NEW INSTRUMENTS AND MEASUREMENT METHODS

Precision measurements of masses of elementary particles using storage rings with polarized beams

A. N. Skrinskiĭ and Yu. M. Shatunov

Institute of Nuclear Physics, Siberian Division of the Academy of Sciences of the USSR, Novosibirsk

Usp. Fiz. Nauk **158**, 315-326 (June 1989)

1. INTRODUCTION

The development of a method of high-accuracy absolute measurement of the energy of beams in storage rings[1] has enabled performing at Novosibirsk an entire series of mass measurements of elementary particles created in electron-positron collisions in the electron-positron-beam instruments VÉPP-2M and VÉPP-4.[4-11] An especially large step in accuracy has been taken for mesons of the ψ and Υ families (up to 100-fold improvement).

The calibration method is based on the correspondence of the energy E and the frequency of spin precession Ω of a relativistic electron moving with the frequency ω_s in a transverse magnetic field:

$$E=\left(\frac{\Omega}{\omega_s}-1\right)\frac{q_0}{q'}\,mc^2. \qquad (1)$$

Here q' and q_0 are the anomalous and normal components of the gyromagnetic ratio.

The relationship (1) is broken only by longitudinal magnetic fields that can exist on the orbit of the particle for various reasons. To estimate the magnitude of the breakdown, it suffices to treat the "turning on" of the longitudinal field H_v on a fixed, straight region of the trajectory. One can show that in this case the reduced frequency of precession $\nu=\Omega/\omega_s-1$ is given by the expression

$$\cos\pi\nu=\cos\pi\nu_0\cdot\cos\frac{\beta}{2}, \qquad (2)$$

Here β is the angle of rotation of the spin about H_v; ν_0 is the reduced frequency without the longitudinal field. Numerical analysis of the possible sources of a longitudinal field in an ordinary storage ring (fringe fields, angles of motions, etc.) shows that the magnitude of the shift $\delta\nu$ does not exceed 10^{-6}. Special attention is required by regions with a longitudinal magnetic field where the angle β can attain an appreciable value (detectors, spin rotators, etc.). One must compensate the rotation of the spin with reverse fields; this coincides with the ordinary condition of suppressing the coupling of orbital oscillations.

The energy spread $\Delta E/E\lesssim 10^{-3}$ existing in electron-positron storage rings is not, in a first approximation, a restriction on the accuracy of measurement of the mean energy of particles in a beam by the method being discussed. In the presence of an accelerating hf potential, the energy of a nonequilibrium particle will oscillate about the equilibrium E_s with the frequency of synchrotron oscillations $\nu_\gamma\omega_s$:

$$E=E_s\left(1+\frac{\Delta E}{E}\sin\nu_\gamma\omega_s t\right).$$

Consequently also the precession frequency of the spin will be modulated at the same frequency. This means that the spectrum of spin frequencies consists of a set of lines spaced apart by $\nu_\gamma\omega_s$ ($\nu_\gamma\sim 10^{-2}$). The central line of the spectrum is the precession frequency averaged over the synchrotron oscillations

$$\Omega=\Omega_s+\langle\delta\Omega\rangle.$$

The shift of the spin precession frequency of a nonequilibrium particle with respect to the equilibrium frequency Ω_s involves the presence of oscillations and nonlinearities of the magnetic field. A particle with a certain amplitude of betatron oscillations A_x has a lag with respect to an equilibrium particle proportional to the square of the transverse momentum

$$p_x^2=A_x^2\left(|f_x|'^2+\frac{1}{|f_x|^2}\right),$$

Here $|f_x|$ is the modulus of the Floquet function. Owing to the condition of synchronization with the accelerating potential, this effect leads to a shift of the energy and frequency of precession with respect to their equilibrium values. The nonlinearity of the magnetic field also causes a certain difference between the frequencies of precession for particles with and without oscillations. A joint treatment of the two effects leads to a formula for the spread of spin frequencies[12]:

$$\delta\Omega\approx\nu\frac{A_x^2}{\alpha}\left\langle n_1\psi_x|f_x|^2-\left(|f_x|'^2+\frac{1}{|f_x|^2}\right)\right\rangle\omega_s. \qquad (3)$$

Here α is the momentum compaction factor

$$n_1=-\frac{R^2}{\langle H_z\rangle}\frac{\partial^2 H_z}{\partial x^2}$$

is the quadratic nonlinearity, and ψ_x is the dispersion function of the storage ring. An estimate of $\delta\Omega$ for different storage rings shows that the spread in spin frequencies does not exceed the magnetic $\sim 10^{-5}\ \omega_s$ and can be regulated by varying the quadratic nonlinearity. The magnitude of the spread can be monitored by measuring the chromaticity of the radial betatron oscillations $\gamma\partial\nu_x/\partial\gamma$, the formula for which coincides in the principal terms with the expression given in angle brackets in (3).

The width of the side lines in the spectrum of spin frequencies is determined by the spread of synchrotron frequencies $\nu_\gamma\omega_s$ and is usually much larger than the width of the central line.

2. RESONANCE DEPOLARIZATION

Experimentally the spin precession frequency of particles in a storage ring can be measured by observing the degree of polarization when a high-frequency electromagnetic

 0038-5670/89/060548-07$01.80

field acts on the beam, with a frequency ω_d satisfying the condition

$$\omega_d \pm k\omega_s = \Omega \quad (k\text{-integer}). \tag{4}$$

When the resonance condition is satisfied, the precession angle of the spin of each particle oscillates from 0 to π at a certain frequency w determined by the magnitude and direction of the hf field. The presence of random processes (external noise modulation in the band $\delta\omega_d$, quantum fluctuations of the synchrotron radiation, etc.) mixes the phases of rotation of the spins and therefore leads to depolarization of the beam. The effective width of the resonance, i.e., the band of frequencies $\Delta\omega_d$ where the rate of depolarization is of the order of the maximum value, depends on the relationship of the quantities w, $\delta\omega_d$, and $\delta\Omega$.

If $w, \delta\omega_d \gg \delta\Omega$, then the accuracy of measurement of Ω is no better than max $(w, \delta\omega_d)$, while the time of polarization is determined by the expression $\tau_d \approx \delta\omega_d / w^2$.

In the opposite case with w: $\delta\omega_d \ll \delta\Omega$, the resonance width equals the spread $\delta\Omega$ of spin frequencies if $\delta\Omega$ exceeds the decrement of radiative decay λ (λ^{-1} is the characteristic time of mixing of the amplitudes and phases of the orbital oscillations of the particles). But in the case $\delta\Omega \ll \lambda$, as usually happens in practice, an additional stochastic averaging of the spread of the frequency Ω to the magnitude $\Delta \approx (\delta\Omega)^2 \lambda^{-1}$ occurs owing to radiation effects.

Evidently, to attain the limiting accuracy of measuring the precession frequency, we must have w and $\delta\omega_d \lesssim \Delta$. The depolarization time in this case is $\tau_d \sim 1/w$, since the component of the polarization transverse to the field vanishes in a time Δ^{-1}.

Thus, despite the energy scatter in the beam, the spin dynamics is such that resonance depolarization can in principle determine the absolute magnitude of the equilibrium energy of particles with the highest accuracy by making use of the knowledge of the magnitude of the anomalous component of the gyromagnetic ratio $q'/q_0 = (1\,159\,652\,193 \pm 4) \times 10^{-12}$ and its rest mass $mc^2 = (51\,099\,906 \pm 15) \times 10^{-7}$ MeV.[13]

3. INSTRUMENTS FOR DEPOLARIZATION

For resonance depolarization one must create in some region of the orbit an hf field that rotates the spin about a direction perpendicular to the direction of equilibrium polarization in this region. In the simple case of polarization along the field H_z, one can use any of the components of the hf field $\widetilde{H}_v$, $\widetilde{H}_x$, and $\widetilde{E}_z$, jointly or separately.

In the first approximation, the longitudinal component $\widetilde{H}_v$ does not influence the transverse motion of the particles, and this can be of fundamental significance near spin-betatron resonances. The precession frequency of the spins about the perturbing field $\widetilde{H}_v$ applied in a region of the orbit of length l will equal

$$w_v = \frac{\widetilde{H}_v}{\langle H_z \rangle} \frac{l}{2L} \omega_s \quad (L \text{ is the perimeter}). \tag{5}$$

In the case of applying transverse fields, in addition to the direct action of $\widetilde{H}_x$ and $\widetilde{E}_z$ on the spin, one must also take account of the rotation of the spin in the fields that arise upon forced vertical motion excited by the applied hf field. Consequently, when the resonance condition (4) is satisfied, the spin will precess about $\mathbf{e}_x$ with the frequency

$$w_x = \nu \frac{\widetilde{H}_x + [\widetilde{E}v]_x}{\langle H_z \rangle} \frac{l}{2L} (1 + F(\theta = 0)) \omega_s. \tag{6}$$

Here we have

$$F(\theta) = \frac{\nu}{2} e^{i\nu\theta} \left(f_z^* \int_{-\infty}^{\theta} k f_z' e^{-i\nu\widetilde{k}} d\theta - f_z \int_{-\infty}^{\theta} k f_z^{*\prime} e^{-i\nu\widetilde{k}} d\theta \right).$$

Here $F(\theta)$ is a periodic function that describes the contribution to the precession frequency from the perturbation of the vertical motion, and we have

$$\widetilde{k} = \int_0^{\theta} K \, d\theta; \quad K = H_z / \langle H_z \rangle.$$

For a storage ring with homogeneous focusing we have $F = \nu^2/(\nu^2 - \nu_z^2)$.

We see from, Eq. (6) that, at high energies ($\nu \gg 1$), it is more expedient for depolarization to use depolarizers with transverse H_x and E_z fields.

In working with colliding beams, the use of a running wave, where $|H_x| = |E_z|$, makes it possible to depolarize either beam by selecting the necessary direction of propagation of the wave, since, when the direction of the wave coincides with the velocity of the particle, the frequency is $w \approx 0$ (to an accuracy of $1/\gamma^2$). Moreover, it is technically possible to depolarize selectively bunches in a given beam by using brief hf field pulses phased with the frequency of rotation of the particles.[14]

One can conveniently seek the depolarization resonance in a regime in which the frequency of the hf field is scanned over a range determined by the error in knowing the energy of the particles in the storage ring. In the initial stage of the experiments this can require a rather high power (≈ 10 kW) and broad-band design of both the hf sources and the devices that create the field at the orbit. As we advance successfully in the accuracy of calibrating the energy, the power becomes very small. In turn, the problem arises of generating an adequately narrow frequency line of the depolarizing potential. One can also attain resonance depolarization at any of the machine resonances of sufficient power $\nu = k$; here we have $\nu = \nu_{x,z} \pm k$ (k integer). However, this requires varying either the energy of the particles or the frequencies of the betatron oscillations ν_x and ν_z. The accuracy of this approach is restricted by the power of the resonance itself or, for spin-betatron resonances, by the spread of the frequencies of the transverse oscillations, which it is difficult to make much better than 10^{-3}.

4. RADIATION POLARIZATION OF ELECTRONS AND POSITRONS

In the practical realization of the potentialities of the method of resonance depolarization, one of the first problems that arises is to obtain polarized beams of the needed energy in the storage ring. Fortunately, electrons and positrons manifest the process of natural radiation polarization upon prolonged movement in a magnetic field.[2] In the absence of depolarizing factors the degree of transverse polarization approaches the limit $\zeta_0 = 8/5\sqrt{3} = 0.92$ with the

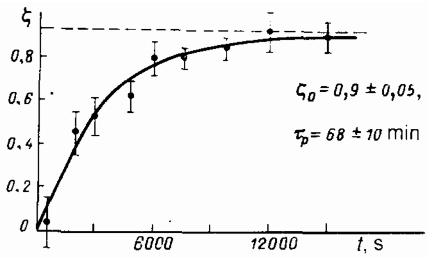

FIG. 1. VÉPP-2M. Radiation polarization, $E = 625$ MeV.

characteristic time $\tau_p \sim 1/E^5$. Under typical conditions of electron-positron storage rings, the latter varies from several minutes to several hours, and can be much smaller than the lifetime of the particles in the storage ring.

Figure 1 shows experimental data that confirm the existence of the process of radiation polarization. The presented curve of growth of the degree of depolarization according to the law

$$\zeta = \zeta_0 (1 - e^{-t/\tau_p})$$

was obtained in 1975 in the storage ring VÉPP-2M at an electron energy $E = 625$ MeV.[3,4]

To monitor the polarization process, one can use any sufficiently fast and polarization-sensitive method of measuring it. The data given above with the VÉPP-2M were obtained by observing the intrabunch scattering effect (IBSE). The coincidence recording of particles that escape the beam in pairs owing to elastic scattering is rather simple and has the high counting rate $\dot{N} \sim 10^3$–10^4 Hz. The relative contribution of the polarization is from 4% to 20%.

This method of measuring the polarization has been well rated at energies from several hundred MeV to 2 GeV.[3,8]

At higher energies one can measure the polarization of electrons and positrons rather effectively using the Compton scattering of circularly polarized photons. In the VÉPP-4 storage ring at 5-GeV energy, the source used was a laser or the synchrotron radiation of an oppositely moving bunch having an appreciable degree of circular polarization of opposite sign above and below the plane of the orbit.[9,11] The quantity to be measured, which was proportional to the degree of transverse polarization of the electrons, was the "up-down" asymmetry in the distribution of secondary γ-quanta (from 2 to 8%).

5. CALIBRATION AND STABILITY OF THE ENERGY OF PARTICLES IN A STORAGE RING

Figure 2 shows the experimental data of measuring the polarization of electrons and positrons in the VÉPP-4 storage ring upon scanning the frequency of the depolarizing instrument with a radial magnetic field near the value of resonance with the frequency of spin precession. At each point the set of events of Compton scattering of photons of the synchrotron radiation by the oppositely directed polarized beam[11] was counted for 100 s. The rate of change of the frequency of the depolarizer was $\approx 4\ s^{-2}$. The jumpwise change in the asymmetry of the secondary γ-quanta from the electrons and positrons that was observed at the same time corresponds to a depolarization of the beams in a narrow

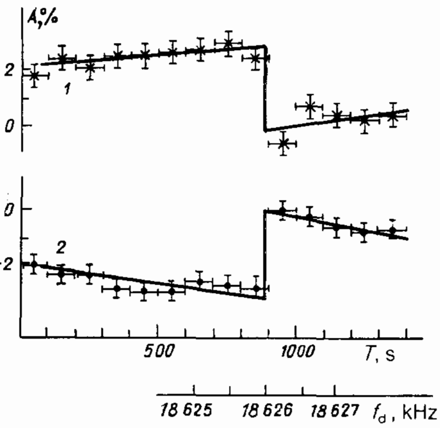

FIG. 2. Results of one of the measurements of the depolarization frequency. *1, 2*–asymmetry in the scattering of synchrotron radiation by e^- and e^+ beams averaged over 100 s. Lower scale–depolarization frequency f_d. Beam currents: $I_- = 5.8$ mA, $I_+ = 6.2$ mA.

interval of the scattering frequency, and yields an accuracy of determining the energy no poorer than 1×10^{-5}.

To realize the high accuracy of calibration of the energy inherent in a given method, one must take special measures for monitoring and suppressing irregular and slow periodic pulsations of the magnetic field of the storage ring, which "blur" the mean spin frequency and lead to the error

$$\Delta\omega_d \approx \frac{\Delta H_z}{H_z} \omega_s.$$

Apparently the accuracy of calibration of the energy in VÉPP-4 given above is determined by this effect. The power supply system of the storage ring magnets has a pulsation level a little better than 10^{-4}, but the "fast" oscillations (as compared withthe depolarization time) do not contribute on the average to the spread to spin frequencies. Upon a further improvement of the stability of the magnetic field, which appears to be technically feasible, the accuracy of a single measurement of the energy can be still considerably improved.

In the VÉPP-2M the introduction of a system for suppressing magnetic-field pulsations to the level of $\lesssim 10^{-6}$ enable an accuracy of measuring the precession frequency close to the "natural" limit–the spread of spin frequencies. The suppression of the latter by using sextupole corrections (see Eq. (3))[15] to the level $\delta\Omega \approx 2 \times 10^{-7}$ led to a situation in which the accuracy of absolute calibration of the mean energy of the particles is determined by the accuracy of knowing the rest mass of the electron.[1]

In performing prolonged experiments the problem arises of the stability of the energy of the particles between calibrations. Instability of the temperature of the environment causes a change in the geometry of the storage ring. The concomitant shifts in the radial position of the magnets, and especially of the quadrupole lenses, leads at a fixed frequency to uncontrolled variations of the energy of the particles.

A stabilization system was introduced into the VÉPP-2M that compensates the geometric deviations of the lenses with a corresponding change in the magnitude of the magnetic field.[16] As a result an energy stability of $\approx 10^{-5}$ was attained over the course of several months.

TABLE I.

Particle	Mass of particle, MeV		Year of publication	Improvement of accuracy
	Tabulated value	Results of experiments		
$K^{\pm}$	493.84±0.13	493.670±0.029	1979	5
K^0	497.67±0.13	497.661±0.033	1987	4
ω	782.4±0.2	781.78±0.10	1983	2
φ	1019.70±0.24	1019.52±0.13	1975	2,5
ψ	3097.1±0.9	3096.93±0.09	1981	10
ψ′	3685.3±1.2	3686.00±0.10	1981	10
ϒ	9456.2±9.5	9460.59±0.12	1986	80
ϒ′	10016.0±10	10023.6±0.5	1984	20
ϒ″	10347±10	10355.3±0.5	1984	20

Evidently a useful step in this direction is to stabilize the temperature of the elements of the storage ring.

6. EXPERIMENTS WITH PRECISION CALIBRATION

To date in the Institute of Nuclear Physics of the Siberian Division of the Academy of Sciences of the USSR a number of "meterological" measurements has already been performed with colliding electron-positron beams using the discussed methodology. The masses of ϕ, ω, $K^{\pm}$, and K^0 mesons have been measured in the VÉPP-2M storage ring, and the masses of ψ-, ψ'-, Υ-, Υ'-, and Υ''-resonances in the VÉPP-4 storage ring (see Table).

6.1. The φ-meson[14]

The measurement of the mass of the φ-meson resonance in 1975 was historically the first. In starting the experiment the absolute scale of energies of the storage ring was calibrated by resonance depolarization with the magnetic field of the storage ring referenced to the measuring device by nuclear magnetic resonance (Fig. 3). The calibration was performed with one electron beam. Radiation polarization to the level $\zeta \approx 80\%$ was attained at the maximum energy of the storage ring, where the time for polarization is $\tau_p \approx 50$ min. Then the energy was decreased crossing a number of weak spin resonances down to the φ-meson region, and the precession frequency was measured by observing the jump in the IBSE upon scanning the frequency of the depolarizer.

The excitation curve of the φ-resonance was measured with the detector OLYA[17] in two channels: $e^+e^- \to K_S^0 K_L^0$ and $e^+e^- \to \pi^+\pi^-\pi^0$. The energy distribution of the events is shown in Fig. 4. Three cycles of measurements were performed in the energy interval from 2×507 to 2×513 MeV with a step $\Delta(2E) = 0.5$ MeV. Each cycle began and ended with a calibration of the energy at the point $E = 509.6$ MeV.

The optimal resonance curve in Fig. 4 is drawn with account taken of the radiation corrections and $\omega\varphi$-interference. It yields a mass $M_\varphi = 1019.52 \pm 0.13$ MeV.

The accuracy of measurement of the mass of the φ-meson attained in the first experiment using the method of resonance depolarization was approximately 2.5 times better than the accuracy of the tabulated value of M_φ averaged over all the preceding experiments.[1)]

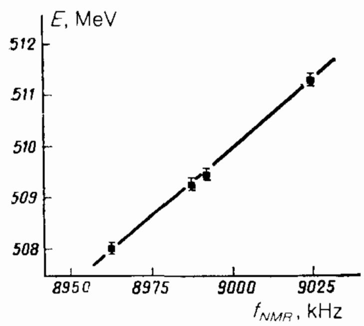

FIG. 3. VÉPP-2M. Calibration of the energy scale of the particles in the region of the φ-meson resonance.

6.2. K^+ and K^- mesons[5]

The possibility of precision measurement of the masses of $K^{\pm}$ mesons involves the fact that kaons are created near the maximum of the φ-mesons resonance with a kinetic energy $W \sim 10$ MeV. Hence a measurement of W with an accuracy of $\approx 10^{-3}$ already yields a good accuracy in determining the mass of the secondary particles if the energy of the primary electrons and positrons is fixed by resonance depolarization.

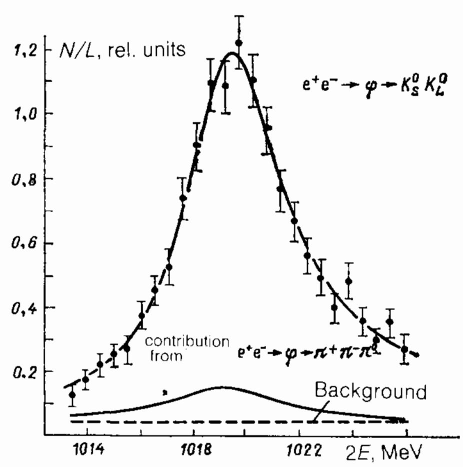

FIG. 4. Measurement of the mass of the φ-meson (1975).

To measure the kinetic energy of the charged kaons a detector was used made of five layers of photoemulsion, which were placed around the collision site immediately after calibrating the energy. Two such cycles of irradiation of the emulsion with an exposure of ≈ 30 min at beam currents of 5×5 mA^2 enabled selection during processing at 350 $e^+e^- \to K^+K^-$ events and determining from them the mass of the charged kaons $M_{K^+} = 493.670 \pm 0.029$ MeV. We should stress that this experiment measured the mean value $(M_{K^+} + M_{K^-})/2$. One can obtain from this result, practically with the same accuracy, the value of the mass M_{K^+}, since the mass of the negative kaon is well known from K-mesoatomic experiments.

6.3. The K^0-meson[6]

The mass of neutral kaons created in the reaction $e^+e^- \to K_S^0 K_L^0$ was determined in VÉPP-2M by using a cryogenic magnetic detector (CMD).[18]

The CMD enables a momentum resolution of about 2.5% at high angular accuracy. This enables one to reconstruct from the vector sum of the momenta of π^+ and π^- the momentum of the K_S^0 that gave rise to them. Moreover, measurement of the minimum angle ψ of separation of the $\pi^\pm$ mesons, which corresponds to the separation of the pions in the rest system of K_S^0 perpendicular to its momentum offers an independent possibility of calculating the mass of the kaon by the formula

$$M_{K_S^0} = \left(E^2 \sin^2\frac{\psi}{2} + 4m_\pi^2 \cos^2\frac{\psi}{2}\right)^{1/2}.$$

Here m_π is the mass of the $\pi^\pm$-meson.

During this experiment a luminosity of about 60 reciprocal nanobarns was collected. From the whole statistics ($\approx 250\,000$ frames), 3713 useful events were selected, from which the mean value of the mass was obtained by both methods of

$$M_{K_S^0} = 497{,}669 \pm 0{,}030 \text{ MeV}.$$

The accuracy of maintenance of the energy of the electrons and positrons during collection of the statistics was no poorer than ± 10 keV. To improve the temperature stability of the storage ring, the radiation polarization was performed directly at the working energy $E = 509.32$ MeV. This became possible owing to elimination of the depolarizing influence of the machine spin resonances and to the increase in lifetime ($\tau_p = 3$ hr). The calibration of the energy by resonance depolarization was performed with normalization of the IBSE to an unpolarized bunch of about the same intensity that was captured into the storage ring after the polarization of the former bunch was reached 50%. The normalization to the unpolarized bunch enables one to eliminate systematic errors in measuring the polarization, and thus to improve the accuracy of measuring the precession frequency.

6.4. The ω-meson[7]

Obtaining polarized beams at an energy near the ω-resonance is practically ruled out owing to the long time of radiation polarization ($\tau_p \approx 8$ hr). Therefore the polarization was conducted at the energy $E = 650$ MeV. Then the energy was lowered to the ω-meson region with fast crossing of the resonances $\nu = \nu_{x,z} - 2$ and adiabatic passage through the integral resonance $\nu = 1$. The amplitude of the resonance required for fulfillment of the condition of adiabaticity was created by introducing a region with a longitudinal magnetic field via short-period reduction of the current in the compensating solenoids of the CMD.

During the experiment at 15 energy-calibrated points, the CMD detector recorded about 4000 $e^+e^- \to \pi^+\pi^-\pi^0$ events. A value of the mass of the ω-meson was obtained from these with allowance for the efficiency of the detector and the radiation corrections of $M_\omega = (781.78 \pm 0.10)$ MeV, and a width of $\Gamma_\omega = 8.3 \pm 0.4$ MeV.

6.5. ψ- and ψ'-mesons[8]

In the region of the ψ-family the radiation polarization time in the VÉPP-4 ($\tau_p \approx 100$ hr) does not allow one to attain any appreciable degree of polarization. However, the booster storage ring VÉPP-3 at the transfer energy of the beams $E = 1.8$ GeV has a polarization time $\tau_p \approx 40$ min. This enables one to inject into the VÉPP-4 an already polarized beam, and moreover, to have simultaneously bunches of polarized and unpolarized particles. This circumstance has substantially facilitated the observation of resonance depolarization from the IBSE, to which the contribution of polarization amounted to about 3%. A depolarizer with a radial magnetic field that was created by plates in the vacuum chamber of the storage ring made possible a depolarization time of the order of a second at the resonance frequency.

The excitation curve of the ψ and ψ' resonances was measured by recording in the OLYA detector the process $e^+e^- \to$ hadrons upon scanning the region of the resonances with a step of $\Delta(2E) = 0.5$ MeV. Seven scanning cycles were performed at the ψ-resonance, and five cycles at ψ'. The energy was calibrated at the beginning and end of each cycle. Within the cycle stability was maintained of the reversal frequency, the correction system, and the driving magnetic field, which was varied strictly in a fixed cycle during scanning and in injecting beams.

In the detector, events were distinguished that had three or more charged particles leaving the collision site. The observed form of the resonance is determined by the spread of energy of the beams and the radiation corrections. The experimental cross section was approximated by the formula

$$\sigma_{exp} = \varepsilon \int_{-\infty}^{\infty} \sigma_T(W')\, G(W - W')\, dW'. \qquad (7)$$

Here $W = 2E$ is the total energy, ε is the probability of detection, W' is the energy of the interacting e^+e^- pair,

$$G(W - W') = \frac{1}{\sqrt{2\pi}\,\sigma_W} \exp\left[-\frac{(W-W')^2}{2\sigma_W^2}\right]$$

is the distribution function of the total energy, and σ_T is the production cross section with account taken of the radiation corrections in the doubly logarithmic approximation.

In processing the experimental data by the maximum-likelihood method, four parameters were considered free: the mass M of the resonance, the energy spread σ_W, the cross section σ_b for production of background events, and the efficiency of detection ε.

Figure 5 shows the masses of the resonances measured

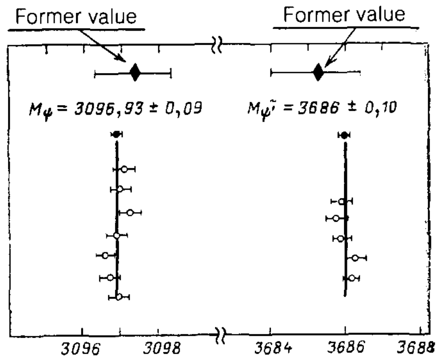

FIG. 5. Masses of the ψ- and ψ'-mesons as measured in different cycles, and their mean values.

independently in each scanning cycle and the averages over all the cycles. The tabulated values of the masses of ψ and ψ' prior to this experiment are also shown there. The final results of the measurements are:

$$M_\psi = 3096{,}93 \pm 0{,}09 \text{ MeV},$$
$$M_{\psi'} = 3686{,}00 \pm 0{,}10 \text{ MeV}.$$

6.6. Υ-, Υ′-, and Υ″-resonances[10,11]

In the region of energies of the Υ-family the time for radiation polarization is quite acceptable for obtaining polarized beams in the VÉPP-4 itself if one eliminates the depolarizing influence of the spin resonances. The overall pattern of spin resonances in this energy region obtained upon measuring the equilibrium degree of polarization using a laser polarimeter is shown in Fig. 6, which also indicates the energy values corresponding to the Υ-resonances. We see that it is quite possible to apply resonance depolarization to measure the masses of the Υ- and Υ″-resonances, whereas Υ′ requires special measures (suppressing the resonance $\nu = 21 - \nu_z$, shifting it by varying the frequency of the betatron oscillations ν_z, or calibrating the energy just below the resonance with subsequent recalculation).

The measurements of the masses of the Υ-family were performed by using the detector MD-1,[19] which recorded events of the process $e^+e^- \to$ hadrons upon scanning the energy with a step of $\Delta(2E) = 1$ MeV. Just as in the previous precision experiments, the set of statistics was divided into cycles with independent calibration of the energy in each of them.

To verify the smallness of the errors involved in the angular deformation of the interaction cross section owing to transverse polarization of the electrons and positrons, in certain cycles a depolarizer with a broad band $\delta\omega_d$ in the region of the resonance frequency was turned on at the time of collection of statistics.

Figure 7 shows the overall results of measuring the cross section for $e^+e^- \to$ hadrons in the region of the Υ-resonance. A value of the mass of the Υ-meson was obtained by the procedure described above of

$$M_\Upsilon = 9460{,}57 \pm 0{,}12 \text{ MeV}.$$

This exceeds the accuracy of prior measurements by a factor of 80.

The analogous curves for excitation of the Υ′- and Υ″-resonances upon processing yield respectively

$$M_{\Upsilon'} = 10023{,}6 \pm 0{,}5 \text{ MeV},$$
$$M_{\Upsilon''} = 10355{,}3 \pm 0{,}5 \text{ MeV}.$$

7. TAKING ACCOUNT OF SYSTEMATIC ERRORS

Possible sources of systematic errors were analyzed in the course of each experiment, in particular the following:

a) the finite width of the depolarizer band;

b) the mutual arrangement of the collision region with the detector and of the accelerating resonators;

c) presence in the ring of electric fields;

d) chromatic aberration of the magnetic optics of the storage ring;

e) collision effects;

f) the influence of spin resonances.

The shift of energy calibration owing to the finite width of the spectrum of the depolarizer is eliminated by alternating the direction of scanning.

The energy shift of the electrons and positrons at the collision site with respect to the mean energy measured by the depolarizer is determined by the losses to synchrotron radiation and amounts to no more than 10^{-6}.

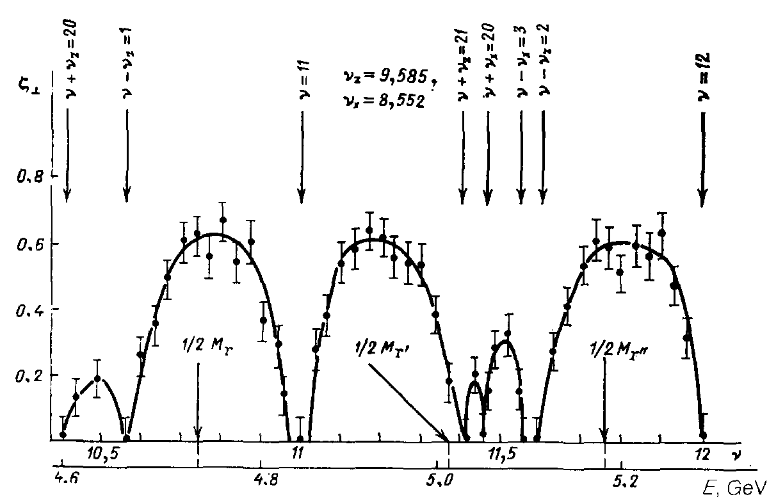

FIG. 6. VÉPP-4. Spin resonances in the Υ-meson region.

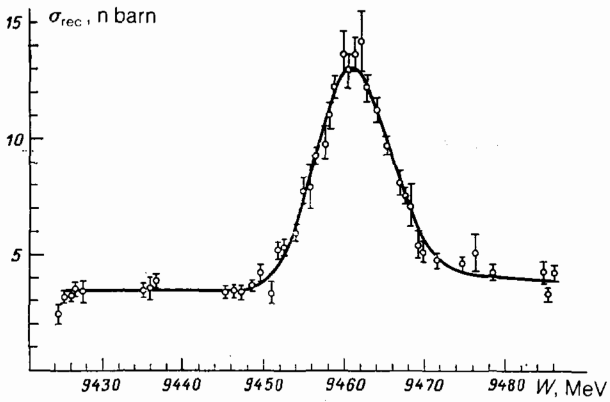

FIG. 7. Cross section for recording multihadron events in the Υ-meson region (results of the 1984 experiment).

The contribution of the radial electric field, which shifts apart the energies of the electrons and positrons, is easily determined upon simultaneously depolarizing them.

The chromatic aberration of the optics of the storage ring has the result that particles with an energy differing from the equilibrium value have an effectively different dimension at the collision site. Hence the maximum specific luminosity will be shifted with respect to the maximum of the energy spread. This effect has been estimated numerically and from measurements of the dependence of the β_z-function at the collision site on the reversal frequency.

In measuring the masses of narrow resonances also uncontrolled distortion of the dimensions of the beams by collision effects may prove substantial. Since the collision effects are of threshold character, one can eliminate their influence by working appreciably below the threshold or by separately processing and comparing the information collected at a luminosity close to the limiting value and far from it.

In calibrating the energy near a machine resonance $\nu = \nu_k = \nu_{x,z} \pm m$ (m integer), a shift of precession frequency can occur by the amount $\delta\nu \approx w_k^2/2(\nu - \nu_k)$, where w_k is the amplitude of this resonance. An analysis of the experimental data (see Fig. 6) shows that the shift $\delta\nu$ does not exceed values of 10^{-6} at all detunings $\varepsilon = \nu - \nu_k$ at which the radiation polarization reaches values of $\gtrsim 20\%$.

8. CONCLUSION

When necessary, the accuracy of measuring masses can be substantially increased further. But the accuracy already attained is a sort of "metrological standard" that enables one to refine substantially the masses of many known particles and resonances by recalculation.

After the experiments in the VÉPP-4 storage ring had been performed, the masses of Υ' (CESR storage ring, Cornell, USA)[21] and of Υ'' (DORIS storage ring, Hamburg, West Germany)[22] were measured by an analogous method. Within the limits of accuracy of the measurements they confirmed our results. At present a measurement of M_{Z^0} in LEP is being prepared at CERN by this method.

We stress that the cycle of experiments described in the review is the result of the work of the large collective ofassociates of the Institute of Nuclear Physics of the Siberian Division of the Academy of Sciences of the USSR, who have participated in the construction and operation of the accelerator and detector complexes of VÉPP-2 and VÉPP-4.

[1)] In 1986 M_φ was measured with an accuracy of ≈ 10 keV,[20] using $\pi^\pm$-, p-, $\bar{p}$-, and $K^\pm$-beams with energies of 100–200 GeV. The high accuracy of this result is based to a considerable extent on the assumption of absence of any special complex physical background that arises in the region of the mass of the φ-meson. The reliability of this assumption can be tested by measuring the value of M_φ with the same or better accuracy with electron-positron colliding beams. The luminosity of the VÉPP-2M storage ring and the resonance-depolarization method today already enable attaining an accuracy of several keV in measuring the mass of the φ-meson. Comparison of these prevision values can reveal also subtle effects of interaction of the φ-meson with nuclear matter.

[1]L. M. Kurdadze *et al.*, *Proceedings of the 5th International Symposium on High-Energy Physics* (In Russian), Warsaw, 1975, p. 148.
[2]A. A. Sokolov and I. M. Ternov, Dokl. Akad. Nauk SSSR **153**, 1052 (1963) [Sov. Phys. Dokl. **8**, 1203 (1964)].
[3]S. I. Serednyakov *et al.*, Zh. Eksp. Teor. Fiz. **71**, 2025 (1976) [Sov. Phys. JETP **44**, 1063 (1976)].
[4]A. D.Bukin, Yad. Fiz. **27**, 976 (1978) [Sov. J. Nucl. Fiz. **27**, 516 (1978)].
[5]L. M. Barkov *et al.*, Nucl. Phys. Ser. B **148**, 53 (1979).
[6]L. M. Barkov *et al.*, Yad. Fiz. **46**, 1088 (1987) [Sov. J. Nucl. Phys. **46**, 630 (1987)].
[7]L. M. Barkvo *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **46**, 132 (1987) [JETP Lett. **46**, 164 (1987)].
[8]A. A. Zholents *et al.*, Yad. Fiz. **34**, 1471 (1981) [Sov. J. Nucl. Phys. **34**, 814 (1981)].
[9]A. S. Artamonov *et al.*, Phys. Lett. B **118**, 225 (1982).
[10]A. S. Artamonov *et al.*, *ibid.* **137**, 272 (1984).
[11]A. E.Blinov *et al.*, *8th All-Union Conference on Accelerators: Proceedings* (In Russian), Protvino, Moscow region, 1982, Vol. 2, p. 268.
[12]A. P. Lysenko *et al.*, Part. Acceler. **18**, 215 (1986).
[13]Reviews of Particles Properties, 1986.
[14]S. A. Belomestnykh, A. E. Bondar', *et al.*, Preprint of the Institute of Nuclear Physics, Siberian Division of the Academy of Sciences of the USSR 83-86 (In Russian), Novosibirsk, 1983.
[15]I. B. Vasserman *et al.*, Phys. Lett. B **198**, 302 (1987).
[16]B. A. Baklakov *et al.*, *Proceedings of the 7th All-Union Conference on Accelerators* (In Russian), Joint Institute for Nuclear Research, Dubna, 1980, Vol. 1, p. 338.
[17]V. M. Aul'chenko *et al.*, Preprint of the Institute of Nuclear Physics, Siberian Division of the Academy of Sciences of the USSR 75-65 (In Russian), Novosibirsk, 1975.
[18]L. M. Barkov *et al.*, Nucl. Instrum. Methods **204**, 379 (1983).
[19]S. E. Baru *et al.*, Preprint of the Institute of Nuclear Physics, Siberian Division of the Academy of Sciences of the USSR 77-75 (In Russian), Novosibirsk, 1977.
[20]H. Dijkstra *et al.*, Z. Phys. C **31**, 375 (1986).
[21]W. W. Mackay *et al.*, Phys. Rev. D **29**, 2403 (1984).
[22]D. P. Barber *et al.*, Phys. Lett. B **135**, 498 (1984).

Translated by M. V. King