ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ СО АН СССР

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Abstract

Results of the search for rare radiative decay modes of the Φ-meson performed with the Neutral Detector at the VEPP-2M collider are presented. For the first time upper limits for the branching ratios of the following decay modes have been placed at 90% confidence level:

$B(\Phi\to\eta'\gamma)<4\cdot10^{-4}$,

$B(\Phi\to\pi^0\pi^0\gamma)<10^{-3}$,

$B(\Phi\to f_0(975)\gamma)<2\cdot10^{-3}$,

$B(\Phi\to H\gamma)<3\cdot10^{-4}$,

where H is a scalar (Higgs) boson with a mass 600 MeV$<M_H<$1000 MeV,

$B(\Phi\to a\gamma)\cdot B(a\to e^+e^-)<5\cdot10^{-5}$,

$B(\Phi\to a\gamma)\cdot B(a\to\gamma\gamma)<2\cdot10^{-3}$,

where a is a particle with a low mass and a short lifetime,

$B(\Phi\to a\gamma)<0.7\cdot10^{-5}$,

where a is a particle with a low mass not observed in the detector.

For several years experiments with the Neutral Detector were performed at the electron-positron collider VEPP-2M [1]. As a result in the Φ-meson energy range branching ratios of the decay modes $\Phi\to\eta\gamma$ and $\Phi\to\pi^0\gamma$ have been measured with high accuracy [2], the decay mode $\Phi\to\eta e^+e^-$ has been discovered [3], the decay mode $\Phi\to\pi^+\pi^-$ has been studied [4]. In this work we present for the first time upper limits for rare and exotic radiative decay modes of the Φ-meson.

The Neutral Detector has been described in detail elsewhere [1—4]. Its main part is an electromagnetic calorimeter consisting of 168 NaI(Tl) counters with a total weight of 2.6 t. Photon energies and angles are measured in 65% of the solid angle. The integrated luminosity of 3 pb^{-1} collected in the Φ-meson energy range corresponds to about 3 million produced Φ's.

1. SEARCH FOR THE DECAY MODE $\Phi\to\eta'\gamma$

SU(3) symmetry and quark model predict the values of the width for allowed transitions of light vector mesons in pseudoscalar with photon emission [5]. We have already reported on six such decays: ρ_0, ω, $\Phi\to\pi^0\gamma$, $\eta\gamma$ [2, 6]. The branching ratios measured are consistent with the nonrelativistic quark model. One more radiative decay mode of such a type can be studied in our experiment:

$$\Phi\to\eta'\gamma. \qquad (1)$$

Different models [5, 7] predict for it a branching ratio of $\sim 10^{-4}$ depending on the quark content of the η'-meson and reaction mechanism. Measurement of this quantity will provide additional information on the η'-meson structure.

The detection of the process (1) is complicated because of the large number of η'-meson decay modes with either small branching ratios or low detection efficiencies. Another difficulty is a large background from the main Φ-meson decay modes. The following reaction provided the most convenient identification:

$$\Phi \to \eta'\gamma \quad \hookrightarrow \eta\pi^+\pi^- \quad \hookrightarrow \gamma\gamma. \tag{2}$$

In this case charged pions have an energy of about 200 MeV and stop in the first layer of NaI(Tl), the invariant mass of two photons equals the mass of the η-meson, and the energy of the softest photon is about 60 MeV. Therefore we selected events with two charged particles stopping in the first layer of NaI(Tl) and three photons. Energy-momentum balance was also required.

The distribution of selected events in the mass of two photons with higher energy and the recoil mass of the softest photon (Fig. 1,*b*) does not agree with that expected from (2) (Fig. 1,*a*). To place an upper limit the experimental distribution was fit by a sum of a smooth function determined by the contributions of decays $\Phi \to \pi^+\pi^-\pi^0$, $\Phi \to K_S K_L$ and $\Phi \to \eta\gamma$, and a peak due to (2). The detection efficiency obtained from the Monte Cardo simulation is 0.9% (here and below the effisiency with respect to the total number of the events of (1) is implied). As a result the following upper limit on the branching ratio is obtained:

$$B(\Phi \to \eta'\gamma) < 4.6 \cdot 10^{-4} \text{ (90\% c.l.)}. \tag{3}$$

An attempt was also made to observe the process (2) using events with two charged particles and two photons, in which a recoil photon escaped detection or merged with other photons. Besides the selection criteria above it was also required that an angle between charged particles be less than 120°. That provided suppression of the background due to $\Phi \to K_S K_L$. The two photon mass distribution of the selected events (Fig. 2,*b*) was fit by a sum of a linear function and expected spectrum (Fig. 2,*a*). Taking into account the detection efficiency of 0.7% the following result is obtained:

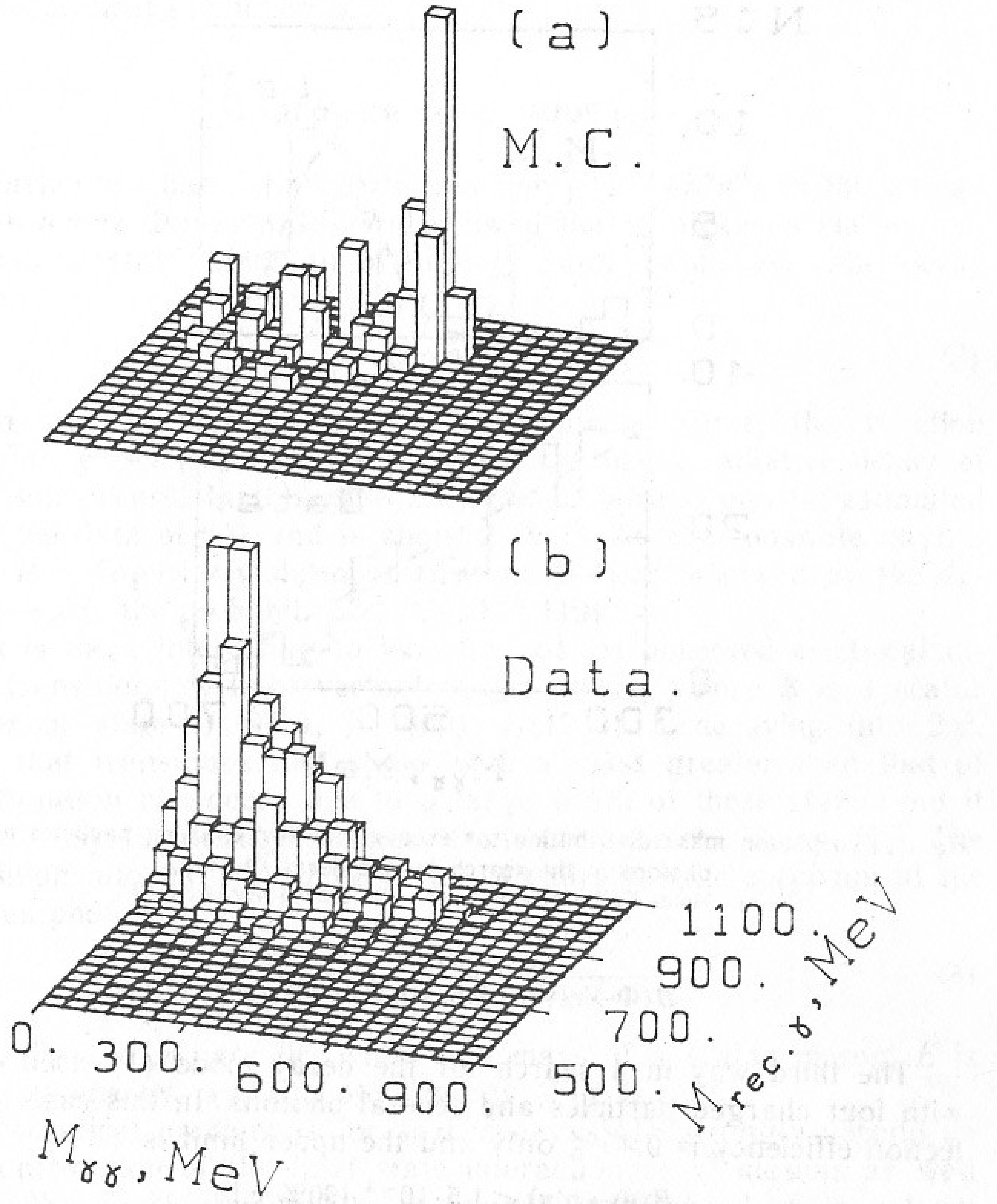

Fig. 1. Two photon mass $M_{\gamma\gamma}$ versus recoil mass of the soft photon $M_{\gamma rec}$ in the search for the decay chain $\Phi \to \eta'\gamma \to \eta\pi^+\pi^-\gamma\gamma \to \pi^+\pi^-\gamma\gamma\gamma$.
a) Monte Carlo, *b*) experiment.

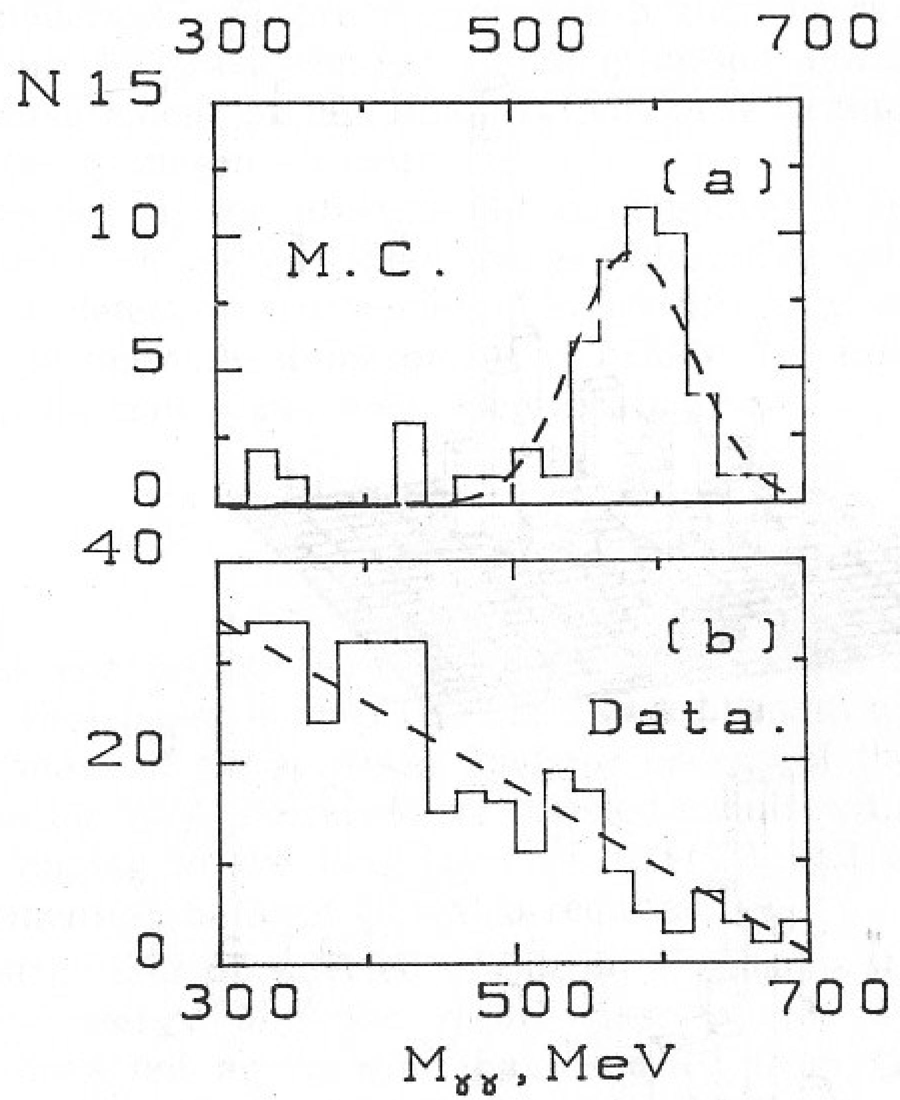

Fig. 2. Two photon mass distribution for events with two charged particles and two photons in the search for the decay $\Phi\to\eta'\gamma$.
a) Monte Carlo, *b)* experiment. The dashed line is the fit.

$$B(\Phi\to\eta'\gamma)<6.8\cdot10^{-4}\ (90\%\ \text{c.l.}). \qquad (4)$$

The third way in a search for the decay mode (1) used events with four charged particles and several photons. In this case the detection efficiency is 0.45% only and the upper limit is

$$B(\Phi\to\eta'\gamma)<1.5\cdot10^{-3}\ (90\%\ \text{c.l.}). \qquad (5)$$

Since the event samples in all three cases were independent, one can combine (3), (4), (5) and obtain

$$B(\Phi\to\eta'\gamma)<4.1\cdot10^{-4}\ (90\%\ \text{c.l.}). \qquad (6)$$

This limit is placed for the first time. Although it is close to the expected value of the branching ratio, it is not yet contradicting to any theoretical prediction.

2. SEARCH FOR DECAY MODE $\Phi\to\pi^0\pi^0\gamma$

Earlier we have studied the reaction $e^+e^-\to\pi^0\pi^0\gamma$ in the energy region above Φ-meson [8] and showed that it proceeds via $\omega\pi^0$ intermediate state. Here an attempt is made to discover the decay mode

$$\Phi\to\pi^0\pi^0\gamma \qquad (7)$$

which can be due to several mechanisms. First, the reaction $\Phi\to\rho^0\pi^0$, $\rho^0\to\pi^0\gamma$ is possible in which the usual radiative decay of ρ^0-meson occurs. In this case the branching ratio can be estimated from the data of [9] and is about $2\cdot10^{-5}$. Another possible mechanism is a G-parity violating transition $\Phi\to\omega\pi^0$ followed by the decay $\omega\to\pi^0\gamma$, the probability is $0.7\cdot10^{-5}$ [10].

It is more interesting to look for not yet observed electrical dipole transitions of light vector mesons $\Phi\to S\gamma$ where S is a scalar or tensor state ($f_0(975)$, $f_0(1300)$, $f_2(1270)$...) decaying into $2\pi^0$. Note that transitions into states with a mass greater than that of the Φ-meson can occur due to a large width of these states and it is not easy to distinguish them from the «direct» decay (7). The transition into the state $f_0(975)$ has a characteristic spectrum of the emitted photon:

$$\frac{d\sigma}{d\omega}=\frac{\text{const}\cdot\omega^3}{(4E(E-\omega)-m_S^2)^2+\Gamma_S^2 m_S^2} \qquad (8)$$

where Γ_S and m_S are the width and mass of a scalar meson, E is the beam energy, ω is a photon energy (Fig. 3,*a*).

Theoretical predictions for such decays [11] strongly depend on the contribution of the final state interaction of π^0 mesons as well as on the quark structure of intermediate states which is not yet clear. For instance, according to the standard classification $f_0(975)$ is a two-quark state with an angular momentum 1. However, the models exist in which $f_0(975)$ is considered as a low-lying four-quark state [12] or a molecular state of pseudoscalar mesons [13]. Therefore, the experimental investigation of the decay mode (7) can provide important information on the structure of scalar mesons.

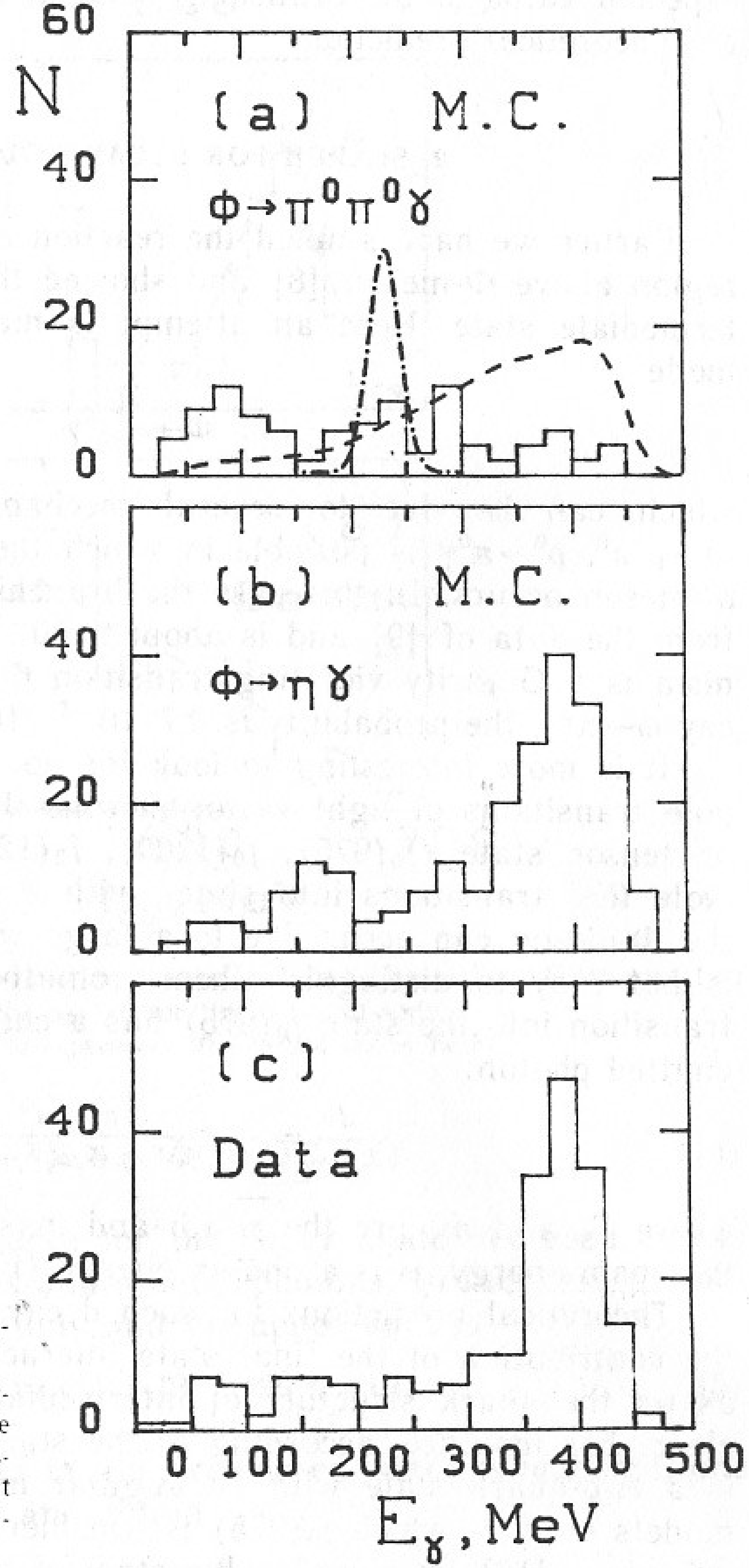

Fig.3. Photon spectrum in the reaction $e^+e^-\to\pi^0\pi^0\gamma$.
a) Monte Carlo simulation: histogram — for the decay $\Phi\to f_0(975)\gamma$, the dashed line — direct decay, the dashed-dotted line — decay $\Phi\to H\gamma$ at $M_H=750$ MeV, *b)* background simulation, *c)* experiment.

To study this decay five-photon events with energy-momentum balance, containing two π^0 mesons were selected. That allowed suppression of the background from the main neutral decay mode of the Φ-meson $\Phi\to K_S K_L$, $K\to\pi^0\pi^0$. To subtract the background due to $\Phi\to\eta\gamma$, $\eta\to3\pi^0$ a simulated recoil photon spectrum has been used (Fig. 3,*b*). This spectrum is close to the experimental one (Fig. 3,*c*). The number of events in the peak corresponding to the recoil mass of the η-meson is consistent with the expected one. The number of events outside the peak ($E_\gamma<330$ Mev) is also consistent with the contribution of the reaction $\Phi\to\eta\gamma$. Using the number of these events and the detection efficiency of 1.2% for the «direct» decay (7) the following upper limit is obtained:

$$B(\Phi\to\pi^0\pi^0\gamma)<10^{-3}\ (90\%\ \text{c.l.}). \qquad (9)$$

For a transition into $f_0(975)$ the detection efficiency under selection criteria above is 2.7%. Taking into account the table value $B(f_0(975)\to\pi^0\pi^0)=26\%$ [9] one obtains

$$B(\Phi\to f_0(975)\gamma)<2\cdot10^{-3}\ (90\%\ \text{c.l.}). \qquad (10)$$

3. SEARCH FOR DECAY $\Phi\to H\gamma$

At the present time one of the important problems of the high energy physics is a search for Higgs bosons [14, 15]. The undetermined value of its mass makes such a search rather difficult. Many models allow the existence of light Higgs particles with a mass about 1 GeV. Experimentally only Higgs particles lighter than 350 MeV are strictly forbidden. If such light particles exist, the radiative decay $\Phi\to H\gamma$ is possible, its branching ratio depends on the Higgs particle mass and is about $10^{-8}-10^{-9}$ [16]. Earlier searches for similar decays of J/Ψ and Υ mesons were performed [17, 18].

In this work we are using the results of ref. 19 claiming that for light Higgs particles the decay $H\to\pi\pi$ is dominant. This allows a search for the process

$$\Phi\to H\gamma\to\pi^0\pi^0\gamma, \qquad (11)$$

which is convenient for the Neutral Detector, since observation of the charged modes of H-boson decay is complicated because of the large background from decay $\Phi\to\pi^+\pi^-\pi^0$. Existence of Higgs bosons will result in a peak in the spectrum of recoil photon in $\pi^0\pi^0\gamma$ events with a width determined by the experimental resolution (Fig. 3*a*). As was already mentioned above, the experimental spectrum (Fig. 3*c*) is determined by the decay $\Phi\to\eta\gamma$, therefore an efficient search for monochromatic photons is possible at $E_\gamma<330$ MeV only. As no peaks are observed in this part of the spectrum, one can place the following upper limit on the branching ratio for Higgs particles with a mass 600 MeV$<M_H<$1000 MeV:

$$B(\Phi\to H\gamma)\cdot B(H\to\pi^0\pi^0)<0.8\cdot10^{-4}\ (90\%\ \text{c.l.}). \quad (12)$$

Using the results of [19], one obtains for this mass region

$$B(\Phi\to H\gamma)<3\cdot10^{-4}\ (90\%\ \text{c.l.}), \quad (13)$$

which is still far from the theoretical predictions and does not exclude the existence of light Higgs particles. However, the favorable background situation in the process under study gives hope to improve in future the results by 2—3 orders of magnitude.

4. SEARCH FOR LIGHT BOSONS

In this section we describe the search for the exotic decay $\Phi\to a\gamma$, where a is a light neutral boson. This particle can, for example, be axion introduced to explain the CP-invariance of strong interactions [20], supersymmetric boson [21] or a mirror particle [22]. Limitations on the probabilities of axion-like radiative decays were obtained for heavy quarkonia at e^+e^- colliders [17,23]. Although these results completely exclude the existence of the standard axion, searches for similar decays are interesting independently of the nature of the particle a. If such particle has a sufficiently short lifetime, it can be observed through its decay into e^+e^- or $\gamma\gamma$, otherwise it cannot be detected.

If its mass $M_a<20$ MeV and the lifetime is small, the process

$$e^+e^-\to\Phi\to a\gamma,\ a\to e^+e^- \quad (14)$$

is observed in the detector as two collinear showers with the energy equal to the beam energy, a shower due to a e^+e^-pair being indistinguishable from that due to a single elecron.

To look for the decay (14) events were selected with one charged particle and one photon. It was required that an acollinearity angle be less than 10°, and the energy deposition of each shower exceeded 0.65*E*, where *E* is one beam energy. These criteria completely s press the background from hadronic decays of the Φ-meson. The main background comes from the two-quantum annihilation with the conversion of one photon in the material of coordinate chambers as well as the process $e^+e^-\to e^+e^-\gamma$, whose cross section has a sharp peak at small masses of the e^+e^- pair (a kind of internal photon conversion in two-quantum annihilation) The cross section of background detection is high, but in contrast to the process under study it does not have the resonance energy dependence. In Fig. 4 we show the energy dependence of the detection cross section. No peak is observed in the Φ-meson region. Fitting it by a sum of background and a Breit-Wigner curve due to the process (14) and taking into account the detecton efficiency of 45%, one can obtain the following upper limit, which is valid when the lifetime $\tau_a<3\cdot10^{-13}$ (sec/MeV)$\cdot M_a$ and the mass $M_a<20$ MeV:

$$B(\Phi\to a\gamma)\cdot B(a\to e^+e^-)<5\cdot10^{-5}\ (90\%\ \text{c.l.}). \quad (15)$$

For the process $e^+e^-\to\gamma\gamma$ similar consideration gives the upper limit for the branching ratio $\Phi\to a\gamma$, where a is a particle with lifetime $\tau_a<5\cdot10^{-13}$ (sec/MeV)$\cdot M_a$ and mass $M_a<20$ MeV decaying via $\gamma\gamma$:

$$B(\Phi\to a\gamma)\cdot B(a\to\gamma\gamma)<2\cdot10^{-3}\ (90\%\ \text{c.l.}). \quad (16)$$

Another possibility studied in the present work is the case of the large lifetime of the particle $\tau_a>7\cdot10^{-12}$ (sec/MeV)$\cdot M_a$ and the mass $M_a<200$ MeV. At such lifetimes its decay mainly occurs outside the detector. Besides that it is assumed that the particle does not interact with matter, so that the signature for the process is a single shower from the interaction point.

For a search events were selected with one well developed photon with the energy close to that of the beam. The detection cross section obtained does not have a Φ-meson peak (Fig. 5). The nonresonant background is determined by the electron and positron bremsstrahlung at the particles of the colliding beam, by three-quantum annihilation, bremsstrahlung at the residual gas and cosmic particles. From the detection efficiency of 20% the following upper limit is obtained:

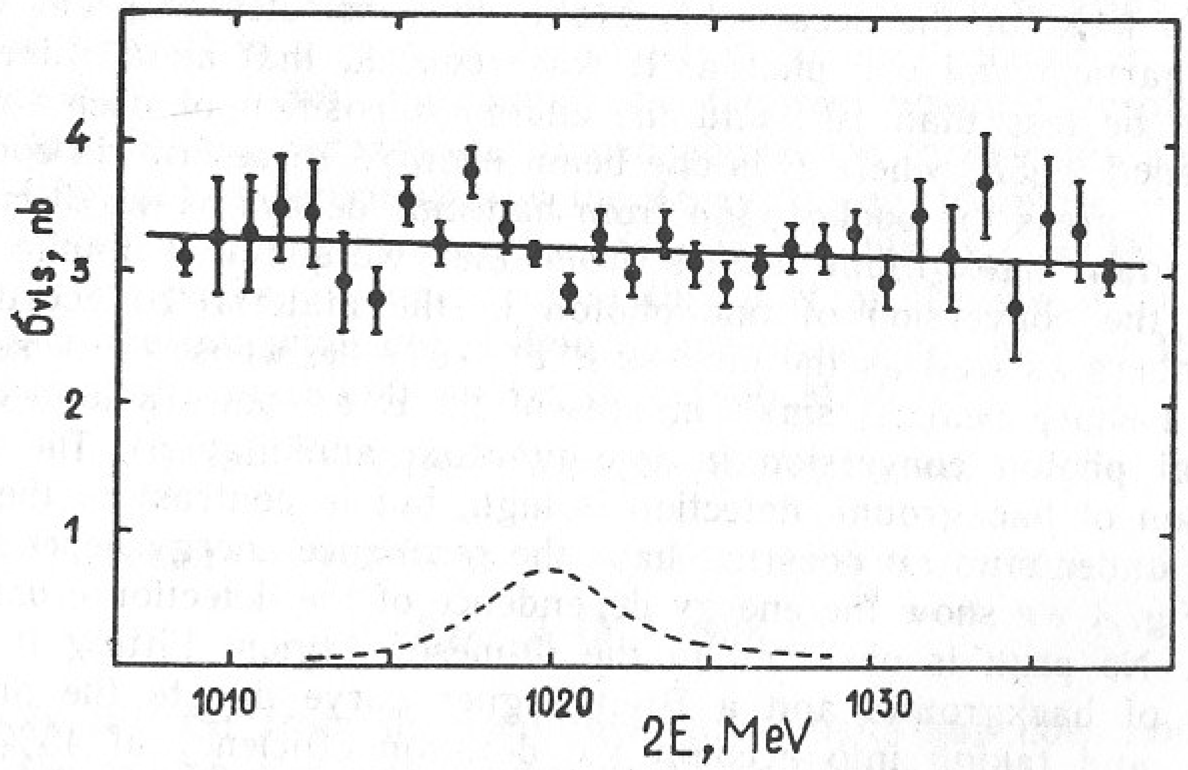

Fig.4. Detection cross section for events with collinear electron and photon. The solid line is the fit, the dashed line is the Φ-meson excitation curve.

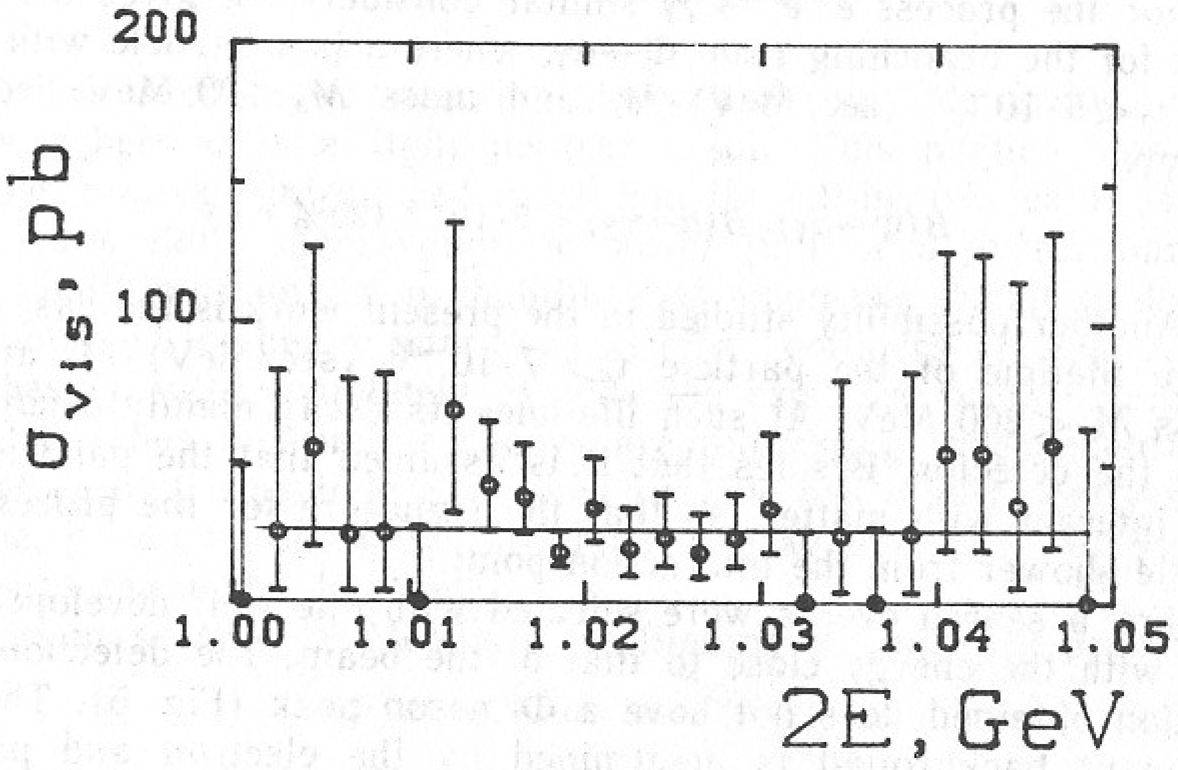

Fig.5. Detection cross section for single photon events.

$$B(\Phi\to a\gamma) < 0.7\cdot 10^{-5}\ (90\%\ \text{c.l.}). \qquad (16)$$

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