POLARIZED BEAMS IN STORAGE RINGS AND HIGH PRECISION MEASUREMENTS OF PARTICLE MASSES

Yu.M. Shatunov and A.N. Skrinsky

The development of the technique for high precision measurement of the absolute beam energy in storage rings [1–2] allowed a series of particle mass measurements to be performed in Novosibirsk using the polarized beams of electron–positron colliders VEPP–2M and VEPP–4 [1–9]. A particularly significant step in accuracy has been achieved for the Ψ and Υ families, where the improvement was two orders of magnitude.

The calibration technique is based on the relation between an energy E and a spin precession frequency Ω of relativistic electron, travelling with a frequency of ω_s in a transverse magnetic field

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

where q', q_0 are the anomalous and normal parts of the gyromagnetic ratio.

The relation (1) is violated only by longitudinal magnetic fields which can, for various reasons, exist at the particle orbit. For evaluating the distortion value it is sufficient to consider the insertion of a longitudinal field H_V on a certain straight section of a trajectory. One can show that in this case the dimensionless spin tune precession frequency $\nu = \Omega/\omega_s - 1$ is given by the following expression:

$$\cos\pi\nu = \cos\pi\nu_0 \cdot \cos\frac{\beta}{2} \,, \tag{2}$$

where β is an angle of spin rotation around H_V; ν_0 is the frequency without longitudinal field.

The numerical calculation of possible sources of the longitudinal field in a standard storage ring (edge fields, motion angles, etc.) shows that the shift value $\delta\nu$ does not exceed 10^{-6}.

Special attention is required for sections with longitudinal magnetic field where β can achieve a noticeable value (detectors, spin–rotators, etc.). The spin rotation should be compensated for by inverse fields, which is equivalent to the standard condition for the suppression of orbital transverse oscillations coupling.

An energy spread existing in electron–positron storage rings $\Delta E/E \leq 10^{-3}$ does not result in a first approximation, in the accuracy limit for the considered method of measuring an average energy of beam particles. In the presence of an accelerating r.f. voltage, an energy of non–equilibrium particle oscillates around the value E_s with a frequency of synchrotron oscillations $\nu_\gamma\omega_s$: $E = E_s\,[1 + (\Delta E/E)\sin\nu_\gamma\omega_s t]$. Hence, the spin precession frequency will be modulated with the same frequency. This means that the spin frequency spectrum consists of a set of side bands spaced by $\nu_\gamma\omega_s$ ($\nu_\gamma \sim 10^{-2}$). The spectrum central line is the precession frequency $\Omega = \Omega_s + \langle\delta\Omega\rangle$ averaged over synchrotron oscillations.

The shift of spin precession frequency of a non–equilibrium particle with respect to that of an equilibrium one Ω_s is due to the presence of oscillations and non–linearities of the magnetic field. A particle with some amplitude of betatron oscillation A_x has a delay with respect to an equilibrium particle proportional to the square of the transverse momentum $p_\perp^2 = A_x^2[|f_x|'^2 + (1/|f_x|^2)]$, where $|f_x|$ is the Flokke function module. Because of the condition of synchronism with an accelerating voltage, this effect leads to the energy and precession frequency shift with respect to their equilibrium values.

Magnetic field non–linearities also lead to some difference in precession frequencies for particles with and without oscillations. The joint consideration of both these effects results in the following formula for the spread of spin frequencies [10]

$$\delta\Omega = \nu\frac{A_x^2}{\alpha}\left\langle n_1\,|f_x|^2\,\Psi_x + \left(|f_x|'^2 + \frac{1}{|f_x|^2}\right)\right\rangle\omega_s \,, \tag{3}$$

where α is an orbit compaction factor and Ψ_x is a dispersion function of the storage ring. Estimation of $\delta\Omega$ for various storage rings shows that the spin frequency spread does not exceed the value $\sim 10^{-5}\,\omega_s$ and can be controlled by variation of quadratic non–linearity. Such a control can be performed by measuring the chromatism of radial betatron oscillations $\gamma\,(\partial\nu_x/\partial_\gamma)$, which value coincides in its main terms with the expression given in relation (3) in brackets $\langle\,\rangle$.

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

The particle spin precession frequency can experimentally be measured in a storage ring by observing the polarization level while affecting the beam by the high frequency electromagnetic field whose frequency ω_d satisfies the following condition:

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

When the resonant condition is satisfied, the spin precession angle for every particle oscillates from 0π to 2π with some frequency w, which is determined by the value and direction of the r.f. field. The presence of stochastic processes (external noise modulation in the band $\delta\omega_d$, quantum fluctuations of synchrotron radiation, etc.) mixes the spin rotation phases and, hence, leads to the beam depolarization. An effective width of a resonance, i.e.

© 1989 Gordon and Breach Science Publishers S.A.
Photocopying permitted by license only.

Particle World, Vol. 1, No. 2, p. 35–39, 1989.

frequency band $\Delta\omega_d$, where the depolarization rate is of the order of its maximum, depends on the ratios of values w, $\delta\omega_d$ and $\delta\Omega$.

If w, $\delta\omega_d >> \delta\Omega$, an accuracy of Ω determination is not higher than a maximum of (w, $\delta\omega_d$) and the time of depolarization is determined by the expression $\tau_d \simeq (\delta\omega_d/w^2)$.

In the opposite case w, $\delta\omega_d << \delta\Omega$ the resonance width is equal to the spin frequency spread $\delta\Omega$, if $\delta\Omega$ exceeds the radiation damping decrement λ (λ^{-1} is a characteristic time for mixing amplitudes and phases of particle orbital oscillations). But in the case $\delta\Omega << \lambda$, which is usual in practice, an additional stochastic averaging of the frequency spread Ω to the value $\Delta \simeq (\delta\Omega)^2\, \lambda^{-1}$ occurs due to radiation effects.

It is clear that for achieving the limiting accuracy in the precession frequency measurement one should have w and $\delta\omega_d \leq \Delta$. In this case, the time of depolarization $\tau_d \sim 1/w$, as the polarization component transverse to the field vanishes during the time Δ^{-1}.

Thus, in spite of the beam energy spread the spin dynamics is such that the resonance depolarization enables one, in principle, to find out an absolute value of particle equilibrium energy with an accuracy limited only by accuracy of the data of an anomalous part of electron gyromagnetic ratio $(q'/q_0) = (1159652193 \pm 4) \bullet 10^{-12}$ and of its rest mass $mc^2 = (51099906 \pm 15) \bullet 10^{-8}$ [11].

For resonance depolarization one should generate the r.f. field on some fraction of orbit which rotates the spin around the direction perpendicular to the direction of equilibrium polarization on the section. In a simple case of polarization along the main field H_z one can use either jointly or separately any of the r.f. field components $\tilde{H}_y$, $\tilde{H}_x$ and $\tilde{E}_z$. At high energies it is possible to depolarize with transverse H, E fields.

When operating with colliding beams, the use of a travelling wave ($|\tilde{H}_x| = |\tilde{E}_z|$) enables one to depolarize any of the beams by choosing a necessary direction of wave propagation since, when the wave direction coincides with particle velocity, the frequency $w \simeq 0$ (with an accuracy $\sim 1/\gamma^2$).

In addition, it is technically feasible to depolarize selectively the bunches of the same beam if one uses short time pulses of r.f. field phased with the particle rotation frequency [12].

In a search for depolarization resonance it is convenient to use scanning by r.f. field frequency within the range determined by an uncertainty of a particle energy. At the initial stage of the experiment this may require a sufficiently high power ($\simeq$ 10 kW) and a large band width both for r.f. sources as well as for devices generating the field at the orbit. With the improvement of the energy calibration accuracy the power becomes very small and the problem arises how to generate a sufficiently narrow frequency line of the depolarizing field.

In the practical realization of the resonance depolarization, one of the main problems is that of obtaining polarized beams of the required energy. Fortunately, for electrons and positrons there is a process of natural radiative polarization during their motion in the magnetic field [13–14]. In the absence of depolarizing factors the polarization degree tends to its limiting value $\zeta_0 = 0.92$ with a characteristic time $\tau_p \sim (1/E^5)$, which under the standard conditions of electron–positron storage rings varies from a few minutes to a few hours and may be less than the lifetime of particles in storage rings.

To control the polarization process any sufficiently fast and sensitive method is suitable. For example, the detection of pairs leaving the beam due to intra–beam scattering is sufficiently simple and at not too high energies has a high counting rate $dN/dt \sim 10^3$ to 10^4 Hz. A relative contribution of polarization is from 4 to 20%.

This method of polarization measurement proved to be well suited to the energy range from a few hundred MeV to 2 GeV [4, 8].

At higher energies the measurement of the electron polarization can be quite effectively done using the Compton scattering of circularly polarized photons. At VEPP–4 at the energy of 5 GeV one used as a source of photons, a laser beam or synchrotron radiation of the counter bunch having a noticeable degree of circular polarization of different sign up and below the orbital plane [7, 9]. The "up–down" asymmetry in the distribution of back–scattered photons (from 2 to 8%) has been measured and is proportional to the degree of transverse polarization.

To achieve high accuracy of the energy calibration, one should take special efforts to control and suppress non–regular and slow periodical oscillations of the storage ring magnetic field, which "diffuse" an average spin frequency and lead to the error $\Delta\omega_d \simeq (\Delta H_z/H_z)\ \omega_s$. A system for the suppression of magnetic field oscillations to the level $\leq 10^{-6}$ provided, at VEPP–2M, an accuracy in the precession frequency measurement close to its "natural" limit — the spin frequency spread. The suppression of the latter with sextupole corrections (formula (3)) to the level $\delta\Omega \simeq 2 \bullet 10^{-7}$ [15] resulted in the situation when the accuracy of absolute calibration of the average particle energy is determined by the existing accuracy of the electron rest mass.

When conducting long–term experiments, there is a problem of energy stability of particles between calibrations. The environment temperature instability causes the change in storage rings geometry. Related to these circumstances, shifts of radial position of magnets, and especially quadrupole lenses, lead to uncontrollable variations in particle energy at a fixed revolution frequency.

The stabilization system has been used at VEPP–2M, which compensates for the lens geometric deviations by the corresponding change of the magnetic field value [16]. As a result, an energy stability achieved is $\simeq 10^{-5}$ during the period of a few months.

It is clear that the temperature stabilization of storage ring components is quite useful.

By now, at INP (Novosibirsk), a number of high–precision measurements have been performed at electron–positron colliders using the technique described here. At VEPP–2M the masses of ϕ, ω, $K^{\pm}$ and K^0 mesons and at VEPP–4 the masses of Ψ, Ψ', Υ, Υ' and Υ'', resonances have been measured.

1. ϕ meson

Chronologically, the mass of the ϕ–meson resonance was the first to be determined by this method in 1975 [1]. At the beginning of the experiment an absolute energy calibration using resonance depolarization was performed in relation to the storage ring magnetic field. The calibration was done with an electron beam only. A radiation polarization up to the level of 80% was achieved at a maximum energy of the storage ring where the polarization time is $\tau \simeq 50$ min. After that, the energy was decreased with an intersection of several weak spin resonances down to the region of the ϕ meson and the precession frequency was measured by the observation of a jump in intrabeam scattering during the scanning of the depolarizer frequency.

The excitation curve of the ϕ resonance was obtained with the detector "OLYA" [17] in two channels $e^+e^- \to K^0_S K^0_L$ and $e^+e^- \to \pi^+\pi^-\pi^0$. The energy distribution of events is shown in fig. 1. Three measurement cycles were performed within the energy range from 2×507 to 2×513 MeV with a step $\Delta(2E) = 0.5$ MeV. Each cycle before and after an energy calibration was performed at $E = 509.6$ MeV.

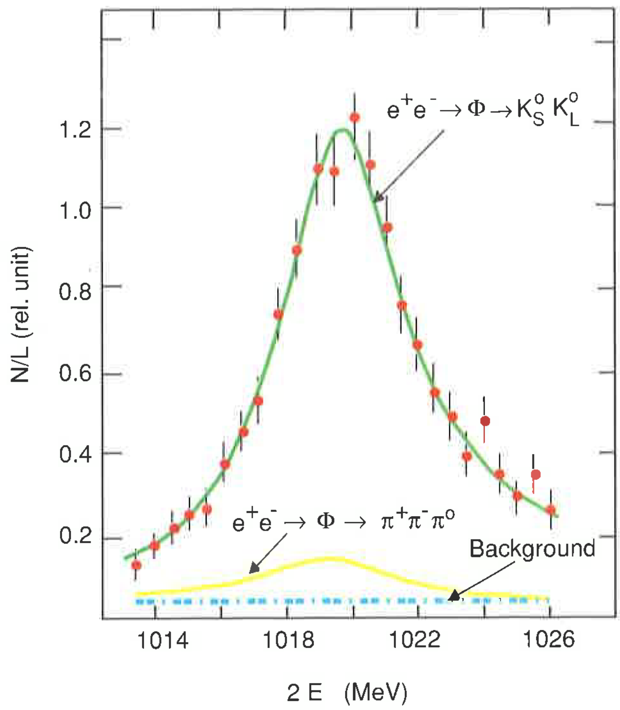

FIGURE 1

ϕ meson mass measurements (1975).

The optimal resonance curve of fig. 1 was drawn taking into account radiative corrections as well as ω–ϕ interference and gave the mass value $M_\phi = (1019.52 \pm 0.13)$ MeV.

An accuracy achieved in the first experiment using resonance depolarization was approximately 2.5 times higher than the world average in all preceding experiments.

2. K^+ and K^- mesons

The possibility of a high precision measurement of the $K^{\pm}$ meson masses results from the fact that in the vicinity of the ϕ–meson resonance peak, kaons are produced with a kinetic energy (KE) of ~ 10 MeV. The measurement of the KE with an accuracy $\simeq 10^{-3}$ provides a determination of secondary particle masses with good accuracy if the energy of primary electrons and positrons is fixed by the resonance depolarization.

For measurements of the kinetic energy of charged kaons the detector used 5 layers of photo–emulsion placed around the collision point immediately after energy calibration. Two cycles of emulsion exposure with $\simeq 30$ min exposure at beam currents of 5×5 mA^2 enabled us to select 350 events after data processing of the reaction $e^+e^- \to K^+K^-$ and determine the mass of charged kaons $M_{K^{\pm}} = (493.670 + 0.029)$ MeV. Note that in this experiment the mean value of $(M_{K^+} + M_{K^-})/2$ was measured. From this result, one can obtain practically with the same accuracy the value of mass M_{K^+} since the negative kaon mass is well known from the K–meson atomic experiments.

3. K^0 meson [4]

A mass of neutral kaons produced in the reaction $e^+e^- \to K^0_S K^0_L$ was determined at VEPP–2M using the Cryogenic Magnetic Detector (CMD) [18].

The CMD provides a momentum resolution of ~ 2.5% and a high angular accuracy enabling to determine the K^0_S momentum from the π^+ and π^- momenta. In addition, the measurement of a minimal angle Ψ between $\pi^{\pm}$ mesons, corresponding to the pion trajectory in the r.m.s. of K^0_S perpendicular to its momentum, provides an additional possibility to calculate the kaon mass from the formula

$$M_{K^0_S} = \left[E^2 \sin^2\frac{\Psi}{2} + 4\,m_\pi^2 \cos^2\frac{\Psi}{2}\right]^{1/2} \qquad (5)$$

From the total number of events (~ 250 000), 3713 useful events have been selected from which the mean mass value was obtained $M_{K^0_S} = (497.669 \pm 0.030)$ MeV.

The accuracy in the electron and positron energy maintenance during the data taking was not worse than ±10 keV. For the improvement temperature stability of a storage ring, the radiative polarization was performed at the operation energy $E = 509.32$ MeV. This became possible after eliminating the depolarizing effect of the machine spin resonances and an increase of the lifetime up to $\tau_p = 3$ h. Energy calibration resonance depolarization was performed using the normalization of intra–beam scattering to the non–polarized bunch of approximately the same intensity which was injected in the storage ring after the polarization of the first one achieved 50%. Such a normalization allows the exclusion of systematic errors in polarization measurements and thereby additionally improve the precession frequency measurements.

4. ω meson [5]

It is virtually impossible to obtain polarized beams at an energy near the ω resonance because of a large time of radiative polarization ($\tau_p \simeq 8$ h). Therefore, the polarization was performed at an energy of $E = 650$ MeV. Then, the energy lowered down to that of the ω meson with fast intersection of resonances $\nu = \nu_{x,z} - 2$ and adiabatic pass of the integer resonance $\nu = 1$. The resonance amplitude required for the adiabaticity condition was produced by the longitudinal magnetic field due to short–time reduction of the compensating solenoid current of the CMD.

From 4000 events of the reaction $e^+e^- \to \pi^+\pi^-\pi^0$ detected at 15 values of calibrated energy, the ω meson mass $M_\omega = (781.78 \pm 0.10)$ MeV and its width $\Gamma_\omega = (8.3 \pm 0.4)$ MeV have been determined.

5. Ψ and Ψ' mesons [6]

In the energy range of the Ψ family the time of radiative polarization at VEPP–4 ($\tau_p \simeq 100$ h) does not allow to achieve a considerable polarization degree. However, the booster storage ring VEPP–3 has the polarization time of $\simeq$40 min at the injection energy of 1.8 GeV that gives a possibility to inject into VEPP–4 the already polarized beam. Besides that, one can have at the same time the bunches of polarized and non–polarized particles. This circumstance facilitated substantially the observation of resonance depolarization using intra–beam scattering, the polarization contribution was ~ 3%. The depolarizer with a radial magnetic field which was produced by plates in the beam pipe of the storage ring VEPP–4, provided a depolarization time of the order of a second at the resonant frequency.

The cross section of the reaction $e^+e^- \to$ hadrons at the Ψ and Ψ' resonances was performed by using the "OLYA" detector during a scan of resonance regions with a step $\Delta(2E) = 0.5$ MeV. At the Ψ resonance seven scanning cycles were performed and five with Ψ' resonance. At the beginning and at the end of each cycle an energy calibration was performed. During the cycle special attention was paid to the stability of the rotation frequency, to the currents of the correction systems and to the guiding magnetic field, which varied strictly by the fixed cycle during the energy scanning and injection of the beams. Events with three and more charged particles coming from the collision point have been selected. The observed shape of the resonance is determined both by the beam energy spread and radiation corrections. The experimental cross section was approximated by the formula

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

$$G(W - W') = \frac{1}{\sqrt{2\pi}\,\sigma_W}\, e^{-\frac{(W - W')^2}{2\sigma_W^2}}, \tag{7}$$

σ_T is the production cross section taking into account radiative corrections in a double logarithmic approximation.

The resonance masses measured independently in each scanning cycle and averaged over all the cycles are given in fig. 2. Also given in the table are the world average values of the Ψ and Ψ' masses prior to this experiment. The final results of measurements are the following:

$$M_\Psi = 3096.93 \pm 0.09 \text{ MeV},$$
$$M_{\Psi'} = 3686.00 \pm 0.10 \text{ MeV}.$$

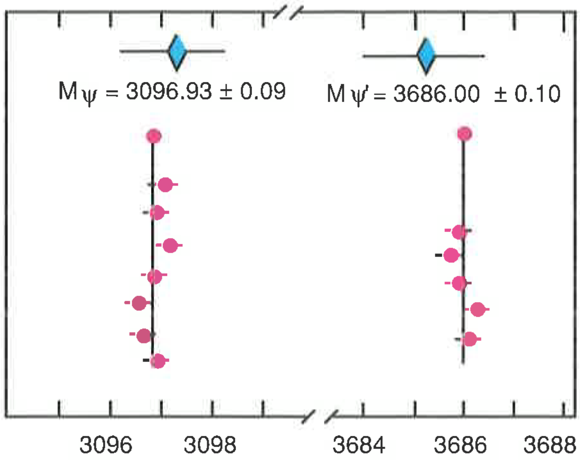

FIGURE 2

ψ and ψ' meson masses, measured in different cycles and their average values.

6. Υ, Υ' and Υ'' resonances [8–9]

Within the energy range of the Υ family, the time of radiative polarization is quite acceptable for obtaining polarized beams at VEPP–4 itself, if one removes the effect of spin resonances.

The mass measurements for the Υ family were performed with the MD–1 detector [19], which detected events of the reaction $e^+e^- \to$ hadrons during energy scanning with a step $\Delta(2E) = 1$ MeV. Similarly to the preceding high–precision experiments data taking was divided into cycles with an independent energy calibration in each cycle.

To check the uncertainties related to an angular deformation of cross section because of transverse polarization, the depolarizer with a broad band $\delta\omega_d$ in the resonance frequency region was continuously on in some cycles of data taking.

From the measurements of the cross section of the reaction $e^+e^- \to$ hadrons in the region of Υ resonance, the following value was obtained for the Υ meson mass: $M_{\Upsilon} = (9460.57 \pm 0.12)$ MeV, with an accuracy 80 times better than that of preceding measurements.

For the masses of the Υ' and Υ'' resonances one obtained respectively

$$M_{\Upsilon'} = (10\,023.6 \pm 0.5)\ \text{MeV},$$
$$M_{\Upsilon''} = (10\,355.3 \pm 0.5)\ \text{MeV}.$$

Table
Particle mass, MeV

Particle	World average value	Experimental results	Accuracy improvement
K^- K^+	493.657 ± 0.020 493.84 ± 0.13	493.670 ± 0.029	5
K^0	497.67 ± 0.13	497.669 ± 0.030	4
ω	782.4 ± 0.2	781.78 ± 0.10	2
ϕ	1019.70 ± 0.24	1019.52 ± 0.13	2.5
Ψ	3097.1 ± 0.9	3096.93 ± 0.09	10
Ψ'	3685.3 ± 1.2	3686.00 ± 0.10	10
Υ	9456.2 ± 9.5	9460.57 ± 0.12	80
Υ'	10 016.0 ± 10.0	10 023.6 ± 0.5	20
Υ''	10 347.0 ± 10.0	10 355.3 ± 0.5	2

Conclusion

The accuracy of mass measurement can further be improved. But even the accuracy already achieved provides the kind of metrological standard allowing the improvement in the mass value measurements for many well-known particles and resonances.

After the experiments at VEPP-4 a similar technique has been used to measure the Υ'' (CESR Storage Ring, Cornell, USA) [20] and the Υ'' (DORIS Storage Ring, Hamburg, FRG) [21], masses consistent with our results.

At the present time, an experiment of M_Z^0 measurement is under preparation at the CERN LEP e^+e^- Collider using the same technique.

The cycle of experiments described here is the result of the work of the large team of INP staff who participated in the development and running of the accelerator and detector facilities of VEPP-2 and VEPP-4.

References

[1] L.M. Kurdadze et al., Proc. of the Vth Intern. Symp. on High-energy Physics, Warsaw (1975) 148.
[2] Ya. S. Derbenev et al., Particle Accel. 10 (1980) 177.
[3] L.M. Barkov et al., Nucl. Phys. B148 (1979) 53.
[4] L.M. Barkov et al., Sov. Journal of Nucl. Phys. 34 (1981) 814.
[5] L.M. Barkov et al., JETP Letters 46 (1987) 164.
[6] A.A. Zholents et al., YaF 34 (1981) 1471.
[7] A.S. Artamonov et al., Phys. Lett. B118 (1982) 225.
[8] A.S. Artamonov et al., Phys. Lett. B137 (1984) 272.
[9] A.E. Blinov et al., VIIIth All-Union Meeting on Accelerators, Protvino (1982).
[10] A.P. Lysenko et al., Particle Accel. 18 (1986) 435.
[11] Reviews of Particle Properties (1986).
[12] G.M. Tumaikin et al., XIIth Int. Conf. on Accel. (1983).
[13] A.A. Sokolov and I.M. Ternov, Sov. Phys. Doklaky 8 (1964) 1203.
[14] S.I. Serednyakov et al., Sov. Phys. JETP 44 (1976) 1063.
[15] I.B. Vasserman et al., Phys. Lett. B198 (1987) 302.
[16] B.A. Baklakov et al., Proc. VIIth All-Union Meeting on Accel., Vol. 1 (1980) 338.
[17] V.M. Aulchenko et al., Reprint INP 75-65, Novosibirsk (1975).
[18] L.M. Barkov et al., Nucl. Instr. and Meth. 204 (1983) 379.
[19] S.E. Baru et al., Reprint INP 77-75 Novosibirsk (1977).
[20] W.W. Mackay et al., Phys. Rev. D29 (1984) 2483.
[21] D.P. Barber et al., Phys. Rev. Lett. B135 (1984) 498.

Address:

Yu.M. Shatunov and A.N. Skrinsky
Institute of Nuclear Physics, Novosibirsk, USSR

Received and reviewed by U. Amaldi, 20 May 1989.