

## RADIATIVE POLARIZATION: OBTAINING, CONTROL, USING

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(Received September 26, 1977)

**This paper is dedicated to the memory of our teacher, Gersh Budker**

Theoretical and experimental studies in the Institute (Novosibirsk) on the behavior of particle polarization in storage rings are reviewed. In theoretical works the motion of particle spins in arbitrary inhomogeneous fields was investigated. Methods are described for obtaining beams with a required polarization direction in storage rings and accelerators. It is shown that variable-direction fields in some parts of the orbit may be used to avoid resonance depolarization during acceleration of polarized particles to high energies. The conditions for the existence of radiative polarization of electrons and positrons are discussed. Methods for measuring the polarization of the single and colliding beams are described. The results of measuring the time and degree of radiative polarization are presented. The action of spin resonances was studied. The use of polarized beams to measure the absolute energy of particles in a storage ring and to compare precisely the anomalous magnetic momenta of electrons and positrons is described.

### I REVIEW OF THEORETICAL RESULTS

The effect of radiative polarization of light high-energy charged particles (electrons and positrons) on their motion in a homogeneous magnetic field was found theoretically in 1963 by Sokolov and Ternov.<sup>1</sup> This effect can be interpreted in a classical way, considering a noncharged particle with a high spin  $S \gg \hbar/2$  and a magnetic moment  $\mu = q\mathbf{S}$ , moving straight across the magnetic field  $H$ . Then in the particle frame, with a magnetic field  $\gamma H$ , due to a precession magnetic-dipole radiation, the magnetic moment will "damp" to a position along the field (minimum of energy) according to the equation

$$\frac{dS_{\parallel}}{d\tau} = \frac{2q}{3c^3} \left( \mathbf{S} \times \frac{d^3\boldsymbol{\mu}}{d\tau^3} \right)_{\parallel} = \frac{2q^5}{3c^3} (\gamma H)^3 S_{\perp}^2,$$

$$\left( S_{\parallel} = \frac{\mathbf{S} \cdot \mathbf{H}}{H}, S_{\perp}^2 = S^2 - S_{\parallel}^2 \right).$$

In the laboratory system

$$\dot{S}_{\parallel} = \frac{2q^5}{3c^3} \gamma^2 H^3 S_{\perp}^2. \quad (1)$$

From this the characteristic time of damping (for small deviations of the magnetic moment from the

field direction) is

$$\tau_p = \left| \frac{4S}{3c^3} q^5 \gamma^2 H^3 \right|^{-1}.$$

When this case is considered in a quantum-mechanical way, the following equation is obtained

$$\dot{S}_{\parallel} = \frac{2q^5}{3c^3} \gamma^2 H^3 S_{\perp}^2 - \frac{2\hbar}{3c^3} \gamma^2 |q^5 H^3| S_{\parallel}. \quad (2)$$

In the classical limit this equation goes to Eq. (1). The equilibrium degree of polarization remains equal to 100% for an arbitrary spin.

For a charged particle with charge  $e$  and gyromagnetic factor  $g$  ( $g = ge/2mc$ ), the corresponding equation has the general form<sup>2</sup>

$$\dot{S}_{\parallel} = \frac{\alpha_{-} S_{\perp}^2}{\hbar} - \alpha_{+} S_{\parallel}, \quad (3)$$

where the coefficients  $\alpha_{\pm}$  do not depend on the spin value and in the ultrarelativistic case are proportional to  $\gamma^2 H^3$ . For spin  $\frac{1}{2}$ , the equation takes the form ( $S_{\perp}^2 = \hbar^2/2$ )

$$\dot{S}_{\parallel} = \frac{\alpha_{-} \hbar}{2} - \alpha_{+} S_{\parallel}$$

The quantum-mechanical sense of the coefficients  $\alpha_{\pm}$  becomes clear from comparison of this equation with an elementary balance equation for spin  $\frac{1}{2}$  as a two-level system:  $\alpha_{+}$  and  $\alpha_{-}$  are the sum and difference of spin-flip probabilities for spin  $\frac{1}{2}$  per unit time:  $\alpha_{\pm} = P_{\uparrow} \pm P_{\downarrow}$ .

Note that for a particle with a high spin the polarization rate is determined by the difference of the spin-flip probabilities ( $\tau_p^{-1} = |(2S/\hbar)\alpha_{-}|$ ), while for spin  $\frac{1}{2}$ , the rate  $\tau_p^{-1} = \alpha_{+}$ .

For the case of a particle with high gyromagnetic factor ( $g \gg 1$ ), the spin-dependent part of the charge radiation can be neglected as compared with the magnetic moment radiation. In this case the particle non-inertial motion is negligible and the reverse transition probability disappears. Thus

$$\alpha_{+} = |\alpha_{-}| = \frac{2\hbar}{3c^3} \gamma^2 |q^5 H^3|,$$

and Eq. (3) coincides with Eq. (2). For a charged particle with  $g \sim 1$ , the quantum fluctuations of radiation result in reverse transitions ( $\alpha_{+} > |\alpha_{-}|$ ) and decrease the equilibrium polarization degree  $\zeta$ . Thus, for an electron in a homogeneous magnetic field  $\zeta = |\alpha_{-}|/\alpha_{+} = 92\%$ .

The evaluation of the polarization time exemplified by an uncharged particle (neutron) was given by V. L. Lyuboshits.<sup>3</sup>

The result obtained by Sokolov and Ternov pointed to the presence of a polarizing mechanism. To clarify the real possibilities of producing polarized light particles in storage rings, it was necessary to study radiative polarization in inhomogeneous fields.

In inhomogeneous fields the polarization state variation occurs both because of the direct-radiation effect and mainly as the result of the orbital-motion perturbation due to radiation.

A study of the direct-radiation effect on the polarization of ultrarelativistic light particles in arbitrary inhomogeneous fields (only small field variations about the radiation formation length were assumed) was performed by V. N. Baier, V. M. Katkov, and V. M. Strakhovenko.<sup>4-7</sup> It was found that the field inhomogeneity did not significantly change the polarizing mechanism resulting from the direct interaction of a spin with radiation.

The importance of studying the effects of radiation influence on polarization via an orbital motion is associated with the fact that the time of orbital motion relaxation is many orders lower than that of polarization. The study of these effects

was started by V. N. Baier and Yu. F. Orlov.<sup>7,8</sup> It was shown that the orbital diffusion caused by quantum radiation fluctuations in the presence of small vertical distortions of closed orbits in a storage ring resulted in spin diffusion. This depolarizing influence of radiation is of a resonance nature and at adequate closeness of the frequencies of precession and disturbance destroys radiative polarization.

For a complete answer to the question of the existence of radiative polarization, it was necessary to make a detailed analysis of polarization behaviour with account of all specific features of particle motion in storage rings. Later a study was made of the spin dynamics not restricted to the usual case of approximately axial magnetic fields.<sup>9-11</sup> Generalization to the case with arbitrary inhomogeneous fields is of practical interest for studying the possibility of obtaining any required polarization direction. Methods and concepts were developed enabling a unified description of the radiative polarization to be obtained in arbitrary electromagnetic fields with account of all significant orbit-spin coupling effects. The analysis makes it possible to describe quantitatively the process of polarization both in the usual cases and in those with variable-direction fields.<sup>2,12,13</sup>

It was stated that for any stationary magnetic (electromagnetic) fields providing the existence of closed (and stable) particle orbits  $\mathbf{r}(\theta)$ , where  $\theta$  is the generalized azimuth, there exist closed (periodically repeated at a given azimuth) spin trajectories  $\mathbf{n}(\theta)$  stable not less than in nearly unidirectional fields (instability is possible only in the vicinity of spin resonances).<sup>9,10</sup> A spin deviating from  $\mathbf{n}$  precesses around  $\mathbf{n}$  (similar to the precession around  $\mathbf{H}$  in a unidirectional field).

This fact provides extensive possibilities, by introducing specific fields, of obtaining any stable direction of the particle spin on the given azimuth in a storage ring (in particular, a longitudinal one).

As regards the procedure, it is reasonable to note that the possibility of realizing, by choosing the magnetic-field geometry, a stable spin motion with a given direction in the required orbit point is analogous to that for the achievement of stability in orbital motion of particles in a storage ring with a complicated form of the equilibrium trajectory. For example, the introduction of a small longitudinal magnetic field in a storage ring (with plane closed orbits) results only in a slight deviation in the equilibrium-polarization stable direction from a vertical one, far from spin resonances. In addition,

the introduction of a field rotating a spin by an angle of order unity at a single transit does not destroy the spin-motion stability and results in a strong variation of the equilibrium polarization  $\mathbf{n}$ .

The well-known situation in which polarized beams may exist is the motion in an accelerator or a storage ring with a magnetic field constant in direction. The natural direction of the stable polarization lies along the field transverse to the particle velocity.

Already in this case, the polarized beams substantially expand the possibilities for carrying out experiments in physics. In particular, one can determine the spin properties of final states by measuring the azimuthal distribution of the reaction products for transversely polarized colliding beams. It becomes also possible to carry out precise experiments.<sup>14-18</sup>

Of great interest is the problem of obtaining beams with any preassigned polarization direction. As an example, in experiments with longitudinally polarized (parallel to the velocity) electron-positron colliding beams of the same helicity, the one-photon electrodynamic channel is closed and therefore all the rest of the annihilation processes, either non-one-photon or nonelectrodynamic, are emphasized.

The first suggestions (1970) for producing the required polarization direction, in particular, longitudinal, were given in Ref. 10 [see also Ref. 7 p. 477 (p. 714)]. Longitudinally polarized beams can be obtained in various ways. Consider simple examples.<sup>10</sup> Introduce a radial magnetic field  $H_x$  into a straight section of the storage ring. To change the spin direction with respect to the velocity by the angle  $\pi/2$ , it is necessary to use for electrons  $H_x l = 23$  kG-m, where  $l$  is the length of the section with the introduced field (for protons  $H_x l = 27$  kG-m; the proximity of the required field values is explained by the fact that the anomalous magnetic moments of an electron and a proton have almost the same absolute value). By varying the value  $H_x$  along the section, any required polarization direction can be obtained at the collision point. To restore the polarization direction along the field and the particle velocity upon its initial direction, the condition  $\int_s H_x(\theta) d\theta = 0$  should be imposed. No special problems are presented in restoration of the orbit at the section output. Such methods provide a high degree of radiative polarization.

When rotating at the present plane by transverse (in respect of velocity) fields, a relation exists

between the velocity angle  $\varphi$  relative to the main orbit plane and the spin angle  $\psi$  with respect to velocity

$$\frac{\varphi}{\psi} = \frac{2}{\gamma(g-2)} \equiv \frac{1}{v}.$$

When radial fields are used, at the point of longitudinal polarization the velocity inclination angle is  $\pi/2v$ . The amplitude of the vertical orbit distortion within the section with radial fields introduced will depend on energy. The choice of a method is determined by specific experimental conditions. For example, the particle trajectory within the section may be of the form shown in Figure 1a. The radial magnetic field is transverse to the plane of the figure and introduced in regions I, II, III. Opposite-direction longitudinal polarizations are produced between regions I, II and II, III (the arrows point to the polarization direction). As another example, the method suggested in<sup>19</sup> can be taken (see Figure 1b). Here longitudinal polarization is produced between regions II and III. (Opposite-direction longitudinal polarization may take place between regions I, II and III, IV.) The characteristic property of this method consists in the fact that the collision of longitudinally polarized particles occurs at the point 0, at a position along the vertical that does not depend on energy.

In a motion along one orbit in any magnetic field, electrons and positrons are polarized in opposite directions due to radiation (in particular, this is also valid at the point of longitudinal polarization, which gives equal helicities). Colliding electron-positron beams with the same polarization direction can be obtained. For this purpose, it suffices to separate the polarized beams' energies

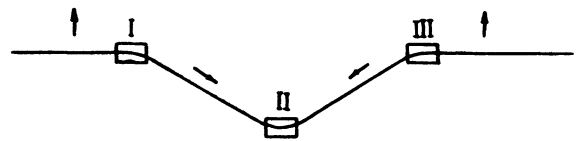


FIGURE 1a Production of longitudinal polarization. Variant 1.

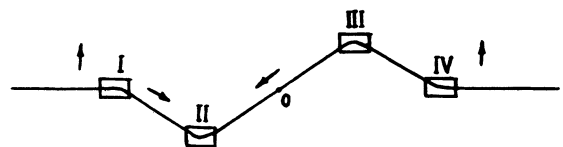


FIGURE 1b. Production of longitudinal polarization. Variant 2.

by a radial electric field and to invert one beam polarization direction by making it pass adiabatically through an induced spin resonance.<sup>11</sup> The state of the reverse-direction polarization is dynamically as stable as the “natural”, and due to radiative processes it will only relax slowly to the latter.

When beams move along different trajectories, as, e.g., in storage rings DORIS (GFR) or DCI (France), the states of beams with any relative signs of longitudinal polarizations can be stable with respect to radiative processes. Thus, at concentric trajectories (similar to those in the above storage rings) equal helicity states occur, provided that at the collision point the trajectory inclination angles to the main orbit planes (the orbit planes are parallel) are equal (head-on collision)  $\varphi = \pi/2v$ . The state with opposite helicities takes place provided that the inclination angles, e.g., are  $\pm\varphi$ , where the beam collision angle is  $2\varphi$ , as shown in Figure 2. Then, polarization of both beams proves to be longitudinal (with accuracy  $\sim \varphi/\gamma$ ) in their center-of-mass system.

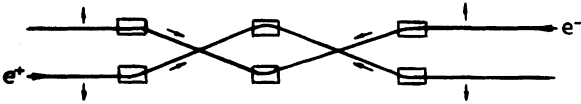


FIGURE 2 Production of longitudinal polarized colliding beams of opposite helicity.

Other examples of longitudinal polarization in a straight section (with spin and orbital motion restoration) can be given by the methods utilizing instead of radial fields combinations of longitudinal and vertical fields<sup>20</sup> or of radial and vertical fields.<sup>21</sup>

To produce longitudinal polarization, a longitudinal magnetic field can be used, thus not distorting the equilibrium particle orbit. Consider an interesting example.<sup>10,22</sup> Let two opposite straight sections be present in a storage ring. Introduce in one of them in the length  $l$  a longitudinal field  $H_v$  rotating the spin vector by a half turn around the rate. The required field value is  $H_v = 2\pi E/gel$ , where  $E$  is the particle energy. In this case, the stable equilibrium polarization  $\mathbf{n}$  in the opposite straight section is directed along (against) the velocity independent of energy, and in the main part of the orbit it is transverse to the guide field, its orientation in the orbit plane at a given azimuth being dependent on energy. The spin orientation in the main region in the field is inverted in a particle revolution. This means that the fractional

part of the spin precession rate around  $\mathbf{n}$  is always equal to half the particle revolution frequency, independent of energy.<sup>†</sup> It is interesting that in this case the spin motion is even more stable than in a usual case of a unidirectional magnetic field; all spin resonances, including those with betatron harmonics, become actually impossible, since the resonance would also imply simultaneous instability of the orbital motion.

In principle, methods of polarization control possible for electrons (positrons) can also be applied to heavy particles. Due to the absence of the effects of radiative polarization, these particle beams should be either injected already polarized or somehow be polarized in the storage ring. For example, one may expect to obtain polarized proton (antiproton) beams in storage rings by using the spin dependence of the nuclear interaction of particles with polarized targets, applying electron cooling to maintain sufficiently small beam sizes.

Preparations for a practical operation with polarized particles in storage rings, including those with complicated field and trajectory configurations, demanded the development of a more extensive and detailed analysis of polarization behaviour in the region of spin resonances. The complete solutions have been obtained for all cases of single crossings of resonances at any rate, which generalize the results given in Ref. 23. The problem of the spin motion at multiple periodic and “noise” crossings of any resonances (both machine and those induced by external high-frequency fields) has been solved.<sup>11</sup>

One of the important problems where the results of studying the spin dynamics can be applied is the depolarization suppression when passing the spin resonances (due to energy change, for ex.) particularly acute for heavy particles (see, e.g., Ref. 24). The compensation of dangerous harmonics of the disturbing fields or the increase of the resonance crossing rate can obviously be recommended. For example, the depolarizing influence of resonances with betatron frequencies can be eliminated by a system providing rapid crossing due to betatron

<sup>†</sup> In storage rings with variable-direction fields, the frequency of spin precession around  $\mathbf{n}$  is defined not only by the energy of a particle but by all structure of the field over the closed orbit.<sup>9,10</sup> In the case considered, the angle of spin rotation around  $\mathbf{n}$  during the period of the particle's revolution in the storage ring does not depend on energy ( $H_v \sim E$ ) and is equal to  $\pi$ .

frequency jumps.<sup>25</sup> To suppress depolarization at resonances with the revolution frequency a method based not on the compensation of dangerous harmonics but on their increase by introducing additional fields to the value when the resonance crossings become adiabatic<sup>26</sup> is effective.

The introduction of fields greatly disturbing the spin motion enables simultaneous suppression of the effects of resonances with betatron frequencies as well. The limiting case may be the above example with the introduction into the straight section of longitudinal field rotating a spin by a half-turn. Distortions in the magnetic-system focusing properties, if necessary, can be compensated by the introduction of additional lenses. In this case, it is of advantage to inject longitudinally polarized particles directly to the opposite section where the equilibrium polarization direction is parallel to velocity.

When accelerating up to high energies ( $v \gg 1$ ), it is easier to invert a spin in the section by magnetic fields transverse to the orbit, since the required value of these fields is approximately  $v$  times lower than the required value of a longitudinal field. The condition of orbit restoration can simultaneously be fulfilled, too. For example, introduce the transverse fields forming an angle  $120^\circ$  to three successive regions I, II and III, as is shown in Figure 3. The figure plane is transverse to the velocity and the magnetic field  $H$  is horizontal.

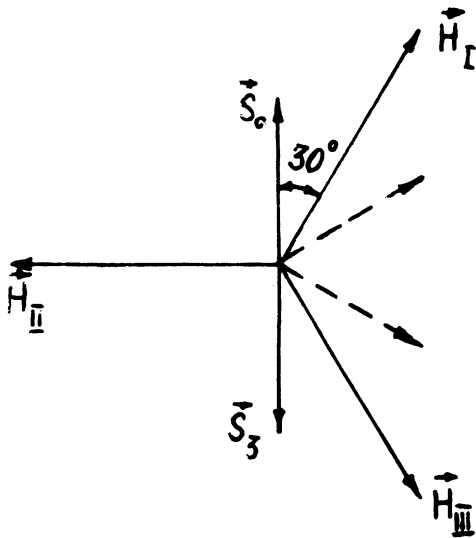


FIGURE 3 The scheme of spin flip by  $180^\circ$  in a straight section around the radial direction with particle velocity restoration.

each region the spin is rotated around the field by the angle  $\pi$ . It can readily be seen that the vertically oriented spin upon its transit of these three regions proves to be inverted  $S_3 = -S_0$ . In this case the particle-velocity direction is restored with an accuracy up to  $v^{-3}$ . (Without further complication of this system, an accurate velocity restoration can also be provided.) The resulting spatial orbit displacement can readily be compensated in the subsequent region by a unidirectional field with zero average value, not distorting the direction of the spin and velocity.

Here again, as in the method with a longitudinal field, the fractional part of the frequency of the spin precession around  $\mathbf{n}$  is equal to half that of the particle revolution.

Since in these cases spin resonances are impossible at any energy, in the process of acceleration the beam-polarization degree will be kept constant.

The switching on of rotating fields during acceleration can be performed adiabatically with the spin and orbital motions kept stable.

The problem of keeping polarization during acceleration or deceleration may be important for light particles as well. For example, electrons can be quickly polarized at high energy and then decelerated to that required for the experiment. An advantageous approach may be fast polarization at a low energy in a special storage ring with a high field, followed by the transition of polarized particles to the main storage ring.

During dynamically slow (adiabatic) passing of a spin resonance in electron and positron storage rings the depolarizing action of quantum fluctuations, which is maximum in the resonance region, should be taken into account. Introducing sufficiently large coherent perturbations (additional fields in straight sections), the resonance can be shifted to such an extent that the depolarization is suppressed due to radiation fluctuations.<sup>26</sup>

On the basis of the results of the spin-dynamics analysis a study was performed of radiative polarization in arbitrary storage rings.<sup>2,12,13</sup> It has been shown that self-polarization may take place in storage rings with great deviations of the equilibrium polarization direction  $\mathbf{n}$  from the axial one. For this case an efficient additional mechanism of radiative self-polarization has been found that is altogether absent in an almost unidirected magnetic field.<sup>2</sup> The effect has a classical interpretation; it results from the dependence of the radiative reaction force on the spin direction. When the equilibrium polarization direction  $\mathbf{n}$  does not coincide with the

velocity rotation axis, this direction  $\mathbf{n}$ , due to its dependence on the particle trajectory, proves to be resonance-modulated at the spin-precession frequency. This results in the appearance of a decrement (or an increment) of the angle between the spin and  $\mathbf{n}$ .

In certain cases when the usual self-polarization effect is completely absent, the above mechanism may provide a high degree of polarization.

For example, in the above storage ring with a longitudinal field rotating a spin in the straight section by a half-turn, the radiative polarization is completely determined by this mechanism. For particle energies for which  $v \lesssim 1$  the polarization degree may reach 60 to 70%. By properly choosing the storage-ring focusing system, a high degree of radiative polarization may also be kept at even higher energies. The order of the polarization time is the same as in a storage ring without a longitudinal field.<sup>22</sup>

It is interesting to note that with account of this effect, maximum polarization degree is achieved in a storage ring with an inhomogeneous field<sup>2</sup> of specific form and equals 95% (92% in a homogeneous field).

For a quantitative description of the radiative polarization kinetics at any point, an investigation was carried out without limitations imposed by the closeness of spin resonances. Since polarizing processes proceed slowly, it proved necessary to take into consideration the higher-order resonances as well. As a result, formulas were obtained determining the region of radiative-polarization existence and enabling us under given conditions to find the direction and degree of the equilibrium polarization and its damping time.

A very important practical problem has been considered on colliding-beams polarization behaviour.<sup>27</sup> It has been shown that the conditions of polarization stability of the colliding beams are close to those of the orbital motion at collision.<sup>†</sup>

The introduction of magnetic "snakes", i.e. regions with a strong variable sign vertical magnetic field  $H(\theta)$ ,<sup>28</sup> proves to be advantageous for

faster polarization.<sup>‡</sup> The minimum number of field oscillations is determined by the admissible amplitude of spatial orbit pulsations in the section. According to Refs. 2, 5–7, the inverse polarization time is

$$\tau_p^{-1} = A\gamma^2 \oint |H|^3 d\theta, \quad (4)$$

where  $A$  is a constant parameter. From this it is seen that by increasing the field over a relatively small length, the polarization time can be significantly decreased. In this case the equilibrium degree of polarization is equal to

$$\zeta = \frac{8}{5\sqrt{3}} \oint \frac{\oint H^3 d\theta}{\oint |H|^3 d\theta}.$$

It is evident that by introducing a "snake", a high degree of polarization can be provided without orbit distortion in the main sections. For this purpose, the condition

$$\left| \int_S |H|^3 d\theta - \left| \int_S H^3 d\theta \right| \right| \ll \int_S |H|^3 d\theta$$

should be fulfilled, providing that the varying-sign fields are greatly different in their values. At the same time the conditions  $\int_S H d\theta = 0$  and  $\int_S \theta H d\theta = 0$  can also be fulfilled. It is reasonable that by this method the sign of the equilibrium polarization can also be changed by varying the signs of the fields in a "snake". In particular, one may reversibly change the particle helicity in a region of longitudinal polarization. Of particular advantage for independent control of the colliding-beams polarization is the two-rings case.

## II METHODS OF POLARIZATION MEASUREMENT

Polarization of electrons and positrons that results from their prolonged motion in a magnetic field can be measured by various methods. The processes

<sup>†</sup> A special study is necessary to do for finding optimal conditions to have good enough luminosity and good enough equilibrium degree of radiative polarization simultaneously. By preliminary estimates, these requirements can be satisfied. They can be relaxed additionally if one uses many bunches regime in two-ring colliding beams facility.

<sup>‡</sup> A similar method was independently suggested by A. Hutton in his work "Control of the Low Energy Characteristics of the LSR Electron Ring Using Wiggler Magnets" [*Particle Accelerators* 7, 177, (1976)]. Note that, in our opinion, the basic formula for relaxation time of polarization used in this work is not quite correct and, therefore, the quantitative results are wrong.

useful for measuring the transverse polarization of high energy particles in a storage ring were proposed and considered in Refs 7, 29–31.

At energies of the order of 1 GeV, polarization of one beam can be measured by the dependence of elastic scattering of the particles in a bunch on their polarization. Because of the energy exchange  $\pm \Delta E$  in scattering, the particles leave the beam and can be detected. This method becomes low in efficiency for higher energies since, owing to a growth in the particle transverse momenta, both the cross section of the process and the polarization contribution decrease.

The cross section of Compton scattering of circularly polarized photons is also dependent on the electron polarization. The asymmetry of secondary  $\gamma$ -quanta with energy  $\sim \gamma^2 \hbar \omega_{ph}$  is maximum for the energy  $\hbar \omega_{ph} \approx mc^2/\gamma$ . For electron energies of the order of several GeV, the maximum asymmetry can be achieved using the ultraviolet (500–1000 Å) part of the synchrotron-radiation spectrum of an electron beam characterized by a considerable degree of the different-sign circular polarization above and below the equilibrium-orbit plane. The following scheme for an experiment can be suggested.

The beam is “prepared” as two succeeding bunches so that the “light” of the first one is reflected and focused by a spherical mirror at a distance of its radius, equal to half the distance between the bunches. The detection of recoil electrons deflected by a guiding magnetic field in coincidence with a secondary  $\gamma$ -quantum makes it possible to choose the required part of the spectrum. The reflection of either of the upper or lower part of the synchrotron radiation (with respect to the electron orbit plane) allows easy alternation of an asymmetry sign. For  $10^{10}$  electrons in each bunch, the number of “useful” events is about  $10^3$  per sec. The same counting rate may be achieved using a continuously operating laser with several watts of power. Lasers are efficient for electron energies of the order of 10 GeV where the asymmetry is maximum in the optical part of the spectrum. The main disadvantage of the Compton-scattering application for polarization measurements apparently consists in the necessity of sharp focusing of photons and precise adjustment of the electron orbit.

Another method of polarization measurements exists that is free of this disadvantage. It uses scattering by a jet of polarized atomic hydrogen. For already achieved densities of polarized hydro-

gen ( $\rho \sim 10^{12} \text{ cm}^{-3}$ ,  $\zeta = 1$ ) at  $E = 1$  GeV and a jet diameter of 0.5 cm, the number of events per second is numerically equal to the electron beam current in mA. The azimuthal anisotropy for the transverse polarization of electrons is  $\pm 10\%$ . In the case of longitudinal polarization, the counting rate of useful events varies by a factor of 8 for parallel and antiparallel orientation of the electron spins in the beam and in the target. The possibility of simultaneous scattering of electrons and positrons as well as weak dependence of the scattering cross section on the particle energy ( $\sigma \sim \gamma^{-1}$ ) make the polarized gas-target application a convenient means for measuring the polarization of both one beam and colliding beams.

The product of the polarization degrees of colliding beams can directly be measured in the experiments on high-energy particle interactions. The cross sections of two-particle reactions depend on the mutual orientation of electron and positron spins.<sup>7</sup> The cross section of the  $\mu$ -meson pair creation is strongly polarization dependent:

$$\sigma_{\mu\mu}\left(\theta = \frac{\pi}{2}, \varphi = \frac{\pi}{2}\right) = 0, \quad \sigma_{\mu\mu}\left(\theta = \frac{\pi}{2}, \varphi = 0\right) = 2\sigma_{\mu\mu}^0.$$

Reactions in which pseudoscalar mesons are produced are less convenient for polarization measurements, because their cross sections are as a rule smaller than  $\sigma_{\mu\mu}$ . However, in the region of resonances where the corresponding cross section greatly increases, the observation of the azimuthal anisotropy of final particles appears to be a convenient method for measuring the transverse polarization. The longitudinal polarization of colliding beams can easily be observed from the elastic scattering of electrons on positrons. The cross section of this process at  $\theta = \pi/2$  varies by a factor of 8 for parallel and antiparallel particle spins.

When operating with polarized beams, it is advisable to be able to depolarize a beam. For this purpose one can use a machine resonance of sufficient power. In many cases, however, it is not of advantage since either beam energy or frequency of betatron oscillations should be changed. A more promising method is provided by the use of an external high-frequency electromagnetic field resonant with the spin precession frequency.

Such excitation should not result in variation of the beam sizes, so the rf-field frequency should not coincide with one of the combinations of orbital

oscillation frequencies. That is why for transverse electron polarization, it is safer to switch on a longitudinal magnetic field. At higher energies, however, when  $v \gg 1$ , the transverse  $H_x$ -field is more convenient for beam depolarization since the required longitudinal fields are considerably larger for the same depolarization time, i.e.,

$$\left| \frac{\int H_v d\theta}{\int H_x d\theta} \right| \approx v.$$

The application of a running wave with  $|H_x| = |E_z|$  provides additional possibilities in two-beam experiments. In the absence of reflection, each of the colliding beams can be depolarized separately by choosing the direction of wave propagation. In addition, it seems possible to depolarize selectively bunches of one beam if short-time pulses in phase with the revolution frequency are used. This method will allow experiments with colliding beams containing simultaneously both polarized and unpolarized particles, other parameters being equal.

### III EXPERIMENTS WITH POLARIZED BEAMS

Experiments on measuring the electron polarization were started in Novosibirsk in 1970 with the storage ring VEPP-2.<sup>7</sup> The first result gave evidence for radiative polarization. However, because of the reconstruction of the VEPP-2 complex the experiments were stopped and continued in 1974–1975 using a new storage ring VEPP-2M.<sup>14,15</sup> Measurements of the transverse polarization degree were performed by detecting elastic scattering of the particles in a bunch. Two systems of scintillation counters have been used in VEPP-2M; one detects electrons with an energy transfer  $\Delta E/E \geq 20\%$ , while the second detects electrons and positrons with  $\Delta E/E \simeq 5\%$ . When the beam was quickly depolarized using a noise-modulated high frequency longitudinal magnetic field (resonant with the spin precession frequency), a jump in the counting rate  $\dot{n}$  of such events was observed as shown in Figure 4. The dependence of this jump value  $\Delta = (\dot{n}_0 - \dot{n}_p)/\dot{n}_0$  on the time (Figure 5) from the beginning of a polarization cycle until switching the depolarizing rf-field allowed determination of the limiting polarization degree  $\zeta = 0.90 \pm 0.15$  and the time of radiative polarization  $\tau_p = 68 \pm 10$  min at an energy of 625 MeV.

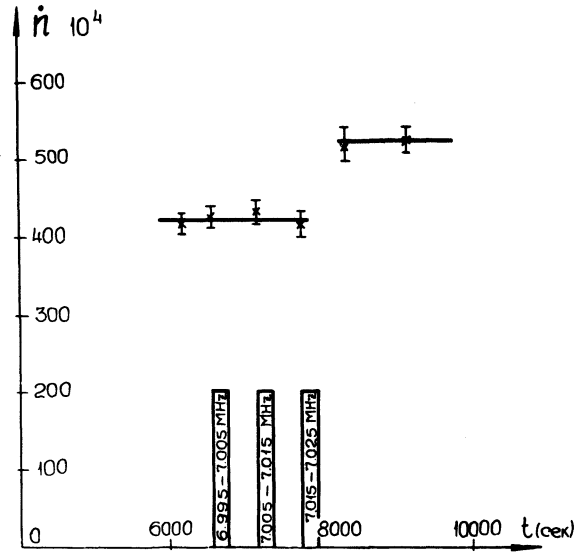


FIGURE 4 The counting rate of elastic scattering events in a bunch versus the depolarizer frequency.

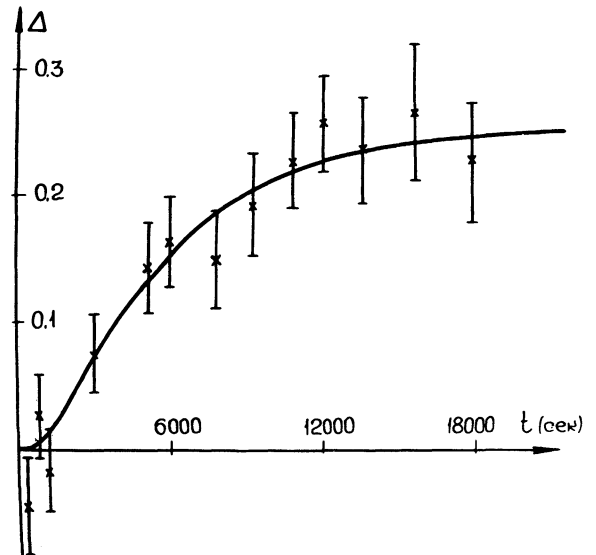


FIGURE 5 The jump in the counting rate during depolarization versus time from the beginning of a polarization cycle.

The good agreement of the measured quantities with those calculated provided evidence for small values of the depolarizing factors at the energy of the experiment (625 MeV), which was expected after numerical estimates of the depolarization time. In the estimate, a model was used in which a perturbation in the form of a skew quadrupole was introduced into the ideal structure of a storage ring (the quadrupole strength was obtained by



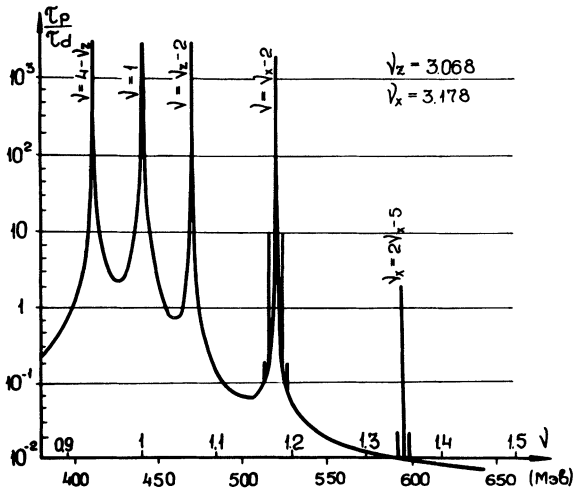
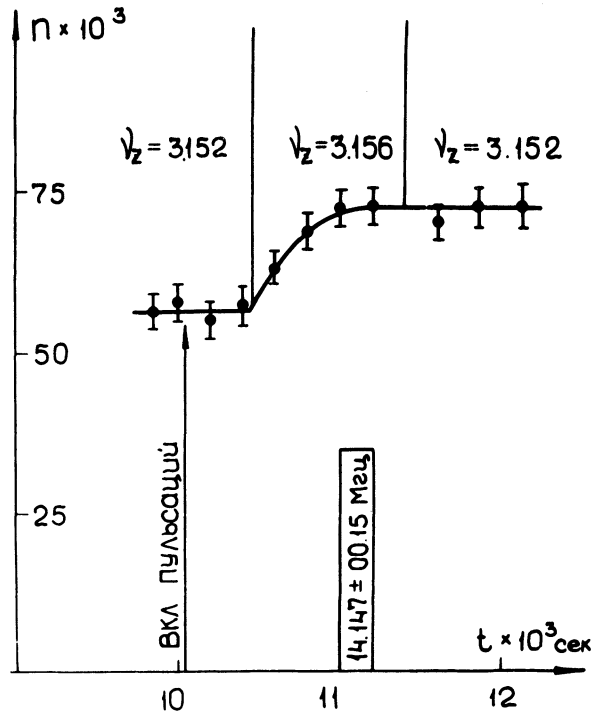


FIGURE 6 Calculation of depolarizing resonances.

measuring the coupling of vertical and radial particle oscillations). The results of the numerical calculations of machine depolarizing resonances whose power is characterized by the ratio of polarization and depolarization times  $\tau_p/\tau_d$  are given in Figure 6. In VEPP-2M, radiative polarization is possible in the energy range above 490 MeV, excluding narrow resonance bands that can easily be "shifted" by choosing the operating frequencies of betatron oscillations  $\nu_x, \nu_z$ . The calculations also showed that resonances can be passed without polarization destruction; that was later examined experimentally. At the rate of energy variation 10 MeV/sec, no pronounced decrease in the beam-polarization degree has been observed upon passing resonances with betatron oscillations of both the first and the second orders.

The linear resonance  $\nu = \nu_z - 2$  has been studied in more detail. Figure 7 shows the behaviour of the counting rate of elastic-scattering events in a polarized beam near this resonance. At the vertical betatron-oscillation frequency  $\nu_z = 3.152$  (exact resonance at  $\nu_z = 3.1565$ ), polarization is maintained for a long time. Switching of noise pulsations of the guiding magnetic field  $\Delta H/H \approx 2 \cdot 10^{-3}$  (resulting in a modulation of the spin precession frequency of the same order) at  $\nu_z = 3.152$  did not change the degree of polarization, while at  $\nu_z = 3.156$  for  $t = 400$  sec resulted in complete beam depolarization, confirmed by the absence of variations in the counting rate when a depolarizing rf-field was switched on for control.


 FIGURE 7 Depolarization at the resonance  $\nu = \nu_z - 2$ .

The calculation for a resonance  $\nu = 1$  (the frequency of anomalous spin precession equal to the revolution frequency at  $E = 440.65$  MeV) showed that at a given rate of energy variation, a resonance cannot be passed without complete depolarization unless special care is taken. To confirm this result, several experiments were performed in which the polarization degree was measured after decreasing the polarized beam energy to the region of an integer resonance and returning it to the initial value with the same rate. Up to 448 MeV, the polarization was maintained, but at 443 MeV and below complete depolarization occurred.

The depolarizing action of the quantum fluctuations of radiation during the crossing of an integer resonance can be suppressed by increasing the perturbation resonance harmonic by introducing a constant field into a straight section.<sup>26</sup> To verify experimentally the possibility of passing an integer resonance without beam depolarization, a solenoid with a longitudinal magnetic field was placed in one of the VEPP-2M straight sections  $\bar{H}_\parallel/\bar{H} = 0.03$ . The calculation shows that this field value is sufficient for secure passing of the resonance with an energy variation rate of 10 MeV/sec. In this

case, the central resonance is being passed dynamically slowly, while the first of the possible side resonances associated with phase oscillations is being passed rapidly.

This experiment was performed in the following way: to a polarized bunch of positrons at  $E = 625$  MeV, an unpolarized bunch of equal current shifted in phase by  $\pi/4$  was added. The comparison of the counting rates of elastic scattering in each bunch provides a continuous and rapid measurement of the polarization degree. At an energy of 510 MeV, by varying  $v_z$  and  $v_x$  in turn, the betatron resonances  $\nu = \nu_z - 2$  and  $\nu = \nu_x - 2$  were "removed", then a longitudinal field was switched on; when the particle energy was decreased to 400 MeV, this field was switched off. A subsequent measurement showed polarization conservation. In a control cycle, repeating all the procedures except the introduction of the longitudinal magnetic field, complete disappearance of the positron polarization was observed. Thus, a possibility to pass integer resonances without beam depolarization has been shown experimentally.

As mentioned above, the condition for colliding beams polarization conservation is close to that for orbit stability at collision. Polarization of colliding beams was measured by a system of counters simultaneously detecting electrons and positrons lost from the beams due to elastic scattering inside the bunches. It was shown that up to currents of  $10 \times 10$  mA at  $E = 650$  MeV, radiative polarization occurred in the usual way. Polarization did not vanish after decreasing the energy to 510 MeV, where it was maintained for a long time. The maximum luminosity of the polarized colliding beams was achieved in the  $\phi$ -meson region,  $2 \cdot 10^{29} \text{ cm}^{-2} \text{ sec}^{-1}$ .<sup>14</sup> Two experiments using polarized colliding beams were performed by studying the azimuthal anisotropy of created particles. At the energy 2.650 MeV, anisotropy in production of muon pairs was observed, which supported polarization of the colliding beams. An investigation of anisotropy in charged-kaon production was carried out at the  $\phi$ -meson energy after  $e^+$  and  $e^-$  beam polarization at 650 MeV for a time  $t = 2\tau_p$ , as shown in Fig. 8. The measured value of the product of the polarization degrees was  $\zeta_+ \zeta_- = 0.63 \pm 0.14$ .

Radiative polarization has also been studied on other electron-positron storage rings. In 1971 the positron-beam polarization was measured on ACO (France) using intra-bunch scattering. For depolarization, passing of an integer machine reson-

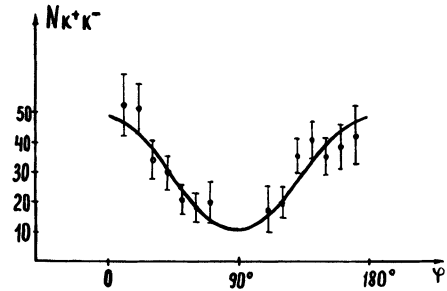


FIGURE 8 Azimuthal anisotropy of  $K^\pm$ -mesons produced with polarized beams.

ance at 440 MeV was used. It was shown that positron polarization was maintained (at good operation points) in the presence of an electron beam up to currents close to the current limits set by beam-beam effects and the action of some machine depolarizing resonances was demonstrated.<sup>32</sup>

In 1975, polarization measurements were performed on the storage ring SPEAR. At first, the polarization of one electron beam was observed according to intra-bunch scattering and depolarization at an integer resonance.<sup>33</sup> Then the polarization of colliding beams was demonstrated by measuring the anisotropy of muon-pair creation at an energy 3.7 GeV.<sup>34</sup>

The experience gained on these three storage rings shows that radiative polarization can be obtained over a wide range of experimental conditions and the luminosity of polarized colliding beams is already sufficient to perform various high-energy physics experiments.

A good example of such an experiment was that carried out by the SPEAR group on the determination of the primary jet spins in multihadronic events.<sup>35</sup> It was shown that polarization greatly facilitated such experiments.

On VEPP-2M, the radiative polarization was used for another type of experiment. The detection of a jump in the variation of the counting rate of elastic scattering events inside a bunch at a definite frequency of the depolarizing field also measures the average spin precession frequency  $\Omega$ . The measuring of the value of  $\Omega = \gamma\mu'/\mu_0\omega_s$  allows determination of the energy for a relativistic electron, since  $\mu'/\mu_0 \equiv (g-2)/2$  is known with high accuracy from the  $g-2$  experiments.

Energy spread in the beam to a first approximation does not restrict the accuracy of this method.<sup>16</sup> A particle-energy deviation by  $\Delta\gamma$  from the average value  $\gamma_0$  in the presence of the accelerating rf-field

results in synchrotron oscillations of frequency  $\omega \ll \Omega$ , which modulate the spin precession frequency. The spectrum of spin motion averaged over phase oscillations has a central line and side-band frequencies at a distance  $n\omega_\gamma$ . The phase-modulation parameters are usually chosen so that the depolarization time  $\tau_d$  is much lower at the central frequency as compared with the sideband ones. The width of the spectrum central line is determined by the difference between the particle energy  $\gamma_0$  averaged over phase oscillations and the equilibrium one  $\gamma_s$  associated, e.g., with quadratic nonlinearity of the storage ring. When compensating this and other nonlinearities, the spin-frequency spread can be minimized to the value determined by the squared energy spread, which enables the determination of the average absolute energy of particles with a limiting accuracy given by the known value of the electron anomalous magnetic moment. In practice, however, this accuracy is restricted by slow irregular pulsations of the storage ring magnetic field "smearing" the average precession frequency. At present, the system stabilizing the magnetic field of VEPP-2M provides one-measurement accuracy of  $\pm 2 \times 10^{-5}$ .

The first application of this method of energy calibration consisted in the  $\phi$ -meson mass measurement.<sup>15</sup> Before the experiment, an absolute calibration of the storage-ring energy scale was performed using resonance depolarization.

Each measurement cycle was started and ended with a control calibration of the beam energy at  $E = 509.6$  MeV. Three cycles measuring the  $\phi$ -meson excitation curve were performed over the energy range 1014–1026 MeV. The luminosity integral was  $L = 4 \times 10^{34}$  cm<sup>-2</sup>.

In the experiment, the decay mode  $\phi \rightarrow K_L + K_S$  was detected by two charged pions produced in the decay  $K_S \rightarrow \pi^+\pi^-$ . The experimental data and optimized curve are shown in Figure 9. The corresponding value of the  $\phi$ -meson mass  $1019.48 \pm 0.13$  MeV/c<sup>2</sup> with the data of other experiments is shown in Figure 10; the accuracy was two times better than the world-average. The same method of beam-energy calibration was used to measure the sum of  $K^+$  and  $K^-$  masses.<sup>17</sup> In this experiment, positrons were polarized at 650 MeV, then the energy was decreased to 509 MeV and at constant parameters, the beam was kept for an hour (for complete stabilization of all thermal regimes). Then a small depolarizer rf-field was switched on, its frequency was slowly changed, and by the jump in the counting rate of positrons scattered inside a

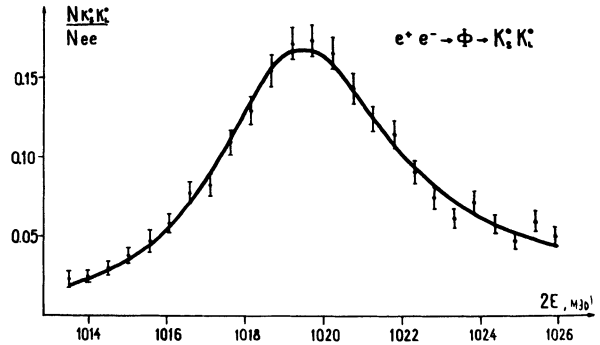


FIGURE 9 Excitation curve of the  $\phi$ -meson.

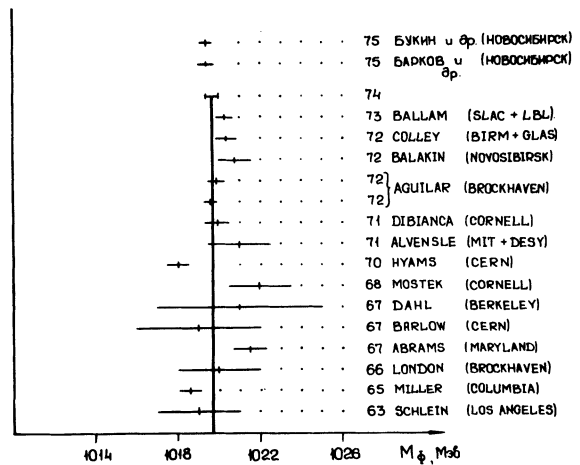


FIGURE 10 World values of the  $\phi$ -meson mass.

bunch, the spin precession frequency was determined, and respectively, the absolute positron energy was obtained with an accuracy of the order  $2 \times 10^{-5}$ . After the injection of an electron bunch a nuclear-emulsion chamber was exposed. The resulting accuracy of the  $K^+ + K^-$  mass determination was about 80 keV (two times better than the world-average). The decay mode  $\phi \rightarrow K^+ + K^-$  was detected in the nuclear emulsion precalibrated by monochromatic protons, which enabled determination of the kaon kinetic energy with an accuracy of 40 keV.

The identity of the particle and antiparticle properties was checked with high accuracy by comparison of the anomalous magnetic moments of electrons and positrons and simultaneous measurement of their precession frequencies (both particles being moved along the same equilibrium orbit in the storage-ring magnetic field).<sup>18</sup>

The experiment was carried out at  $E = 625$  MeV at the same time using electron and positron beams.

After the doubled period of the polarization time, a small depolarizer field was switched on and its frequency was slowly varied. The jump in the counting rate of the scattered  $e^+$  and  $e^-$  (inside the bunch) gave their precession frequencies. The comparison of these frequencies provides that of the electron and positron anomalous magnetic moments. These moments were shown to be equal to an accuracy not worse than  $1 \cdot 10^{-5}$ , two orders better than the accuracy of other experiments measuring the anomalous magnetic moment of a positron.

To demonstrate the actual resolution of the method, the electron and positron energies were slightly separated by a radial electric field. From the measurements, it can easily be seen that the precession frequencies were also separated by the expected value.

In conclusion, it can be said that the field of applications is well enough known, so that where designing new storage rings, one should take into account the necessity to have good conditions for the generation, control and using of radiative polarization.

#### ACKNOWLEDGEMENTS

The authors are very pleased to thank Profs V. A. Sidorov, and L. M. Barkov, Drs. L. M. Kurdadze, A. D. Bukin, M. S. Zolotarev, V. P. Smakhtin, I. A. Koop, N. I. Krupin, E. P. Solodov, I. B. Wasserman, and S. I. Mishnev for their participation in experiments and Profs. G. I. Budker, S. T. Belyaev, V. N. Baier for their constant attention and useful discussions.

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