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ABSOLUTE CALIBRATION OF BEAM ENERGY IN THE STORAGE RING Φ - MESON MASS MEASUREMENT

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ABSTRACT

A method is described allowing determination of the particle energy in an electron-positron storage ring by measuring the frequency of particle spin precession with the help of resonance beam depolarization by a high-frequency field. The problem of the accuracy in the measurements of the average energy of beam particles is discussed. It is shown that in practical cases the accuracy is restricted primarily by irregular pulsations of the guiding magnetic field.

The method developed has been used for more accurate determination of the Φ-meson mass. The energy scale was calibrated with the accuracy $\pm 1 \cdot 10^{-4}$. The following value of the Φ -meson mass has been obtained $m_{\Phi} = 1019.4 \pm 0.3$ Mev.

Studies of vector mesons in the experiments with the electron-positron colliding beams exhibited the advantages of the new technique of investigation, one of them being high energy resolution. It is restricted by a natural energy width of the beam which is about 10^{-3} near Φ-meson. Methods of absolute calibration of the particle energy in the storage ring used up to now (measurement of magnetic field distribution, measurement of phase oscillations frequency etc.) provided an accuracy slightly better than 10^{-2} whereas the accuracy 10^{-4} by an order of magnitude better than the energy spread was of practical interest.

Besides that the energy spread contribution to the indeterminacy in the reation energy can be considerably decreased by energy decomposition of particle beams in the interaction region. Energy decomposition must be sufficiently strong to eliminate the "intermixing" of particles due to betatron (transverse) oscillations. If the direction of decomposition coincides for both particles (more energetic electrons collide with more energetic positrons) to determine the reaction energy one must know with high accuracy the coordinates of the collision point in the decomposition direction. If these directions are opposite for electrons and positrons the collision energy will be the same through the whole section of colliding beams (the accuracy is restricted by betatron intermixing and corrections of the order of $\left(\frac{\Delta E}{E}\right)^2$.

This proposal arises the question of absolute calibration of the particle beam energy in the storage ring with an accuracy considerably better than 10^{-4}. Discovery of new sharp resonances (Gypsy-mesons) increased the urgency of these problems.

In this work a new method is proposed allowing determination of the absolute value of the average energy of an electron (positron) beam in the storage ring by measuring frequency of particle spin precession. The accuracy of the method is not connected with the energy spread of beam particles and attained the value 10^{-4} in the first experiments.

1. Estimate of the method accuracy

In the plane orbit approximation the angular frequency of spin rotation around the direction of the guiding magnetic field H_z can be written after averaging over fast betatron oscillations as /1/

$$\Omega = \omega\left(1+\gamma\frac{q'}{q_0}\right) = \frac{e\bar{H}_z}{\gamma mc}\left(1+\gamma\frac{q'}{q_0}\right) \qquad (1)$$

where ω - revolution frequency, γ - relativistic factor, q', q_0 - anomalous and normal parts of the magnetic moment q. Synchrotron oscillations of the particle energy near the average value γ_0 with the frequency ω_γ lead to modulation of the spin precession frequency

$$\Omega = \Omega_0 + \Delta\cos\omega_\gamma t \qquad (2)$$

where $\Omega_0 = \omega_s\left(1+\gamma_0\frac{q'}{q_0}\right)$, ω_s - frequency of the accelerating voltage, $\Delta = q'\sigma_\gamma/q_0$, σ_γ - the rms energy deviation. In the presence of modulation the frequency spectrum of spin motion has a central frequency Ω_0 and side frequencies $\Omega_0 \pm n\omega_\gamma$ (n - integer) /2/. In the ideal case of the stable magnetic field the width of central line depends on the spread of average energies γ_0 near the equilibrium value γ_s.

The value of the latter spread $\gamma_0 - \gamma_s$ due to dependence H_z upon the squared amplitudes of radial betatron and phase oscillations is much less than the energy spread $\sigma_\gamma \simeq \gamma_0 \times 10^{-3}$. The linewidth δ corresponding to the spread γ_0 is determined predominantly by the quadratic non-linearity of the guiding magnetic field so that

$$\delta \sim \frac{\partial^2 H_z}{\partial x^2}\cdot\frac{\overline{x^2}}{\bar{H}_z}\,\omega_s\gamma_s\frac{q'}{q_0} \qquad (3)$$

where $\overline{x^2}$ - the radial size squared.

Estimate for VEPP-2M gives $\delta \sim (10^{-5} - 10^{-6})$ and can be in principle decreased due to compensation $\frac{\partial^2 H_z}{\partial x^2}$. At such a small value the width of the basic line will be completely determined by slow irregular pulsations of the magnetic field in our case being $\sim 10^{-4}$.

2. Measurement of precession frequency

To measure the frequency of spin precession one can use the method of resonance beam depolarization by highfrequency electromagnetic field /3/. In this work the longitudinal field H_v has been used with a frequency

$$\omega_d = \omega_s \left(2 - \gamma_s \frac{q'}{q_0}\right) \tag{4}$$

For fast search of a resonance the frequency modulated depolarizing field is convenient:

$$\omega_d = \overline{\omega_d} + \Delta\omega_d \cos \Omega_d t \tag{5}$$

The depolarization time at the basic resonance is

$$\tau = \frac{\Delta\omega_d}{W_0^2} \tag{6}$$

where $W_0 = \frac{H_v \ell}{H_z 2L}$ - frequency of precession around the direction H_z;
ℓ/L - effective relative length of the longitudinal field.

The power of side resonances decreases sharply with an increase of their number. It can be shown that

$$(\tau_d)_n \approx (\tau_d)_0 \frac{n!\, 4^n}{\left(\frac{\Delta}{\omega_\gamma}\right)^{2n}} \tag{7}$$

Under these conditions the central line can be easily separated measuring the depolarization time. In the experiment the depolarization was observed by measuring the counting rate of electrons lost from the beam owing to Touschek effect /3/. Measurements were performed as follows: the electron beam after the polarization at the high energy was shifted to the energy of the experiment, the counting rate N normalized to the electron current squared was measured, then a depolarizer was switched on at the given frequency and the relative variation of the counting rate $\Delta N/N$ was measured characterizing the polarization degree.

Results of the depolarization time measurements are presented in Fig.1 showing that the qualitative picture of resonances is close to the expected one. The depolarization time at the side resonance is slightly greater than that in (7), this fact presumably due to the width of a side line which is determined by the spread of phase oscillation frequencies $\Delta\omega_\gamma$ connected with the relatively high non-linearity of phase motion. No depolarization was observed between the resonances. The width of a depolarizer band in these measurements was about 30 kHz. Further the band was decreased to 2 kHz. Depolarization at the central resonance allowed determination of the average particle energy with the accuracy $\Delta E/E \simeq \pm 10^{-4}$ (Fig.2), by an order of magnitude smaller than the energy spread.

3. Φ-meson mass measurement

Measurement of the Φ-meson mass was the first application of the new method of beam energy calibration. With this aim 3 cycles of measurements using the "OLYA" detector /4/ were performed to obtain the Φ-meson excitation curve in the reaction $e^+e^- \to \varphi \to K_L K_S \to 2\pi$

The "Olya" detector consists of 16 coordinate wire spark chambers with core memory ($\simeq$ 10.000 ferrites), 16 triggering scintillation counters and 16 scintillation counters composing 8 sandwiches for particle identification. To suppress the background due to cosmic particles the time-of-flight circuit has been used as well as the circuit synchronizing the detector triggering with the phase of particle revolution in the storage ring. The total solid angle covered by the detector is $0.65 \times 4\pi$ steradian.

Before the beginning of the experiment an absolute calibration of the storage ring energy scale was performed by the

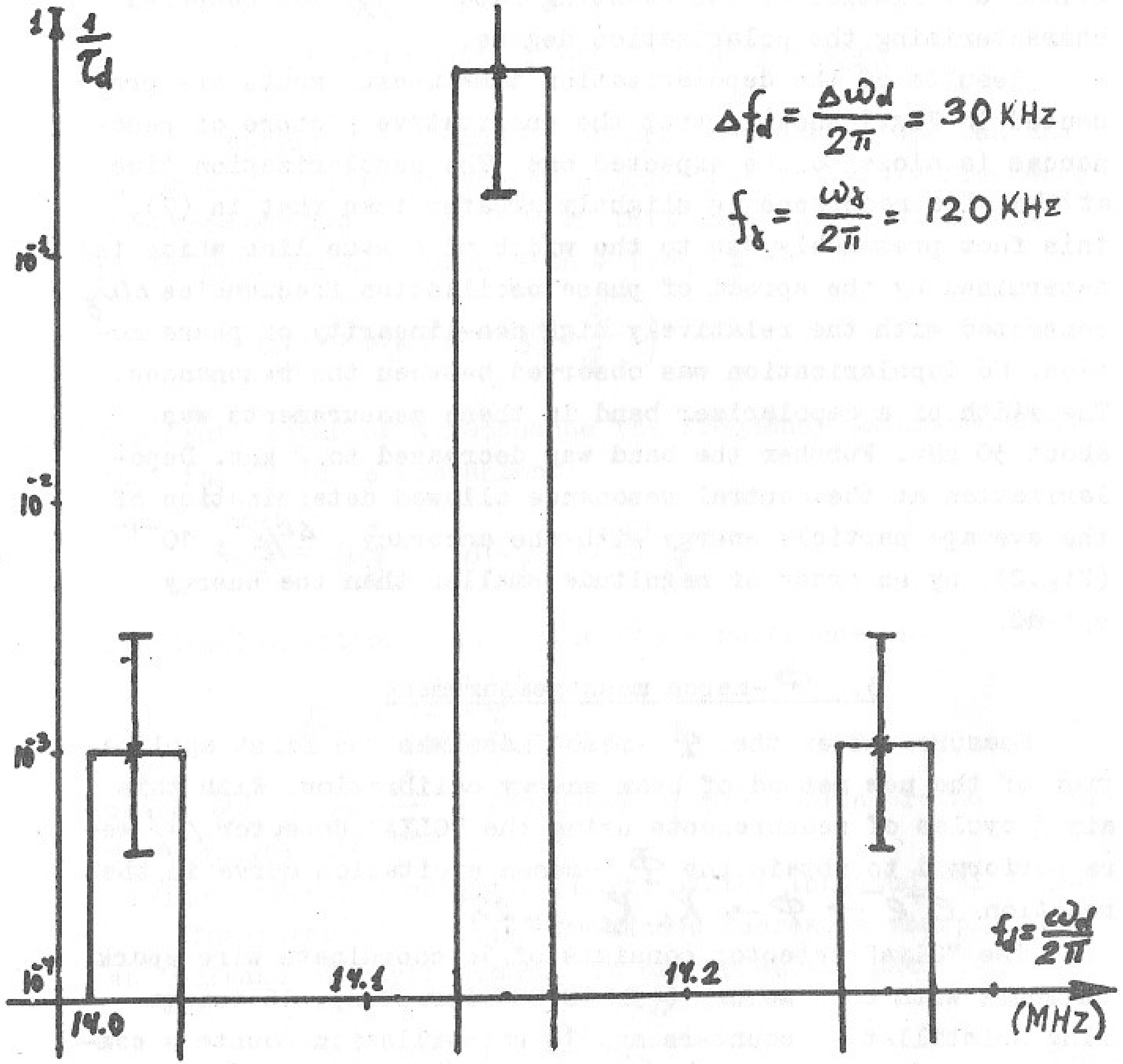

Fig.1 Dependence of inverse depolarization time upon the frequency of an external depolarizer

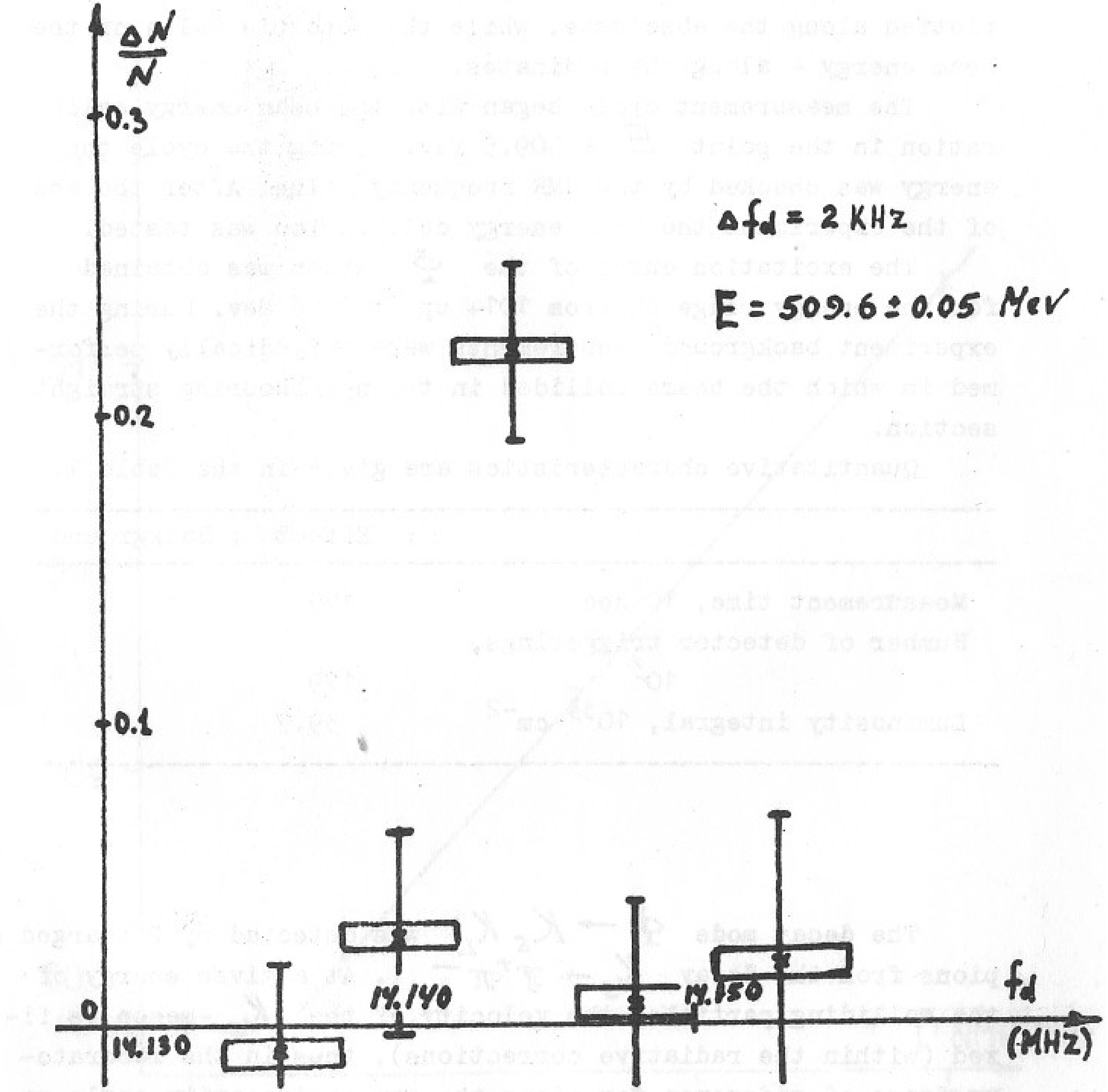

Fig.2 Jump of counting rate versus depolarizer frequency

resonance depolarization method. Fig.3 shows the calibration straight line. Nuclear magnetic resonance (NMR) frequency is plotted along the abscissae, while the absolute value of the beam energy - along the ordinates.

The measurement cycle began with the beam energy calibration in the point E = 509.5 Mev. During the cycle the energy was checked by the NMR frequency value. After the end of the experiment the beam energy calibration was tested.

The excitation curve of the Φ -meson was obtained for the energy range 2E from 1014 up to 1026 Mev. During the experiment background measurements were periodically performed in which the beams collided in the neighbouring straight section.

Quantitative characteristics are given in the Table 1.

	Effect	Background
Measurement time, 10^3 sec	179	
Number of detector triggerings, 10^3	179	
Luminosity integral, 10^{33} cm^{-2}	39.7	

The decay mode $\Phi \to K_S K_L$ was detected by 2 charged pions from the decay $K_S \to \pi^+\pi^-$. At a given energy of the colliding particles the velocity of the K_S -meson is fixed (within the radiative corrections), thus in the laboratory frame of reference for pions the non-collinearity angle varies from 0° up to ω_{max}. In Fig.4 the ω- distribution of non-collinear events is presented. The vertical line corresponds to the boundary of Φ -meson decay modes separation. The boundary angle ω = 36° is equal to the limiting non-collinearity angle at the energy 2E = 1026 Mev. Events with the non-collinearity angle $\omega > 36°$ were due to the mode $e^+e^- \to \pi^+\pi^-\pi^0$

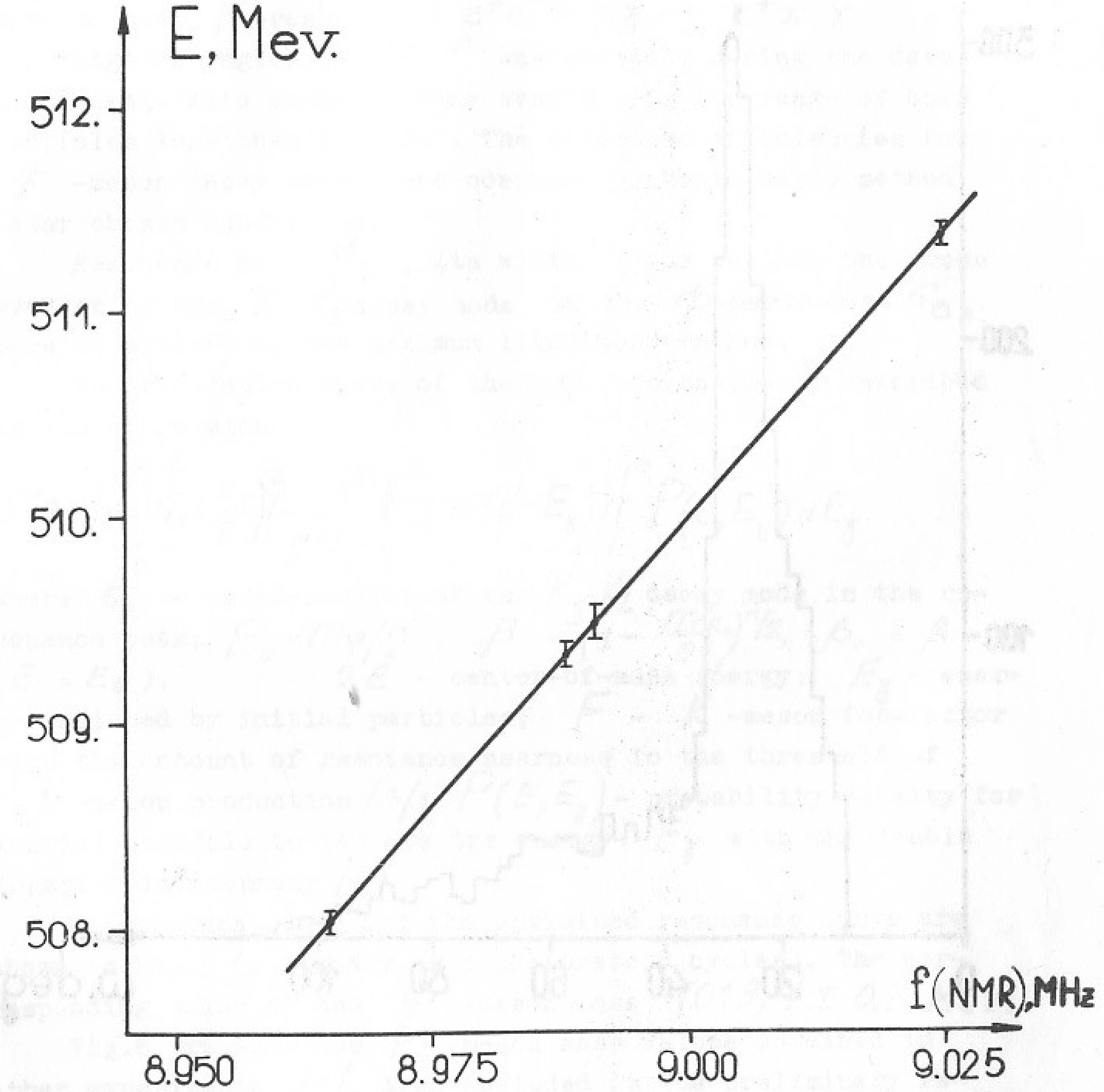

Fig.3 Energy value measured by resonance depolarization versus NMR frequency

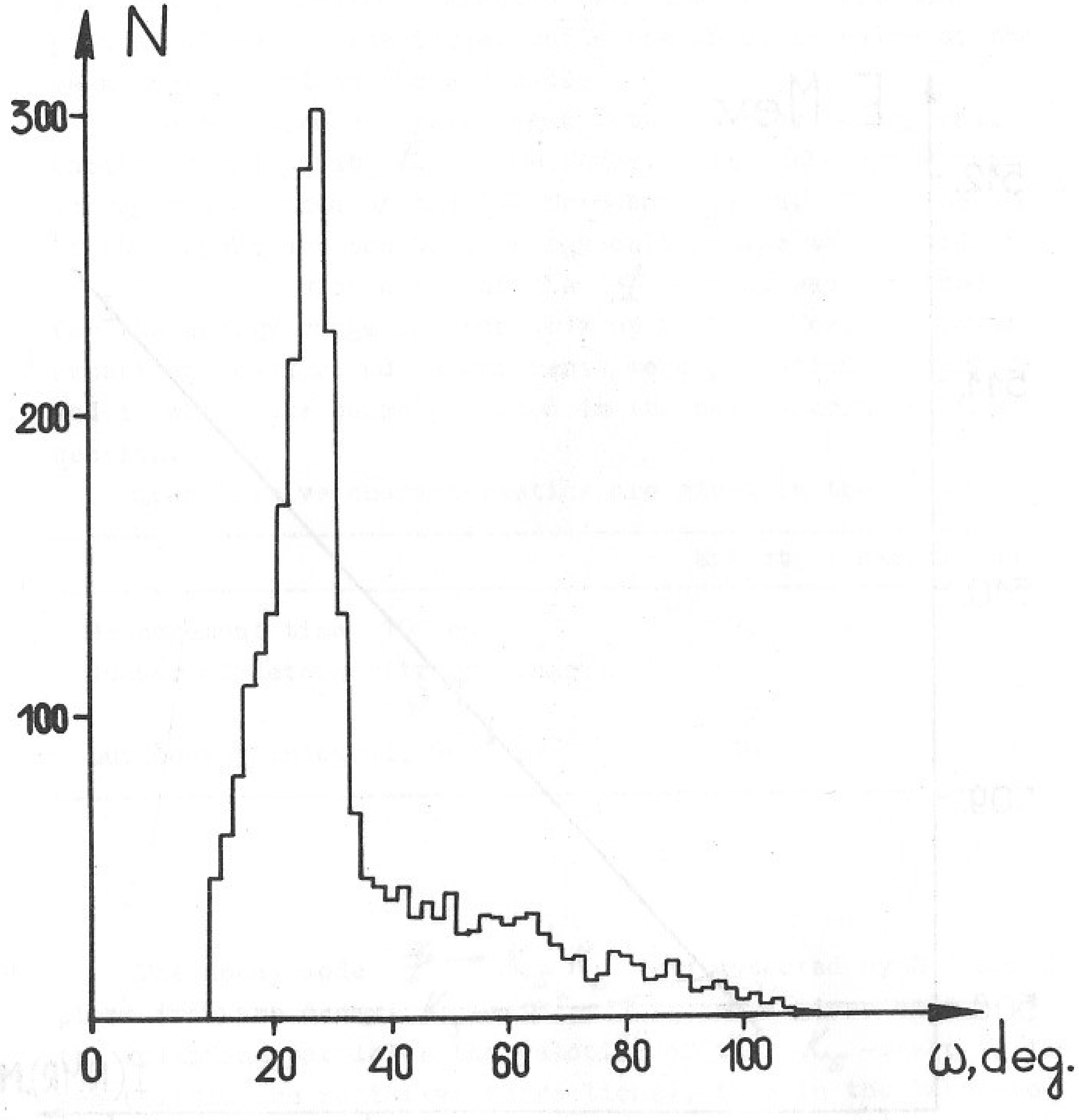

Fig.4 ω distribution for non-collinear events

To reduce the contribution of background processes - double electroproduction ($e^+e^- \to e^+e^-e^+e^-$) and return to the ρ -resonance ($e^+e^- \to \rho\gamma \to \pi^+\pi^-\gamma$) the range of angles $|\Delta\varphi| < 5^\circ$ was excluded during the data processing. Also excluded were events with the range of both particles less than 23 g/cm^2. The detection efficiencies for Φ -meson decay modes were computed by Monte Carlo method under chosen conditions.

Resonance mass M_ϕ , its width as well as the cross section of the $K_S K_L$ decay mode in the Φ-meson peak σ_0, were determined by the maximum likelihood method.

The excitation curve of the Φ -resonance is described by the expression

$$\sigma(2E) = \int_0^E \sigma_0 \left(\frac{E_0}{E}\right)^2 \left(\frac{\beta}{\beta_0}\right)^3 \left|F\left(4E(E-E_\gamma)\right)\right|^2 P(E,E_\gamma)\, dE_\gamma$$

where σ_0 - cross-section of the $K_S K_L$ decay mode in the resonance peak; $E_0 = m_\varphi/2$, $\beta = \left(1 - \frac{m^2_{K_0}}{E^2}\right)^{1/2}$, $\beta_0 = \beta$ $(E = E_0)$, $2E$ - center-of-mass energy; E_γ - energy radiated by initial particles; F - K -meson formfactor with the account of resonance nearness to the threshold of K -meson production /5/; $P(E,E_\gamma)$- probability density for initial particle to radiate the energy E_γ with the double logarithmic accuracy /6/.

Experimental data and the optimized resonance curve are shown in Fig.5 (a summary of 3 measurement cycles). The corresponding value of the Φ -meson mass 1019,4 ± 0.3 MeV.

Fig.6 presents the Φ -meson mass values obtained in other experiments /7/. Also included is the preliminary result obtained in VEPP-2M by the group of Professor L.M.Barkov using nuclear emulsions: M_Φ = 1019.4 ± 0.4 Mev.

The authors are grateful to M.N.Egorichev for design of the depolarizer and to the whole staff of VEPP-2M participated in the experiment.

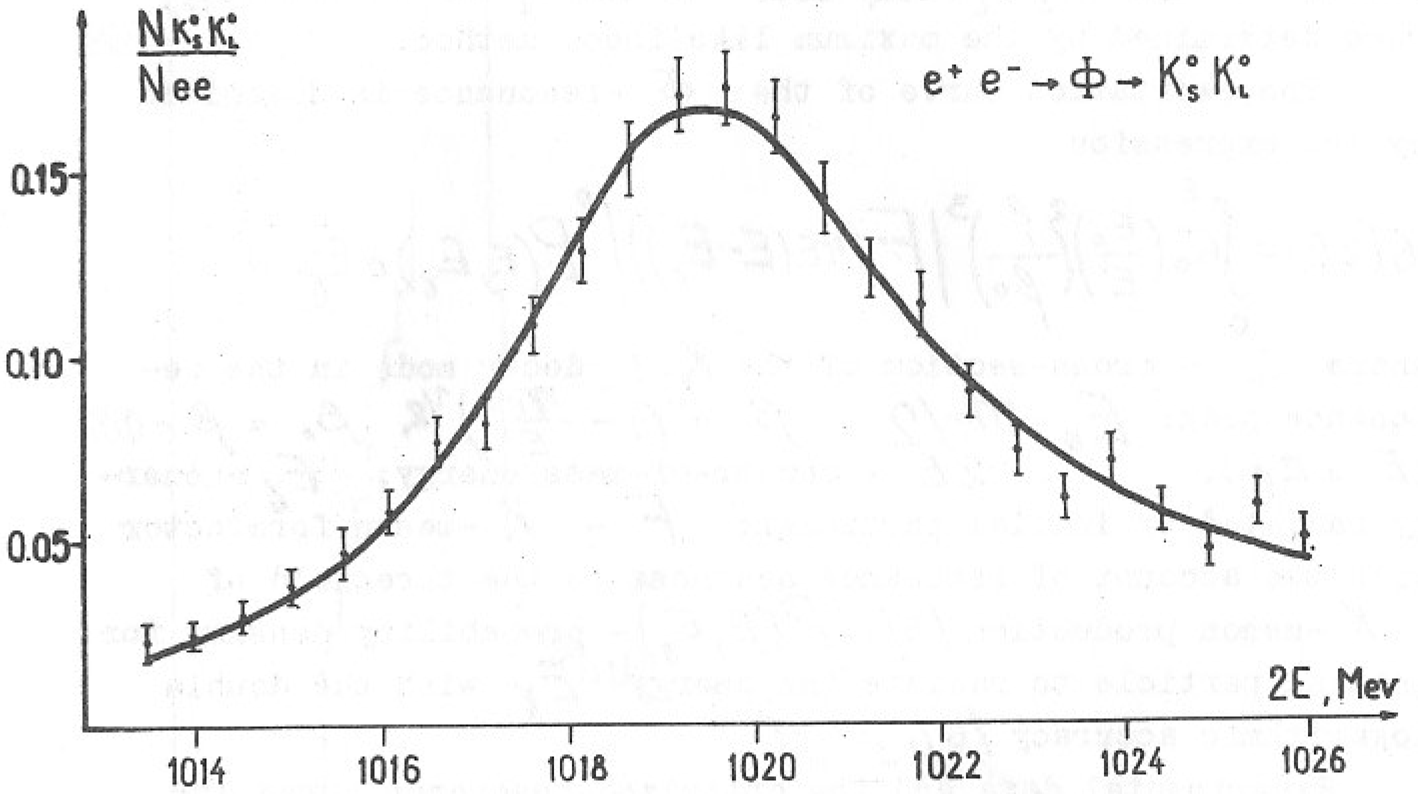

Fig.5 Excitation curve for the mode $\Phi \to K_S^0 K_L^0$

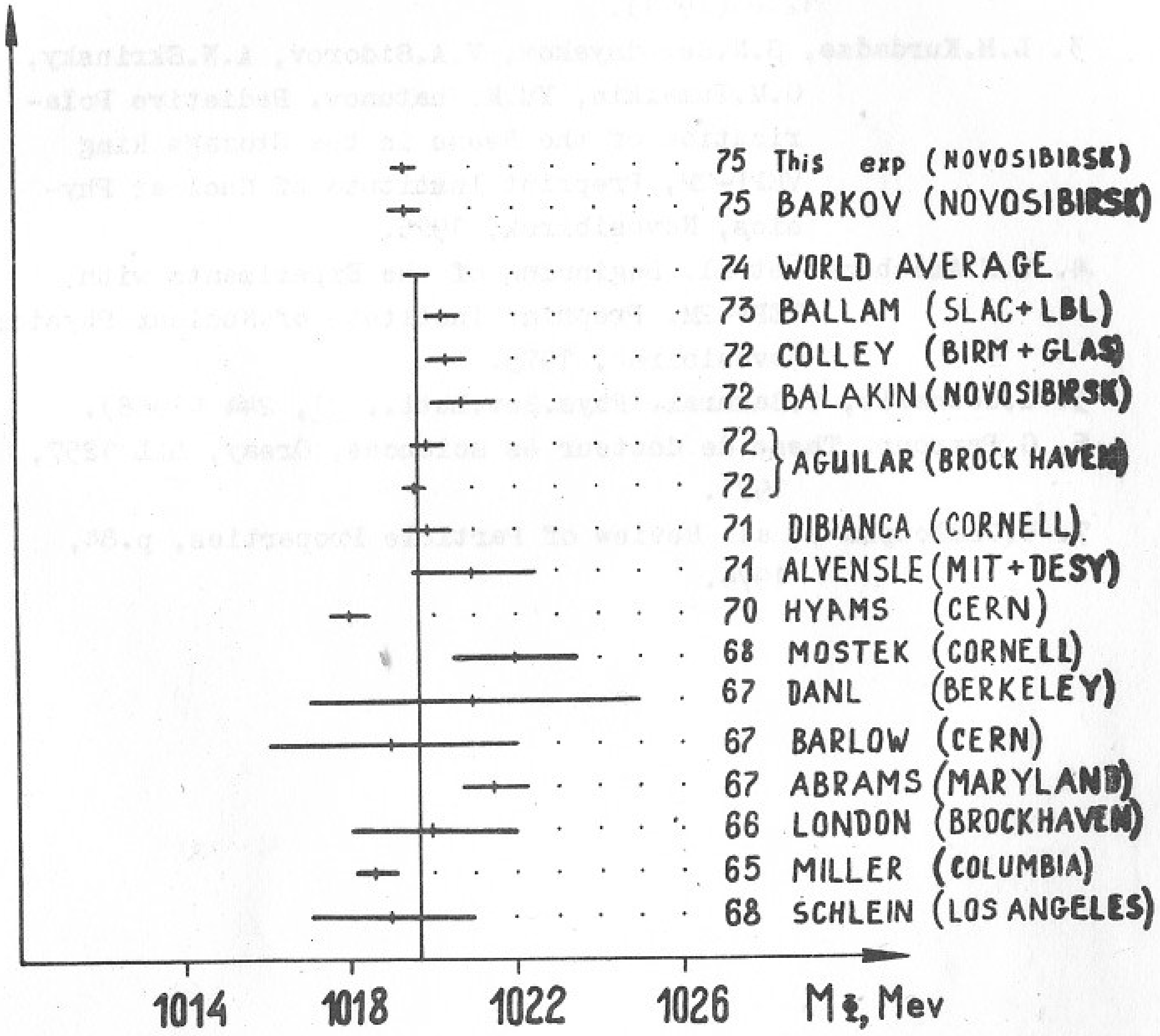

Fig.6 Experimental data on the Φ -meson mass

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