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ИНСТИТУТ
ЯДЕРНОЙ ФИЗИКИ СОАН СССР

ПРЕПРИНТ И Я Ф 77 - 97

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ϕ- MESON : HIGH ACCURACY MASS MEASUREMENT, OBSERVATION OF $\omega - \phi$ INTERFERENCE

Новосибирск
1977

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ABSTRACT

Φ - resonance excitation curves have been measured in the reactions $e^+e^- \to K^0_S K^0_L$ and $e^+e^- \to \pi^+\pi^-\pi^0$ using the electron positron storage ring VEPP-2M. The integrated luminosity in the experiment was 42.4 nb^{-1} Absolute calibration of the beam energy in the storage ring was performed in the experiment with an accuracy 10^{-4}. The following values of the resonance parameters have been obtained:

$$m_\Phi = (1019.52 \pm 0.13)\,\mathrm{MeV} \qquad \Gamma_\Phi = (4.36 \pm 0.19)\,\mathrm{MeV}$$

$$\sigma(K_SK_L) = (1.40 \pm 0.09)\,\mu b \qquad \sigma(3\pi) = (0.79 \pm 0.09)\,\mu b$$

By the shift of the resonance peak in the channel $\Phi - 3\pi$ a relative phase of $\omega - \Phi$ interference has been determined, sensitive to a model of SU(3) symmetry violation. Experimental data give evidence for the "mass mixing" model.

1. INTRODUCTION

Φ - meson resonance was already investigated with the electron-positron colliding beams [1-3] . New study was stimulated by new possibilities offered by VEPP-2M [4] . Large luminosity of the storage ring (up to 10^{30} $cm^{-2}sec^{-1}$) allows measurements with high statistical accuracy whereas a convenient interaction region - to use a detection system (the "OLYA" detector) with large solid angle.

This work presents the results of the resonance curve measurement by two channels of e^+e^- annihilation:

$$e^+e^- - \Phi - \pi^+\pi^-\pi^0$$

$$e^+e^- - \Phi - \underset{\hookrightarrow \pi^+\pi^-}{K_S^0 K_L^0}$$

The main goal of the experiment was high accuracy Φ - meson mass measurement as well as determination of a relative sign of ω and Φ - resonance amplitudes in the 3π channel. Preliminary results of this experiment have been published in [5, 6].

High accuracy measurement of the Φ - meson mass became possible after development of the method allowing absolute calibration of the beam energy in storage rings [5,7] . The method is based on the measurement of a spin precession frequency of beam particles circulating in the storage ring. The ratio of the spin precession frequency Ω and a storage ring revolution frequency ω_s is dependent only on the particle energy and the relative value of its anomalous magnetic moment:

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

Spin precession frequency is determined by resonance depolarization of the beam polarized in the storage ring resulting in a well detected jump of the counting rate of the particles leaving the beam due to Touschek effect (elastic scattering inside a bunch). Resonance influence upon the beam can be made sufficiently small providing slow depolarization and averaging of the particle energy over a period of synchrotron oscillations.

This circumstance allows calibration of the storage ring energy scale with an accuracy much better than an energy spread of beam particles.

Two resonance with the common decay mode $\omega, \Phi \to 3\pi$ must interfere, the relative sign of their amplitudes being sensitive to a model of SU(3) symmetry violation [8] . The "mass mixing" model (an opposite sign) predicts a small shift of the resonance peak to the left while the "current mixing" model - to the right. Measurement of the resonance curve by two decay modes allows to determine the shift of the resonance curve in the $\Phi \to 3\pi$ channel with respect to the peak in the $\Phi \to K_S^0 K_L^0$ channel whose position does not change.

2. "OLYA" Detector

Fig. 1 shows the lay-out of the "OLYA" detector. It contains 32 scintillation counters (40 photomultipliers) and 16 coordinate wire spark chambers (10.000 wires) and consists of four identical quadrants covering a solid angle of 0.64 x 4π steradian.

Each quadrant of coordinate spark chambers consists of four two-coordinate wire chambers with core memory, the chambers being used for determination of an interaction point and particle angles.

The detector is triggered by coincidence of scintillation counters C1, C2, C3-1 and C3-2, the energy threshold for pions and charged Kaons being 45 MeV and 65 MeV respectively. Triggering requires at least two charged particles in different quadrants.

The counters C4, C5, C6 and C7 form a scintillation sandwich, each its plate being viewed by a separate photomultiplier. During data processing information about pulse heights in each plate is used to separate electrons and mesons.

For suppression of cosmic background time-of-flight between the C3 counters of opposite quadrants is measured [9] .

For events of effect (particles coming from the beam) it must equal zero, while for cosmic particles - 2 nsec. Time resolution (FWHM) of the system measuring time-of-flight is 0.7 nsec. Additional suppression of cosmic particles by a factor of 7 is due to synchronization of detector triggering with the moment of beam collision.

The apparatus described constitutes the first part of the detector "OLYA", the second one will have in addition shower and range chambers (6.000 wires more).

Luminosity monitoring is performed by detecting double Bremsstrahlung by two total absorption NaJ(Tl) counters located at the opposite sides of the interaction region along the beam direction.

Control of the "OLYA" operation mode, data acquisition, tests and primary data processing are performed by a minicomputer "M-6000" connected with a computer "Minsk-32" through the system "RADIUS" [10], information is recorded on magnetic tapes of "Minsk-32" which is also used for subsequent data processing.

3. Experiment

All experimental information has been accumulated during three cycles of scanning the energy range $2E$ from 10135 to 1026.0MeV with step $\Delta(2E) = 0.5$MeV. Before the experiment absolute calibration of the storage ring energy scale was done. The calibration straight line is shown in Fig. 2 where an absolute value of the beam energy measured by resonance depolarization is plotted versus nuclear magnetic resonance (NMR) frequency.

A measurement cycle began with an energy calibration at E = 509.6MeV. During the cycle the measured energy was tested by NMR frequency. After experiment energy calibration was repeated. The total accuracy of energy calibration was

$$\Delta(2E)/2E = 1.0 \times 10^{-4}$$

Measurements were performed at the following parameters of the storage ring: electron current ~ 10mA, positron current ~ 10 mA, luminosity - $(1 \div 5) \times 10^{29}$ cm^{-2}sec^{-1}, beam lifetime about 30 minutes. Beams stored in the booster ring VEPP-2 were injected into VEPP-2M each 15 minutes at the energy of the experiment allowing practically continuous measurements. The average counting rate of "OLYA" was 1 Hz, 0.3 Hz being due to effect events ($e^+e^- \to e^+e^-$, K_sK_L, 3π etc.). $185 \cdot 10^3$ triggerings of the detector were recorded during the time $T = 184 \cdot 10^3$sec, the integrated luminosity being 42.4 nb^{-1}.

4. Data processing

The Φ-meson decay modes under investigation were detected by two charged pions. Events were selected having two tracks in coordinate chambers which coming from point (intersecting within 10 mm).

Separation of different modes was made using a spacial acollinearity angle ω. At the given energy of colliding beams a velocity of produced K^0 - mesons is fixed (within the radiative corrections), thus in the laboratory frame a spacial collinearity angle for pions from K_s^0 - decay varies from 0 up to ω_{max}. For a detection efficiency of pions to be independent of the energy the restriction $\omega < 36^\circ$ has been imposed, this limit being higher than the maximum angle in the whole energy range. Events with $\omega > 36^\circ$ were ascribed to the mode $e^+e^- \to \pi^+\pi^-\pi^0$ The distance from the beam axis to the intersection point of two tracks was required to be less than 30 mm for $K_s \to \pi^+\pi^-$ events (about 5 decay lengths) and 10 mm for 3π events. To eliminate the collinear events corresponding to the reactions $e^+e^- \to e^+e^-$, $\mu^+\mu^-$, $\pi^+\pi^-$ the restriction $\omega > 15^\circ$ was held. Under these conditions the main background is due to the process of electron-positron pair electroproduction $e^+e^- \to e^+e^- + e^+e^-$, characteristic of the low kinetic energy of the particles entering the detector as well as the coplanarity of a produced pair with the beam axis. Therefore events with a range of both particles less than 23g/cm^2 and

those with an acoplanarity angle $|\Delta\varphi| < 10^\circ$ have been rejected.

Fig.3 presents a histogram for the ω distribution of events selected. Vertical dashed lines correspond to the separation boundaries for collinear pairs, events of $K_s^0 \to 2\pi$ and 3π. The total number of experimental events selected under these criteria was $N(K_s^0) = 2732$ and $N(3\pi) = 949$. The energy distribution of the events is given in Table 1.

The detection efficiencies calculated by the Monte-Carlo method with the account of ionization losses, multiple scattering and nuclear absorption appear to be the following:

$$\varepsilon(K_s^0) = (11.3 \pm 0.5)\% \quad and \quad \varepsilon(3\pi) = (6.4 \pm 0.6)\%$$

The luminosity was determined by elastic electron-positron scattering at large angles. Events of this process must satisfy the following criteria: large pulse height in sandwiches, acollinearity angle $|\Delta\theta| < 5^\circ$, acoplanarity angle $|\Delta\varphi| < 3^\circ$. The cross-section of elastic scattering detection with a radiative correction equal to - 9.1% was

$$\sigma(ee) = (527 \pm 6)\text{nb}$$

22344 events of elastic scattering have been detected, their energy distribution and the corresponding integrated luminosities being shown in Table 1.

5. Optimization of Φ - meson parameters

To determine Φ-meson parameters the joint data processing of two modes $\Phi \to K_s^0K_L^0$ and $\Phi \to 3\pi$ was performed using maximum likelihood method. The cross-section was written as

$$\sigma_j(E) = \sigma_j^{(\omega)}[1 + \delta_j(E)][1 + P_j(E)]$$

where j = 1 or 2 - decay mode number (K_sK_L or 3π), $\delta_j(E)$ - - radiative correction; $P_j(E)$ - correction for the energy spread of beam particles, $\sigma_j^{(\omega)}$ - resonant cross-section. For the K_sK_L mode

$$\sigma_1^{(\omega)}(E) = \sigma_1^{(\omega)}|F_\Phi|^2\left(\frac{E_0}{E}\right)V_K$$

while for 3π mode taking into account the interference

$$\sigma_2^{(1)}(E) = \left|\sqrt{\sigma_\Phi^{(0)}}\,F_\Phi + \sqrt{\sigma_\omega^{(0)}}\,F_\omega \cdot e^{i\alpha}\right|^2 \left(\frac{E_0}{E}\right) V_{3\pi}$$

Here $E_0 = m_\Phi/2$, $\sigma_j^{(0)}$ - cross-section in the resonance peak, V_K - Kaon phase space, $V_{3\pi}$ - phase space for a decay $\Phi \to \rho\pi \to \pi^+\pi^-\pi^0$; α - relative phase of ω and Φ amplitudes, F_ω, F_Φ - resonance formfactors written with the account of a close threshold of produced particles and normalized to unity at the peak [11] .

The radiative corrections were calculated by the formula

$$\delta_j(E) = [\sigma_j^{(1)}(E)]^{-1} \cdot \int_0^E \sigma_j^{(1)}\left(\sqrt{E(E-E_\gamma)}\right) \cdot P(E,E_\gamma)\, dE_\gamma - 1$$

where $P(E,E_\gamma)$ - probability density of radiative losses written with double logarithmic accuracy [12] :

$$P(E,E_\gamma) = A\left(\frac{E_\gamma}{E}\right)^\beta \left(1 - \frac{E_\gamma}{E} + \frac{1}{2}\left(\frac{E_\gamma}{E}\right)^2\right)\frac{1}{E_\gamma}\,; \quad A = \beta\,\frac{(1+\beta)(1+\frac{\beta}{2})}{1+\frac{3}{4}\beta+\frac{1}{4}\beta^2}\,; \quad \beta = \frac{4\alpha}{\pi}\left(\ln\frac{2E}{m_e} - \frac{1}{2}\right)$$

Fig.4 shows the energy dependence of the radiative corrections δ_j calculated at the optimal values of resonance parameters.

The center-of-mass energy (2E) of the colliding beams has a Gaussian distribution with a rms spread Δ . At 2E = m_Φ Δ = 0.26 MeV and exhibits weak energy dependence. The correction for this energy spread was calculated as follows:

$$\rho_j(E) = [\sigma_j^{(2)}(E)]^{-1} \cdot \int_{-\infty}^{\infty} \sigma_j^{(2)}\left(E + \frac{t}{2}\right) \frac{1}{\sqrt{2\pi}\,\Delta}\, e^{-\frac{t^2}{2\Delta^2}}\, dt - 1$$

where

$$\sigma_j^{(2)}(E) = \sigma_j^{(1)}(E)\left[1 + \delta_j(E)\right]$$

The calculated values for corrections ρ_1 and ρ_2 are practically equal, thus we assumed $\rho_1 = \rho_2 = \rho$. Energy dependence of this correction is shown in Fig.5 at optimal values of resonance parameters.

The detection cross-section can be expressed through the cross-section $\sigma_j(E)$ and detection efficiency ε_{ij} :

$$\sigma_i^{det} = \sum_j \varepsilon_{ij}\, \sigma_j^{(2)}(E)$$

The value ε_{12} = (2.0 ± 0.3)% corresponds to the detection efficiency of 3π in a region of K_S^0 - events selection, while ε_{21} = (0.07 ± 0.04)% is the detection efficiency of K_S^0 in a region of 3π events. ε_{21} is negligibly small and was assumed to be zero. Detection efficiencies ε_{ij} were calculated as mentioned above by the Monte-Carlo method.

The expected number of events $\bar{n}_{ik}$ at the K-th energy is

$$\bar{n}_{ik} = L_k \sigma_i^{exp}(E_k) + L_k \sigma_i^{\Phi}$$

where L_k = luminosity, $L_k\sigma_i^{\Phi}$ - contribution of non-resonant background processes.

The likelihood function has the form

$$\mathcal{L} = -\ln W = \sum_{i,k}\left[\bar{n}_{ik} - n_{ik} + n_{ik}\ln\frac{n_{ik}}{\bar{n}_{ik}}\right]$$

where n_{ik} - number of events detected at the K-th energy:

$n_{1k} = N(K_S^0)$, $n_{2k} = N(3\pi)$ see Table 1.

6. Results of the experiment

The likelihood function was optimized by the following parameters: m_Φ , Γ_Φ , $\sigma_{K_SK_L}^{(0)}$ and $\sigma_{3\pi}^{(0)}$ - cross-sections in the peak, σ_i^{Φ} - level of non-resonant background and α - relative phase of $\omega - \Phi$ interference.

The level of non-resonant background σ_i^{Φ} was determined by processing the data taken in the experiment of 1975 [6] in the energy range 2E from 980 to 1000 MeV. The luminosity integral in this energy range was 8 nb^{-1} . Under the selection criteria of 3π and K_S events the following values of σ_i^{Φ} were obtained:

$$\sigma^{\Phi}(3\pi) = (5.0 \pm 0.9)\,nb \,, \qquad \sigma^{\Phi}(K_S) = (7.8 \pm 1.1)\,nb$$

First of all the relative phase α was determined. Its optimal value appears to be $\alpha = 172 \pm 45^\circ$ at $P(\chi^2)$ = 97%. For a fixed value $\alpha = 0^\circ$ (alternative choice) the probability of statistical agreement is $P(\chi^2)$ = 0.7%.

At fixed $\alpha = 180^\circ$ the following parameters of the Φ-resonance have been obtained:

$$m_\Phi = (1019.52 \pm 0.13)\,\text{MeV}$$
$$\Gamma_\Phi = (4.36 \pm 0.19)\,\text{MeV}$$
$$\sigma^{(0)}_{K_SK_L} = (1.40 \pm 0.09)$$
$$\sigma^{(0)}_{3\pi} = (0.79 \pm 0.09)$$

Using table values [13] of the Φ-meson decay mode branchings:

$$B(\Phi \to K^+K^-) = 0.466 \pm 0.023$$
$$B(\Phi \to \eta\gamma) = 0.020 \pm 0.004$$

as well as the experimental cross sections $\sigma^{(0)}_{K_SK_L}$ and $\sigma^{(0)}_{3\pi}$ the following parameters of the resonance have been obtained:

$$\sigma_\Phi = (4.26 \pm 0.30)\,\mu b$$
$$B(\Phi \to K_SK_L) = 0.328 \pm 0.024$$
$$B(\Phi \to 3\pi) = 0.186 \pm 0.022$$
$$B(\Phi \to ee) = (3.00 \pm 0.21)\text{x}10^{-4}$$
$$\Gamma_{\Phi \to ee} = (1.32 \pm 0.10)\,\text{KeV}$$
$$\hat{g}^2_\Phi/4\pi = 11.7 \pm 0.9$$

A constant $\hat{g}^2_\Phi/4\pi$ was calculated with a correction for a finite width of the resonance [14]. Experimental values of the cross-sections and optimal resonance curves are presented in Figs. 6 and 7.

Dashed lines correspond to optimal cross-sections of non-resonant background. In the 3π mode resonance curves for different interference signs are shown.

The above value of the Φ- meson mass contains the correction for vacuum polarization by the Φ- meson (Δm = 10KeV), the error takes into account the uncertainty due to (ρ,ω)-Φ interference in the $K^0_S K^0_L$ mode (± 50KeV).

Independent measurement of the Φ- meson mass was recently performed at VEPP-2M using nuclear photoemulsions [6,15] and gave m_Φ = (1019.69 ± 0.28) MeV. Both results are the most accurate today and coincide within the errors with a table value m_Φ = (1019.70 ± 0.24) MeV [13].

The obtained value of the interference phase corresponds to the opposite sign of ω - and Φ - resonance amplitudes. The same interference sign + (α = 155° ± 29) was earlier obtained in Orsay [16]. Both results provide convincing evidence for the "mass mixing" model.

In our previous work [6] the preliminary result on the measured branching ratio $\Phi \to \pi^+\pi^-$ was presented. The following restriction was finally obtained:

$$B(\Phi \to \pi^+\pi^-) < 4.8\text{x}10^{-4} \qquad \text{at } \alpha = 180^\circ$$
$$B(\Phi \to \pi^+\pi^-) < 6.6\text{x}10^{-4} \qquad \text{for any } \alpha$$

at 95% confidence level, where α is a relative phase of amplitudes $A(\rho \to 2\pi)$ and $A(\Phi \to 2\pi)$.

In conclusion the authors thank N.N.Achasov, V.N.Baier, A.I.Vainshtein for useful discussions and whole staff of the laboratory participated in the experiment and its data processing.

2E,Mev	$N(ee)$	$L\ nb^{-1}$	$N(K_s)$	$N(3\pi)$
I0I3.46	627	I.I9	I7	I3
I0I3.96	985	I.87	36	2I
I0I4.50	920	I.75	43	25
I0I5.02	9II	I.73	49	23
I0I5.56	593	I.I3	34	3I
I0I6.06	99I	I.88	80	3I
I0I6.58	964	I.83	93	35
I0I7.I0	944	I.79	I06	50
I0I7.62	95I	I.80	I50	56
I0I8.I4	9I3	I.73	I74	60
I0I8.66	935	I.77	2I8	82
I0I9.20	887	I.68	204	66
I0I9.70	922	I.75	239	77
I020.24	893	I.69	209	64
I020.76	850	I.6I	I73	45
I02I.26	I004	I.90	I63	52
I02I.80	907	I.72	I29	39
I022.32	974	I.85	II6	30
I022.84	984	I.87	I03	32
I023.36	90I	I.7I	76	27
I023.86	855	I.62	88	22
I024.40	870	I.65	66	I9
I024.92	846	I.6I	53	20
I025.44	844	I.60	63	I3
I025.94	873	I.66	50	I6

Table 1.

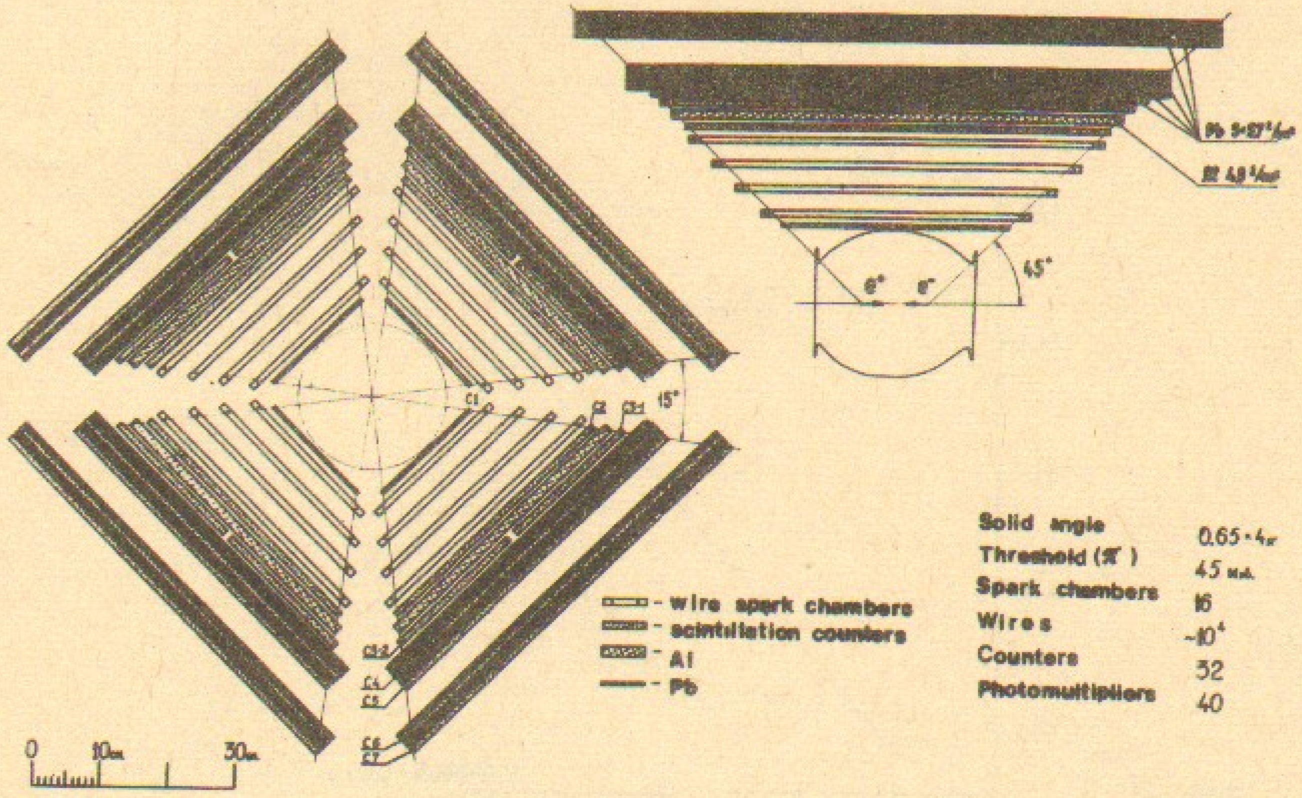

Fig. 1. "OLYA" detector

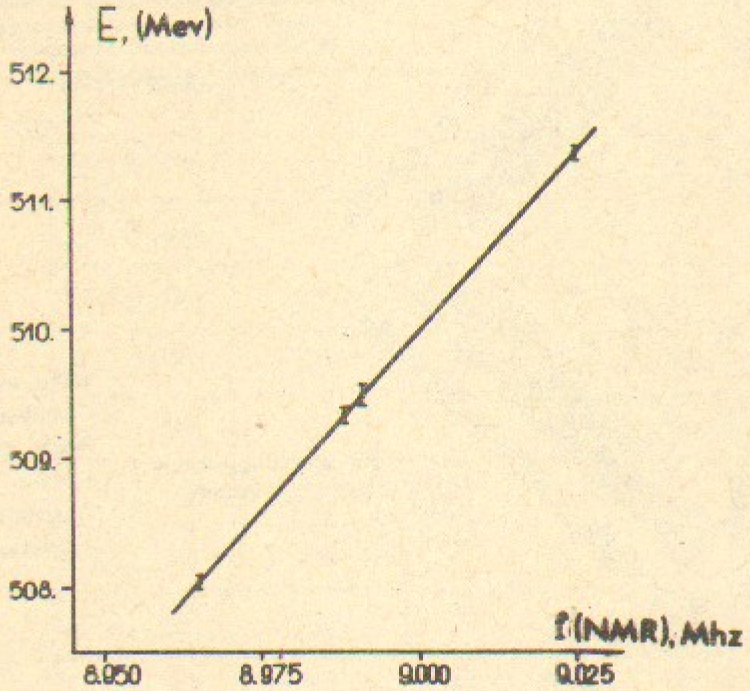

Fig. 2. Calibration of VEPP-2M energy scale: absolute energy value along the vertical axix, NMR probe frequency along the horizontal one.

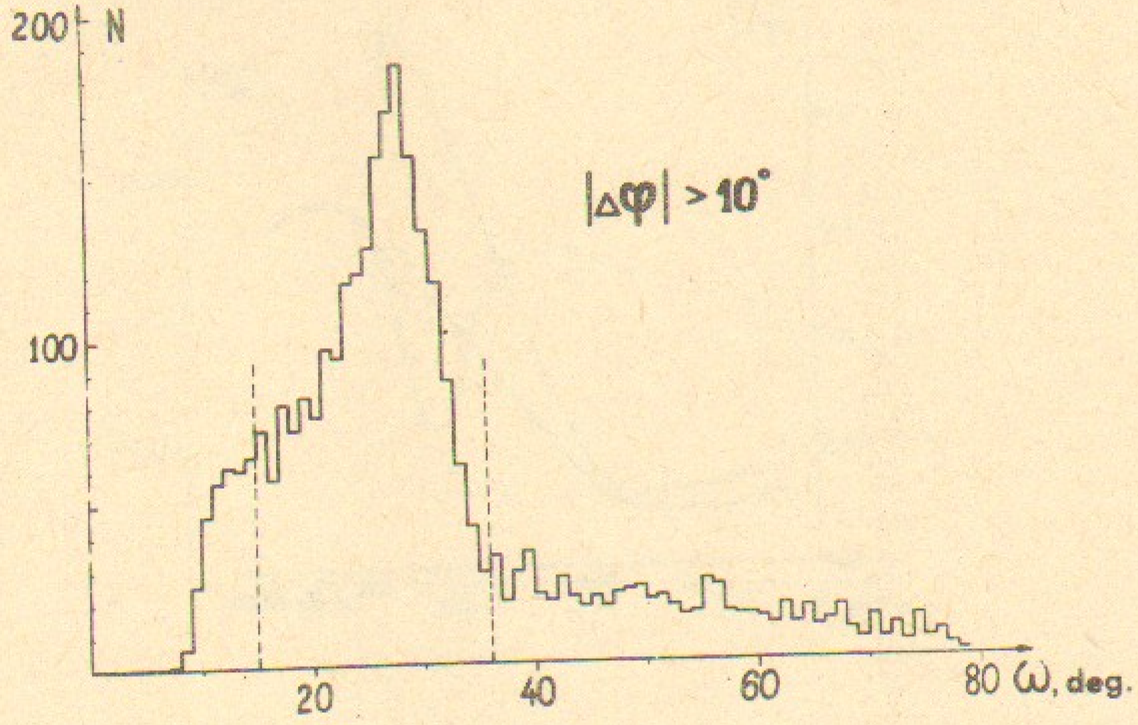

Fig.3. Distribution of events with respect to a spacial acollinearity angle ω .

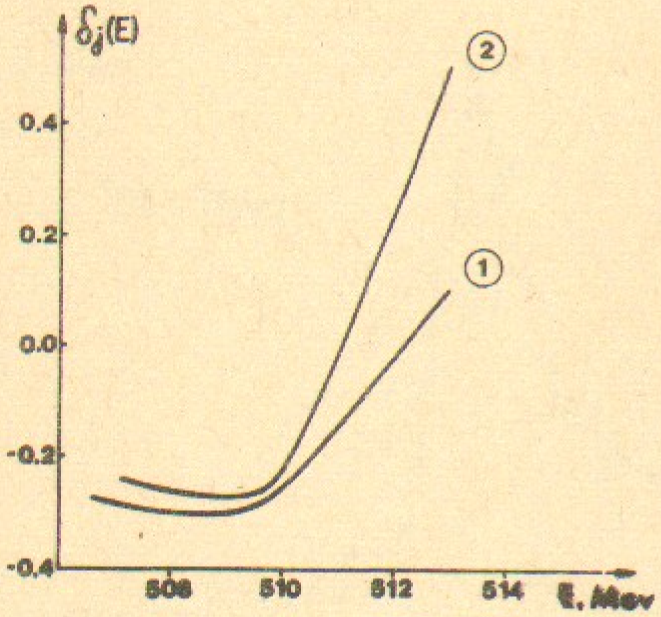

Fig.4. Radiative corrections to the cross-section of the process $e^+e^- \to K^0_S K^0_L$(1) and $e^+e^- \to \pi^+\pi^-\pi^0$ (2).

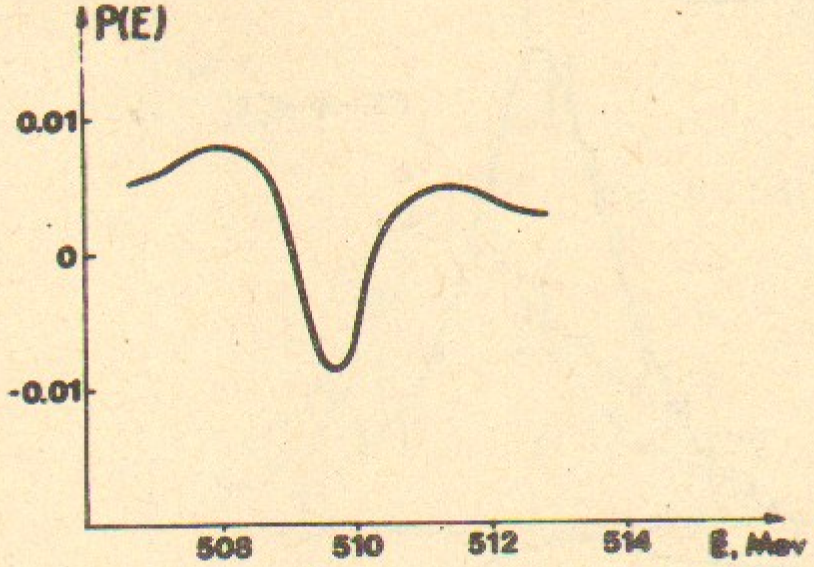

Fig.5. Correction for a beam energy spread.

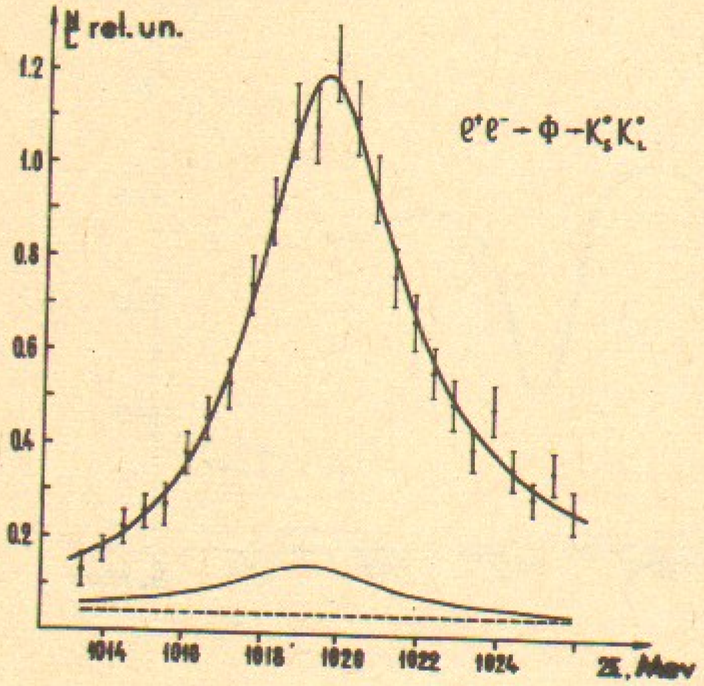

Fig.6. Results of the fit in the $e^+e^- \to \underset{\lfloor \to \pi^+\pi^-}{K^{o}_{S}}K^{o}_{L}$ channel. Dashed line shows a background pedestal, solid thin line - admixture of $e^+e^- \to \pi^+\pi^-\pi^0$ channel.

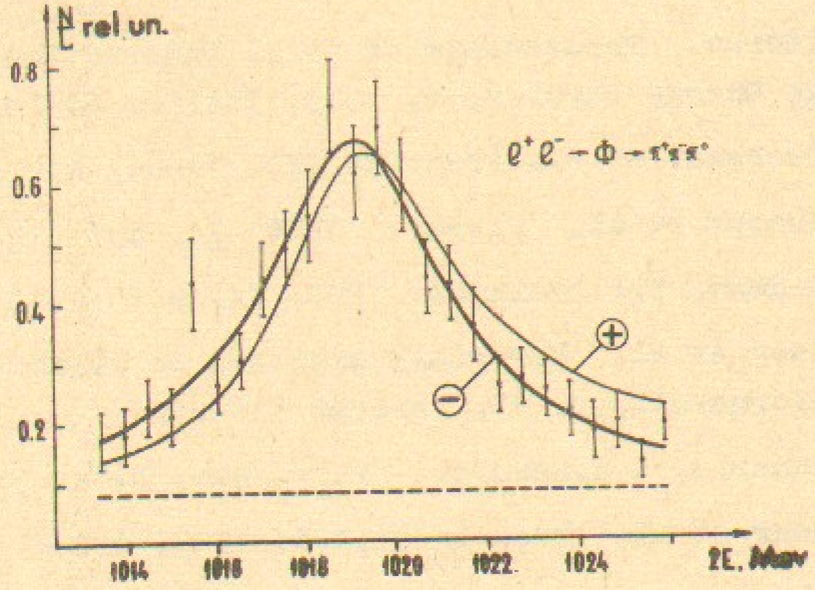

Fig.7. Results of the fit in the $e^+e^- \to \pi^+\pi^-\pi^0$ channel. Dashed line shows a background pedestal, solid thin line corresponds to the cross-section of the process at "incorrect" ω, Φ interference phase $\alpha = 0$.

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Работа поступила - 28 марта 1977 г.

Ответственный за выпуск - С.Г.ПОПОВ
Подписано к печати 3.IX-1977 г. МН 03012
Усл. 0,8 печ.л., 0,6 учетно-изд.л.
Тираж 250 экз. Бесплатно
Заказ № 97.

Отпечатано на ротапринте ИЯФ СО АН СССР