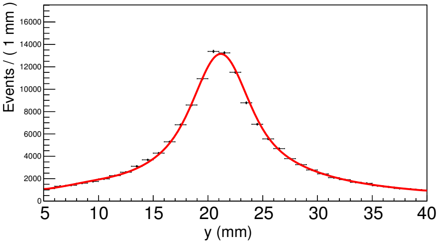


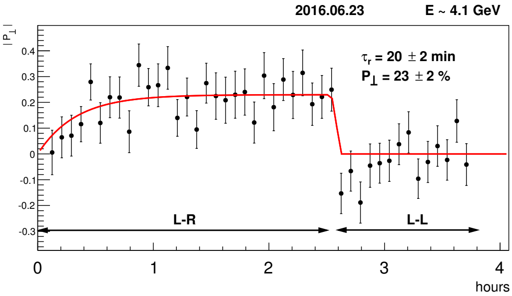


- 527 nm Nd:YLF solid state laser with 180 μJ pulse energy at 2 kHz, 6ns pulse length
- Circular polarization prepared by KD*P Pockels cell or by $\lambda/4$ wave plate
- two-coordinate GEM detector with $2X_0$ Pb converter for photon registration

First measurements by VEPP-4M laser polarimeter







Synchrotron Spin-light polarimeter

Classical synchrotron light

$$W_0 = \frac{2}{3}\frac{e^2 c}{R^2}\gamma^4$$

Magnet dipole synchrotron light

$$W_{md} = \frac{2}{3}\frac{\mu_0^2}{c^3}\omega_0^4\zeta^2 \propto \hbar^2$$

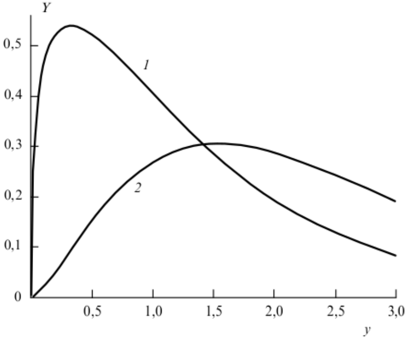
Interference between them

$$W_{mixed} = 2\sqrt{W_0 W_{md}} \propto \hbar$$

For $\omega/\omega_c > 10$, $B = 1T$,
$E = 10 \div 100$ GeV

$$\delta = \frac{W_{mixed}}{W_0} \sim \zeta\omega/E \approx 10^{-4} \div 10^{-3}$$

- Suggested by Korchuganov, Kulipanov, Mezentsev (1977)
- Implemented at BINP (1982) (Belomestnykh, Bondar et al)



Conclusion

Advantages

- Most precise method of beam energy calibration (10^{-6})
- Allow one to calibrate another method (Compton backscattering edge, etc...)

Disadvantages

- Requires transverse polarized beam
- Need special time to measure spin precession frequency
  - Need beam energy interpolation between calibrations. NMR,temperatures, moon phase...
- Measure average energy beam energy while we need energy at interaction point

Method can be used in future high precision mass measurement

- Υ mesons mass measurement at VEPP-4M with KEDR detector.
- τ lepton mass measurement at Super c-τ factory (CDR 2011)
- new Z-boson mass measurement at future colliders

THANK YOU