ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ
СО АН СССР

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LARGE IMPACT PARAMETERS CUT-OFF IN BREMSSTRAHLUNG AT COLLIDING BEAMS

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Abstract

In investigating the $e^+e^- \rightarrow e^+e^-\gamma$ process the radiation probability is observed to be substantially less than that calculated in the standard QED. The effect is due to the fact that the characteristic impact parameters in the process are much greater than the transverse sizes of colliding beams. In the present paper the applicability of the theoretical calculation to the experimental condition is analysed. The Compton scattering γ-spectrum of the synchrotron radiation by a colliding beam is measured.

1. INTRODUCTION

The process of single bremsstrahlung (SB), $e^+e^- \to e^+e^-\gamma$, is of great importance in the experiments with colliding beams. Its cross section is considerably larger than that of all other processes, that is why the SB is very convenient for the luminosity measurements. For many processes the SB appears to be a background. At high luminosities the SB determines the lifetime of particles in a storage ring. The SB was the first processes to be detected with colliding beams /1/. The SB cross section was measured with an accuracy of 30% at the VEP-1 storage ring /2/. Excluding the works in which the large-angle photon production has been studied, there are no other publications devoted to the experimental examination of the single bremsstrahlung. The SB cross section is calculated in Refs./3,4/.

In 1953 Landau and Pomeranchuk noticed that the bremsstrahlung of relativistic electrons has an interesting feature /5,6/: radiation with frequency ω is formed at a great length (the coherent length):

$$l_c \sim \frac{\gamma(E-\omega)}{m\omega} \qquad (1)$$

where $\gamma = \frac{E}{m}$, m is the electron mass, E the energy. If an electron undergoes any external influence at this length, then the radiation fails. For the bremsstrahlung in matter the multiple scattering appears to be such an influence /5,6/. This phenomenon was observed in /7/. In principle, the external magnetic field can also affect the bremsstrahlung. The bremsstrahlung on the nucleus in a magnetic field was considered in Ref./8/, where this effect was shown to be small for the practically used fields. In the experiments with colliding e^+e^- beams, as shown by Nikishov /9/, Baier and Katkov /10/, the influence of a magnetic field should be much stronger than in the radiation on the nucleus.

Our experiment has been stimulated by the scant experimental data on the SB and by the papers /9,10/. The experiment has shown that the SB cross section is much less than that obtained by the standard Quantum Electrodynamics calculations /3,4/. We have suggested that the effect is due to the large impact parameters cut-off, since the characteristic impact parameters in the process are considerably larger as compared to the transverse sizes of colliding beams. It turned out that the question on the applicability of the SB cross section calculations to the experimental conditions have not been discussed, and moreover the calculations available have been often inapplicable under the real conditions.

In this paper the conditions for applicability of the SB calculations are analysed, and the experimental results of the photon spectrum investigation in a wide range of photon energies are presented. The first results were obtained in May, 1980 and reported at the autumn session of the Nuclear Physics Division of the USSR Academy of Sciences. These have stimulated the theoretical research (see Refs./11-13/). In June, 1981 we carried out the second cycle of the experiments with a view to a more detail investigation of the discovered effect.

2. CONDITIONS FOR APPLICABILITY OF THE SB STANDARD CALCULATIONS

The SB process diagram is shown in Fig.1. The radiation is mainly concentrated in the narrow cones with an angle of $\sim \frac{1}{\gamma}$ along the direction of the primary particle motion. The SB cross section is given by the formula /3,4/

$$\frac{d\sigma}{d\omega} = 4\alpha r_0^2 \frac{1}{\omega}\left(\frac{E-\omega}{E}\right)\cdot\left(v-\frac{2}{3}\right)\cdot\left[\ln\frac{m}{q_{min}}-\frac{1}{2}\right], \qquad (2)$$

where $v=\frac{E-\omega}{E}+\frac{E}{E-\omega}$, $q_{min}=\frac{m}{4\gamma^2}\cdot\left(\frac{\omega}{E-\omega}\right)$, α is the fine structure constant, r_0 – the classical electron radius. The value of the cross section integrated over the photon energy (the threshold ω = 0.5 MeV) is $5\cdot10^{-25}$ cm^2 at E = 1800 MeV. Radiative corrections to formula (2) constitute less than 1% /4A/.

The main contribution to the photon emission with the energy ω comes from the virtual photons with energy $\omega_v=\frac{m}{4\gamma}\cdot\frac{\omega}{(E-\omega)}$. Substituting this value into eq.(1), one can see that the virtual photons are formed at a very large length /10/:

$$l_v \sim \frac{4\gamma^3}{m}\cdot\frac{(E-\omega)}{\omega}. \qquad (3)$$

When E = 1800 MeV and ω = 0.5 MeV, l_v = 1 km!

One can point out three macroscopic effects which impose the restrictions on the conditions for applicability of formula (2) in the experiments:

1) Length of the storage ring straight section.

This effect was discussed in Ref./14/ and, in more detail, in Ref./11/. For the validity of formula (2), it is necessary that the straight section length L be larger than the forming length of a virtual photon (3):

$$L > l_v. \qquad (4)$$

Usually, in the storage rings L = 1÷10 m.

2) The transverse beam size.

The virtual photons are emitted at an angle of $\sim\frac{1}{\gamma}$. So, in the SB, the impact parameters, $\rho\sim\frac{l_v}{\gamma}$, are of importance. For the validity of formula (2) it is necessary that the beam sizes σ be larger than the characteristic impact parameters:

$$\sigma > \rho \sim \frac{4\gamma^2}{m}\cdot\left(\frac{E-\omega}{\omega}\right). \qquad (5)$$

Under our experimental conditions $\rho = 5$ cm, whereas the r.m.s. beam size equals $3\cdot 10^{-3}$ cm.

The finiteness of the beam transverse size results in a decrease of the virtual photon forming length to the value

$$\ell_\perp \sim \frac{\sigma_z^2\,\omega}{\gamma^2} \qquad (6)$$

In our experiment $\ell_\perp = 0.5$ mm.

3) Magnetic field intensity.

The influence of a magnetic field on the SB process was considered in Refs./10,13-15/. The magnetic field reduces the length of formation of a virtual photon down to the value

$$\ell_H \sim \ell_v / a^{2/3} \quad \text{, where} \qquad (7)$$

$$a = 4\gamma^3 \frac{H}{H_0}\cdot\left(\frac{E}{\omega} - 1\right), \quad H_0 = 4.41\cdot 10^{13}\ \mathrm{Gs}$$

At $E = 1800$ MeV and $\omega = 0.5$ MeV, $\ell_H = 20$ cm.

To use formula (2), it is required that

$$\ell_H > \ell_v \quad , \qquad (8)$$

i.e.

$$H < \frac{H_0}{\gamma^3}\cdot\frac{\omega}{E-\omega} \qquad (9)$$

At $E = 1800$ MeV and $\omega = 0.5$ MeV, $H = 0.05$ Gs.

If the collisions occur inside the magnetic field, then the Compton scattering of the synchrotron radiation (SR) by a colliding beam should be taken into account /13-15, 18/.

Thus, at $E = 1800$ MeV, $\omega = 0.5$ MeV one can use formula (2) if the beam transverse size is larger than 5 cm, the straight section length is larger than 1 km, and the magnetic field in this region is lower than 0.05 Gs. Under the conditions of our experiment formula (2) is valid only for the hard component of the spectrum at $\omega > 1000$ MeV. Among the three effects mentioned above, most essential is that associated with the finite transverse sizes of the beams. It is predominant for all the other operating storage rings as well.

After the first cycle of our experiment a formula, which takes into account the beam transverse sizes, has been derived /12,13/. For the Gaussian distribution of the beam density, the cross section takes the form

$$\frac{d\sigma}{d\omega} = 4\alpha r_0^2 \frac{1}{\omega}\left(\frac{E-\omega}{E}\right)\left(v - \frac{2}{3}\right)\left\{\ln\left[\frac{\sigma_x\sigma_z}{\lambda_c(\sigma_x\sigma_z)}\right] + \ln 2 + \frac{C}{2} + \frac{v-\frac{5}{9}}{v-\frac{2}{3}}\right\},$$

where $C = 0.577$ is the Euler constant; σ_z, σ_x are vertical and radial beam sizes, respectively; λ_c is the Compton wavelength of an electron. The formula holds when $\frac{q_{min.}}{\gamma}\cdot\frac{\sigma_z\sigma_x}{(\sigma_x+\sigma_z)} \ll 1$.

The theorists have analysed the other possible macroscopic effects in the $e^+e^- \longrightarrow e^+e^-\gamma$ process /11,13/. In the paper /11/ it has been concluded that the suppression of the emission probability observed in our experiment is due to a stronger effect than the large impact parameters cut-off. This effect is argued to be associated with the particle scattering by a colliding beam with the emission of a virtual photon. No qualitative explanation of the phenomenon is made in this paper, and a strict quantum-electrodynamical calculation is absent, too. As will be seen below, the results of this paper contradict the experimental data.

3. EXPERIMENTAL SET-UP. NORMALIZATION

The experiment was carried out with the storage ring VEPP-4 /16/ in the interaction region intended for the magnetic detector MD-1 /17/. During the first series of experiments three magnets with a small vertical aperture (5 cm) were installed in place of the magnet of the MD-1 detector. The presence of these magnets made it possible to have any field within the range ±6 kGs in the interaction region. The second series of measurements was carried out with the magnet of the MD-1 detector. The vacuum chamber around the interaction region had a 10 cm aperture in the 1981 experiment instead of a 2 cm one in the 1980 experiment.

A geometrical scheme of the experiment in 1981 is shown in Fig.2. The angle of rotation of a particle trajectory is 16°. The distance from the interaction region to the counters is 4.8 m. The design of the interaction region greatly differs from the conventional one. An interaction region is usually arranged inside a long straight section, that leads to a high background caused by the residual gas bremsstrahlung. The design of our interaction region provides a low background level, since the radiation from a small part of the orbit gets to the detector. At the same time, the presence of the perpendicular magnetic field in the interaction region gives rise to the appearance of the background caused by the Compton scattering of the SR by a colliding beam.

Normalization was performed by the double bremsstrahlung (DB) process $e^+e^- \to e^+e^-\gamma\gamma$. As is known /19-23/, this process is formed at the distances of the order of the electron Compton wavelength, $\lambda_c = 3.8\cdot10^{-11}$ cm. Thus, the macroscopic factors should have no influence on the DB process.

4. EQUIPMENT

The effect of decreasing the SB cross section, which results from the large impact parameter cut-off, increases with lowering the photon energy. Besides that, when decreasing the photon energy the background of the Compton scattering of the SR by a colliding beam diminishes. In view of this, it is profitable to extend the range of photon energies to be measured to the region of low energies. In the experiment the photon spectrum within the interval 0.4-1840 MeV was measured. The photons with an energy lower than 0.3 MeV are absorbed, to a considerable extent, by a synchrotron radiation receiver (2 mm Cu).

To detect the photons, a NaI(Tl) crystal of $47\times12\times12$ cm^3 in size was used /24/ (counter 1 in Fig.2). The light was collected by two photomultipliers: the FEU-110 for the 0.4-21 MeV region and the FEU-84 for the 21-1840 MeV region. The nonlinearity of the amplitude characteristics did not exceed 1%, that was checked with the help of photodiodes. The absolute calibration was performed with the isotopes Cs^{137}, Zn^{65}, by the cosmic radiation and at the edge of the SB spectrum. The calibration accuracy was not worse than 10%.

The examination of the stability of photomultiplier gains have shown that the instabilities can be of the order of 20% because of the changes in counting rates. Therefore, the following stabilization system was created. With the help of a photodiode, the current through the photomultiplier was set by a factor of ten greater than that at a maximum operating counting rate. The photodiode was operating in the regime of synchronization with the beam phase in the storage ring. The stability control was carried out continuously, during the whole experiment, with the help of isotopes, photodiodes and at the edge of the SB spectrum. The instability did not exceed 2%.

For a decrease of the background from the external radiation, own crystal radiation, and from the radiation induced in the crystal by the beam, NaI(Tl) was covered by the lead, and the synchronization with the phase of particle revolution in the storage ring was applied. The strobe pulse lasted 100 nsec. The revolution time of the beam in the storage ring was 1.22 μsec. The resolution time of counter 1 was 30 nsec (FWHM). To obtain such a resolution, the threshold of a discriminator of fast coincidences was set at the level 1/10 from the minimum measurable amplitude. The dead time of the counter-1 electronics was 16 μsec, allowing to avoid the afterpulse detection.

To detect the DB, counter 1 was connected in coincidence with counter 2, which was quite identical to the former. The counter 2 threshold was equal to 11 MeV and was chosen in such a way to avoid the second responses of the discriminator during 1 μsec after the main pulse. The dead time of counter 2 was equal to 1 μsec and, since the revolution time of the beam was 1.22 μsec, counter 2 had no discounts. This circumstance is very essential, since the discounts in counter 1 have no influence on the ratio of SB to DB. With the radiative corrections taken into account, the calculated value of the DB detection cross section is equal to $6.7 \cdot 10^{-28}$ cm^2. The background from accidental coincidences for DB was measured simultaneously with the effect measurements. For this purpose, the coincidence counting rate of counters 1 and 2 was measured with a delay of one of the counters' pulse by the revolution time of particles in the storage ring.

The photomultiplier amplitudes were measured with an analog-to-digit converter (2000 channels) in the CAMAK standard. For a flexible control of a shape of the spectrum, the discriminators were used, which divided the spectrum into four parts with approximately equal counting rates. The information from discriminators was transferred to the pulse scalers. These scalers also received the information about the counting rate of SB in counter 2 and about that of DB. To check the background variations, counter 3 (designed on the basis of NaI(Tl)) with the sizes 30x12x4 cm^3 /24/ was used.

The control of the beam position at the interaction point was performed through SB detection by proportional chambers. During the experiment, the instability of a beam position did not exceed 1 mm, that could give the systematic error not larger than 0.5% to the DB counting rate. The whole equipment has been checked in the DB experiment.

5. EXPERIMENT

In 1981 several series of measurements were performed, in which the vertical and azimuthal sizes of the beam and the electron current were changed, as well as one measurement with the beams displaced in the vertical direction by $3\sigma_z$. The main beam characteristics in the 1981 measurements are presented in Table 1.

The magnetic field in the 1981 experiment was not changed and equaled 5 kGs. In 1980 three measurement series were performed at 3 values of the magnetic field at the interaction point: 0, +3, -3 kGs. The beam sizes were approximately the same as in series 4 (Table 1).

Table 1

$\sigma_x, \sigma_z, \sigma_\varphi$ are the vertical, radial and azimuthal sizes of the beams, respectively; ΔZ is the vertical displacement of the beams.

Series	σ_z, μm	σ_x, mm	σ_φ, sm	I^-, μA	I^+, μA	ΔZ, μm
1	13	0.45	2	200-300	200-300	0
2	13	0.45	2	200-300	200-300	40
3	56	0.39	2	350-450	350-450	0
4	24	0.45	2	350-450	350-450	0
5	24	0.45	3	50-70	350-450	0

The measurement procedure was the following. The background was measured during 50 sec; for this purpose the beams were displaced by $15\sigma_z$, after that the beams were bringed together and the effect was measured during 300 sec. Then, the background was measured again. The effect or background measurement was called a shot. Every "background-effect-background" measurement was called a run. During data processing the averaged background was subtracted. The operation conditions of the storage ring were chosen so that the background be minimal and do not be changed if the beams are displaced or bringed together.

6. BACKGROUND

As has already been noted, there are two types of background in our experiment.

1. The background from the bremsstrahlung on the residual gas.

This background does not change under the vertical displacement of the beams and, hence, can be measured and subtracted. As the calculations and measurements have shown, the background from the bremsstrahlung on the residual gas directly from the interaction region is negligible. The main background has the following origin. Electrons, that lost the energy because of the bremsstrahlung on the residual gas in the ring and the straight section of the VEPP-4, hit the wall of the vacuum chamber in the interaction area. They initiate in it an electromagnetic shower. It is the photons from this shower that give the main background counting rate. This picture is confirmed by the linear dependence of the background from the vacuum in the straight section of the VEPP-4 and also by the wide, $\sim 10 \frac{1}{\gamma}$, angular distribution of the background.

Before the beginning of the experiment we tested the independence of the background on the magnitude of beam separation up to $20\sigma_z$. The magnitude of a background was controlled during the whole experiment by counter 3. Besides that, the correctness of this method of background subtraction was checked by indirect methods. In each run the stability of the shape of the spectrum was checked using signals from discriminators. The shape was the same in all runs with an accuracy better than 1% notwithstanding that the background-to-effect ratio was $10 \div 30\%$. In each run we determined the ratio of the SB counting rate in channel 1 to that in channel 2. This ratio was reproduced in different runs with an accuracy better than 1%, independently of background conditions. The measured level of background is shown in Fig.3.

2. Background due to Compton scattering of synchrotron radiation by a colliding beam

The phenomenon of Compton scattering of the SR by a colliding beam was not earlier studied experimentally.

In the paper /13/ it was noted that in the bremsstrahlung process in a magnetic field there is no sharp boundary between real intermediate photons and virtual photons. An exact calculation is very complicated and has not been done up to now. We **have made** such a computation, regarding all the photons to be **real.** Some estimates, according to Ref./13/, show that such a calculation gives an increase of the background by 5-10% in the area $\frac{\omega}{E}>10^{-2}$ and by 2-3 times in the area $10^{-4}<\frac{\omega}{E}<10^{-3}$. This error in the background calculation gives not more than a 2-3% error in a measurement of the SB in all area of the spectrum.

The correctness of the background calculations was checked in the experiment. To do this, we measured the spectrum with the beams separated by $3\sigma_z$ in the vertical direction ($\sigma_z \simeq 13\,\mu$m). From this spectrum we subtracted the spectrum measured with the beams brought together. The results of these measurements are shown in Fig.4. A shaded area is a calculation. The width of this area corresponds to the mean-square errors. An error is due, mainly, to our inexact knowledge of beam sizes and a value of the beam separation. One can see that the experiment coincides with the calculation with an accuracy of about 15%.

Our measurements in 1980 without the magnetic field and those in 1981 with the magnetic field gave the same results for the SB spectrum after the subtraction of the scattering of the SR by a colliding beam.

7. RESULTS

The experimental results were correlated with respect to the detection efficiency of the NaI(Tl) crystal. This efficiency was computed using the MC method. The results of the calculation are shown in Fig.5. The inefficiency was mainly due to the photon absorption in the radiation receiver (2 mm of Cu) and in the box wall (10 mm of Al) of the NaI(Tl) counter.

Fig.6 presents the results of the spectrum measurements carried out in 1980 and 1981. In both cases the calculated background from the scattering of the SR by a colliding beam was subtracted. Curve 1 is the standard QED calculation. Curve 2 is the calculation with taking into account the large impact parameter cut-off; the width of the shaded area corresponds to two mean-square errors. The factors determining the error are, in general, systematical ones. These are presented in Table 2.

Table 2.

1. Absolute calibration of thresholds	0.43 MeV - 2% 11.0 MeV - 3.5%
2. Stability of thresholds	0.43 MeV - 0.5% 11.0 MeV - 1%
3. Statistical error of DB events	- 1.5%
4. Calculation of the crystal detection efficiency	- 2.5%
5. Subtraction of the background	- 2.0%
6. Stability of beam orbits	- 0.5%
7. Nonlinearity of electronics in the range of low amplitudes	- 1.5%
8. Nonlinearity of amplitude characteristics of a photomultiplier	- 1.0%
Total	6.0%

The results of the 1980 and 1981 experiments coincide within the experimental error and with the theoretical calculations. Overestimation of the calculated values over the experimental ones lies within two standard errors.

Fig.7 demonstrates the dependence of the ratio $N_\gamma/N_{2\gamma}$ on the vertical beam sizes, where N_γ is the number of SB events in the range 0.5÷3.0 MeV, $N_{2\gamma}$ the number of DB events. The curve is the calculation, taking into account the large impact parameter cut-off /12,13/. This curve was calculated by the maximum likelyhood method, the free parameter is a normalizing factor. As is seen, the experiment well coincides with the calculation: $P(\chi^2)=0.45$. The light circles show the results of the calculation according to the paper /11/, in which it has been suggested that the particle scattering by a colliding beam with the virtual photon emission plays a dominant role. This calculation is in contradiction with the experimental data: $P(\chi^2)=3\cdot 10^{-5}$.

Since in the process $e^+e^- \to e^+e^-\gamma$ the large impact parameters are essential, a noticeable probability of SB has to be even the beams are separated on the distances larger than their sizes. The corresponding calculations for the Gaussian distribution of the particle energy in the beams were performed in Ref. /12/. The measured dependence of the ratio $N_\gamma/N_{2\gamma}$ on the beam separation in the vertical direction is presented in Fig.8 ($\sigma_z=13\ \mu m$). One can see that the calculation well coincides with the experiment: $P(\chi^2)=0.5$.

8. CONCLUSION

Our experiment shows that the experimentally discovered suppression of the radiation probability is due to the large impact parameter cut-off. The analysis of the standard QED calculations shows that the region of their applicability is limited, since for the SB the macroscopic effects are essential. The strongest of these effects, practically for all e^+e^- machines, is the effect of the large impact parameter cut-off.

It should emphasize that in the case in which the characteristic impact parameters of the process are comparable or greater than the beam size, the concept of an effective cross section is inapplicable, in its usual sense. But, in principle, one can introduce here the concept of a cross section, as it was done in Refs./12,13/ for derivation of formula (10).

In conclusion, it is necessary to note that the effects associated with the cut-off of the large impact parameters, increase with energy. At $E>5$ GeV, under certain kinematical conditions, they can manifest themselves in the process $e^+e^- \to e^+e^-e^+e^-$, and at $E>200$ GeV in the process $e^+e^- \to e^+e^-$ + hadrons as well.

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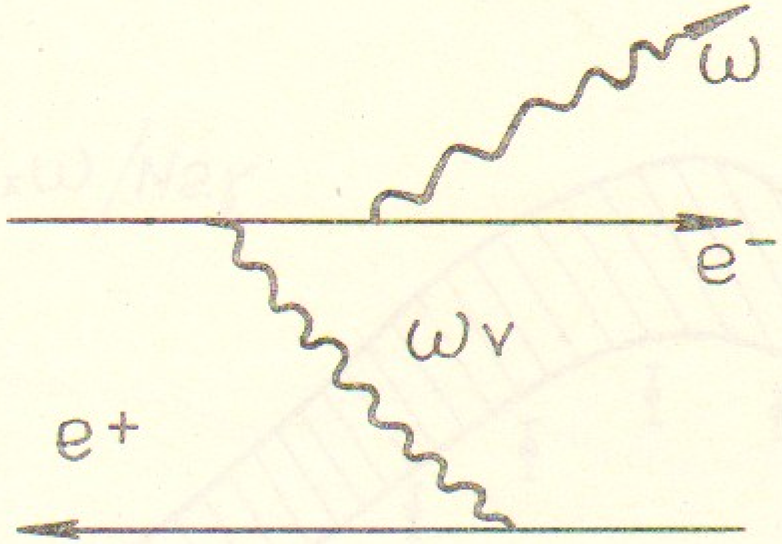

Fig.1

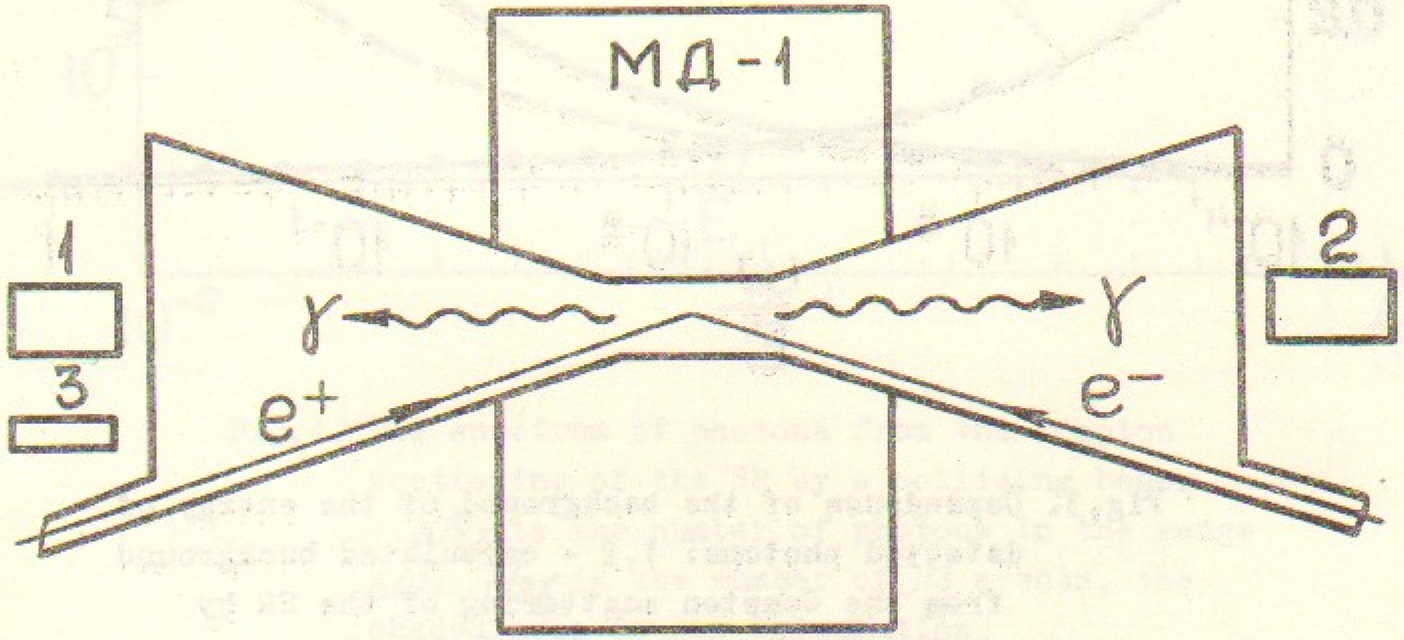

Fig.2. Schematic view of the experimental lay-out:
1,2 - NaI(Tl) counters for SB and DB detection,
3 - NaI(Tl) counter for background control

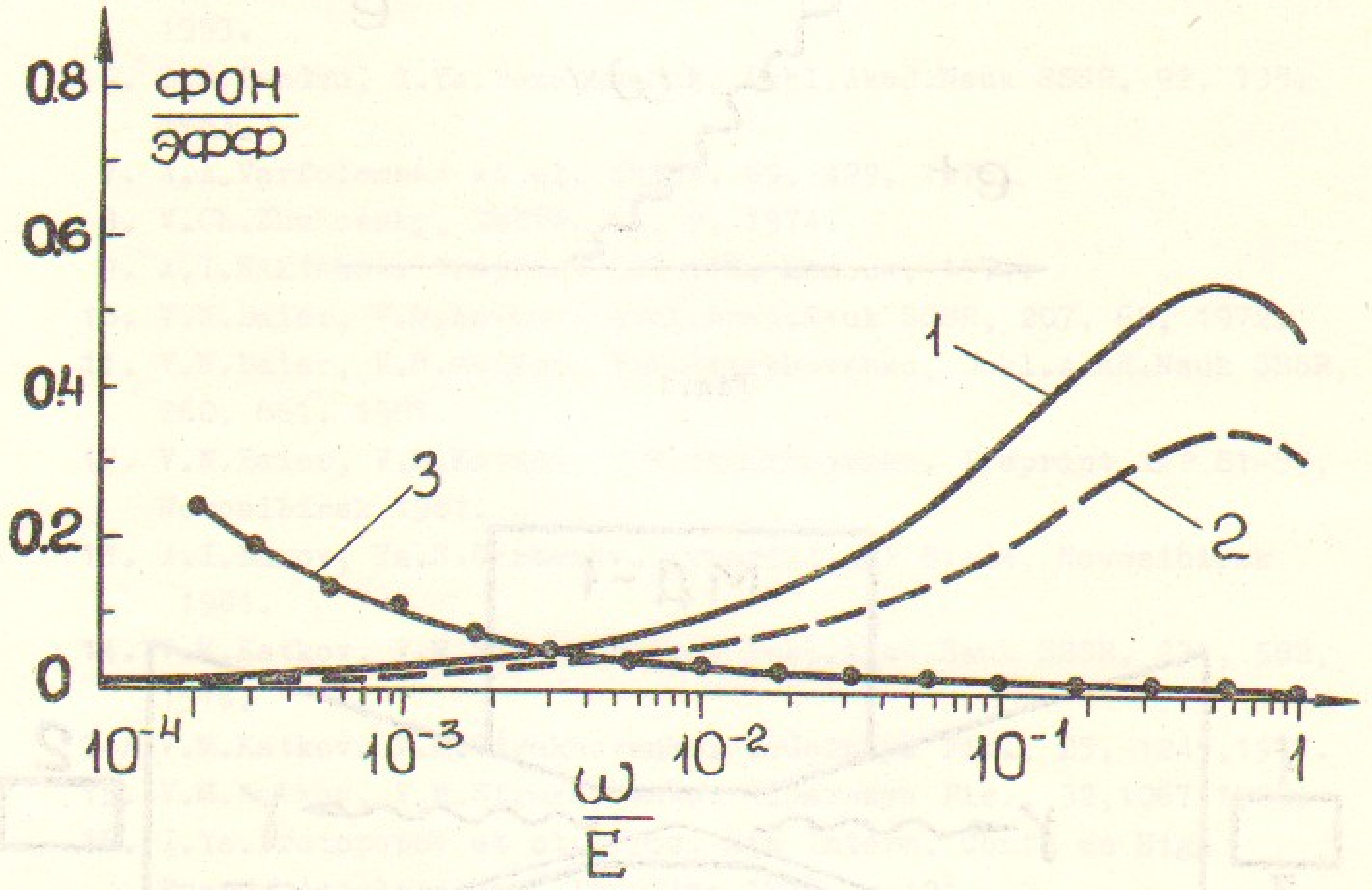

Fig.3. Dependence of the background of the energy of detected photons: 1,2 - calculated background from the Compton scattering of the SR by a colliding beam for the 56 μm and 12 μm beam sizes, respectively, 3 - measured background from the bremsstrahlung on the residual gas.

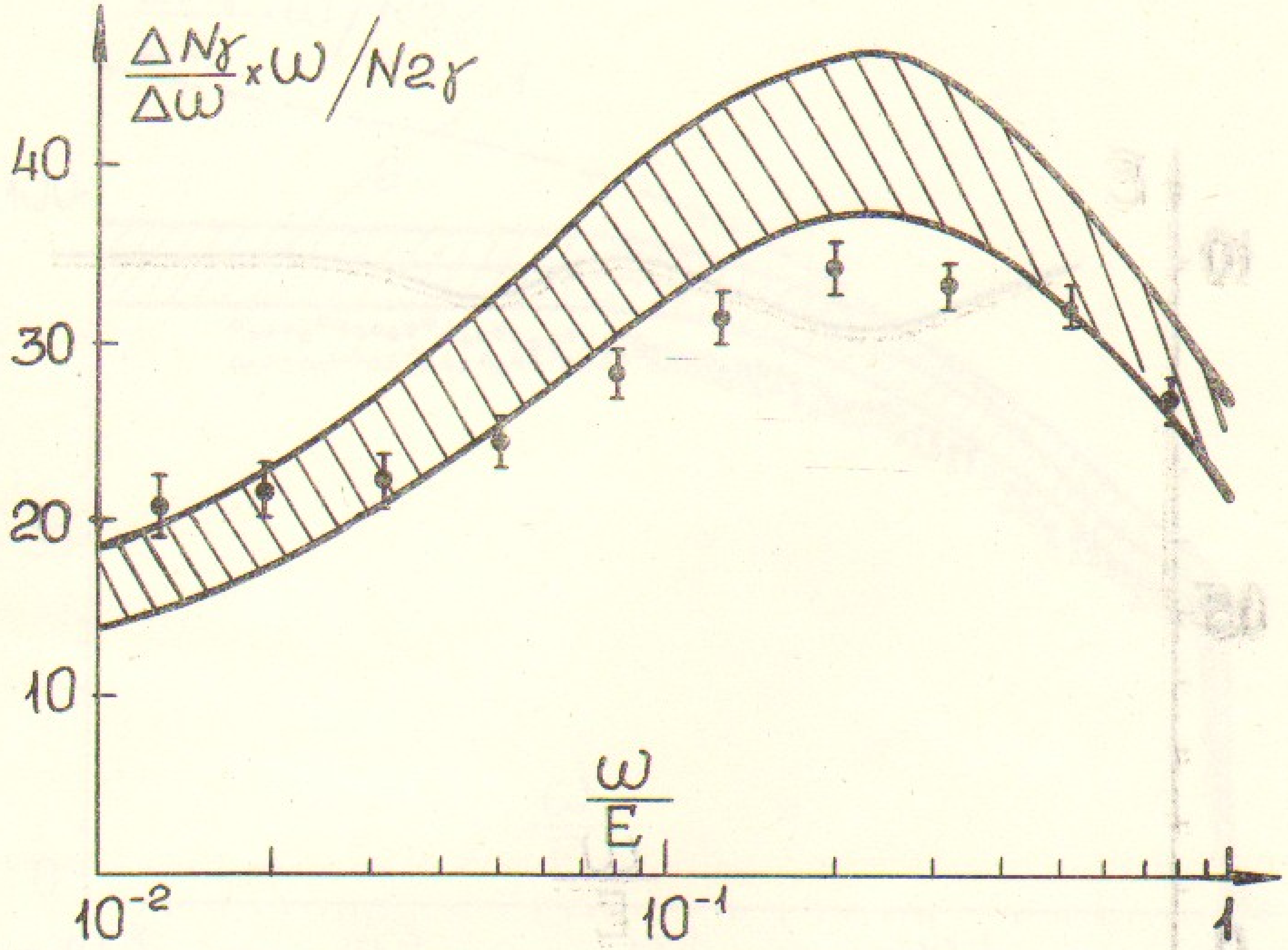

Fig.4. The spectrum of photons from the Compton scattering of the SR by a colliding beam: ΔN_γ is the number of photons in the range $\Delta\omega$, $N_{2\gamma}$ is the number of DB events, the shaded area is the calculation.

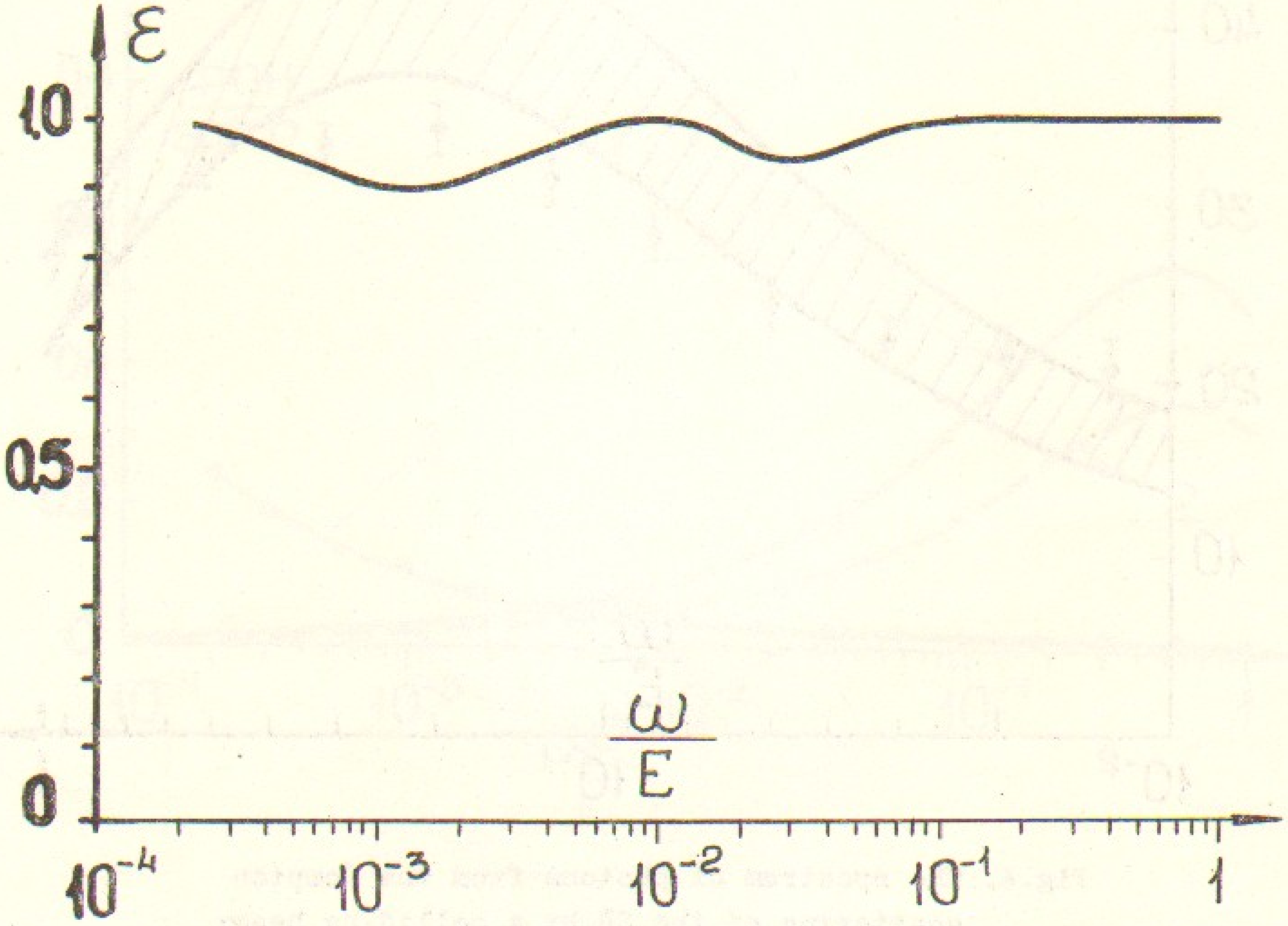

Fig.5. Detection efficiency of the NaI(Tl) crystal.

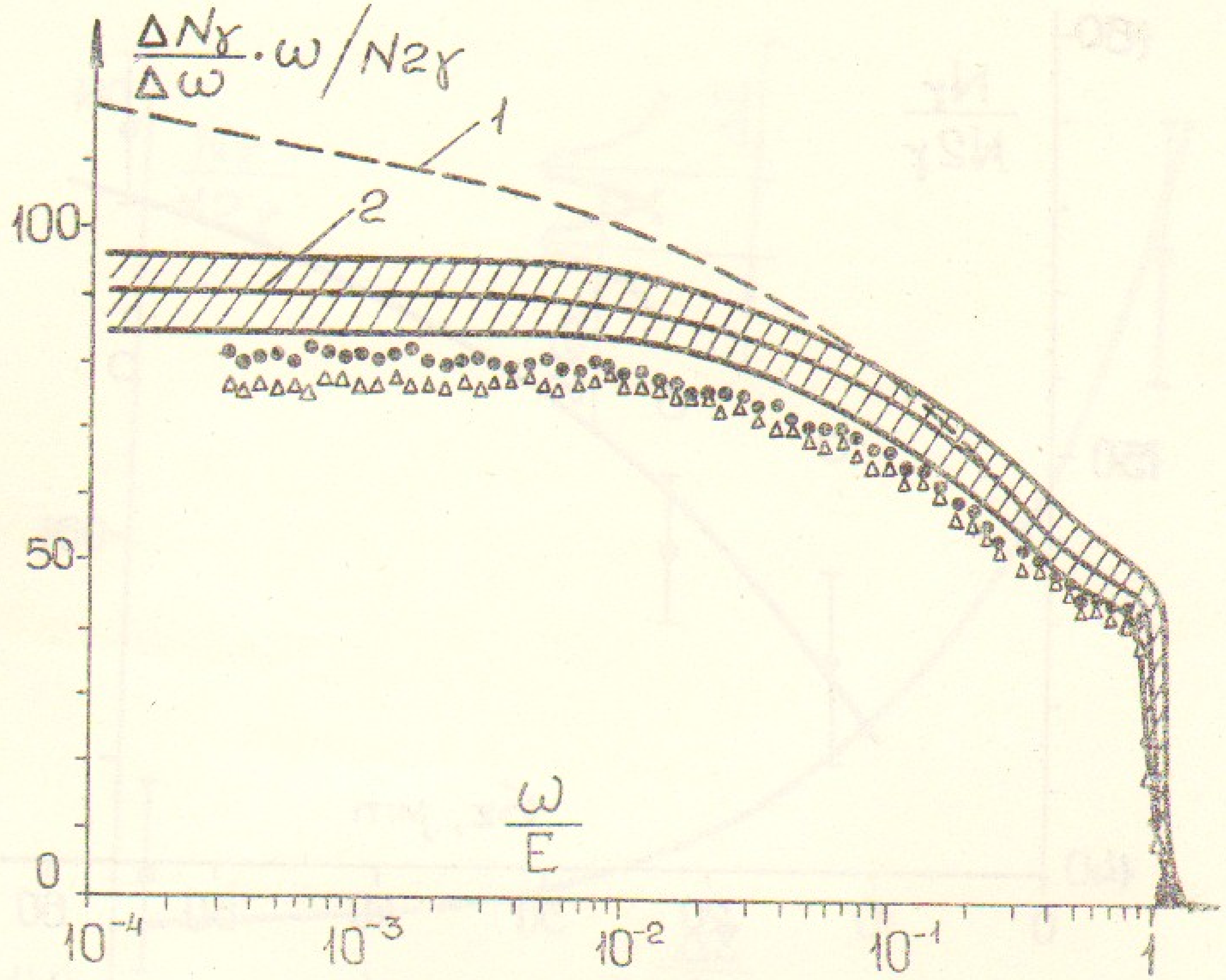

Fig.6. A spectrum of SB photons:

● - experiment in 1980, $\sigma_z = 23 \pm 3\ \mu m$

△ - experiment in 1981, $\sigma_z = 24 \pm 3\ \mu m$

1 - standard QED calculation

2 -calculation, taking into account the effect of large impact parameter cut-off /12,13/.

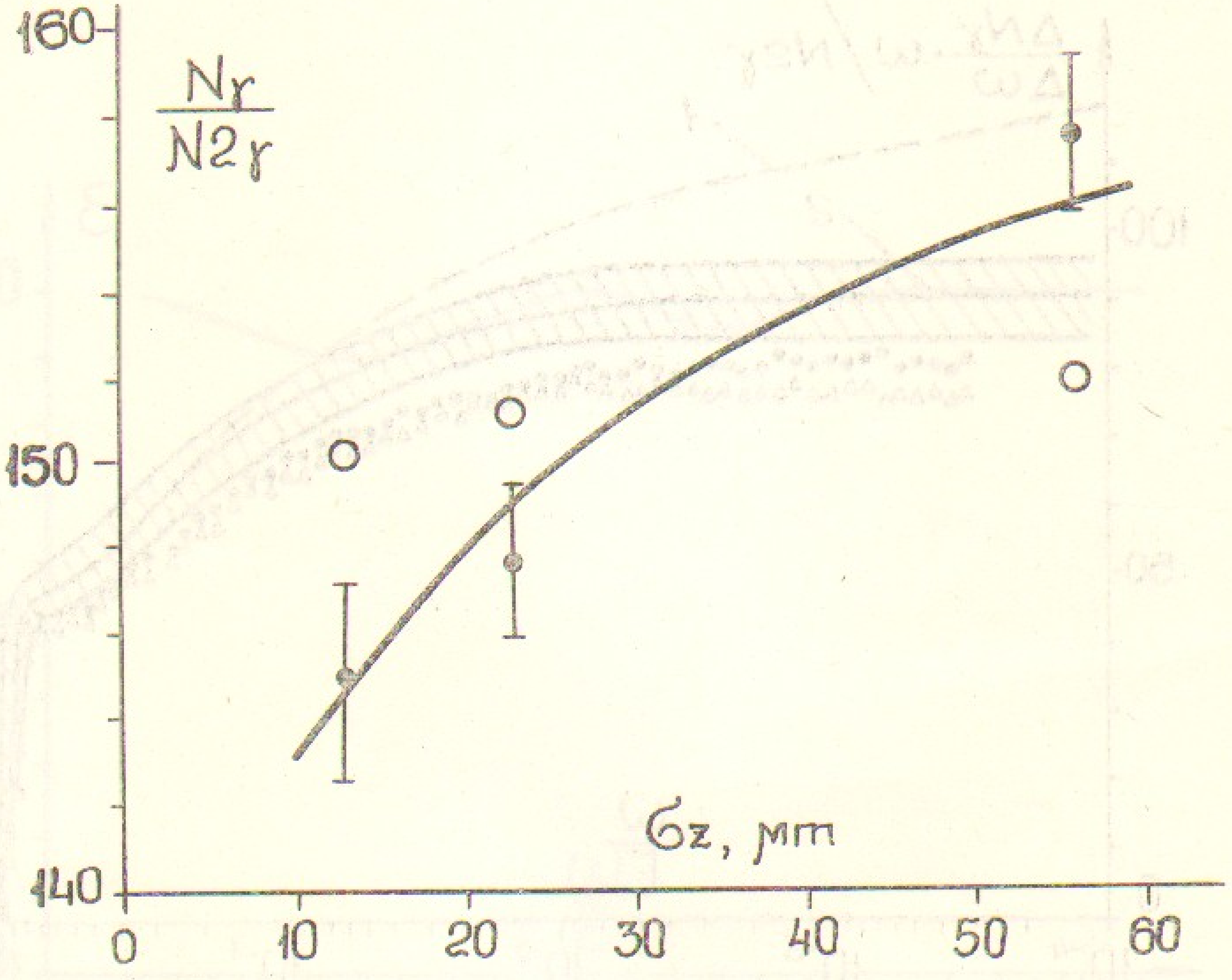

Fig.7. The dependence of the ratio $N_\gamma/N_{2\gamma}$ on the vertical beam sizes: N_γ is the number of the SB photons in the range 0.5÷3.0 MeV, $N_{2\gamma}$ is the number of DB photons, the curve is a calculation, taking into account the effect of large impact parameter cut-off /12,13/; O-denotes the calculation according to Ref./11/.

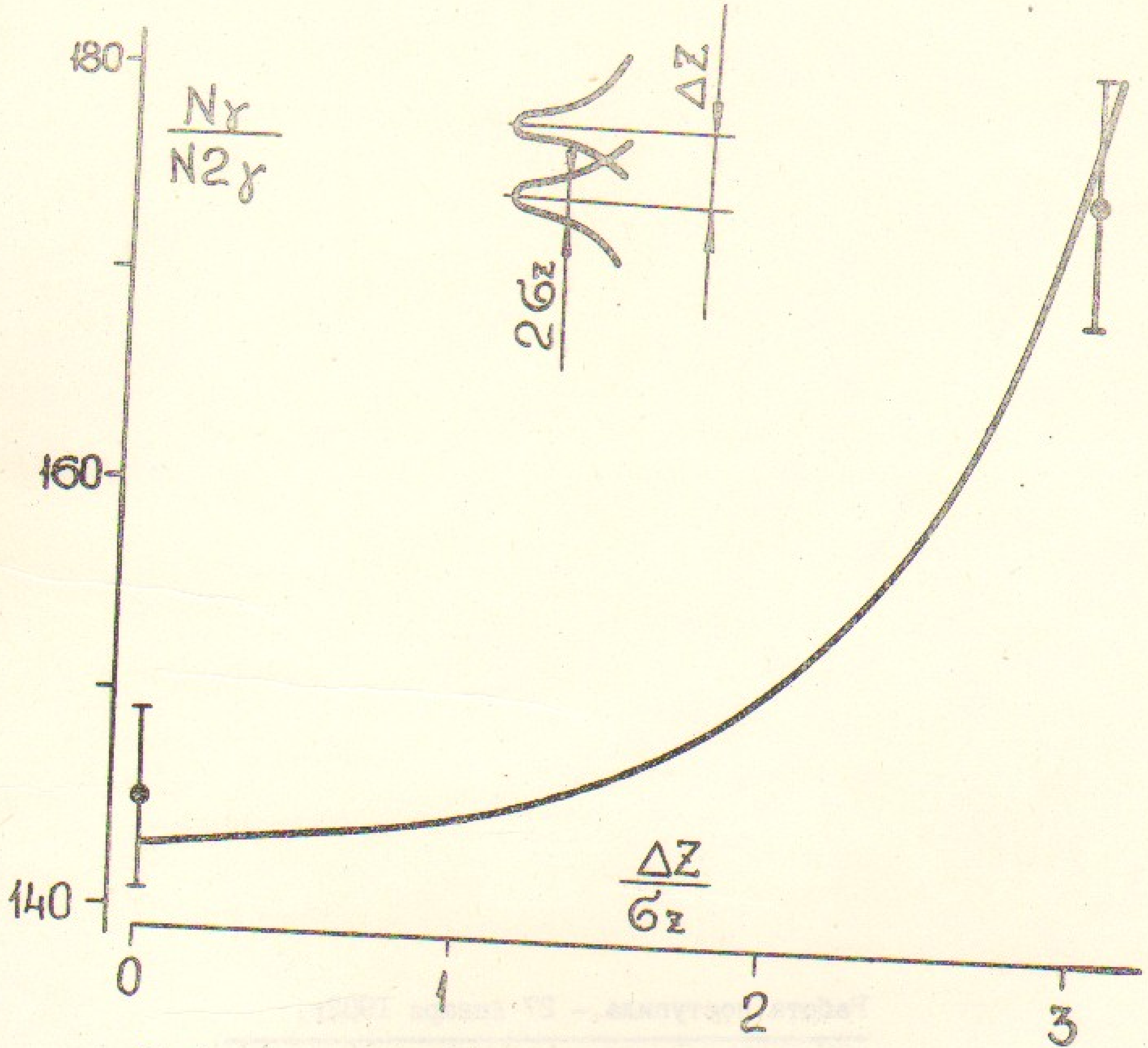

Fig.8. The ratio $N_\gamma/N_{2\gamma}$ vs the beam vertical separation: N_γ is the number of SB photons in the range 0.5-3 MeV, $N_{2\gamma}$ is the number of DB photons, the curve is a calculation /12/.

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