Soft Photon Production in 450 GeV/c p–Be Collisions

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Abstract

We have measured the inclusive $p_T$ spectra of soft photons produced at central and backward rapidities in 450 GeV/c p–Be collisions down to 1 MeV/c in transverse momentum. In the region $1 < p_T < 20$ MeV/c an excess of photons over those expected from hadronic decays is observed. This excess is comparable, within systematic errors, with estimates of direct photons produced via hadronic bremsstrahlung. An upper limit is derived on the presence of additional sources of direct photons at small transverse momentum.

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1 Introduction

The inclusive spectra of photons observed in high-energy hadron–hadron collisions are dominated over a wide range of transverse momentum by photons from the decay of neutral hadrons ($\pi^0$, $\eta$, ...). Additional sources are difficult to detect at moderate $p_T$, and experimentally only upper limits exist. Direct photons have been observed in the region $p_T > 2-3$ GeV/c and, owing to the finite rest mass of the hadrons, at very low $p_T$ [below $m(\pi^0)/2$]. Over a period of many years the high-$p_T$ region has been extensively investigated and is now rather well understood in terms of hard processes such as QCD Compton scattering.

In contrast, the $p_T$ region below $\approx 50$ MeV/c has attracted attention only rather recently and few experiments have investigated low-$p_T$ photons [1-5]. The results obtained are ambiguous: at low $\sqrt{s}$, the observed yield is compatible with hadronic bremsstrahlung [1], whereas at higher $\sqrt{s}$ the cross-section for low-$p_T$ photons was found to be significantly above the bremsstrahlung level [2-4]. Preliminary results of an earlier experiment done by the HELIOS Collaboration seemed to indicate a quadratic dependence of the excess on the charged-particle multiplicity [5]. An upper limit obtained at the ISR, however, rules out a further strong increase with $\sqrt{s}$ [6].

Some of these results are in apparent conflict with the expectation that hadronic bremsstrahlung should be the only, or at least the dominant, contribution to photon production for wavelengths much larger than the size of the photon-emitting system [7]. They have been related to the so-called ‘anomalous’ lepton pair continuum (virtual photons with masses below that of the $p/\omega$) and to a rise seen in the $e/\pi$ ratio at low $p_T$ (see, for example, Ref. [3] and references therein).

In this letter we report the results of an experiment on soft direct photon production in p–Be interactions at an incident proton momentum of 450 GeV/c. To discriminate against the copious background of soft photons not originating from the target and to minimize systematic errors, we have used in parallel two independent detectors, one using photon conversions and the other using time of flight (TOF) for photon identification. In addition, we have measured indirectly the associated hadron multiplicity via transverse-energy production in the same acceptance with a large hadron calorimeter.

2 Experimental set-up and data analysis

The data were taken in a modified set-up of the HELIOS experiment at the CERN SPS [8]. As shown in Fig. 1, two types of photon detectors were used: a combination of gas chambers, converter plates and a BGO matrix for the conversion method located at one side of the beam, and a BaF$_2$ array for the TOF method located at the opposite side. The target area was equipped with a number of scintillator counters: a beam scintillator to provide a fast timing signal, a large counter with a central hole to veto upstream interactions, and six paddles placed 19 cm downstream of the target used as an interaction trigger. The targets (2.5% and 5% interaction length Be) were mounted in a special low-mass support to avoid secondary interactions. A part of the HELIOS uranium–scintillator calorimeter, located 3 m downstream from the two photon detectors, was utilized to measure and trigger on transverse energy in the pseudorapidity range $|\eta_{cm}| < 0.5$.

2.1 The BaF$_2$ detector

The BaF$_2$ array [9] was assembled from 19 hexagonal crystals (inner diameter 5 cm, 15 $X_0$) and read out with fast, quartz-window phototubes. It was located about 4 m downstream from the target (Fig. 1) and could be moved from $\theta = 3.7^\circ$ ($Y_{cm} = 0$) to
\[ \theta = 40^\circ (Y_{cm} = -2.4) \]. A scintillator in front of this array was used to reject charged particles. To allow for systematic checks and estimate the background from neutral hadrons, a 10% Pb converter followed by a second scintillator was installed in front of the BaF$_2$ for part of the run to positively identify converted photons by requiring no signal in the first and twice the pulse height of minimum ionizing particles in the second scintillator.

![Diagram of experimental setup](image)

**Figure 1**: Experimental set-up. The BaF$_2$ array could be moved between the two extreme positions shown in the figure. The BGO assembly, including proportional and drift chambers, is shown in the inset.
The energy response of the BaF$_2$ calorimeter was measured with a $\gamma$ source and in a test beam at the CERN PS. After correcting for back- and side-leakage, evaluated with the GEANT Monte Carlo, the response was measured to be linear to better than 2% over the energy range $6\text{ MeV} < E < 4\text{ GeV}$. The energy resolution varied from 15% at $E = 6\text{ MeV}$ to 1.6% at $E = 4\text{ GeV}$ and can be parametrized as $\Delta E/E = 3.2\%/\sqrt{E}$ for $E > 0.5\text{ GeV}$. During data taking, the calibration was stabilized by continuously monitoring the energy loss of minimum ionizing particles.

The timing resolution of a single crystal was measured with a well-focused, monochromatic test beam to be $\sigma = 80\text{ ps}$ at $E = 2\text{ GeV}$. In the actual measurement, the overall timing resolution, including the contribution of the start counters, long-term variations, and geometrical variations in the light propagation time within the 30 cm long crystals, varied between $\sigma = 500\text{ ps}$ at $E = 10\text{ MeV}$ and $\sigma < 250\text{ ps}$ at $E > 300\text{ MeV}$.

In order to ensure that the measured photons originate in the target, we utilized the excellent timing property of BaF$_2$. Measuring the TOF of photons is equivalent to measuring their path length before reaching the detector. By requiring this path length to be consistent with the distance between target and detector, we could reject most of the background photons arising from showers in the material surrounding the experiment. We took great care to minimize any material which might serve as a source of secondary photons with TOF differences less than our cut of $\approx 1\text{ ns}$, which corresponds to a path-length variation of 30 cm. The importance of "pointing" back to the target can be seen in Fig. 2, where the TOF is shown as a function of the photon energy. An increasing contribution of out-of-time (secondary produced) photons can be identified at low $E_{\gamma}$, amounting to almost 50% of all photons with $E < 100\text{ MeV}$ ($p_T < 6\text{ MeV}/c$ at $Y_{cm} = 0$). Secondary production in the target itself was studied with targets of different thicknesses and found to be small. The contamination by neutral hadrons ($n, K^0$) was reduced by the TOF cut and a shower-shape analysis to a negligible level, as was verified experimentally with the data sample of converted photons.

![Figure 2](image)

Figure 2: Time of flight as a function of photon energy in the BaF$_2$ at $Y_{cm} = 0$. An increasing fraction of secondary photons, which are produced in the material surrounding the experiment and therefore reach the detector at late times, can be seen at small photon energies.
In order to improve the position resolution to $\approx 14\%$ of the crystal diameter and to recognize overlapping showers, a shower-shape analysis [10] was performed for each photon by comparing the lateral profile with the one expected from GEANT simulations (version 3.13). Only single photons inside a fiducial volume (central seven crystals) and with a minimum energy of 10 MeV were accepted.

The data were corrected for trigger efficiency, pattern recognition, and analysis cuts. The energy dependence of these corrections is very weak ($< 10\%$). At forward angles, an additional correction of 10–20\% had to be applied for background photons (not originating directly from the target) which could not be rejected by the TOF cuts (see below). At high $p_T$ ($> 500$ MeV/c) corrections for pile-up of more than one photon in the detector led to large systematic errors, particularly at forward angles.

The systematic errors were estimated by varying analysis cuts, allowing for calibration errors (energy and position) and comparing data sets taken with different triggers and experimental conditions. The individual sources were estimated as a function of $p_T$ and added in quadrature; the resulting total systematic error is less than $\pm 8\%$, for $p_T > 30$ MeV/c, and increases to $^{+16}_{-10}\%$, for $p_T < 2$ MeV/c.

Further details on data analysis and systematic errors can be found in Ref. [11].

2.2 The BGO detector

The data of the second experiment were taken with the BGO detector (Fig. 1). Photons were identified by their conversion in two thin (10\% and 3\% $X_0$) iron foils sandwiched between three multiwire proportional chambers (MWPCs), each of which has a signal efficiency of more than 99\%. The tracks of the generated $e^+e^-$ pair are recorded in a small drift chamber measuring the $x$ and the $y$ projections of the track with a precision of $\approx 400$ $\mu$m per module, corresponding to an angular resolution of $\approx 7$ mrad. The energy is measured using a $6 \times 6$ matrix of BGO crystals ($2 \times 2 \times 20$ cm$^3$ each, 18 $X_0$ depth) with a resolution of $\Delta E/E = 2.6%/\sqrt{E}$. The photon trigger required either the absence of a signal in the first MWPC and a signal in the second and third planes to select conversions in the first (thicker) converter foil (CONV1-trigger), or the absence of a signal in the first two MWPCs and a signal in the third MWPC to select conversions in the second (thinner) converter (CONV2-trigger). Owing to the high efficiency of the MWPCs the probability for a charged particle to generate a false photon signal is small ($\approx 0.7\%$ for the CONV1-trigger and $< 0.1\%$ for the CONV2-trigger). The average detection efficiency for a converted photon is 77\% for CONV1 and 62\% for CONV2 triggers.

To determine the photon energy the electromagnetic showers in the BGO matrix are reconstructed by fitting a two-dimensional Gaussian distribution to the energy deposited in an array of $3 \times 3$ crystals. This ensures that the total energy of the photon is sampled even if the pair is opened by multiple scattering and only one electron track is reconstructed owing to the limited double-track resolution of the chamber. The impact point of the pair is found with a precision of 2.5 mm, which allows an unambiguous match between the BGO shower and the tracks reconstructed in the drift chamber. To minimize the losses due to the side leakage of the electromagnetic showers in the BGO, the reconstructed shower centres are required to be located within the inner sixteen crystals of the $6 \times 6$ array. Only events with exactly one shower within this fiducial area are accepted in order to avoid fake soft photons arising from split showers. Another cut is made on the shower radius to suppress the background of minimum ionizing particles in the calorimeter. Photons not originating from the target are rejected by pointing the tracks measured in the drift chamber back to the primary vertex. The $p_T$-dependent correction
for acceptance and the reconstruction efficiency were determined by means of a full
detector simulation based on GEANT. In the region of $p_T < 15$ MeV/c the efficiency of the
detector changes rapidly as a function of the decreasing conversion probability and the
increasing probability of losing one or both converted electrons by absorption or deflection
in the detector material between the conversion point and the BGO calorimeter. The
accessible momentum range was limited at high $p_T$ by the dynamic range of the readout
electronics which starts to saturate at $p_T > 500$ MeV/c.

The systematic error on the BGO data was estimated by varying the analysis cuts
and changing the parameters of the detector simulation within reasonable limits. The
resulting error is of the order of a few per cent for $p_T > 30$ MeV/c and increases up
to 20% for $p_T < 5$ MeV/c. The uncertainty in the energy scale ($< 5\%$) leads to an
additional error of $\approx 20\%$ at small $p_T$. The individual errors were combined quadratically
for each bin separately for positive and negative contributions. To account for a remaining
systematic difference of about 20% between the CONV1 and the CONV2 samples in the
region 10 MeV/c < $p_T$ < 25 MeV/c (Fig. 3) the total systematic error has been increased
by a scaling factor ($S = 1.14$) determined from the $\chi^2$ of both samples with respect to
their mean. The resulting systematic error is less than 10% in the region 15 MeV/c <
$p_T$ < 300 MeV/c and rises up to 55% for $p_T$ < 5 MeV/c owing to the large acceptance
corrections at small $p_T$.

Further details on data analysis and systematic errors can be found in Ref. [12].

![Graph](image)

**Figure 3:** Inclusive photon $p_T$ distribution from the BGO for two different triggers (open symbols CONV1, full symbols CONV2, see text). The full lines represent the contribution (upper and lower limits) from the decay of hadrons; they are normalized to the data in 100 < $p_T$ < 300 MeV/c.
3 Background calculations

The main contribution to the inclusive photon spectrum in $0.01 < p_T < 1$ GeV/c comes from hadronic decays of meson and baryon resonances. In order to evaluate the systematic errors in the background calculation, we used a number of Monte Carlo generators and independently an analytic deconvolution of the measured inclusive photon $p_T$ and rapidity distribution. Below 10 MeV/c, the only additional known source of direct photons is hadronic bremsstrahlung, which was calculated in the soft photon limit.

3.1 Hadronic decays

The hadronic decay spectrum was estimated in several independent ways. The first used a Monte Carlo program [13] based on a parametrization of particle production at the CERN ISR. The $\pi^0 p_T$ spectra were generated by averaging over published $\pi^+$ and $\pi^-$ data, and isospin-breaking contributions (e.g. $\eta \rightarrow 3\pi^0$) were added separately. Because of lack of experimental data for heavier mesons ($\eta$, $\eta'$, $\omega$) at low $p_T$, their cross-section relative to pions was fixed at high $p_T$ according to experimental results ($\eta/\pi = 0.55$, $\eta'/\pi = \omega/\pi = 0.9$), and scaling with the transverse mass was used to obtain the respective $p_T$ distributions [13]. The contribution of baryonic decays ($\Sigma^0$, $\Sigma^+$) was added but found to be small.

The resulting photon spectra were then compared with the ones generated with the LUND Monte Carlo (PYTHIA 5.3 in minimum bias mode) and the nucleus–nucleus generator VENUS 3.11 [14] (simulating p–Be collisions). The spectra of the three generators, when normalized with respect to each other at high $p_T$ (100–300 MeV/c), differ in their shape at low $p_T$ (< 100 MeV/c) by 5–15%, depending on rapidity and $p_T$.

In addition, we used an independent method to estimate the decay background directly from the measured photon $p_T$ and rapidity distributions [15]. This formalism, originally developed by Sternheimer [16] and subsequently used in Refs. [2, 3], is based on an analytical deconvolution of the photon cross-section $d\sigma(\gamma)/dydp_T$ with $p_T > m(\pi^0)/2$, to extract the corresponding $\pi^0$ cross-section $d\sigma(\pi^0)/dydp_T$.

The systematic error was estimated by comparing the various background calculations. We found that the decay photon spectrum is rather insensitive to contributions from hadrons other than $\pi^0$'s, which are the dominant source of low-$p_T$ photons (> 80% for $p_T < 200$ MeV/c), and to the exact shape of the $\pi^0 p_T$ distribution. The biggest uncertainty, of the order of 15% for $p_T < 30$ MeV/c, is introduced by changing the $\pi^0$ rapidity distribution. Owing to the kinematics of the $\pi^0$ decay, a major fraction of the soft photons measured, for example, at $Y_{cm} = 0$ originate from $\pi^0$'s which are produced at a rapidity of $|Y_{cm}| > 1$.

3.2 Hadronic bremsstrahlung

Besides hadronic decays, the only additional known source of prompt photons at low $p_T$ comes from hadronic bremsstrahlung. The contribution was calculated in the soft-photon limit [2, 7, 17] by summing coherently over the incoming and outgoing electromagnetic currents:

$$\frac{d^2 N(\gamma)}{dydp} = \frac{\alpha}{4\pi^2} \frac{1}{p_T} \left[ -J(y, \phi) \times J(y, \phi) \right],$$

$$J(y, \phi) = \sum_{j=1}^{N_{ch}} q_j \bar{P}_j \left[ \sqrt{m_j^2 + p_{Tj}^2} \cosh (y_j - y) - p_{Tj} \cos (\phi_j - \phi) \right].$$
The sum in $\vec{J}$ runs over all charged particles $j$ with four-momentum $P_j$, with the initial-state particles having their charge $q_j$ reversed. This formula is exact in the soft-photon limit to the order of $1/p_T$ and was used in Refs. [1-3] to evaluate the level of bremsstrahlung from the measured exclusive charged-particle distributions on an event-by-event basis. We did not measure the charged particles in our experiment, but use the LUND Monte Carlo instead to model the distributions and correlations of all final-state hadrons. A comparison of the cross-section for bremsstrahlung using either data or LUND generated events was performed by Chliapnikov et al. [2], yielding almost identical results.

To test the model dependence of our bremsstrahlung calculation, we used different versions of the LUND generator (LUUOPT from JETSET 6.1 and PYTHIA 5.3), included Bose–Einstein correlations, ‘mini-jets’ ($q_T > 2$ GeV/c), diffractive reactions, etc. In order to be independent of absolute cross-sections, we use the relative ratio of bremsstrahlung to decay photons in the Monte Carlo to normalize to our data. This ratio is largely independent of the charged-particle multiplicity and the various Monte Carlo options used, varying at most by $\approx \pm 10\%$ at $Y_{cm} = 0$ and $\approx \pm 25\%$ at $Y_{cm} = -2.4$.

4 Results and discussion

The corrected $p_T$ spectra obtained with the BGO (conversion method) in p–Be reactions at $Y_{cm} = 0$ are shown in Fig. 3 for the two different trigger samples (CONV1 and CONV2), normalized with respect to each other for $100 < p_T < 300$ MeV/c. Because the two data sets are only marginally consistent within statistical errors, their common (and correlated) systematic error has been increased by a scale factor of $S = 1.14$. The decay background, shown as solid lines for upper and lower limits, is normalized to the data in the range 100–300 MeV/c; the underlying assumption that direct photon production is small in this region is supported by data from pp collisions, where it is found that $\gamma$(direct)/$\pi^0 < 2\% [18]$ at medium $p_T$. The upper and lower curves reflect the systematic error in the shape of the background for $p_T < 100$ MeV/c using different Monte Carlo generators and the analytic deconvolution method. The BaF2 data are shown in Fig. 4a together with the combined BGO results at $Y_{cm} = 0$, and in Fig. 4b for $Y_{cm} = -0.5$, including in all cases statistical (vertical lines) and total errors (square brackets, statistical and systematic contributions added in quadrature). The BGO and BaF2 results at $Y_{cm} = 0$ (Fig. 4a) differ somewhat at small values of $p_T$; however, the two data sets are consistent within the shown total errors.

A significant excess of photons over the contribution from hadronic decays is clearly visible at both rapidities well below the Jacobian peak, i.e. for $p_T < 15$ MeV/c. This excess is comparable in size with the level of hadronic bremsstrahlung as estimated in the soft photon approximation (dashed lines in Fig. 4, including systematic errors). A quantitative comparison is made in Fig. 5, where the decay background has been subtracted from the data. The full line shows the bremsstrahlung contribution with its characteristic $1/p_T$ dependence. The broken lines represent the systematic uncertainty in the calculated photon yield (decay + bremsstrahlung). At low $p_T (< 10$ MeV/c), the decay contribution is negligible and the error ($\approx 10\%$) is dominated by the bremsstrahlung calculation. At high $p_T (> 15$ MeV/c), bremsstrahlung amounts to only a small fraction of the total photon yield and the error is completely determined by the accuracy of the decay background estimate (again $\approx 10\%$).

Given the difficulty of measuring extremely low energetic photons down to 10 MeV in the presence of intense sources of experimental background at beam energies of several hundred GeV, the agreement between data and the bremsstrahlung estimate is remark-
able. In particular, at very low $p_T$ ($< 3$ MeV/c) at $Y_{cm} = 0$ (Fig. 5a), and at all $p_T$ at $Y_{cm} = -0.5$ (Fig. 5b), the difference is less than 50% and not significant within our systematic errors. An excess of about a factor of two between data and bremsstrahlung is visible in the BaF$_2$ data at $Y_{cm} = 0$ between 2 and 10 MeV/c, corresponding to about $2\sigma$ in the systematic error shown in Fig. 5a. However, this excess appears only in this particular $p_T$ range and angular setting. It might be due to some side leakage of low-energy tails from showers which develop in the material of the BaF$_2$ support or detector housing. This type of background, which is important only at $Y_{cm} = 0$ where the detector is placed at small angles close to the beam, arises essentially from the edges of the detector and cannot be rejected completely by the TOF cut (see Section 2). We therefore prefer to quote an upper limit on prompt photons, calculated under the assumption of Gaussian distributed errors, which includes the statistical errors in the data as well as the systematic errors in data, bremsstrahlung, and decay-background as mentioned above. The upper limit, corresponding to an excess of 1.64$\sigma$ in the combined total error (i.e. 90% confidence level for a Gaussian error distribution), of the ratio data minus decay-background divided by bremsstrahlung is plotted in Fig. 6 as a function of $p_T$. At very low $p_T$ ($< 3$ MeV/c), our data limit possible additional sources of direct photons beyond the expected level of bremsstrahlung to at most 30–50%. This limit increases with $p_T$ up to a factor of two at $p_T \approx 10$ MeV/c. At higher $p_T$, the rapidly increasing ratio of decay-background to bremsstrahlung excludes, in practice, any sensitive measurement of a signal comparable in size to bremsstrahlung if the decay-background is not known with a precision considerably better than a few per cent. This would require, in particular, a precise knowledge of the $\pi^0$ distribution (both in rapidity and $p_T$) over most of the phase space, because the soft part of the spectrum is dominated by decays of $\pi^0$'s created more then one unit of rapidity away from the rapidity of observation. From our systematic studies with different event generators and the unfolding of the measured photon distribution, this seems very difficult to achieve at present.

To test the multiplicity dependence of soft photon production, we have analysed our data for different values of $E_T$ as measured in the hadron calorimeter ($0 < E_T < 2$ GeV, $2 < E_T < 5$ GeV, $E_T > 5$ GeV; average measured, i.e. uncorrected $E_T \approx 2$ GeV in minimum bias collisions). Our results, when normalized to the $\pi^0$ production, are essentially independent of $E_T$ and therefore of the charged-particle multiplicity.

Earlier, unpublished data [5] taken with the same BGO calorimeter, but in a different set-up within the HELIOS experiment, have indicated an excess of soft photons significantly above the bremsstrahlung, increasing linearly with charged-particle multiplicity. Because the present data were taken under much improved experimental conditions, we suspect that this excess was of instrumental origin or due to unidentified background sources.

To summarize, we have measured the production of soft photons down to 1 MeV/c $p_T$ in p–Be reactions at 450 GeV/c with two independent methods, detectors and analysis chains. Great care has been taken to minimize or reject the copious sources of experiment-related background photons. We observe a significant excess of direct photons at very low $p_T$ ($< 15$ MeV/c) above the background from hadronic decays. This excess is consistent throughout the measured rapidity range ($0 < Y_{cm} < -1.4$) with the expected contribution from hadronic bremsstrahlung. The upper limit of additional 'anomalous' sources relative to the bremsstrahlung is about 30–50% at $p_T < 3$ MeV/c and about a factor of two at $p_T \approx 10$ MeV/c.
Our results are consistent with the findings of Ref. [1] and also in line with a recent new upper limit on the production of soft virtual photons (anomalous lepton pairs) [19]. We do not confirm reports of a significant excess seen in Refs. [2–4], amounting to several times (> 5) the level of bremsstrahlung. If this discrepancy is not due to experimental effects, it would be necessary to assume a very strong angular dependence, because the data of Refs. [2–4] were taken in a different kinematic region at very small angles with respect to the beam.

Figure 4: a) Inclusive photon $p_T$ distribution from the BaF$_2$ (open symbols) and the combined data from the BGO (closed symbols) at $Y_{cm} = 0$. b) Photon distribution at $Y_{cm} = -0.5$ (BaF$_2$ data). The full lines show the decay contribution, the broken lines the expected yield from hadronic bremsstrahlung; the range reflects, in both cases, the estimated uncertainties.
Figure 5: The $p_T$ distribution for direct photons after subtraction of the decay background. The full line gives the expected yield of photons from hadronic bremsstrahlung, the broken lines show the upper and lower limits including the systematic errors in the shape of the decay background and the bremsstrahlung calculation (see text). a) BGO and BaF$_2$ data at $Y_{cm} = 0$. b) BaF$_2$ data at $Y_{cm} = -0.5$. 
Figure 6: Upper limit (90% confidence level) of direct photons relative to the expected yield of hadronic bremsstrahlung, i.e. \((\text{data} - \text{decay background})/\text{bremsstrahlung}\). At \(p_T < 3 \text{ MeV}/c\), direct photons exceed the level of bremsstrahlung by at most 30–50%.

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References

[9] The BaF$_2$ array was used also in AGS experiment E855.