Study of the radiative polarization of beams in the VÉPP-2M storage ring

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The radiative polarization of beams in the electron-positron storage ring VÉPP-2M has been studied experimentally. The polarization of a single beam was measured by the change in counting rate of particles scattered within a bunch on resonance depolarization by an external electromagnetic field. The experimental values obtained for the time and degree of polarization are in good agreement with theoretical predictions. It is shown that it is possible to traverse the beam energy region 450–670 MeV without destroying the polarization. Preservation of the polarization in the presence of an intense colliding beam has been demonstrated.

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1. INTRODUCTION

It is well known[1,2] that during extended motion in a magnetic field electrons and positrons in the absence of depolarizing factors can become polarized as a consequence of radiation by them of photons. The degree of polarization in simple cases approaches a limiting value

$$\zeta_0=8/5\sqrt{3}=0.924 \tag{1}$$

according to a law $\zeta=\zeta_0[1-\exp(-t/\tau_p)]$ with a characteristic time

$$\tau_p=\left[\frac{5\sqrt{3}}{8}\frac{me^2c}{\hbar^2}\gamma^2\left(\frac{H}{H_0}\right)^3\right]^{-1}, \tag{2}$$

where γ is the relativistic factor, H is the magnetic field strength, and $H_0=4.41\times10^{13}$ Oe.

For most electron-positron storage rings the polarization time may be less than the lifetime of the circulating beams. Thus, the possibility appears of obtaining intense beams of electrons and positrons with a high degree of polarization and in this way to significantly broaden the group of experiments on electromagnetic interactions in colliding beams.

The first measurements of polarization of a beam of electrons in a storage ring were made in Novosibirsk in 1970 in the VÉPP-2 apparatus.[3] In this experiment the existence of the radiative polarization effect was demonstrated. However, as a result of redesign of the VÉPP-2 complex these experiments were terminated in order to continue them in the new storage ring VÉPP-2M.[4] Similar measurements were made in 1972 in the storage ring ACO at Orsay, France.[5]

2. DEPOLARIZING RESONANCES

The problem of spin motion in a magnetic field has been considered by a number of authors (see for example Bargmann *et al.*[6] and Derbenev *et al.*[7]). In a uniform field the spin precesses with a frequency

$$-\mathbf{W}=\left(\frac{q_0}{\gamma}+q'\right)(\mathbf{H}_x+\mathbf{H}_z)+\frac{q}{\gamma}\mathbf{H}_v, \tag{3}$$

where $\mathbf{H}_x$, $\mathbf{H}_z$, and $\mathbf{H}_v$ are the transverse and longitudinal components of the magnetic field $\mathbf{H}$ with respect to the velocity; q' and q_0 are the anomalous and normal parts of the gyromagnetic ratio q. In the approximation of plane orbits ($H_v=\mathbf{H}_x=0$), in a polarized beam all particles have spin projections on the direction of $\mathbf{H}_z$ which are constant with time.

Under actual conditions in accelerators and storage rings the presence of small nonuniformities in the field leads to some depolarization as the result of spread in the particle trajectories. The amount of depolarization is small if the spin precession frequency is not a multiple of any harmonics of the perturbation. If the resonance condition is satisfied,

$$\nu=n+m\nu_z+k\nu_x+l\nu_\gamma, \tag{4}$$

where $\nu=\gamma q'/q_0$; ν_z, ν_x, ν_γ are the frequencies of vertical and radial betatron and synchrotron oscillations in units of the frequency of revolution ω_s, rotation of the spins will occur around the direction of the perturbing field, which leads to depolarization of the beam as a result of the spread in amplitudes and phases of the betatron oscillations.

Outside the resonances it is possible to have a diffusion of the average spin value due to stochastic jumps in the energy and transverse momentum of the particle (scattering by the residual gas, quantum fluctuations of the radiation, and so forth).[8,9] The rate of diffusion is determined by the detuning (difference of the frequency from the nearest resonance) and by the magnitude of the corresponding harmonic of the perturbation; its effect is characterized by the ratio of the polarization and depolarization times τ_p/τ_d. Calculation of this quantity in the general case requires a knowledge of all perturbations. However, for evaluation of depolarizing resonances it is sufficient to use a model with introduction into the storage-ring magnetic structure of a concentrated rotated quadrupole giving a gradient $\partial H_x/\partial x$. The results of a calculation performed with this model are shown in Fig. 1. The magnitudes of all harmonics of the perturbation $(\partial H_x/\partial x)_n$ are assumed identical and equal to the magnitude of the zero harmonic $(\partial H_x/\partial x)_0 \approx 0.01 H_z/R_0$ measured experimentally. It can be seen in Fig. 1 that in the energy region of VÉPP-2M from

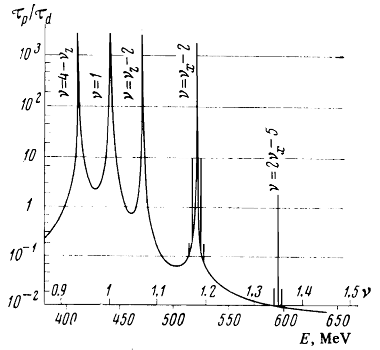

FIG. 1. Evaulation of the strength of depolarizing resonances, characterized by the ratio of the polarization and depolarization times, for $\nu_x=3.178$ and $\nu_z=3.068$.

450 to 670 MeV it is possible to obtain polarized beams everywhere except in narrow resonance bands, which can easily be moved by selection of the working point in the frequencies of betatron oscillations.

3. METHOD OF POLARIZATION MEASUREMENT

As in the first experiments in VÉPP-2 on measurement of the degree of polarization of electrons, we chose a method utilizing the dependence of the cross section for elastic scattering of the particles inside a bunch (the Touschek effect) on polarization.[10] In the rest system of the bunch the particles, colliding during their transverse oscillations, are scattered at some angle such that part of the transverse momentum is transferred to longitudinal momentum. In the laboratory system the longitudinal momentum is increased by a factor of γ as a consequence of the relativistic transformation. Thus, two particles after scattering will have longitudinal momenta different from the equilibrium value by $\pm\Delta p_{\parallel}$ and can be separated by the magnetic field of the storage ring in different directions from the equilibrium orbit and recorded in some manner.

Calculation of the dependence of the number of elastic scatterings in the bunch was carried out for the first time by Baǐer and Khoze[10] on the assumption that the transfer of momentum $\Delta p_{\parallel}$ was small and that the transverse betatron motion was one-dimensional. However, in practice, cases are possible in which the mean square vertical momentum δq_z is of the order of the radial momentum δq_x, and then it is necessary to consider the scattering of electrons with spins arbitrarily oriented in the plane of the transverse motion. In addition, in measurement of the polarization, cases of scattering with rather large transfer of momentum are interesting. As the result of a calculation free of the limitations mentioned, the following expression was obtained for the number of elastic-scattering events per unit time with transfer of momentum greater than $\Delta p_{\parallel}$:

$$\dot{N}=\frac{N^2}{2^{1/2}V\gamma^2\delta q_x\delta q_z}\int\limits_{q_{min}}^{\infty} q^2(1+q^2)^{1/2}\,dq\left\{\sigma_0 I_0\left(\frac{\alpha q^2}{2}\right)\exp\left(-\frac{q^2}{2\delta q^2_{\text{eff}}}\right)\right.$$
$$\left.+\zeta^2\left[\sigma_\perp\Phi\left(\frac{1}{2},\,2,\,\alpha q^2\right)+\sigma_\parallel\Phi\left(\frac{3}{2},\,2,\,\alpha q^2\right)\right]\exp\left(-\frac{q^2}{\delta q_z^2}\right)\right\}, \tag{5}$$

where N is the number of particles in the beam, V is the volume of the beam,

$$\eta=\frac{\Delta p_\parallel}{p_\parallel},\quad q^2_{min}=\frac{\eta^2}{1-\eta^2},\quad \alpha=\frac{1}{\delta q_x^2}-\frac{1}{\delta q_z^2},$$
$$\delta q^2_{\text{eff}}=\frac{\delta q_x^2\,\delta q_z^2}{\delta q_x^2+\delta q_z^2},$$

I_0 is a Bessel function of imaginary argument, Φ is the confluent hypergeometric function, $r_0=e^2/mc^2$ is the classical electron radius,

$$\sigma_0=\frac{\pi r_0^2(1+2q^2)^2}{2q^4(1+q^2)}\left[\ln a+\frac{1}{a^2}-1+\left(\frac{q^2}{1+2q^2}\right)^2(1-a-4\ln a)\right],$$
$$\sigma_\perp=\frac{\pi r_0^2}{2q^4(1+q^2)}\left[(1+3q^2)\ln a-\frac{1}{2}a^2q^2(1+2q^2)+q^2(2+q^2)a-\frac{3}{2}q^2\right],$$
$$\sigma_\parallel=\frac{\pi r_0^2}{2q^4(1+q^2)}[q^2(2+q^2)-aq^3(2+q^2)+(4q^2+1)(2q^2+1)\ln a],$$
$$a=\eta(1+q^2)^{1/2}/q.$$

The contribution of the polarization to the number of elastic scatterings can conveniently be characterized by the ratio

$$\Delta=\Delta_{max}\zeta^2=(\dot{N}_0-\dot{N}_p)/\dot{N}_0, \tag{6}$$

where $\dot{N}_0$ and $\dot{N}_p$ are the numbers of scatterings for unpolarized and polarized beams.

The theoretical behavior of Δ_{max} as a function of η for the condition $\delta q_x\gg\delta q_z$ is shown in Fig. 2a for several values of δq_x. The opposite limiting case $\delta q_z\gg\delta q_x$ is shown in Fig. 2b. In this case in the beam system scattering occurs with spins parallel to the momenta, which is more sensitive to the polarization of the particles. Comparison of Figs. 2a and b shows that, for the same transverse momentum, Δ_{max} is greater for vertical motion of the particles and the difference becomes particularly important in the region $\eta\gtrsim 0.1$.

In Fig. 3 we have shown the dependence of Δ_{max} on the vertical momentum δq_z for several values of η. It can be seen that the contribution of the polarization is maximal for a certain δq_z. The decrease of Δ_{max} in regions of large δq_z is due to the increase in the total transverse momentum $(\delta q_z^2+\delta q_x^2)^{1/2}$. It should be noted that the number of events drops rapidly with increasing energy (as

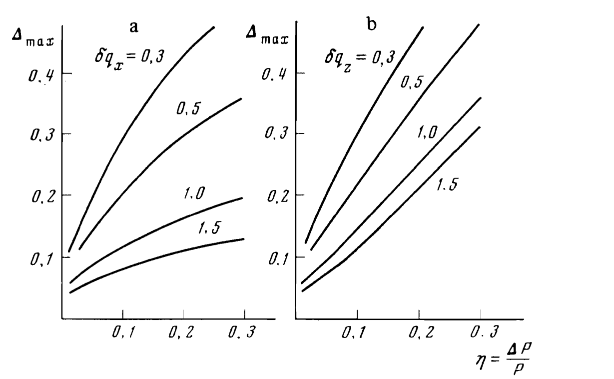

FIG. 2. Polarization contribution Δ_{max} as a function of momentum transfer η in the one-dimensional case: a) for radial motion ($\delta q_x\gg\delta q_z$); b) for vertical motion ($\delta q_z\gg\delta q_x$).

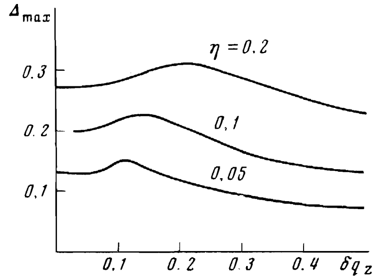

FIG. 3. Polarization contribution Δ_{max} as a function of vertical momentum δq_z; $\delta q_x = 0.56$.

E^{-7}) for the specified storage ring with the natural beam size. The contribution of the polarization also decreases as the result of the rise in transverse momentum.

4. BRIEF DESCRIPTION OF THE STORAGE RING VÉPP-2M [11]

The ring of the strong-focusing storage ring VÉPP-2M consists of eight sections of a magnetic system with four short and four long (85 cm) straight sections. In one of the long straight sections is placed a resonator at a frequency of 200 MHz (the 12th harmonic of the revolution frequency). The mean radius of the equilibrium orbit is 2.84 m and the maximum energy is 670 MeV. An automatic control system employing a computer of the M-6000 type[12] provides independent variation of the working frequencies of betatron oscillations, adjustment of the position of the equilibrium orbit, and smooth variation of the size and energy of the beam over wide limits.

Monitoring of the behavior and size of the beam in the storage ring is accomplished by means of the synchrotron radiation of the electrons and positrons and by measurement of the luminosity. The average vacuum in the storage-ring chamber is about 10^{-9} torr, but the lifetime at currents of ~1 mA is already determined by the elastic scattering of the particles inside the bunches.

5. COUNTER SYSTEM FOR POLARIZATION MEASUREMENT

The experimental arrangement (Fig. 4), which was chosen with consideration of the design features of the vacuum chamber and the magnetic structure of the storage ring, provides a rather high counting rate with a large contribution of the polarization and a low background level.

Two particles with energy E_0 redistribute the energy between them as the result of interaction (in any part of a straight section) and, entering the magnetic field of a bending magnet, are separated and travel in different directions from the equilibrium orbit. The design of the vacuum chamber does not permit detection of electrons turning toward the inside of the storage ring. Only electrons whose trajectories pass through the outer region of the bending magnet are detected. The detection system consists of three thin scintillation counters placed on a calculated trajectory and a total-absorption counter of the sandwich type. The sandwich has an energy resolution of 100% and a detection threshold of about 200 MeV, which permits the low-energy background to be completely cut off. All of the counters and the sandwich are connected in 4-fold coincidence with a resolving time of about 40 nsec. The geometry selected provides detection of electrons with energies from 1.18 E_0 to 1.3 E_0.

It is clear that the main fraction of the scatterings occurs near the center of the straight section where the bunch has the smallest transverse dimensions. To improve the background conditions and increase the contribution of the polarization, we selected an asymmetric variant of magnetic-structure correction, for which the beam in the working straight section has the following parameters: $V = 3\times10^{-3}$ cm^3, $\delta q_x = 0.56mc$, and $\delta q_z = 0.25mc$. In this variant the calculated value of transferred momentum is $\Delta_{max} = 0.30$ and the counting rate (5) of 4-fold coincidences averaged over the straight section and normalized to the square of the circulating current is

$$\dot{n} = 0.05(1 - \zeta^2\Delta_{max})\ \text{Hz/mA}^2.$$

Possible sources of background triggers are elastic scattering and bremsstrahlung in the residual gas and also elastic scattering inside the beam with small energy deviations from equilibrium ($\eta \gtrsim 1\%$). Experimental estimates of the background conditions were carried out by studying the dependence of the 4-fold coincidence rate on the beam parameters. As a result of these measurements it was demonstrated that the background amounts to several percent of the counting rate under typical operating conditions. The measured counting rate of useful events turned out to be close to the calculated value: ≈ 0.05 Hz/mA^2. To obtain adequate statistical accuracy the duration of the measurement must be several hundred seconds with a current of about 10 mA.

6. DEPOLARIZER

In the experiments on measurement of the beam polarization we made systematic use of a depolarizer—a device which produces a high-frequency longitudinal magnetic field H_v. The depolarizer is a current loop surrounding the vacuum chamber. The loop is part of a resonant circuit excited by an external oscillator at a frequency close to

$$\omega_d = \omega_s(\gamma q'/q_0 - 1). \quad (7)$$

As a result of the fact that the absolute value of the

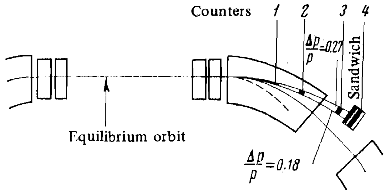

FIG. 4. Diagram of counter location for detection of electrons scattered inside the bunch.

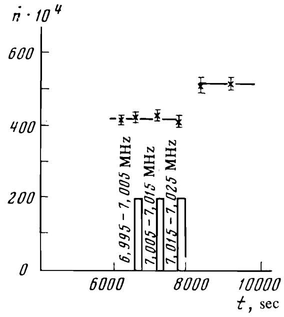

FIG. 5. Relative variation of counting rate as a function of depolarizer frequency.

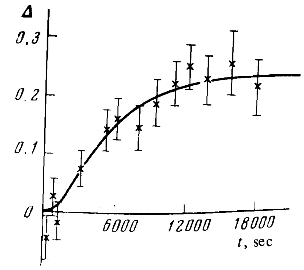

FIG 7. Degree of polarization as a function of time.

energy of the particles in the beam is known with insufficient accuracy, it is desirable to use a high-frequency field modulated in frequency. The extent of the modulation is chosen so as to cover the entire range of uncertainty of the energy value.

The strength of the magnetic field is determined by the time for which it is necessary to depolarize the beam. The depolarization time is

$$\tau_d = \frac{\Delta\omega_d}{\omega_s\omega_d}\left(\frac{H_z}{H_v}\frac{2L}{l}\right)^2$$

where l is the effective length of the longitudinal magnetic field and L is the perimeter of the orbit. The high-frequency system used at the present time has $l/L = 3\times 10^{-3}$; $(\Delta\omega_d)_{\max} = 2\times 100$ kHz and the magnetic field is up to $H_v = 10$ Oe, which permits depolarization of the beam in the time of ~100 sec.

7. RESULTS OF POLARIZATION MEASUREMENT

Measurement of the degree of polarization was carried out as follows. In each cycle of measurements an electron current $I \approx 30$ mA was maintained at a definite energy for some period of time. The counting rate normalized to I^2 was measured, and then the depolarizer was turned on for a time of 100 sec and after it was turned off the counting rate was measured again. In Fig. 5 we have shown the behavior of the counting rate as the depolarizer frequency is changed. It can be seen that after operation of the depolarizer at a definite frequency the counting rate rises discontinuously. At other beam energy values the depolarizer frequency at which the jump in counting rate occurs varies according to Eq. (7) (Fig. 6).[1)]

Figure 7 shows the magnitude of the discontinuity Δ as a function of the time elapsed from the beginning of the cycle to the moment of turning on the depolarizer at the resonant frequency. The curve has been drawn through the experimental points with allowance for the analytic dependence of the degree of polarization on the time (1) with the following parameters: $\zeta_{\max} = 0.92 \pm 0.15$, $\tau_p = 68 \pm 10$ min. The error in determination of $\zeta_{\max}$ is due mainly to the uncertainty in measurement of the mean square transverse momenta δq_x and δq_z in the beam and the transferred momentum $\Delta p/p$, which are necessary in calculation of the coefficient $\Delta_{\max}$. The two experimentally measured quantities are in good agreement with the theoretical values $\zeta_0 = 0.924$ and $\tau_p = 72$ min, which indicates the absence of appreciable depolarizing factors at the energy of the experiment $E = 625$ MeV.

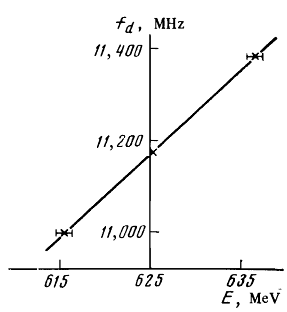

FIG 6. Change of depolarization resonance frequency with change of beam energy.

In addition, it was shown that the polarization is not destroyed on changing the energy from 670 to 450 MeV and back in a period of 100 sec. Crossing of the spin resonances $\nu = \nu_x - 2$ and $\nu = \nu_z - 2$ does not lead to an appreciable depolarization, which is consistent with rough calculations (Fig. 1).

The depolarizing influence of a colliding beam has been analyzed by Kondratenko.[14] It was shown that outside depolarizing resonances (4) the radiative polarization effect is preserved if the interaction of the colliding beams (collision effects) is small, i.e., if the condition of existence of the colliding beams themselves is satisfied.

A measurement was made of the polarization of an electron beam in the presence of a positron beam. The initial currents of electrons and positrons were 15–20 mA. To increase the lifetime of the beams the mode of operation of the storage ring was changed in such a way that the working point in betatron oscillations corresponded to the coupling resonance $\nu_x - \nu_z = 0$ (circular beams). After a time $t = 2\tau_p$ the mode of operation was returned to the initial working point with small transverse dimensions and a measurement was made of the polarization of the electrons by the means described above. As a result the preservation of the electron polarization in the presence of a colliding beam was confirmed.

For observation of the polarization of electron-positron colliding beams an experiment was carried out to measure the azimuthal asymmetry of μ-meson production in the reaction $e^+e^- \to \mu^+\mu^-$. The results obtained[15] indicate existence of a transverse polarization of the two beams. The luminosity achieved for polarized colliding beams is 2×10^{29} cm^{-2} sec^{-1}.

Thus, we have demonstrated the possibility of performing experiments in polarized colliding beams of electrons and positrons.

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[1)]This variation is a method for the accurate absolute measurement of the electron energy in a storage ring, since the anomalous magnetic moment of the electron is known extermely accurately, to $\sim 3\times 10^{-6}$. The accuracy achieved by this method in absolute calibration of the energy of the VÉPP-2M storage ring[13] is 10^{-4}.

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Non-adiabatic frequency resonant radiation

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A formula for the probability of non-adiabatic multiphoton excitation of a molecule from the electronic ground level to an excited level in the field of an external electromagnetic wave is derived by the WKB method. Resonant excitation of vibrations by laser radiation and multiphoton transitions due to the interaction between the electron and the "hot" vibrations are investigated separately.

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1. Many recent experimental and theoretical papers are devoted to the excitation and decay of molecules under the influence of laser radiation of frequency close to the frequencies of dipole-active molecular vibrations (see, e.g., [1–4]). Investigations of the pure vibrational mechanism of excitation and breakup of molecules have by now become traditional.[5,6]

The electronic mechanism of multiphoton excitation of molecules was investigated on the basis of perturbation theory.[7,8] The non-adiabatic channel of multiphoton excitation of molecules in a strong electromagnetic field, has insofar as we know, not been considered. (Naturally, the dissociation limit of the molecule with respect to a given vibration should lie higher than the electron-excitation energy.)

The existence of various dipole moments (d_{ii}, $i=1, 2$) for the ground (1) and excited (2) terms of the molecule leads, in principle, to a new situation for multiphoton transitions, in comparison, say, with multiphoton transitions between two nondegenerate electronic states in an atom.[9] In this case the situation is closer to the scheme of multiphonon transitions in a solid, owing to the possibility of a real intersection of the terms and the appearance of effects of the Landau-Zener type.[10]

An electromagnetic (EM) wave can interact either directly with the dipole moment of an electron or with a dipole-active vibration.[11] The buildup of the latter also activates multiphoton transitions of the electron. We consider first the case when the wave frequency ω is not at resonance with the frequency Ω of the active vibra-