PRODUCTION OF PHOTONS AND SEARCH FOR CENTAURO EVENTS AT THE SPS COLLIDER

UA5 Collaboration

Bonn¹-Brussels²-Cambridge³-CERN⁴-Stockholm⁵

K. Alpgård⁵, R.E. Ansorge³, B. Åsman⁵, S. Berglund⁵, K. Berkelman^{4*},
D. Bertrand², K. Böckmann¹, C.N. Booth³, C. Buffam⁴, L. Burow¹, P. Carlson⁵,
J.-L. Chevalley⁴, B. Eckart¹, G. Ekspong⁵, I. Evangelou^{4x}, J.-P. Fabre⁴, K.A. French³,
J. Gaudaen^{2**}, M. Gysen⁴, K. von Holt¹, R. Hospes¹, D. Johnson², K. Jon-And⁵,
Th. Kokott¹, R. Mackenzie⁴, M.N. Maggs³, R. Meinke¹, Th. Müller¹, H. Mulkens^{4***},
D.J. Munday³, A. Odian^{4†}, M. Rosenberg¹, J.G. Rushbrooke³, H. Saarikko^{1††},
T. Saarikko¹, F. Triantis^{4x}, Ch. Walck⁴, C.P. Ward³, D.R. Ward³, G. Weber^{4xx},
A.R. Weidberg³, T.O. White³, G. Wilquet² and N. Yamdagni⁵

- 1 Physikalisches Institut der Universität Bonn, Fed. Rep. Germany.
- 2 Inter-University Institute for High Energies (ULB-VUB), Brussels, Belgium.
- 3 Cavendish Laboratory, Department of Physics, Cambridge University, UK.
- 4 CERN, Geneva, Switzerland.
- 5 Institute of Physics, University of Stockholm, Sweden.

ABSTRACT

The pseudorapidity distribution of photons produced in $p\bar{p}$ interactions at $\sqrt{s} = 540$ GeV has been measured and compared with that of charged particles. The correlation between photon and charged-particle production has been studied. A search amongst high multiplicity events for any having the properties of the Centauro events reported in cosmic-ray experiments has revealed no candidates in a sample of 3600 inelastic events.

(Submitted to Physics Letters)

-
- *) Visiting scientist from Cornell University, Ithaca, NY, USA.
**) Also at the Universitaire Instelling Antwerpen, Antwerp, Belgium.
***) Now at IIHE (ULB-VUB), Brussels, Belgium.
†) Visiting scientist from SLAC, Stanford, Calif., USA.
††) Visiting scientist from Helsinki University, Finland.
x) Visiting scientist from Ioannina University, Greece.
xx) Visiting scientist from Hamburg University and DESY, Hamburg, Fed. Rep. Germany.

INTRODUCTION

In this paper we present data on the photon content of multihadron events produced in $p\bar{p}$ interactions at the CERN Super Proton Synchrotron (SPS) Collider using the UA5 detector. The results cover the same range of pseudorapidity η as the published charged-particle data from this experiment [1,2], namely $|\eta| < 5$ with $\eta = -\ln \tan \theta/2$, where θ is the c.m. production angle. This permits a first comparison of the main features of photon and charged-particle production at 540 GeV c.m. energy.

In cosmic-ray experiments there have been suggestions [3] of the existence of an unusual class of hadronic events, called 'Centauros', which are thought to be characterized by high charged multiplicities ($n_{ch} \sim 50-100$) and a seeming absence of accompanying photons. These events could be the result of a collision between a projectile of energy $\gtrsim 1500$ TeV/nucleon and an atmospheric nucleon, equivalent to a c.m. energy $\sqrt{s} \gtrsim 1700$ GeV. The SPS Collider offers the highest available energy at accelerators, and so we have examined high multiplicity events in detail to see whether any evidence exists for a category of events resembling Centauros.

The UA5 streamer chamber detector is able to record charged particles with a good two-track resolution over almost the entire 4π solid angle [4]. This detector enables us to separate e.m. showers, induced by photon conversions, from primary charged tracks coming from the $p\bar{p}$ collision, and to analyse events of the highest observed multiplicity (up to $n_{ch} \sim 100$). Data were taken on 16,000 hadronic events in October-November 1981, from a first sample of which physics results on charged-particle rapidity distributions [1] and multiplicities and their moments [2] have already been published. The reader is referred to these publications for information concerning the UA5 detector, run conditions, and techniques of analysis of produced primary charged particles.

The trigger used was sensitive to essentially all inelastic events except the single diffraction component [1]. The present results are based on 1860 completely measured and reconstructed events consisting of 1300 minimum bias events

and 560 events obtained by a special premeasurement scan. The fraction of events of high observed multiplicity thought suitable for a Centauro search ($n_{ch}^{obs} \geq 50$) comprised $\sim 4\%$ of the triggered events. The premeasurement scan was carried out in order to enrich the fraction of high multiplicity events included in this sample by about a factor of two. The photon analysis is based on e.m. showers resulting from photon conversions in the walls of the vacuum chamber situated between the two streamer chambers, or in lead-glass plates placed inside the visible volume of one of the chambers.

SELECTION OF PHOTONS

The vacuum chamber was a 0.4 mm thick corrugated stainless-steel pipe of elliptical (60 mm $\times$ 152 mm) cross-section. The photons traversed an average thickness in the range 0.05 to 2.6 radiation lengths, depending on their angle of entry into the material of the beam pipe.

The procedures for measurement, reconstruction, and association of tracks with primary or secondary vertices have already been described [1]. Where a secondary vertex was found to be close to the material of the beam pipe, it was regarded as a candidate for an e.m. shower produced by a photon coming from the primary collision. The line joining the primary to the secondary vertex was taken as the direction of the photon which converted in the beam pipe and hence was used to calculate its pseudorapidity.

It was necessary to separate electromagnetic showers in the beam pipe from hadronic showers or spurious chance associations of tracks. Our cuts to separate these showers exploited the fact that secondaries in electromagnetic processes tend to be produced at small angles, thus leading to well-collimated showers. The shower multiplicity was required to lie in the range 2 to 10. Two angles for each secondary shower were then defined: i) the "minimum deflection" δ , which is the space angle between the interacting photon and the secondary track lying closest to that direction; and ii) the average opening angle of the shower, α . Electromagnetic showers are characterized by small values of α and δ . The optimal cuts on α and δ at each value of pseudorapidity were chosen using the Monte Carlo

program described below. (For example, the values chosen in the range $2 < |\eta| < 3$ were $\delta < 9^\circ$ and $\alpha < 23^\circ$.) The purity of the resulting sample of 4,800 electromagnetic showers was typically improved from $\sim 50\%$ to $\sim 85\%$ by these cuts.

Additional information on photon production in the range $|\eta| < 1$ was obtained by observing the showers emerging from lead-glass plates, one radiation length thick, placed symmetrically in the sensitive volume of one streamer chamber on either side of the beam axis [4]. These results are based on a careful scan of 700 events of all multiplicities. In this case the presence of a neutral shower was indicated by one or more tracks emerging from a plate, with no adjacent incoming charged track seen within 2.5 cm. The cut $\delta < 45^\circ$ (projected onto the film plane) was then applied to reduce contamination. After these cuts, 870 showers remained for analysis.

PSEUDORAPIDITY DISTRIBUTION OF PHOTONS

To extract true η distributions of primary photons it was necessary to correct the data for the geometrical acceptance of the chambers, conversion probability, the topological and angle cuts mentioned above, and trigger, scanning, and measurement losses [1]. A Monte Carlo program generated events according to p_T -limited phase-space having a value $\langle p_T \rangle = 200$ MeV/c for photons. The whole process of measurement and selection of showers was simulated. At any pseudorapidity the ratio of the true number of photons produced to those finally identified represented a correction factor that was applied to the experimental η distribution. In the case of the vacuum chamber this factor took values in the range 2.9 to 31, whereas for the plate a correction factor of about 8 was necessary.

The resulting distribution $1/\sigma \, d\sigma/d\eta$ for photons folded about $\eta = 0$ is shown in fig. 1a. We see that the lead-glass measurement is consistent with an extrapolation to $\eta = 0$ of the other values. The distribution for charged particles based on the same event sample is shown for comparison. Integrating up to $|\eta| = 5$, one obtains $\langle n_Y \rangle = 34 \pm 2$, about 30% more than $\langle n_{ch} \rangle = 26.5 \pm 1$ in the same

pseudorapidity range. This difference arises mostly at small $|\eta|$ ($\lesssim 2.5$). However, $K_S^0 \rightarrow \pi^0 \pi^0 \rightarrow 4\gamma$ will contribute to the photon distribution, whilst charged kaons, protons, and antiprotons will occur in the charged-particle distribution. After subtracting these contributions^{*)} there should remain photons predominantly from π^0 's, on the one hand, and $\pi^\pm$'s on the other, and the result is shown in fig. 1b.

The difference in shape between the photon and $\pi^\pm$ distributions can be accounted for as a kinematic effect of the $\pi^0 \rightarrow 2\gamma$ decay process. The dashed curve of fig. 1b shows the result of a Monte Carlo calculation in which π^0 's were produced with the same rapidity distribution as we observe for charged particles, and gives a satisfactory description of the data. However, integrating the data points in fig. 1b up to $|\eta| = 5$, one finds $\langle n_\gamma \rangle = 31.5 \pm 2$ and $\langle n_{\pi\text{ch}} \rangle = 22.5 \pm 1$, which is in strong disagreement with the empirical result at lower energies that $\langle n_{\pi^0} \rangle \simeq \frac{1}{2} \langle n_{\pi\text{ch}} \rangle$ if we assume that π^0 's are the only source of photons. An alternative interpretation of the data could be to assume $\langle n_{\pi^0} \rangle = \frac{1}{2} \langle n_{\pi\text{ch}} \rangle$ and to account for the excess photons in terms of η -meson production. The solid curve in fig. 1b shows a Monte Carlo prediction based on these assumptions and using a ratio $\eta/\pi^0 = 32\%$. This interpretation can also describe the data adequately. An ISR experiment [6] obtains a value of $20 \pm 12\%$ for the η/π^0 ratio at $\sqrt{s} = 53$ GeV.

PHOTON/CHARGED-PARTICLE MULTIPLICITY CORRELATION

In fig. 2a we show the number of events plotted against the number of particles $n_{\text{ch}}^{\text{obs}}$ observed in the range $|\eta| < 4$ for different values of the number of photons observed in the range $1.5 < |\eta| < 4$. These more restricted rapidity ranges were selected to minimize systematic errors. To obtain the true correlation between $\langle n_\gamma \rangle$ and n_{ch} , several corrections were needed. Firstly, the average detection efficiency connecting the observed number of photons to the true number of photons was calculated for each value of $n_{\text{ch}}^{\text{obs}}$ using the Monte Carlo program. The charged multiplicity was then corrected using a matrix $P(n_{\text{ch}}, n_{\text{ch}}^{\text{obs}})$ obtained

*) Estimated from observed K_S^0 decays [5], assuming $K^0 = \bar{K}^0 = K^+ = K^-$, and observed $\Lambda/\bar{\Lambda}$ decays [5], assuming $p/\bar{p} \simeq 2\Lambda/\bar{\Lambda}$, as suggested by the low-energy data up to ISR energies.

from the Monte Carlo simulation, which gave the probability that an event of observed multiplicity n_{ch}^{obs} had true multiplicity n_{ch} . The data were finally corrected for trigger losses of low multiplicity events, which depended on both charged and photon multiplicity. The result, corrected in this way to refer to the full rapidity range, is shown in fig. 2b, where the error bars indicate the statistical errors. The data points up to $n_{ch} \approx 50$ appear to lie on a straight line, which may be expressed as

$$\langle n_Y \rangle_{ch} = (8.0 \pm 3.0) + (0.90 \pm 0.08) n_{ch}$$

as shown in the figure. For comparison we show the ISR result at $\sqrt{s} = 62.8$ GeV [7].

The s-dependence of the slope $d\langle n_Y \rangle / dn_{ch}$ at various energies, including ISR energies determined for $n_{ch} \leq \langle n_{ch} \rangle$, is shown in fig. 2c [7,8].

SEARCH FOR CENTAURO EVENTS

In recent years cosmic-ray experiments have reported evidence for the existence of Centauro events characterized by a large charged multiplicity and a photon multiplicity consistent with zero. The UA5 data displayed in fig. 2a do not lend support to the existence of such a class of events. The few events with highest charged multiplicity and lowest photon multiplicity do not populate a separate region of the plot, but comprise the tail of the main distribution.

However, the data upon which the Centauro hypothesis was based were obtained mostly by the Brazil-Japan emulsion chamber detector [3], with a threshold for hadron detection having good efficiency only for $\eta_{lab} \geq 9.5$, which as we shall see is a relevant point for our analysis. The basic observations can be summarized as follows: averaged over five events, the number of hadrons (excluding hadrons decaying only into γ 's) coming from the primary interaction was 75, their observed total energy was 348 TeV, and the number of photons estimated in the primary interaction was consistent with zero. Based on the so-called Centauro-I, for which the laboratory angle and hence the pseudorapidity measurements were most reliable, 56 of the produced 75 hadrons (i.e. 75%) lay in the rapidity range $\eta_{lab} > 9.5$. In this same η -range no photons were detected.

For the sake of comparison with our Collider data, we assume that all the Centauro events were produced by the collision of a primary hadron with an atmospheric nucleon, although other possible interpretations have been suggested [9]. An average incident primary energy of about 1700 TeV is estimated with the value of the gamma-ray inelasticity $k_\gamma = 0.2$ given in [3]. For such an energy the rapidity of the c.m. of the interaction is 7.6 units when measured in the laboratory, and hence the 56 produced hadrons with $\eta_{lab} > 9.5$ would have $\eta > 2$ in the c.m. system.

These observations suggest that we should search amongst our data for any events having an equivalent number of particles. If Centauros were present we would expect $\sim 56 \times 0.9 \times 0.85 = 43$ charged particles in either $\eta > 2$ or $\eta < -2$ (which for conciseness we shall indicate below simply as $\eta > 2$). The factor 0.9 is the proportion of hadrons (excluding those decaying to γ 's) that we estimate are produced as charged particles in normal events, and 0.85 represents our average charged-particle detection efficiency for $\eta > 2$. Allowing for a possible dependence on s of $\langle n_{ch} \rangle$ and the central rapidity density [1,2] would give a more conservative estimate of the expected number of charged particles, namely ~ 30 instead of 43. Using our events with $n_{ch}^{obs} > 50$, we show in fig. 3 the distribution of events as a function of observed charged-hadron multiplicity $n_{ch}^{obs} (\eta > 2)$ for each value of observed photon multiplicity $n_\gamma^{obs} (\eta > 2)$. It can immediately be seen that there is no event with $n_{ch}^{obs} (\eta > 2)$ even remotely comparable to the expected value of $\sim 30-40$.

It has been suggested [3] that the hadrons occurring in Centauro events are baryons and antibaryons only. If this were the case, the factor 0.9 used above should become 0.5, so that the region populated would become $n_{ch}^{obs} (\eta > 2) \gtrsim 17$. A Monte Carlo study of events of this multiplicity with no primary photons gives $n_\gamma^{obs} (\eta > 2) = 1 \pm 1$, owing to secondary hadronic interactions in the vacuum chamber. Twenty-four events having $n_\gamma^{obs} (\eta > 2) \leq 2$ are therefore consistent with having zero primary photons, and so at first sight could be candidates at the level of ~ 1 in 150 of minimum bias events. However, they merge continuously

with the normal events and so would more reasonably be described as background for a Centauro search.

SUMMARY

In a first study of the production of photons in $p\bar{p}$ interactions at $\sqrt{s} = 540$ GeV the following characteristic features have been observed:

- i) The average number of photons per event in the range $|\eta| < 5$ is 34 ± 2 , about 30% higher than the mean number of charged particles.
- ii) After allowing for the effects of kaons and $p/\bar{p}$, the ratio $\langle n_\gamma \rangle / \langle n_{\pi\text{ch}} \rangle = 1.4 \pm 0.1$, indicating a strong disagreement with the empirical rule $\langle n_{\pi^0} \rangle = \frac{1}{2} \langle n_{\pi\text{ch}} \rangle$ which could for example be accommodated by η -meson production in the proportion $\eta/\pi^0 \sim 30\%$.
- iii) The correlation between photon and charged-hadron production can be expressed by the straight-line dependence

$$\langle n_\gamma \rangle_{n_{\text{ch}}} = (0.90 \pm 0.08) n_{\text{ch}} + (8.0 \pm 3.0),$$

the correlation strength as measured by the slope being higher than at ISR energies.

- iv) No high multiplicity events having features corresponding to the Centauro events reported in cosmic-ray emulsion chambers have been observed in our event sample equivalent to 3600 minimum bias events.

Acknowledgements

We are indebted to the many members of the CERN staff, particularly from SPS and EF Divisions, who have contributed to the success of the SPS/Collider and of our experiment. From the Brussels group, thanks are due from D.B. and G.W. for the financial support of the Fonds National de la Recherche Scientifique and the Institut Interuniversitaire des Sciences Nucléaires, and from J.G. and D.J. to the Interuniversitair Instituut voor Kern Wetenschappen for financial support.

We also acknowledge with thanks the financial support of the Bonn group by the Bundesministerium für Wissenschaft und Forschung, of the Cambridge group by the UK Science and Engineering Research Council, and of the Stockholm group by the Swedish Natural Science Research Council. Last, but not least, we acknowledge the contribution of the engineers, scanning, and measuring staff of all our laboratories.

REFERENCES

- [1] K. Alpgård et al., Phys. Lett. 107B (1981) 310.
- [2] K. Alpgård et al., Phys. Lett. 107B (1981) 315.
- [3] C.M.G. Lattes, Y. Fujimoto and S. Hasegawa, Phys. Rep. C65 (1980) 151.
- [4] UA5 Collaboration (Bonn-Brussels-Cambridge-CERN-Stockholm), Phys. Scr. 23
(1981) 642.
- [5] K. Alpgård et al., Strange-particle production at the CERN SPS Collider,
Submitted to Physics Letters.
- [6] G. Jansco et al., Nucl. Phys. B. 124 (1977) 365.
- [7] H. Albrecht, Thesis, University of Heidelberg, 1979.
- [8] J. Whitmore, Phys. Rep. 10C (1974) 273 and 27C (1976) 187.
- [9] J.D. Bjorken and L.D. McLerran, Phys. Rev. D 20 (1979) 2353.
D.G. Sutherland, Proc. Conf. on Cosmic Rays and Particle Physics, Bartol,
Del., 1978 (Amer. Inst. Phys. Conf. Proc. No. 49, New York, 1979), p. 503.

Figure captions

- Fig. 1a : Pseudorapidity distribution of photons and charged particles based on the same sample of 1300 minimum bias events. The error bars indicate statistical errors only. The systematic uncertainties are in the range 8-15% for photons and $\sim 5\%$ for charged particles.
- Fig. 1b : Pseudorapidity distributions of photons and charged particles with charged kaons and p and $\bar{p}$ removed from the charged-particle distribution and photons from $K_S^0 \rightarrow 2\pi^0 \rightarrow 4\gamma$ removed from the photon distribution. Dotted lines: Monte Carlo prediction assuming all photons come from π^0 decay. Solid curve: Monte Carlo prediction assuming that $\langle n_{\pi^0} \rangle = \frac{1}{2} \langle n_{\pi\text{ch}} \rangle$ and that the remaining photons come from η decay.
- Fig. 2a : Number of events plotted against the observed charged multiplicity, for different values of the observed multiplicity of photons. The figure contains 1860 events.
- Fig. 2b : The true average number of photons plotted against the true charged multiplicity (see text). For comparison, the data at $\sqrt{s} = 62.8$ GeV [7] are shown.
- Fig. 2c : Strength of photon/charged-particle correlation as expressed by values of $d\langle n_\gamma \rangle / dn_{\text{ch}}$, presented for different c.m. energies. The data are from refs. [7] and [8].
- Fig. 3 : Number of events plotted against multiplicities of charged particles observed at pseudorapidities greater than 2 or less than -2. The distributions are drawn separately for each value of observed photon multiplicity in the same range of pseudorapidity. The region which would be populated by Centauro-like events if produced at the Collider and observed with our detector is indicated.

Fig. 1

Fig. 2 (a)

Fig. 2

Fig. 3