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SCATTERING OF HIGH ENERGY ELECTRONS OFF THERMAL PHOTONS

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Abstract

We have measured the scattering of the LEP beam from the thermal photon background in the beam pipe. The results agree with the predicted rate for a Planck distribution and set a limit $\omega_C < 0.04$ eV on the cut-off frequency appearing in models of stochastic electrodynamics.

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INTRODUCTION

Photon-electron scattering is a fundamental process that has been extensively studied. Here we report on the scattering of high energy electrons, $E_o = 45.6$ GeV, from a distribution of thermal photons, $\overline{\omega}_o \sim 0.07$ eV. The experiment was performed at the CERN large electron-positron collider (LEP) [1]. The pipe in which the beams circulate is under high vacuum ($P \sim 10^{-10} - 10^{-9}$ torr) to avoid beam losses, but it is also a black body cavity at T = 300°K. Thus the circulating beams travel through a sea of photons whose density and spectrum are given by the Planck distribution. While the 4-momentum transfer in these collisions is small $[-(\omega_1 - \omega_2)^2 < m_e]$, the energy transfer can be a significant fraction of the beam energy. Thus at LEP, the beam-thermal photon scattering can be directly observed, but it also contributes to beam losses [2,3].

DESCRIPTION OF THE EXPERIMENT

For head-on collisions of an electron of energy E ($\gamma = E/m_e$), with a photon of energy ω_o, the energy of the scattered photon is given in terms of the c.m. scattering angle ϑ, by [4]

$$\omega' = \omega_o \frac{1+2\gamma^2\ (1-\cos\vartheta) + (2\omega_o\gamma/m)\ (1+\cos\vartheta)}{1+(4\omega_o\gamma/m)} \tag{1}$$

The scattering in the c.m. is adequately described by the Thomson cross-section [5]

$$\frac{d\sigma}{d(\cos\vartheta)} = \pi r_o^2\ (1 + \cos^2\vartheta) \tag{2}$$

where $r_o = e^2/m_e = 2.82 \times 10^{-12}$ cm is the classical electron radius.

The density of thermal photons is given by the Planck distribution

$$\frac{dn_\gamma}{d\omega} = \frac{\omega^2}{\pi^2} \frac{1}{e^{\omega/kT} - 1} \tag{3}$$

and we assume an isotropic distribution in space. The rate of scattered photons was calculated from Eqs. 1-3 after averaging over the electron-photon angle of incidence and integrating over the c.m. scattering angle. This is justified because in the laboratory system the entire spectrum is practically contained in the angular range up to $\theta \sim 1/\gamma$. Since at LEP $\gamma = 10^5$ the angular distribution of the scattered high energy photons is determined by the angle of the incident electron with respect to the equilibrium orbit. The results of this calculation for a 500 m interaction length and a beam current of 1 mA are shown in Fig. 1 for $E_o = 20$ and 45.6 GeV.

The other source of high energy photons is beam-gas bremsstrahlung. The differential cross-section for this process

$$\frac{d\sigma}{dE_\gamma} = 4 r_o^2 \, (\alpha Z^2) \, \frac{F(E_\gamma / E_o, Z)}{E_\gamma} \tag{4}$$

is of the same order as for Thomson scattering provided $(\alpha Z^2) \sim 1$. In Eq. (4), $\alpha = 1/137$ is the fine structure constant and $F(E_\gamma / E_o, Z)$ is a slowly varying function for which we used the average value $F = 5$. The residual gas in the beam pipe is primarily CO molecules and we have therefore set $Z^2 = 100$. The resulting yield from the bremsstrahlung process for a pressure $P = 2 \times 10^{-10}$ torr evaluated for the same interaction length and beam current as for the thermal photon scattering is included in Fig. 1.

The geometry of the experiment is shown in Fig. 2. High energy photons produced by the electron beam over the entire straight section of LEP emerge from a thin aluminium window 20 mm high and 50 mm wide, located just before QL13. The detector was a $15 \times 15 \times 40$ cm^3 leadglass block [6] located at a distance of 45 m from the window. To reduce the effect of synchrotron radiation, the block was surrounded by a 2 cm Pb shield. The leadglass was viewed by a single 5-inch photomultiplier, and the signal was measured by an integrating ADC [7]. The counter was calibrated with cosmic ray muons before being brought in the LEP tunnel and was monitored thereafter by the end-point of the bremsstrahlung spectrum [8]. The counter was operated so as to provide good resolution in the range of few GeV. To explore the high energy region, we maintained the same photomultiplier gain (HV) but attenuated the signal before sending it to the ADC. The calculated resolution was of order $\Delta E_\gamma / E_\gamma \sim 0.13/\sqrt{E_\gamma}$ for $E_\gamma \leq 5$ GeV and remained constant at 0.06 thereafter [9].

EXPERIMENTAL RESULTS

Data obtained with electrons of energy $E_o = 45.6$ GeV circulating in four bunches for a total current I = 530 µA are presented in Fig. 3. In (a) of the figure is shown the high energy part of the spectrum. The solid curve is a fit to the data of the form $A/E\gamma$ for $E\gamma > 15$ GeV. It yields $A = 876 \pm 62$ (counts/s - mA -0.2 GeV) corresponding to an average pressure in the straight section $P = 5 \times 10^{-10}$ torr [10]. The experimental resolution of $\Delta E\gamma/E\gamma = 0.06$ has been used to fit the end-point of the spectrum at $E\gamma = 45.6$ GeV. In (b) of the figure is shown the low energy part of the spectrum which extends to $E\gamma = 2$ GeV. The dashed curve is the bremsstrahlung fit to the data with $E\gamma > 10$ GeV and yields a constant $A = 730 \pm 40$ (counts/s - mA -0.2 GeV). The solid curve is obtained by adding the contribution from the thermal photon scattering after correction for geometrical acceptance [11]; no fitting to the data or normalization correction has been made.

It is evident that the bremsstrahlung spectrum cannot reproduce the data and that the thermal photon scattering exceeds the bremsstrahlung yield by a factor of four, at $E\gamma = 2$ GeV. As a check of these results we also took data at two different beam energies, $E_o = 20$ and 45.6 GeV, with a single electron bunch of low current, I = 58 µA. These data are shown in Fig. 4(a) for the high energy part and in Fig. 4(b) for the low energy part of the spectrum [12]. The solid curves in Fig. 4(a) are the bremsstrahlung fit corresponding to a pressure $P = 1.5 \times 10^{-10}$ torr, as expected for the lower beam current. The same fit is indicated by the dashed curve in Fig. 4(b), whereas the solid curves include the, acceptance corrected, contribution from the thermal photon scattering. In this case, the low energy data could be measured down to $E\gamma \sim 1$ GeV and show qualitative agreement with the theoretical prediction. In particular the difference between the two data sets clearly indicates the presence of the thermal photon contribution which is now dominant.

The low current data, shown in Fig. 4 correspond to a trigger rate of 0.063 per bunch passage. Therefore the probability of two photons reaching the counter during one bunch passage is $\sim 2 \times 10^{-3}$ and can be ignored. Furthermore the contribution from synchrotron radiation, which consists of many low energy photons reaching the counter simultaneously [13], if present, would have triggered the counter at every passage.

DISCUSSION

In models of stochastic electrodynamics [14] the Planck distribution is modified from Eq. 3 to the form :

$$\frac{dn_\gamma}{d\omega} = \frac{\omega^2}{\pi^2}\left[\frac{1}{e^{\omega/kT}-1} + \frac{1}{2}\,g(\omega - \omega_c)\right] \tag{5}$$

where $g(\omega - \omega_C) = 1$ for $\omega \leq \omega_C$ and is zero for $\omega > \omega_C$. Namely the "zero-point energy" modes, up to the cut-off frequency ω_C, are assumed to correspond to real photons which would then be scattered by the electron beam. From the agreement of the data with the predicted rate we can set a limit on the cut-off frequency, $\omega_C < 0.04$ eV.

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REFERENCES AND NOTES

[1] LEP design report CERN-LEP/84-01 (1984).

[2] V.I. Telnov, Scattering of electrons on thermal radiation photons in electron-positron storage rings, Novosibirsk preprint 86-175 (1986).

[3] A.C. Melissinos and G. von Holtey, Scattering of the LEP beam from the 300°K thermal radiation, LEP Note 628 (1990).

[4] We use units $\hbar = c = 1$. Eq. 1 has been written for the case $\gamma >> 1$.

[5] In the c.m. system the average photon energy is $<\overline{\omega}> = 7$ keV for which the Thomson cross-section is still quite valid.

[6] B.J. Blumenfeld et al., Nuclear Instruments and Methods 97 (1971) 427.

[7] Lecroy Research Corporation QVT. The data were taken with an internal trigger, but similar results were obtained when triggering on the passage of the electron bunch.

[8] During a 3-month period in the LEP tunnel we noticed a decrease in the gain of the leadglass block. However, inspection of the block showed no loss of transparency.

[9] At energies $E_\gamma > 5$ GeV the shower is not any more contained laterally in the single block so that the resolution is degraded. In addition, the 2 cm of Pb shielding also contribute to the degradation of the resolution.

[10] The actual pressure over the entire straight section is not known and depends on the total current. However, the pressure deduced from the bremsstrahlung measurement is within the expected range.

[11] The acceptance through the 20×50 mm^2 window, for γ's produced over the entire straight section is 0.70 and practically energy independent. It was calculated by a Monte-Carlo method using a modified version of the program TURTLE.

[12] In this case, the 45.6 GeV data had to be renormalized to the 20 GeV data by a factor of 4.7 because of greatly reduced acceptance. This was due to a bad orbit as also evidenced by the beam pick-ups.

[13] C. Fischer and G. von Holtey, LEP Note 618 (1989).

[14] F. Cardone "On a possible measurement of the zero-point radiation contribution to the Planck's distribution", private communication and submitted to Physics Letters B. See also T.H. Boyer, Phys. Rev. D29, (1984), 1096.

FIGURE CAPTIONS

Fig. 1 The yield of high energy gammas from thermal photon scattering at $E_o = 20$ (diamonds) and 45.6 GeV (squares). The bremsstrahlung contribution for a pressure $P = 2 \times 10^{-10}$ torr and for a 500 interaction length is also shown.

Fig.2 Schematic of LEP straight section 1 showing the location of the apparatus.

Fig. 3 Energy distribution of gammas produced by the electron beam in straight section 1. (a) High energy part showing the bremsstrahlung fit, (b) low energy part : The dashed curve is the bremsstrahlung fit, whereas the solid curve includes the thermal photon contribution.

Fig. 4 As in Fig. 3 but data obtained at two beam energies. $E_o = 20$ and 45.6 GeV is shown. The data were obtained with a single bunch at very low current. (a) High energy part with bremsstrahlung fit. (b) Low energy part with the bremsstrahlung fit (dashed curve), and including the thermal photon contribution (solid curves).

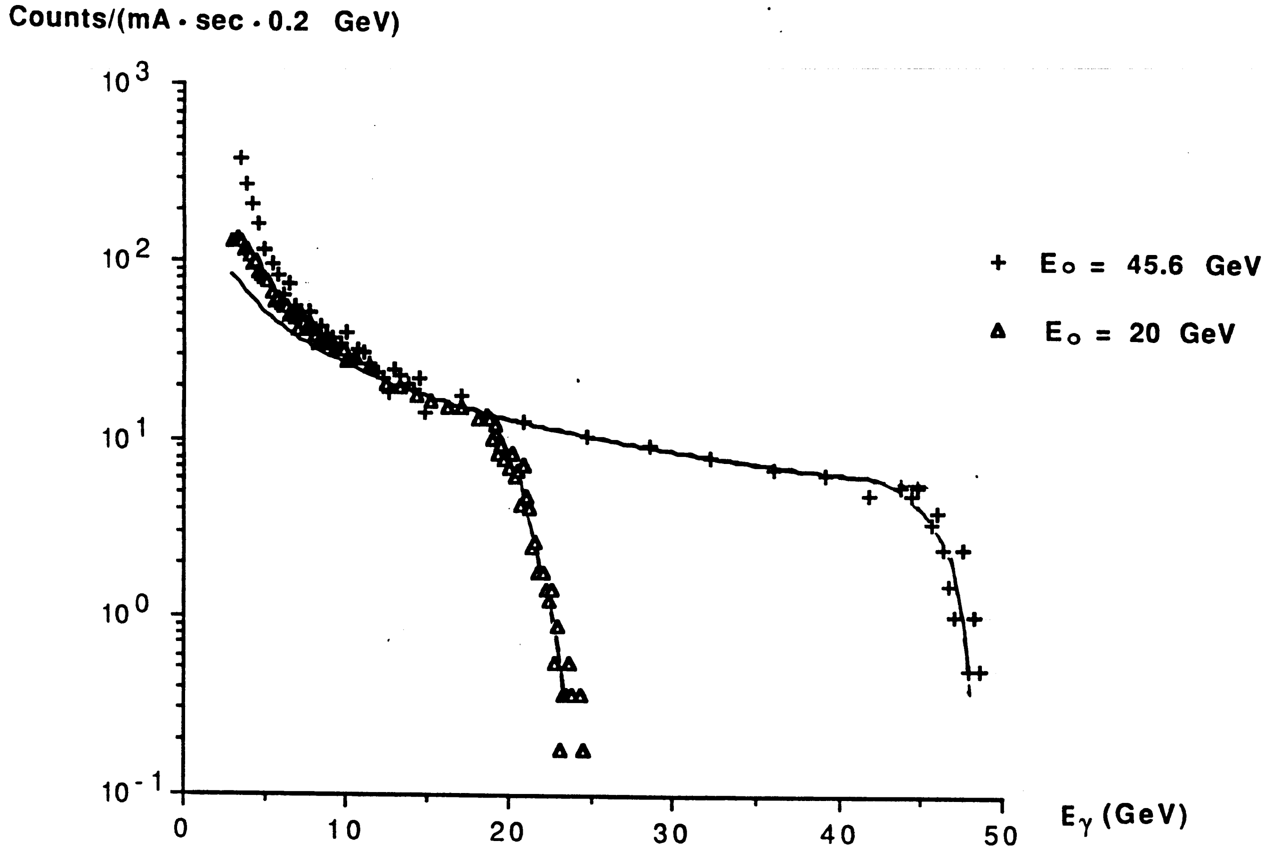
Counts/(mA · sec · 0.2 GeV)
10^3
10^2
10^1
10^0
10^{-1}
0
10
20
30
40
50
E_γ (GeV)
+ E_o = 45.6 GeV
Δ E_o = 20 GeV

Fig. 4 a)

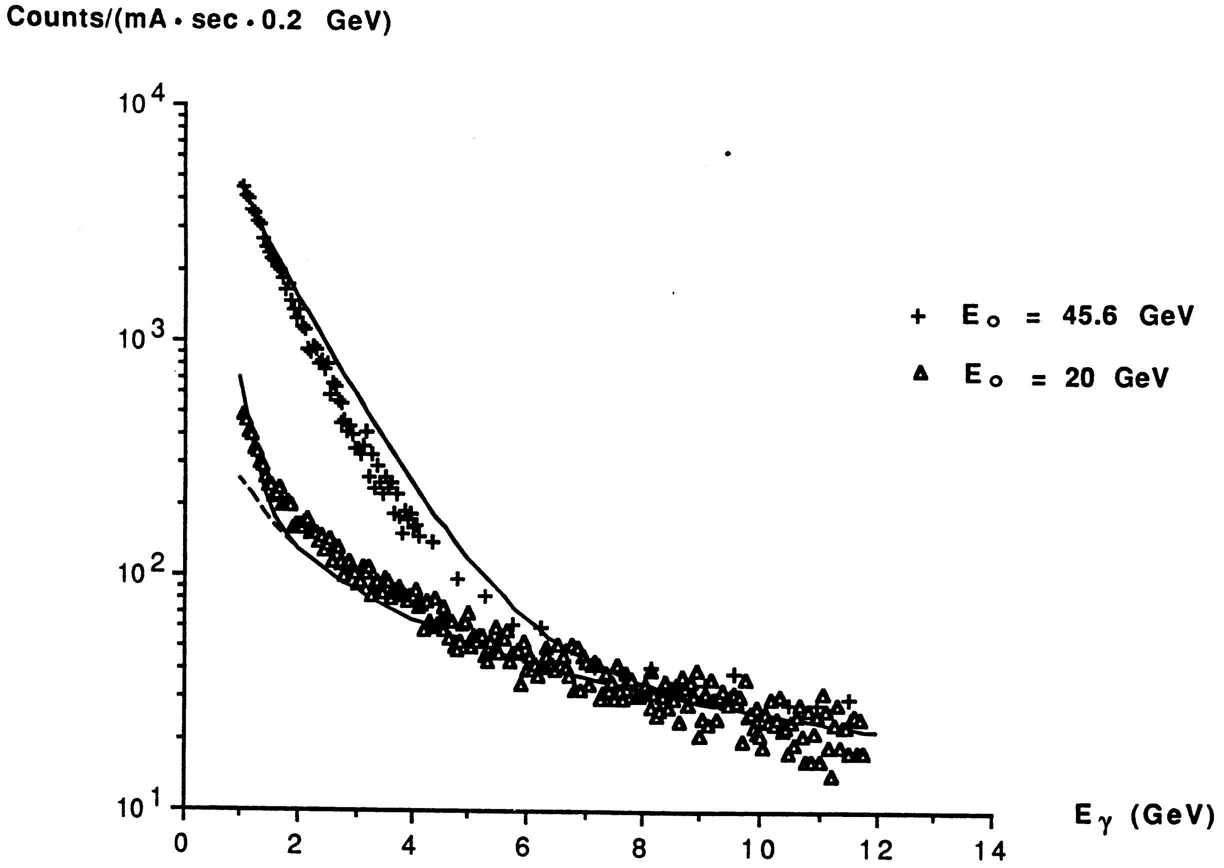
Counts/(mA · sec · 0.2 GeV)
10^4
10^3
10^2
10^1
0
2
4
6
8
10
12
14
E_γ (GeV)
+ E_o = 45.6 GeV
Δ E_o = 20 GeV

Fig. 4 b)

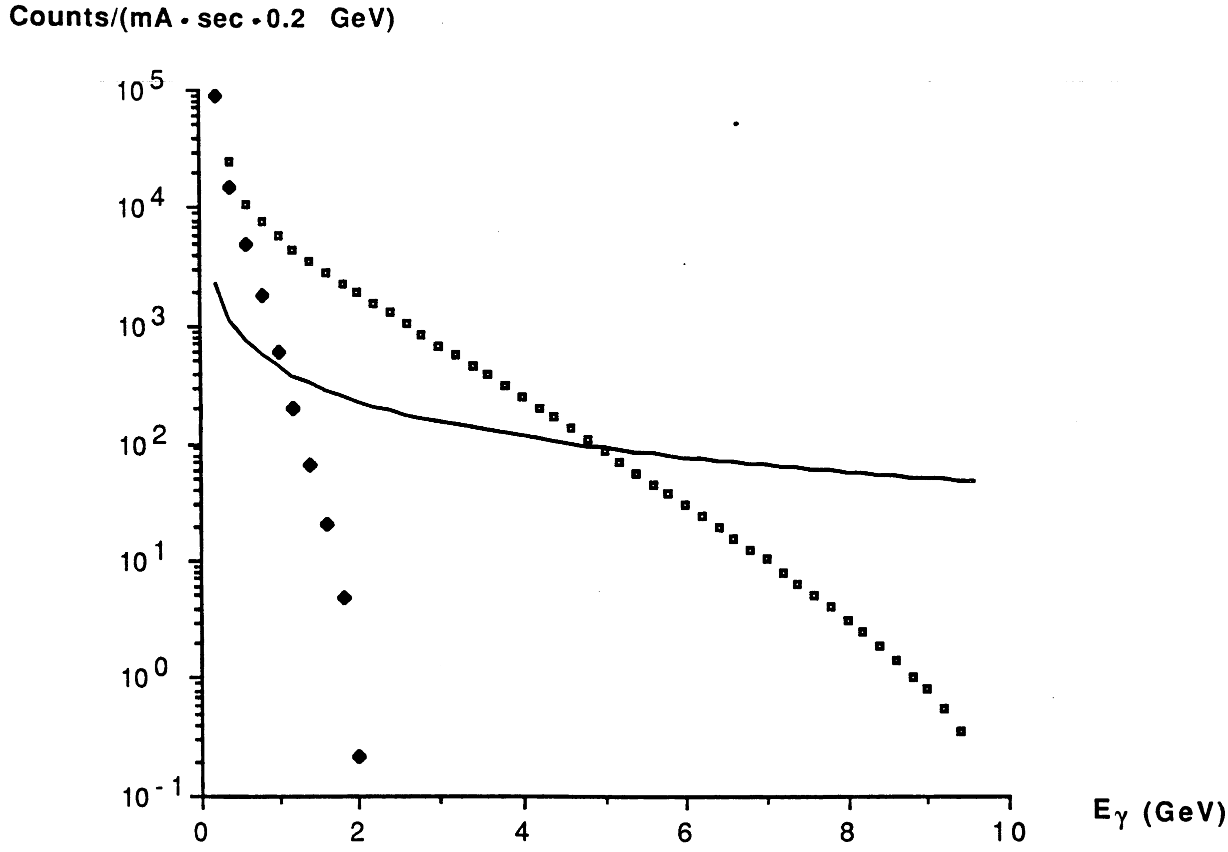
Counts/(mA • sec • 0.2 GeV)
10 5
10 4
10 3
10 2
10 1
10 0
10 - 1
0
2
4
6
8
10
Eγ (GeV)

Fig. 1

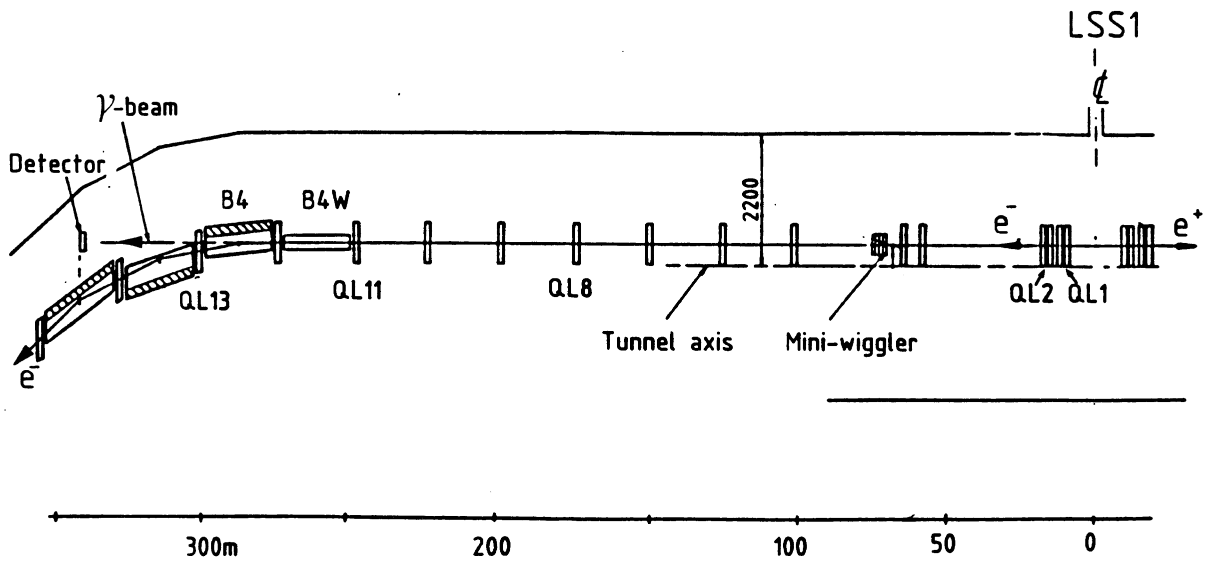
LSS1
γ-beam
Detector
B4
B4W
2200
e⁻
e⁺
QL13
QL11
QL8
QL2
QL1
Tunnel axis
Mini-wiggler
e⁻
300m
200
100
50
0

Fig. 2

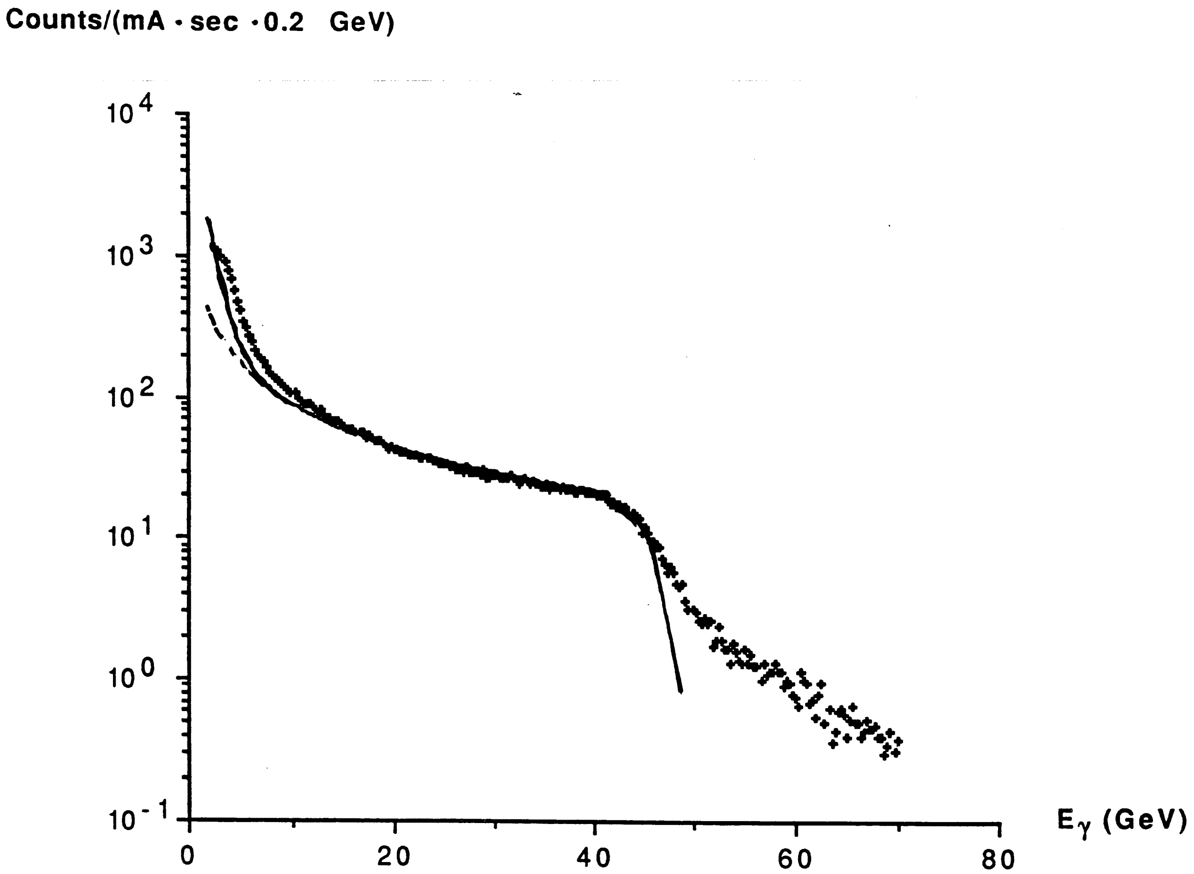
Counts/(mA · sec · 0.2 GeV)
10^4
10^3
10^2
10^1
10^0
10^-1
0
20
40
60
80
Eγ (GeV)

Fig. 3 a)

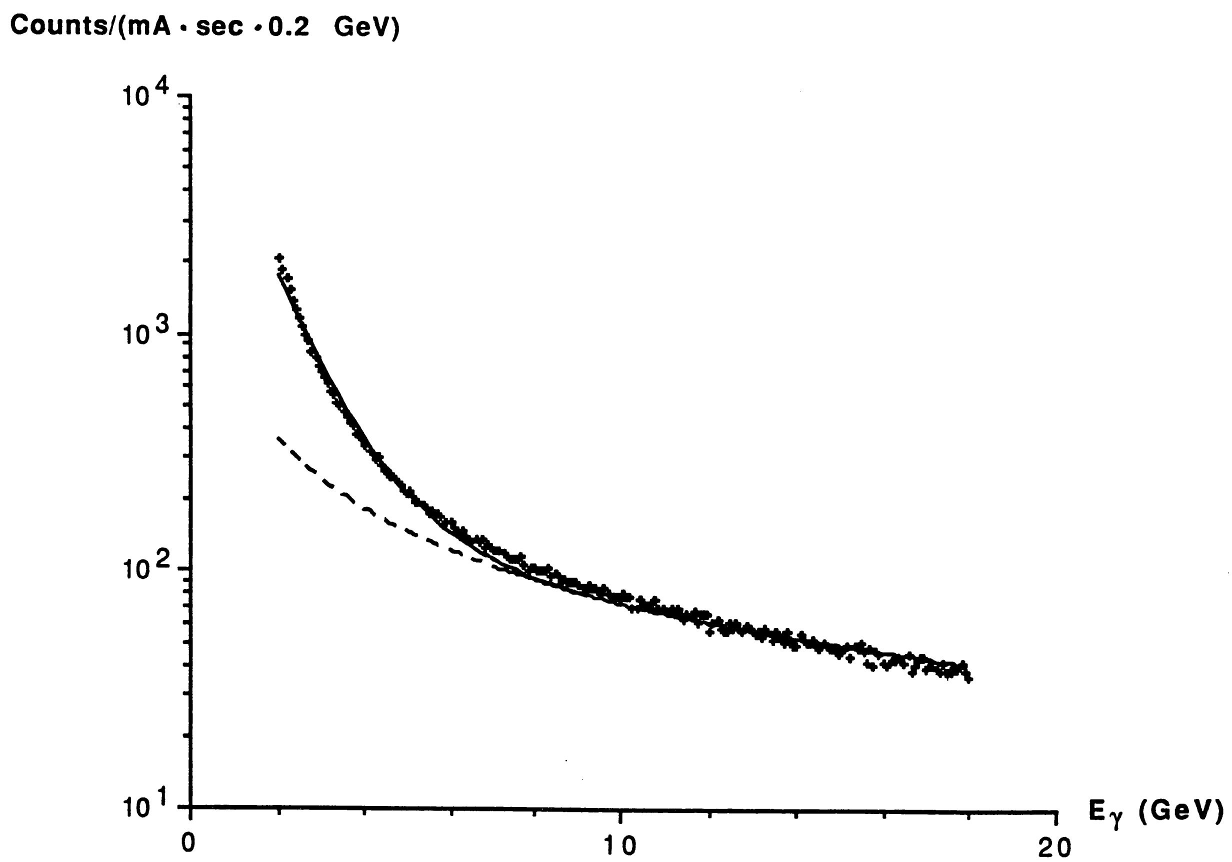
Counts/(mA · sec · 0.2 GeV)
10^4
10^3
10^2
10^1
0
10
20
Eγ (GeV)

Fig. 3 b)