ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ СО АН СССР

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PREPRINT 87-117

НОВОСИБИРСК

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ABSTRACT

The anomalous magnetic moments of the relativistic electrons and positrons have been compared by measuring the spin precession phase difference at a given time interval. The difference in the anomalous magnetic moments between the electron and the positron has been shown to lie within $1\cdot10^{-8}$ at 95 per cent confidence level which improves the accuracy of the previous measurements by an order of magnitude.

INTRODUCTION

The spin dynamics properties are used for a long enough time to determine the magnetic moments of atoms and elementary particles by measuring the rotation angle or the frequency of the spin precession in the magnetic field. Up to date the accuracy record of $\sim4\cdot10^{-9}$ is held by the measurement of the ratio of the electron anomalous magnetic moment μ' to the normal one μ_0 that has been performed for a single electron in the magnetic trap [1].

The anomalous magnetic moments (AMM) of a particle and its anti-particle are relevant to the verification of the CPT-theorem which predicts their identity in absolute value. Comparisons of AMM for electrons and positrons with 10^{-7} accuracy were performed in two experiments: for non-relativistic particles the magnetic trap was used where $(g-2)$ factors were measured independently for the electron and positron [2], and in our previous experiment at VEPP-2M, where the AMM difference for the ultra-relativistic electrons and positrons was measured in the electron-positron storage ring [4]. An electron-positron storage ring where both particles and anti-particles rotate in the same magnetic fields (and so do their spins) is the most adequate to the problem of comparison of the anomalous magnetic moments of these particles.

The spin precession frequency for an ultra-relativistic particle circulating in the storage ring with the transverse magnetic field of H_z can be presented in the form:

$$\Omega=\omega_s+2\mu'\langle H_z\rangle=\omega_s\left(1+\gamma\,\frac{\mu'}{\mu_0}\right), \qquad (1)$$

where $\omega_s=\frac{e\langle H_z\rangle}{\gamma mc}$ is the revolution frequency as specified by the accelerating RF source.

In the previous experiments at the storage ring VEPP-2M [3, 4] the electron and positron AMM comparison was performed in the simultaneous measurement of the spin precession frequencies Ω^-, Ω^+ of electrons and positrons by the resonant depolarization technique [5]. The AMM comparison error of this technique in an idealistic case can be done much less than the spin frequency spread. Practically the accuracy is limited by the stability of the accelerating RF frequency and by the uncontrollable drift of the magnetic field value in the storage ring.

THE ESSENCE OF THE TECHNIQUE

Free of the above limitations is another technique where the difference in the spin precession angles between electrons and positrons $\Delta\varphi=\int_0^{\Delta t}(\Omega^+-\Omega^-)\,dt$ is measured during the time of Δt, which is limited by the depolarization time. The best sensitivity in this technique is attained when the polarization is directed perpendicularly to $\vec{H}_z$. The radiative polarization aligns the magnetic moments of electrons and positrons circulating in the storage ring in parallel to the magnetic field. The coherent spin rotation to the horizontal plane can be done by applying a radio-frequency field $\vec{\tilde{H}}\perp\vec{H}_z$ with the frequency f sweeping at the rate of $\dot{f}$ across the vicinity of the resonant frequency $f_r=\frac{\Omega}{2\pi}$. If the adiabaticity condition [6] is satisfied: $w^2\gg 2\pi\dot{f}$, where $w=\frac{2\mu'\langle\tilde{H}\rangle}{\gamma}\simeq\frac{\langle\tilde{H}\rangle}{\langle H_z\rangle}\omega_s$, then the variation of the tune offset $\Delta f=f-f_r$ from the initial value of $\Delta f_0\gg w/2\pi$ to zero results in 90 degree rotation of the polarization direction while the degree of polarization degrades insignificantly. After that the radio-frequency field is switched off.*)

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*) The possibility of the adiabatic spin flip of electrons and positrons in the storage ring by means of the radio-frequency field was studied in Ref. 7. An RF device for coherent spin rotation was named «flipper».

Further on the spin precession proceeds in the horizontal plane as can be seen from the harmonic oscillation of the longitudinal polarization actually observed for example in the experiment on muonic $(g-2)$ measurements [8]. In our case the longitudinal polarization can be detected in the elastic scattering on the polarized atomic hydrogen jet target simultaneously for electrons and positrons.

As far as we are only concerned about the difference in the phase advance $\Delta\varphi$, it can be measured without turn-by-turn observation of the polarization directon. If the radio-frequency field is repeatedly switched on within the time interval Δt while its frequency sweeps oppositely from f_r to f_0, then the transverse polarization of the beams will be restored, that is stable with respect to depolarizing effects. However its degree and sign will be arbitrary because the phases of the spins with respect to the field direction $\tilde{H}$ are random at the moment when the field switches on for the second time. The information on the difference in the phase advance over this time interval can be obtained from the comparison of the restored polarization degrees for the electrons and the positrons.

The restored transverse polarization degree S_1 averaged over the beam distribution is related to the initial one S_0 by the equation:

$$S_1=S_0\left(\cos^2\theta+\sin^2\theta\cdot\cos\bar{\varphi}\cdot e^{-\frac{1}{2}(\delta\varphi)^2}\right), \qquad (2)$$

where θ is the spin direction angle with respect to the vertical, $\delta\varphi$ is the rms spread in the precession angles around the average angle $\bar{\varphi}$ at the moment Δt of the second switch on of $\tilde{H}$.

THE SPIN FREQUENCIES SPREAD

The angular spread $\delta\varphi$ is due to the spread of the spin frequencies averaged over the particle's motion which results in the beam depolarization thus limiting the free precession time Δt. As shown in Ref. 9, the spin frequencies spread $\delta\Omega$ is determined by the nonlinear perturbation of the particle motion in the storage ring, it can be done much less than the radiation damping rate $\lambda\simeq 10^{-5}\omega_s$. In this case for the time $\Delta t>\lambda^{-1}$ the diffusion due to the quantum fluctuations of the synchrotron radiation will mix up the particles' oscillations amplitudes and phases, therefore the spin precession frequencies will be mixed within the steady state spread $\delta\Omega$. With the account of the diffusion the depolarization time τ_d will be much longer, than $(\delta\Omega)^{-1}$, it can be estimated from the relation:

$$\tau_d \simeq \frac{\lambda}{(\delta\Omega)^2}. \qquad (3)$$

The presence of the spin frequencies spread resulting in the depolarization sets the basic limitations on the accuracy of the technique in question, that is why much attention has been paid to studying this problem. Experimental study of the depolarization rate was performed at various settings of the storage ring sextupole corrections that compensate for the reduction in the average energy of the oscillating particle with respect to the synchronous particle. The depolarization has been shown to be minimal when the sextupole setting gives zero chromaticity in the radial betatron oscillations. The measurements presented below give for this setting of the storage ring VEPP-2M optics the spin frequencies spread within $\delta\Omega \simeq 2\cdot 10^{-7}\omega_s$ which enables $\frac{\Omega\Delta t}{2\pi} \simeq 10^7$ spin revolutions over the free precession time while the beam polarization degree degrades permissibly.

POLARIZATION DEGREE MEASUREMENTS

Similarly to the previous experiments at VEPP-2M the beam polarization degree was detected by the intra-beam elastic scattering of the particles [10]. The scintillation counters system for detection of the particles, lost due to this process, gives the counting rate $\dot{N} = 40 J^2 (1 - 0.1 S^2)$, where J is the beam current in milliamps. The maximum contribution of the polarization at $S = 1$ comes to 10 per cent. The accelerating voltage phase-lock enables the concurrent detection of the counter-rotating electrons and positrons in the same system.

In the routine experiment conditions at the energy of $E = 650$ MeV the currents of the electrons and the positrons after the radiative polarization were $J^- \simeq J^+ = 5$ mA that provides for the counting rate of $\dot{N} = 10^3$. The square counting rate dependence of S reduces the polarimeter sensitivity to low polarization degrees of $S \leqslant 0.2$. To determine the sign of S_1 after the RF-field action the natural radiative polarization process can be used which changes the polarization degree according to the equation:

$$S = S_m + (S_1 - S_m)\, e^{-\frac{t}{\tau_p}}, \qquad (4)$$

where $S_m = 0.92$ is the maximum possible degree, τ_p is the characteristic polarization time (on VEPP-2M $\tau_p = 3200$ s at the energy of 650 MeV).

In Fig. 1 the time dependence is presented of the counting rate (normalized on the beam current squared) of the elastic scattering events in a typical experimental run. The measurements begin after the time $t = 3\tau_p$ past the injection, when the polarization degree builds up to $S_0 \simeq 0.85$. At the point A the RF flipper device*) is switched on twice for short periods of time to rotate the spins to the horizontal plane then back upright. 10 minutes past at the point B and further on the depolarization is performed by another RF device named depolarizer ($\tau_d = 10$ s). Relating the leaps at the points A and B one can determine both the absolute value of S_1/S_0 and the sign of S_1 that is evident in the comparison of Fig. 1,*a* where $S_1/S_0 = -0.8$ and Fig. 1,*b* where $S_1/S_0 = 0.8$.

EXPERIMENTAL RESULTS

In each measurement run the RF field was switched on with the initial tune $\Delta f_0 = 15$ kHz off the resonance to approach it at 50 kHz/s rate. Switching off and subsequent switching on in 0.1 s was made in the vicinity of the true resonance frequency $f_r = \frac{(\Omega - 2\omega_s)}{2\pi}$ with an error ε that is not known *a priori*. This error is due to the particles' average energy stability in the storage ring. The stabilization system that governed the guide field level according to the on-line data of the remote electro-mechanical measurements of the storage ring dipoles and quadrupoles horizontal alignment [11], provided for the long-term energy stability of $\Delta E/E = \pm 1.5\cdot 10^{-5}$ to be maintained.

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*) The radio-frequency ($f = \frac{\Omega - 2\omega_s}{2\pi} = 7.93$ MHz) longitudinal (along the velocity) magnetic field of $\tilde{H} = 100$ Gs amplitude is generated on the orbit section ($l = 40$ cm) by the inductance coil connected to the resonant circuit powered with some kilowatt transmitter to provide for the resonant harmonic value w up to $w \cong 6\cdot 10^{-5}\omega_s \approx 2\pi\cdot 10^3$ Hz. The control system enables the transmitter tune to scan in ± 100 kHz band in $10^{-1} - 10^2$ s.

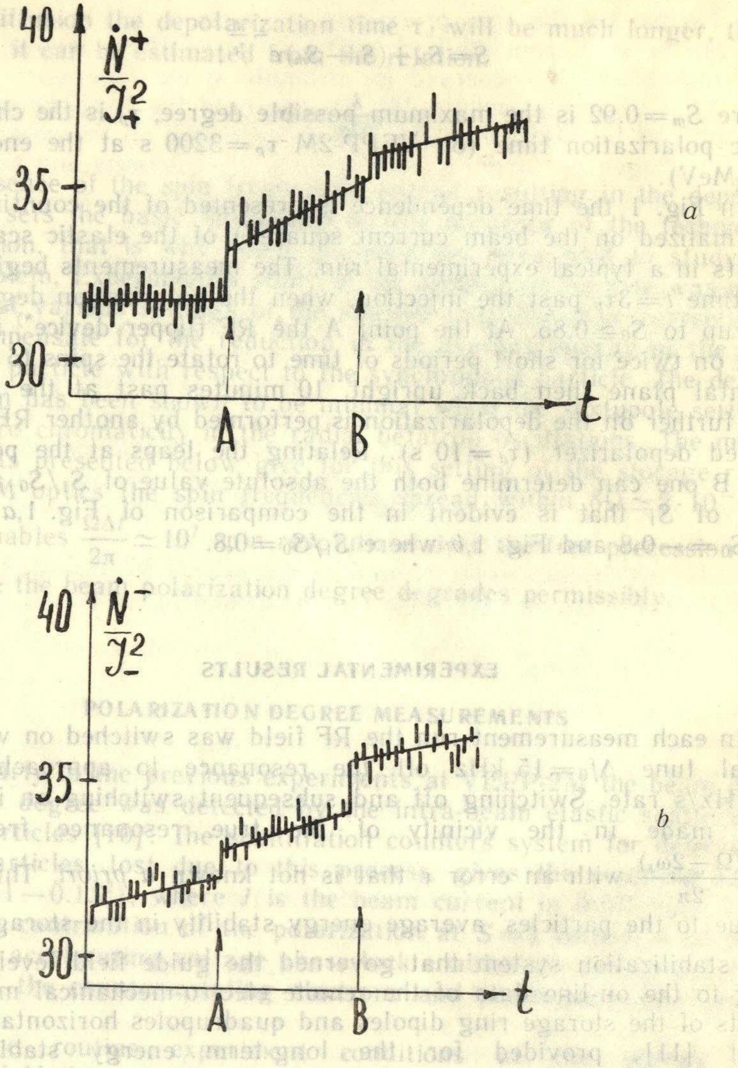

Fig. 1. Time dependence of the elastic scattering event rate, normalized on the beam current squared, for the typical run when the restored polarization of the positron (*a*) and the electron (*b*) beam differed in sign ($S_1^+/S_0=-0.8$, $S_1^-/S_0=0.8$).

The energy calibration by means of the resonant depolarization technique was made in each experimental run about 1 — 1.5 hours past the measurement run. Only the runs with $|\varepsilon|\leqslant 400$ Hz were selected that corresponds to spin deflection angle of $70°<\theta<110°$ from the vertical ($\operatorname{tg}\theta=w/\varepsilon$).

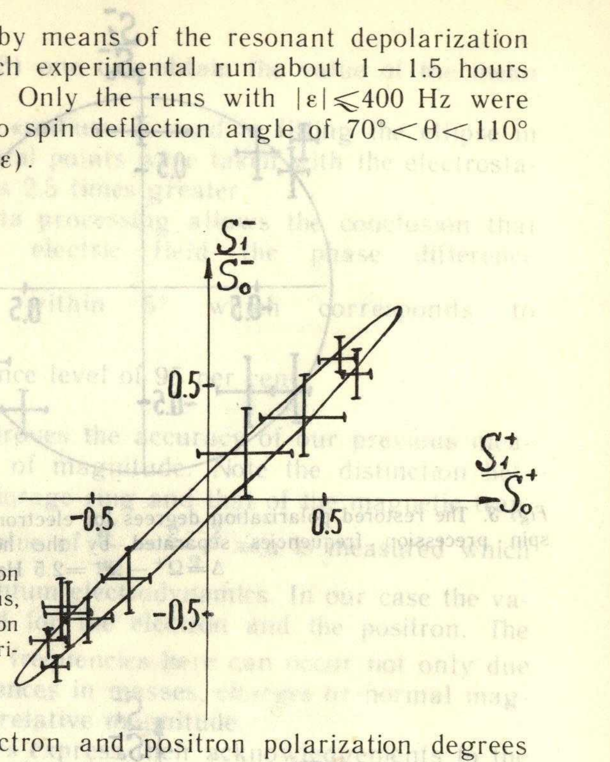

Fig. 2. The restored polarization degrees for electrons and positrons, measured without spin precession frequencies separation by the horizontal electrostatic field.

The results for the electron and positron polarization degrees measured in the runs thus selected are shown in Fig. 2. The experimental points are fitted by the least squares with a parametrically specified ellipse:

$$S_1^+/S_0=S\cos\varphi\,,\qquad S_1^-/S_0=S\cos(\varphi+\Delta\varphi)\,,\tag{5}$$

where $S=S_0 e^{-\frac{(\delta\varphi)^2}{2}}$ is a remanent polarization degree after free precession, $\Delta\varphi$ is the desired difference in the precession angles between the electrons and the positrons.

To better determine the value of S the measurement runs were made with the static horizontal electric field $\vec{\mathscr{E}}_r$, imposed on one of the orbit sections to cause the precession frequencies separation:

$$\Delta=\Omega^+-\Omega^-=4\mu' c\langle\mathscr{E}_r\rangle=2c\frac{\langle\mathscr{E}_r\rangle}{\langle H_z\rangle}\omega_s\simeq 2.5\,\text{Hz}\,.\tag{6}$$

The results of these runs shown in Fig. 3 give $S=0.8\pm0.03$. Hence

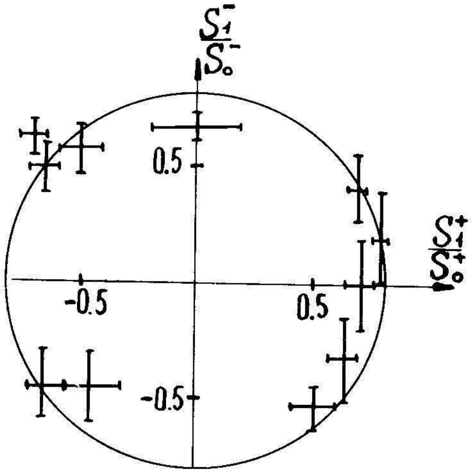

Fig. 3. The restored polarization degrees for electrons and positrons, measured with spin precession frequencies separated by the horizontal electrostatic field at $\Delta = \Omega^+ - \Omega^- = 2.5$ Hz.

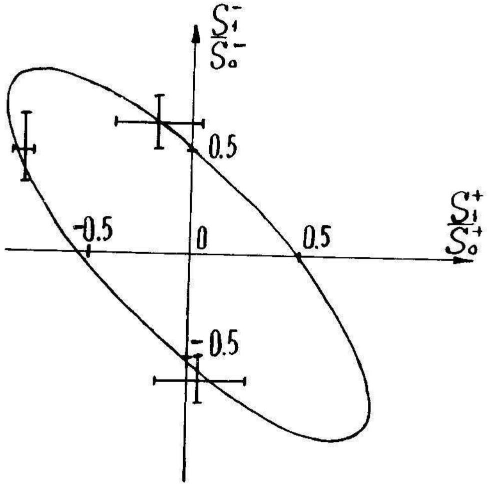

Fig. 4. The spin frequency separation is 2.5 times greater, than in Fig. 3.

in particular using Equ. (3) one can obtain the value of the mean spin frequencies spread.

The same value of the «radius» is used in fitting the ellipse in Fig. 4 where the experimental points were taken with the electrostatic separation of frequencies 2.5 times greater.

The total measured data processing allows the conclusion that in the absence of the electric field the phase difference $\Delta\varphi = \int_0^{0.1\ \mathrm{s}} (\Omega^+ - \Omega^-)\,dt$ is within 5° which corresponds to $\frac{\Delta\mu'}{\mu'} \leqslant 1 \cdot 10^{-8}$ at the confidence level of 95 per cent.

The result obtained improves the accuracy of our previous measurement [4] by an order of magnitude. Note the distinction between the technique of the storage ring and that of the magnetic trap. In the magnetic trap the value of $\frac{\mu'}{\mu_0} = \frac{g-2}{2} = a$ is measured which is directly calculable in quantum electrodynamics. In our case the values $\mu' H = \gamma a$ are compared for the electron and the positron. The difference in the precession frequencies here can occur not only due to μ' but also due to differences in masses, charges or normal magnetic moments of the same relative magnitude.

In conclusion the authors express their acknowledgements to the personnel of the storage ring VEPP-2M that maintained the machine to make the experiment possible.

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Сравнение аномальных магнитных моментов электрона и позитрона, эксперимент 1987 г.

Ответственный за выпуск С.Г.Попов

Работа поступила 3 августа 1987 г.
Подписано в печать 20.08. 1987 г. МН 00461
Формат бумаги 60×90 1/16 Объем 0.9 печ.л., 0.8 уч.-изд.л.
Тираж 230 экз. Бесплатно. Заказ № 122

Набрано в автоматизированной системе на базе фотонаборного автомата ФА1000 и ЭВМ «Электроника» и отпечатано на ротапринте Института ядерной физики СО АН СССР,
Новосибирск, 630090, пр. академика Лаврентьева, 11.