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ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ
СО АН СССР

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Abstract

High precision measurement of the Υ-meson mass has been performed at the storage ring VEPP-4 using the MD-1 detector. The resonance depolarization method has been used for the absolute calibration of the beam energy that allowed to improve the accuracy of Υ-mass measurement by factor of ten. The following mass value has been obtained

$$M = 9459.7 \pm 0.6 \text{ MeV}.$$

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1. Method of resonance depolarization

This work continues the cycle of experiments on the precise measurement of particle masses, performed at the Novosibirsk electron-positron colliders by the resonance depolarization method /1-6/. This method has been developed in 1975 /1,2/ and was used at VEPP-2M for measurements of the Φ -meson /3/, charged /4/ and neutral* kaon masses and lätter at VEPP-4 for measurements of the Ψ and Ψ'-meson masses /5,6/.

The calibration method is based on the measurement of the spin precession frequency Ω of beam electrons around the guiding magnetic field. The precession frequency

$$\Omega = \omega_0 \cdot \left(1 + \gamma \cdot \mu'/\mu_0\right),$$

where ω_0 is the revolution frequency, μ'/μ_0 is the ratio of anomalous and normal parts of the magnetic moment. The revolution frequency is set by the external generator and is measured with a high accuracy - better than 10^{-6}, while the spin precession frequency is determined by the resonance depolarization of the polarized beam. The beams depolarize when the frequency of the external field coincides with that of the spin precession. Fixing the fact of depolarization and measuring the corresponding depolarizer frequency one can thereby perform the absolute calibration of the storage ring energy.

This method allows to measure the average energy of electrons with an accuracy much better than the beam energy spread. The point is that synchrotron oscillations of particles lead to the modulation of the precession frequency with a frequency of synchrotron oscillation ω_γ. Besides the main line the spectrum of the spin motion contains a set of additional lines at frequencies differing by $\pm n\,\omega_\gamma$ (even ω_γ) from the main line. The strength of the depolarizer field should be chosen small enough to provide averaging of the particles energies over many period of synchrotron oscillations.

The width of the main line in the present experiment was determined by the quadratic nonlinearity of the guiding magnetic field of the storage ring and was $\Delta\Omega/\Omega \lesssim 10^{-5}$, i.e. by a factor 50 less than the beam energy spread. The mag-

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* L.M.Barkov et al. (to be published).

netic field pulsations did not exceed 10^{-6}.

2. Experimental set-up

The experiment has been performed at the storage ring VEPP-4 /7/ using the detector MD-1 /8,9/. The cross section of the process

$$e^+e^- \longrightarrow \Upsilon \longrightarrow \text{hadrons}$$

was measured as a function of the beam energy. The layout of the experiment is shown in Fig. 1. The magnetic field of the detector is transverse to the orbit plane of the storage ring, the angle of the orbit bending equals 16°. The magnetic field in the detector in the present experiment was 10.5 kG. For trigger and analysis of events coordinate chambers, scintillation counters and shower-range chambers were used.

The luminosity was measured by the processes of single bremsstrahlung and small angle Babha scattering. Note that under the real experimental conditions the well-known formulae for single bremsstrahlung are invalid and one should take into account the effect of the cut-off of the large impact parameters by the transverse beam size /16/. The detection of bremsstrahlung photons was performed by NaJ(Tl) counters placed at the distances of 10 m in electron and positron directions. In front of the counters lead plates of 7 mm thickness were placed to protect counters from synchrotron radiation. The threshold for photon detection was 400 MeV, the counting rate was 100 kHz at the luminosity $1\cdot10^{30}\,\text{cm}^{-2}\text{sec}^{-1}$, the background level was 0.1%. The events of elastic e^+e^--scattering were detected by scintillation counters placed above and below the beam, the electrons were detected at the angles 15÷35 mrad. The counting rate at the energy 4.7 GeV was 22 Hz at the luminosity $1\cdot10^{30}\,\text{cm}^{-2}\text{sec}^{-1}$, the accidental coincidence background level was 50%.

Thus, the luminosity measurement were provided by three independent systems, measuring single bremsstrahlung in electron and positron directions as well as elastic scattering at small angles. The stability of the ratios of all three luminosity monitors during the experiment was in the range ±5%.

3. Measurement of spin precession frequency

To measure polarization two methods were employed, based on the same physical phenomenon-circularly polarized photons scattered background by transversely polarized electrons lead to "up-down" asymmetry in the angular distribution /10/.

In the first method[*] the well known way of laser light scattering was used /10-12/. The solid state (YAG) laser with frequency doubling used in the experiment had a wave length of 5300 A°, an average power of 1 Wt, a repetition rate of 10 kHz and a pulse duration of 70 nsec. To remove systematical errors the photon circular polarization was changed alternatively from right to left with a frequency of 5 Hz. The detection of the photons was performed by the proportional chambers with the 1 X_0 tungsten converter in front of it. Behind the chamber the NaJ(Tl) counter was placed. At the electron polarization degree of 0.8 the asymmetry A = (up-down)/(up+down) was 1.3%. The statistical accuracy at the beam currents 3 mA was 0.2% for the measurement time of 150 sec.

The second methods[**] has been developed in our Institute and was used in the experiment for the first time. Instead of the laser light the synchrotron radiation generated in the magnetic field of MD-1 by the oppositely moving beam is used here.

It is known that the synchrotron radiation is polarized and the type of polarization depends on the direction of the photon motion: in the orbit plane-linear polarization, above and below the orbit-circular polarization. To provide collision with circularly polarized photons the beam orbits were vertically separated. An optimal separation in the given experiment was 120 μm at the r.m.s vertical beam size 30 μm and was chosen by the consideration of the maximum ratio of the effect rate to that of the background due to single bremsstrahlung

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[*] P.V.Vorobiov et al. (to be published)

[**] A.E.Blinov et al. (to be published).

and residual gas.

The essential advantage of the last method in comparison with that based on the laser is a larger asymmetry. The maximum asymmetry occurs when the incident photon energy in the electron rest system is equal to the electron mass. For the beam energy of 5 GeV the optimal photon energy is equal to 25 eV, that is by one order of magnitude higher than that of laser photons. There are many such photons in the synchrotron radiation spectrum, their selection was carried out by the scattered photon energy.

To detect scattered photons and to measure their energy the NaJ(Tl) counters used for luminosity monitoring were employed. The measurement of the "up-down" asymmetry was done by two scintillation counters (Fig. 1) having the gap of 1 mm in the vertical direction. The lead converter of 7 mm thickness in front of scintillation counters also served as the protection from the powerful synchrotron radiation.

To exclude the influence of the instability of the orbit position the special doubled ionization chambers were installed in front of lead convertor from both sides. The data on the current in the chambers were used through the computer program for orbit correction to stabilize the vertical beam position and the angle in the vertical plane.

Note, that in this method of polarization measurements there is the unstudied effect leading to appearing of the systematical "asymmetry" and connected with the beam geometry in the collision point. However, this "asymmetry" is stable enough and do not hamper the polarization measurement.

At the beam polarization degree 0.8 the measured asymmetry is equal to 5% both in electron and positron directions. The statistical accuracy with the current 3×3 mA^2 is o.5% for measuring time of 100 sec.

The beam depolarization was performed by the high frequency radially directed magnetic field of 0.03 G created between 1.3 meter long parallel planes. The depolarization was performed by slow scanning of the variable field frequency (0.5 kHz for 100 sec). Depolarization time was 50 sec.

Figure 2 presents data of one of the measurements of the depolarization frequency. Three series of the experimental points correspond to the measurements by scattering of synchrotron radiation on the electron beam (upper series), positron beam (middle series) and by laser light scattering on the electron beam (lower series). Time zero corresponds to the moment of the beam injection. The depolarizer was switched on at the moment t = 1000 sec. Lower scale shows the frequencies of the depolarizer. The fact of depolarization is clearly seen. The statistical treatment of this data has shown, that the polarization degree to the moment of depolarization was 0.4 and three systems have given the next values of the depolarization frequencies and their errors (kHz)

18605.91 ± 0.11 - synchrotron radiation at e^- beam,
18606.03 ± 0.07 - synchrotron radiation at e^+ beam,
18606.14 ± 0.22 - laser light at e^- beam.

All three measurements agree within the experimental errors(the error in the depolarization frequency 0.2 kHz corresponds to the energy error 0.2 MeV in the resonance mass scale).

The measurements performed by the laser method have shown that the beam energy does not depend of the beam separation.

The bandwidth of the depolarization line was determined mainly by the RF-generator parameters and was equal 0.35 kHz. To exclude systematical errors the generator bandwidth was controlled in the measurement in which the depolarizer frequency approaches the resonance one from below or above.

The calculated polarization time at the Υ-meson energy is 50 min. The influence of the depolarizing effects strongly depends on the magnetic structure of the ring, energy and the current of the colliding beam. At the indicated above orbit separation the depolarization effects become strong at the beam current greater than 4÷5 mA. For the unseparated beams this effect become notable at the current 1÷2 mA.

4. Experiment

During the experiment VEPP-4 had the next parameters. The maximum luminosity was determined by the collision effect and was about $1\cdot10^{30}$ $cm^{-2}sec^{-1}$ at the current 6 x 6 mA^2, β- function in the collision point: $\beta_z = 45$ cm, $\beta_r = 340$ cm.

The electrons or positrons were stored in the booster storage ring VEPP-3 and then were injected in the ring VEPP-4 at the energy 1.8 GeV. The amount of positrons corresponded to beam current 5 mA in VEPP-4 was stored for the 20 minutes. The electron storage rate was 10 times higher.

The experiment was carried out by the next way. After beam energy rising up to necessary energy the beams were polarizing for some time and then the resonance depolarization were performed. Usually it took of about 0.5 hour. Then we had data taking during 2-3 hour with the integrated luminosity of about 2 nb^{-1}. Then energy calibration was repeated. To this moment in the VEPP-3 the necessary amount of positrons were prepared. The energy of VEPP-4 was lowered up to the injection energy, a new bunch of positrons was injected in VEPP-4, the electron bunch was storaged and injected in a few minutes after, the energy of VEPP-4 rised up to the next energy point. Then the procedure described above was repeated.

The primary current as a rule did not exceeded 3.5 mA, because at larger current as was pointed out above there are no beam polarization.

There was about 100 energy calibration measurements during the experiment. The depolarization was performed usually at the beam polarization degree of 0.2÷0.5. The measured depolarization frequencies, obtained by synchrotron radiation scattering on electrons and positrons coincided within experimental errors. The joint treatment of this data has given the accuracy of energy measurements 0.05÷0.4 MeV (in the mass scale), which depended primarily on the polarization degree.

Two scanning series of Υ-meson mass has been done. In each cycle the luminosity integral of about 40 nb^{-1} was collected. The whole experiment took three weeks. During this time the monotonic drift of the VEPP-4 energy was observed at the fixed current in the magnets and constant revolution frequency. The energy shift reached the value of $6\cdot10^{-4}$. The magnetic field, measured by NMR did not changed. Apparently, this effect is connected with changing of magnet position due to temperature walk (June). This hypothesis agrees with the data on orbit position obtained by pick-up electrodes.

The energy calibration in the each run done before and after data taking as a rule coincided with each other within accuracy of measurements. Only in some runs the energy difference reached 0.7 MeV (in the mass scale). In the first scanning series in those runs where there was polarization during the time of data taking the energy calibration by the laser was done. These measurements have shown that there are no energy shifts inside one run within the accuracy of the measurement.

During the second scanning cycle the depolarizer was switched on all the time in the region of the spin precession frequency. It was done to exclude the possible error, connected with the dependence of the detection efficiency on the beam polarization.

To study background conditions part of the time was spent on the experiment with separated beams. In the first scanning cycle this time was about 10%. In the second cycle the background data were taken during the energy calibration and this time was about 50%.

5. Data processing

The multihadron events were selected by the computer analysis and by visual scanning at display. The data with separated beams have shown that under the selection criteria the background is negligibly small. Figure 3 presents the joint result of the two scanning cycles. Abscissae: doubled beam energy; ordinates: the detection cross section (ratio of the number of multihadron events to the integrated luminosity).

It is known that a shape of the experimental resonance curve is determined mainly by the beam energy spread, radiative corrections and nonresonant continuum. The detection cross section was approximated by the following formulae:

$$\sigma_{vis}(W) = \varepsilon_{nr}\cdot\sigma_{nr} + \varepsilon_r\cdot\int_{-\infty}^{+\infty}\sigma_r(W')\cdot G(W-W')\,dW'$$

where ε_{nr} and ε_r are detection efficiencies for continuum and resonance, σ_{nr} and σ_r are the corresponding cross section, $G(W-W')$ is the luminosity distribution over the energy. The expression for σ_r taking into account the radiative corrections with double logarithmic accuracy is given in /13/.

$G(W-W')$ is determined by the beam energy spread and is usually approximated by

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

where $W=2E$, $\sigma_W=\sqrt{2}\cdot\sigma_E$, σ_E is the rms energy spread in one beam. Following the integration procedure, proposed in /14/ and replacing the Breit-Wigner curve for the resonance by the delta function keeping the area under the curve constant

$$S_r = \int_0^{\infty}\sigma_0\,\frac{M^2\Gamma^2\,dW}{M^2\Gamma^2+(M^2-W^2)^2},$$

one obtains:

$$\sigma_{vis}(W) = \varepsilon_{nr}\cdot\sigma_{nr} + \varepsilon_r\cdot\sigma_r(W),$$

$$\sigma_r(W) = S_r\cdot\left[G_r(W-M) + \delta\cdot G(W-M)\right],$$

$$G_r(x) = \left(\frac{2\sigma_W}{M}\right)^{\beta}\cdot\frac{\Gamma(1+\beta)}{\sqrt{2\pi}\cdot\sigma_W}\cdot\exp\left(-\frac{x^2}{4\sigma_W^2}\right)\cdot\mathcal{D}_{-\beta}\left(-\frac{x}{\sigma_W}\right),$$

$$\delta=\frac{2\alpha}{\pi}\left(\frac{\pi^2}{6}-\frac{17}{36}\right)+\frac{13}{12}\beta,\quad \beta=\frac{4\alpha}{\pi}\left(\ln\frac{W}{m_e}-\frac{1}{2}\right).$$

M is the resonance mass, $\Gamma(1+\beta)$ is the gamma function, $\mathcal{D}_{-\beta}$ is the Weber function of parabolic cilinder.

4 free parameter were fitted: resonance mass M, energy spread σ_W, detection cross section for continuum $\varepsilon_{nr}\cdot\sigma_{nr}$ and the product $\varepsilon_r\cdot S_r$.

To check whether or not some systematical errors are present due to some detector instabilities or to variation of condition in the storage ring the experimental data were separated in some parts. Their analysis did not reveal any systematical errors. The joint processing of the data has given the following values:

$$M = 9459.6 \pm 0.6 \text{ MeV} \qquad \sigma_W = 3.7 \pm 0.6 \text{ MeV}.$$

The obtained value of the beam energy spread σ_W is in agreement with the estimated value of 4 MeV.

Different effects leading to systematical errors have been analysed.

1. The luminosity distribution over the energy is not the convolution of gaussian energy spread distributions in the beams. The point is that there is some achromatism in a focusing system and β_z depends on the particle energy leading to the dependence of the beam transverse size on the particle energies. The effect has been studied experimentally. The dependence of β_z on the revolution frequency (i.e. on the particle energy) has been measured. The experimental data agree with the calculations and give the next form of the luminosity distribution:

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

where a = 50±20.

This effect leads to the shift of the mass value by 0.10 ± 0.04 MeV.

Possible distortion of $G(W-W')$ can arise due to another effect. There are electrical fields in the storage ring used for separation of the beams in the technical straight section and putting them together in the interaction point. Optimal electrical fields can differ for different particle energies. The measurements shown that this effect is negligible.

2. It is known that the energy beam spread can depend on the current. The measurement in the current range up to 5 mA has shown that the longitudinal beam size does not depend on the current. It means that the energy spread does not depend on the beam current as well

3. Fitting the resonance we assumed that each point has no error in the energy. We have performed data fitting many times distributing the energy points by the gaussian law with their errors, each time determining the mass value. This procedure has shown, that the energy calibration introduces the error of 0.03 MeV in the mass value.

No other notable effects leading to systematical errors have been discovered and we give the next value of the Υ-meson mass

$$M = 9459.7 \pm 0.6 \text{ MeV}.$$

The world-average mass value /15/

$$M = 9458 \pm 6 \text{ MeV}$$

In conclusion the authors express their gratitude to many people whose labor provided the performance of the present experiment.

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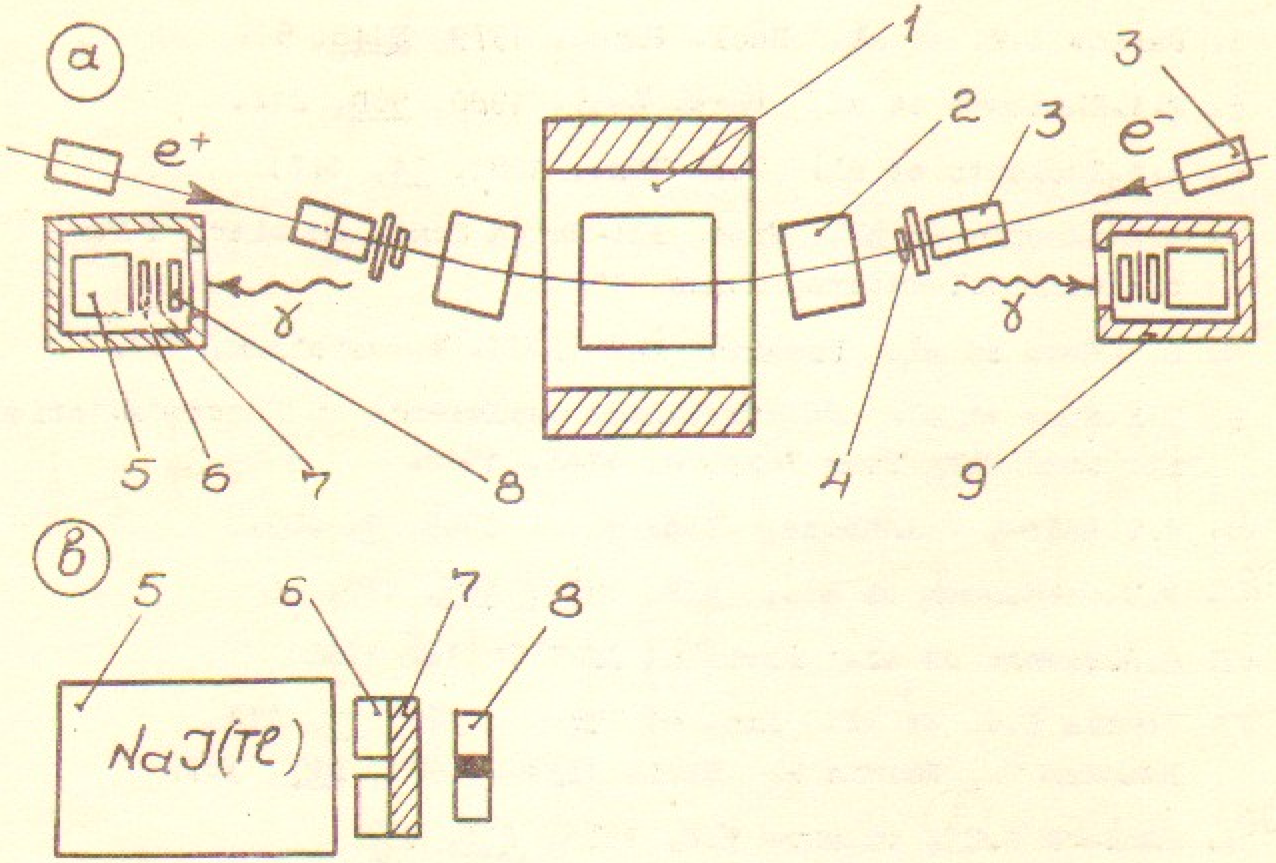

Fig. 1. Detector MD-1 (a - upper view, b - side view of device for the polarization measurements: 1 - central part of MD-1, 2 - additional bending magnets, 3 - lenses, 4 - counters for luminosity monitoring by small angle elastic scattering, 5 - counters for luminosity monitoring by $e^+e^- \to e^+e^-\gamma$ and for polarization measurement by SR, 6 - counters for measuring the "up-down" asymmetry, 7 - lead plate of 7 mm thickness, 8 - doubled ionization chambers, 9 - lead shield.

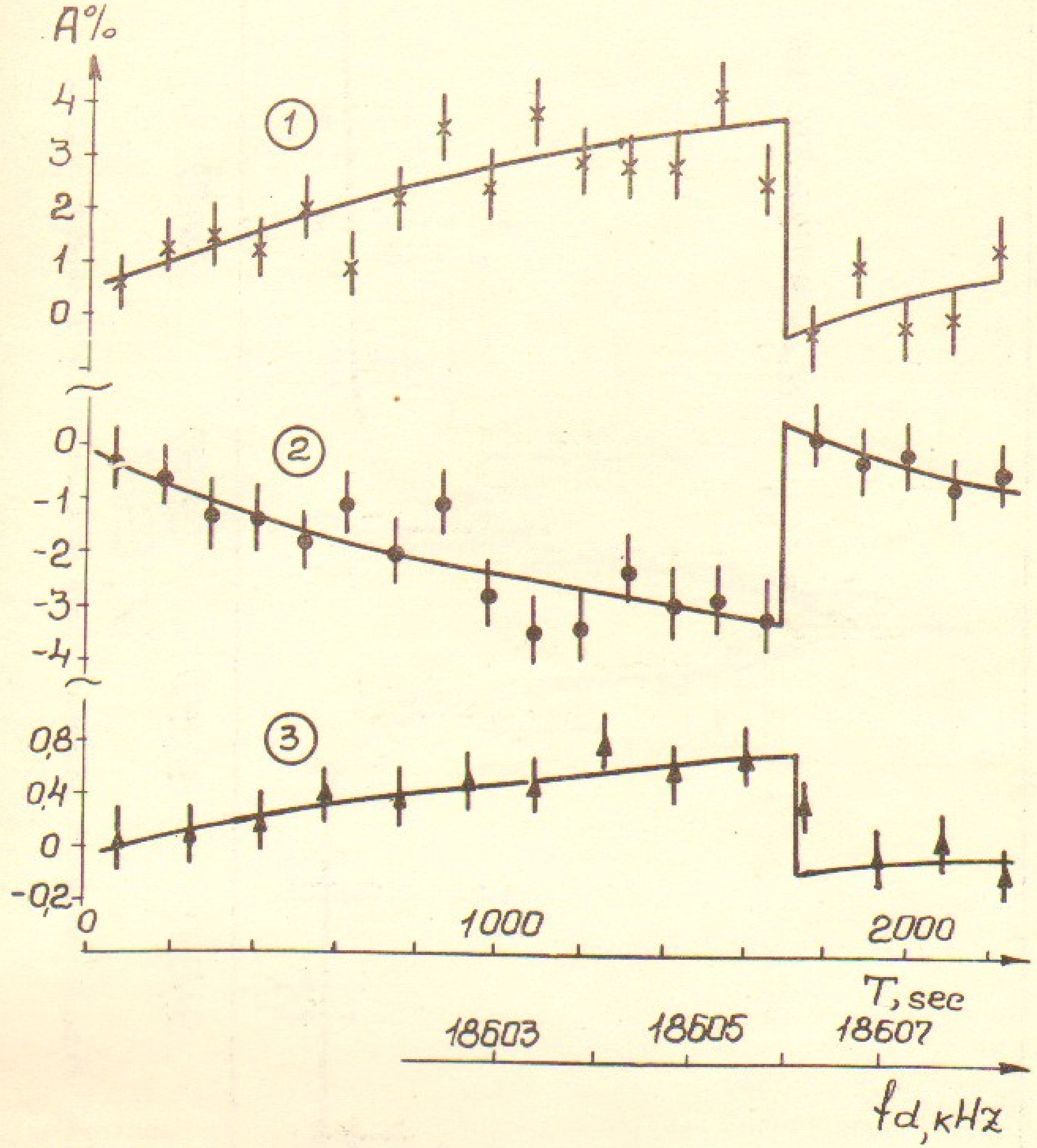

Fig. 2. Res[illegible] one of the depolarization frequency measurement by three system: 1 and 2 - SR scattering on e^- and e^+ beams, 3 - laser light scattering on e^- beam. A = (up - - down)/(up + down). Lower scale shows the depolarizer frequency f_d . Beam currents are $I_- = 2.4$ mA, $I_+ = 3.8$ mA.

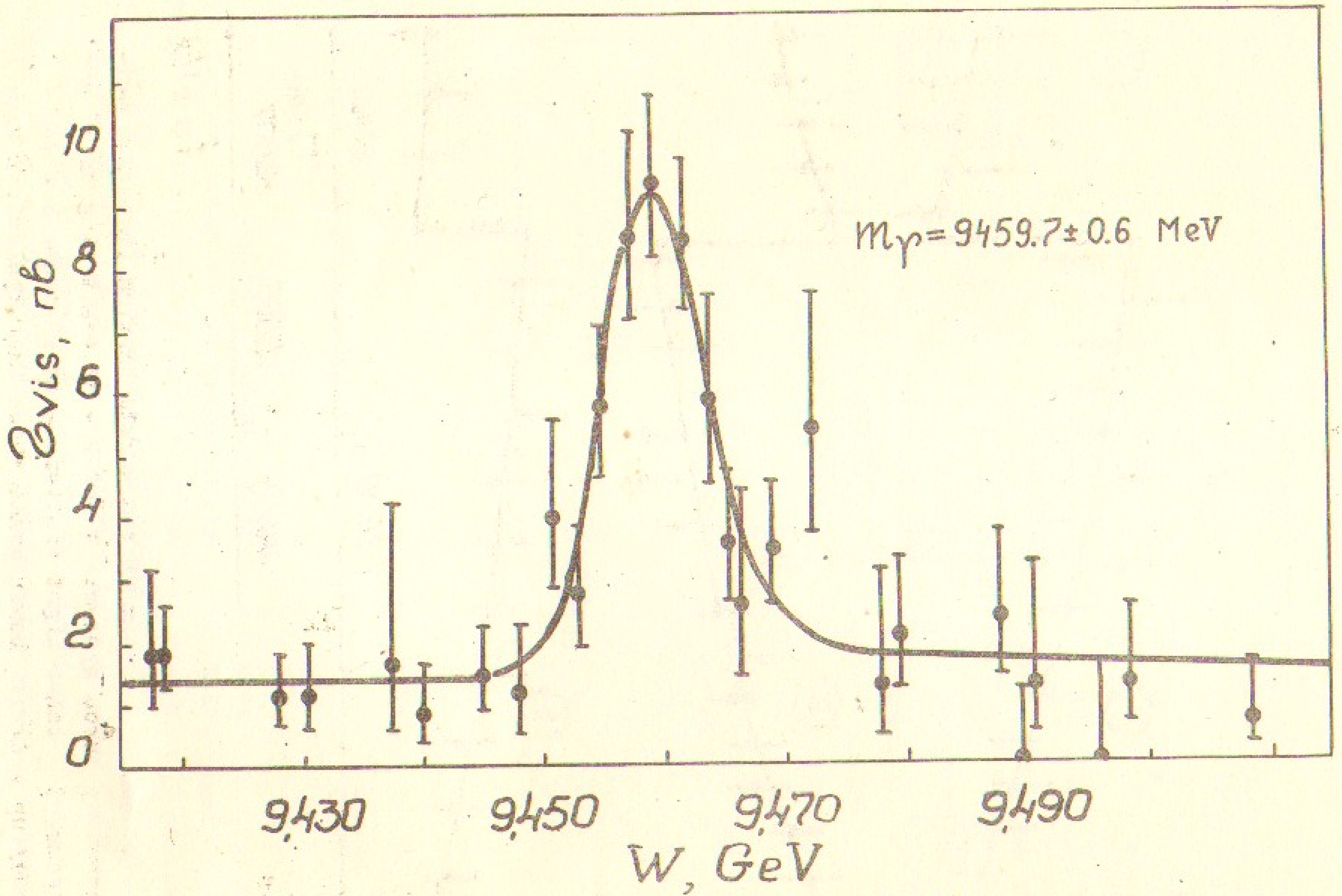

Fig. 3. Observed hadronic cross section in the Υ energy region.