СИБИРСКОЕ ОТДЕЛЕНИЕ АН СССР
ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ

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ПРЕПРИНТ 80-156

Новосибирск

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A b s t r a c t

High precision measurement of the Ψ - and Ψ' - resonance masses has been performed at the new storage ring VEPP-4. The resonance depolarization method has been used for the absolute calibration of the beam energy. Application of this technique allowed to improve the accuracy of the Ψ - and Ψ' - mass measurements by a factor of more than twenty. The following mass values have been obtained :

$$m_{\Psi} = 3096.93 \pm 0.09 \text{ MeV}, \qquad m_{\Psi'} = 3686.00 \pm 0.10 \text{ MeV},$$

the mass difference is correspondingly

$$m_{\Psi'} - m_{\Psi} = 589.07 \pm 0.13 \text{ MeV}$$

At the end of 1979 the electron-positron storage ring VEPP-4 came into operation in Novosibirsk [1]. The first experiment with the new collider has been performed using the "OLYA" detector installed in one of three experimental sections. During March-April the measurement of Ψ - and Ψ' - resonance masses was conducted.

In all previous experiments devoted to the study of narrow resonances at the electron-positron colliders the accuracy of the resonance mass determination was about 10^{-3}. This value of the mass uncertainty was due to the accuracy in the knowledge of the collider energy scale, i.e. the accuracy in the calculation of the field integrated along the equilibrium orbit of the storage ring. It is clear that substantial improvement in this method is unlikely.

In 1975 the method of the absolute calibration of the energy scale by the polarized beam resonance depolarization has been developed at the VEPP-2M collider [2,3]. Later it was successfully used there for experiments on the high precision measurement of the Φ - resonance mass [4] and the $k^{\pm}$ - meson mass [5].

The calibration method is based on the measurement of the spin precession frequency of beam electrons. In the plane orbit approximation the ratio of the frequency Ω of spin precession around the guiding magnetic field to the revolution frequency ω = 818.780 kHz has the following form

$$\frac{\Omega}{\omega} = 1 + \gamma \frac{\mu'}{\mu_0}$$

and depends only on the particle energy ($\gamma = E/m$) and the ratio of anomalous and normal parts of the magnetic moment. The beam revolution frequency is easily measured with the high accuracy - better than 10^{-6}, while the spin precession frequency is determined by the resonance depolarization of the polarized beam.

The electron beam polarized during two hours ($\sim 2\tau_{pol}$) in the booster storage ring VEPP-3 and then was injected in the ring of VEPP-4. The beam depolarization was performed by the high frequency transverse magnetic field with a smoothly varying frequency (bandwidth $\sim 7 \cdot 10^{-6}$). The variable field was created between one meter parallel planes inside the storage ring vacuum chamber. The depolarization was performed by slow scanning of the variable field frequency. The beam depolarized when the depolarizer frequency coincided with that of the spin precession. The resonant influence was chosen so that the depolarization process was slow enough to provide averaging of the particle energies over many periods of synchrotron oscillations ($\sim 10^3$). This circumstance allows to determine the average absolute beam energy with an accuracy much better than the beam energy spread.

The variation of the beam polarization at the moment of depolarization was detected by measuring the counting rate of the particles leaving the beam due to Touschek effect (effect of internal scattering), the cross section of the latter depending on the polarization degree. Scattered electrons were detected by four scintillation counters installed in pairs at the internal and external side near the equilibrium orbit. Under specific conditions of VEPP-4 the counting rate variation during depolarization was (1-3)% only hampering the reliable measurements. Therefore immediately after an injection of the polarized beam into VEPP-4 the unpolarized electron bunch of the same intensity was injected in another separatrice and the ratio of the counting rates due to the polarized and unpolarized beams was measured for normalization. Such scheme allowed reliable and stable detection of the moment of depolarization. Figure 1 presents the experimental values of the normalized counting rate of the particles from the polarized beam versus smoothly varying depolarizer frequency. The beam depolarization is clearly seen from the jump in the counting rate variation. A solid line corresponds to the optimal jump description. The relative accuracy of the beam energy measurement equals here $3 \cdot 10^{-5}$.

The presence of the field pulsations in the storage ring magnetic system leads to a notable bandwidth of spin frequencies. This fact results in a systematical error of the energy which

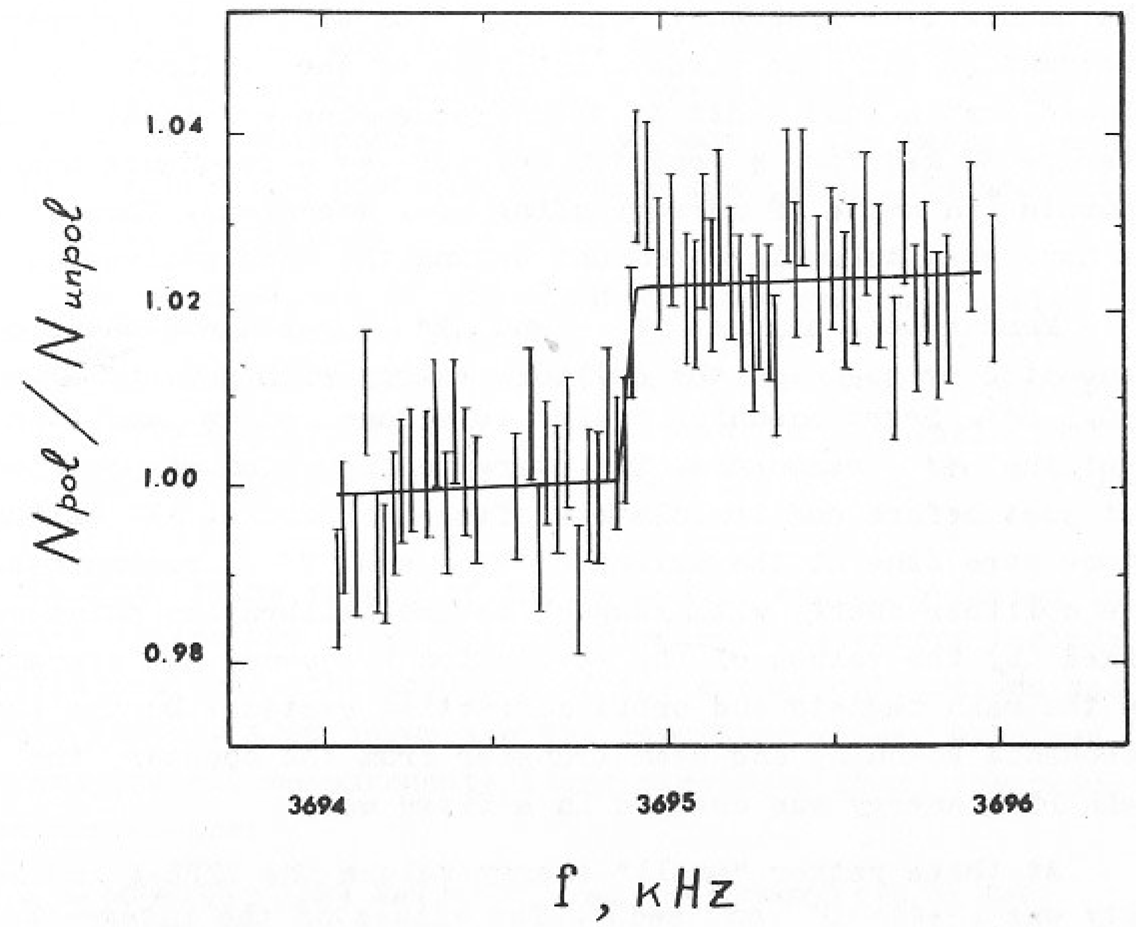

Fig. 1. Experimental values of the normalized counting rate of the particles leaving a beam due to Touschek effect versus a depolarizer frequency. The frequency corresponding to the jump middle is equal to the spin precession frequency of beam electrons.

is shifted up or down depending on the direction in which a depolarizer frequency approaches the resonance one. The finite bandwidth of the depolarizer frequencies produces the same effect. Therefore, for control different energy calibrations were carried out with a subsequent change of the direction of the depolarizer frequency scanning (from smaller to greater frequencies and vice versa). Analysis of the calibrations showed that a band width of spin frequencies was equal in the average 80 keV for Ψ and 100 keV for Ψ' - resonance measurements (in units of corresponding c.m. energies). These values have been taken into account during the data processing.

Measurement of the Ψ - and Ψ' - resonance shape was conducted by scanning the collider energy with a step $\Delta(2E) = 0.5$ MeV. Seven scanning cycles were done at Ψ and five - - at the Ψ' - resonance. The energy calibration was carried out just before and immediately after each cycle. All calibrations were done at the maxima of Ψ - and Ψ' - resonances. The collider energy with respect to the calibration point was fixed by the values of the revolution frequency and currents in the main magnets and orbit correction systems. During the resonance scanning and beam transfer from the booster the main ring energy was changed in a fixed way.

At these rather "small" energy values the VEPP-4 luminosity was $(2\div4)\cdot 10^{28}$ $cm^{-2}sec^{-1}$. The values of the integrated luminosity in each scanning cycle were chosen so that, first, statistical error of the mass measurement was not larger than that of the energy calibration and, second, the duration of one cycle, i.e. the time between two calibrations was as small as possible. The integrated luminosity collected in the experiment was 4.0 nb^{-1}. The luminosity was measured by the detection of small angle Bhabha scattering (about 20 mrad).

During data processing multihadronic events coming from the interaction region were selected. In total 502 such events have been found at Ψ , and 413 - at the Ψ' - resonance.

In each scanning cycle resonance parameters were optimized. In the resonance curve parametrization radiative corrections as well as the beam energy spread were taken into account. The processing procedure was similar to that described in [6].

The absolute energy value in each scanning cycle was obtained by averaging the calibration energies before and after the cycle. In the optimization the resonance masses and the beam energy spread have been found for each measurement cycle. The average beam energy spread σ_E was 0.5 MeV at Ψ and 0.7 MeV at Ψ' - resonance. The dependence of the energy spread on the electron and positron currents was taken into account in the data processing.

From the analysis of the obtained mass values a scale factor/7/ for the errors has been found so as to take into account the uncontrollable variations of the collider energy during a scanning cycle. The optimal value of the scale factor was 1.5 for the measurements at Ψ and 1.4 at the Ψ' - resonance.

In Fig. 2 the values of the resonance masses obtained in separate cycles are shown by open circles. The errors include a statistical one, the accuracy of the energy calibration and a scale factor. Also shown are the resulting values obtained by averaging all measurements (dark circles). Thus, the resonance masses are:

$$m_{\Psi} = 3096.93 \pm 0.09 \text{ MeV}, \qquad m_{\Psi'} = 3686.00 \pm 0.10 \text{ MeV},$$

and the mass difference is correspondingly equal to

$$m_{\Psi'} - m_{\Psi} = 589.07 \pm 0.13 \text{ MeV}.$$

At each stage of the data processing systematical errors have been analyzed. The following sources of systematics were taken into account:

1) For convenience of optimization the resonance Breit-Wigner formula was replaced by a δ - function one. For the check, in three cycles the optimization was also performed with a Breit-Wigner resonance shape and brought consistent results, the difference being less than 5 keV.

2) The expressions for radiative corrections used in opti-

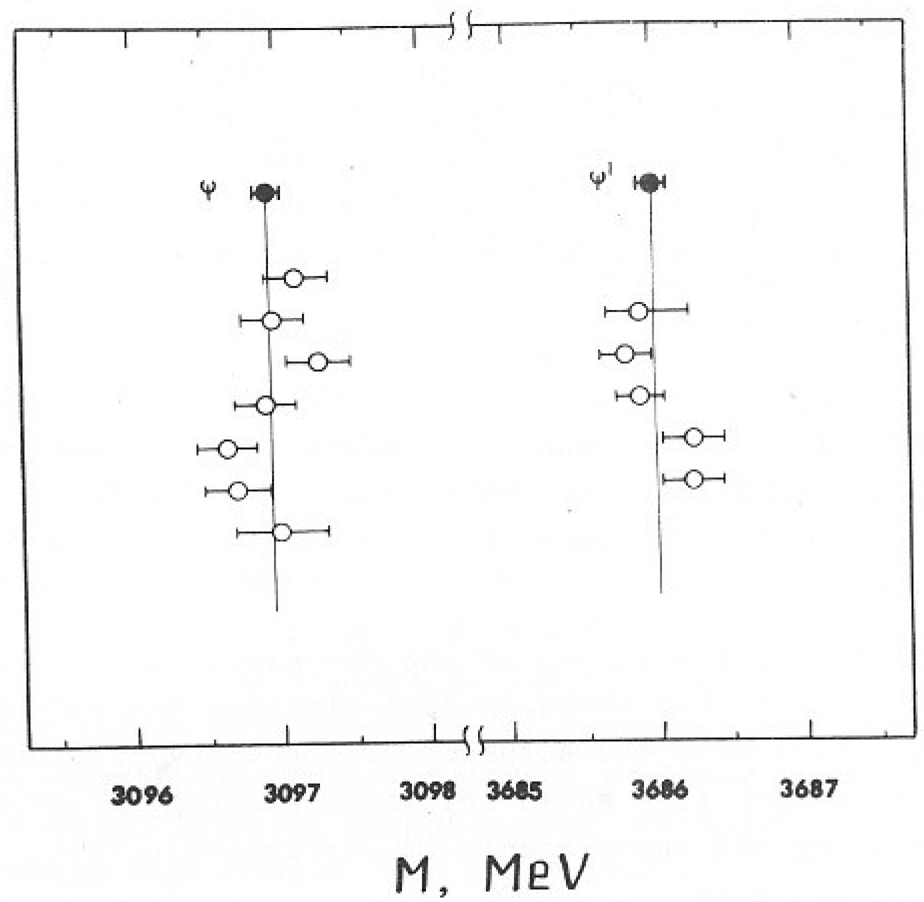

Fig. 2. Results of the Ψ and Ψ'– meson mass measurement at VEPP–4. Open circles – mass values obtained in separate measurement cycles, dark circles – weighted average values.

mization were calculated in double logarithmic approximation. Variation of the radiative corrections by a value of the calculation accuracy (~ 100% for a virtual correction and ~ 2% for a Bremsstrahlung one) led to a mass shift less than 20 KeV.

3) The luminosity was calculated by events of Bhabha scattering at small angles $\theta \sim 20$ mrad. Interference of the QED reaction with a channel $\Psi \rightarrow e^+ e^-$ led to a mass shift less than 0.3 KeV for the Ψ – resonance.

4) Analysis of the possible energy dependence of the detection efficiencies did not reveal notable effects in the investigated energy range.

5) During energy scanning and energy calibration the NMR frequency was also recorded. During the data processing described above this information was not used. Independent data processing in which the energy scale and values of the calibration energies were obtained using the NMR frequencies brought results very close to the original ones, the difference beeng less than 10 KeV.

No other notable effects leading to systematical errors have been discovered. Thus, the described technique of the absolute energy calibration allowed to improve the accuracy in the values of Ψ and Ψ' – meson masses by a factor of more than twenty.

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Работа поступила - 22 мая I980 г.

Ответственный за выпуск - С.Г.Попов
Подписано к печати 3.УП-I980 г. МН 072I0
Усл. 0,6 печ.л., 0,5 учетно-изд.л.
Тираж 250 экз. Бесплатно
Заказ № I56.

Отпечатано на ротапринте ИЯФ СО АН СССР