ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ СО АН СССР

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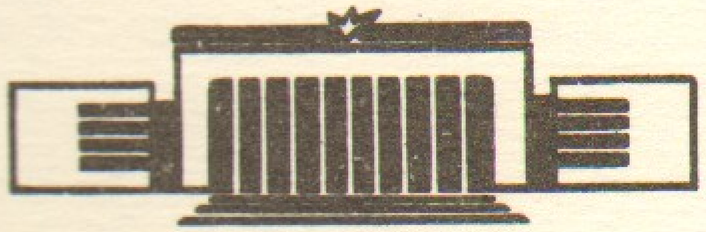

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A HIGH PRECISION MEASUREMENT OF THE Υ, Υ' and Υ'' - meson masses

Preprint

Novosibirsk

A HIGH PRECISION MEASUREMENT OF THE Υ, Υ' and Υ''- meson masses*)

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Abstract

An experiment 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 the mass measurement by a factor of ten. The following mass values of Υ, Υ' and Υ'' mesons have been obtained:

$$M(\Upsilon) = 9460.6 \pm 0.4 \text{ MeV}$$
$$M(\Upsilon') = 10023.8 \pm 0.5 \text{ MeV}$$
$$M(\Upsilon'') = 10355.5 \pm 0.5 \text{ MeV}$$

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1. Method of resonance depolarization

This work continues the cycle of experiments on the precise measurement of particle masses performed in our Institute at electron-positron colliders by the resonance depolarization method /1-7/. 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 /5/ kaon masses and later at VEPP-4 for measurements of the ψ, ψ'/6/ and Υ-meson masses /7/.

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

The precession frequency

$$\Omega = \omega_0 \left(1 + \gamma \frac{\mu'}{\mu_0}\right),$$

where ω_0 is the revolution frequency, γ is a relativistic factor of electrons, 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 r.f. magnetic 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 energy spread of the beam. The point is that synchrotron oscillations of particles lead to the modulation of the precession frequency with a frequency of synchrotron oscillations ω_γ. Besides the main line the spectrum of the spin motion contains a set of additional lines at frequencies differing by $\pm n \cdot \omega_\gamma$ (even n) from the main line. The strength of the depolarizer field should be chosen small enough to provide the depolarization time much longer than the damping time 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 contribution of the magnetic field pulsation to the line width did not exceed 10^{-6}.

2. Experimental set-up

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

$$e^+e^- \rightarrow \text{hadrons}$$

was measured as a function of the beam energy in a region of Υ'', Υ' and Υ mesons.

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 field strength was 12 kGs at the beam energy 5 GeV. Coordinate and shower-range chambers and scintillation counters were used in this experiment. In the trigger firing of at least 4 scintillation counters and 16 layers of shower-range chambers was required. According to the Monte Carlo simulation the efficiency of the trigger for this process was about 95%. The trigger counting rate was 0.2-0.4 Hz at currents 6 x 6 mA^2. Special on-line selection of multihadron events was performed by a computer using more strict requirements on the event topology. The efficiency of this selection was about 50% and a background level did not exceed 20% of the effect value in the nonresonant region. To detect elastic scattering and pair production special "collinear" trigger was arranged. The check-up of detector elements was performed twice a day. Efficience of chambers and counters was controlled by cosmic particles, trigger device was checked up under the softest trigger condition (firing of any coordinate chamber) in presence of beams in the storage ring.

The luminosity was measured by the processes of single bremsstrahlung and Bhabha scattering. The calculation of single bremsstrahlung cross section was carried out by formulae which took into account the effect of the cut-off of the large impact parameters by transverse beam size /10/. Detection of single bremsstrahlung photons was performed both in electron and positron directions. The counting rate was 150 kHz at the luminosity 10^{30} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, the background level did not exceed

0.02%. The ratio of photon counting rates in positron and electron directions was constant during the experiment with the accuracy ±1%. The events of small angle elastic scattering were detected by scintillation counters. The counting rate was 22 Hz at the energy 4.7 GeV and the luminosity $1 \cdot 10^{30}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, the accidental coincidence background level was 10%. The relative stability of two luminosity monitors during the experiment was in the range ±3%. The ratio of elastic scattering events detected by a shower-range system ($\theta \gtrsim 10°$) and by counters at small angles was stable within the statistical accuracy.

3. Measurement of spin precession frequency

Polarization of beams in the storage ring was determined by the "up-down" asymmetry in backward scattering of circular polarized photons on linearly polarized electrons (positrons) /11/. As a photon source the synchrotron radiation generated in the detector magnetic field by the oppositely moving beam was used. This method has been developed in our Institute and was first used in the Υ-meson mass measurement in 1982 /7,12/. The degree of the circular polarization of synchrotron radiation depends on the angle between a photon direction and an orbit plane. For the polarization degree of scattering photons to be close to 100% beam orbits were separated vertically by 120 μm in the interaction point. At the rms vertical size of the beam of 30 μm this separation provides an optimal statistical accuracy of effect in the presence of background due to single bremsstrahlung and residual gas.

To detect scattered photons and to measure their energy the NaI (Tl) counters of total absorption were employed. The measurement of the "up-down" asymmetry was done by two scintillation counters (Fig. 1) having a gap of 1 mm in the horizontal direction. The lead converter of 13 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 ionization chambers, detecting synchrotron radiation were installed in front of lead converter from both sides. The data on the current in the chambers were used for orbit correction to stabilize the vertical beam position and the angle in the vertical plane.

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 5×5 mA^2 is 0.4% 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 parallel planes 1.3 meter long. The depolarization was performed by slow scanning of the variable field frequency (0.4 kHz for 100 sec). Depolarization time was 50 sec.

Figure 2 presents data of one of the measurements of the depolarization frequency. Two series of the experimental points correspond to the measurements by scattering of synchrotron radiation on the electron beam (upper series) and positron beam (lower series). Lower scale shows the depolarizer frequencies. Data processing gave the following values of the depolarization frequencies and their errors (kHz)

19025.95 ± 0.05 - synchrotron radiation at e^- beam,
19026.00 ± 0.05 - synchrotron radiation at e^+ beam.

The joint treatment gives 19025.98 ± 0.03 (the error, in the depolarization frequency 0.10 kHz corresponds to the energy error 0.11 MeV in the mass scale).

The bandwidth of the depolarization line was determined mainly by the RF-generator parameters and was equal to 0.30 kHz. To exclude systematic errors the bandwith 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 depends on the magnetic structure of the ring, energy and the current of the colliding beam.

IV. Experiment

The experiment has been carried out from the middle of December 1982 up to the end of May 1983. Five scanning series in the Υ''- meson region, four in the Υ' region and one in the Υ -meson region have been done. At the beginning the storage ring had the following parameters: $\beta_z = 45$ cm, $\beta_r = 340$ cm, $L_{max} = 1 \cdot 10^{30}$ cm^{-2} s^{-1} at currents 6×6 mA^2. In January 1983 β_z in the interaction point was decreased to 19 cm that provided $L_{max} = 3 \cdot 10^{30}$ cm^{-2}s^{-1} at currents 9×9 mA^2. The electrons or positrons were stored in the booster VEГP-3 and then injected into the VEPP-4 ring at an energy of 1.8 GeV. The number of positrons necessary for obtaining beam current 5 mA in VEPP-4 was stored in VEPP-3 during 20 minutes. The electrons storage rate was 10 times higher. The life time of the beams in VEPP-4 was about 5 hours.

The measurement in the Υ''- and Υ - meson regions was carried out in the following way. After beam energy increase in VEPP-4 up to a necessary value the energy calibration was performed, then data were taken during 3-4 hours. In the next cycle the procedure was repeated but with the one difference - the sequence between the energy calibration and data taking was changed. The calibrations in the neighbouring energy points were performed with opposite scanning direction of the depolarizer.

To control the energy stability of the storage ring during data taking in some cycles the energy calibration was performed before and after data taking with the same direction of frequency scanning. The analysis of such calibration pairs has shown that the systematic energy shift was - 0.03 ± 0.03 MeV in the mass scale.

During the calibration, when beams were vertically separated, the background data were recorded on a tape.

To exclude possible influence of the beam polarization on the detection efficiency for multihadron events, during data taking the beams were kept unpolarized by a depolarizer.

The energy calibration was carried out usually at the degree of beam polarization 0.2-0.5. The accuracy of energy measurements depended on the degree of beam polarization and was 0.05÷0.2 MeV (in a mass scale).

In the energy region of Υ' the polarization degree of the beams in the VEPP-4 is small due to coincidence of the spin precession frequency with that of betatron oscillations /13/. This has excluded a possibility of the energy calibration in these very points in which data were taken. The calibrations were carried out in the point being apart from resonance by 60 MeV (in mass scale), the energy in the point of the measurement was determined by extrapolation using the magnetic field value. The extrapolation curve has been obtained in special measurements by the energy calibration below and above of resonance, where the degree of the polarization was sufficient for the energy calibration. The calibration curve was obtained several times during the experiment.

During the whole experiment the alteration of the magnetic field of storage ring was carried out by one standard cycle. After injection the energy was increased up to the point where the calibration was performed, then the energy was raised up to the point where data were taken. After that the energy was raised up to the fixed point much above the resonance and then was lowered to the injection energy. In some cycles two calibrations have been performed during the energy raising in the points placed below the resonance by 120 and 60 MeV. The estimations show that the error in the Υ'-meson mass connected with the extrapolation procedure does not exceed 0.05 MeV.

Using the above described way a half of the statistics has been taken (1 and 2 scanning series). The remaining half of the statistics (3 and 4 series) has been taken under somewhat differing conditions of the storage ring operation. Just after injection the energy was raised up to a maximum fixed point and than was lowered onto the point where the data were taken, after that the energy was lowered by 60 MeV and the energy calibration was carried out. The calibration curve of

the energy dependence on the magnetic field measured in this regime of the storage ring operation did not coincide with the first one. The mass error due to extrapolation in these series does not exceed 0.2 MeV.

The main results of the experiment are presented in the Table I, in which the data of the experiment performed in 1982 are shown as well /7/.

Table 1

Particle	Time of the data taking	Number of the energy calibrations	The integrated luminosity, nb^{-1}	Number of recorded events	
				effect + + background	background
Υ''	14 December 82- - 3 April 83	370	1250	$6.5\cdot10^5$	$1.9\cdot10^5$
Υ'	9 April 83 - - 19 May 83	180	600	$2.2\cdot10^5$	$0.8\cdot10^5$
Υ	20 May 83 - - 24 May 83	20	130	$3.0\cdot10^4$	$0.6\cdot10^4$
Υ	6 June 82 - - 30 June 82	100	70	$1.8\cdot10^5$	$0.6\cdot10^5$

V. Data processing

On the basis of Monte Carlo simulation and background measurements the selection criteria for multihadron events have been chosen. The results of data processing for each resonance are presented in Figs. 3,4,5, in which the detection cross section is plotted versus c.m. energy.

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:

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

where ε_{nr} and ε_r are detection efficiencies for continuum and resonance, σ_{nr} and σ_r are the corresponding cross sections, $G(W-W')$ 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 /14/.

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

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

where $W = 2 \cdot E$, $\sigma_W = \sqrt{2} \cdot \sigma_E$, σ_E is the rms energy spread in one beam. Following the integration procedure, proposed in /15/ and replacing the Breit-Wigner curve for the resonance by the delta function keeping the area under the curve constant

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

one obtains:

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

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

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

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

M is the resonance mass, $\Gamma(1+\beta)$ is the gamma function, $D_{-\beta}$ is the Weber function of parobolic cylinder. Four parameters 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 conditions in the storage ring the experimental data were divided into separate groups (different series, small specific luminosity below the resonance maximum and the large one above and vice versa, the beginning and the end of the series etc.).

Their analysis did not reveal any evident systematical errors.

The obtained values of the energy spread $\sigma_W(\Upsilon) = 4.4 \pm 0.4$ MeV, $\sigma_W(\Upsilon') = 4.9 \pm 0.5$ MeV and $\sigma_W(\Upsilon'') = 5.4 \pm 0.6$ MeV are in agreement with estimated numbers 4 MeV, 4.5 MeV, 4.8 MeV correspondingly.

Different effects leading to systematical errors have been analysed. The most essential are:

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 chromatism in a focusing system and β_z depends on the particle energy caused 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 agrees with the calculations and gives the next form of the luminosity distribution:

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

where $a = -20 \pm 10$ for $\beta_z = 45$ cm and $a = -14 \pm 3$ for $\beta_z = 19$ cm.

This effect leads to the shift of the mass value by -0.04 ± 0.02 MeV. (there is an error in /7/: the correction 0.1 MeV was made instead of -0.04 MeV).

2. 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 electric field can differ for different particle energies. The measurements shown that this effect is negligible.

3. The collision effects can lead to dependence of the transversal beam size on the particle energy.

4. The beam energy spread can be increased with appearance of the phase instabilities. Special attention was paid to the absence of such instabilities during the experiment.

5. The interaction point is situated asymmetrically relative to r.f. cavities; the mass shift effect associated with this circumstance is negligible.

6. Fitting the resonance curve 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. The procedure has shown that the energy calibration errors introduces the error of 0.02-0.05 MeV in the mass value (different series).

The total inaccuracy of the mass measurements due to all effects mentioned above is less than 0.2 MeV by our estimations.

The obtained value of the Υ -meson mass, 9461.0±0.5 MeV is in a statistical agreement with data of the experiment /7/: $M(\Upsilon)$= 9459.6±0.6 MeV. The results of a joint processing of these experiments as well as values of Υ' and Υ'' meson masses obtained in the present experiment are presented in Table 2. Here the corresponding mass values from the Table of Particle Properties are also quoted /16/.

Table 2

Quantity	Tables of Particle Properties value, MeV	Result of this experiment, MeV
$M(\Upsilon)$	9456±10	9460.6±0.4
$M(\Upsilon')$	10016±10	10023.8±0.5
$M(\Upsilon'')$	10347±10	100355.5±0.5
$M(\Upsilon')-M(\Upsilon)$	559±3	563.2±0.7
$M(\Upsilon'')-M(\Upsilon)$	891±4	894.9±0.7

In conclusion the authors express their gratitude to many of our Novosibirsk colleagues whose labor provided the possibility of performing the present experiment. Special thanks are due to Yu.M.Shatunov for useful discussions.

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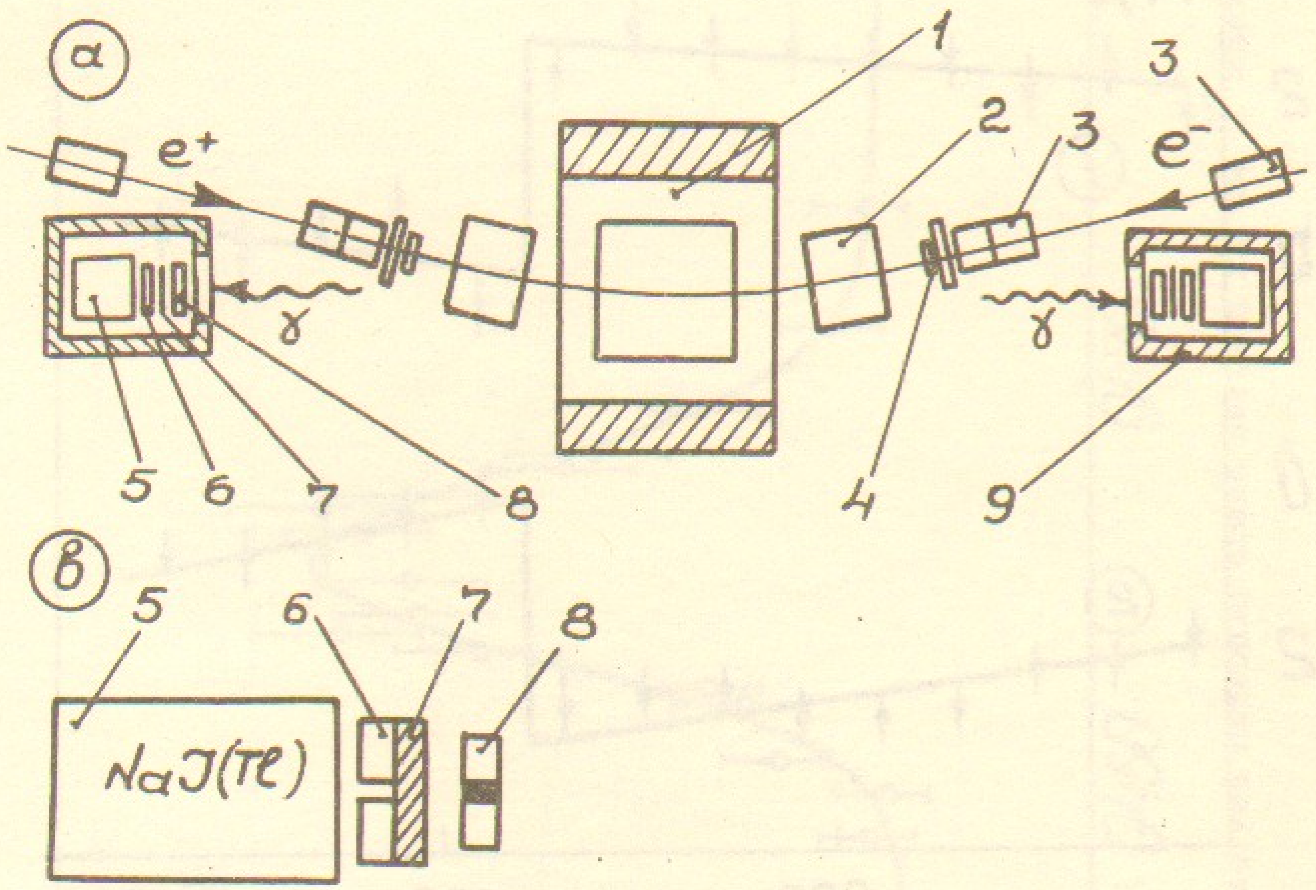

Fig. 1. Detector MD-1 (a - upper view, b - side view of device for the polarization measurements): 1 - central part of MD-1, 2 - additional bending magnets, 3 - lenses, 4 - counters for luminosity monitoring by small angle elastic scattering, 5 - counters for luminosity monitoring by $e^+e^- \to e^+e^-\gamma$ and for polarization measurement by SR, 6 - counters for measuring the "up-down" asymmetry, 7 - lead plate of 13 mm thickness, 8 - doubled ionization chambers, 9 - lead shield.

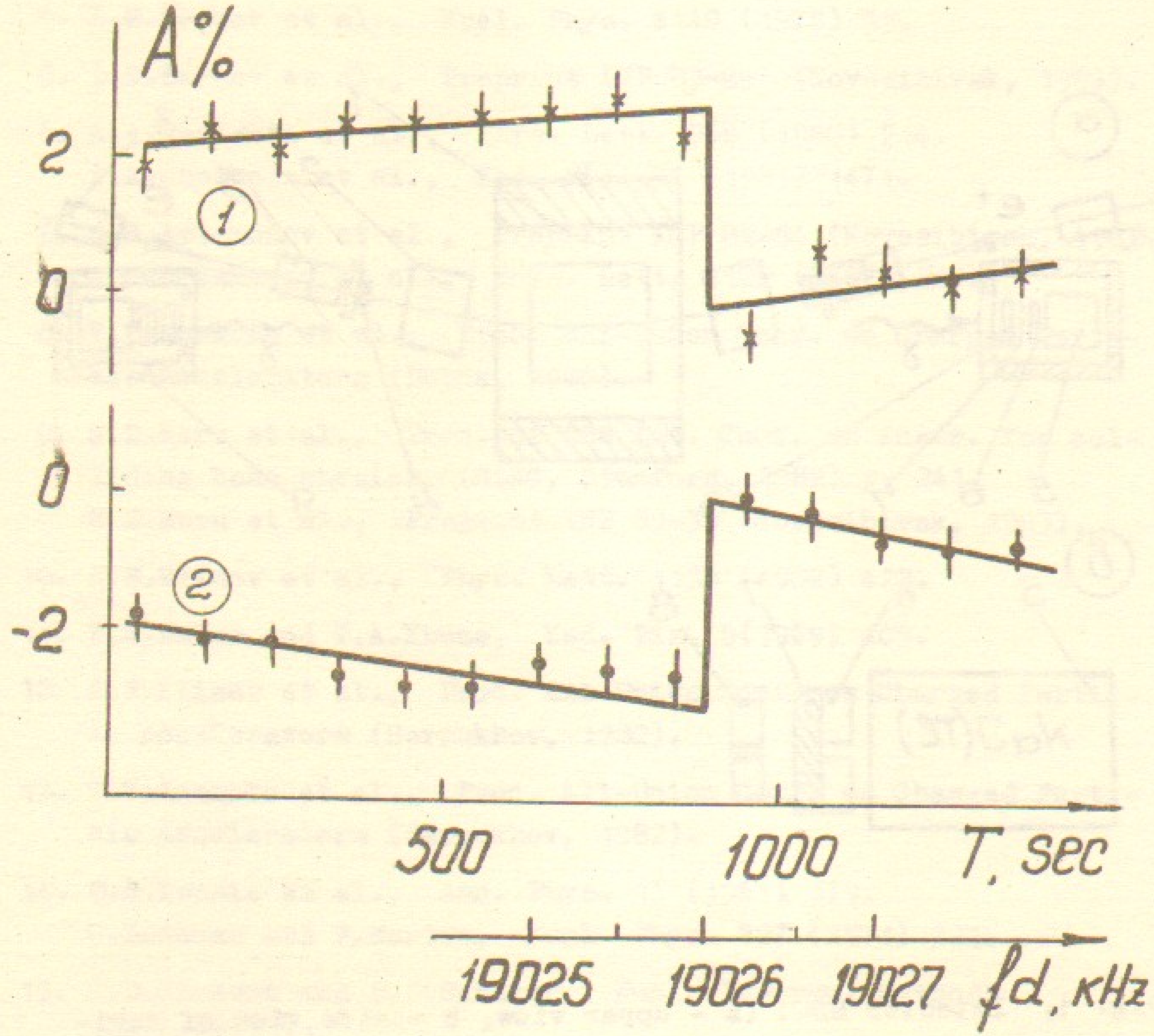

Fig. 2. Result of one of the depolarization frequency measurement.
1 and 2 - SR scattering on e$^-$ and e$^+$ beams.
A = (up-down)/(up+down) is averaged over 100 sec.
Lower scale shows the depolarizer frequency f_d. Beam currents are $I_- = 5.8$ mA, $I_+ = 6.2$ mA.

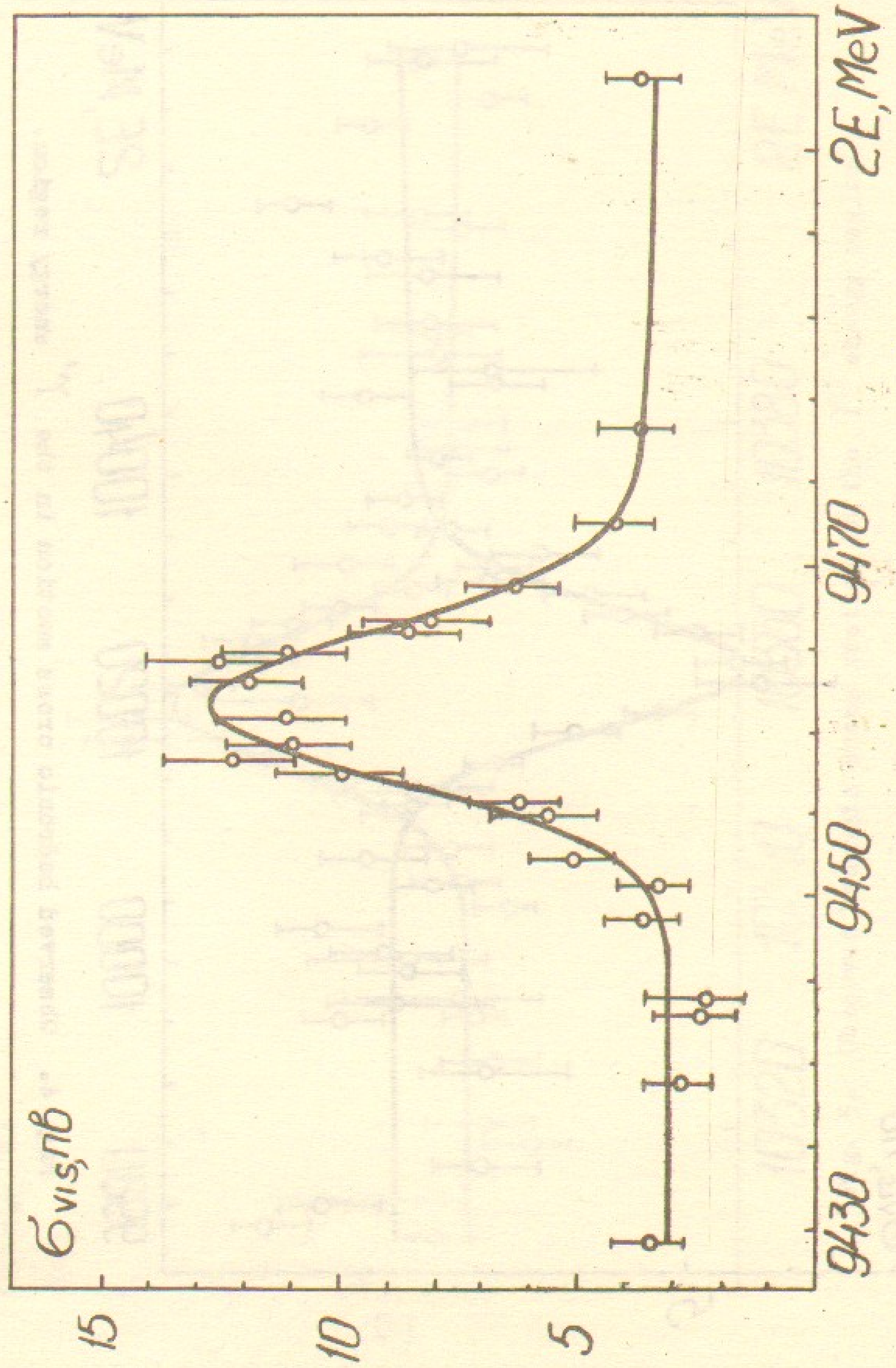

Fig. 3. Observed hadronic cross section in the Υ' energy region.

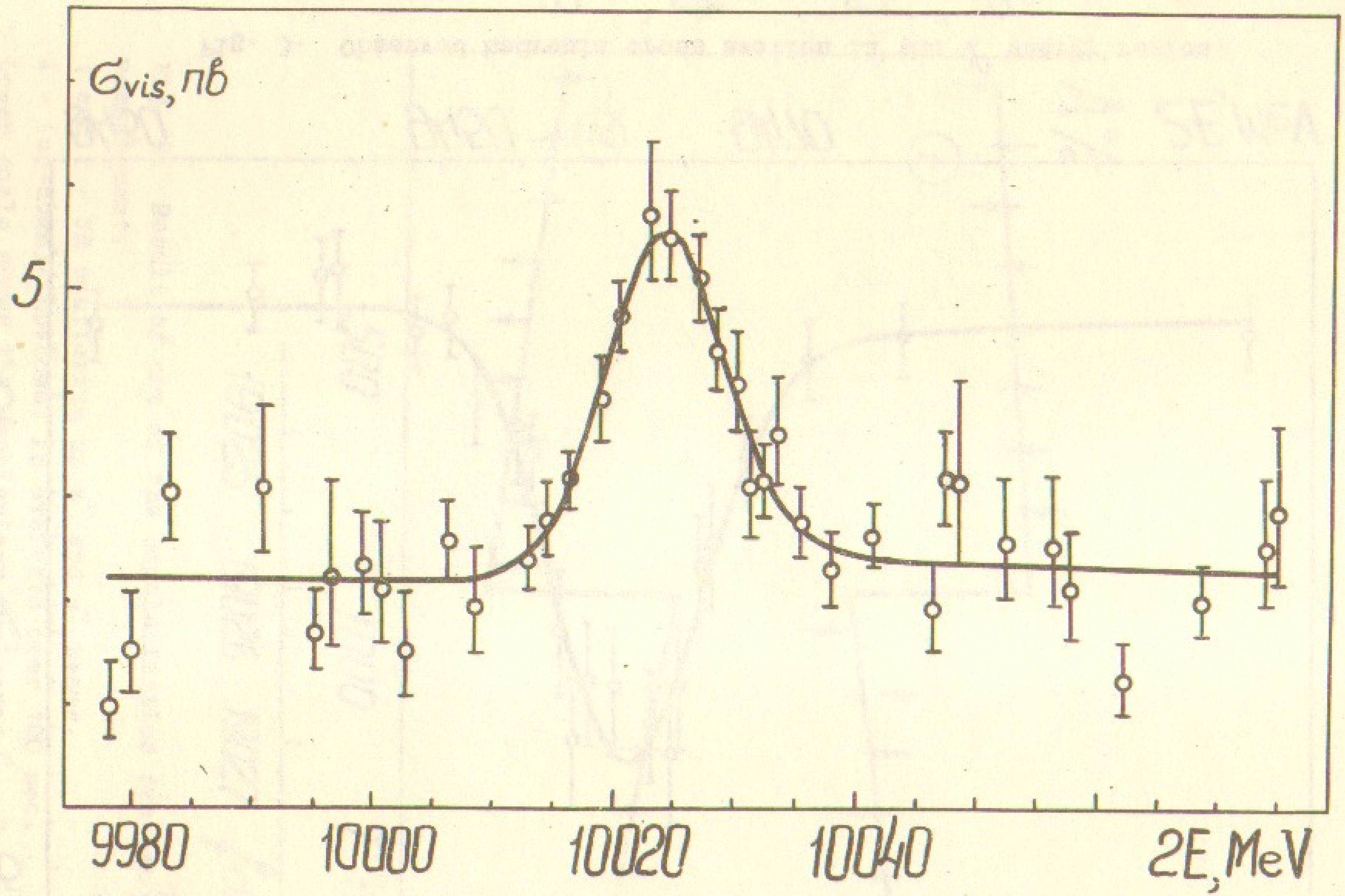

Fig. 4. Observed hadronic cross section in the Υ' energy region.

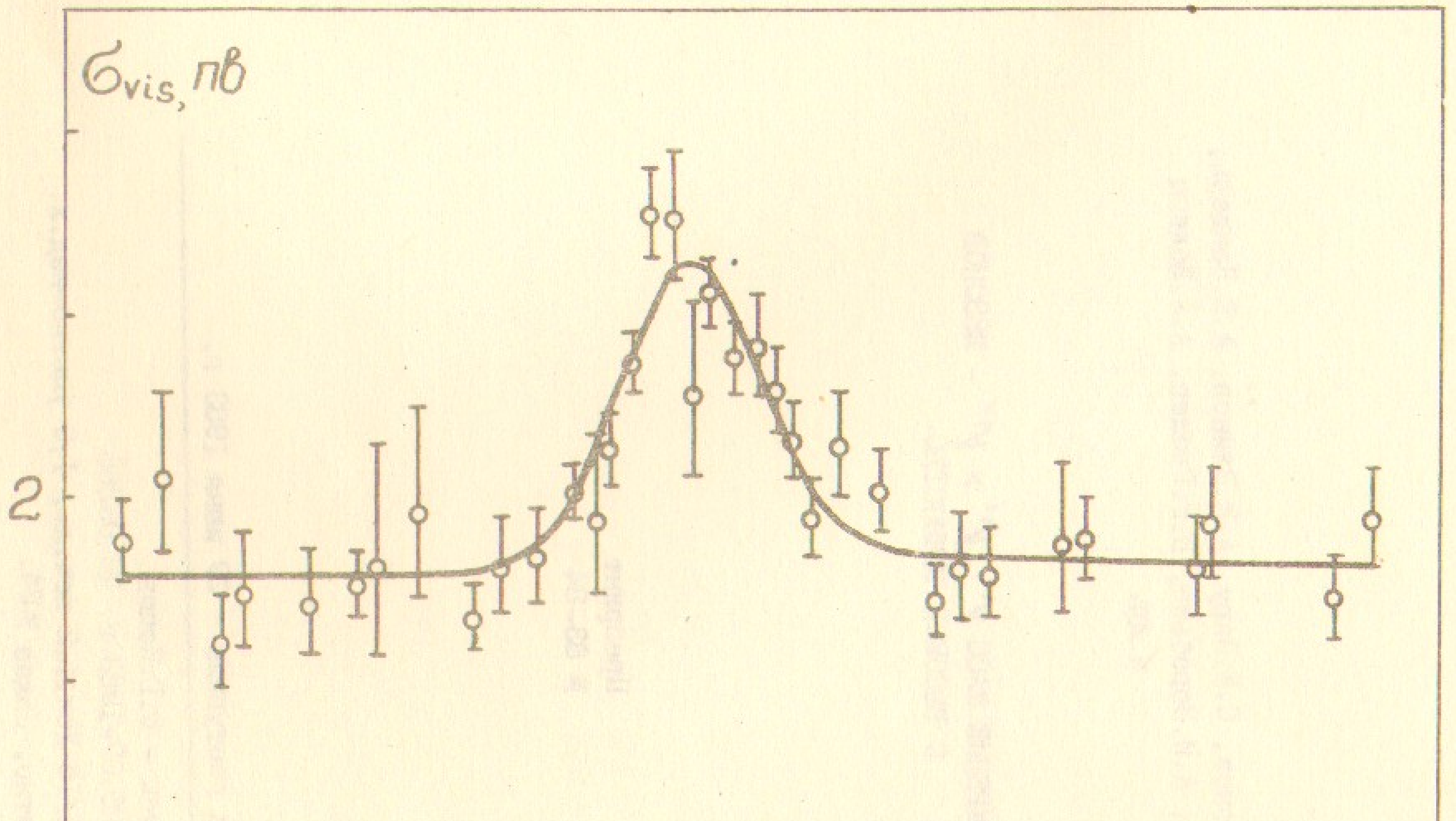

Fig. 5. Observed hadronic cross section in the Υ'' energy region.

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и др.

ИЗМЕРЕНИЕ МАСС ψ, ψ' и ψ'' - МЕЗОНОВ С ВЫСОКОЙ ТОЧНОСТЬЮ

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