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ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ СО АН СССР

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PAIR PRODUCTION AND RADIATION IN ORIENTED SINGLE CRYSTALS: STATUS OF THEORY AND EXPERIMENT

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НОВОСИБИРСК

PAIR PRODUCTION AND RADIATION IN ORIENTED SINGLE CRYSTALS: STATUS OF THEORY AND EXPERIMENT

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Abstract

The modern status of the theory is presented and a comparison with the whole set of experimental data is made. General conclusion: the theory describes the data satisfactorily.

1. The process of photon emission by charged particles and of electron-positron pair creation by a photon are essentially modified in comparison with an amorphous medium when the initial particle is incident at a small angle θ_0 to the direction of the axes or planes of a single crystal. This is due to a collective interaction of some subset of regularly situated atoms of a crystal lattice with the projectile. These problems have been under active investigation during the last years.[1-17] Recently, the authors have developed a general theory of pair creation by photons and radiation of high-energy particles in oriented single crystals which is valid[8-10,12,13] for any energy and any angle of incidence θ_0. It is shown that the important characteristic angle of the problem is $\theta_0 \simeq \theta_V \equiv V_0/m$, where V_0 is the scale of the axis (plane) potential and m the electron mass.

At $\theta_0 \gg V_0/m$, the general theory transforms into the theory of coherent radiation and pair photo-production which was developed in the fifties. From this theory follows that at some particular angles of incidence there is a constructive interference of the contributions to the radiation or pair production at different centers. At definite angles θ_0 and energies, the probability of coherent radiation and pair photo-production (see Refs. 18 and 19 and references therein) differ substantially from the probability of independent (incoherent) radiation and pair production at separate centers, which occur in an amorphous medium (the Bethe-Heitler mechanism). If the angle θ_0 is decreasing but still $\theta_0 > V_0/m$, one obtains from the general theory a modified theory of coherent processes, which has not been discussed earlier. Note that in the coherent theory the perturbation theory is used just as for the Bethe-Heitler mechanism.

At small angles of incidence $\theta_0 \ll V_0/m$, the mechanism of radiation and pair production in a constant external field is acting (for radiation the terms 'magnetic bremsstrahlung' or 'synchrotron limit' are often used). In this situation the effects of the external field should be taken into account exactly by not using the perturbation theory. Constant field mechanism means that the field of the axis (or plane) can be considered constant over the radiation or pair creation formation length $l_f \sim m a_s/V_0$ (where a_s is the effective screening radius), see Refs. 20 and 6. The rest of the problem then reduces to selecting an adequate potential and performing appropriate averages (see Refs. 20-21 and 12-13 for radiation and 6-10 and 14-17 for pair creation). For pair creation it was assumed that capture of the particles of the created pairs into channels play an important role,[22-24] this assumption was, however, not confirmed. In this region of the general theory follow both the constant field limit and the correction to it is $\sim \theta_0^2$. It is important that for high energies the characteristic lengths of the processes of radiation or pair creation appear to be one or two orders of magnitude shorter than that in a corresponding amorphous medium. Due to this fact, specific electron-photon showers will occur in the oriented single crystals.[25] Most strongly, these effects manifest themselves at small angles θ_0 when they are occurring in the external constant field.

For the time being, a series of experiments have been made in which photon and electron beams of SPS at CERN have been used.[1-5] In the present paper the experimental data will be compared with theory.

2. The behaviour of the pair production probability in the crystal depends essentially on the parameter

$$\varkappa = \frac{\omega}{m}\frac{E}{E_0} ,$$

where ω is the photon energy, E the electric field (at a given distance from the axis), and E_0 the critical field $E_0 = m^2/e = 1.32 \cdot 10^{16}$ V/cm. For $\varkappa \ll 1$, the probability W_e^F of the pair production in the field (averaged over the distances from the axis) is exponentially small ($W_e^F \sim \exp(-8/3\varkappa)$) and in single crystals only coherent pair production is a specific effect. For $\varkappa \sim 1$ the probability W_e^F becomes equal to the probability of the incoherent pair production in a corresponding amorphous medium W_{BH} at a photon energy $\omega = \omega_t$ and for $\varkappa \gg 1$ one has $W_e^F \gg W_{BH}$. An orientation dependence of the pair creation probability $W_e(\theta_0)$ reflects the discussed behavior: for $\varkappa \ll 1$ the function $W_e(\theta_0)$ has a minimum at $\theta_0 = 0$, increasing with θ_0 up to a coherent maximum and then decreasing. With a further increase of the energy, the minimum at $\theta_0 = 0$ goes over to a maximum (for $\varkappa > 1$) and with a further increase of energy, the width of this maximum narrows. This rebuild of the picture of orientation dependence is due only to the interrelation between values of probability in the external field $W_e^F(\omega)$ and in the coherent region $W_e^{coh}(\omega)$ (at a given photon energy ω or $\varkappa$). This problem was analysed in detail in Refs. 9-10.

The dependence of the total probability of pair production $W_e^F(\omega)$ on a photon energy ω was measured experimentally[1,3,5] as well as the orientation dependence $W_e(\theta_0)$ for some intervals of ω in the cooled (T=100K) Ge single crystal aligned near the axis <110>. In this situation $W_e^F = W_{BH}$ at $\omega = \omega_t = 50$ GeV and a rebuild of the orientation dependence picture occurs at $\omega \simeq 230$ GeV (see Fig. 3 in Refs. 9 and 10).

The function W_e^F (at $\theta_0=0$) was presented in Fig. 1 of Refs. 8-10. The same curve is shown here in Fig. 1 (the modified incoherent contribution[8] $W_{BH}^M=0.28cm^{-1}$ is added, note that $W_{BH}=0.32cm^{-1}$). The data are taken from Ref. 5. There is quite a good agreement between theory and experiment. The same conclusion is contained in Ref. 5. Now there is a complete agreement also in the theoretical calculation of $W_e^F(\omega)$. The orientation dependence measured in Ref. 5 was there compared only with calculations in which the field of one axis was taken into account[15,16] applicable for $\theta_0<V_0/m$-0.2mrad only. Unfortunately, there is no comparison in Ref 5 with the orientation dependence $W_e(\theta_0)$ found in Refs. 9-10 (see Fig. 4), valid for any θ_0. The curves of orientation dependence are presented in Fig. 2, they are obtained using Refs. 8-10 with additional averaging over the energy intervals, just as in the data of Ref. 5. In general, a quite satisfactory agreement is observed between theory and experiment. Though, for the energy intervals 40-60 GeV and 120-150 GeV there are some discrepancies (not exceeding 20%). It is necessary here to increase both the accuracy of the data (there is also a discrepancy in the coherent region) and improve the theoretical calculations (some approximations were made in the region $\theta_0\sim V_0/m$). It was mentioned that the shift to the left of the maximum of the curve $W_e(\theta_0)$ is due to the more rapid increas with energy ω, the probability $W_e^F(\omega)$ compared with $W_e^{coh}(\omega)$. As a result, the function $_e(\theta_0)$ has a maximum at $\theta_0=0$ starting with an energy where $\varkappa_s\cong(5.1-5.3)\sqrt{\eta}$ ($\varkappa_s=\omega V_0/m^3a_s$, η being the potential parameter for the estimations $\eta\cong 2u_1{}^2/a_s{}^2$, and u_1 the amplitude of thermal vibrations). For the case under consideration this energy is $\omega\cong 230$ GeV. Thus, 1) the position of the maximum of the function $W_e(\theta_0)$ is specific for a given crystal and axis; 2) starting from some energy functions, $W_e(\theta_0)$ has the maximum at $\theta_0=0$. This result is in disagreement with the claim of Ref. 5 that the function $W_e(\theta_0)$ has the maximum at $\theta_0\sim(\alpha\gamma)^{-1}$, meaning that the position of the maximum is not dependent on the crystal and the axis and if shifted to $\theta_0=0$ at $\gamma\to\infty$ only.

3. There are two parameters determining the radiation properties.[12,13] The first one of them, $\varrho=2\gamma^2[\langle\underline{V}^2\rangle-\langle\underline{V}\rangle^2]$ where $\gamma=\varepsilon/m$, ε being the energy of the particle, and $\langle\underline{V}\rangle$ ($\langle\underline{V}^2\rangle$) the average value of the (squared) velocity of the particle, determining the radiation multipolarity; at $\varrho\ll 1$ the radiation is a dipole while at $\varrho\gg 1$ it is of a magnetic bremsstrahlung nature. The second parameter

$$\chi = \frac{\varepsilon}{m}\frac{E}{E_0}$$

determines the quantum (recoil) properties of the radiation; note that already at $\chi=0.1$ the radiation recoil is significant and at $\chi=1$ it dominates. The value of ϱ and the radiation behaviour are dependent on θ_0, the angle of incidence respect the given axis. Below, we will be mainly interested in the region $\theta_0\lesssim\theta_c=\sqrt{2V_0/\varepsilon}$, then $\varrho=\varrho_c=2V_0\varepsilon/m^2$ and for energies under discussion, $\varrho_c\gg 1$. Indeed, for cooled (T=100K) Ge, axis <110>, what corresponds to the conditions of the experiment,[2-4] one has for the energy* $\varepsilon=150$ GeV $\varrho_c\cong 132$.

A local description of the radiation is possible in the magnetic bremsstrahlung limit and due to this for the summation of the radiation contributions of different particles it is enough to

* All the estimates below will be done for this condition.

know their distribution in the transverse to the axis phase space. The dominant processes that change this distribution are radiation and multiple (incoherent) scattering. One can characterize the multiple scattering by the length $l_d(\varepsilon)=\alpha U_0 \varepsilon L_{rad}/2\pi m^2$ (L_{rad} being the radiation length in the corresponding amorphous medium and U_0 the depth of the potential well) at which the increment of the angle due to multiple scattering is $\sim \theta_c$. The characteristic length at which the particle loses its energy $L_{ch}(\varepsilon)=\varepsilon/I(\varepsilon)$, where $I(\varepsilon)$ is the total intensity of the radiation. If the energy increases, $l_d(\varepsilon)$ increases too while L_{ch} decreases (up to its minimum of $\varepsilon \sim 1$TeV), so that there is a particular value $\varepsilon=\varepsilon_{cr}$ when $l_d(\varepsilon_{cr})=L_{ch}(\varepsilon_{cr})$ (see Ref. 26). For Ge one has $\varepsilon_{cr} \simeq (40-60)$ GeV depending on the axis and the temperature. For $\varepsilon>\varepsilon_{cr}$ the radiation angles are inside the angle θ_c. In this region it is impossible to neglect the influence of the radiation on the kinetic of the process; indeed, under the conditions discussed, l_d(150 GeV)=0.51cm, L_{ch}(150) GeV)=0.1cm. However, one should take into account that these values of l_d and L_{ch} are, strictly speaking, for above the barrier motion, i.e. for particles with transverse energy $\varepsilon_\perp > U_0$, for which any distance from the axis is accessible and the distribution over the transverse coordinates is uniform. To be definite, let us use the axially symmetric potential of the axis, introduced in Ref. 27, which for the electrons is convenient to write in the form

$$U(x) = V_0 \ln[(1+1/\eta)/(1+1/(x+\eta))] , \qquad (1)$$

where $x=\varrho^2/a_s^2$, ϱ being the distance from the axis, a_s the screening radius. The quantities V_0, η, a_s x_0 are the potential parameters (see the Table of Ref. 13), $U_0=U(x_0)$, in our case $x_0=19.8$, $\eta=0.063$.

An electron with definite transverse energy $\varepsilon_\perp$ when $\varepsilon_\perp<U_0$ is moving in the region $x<x_1$, where x_1 is defined by $U(x_1)=\varepsilon_\perp$. Assuming that the distribution over x is uniform in the whole accessible region, one obtains that with the decreasing of $\varepsilon_\perp$ (or x_1), the multiple scattering increases proportionally $(x_0+\eta)/(x_1+\eta)$ due to the increase of the mean nucleus density and at $x_1 \simeq 1$ multiple scattering may be a dozen times more intense than for above the barrier electrons. The intensity of the radiation also increases but somwehat slower and, for example, at $x_1=1$ it is 12.5 more intense then for above the barrier of particles. Thus, the crystal may be thin for above the barrier electrons and in the same time thick for the part of the channeled electrons. The situation for positrons is opposite: With the decreasing of $\varepsilon_\perp$ starting from U_0, decreases both the multiple scattering on the nucleus and the intensity of the radiation since the region near the axis becomes for these positrons less and less accessible. So if one excludes very thin crystals, in which the mentioned mechanisms have no time to manifest themselves, we have to consider the complicated kinetic problem which is still not solved, even without radiation effects. In the present paper we will make a qualitative analysis of the situation, looking for the evolution of the mean value $z=\langle\varepsilon_\perp\rangle/U_0$. It is supposed that the initial particles have $z=z(0)<1$. Variation of the functions z and ε is described by a set of equations

$$\frac{dz}{dl} = \frac{1}{l_d(\varepsilon)} \frac{x_0+\eta}{x_1+\eta} - f_1(\varepsilon,z)$$
$$\frac{1}{\varepsilon}\frac{d\varepsilon}{dl} = - f_2(\varepsilon,z) \qquad (2)$$

where

$$f_1(\varepsilon,z) = \int_0^{x_1} \frac{dx}{x_1}\,(z - \frac{U(x)}{U_0})\,\frac{I(x)}{\varepsilon}$$

$$f_2(\varepsilon,z) = \int_0^{x_1} \frac{dx}{x_1}\,\frac{I(x)}{\varepsilon} \qquad (3)$$

Here, $I(x)$ is the local value of the total radiation intensity in the field of the axis. In eq. (2) we used the variable x_1 defined by equality $z=U(x_1)/U_0$. We have analysed the set (2) under some simplified assumptions. For example, functions f_1 and f_2 in the considered interval of energy ε depend weakly on ε and in a first approximation, this dependence may be neglected. For $\varepsilon_0 \equiv \varepsilon(0)=150$ GeV, the first term in eq. (2), which takes into account the influence of multiple scattering, is larger than f_1 if $x_1(0)<1.3$ ($z(0)<0.81$). This means that for particles which possess the lower values of $x_1(0)$, the mean transverse energy is increasing from the very beginning (starting from $l=0$). For particles possessing somewhat larger values of $x_1(0)$, the quantities x_1 and z first decrease as a result of radiation but afterwards due to the decrease of x_1 and mainly due to the energy losses, they become increasing at some depth l. It follows from the solution of eq. (2) that particles losing the main part of their energy in relatively thin crystals, have the 'trajectories' $x_1(l)$ which is confined by some x_1 for all $l \leq L$. For example, in a crystal of thickness $L_1=1.85\cdot10^{-2}$cm all electrons losing energy $\Delta\varepsilon>0.6\varepsilon_0$ have $x_1(l)<4.2$ and for $L_2=4\cdot10^{-2}$cm one has $x_1(l)<11$ for the same $\Delta\varepsilon$.

Thus, there is a group of electrons which, all the time when crossing the crystal, is at significantly shorter distances from the axis than from the maximal distance x_0, i.e. in the region of the higher electric field. The radiation intensity and the probability of this group are enhanced significantly e.g. for

$x_1=2.5$ and $\varepsilon=150$ GeV one has seven times the enhancement for intensity and five times for probability. The radiation spectrum of this group is somewhat harder than that of above the barrier electrons, but the large energy losses are mainly due to a high multiplicity rate of the radiation. A high rate of the multiple scattering and the sizeable dispersion in energy distribution of radiated electrons lead to a strong mixing of the electrons of this group, so that for them distribution over x effectively becomes uniform.

From the analysis fulfilled, one obtains the following simple model which takes into account the influence of the radiation on kinetics. Let us divide all the particles into two groups using an initial distribution in $\varepsilon_\perp$. To the first group belong particles $x_1(0)<x_b$ ($x_b<x_0$) and to the second group all the other particles as channeled as well as above the barrier ones.* It is assumed in the following that the particles of the first group have the uniform distribution over the coordinate for the whole crystal thickness corresponding to some particular value $x_1=x_{ef}<x_b$ and the distribution of all other particles is the same as of the above barrier ones.

Now, knowing the particle distribution, we can calculate the characteristics of the radiation. One can estimate the value of x_b using the solution of the set of equations (2) with allowance for disperson of the distribution in ε and $\varepsilon_\perp$. However, strictly speaking, in the frame of the used consideration both x_b and x_{ef}

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* In a more detailed model one can divide all the particles into three groups: 1) with $x_1(0)<x_b$, 2) all other channeled particles, 3) above the barrier particles, and define their own x_{ef} for the first and the second group.

are the fitting parameters.

When the thickness of the crystal is increasing the values x_b and x_{ef} are increasing too and when x_b becomes equal to x_0 (for the conditions under consideration this thickness is $L \simeq 8 \cdot 10^{-2}$ cm) energy loss of the particles of the second group become similar to those of the particles of the first group such that the contribution of the particles of the first group into spectral distribution over $\Delta\varepsilon$ stops to be distinguished. One should take into account that the number of particles in the first group is always small. So, for $\theta_0=0$ and $\Delta\theta_0=30\mu$rad, only 19% of the particles are channeled from the beginning and, of course, a smaller part of the particle has $x_1(0)<x_b$. A peak (due to the first group) in the spectral distribution over $\Delta\varepsilon$ disappears also in the case of a very small thickness of the crystal because the decrease of the number of the particles in the group (x_b is decreasing) but mainly because of the decreasing multiplicity rate of the radiation. In the conditions of the experiment,[4] it occurs at $L \simeq (5-7)\cdot 10^{-3}$ cm. The value of x_b will be decreasing with the energy increase for the crystals of the fixed thickness and for the above the barrier particles may become significant for their radiative capture into the channel.

Starting a comparison of the theory and the experimental data, let us recall that the detector used in Refs. 2-4 actually sum up the energies of all the radiated photons during the passage so that the distribution of energy losses $y=\Delta\varepsilon/\varepsilon_0$ are really measured. We will present in some figures the photon spectra which significantly differ from the energy loss spectra because of high multiplicity rate. In this case it will be $y=\omega/\varepsilon$, where ω is the photon energy. We will present function

$$F = \frac{a}{L}\, y \frac{dN_1}{dy} + \frac{(1-a)}{L}\, y \frac{dN_2}{dy}, \qquad (4)$$

where, according to the model used, a is the part of the electrons in the first group (index 1). For L=0.14cm we have to put a =0, as it was explained above. The calculation of the orientation dependence of the total energy loss for this thickness was carried out in Ref. 12 and agrees well with experiment.[2,3] The distribution dN_2/dy was found in Ref. 25, where in Fig. 5 is shown the distribution of the particles over energy, which differs from dN_2/dy by a substitution of $y \to 1-y$ only. These results are presented in Fig. 3 in form (4) as well as the experimental data.[2,3] Quite satisfactory agreement of the theory and data* is seen and a drastic difference of the true photon spectra (curve 1) and the energy loss spectra (curve 2) being due to the high multiplicity rate (see discussion in Ref. 25).

For L=0.04cm we use $x_b=11$ and $x_{ef}=6$. Then, for $\theta_0=0$ and the angular divergence of the beam $\Delta\theta_0=30\mu$rad, one obtains $a \simeq 0.15$. The first group particle contribution is demonstrated in Fig. 4. We present the value F at a=0 (curve 2) and a=0.15 (curve 3) as well as the true spectra (curve 1). The data taken from Ref. 3 and also represented in Fig. 4, argue in favour of the existence of the particles of the first group. There are some discrepancies in

* Let us note that the position of the peak (for L=0.14cm) coincides with the theoretical one in Fig. 3 if one takes the data from Fig. III-15 in Ref. 28.

absolute values, possibly connected with the fact that normalization of the curve for L=0.04cm in Fig. 2 of Ref. 3 differs essentially from 1.

For $L=1.85\cdot10^{-2}$cm we use $x_b=4.2$ and $x_{ef}=2.5$. Then for $\theta_0=0$ and $\Delta\theta_0=30\mu$rad one obtains a=0.087 and for $\theta_0=17\mu$rad one has a=0.073. Unfortunately, the spectral distribution in Fig. 3 of Ref. 4 are presented without background subtraction. To avoid this problem, we compared with theory the difference of data for $\theta_0=0$ and $\theta_0=96\mu$rad as well as for $\theta_0=17\mu$rad and $\theta_0=96\mu$rad. All the particles are above the barrier for $\theta_0=96\mu$rad, even with allowance of angular spread in the incident beam (a=0), so that the mentioned difference in the model used is given by the expression

$$\Delta F = \frac{a\cdot y}{L}\left(\frac{dN_1}{dy} - \frac{dN_2}{dy}\right) \quad . \qquad (5)$$

This value for $\theta_0=0$ is shown in Fig. 5 (curve 2) and for $\theta_0=17\mu$rad in Fig. 6. There is quite a good agreement between the calculations and the data, what one can consider as a confirmation of the proposed model of the kinetics. The peak itself in the distribution over $\Delta\varepsilon$ appears due to a high multiplicity rate of the radiation of the particles of the first group. It clearly follows from a comparison of the distribution over $\Delta\varepsilon$ in Fig. 5 with true photon spectra of the same group (curve 1). An additional illustration is shown in Fig. 7 where for thickness $L=1.85\cdot10^{-2}$cm the calculated dependence of the multiplicity (for photon energies $\omega>1$ GeV) on a relative energy loss $\Delta\varepsilon/\varepsilon_0$ is presented: n_1 for the particles of the first group (curve 1) and n_2 for the particle of the second group (curve 2). The observed distribution of the multiplicity is given by the expression $n=an_1+(1-a)n_2$. In Fig. 8 the spectral distribution of the energy loss (curve 4) and true photon spectra (curve 3) are shown for $\theta_0=96$mrad, where electrons and

positrons should radiate in the same manner. As it was mentioned, for positrons at $\theta_0=0$ the crystal with $L=1.85\cdot10^{-2}$cm is a thin one so that we calculated the energy loss distribution (curve 2) and the true photon spectra (curve 1) using the initial particle distribution. It is seen that due to a flux redistribution the radiation of the positrons at $\theta_0=0$ is much weaker than that of the above barrier particles and because of the low multiplicity rate curves 1 and 2 nearly coincide.

Thus, the analysis presented in the present paper shows that the theory quite satisfactorily describes the whole set of the pair production and radiation experimental data in oriented crystals. It should be stressed, however, that the explanation of the radiation data, especially the "new channeling effect",[4] has required a deeper understanding of the kinetic phenomena. Further investigations, both theoretical and experimental, are needed to obtain a complete picture of the radiation in oriented single crystals. It would be worth to diminish the angular width of the incident electron beam; it is also desirable to continue the measurements using crystals of different thicknesses. It would be interesting to make measurements for some particular thicknesses at different energies. In our opinion, the final processing of the existing data is desirable too.

FIGURE CAPTIONS

Figure 1:

The dependence of the total probability of the pair production on photon energy. The curve is taken from Refs. 8-10, the data from Ref. 5.

Figure 2:

The orientation dependence of the total probability of the pair production in given energy intervals. The theory is from Refs. 9 and 10, the data from Ref. 5.

Figure 3: The spectral distribution for crystal thickness L=0.14cm from eq. (4). Curve 1 is a true photon spectra, curve 2 an energy loss distribution. The theory is from Refs. 9, 10 and 25, the data from Refs. 2 and 3.

Figure 4:

The spectral distribution for crystal thickness L=0.04cm in the form (4). Curve 1 is the true photon spectra. Curves 2 and 3 are the energy loss distribution, curve 2 for a uniform distribution and curve 3 contains also the contribution of the particle of the first group. The data are from Refs. 2 and 3.

Figure 5:

The spectral distribution in the form (5) for $L=1.85\cdot10^{-2}$ cm and the angle of incidence $\theta_0=0$. Curve 1 is the true photon spectra, curve 2 the energy loss spectrum. The data are from Ref. 4.

Figure 6:

The same as in Fig. 5 for $\theta_0=17\mu$rad. Curve 2 only.

Figure 7;

The dependence of multiplicity on energy losses. Labels 1 and 2 are for the particles of the first and second group, respectively.

Figure 8:

The spectral distribution in the form (4), $L=1.85\cdot10^{-2}$cm. The true photon spectra, curve 1 for positrons at $\theta_0=0$ and curve 3 for both electrons and positrons at $\theta_0=0=96\mu$rad. The energy loss distribution in the same conditions, curves 2 and 4, respectively.

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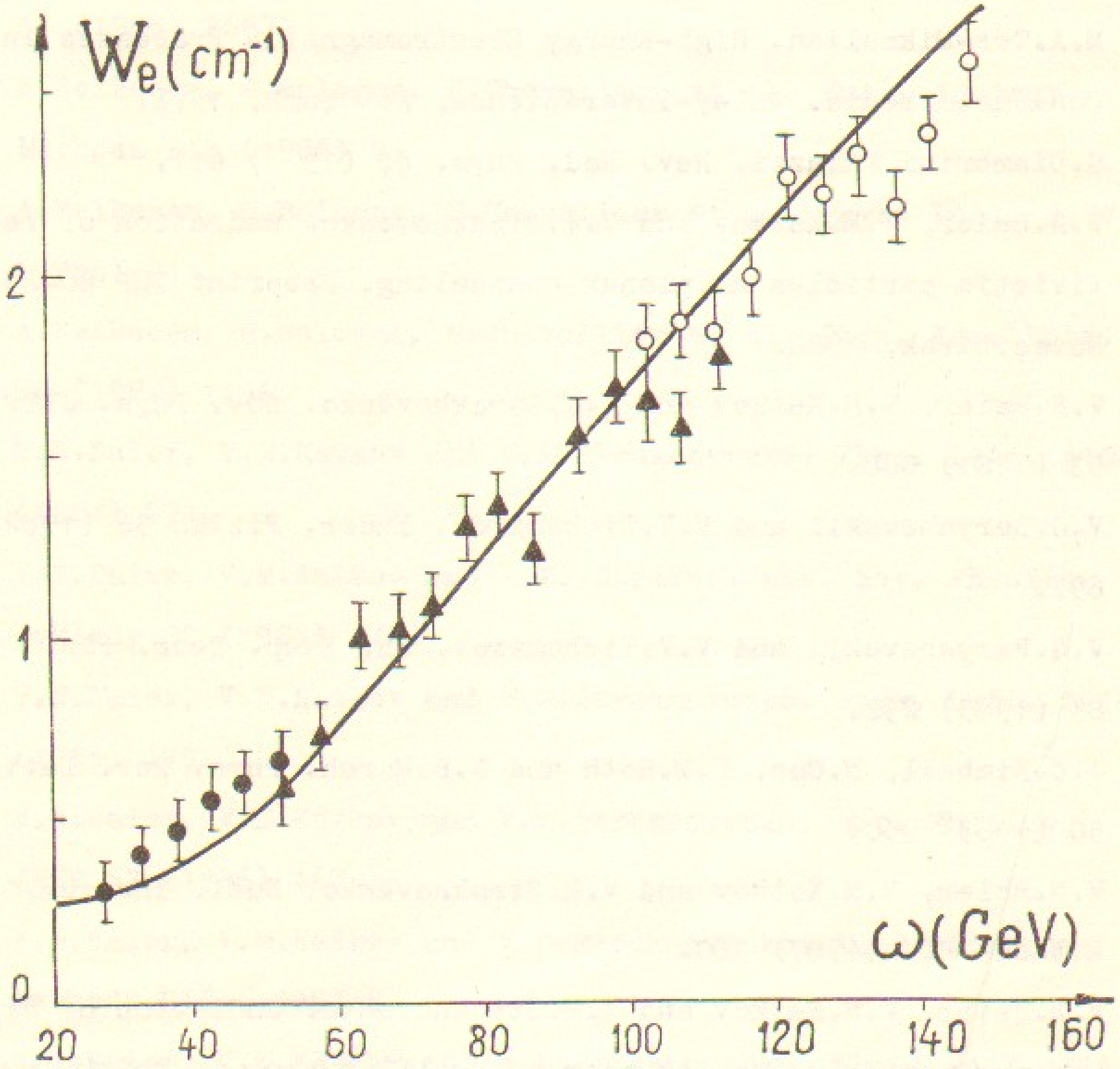
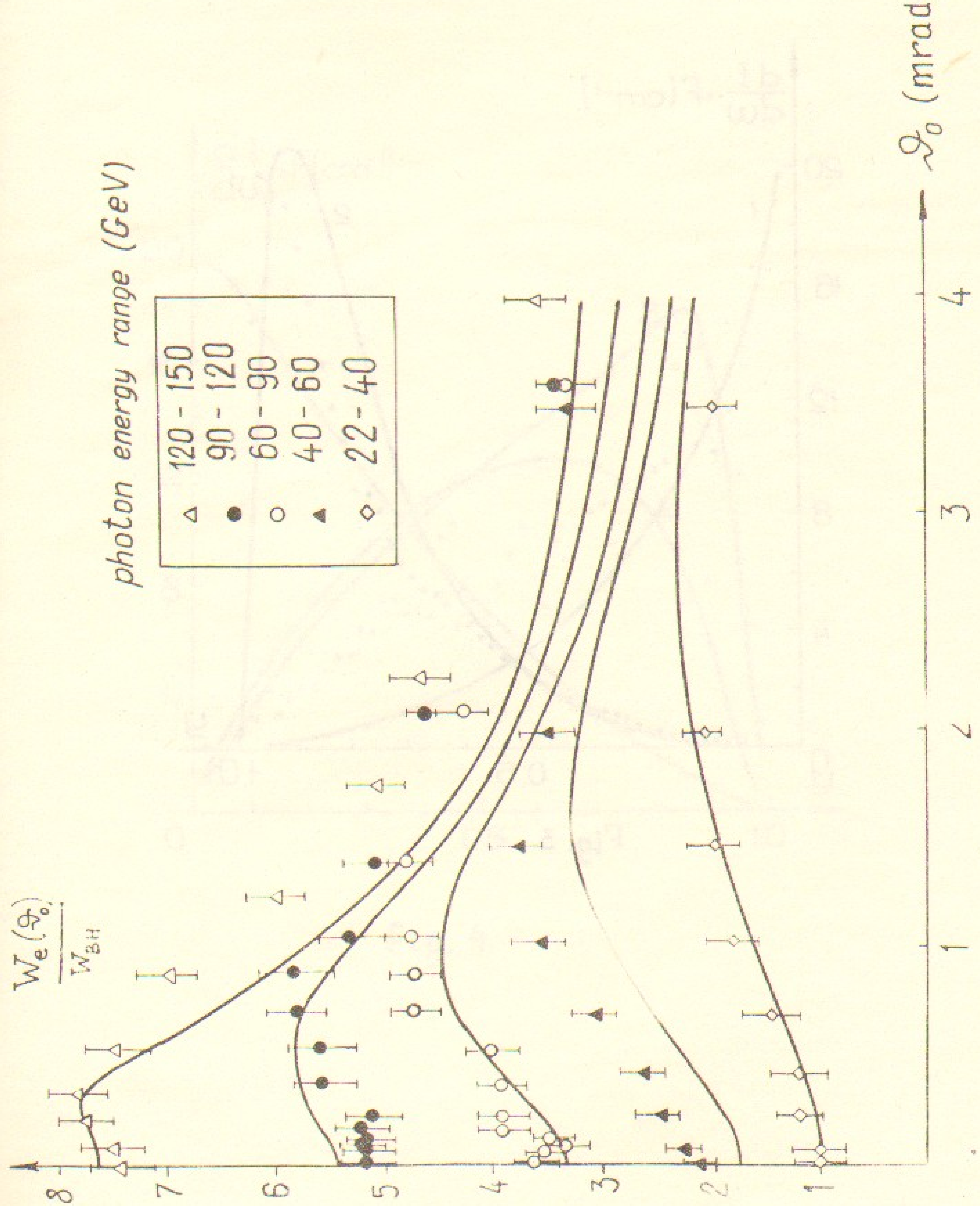


We(cm-1)
ω(GeV)
0
1
2
20
40
60
80
100
120
140
160

Fig.1



We(ϑo)/WBH
photon energy range (GeV)
120 - 150
90 - 120
60 - 90
40 - 60
22 - 40
ϑo (mrad)
1
2
3
4
5
6
7
8

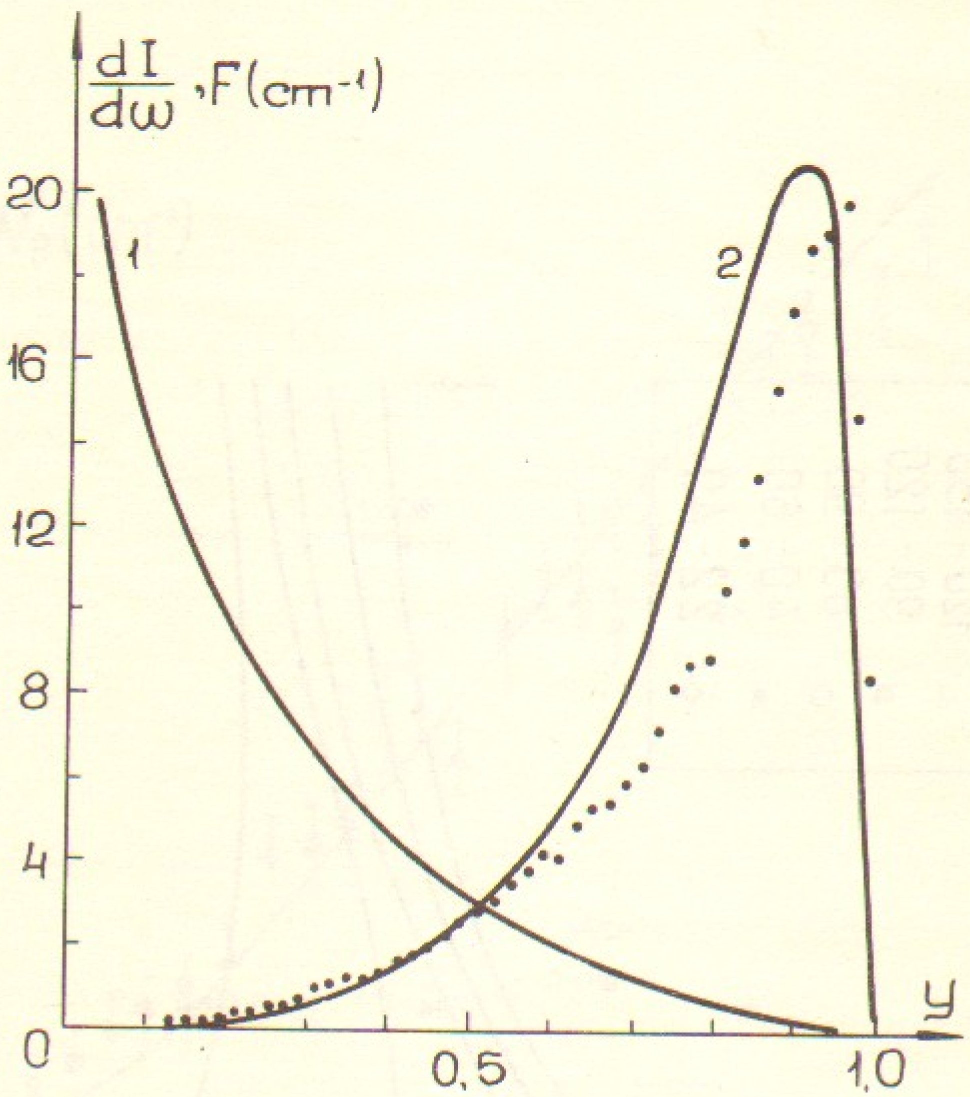


Fig. 3

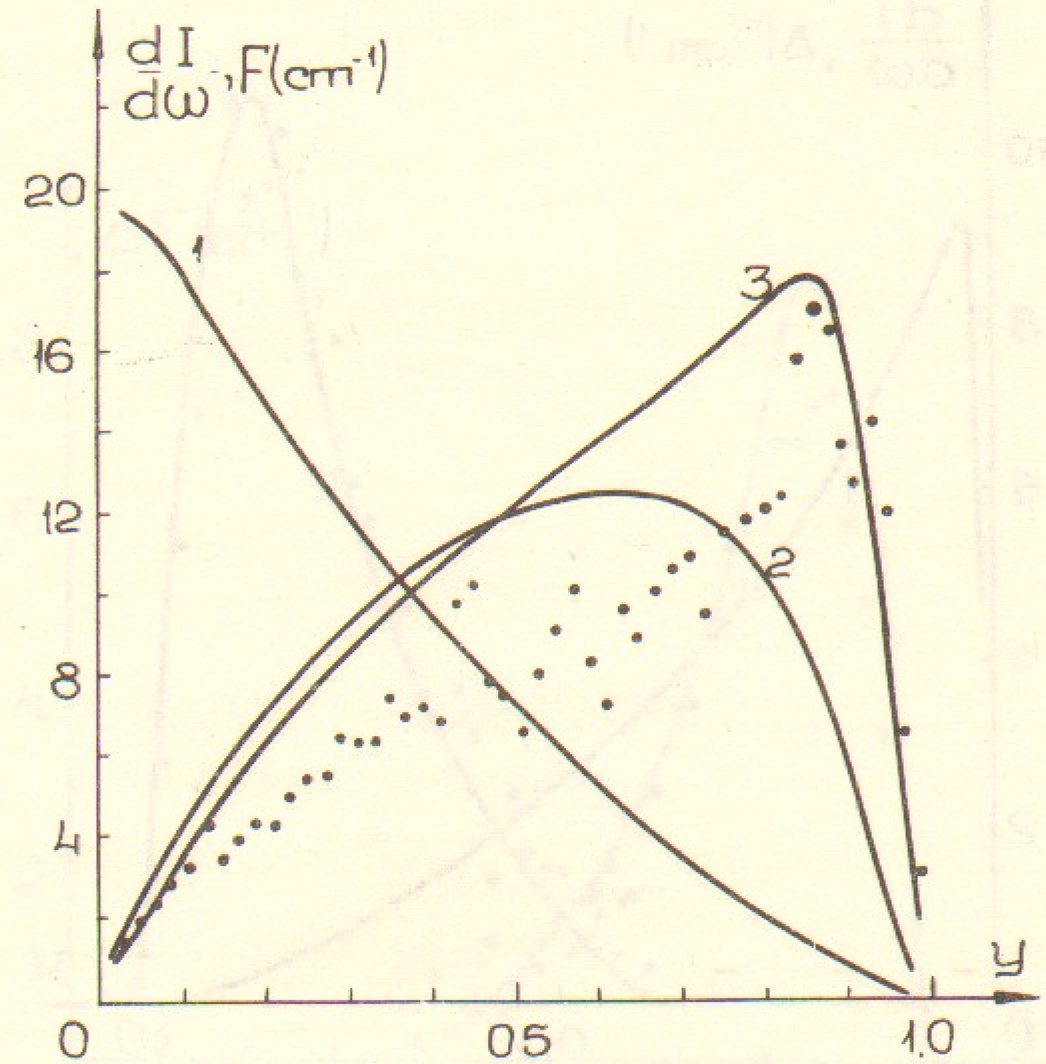


Fig. 4

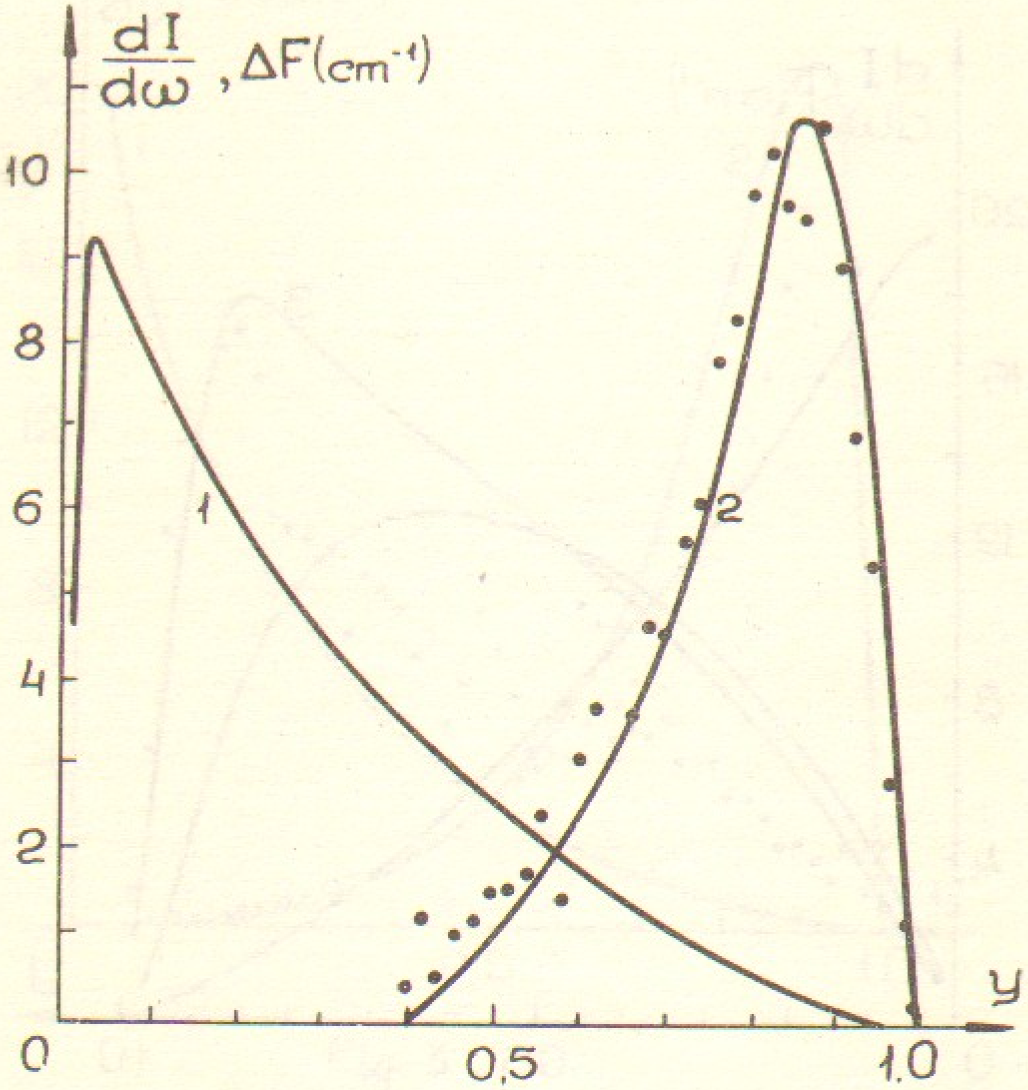


Fig. 5

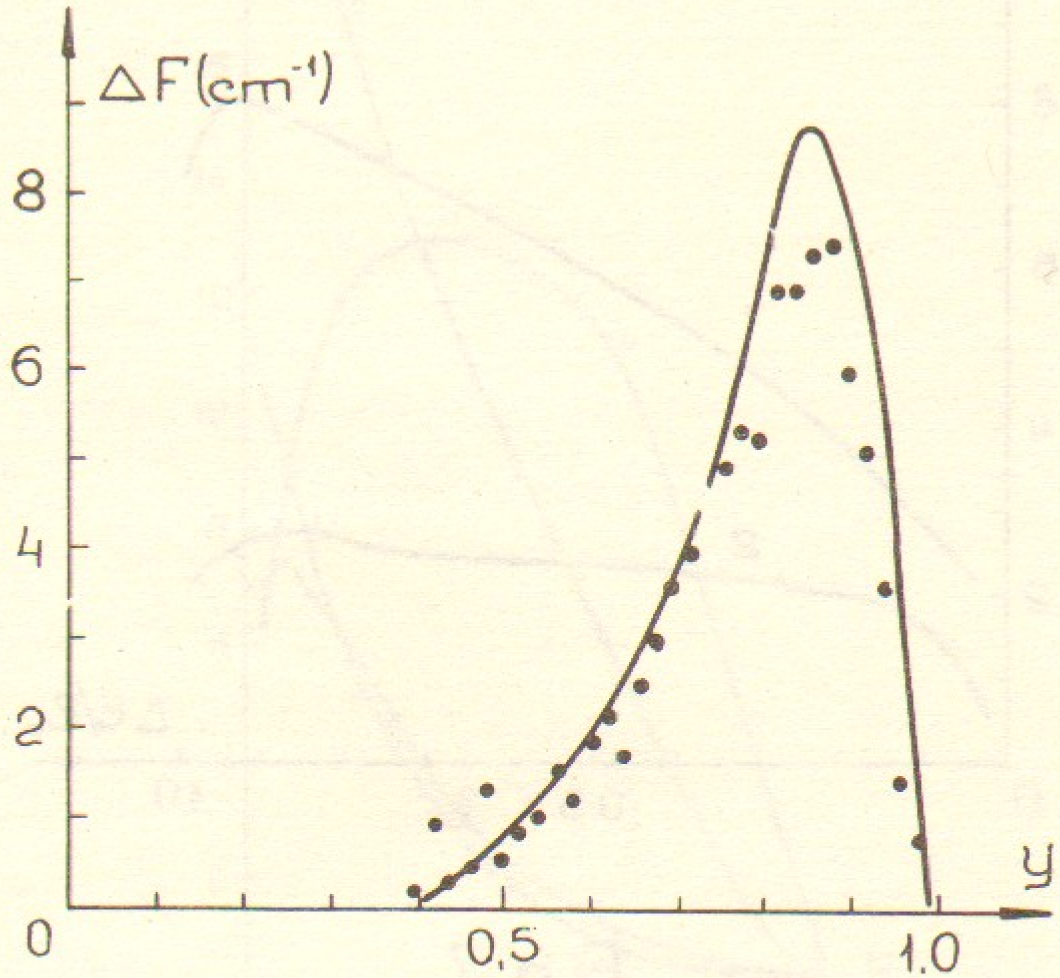
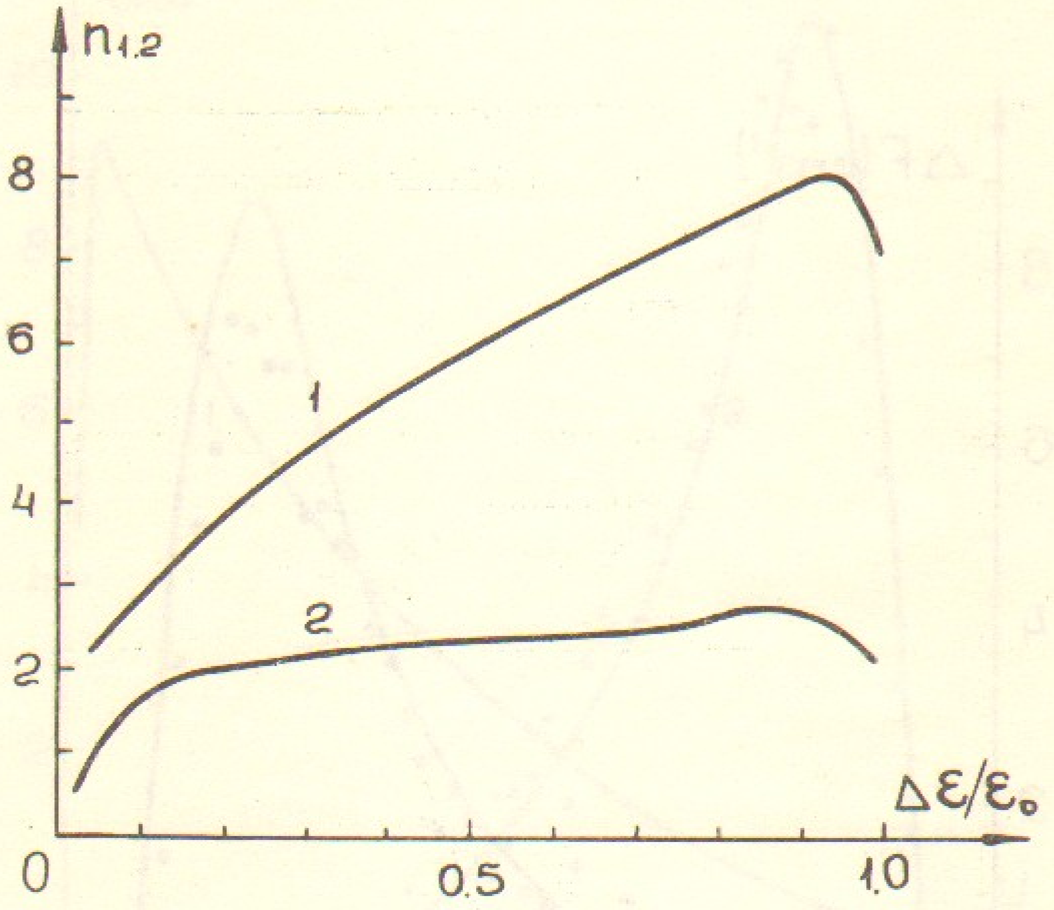
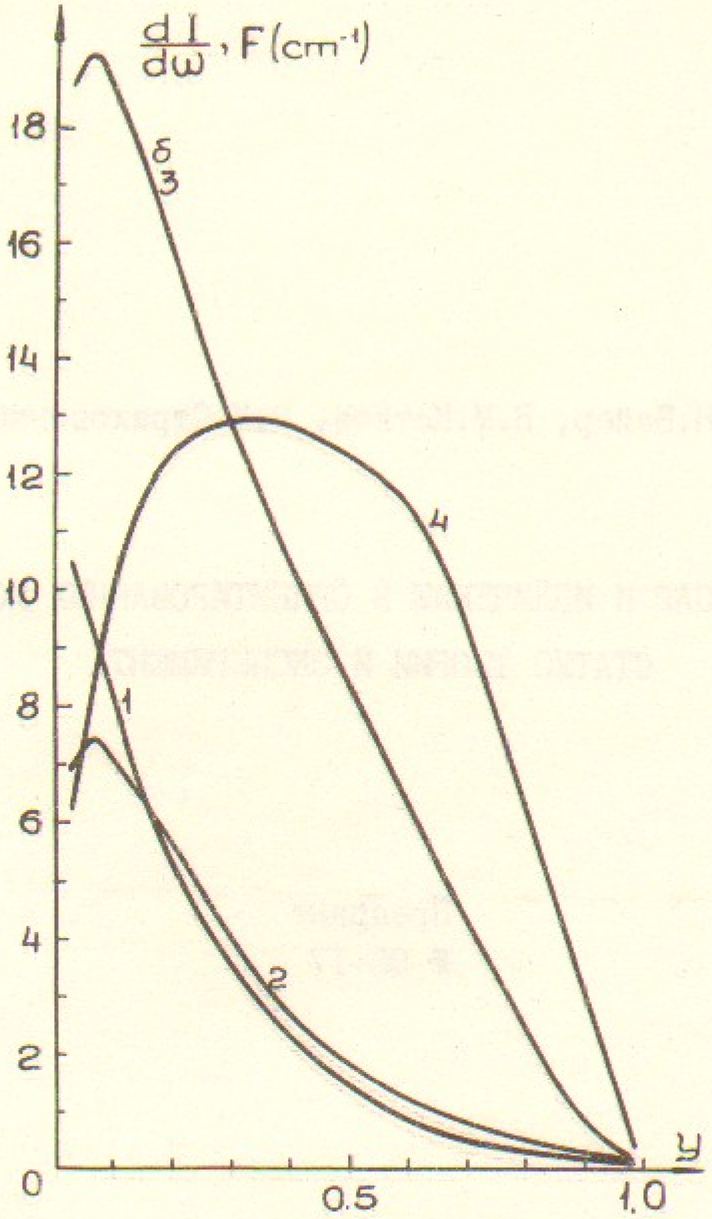


Fig. 6



n1.2
8
6
4
2
0
0.5
1.0
ΔE/E0
1
2

Fig.7



dI/dω, F(cm⁻¹)
18
16
14
12
10
8
6
4
2
0
0.5
1.0
y
δ
3
4
1
2

Fig.8

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РОЖДЕНИЕ ПАР И ИЗЛУЧЕНИЕ В ОРИЕНТИРОВАННЫХ МОНОКРИСТАЛЛАХ:
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