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Photostar Production between 500 and 1100 MeV.

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Summary. — Experimental results are reported on the photoproduction of stars in photographic emulsions exposed to a high energy bremsstrahlung beam of maximum energies between 500 and 1100 MeV. The cross-sections, per number of equivalent quanta and per photon are calculated. The results are compared with those which can be derived using experimental values of the cross-sections for single and multiple pion photoproduction. Good agreement is found.

1. – An interesting feature of the interaction of photons with atomic nuclei is the photodisintegration of the nucleus, or production of photostars. This process has been studied so far, up to 500 MeV, by MILLER (1), KIKUCHI (2), GEORGE (3), and PETERSON and ROOS (4). We have extended this investigation up to 1100 MeV at the Frascati electronsynchrotron.

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(1) R. D. MILLER: *Phys. Rev.*, **82**, 260 (1951).
(2) S. KIKUCKI: *Phys. Rev.*, **86**, 41 (1952).
(3) E. P. GEORGE: *Proc. Phys. Soc.* (*London*), A **69**, 110 (1956).
(4) V. Z. PETERSON and C. E. ROOS: *Phys. Rev.*, **105**, 1620 (1957).

2. – The experimental arrangement is shown in Fig. 1. The γ-ray beam goes through a collimator 18 mm in diameter, a broom magnet, the shielding, the emulsion, and the monitor. The latter one was a quantameter of the Wilson type, for which we have used the constant $4.82 \cdot 10^{18}$ MeV/coulomb, a theoretical value agreed upon with Cornell [5].

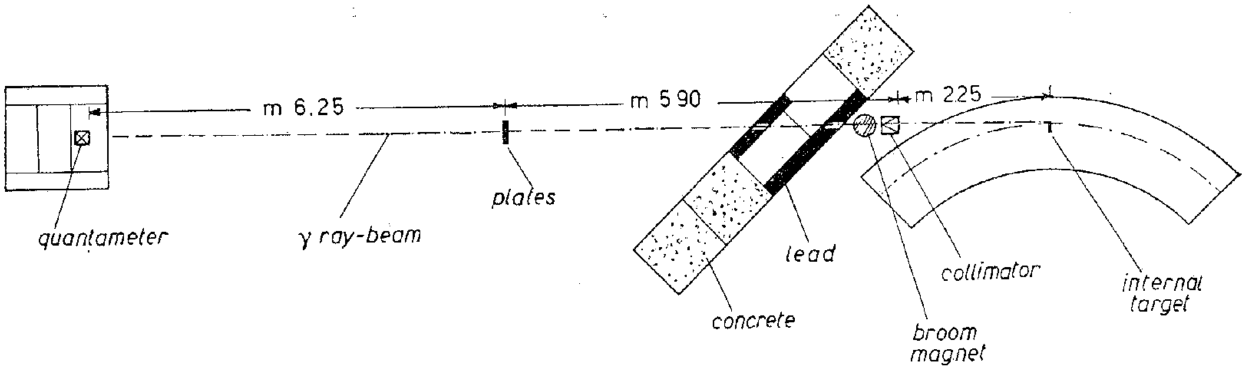

Fig. 1.

Fourteen 200 and 400 μm Ilford G-5 plates were exposed at normal incidence, one by one to the single energies. Each plate was coupled to a Ferrania « N » X-ray film, which was later used to determine exactly the zone to be scanned on the nuclear plate, and to give a point by point dosimetry. The beam diameter at the point where the plates were exposed was 5 cm.

The plates were scanned with either a 55×6 or a 50×8 optics, over a strip diametrical to the beam, partly in Naples and partly in Rome; the results have been mutually controlled. Scanning speed was about 0.3 cm²/day × scanner. Efficiencies have been determined with the double scanning method. On the basis of this determination, an efficiency of $(90 \pm 5)\%$ has been attributed on the average to the experimental data.

3. – The cross-section per equivalent quantum and per emulsion nucleus, assuming an axially symmetric beam, is given by

$$\sigma_Q = \frac{N_s}{ND} = \frac{2\pi \int_0^{r_0} p(r) r \, \mathrm{d}r}{N 2\pi A \int_0^{r_0} y(r) r \, \mathrm{d}r}, \tag{1}$$

where N_s is the total number of stars in the plate; D the total dose in equivalent quanta; N the number of nuclei per cm² (hydrogen excluded); r the distance from the beam axis; r_0 the beam cross-section radius on the plate;

(5) R. R. WILSON: *Nucl. Instr.*, **1**, 101 (1957).

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$\varrho(r)$ the star density (in cm^{-2}); $y(r)$ the dosimetric co-ordinate ($1 \geqslant y(r) \geqslant 0$ for $0 \leqslant r \leqslant r_0$), and A a constant depending only on the exposure parameters. Defining $R = n(r)/y(r)$, with $n(r) = \varrho(r) \times s$ being the number of stars found within a small fixed area s, then one expects R to be constant. Therefore

$$\sigma_Q = \frac{R}{NAs}\,, \tag{2}$$

where A is determined by integration of $y(r)$ at each energy, and the mean value of $n(r)/y(r)$ over the plate is taken for R. The fact that R is indeed approximately constant, for each energy, supports the assumption, implicit in our method of treating the data, that the ratio of high to low energy photons is roughly constant over the beam cross-section.

Three methods have been used to determine a possible neutron contamination of the beam: 1) a further exposure with a lucite absorber in front of the collimator so as to greatly enhance the number of neutrons in the beam; 2) the analysis of the stars so as to establish the percentages due to light or to heavy nuclei; 3) the study of the distribution of single prong stars as a function of the radial distance from the beam axis and a study of their forward-backward ratio. The conclusion is that the contribution of the neutrons is negligible. Equally negligible is the contribution of the radioactive contamination of the emulsion and of the cosmic rays, as seen from the scanning of unexposed areas.

To compare our results with those of previous authors, Fig. 2 shows σ_Q for production of 3 or more prong photostars, plotted against maximum bremsstrahlung energy on a semilog diagram. Monitor calibration uncertainties and possible differences in scanning criteria may account for the unsatisfactory agreement at 500 MeV with the results of PETERSON and ROOS. As it is seen σ_Q increases monotonically, as it should, since it includes the effects of all quanta in the beam, which increase in number with increasing energy for a given value of Q. The errors on the individual points are not only statistical, but comprise the uncertainties on the efficiencies. On the other hand, errors due to the measurement of the dose, to the determination of the maximum energy, and so on, have not been taken into account.

Our points—with the possible exception at 1100 MeV—seem to lie on a straight line, as shown in Fig. 2. The cross-section σ_k per photon of a given energy when the bremsstrahlung spectrum is of the form [6] $f(k) = Q/k$ is given by

$$\sigma_k = \frac{d\sigma_Q}{d(\ln E_\gamma^{max})}\,. \tag{3}$$

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[6] G. DIAMBRINI, A. S. FIGUERA, B. RISPOLI and A. SERRA: private communication.

Hence, in our case, σ_k is directly given by the slope of the straight line in Fig. 2. However, to obtain the correct value of σ_k one has to consider the contribution of the 1 and 2 prong stars. An analysis of the 2 prong events shows that the

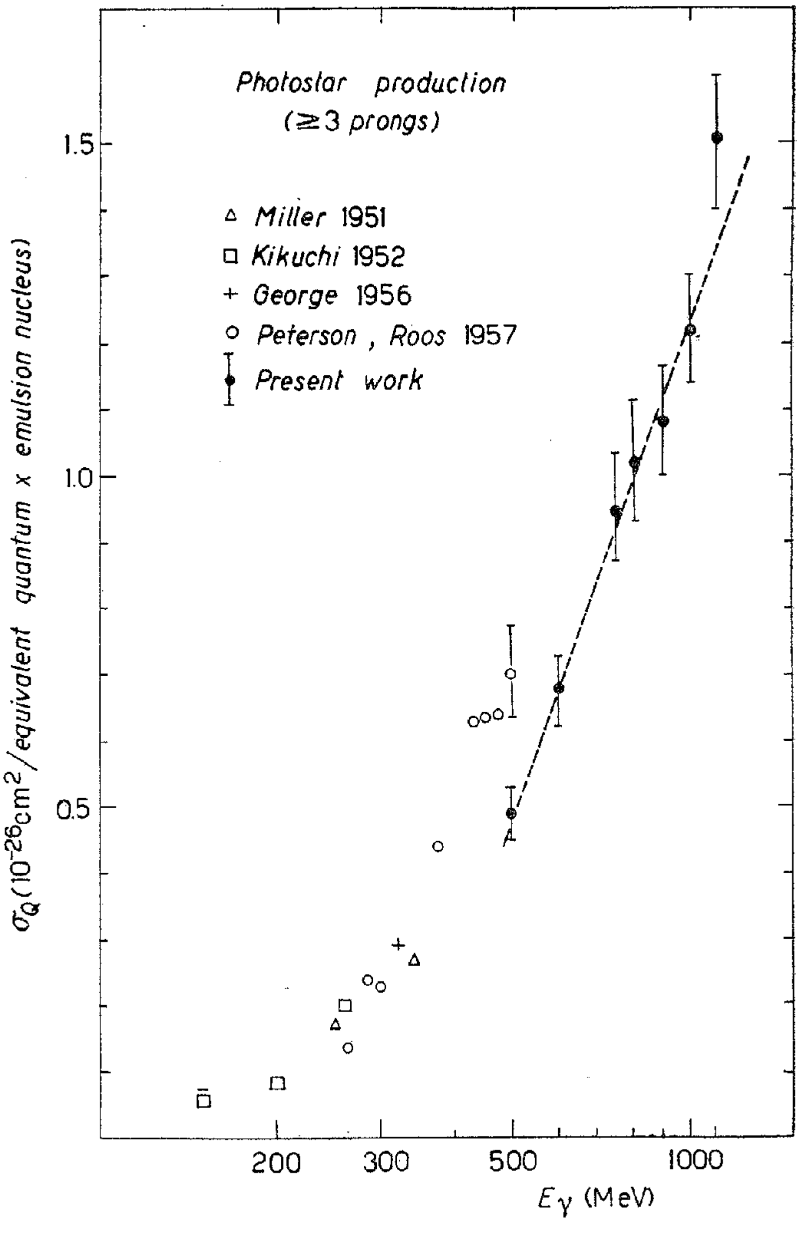

Fig. 2.

number of these to be attributed to scattering of a single track is negligible: over a carefully examined sample, we found 90% of sure stars, 9% of « probable » stars (4), and 1% of « probable » scatterings. The experimentally determined percentage of 2 prong stars is, according to our data, 35% of the 3 or more prong stars, at all energies.

As for the one prong stars, let us define the cross-section σ_{Q1} per equivalent quantum and per emulsion nucleus for production of 1 prong stars. A somewhat difficult experimental determination of σ_{Q1} has been carried out at various energies. Within the experimental errors σ_{Q1} turns out to be practically independent of energy. If it were exactly so, then equation (3) would show the corresponding cross-section per quantum to be zero: $\sigma_{Q1} = 0$. In that case all the—rather frequent—one prong stars ought to be attributed to the giant resonance and quasi-deuteron low-energy processes. Our experimental errors allow the possibility for some increase of σ_{Q1} with energy, but the estimated contribution to the total cross-section per quantum is in any case less than some 10 %. We will ignore this supposed contribution in the final calculation.

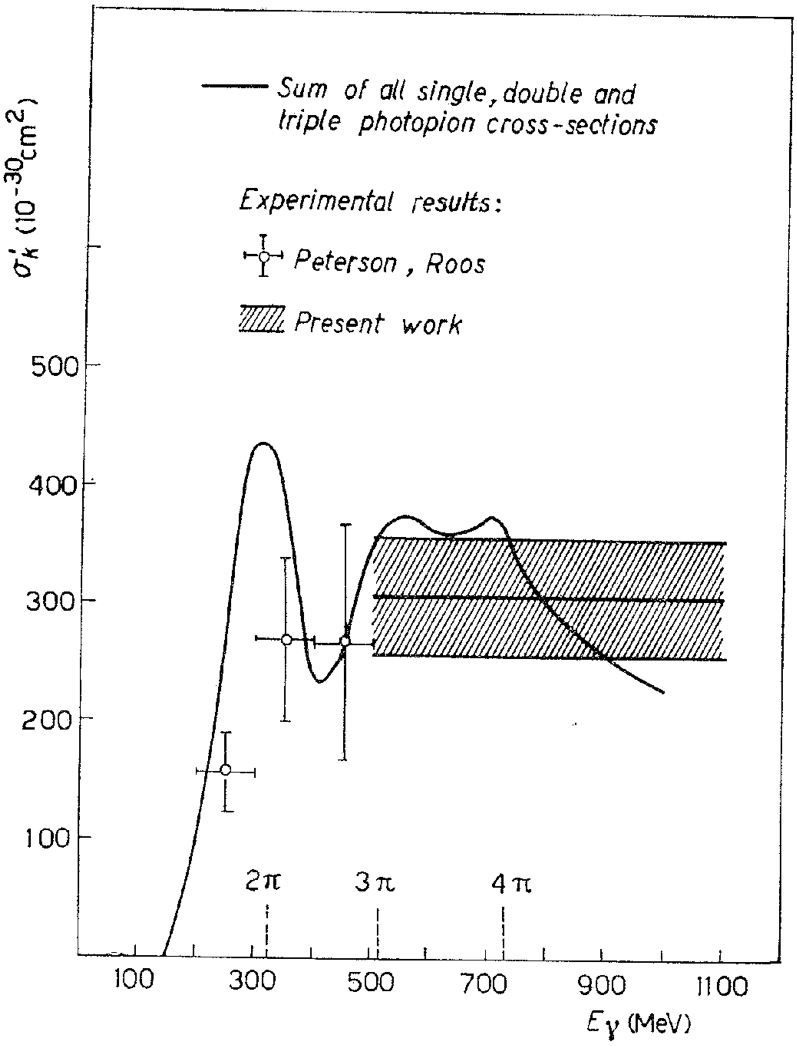

Fig. 3.

Our data then show that σ_k should be constant over the energy interval considered, and for the production of 1 or more prong photostars is equal to $\sigma_k = (146 \pm 22) \cdot 10^{-28}$ cm²/nucleus. For the interpretation of this result, it is convenient to express it per nucleon rather than per nucleus. In this way one obtains

(4) $$\sigma'_k = (306 \pm 60) \cdot 10^{-30}\ \text{cm}^2/\text{nucleon} \qquad 500 \leqslant k \leqslant 1100\ \text{MeV}.$$

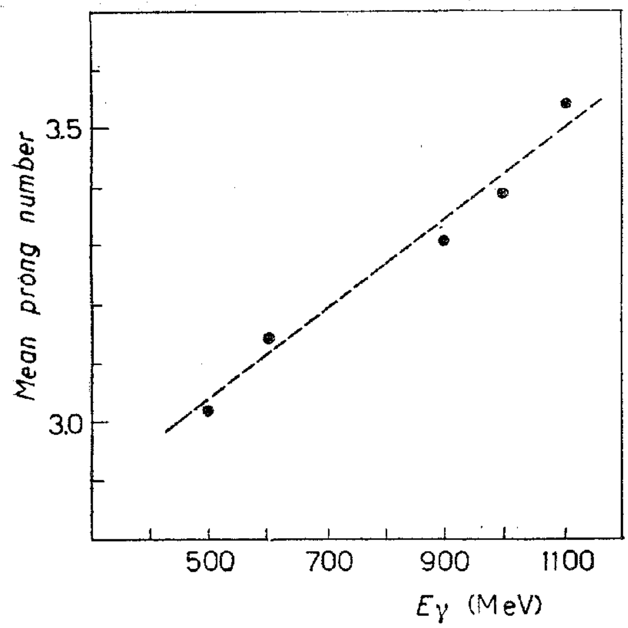

Fig. 4.

Fig. 3 shows our result, as a straight line, and those of previous authors at lower energies. The error band shown is limited by the maximum and minimum slopes of the straight lines which can be fitted within the experimental errors in Fig. 2. Multiple photopion thresholds are also indicated.

Fig. 4 shows the mean number of prongs as a function of peak bremsstrahlung energy. It is seen that this number increases steadily with energy.

4. – WILSON (7) suggested that the photostar production process at hig energies consists of the photoproduction of pions on the nucleon, and the subsequent absorption of these pions by the nucleus. An optical model calculation for σ_k' as a function of the mean cross-section for photoproduction of charged and neutral pions in hydrogen has been carried out by REFF (8), with the absorption mean free path λ for pions in nuclear matter as a parameter. An upper limit to σ_k' is obviously obtained by putting $\lambda = 0$, which is equivalent to assume that all pions are reabsorbed, and by neglecting the effects of the binding of the nucleons in the nucleus.

We have calculated σ_k' using the experimental values of the photoproduction cross-sections known up to now, and using, for the single pion photoproduction the data of BERNARDINI (9), while for the double and triple photoproduction we have used to the data of SELLEN *et al.* (10). The resulting curve is shown in Fig. 3. As it is seen the experimental values of σ_k' are in good agreement with the curve. It is to be noted that the agreement gets better if, as PETERSON suggested (11), one takes into account the motion of the nucleons within the emulsion nuclei, thus smoothing out the curve. It is to be equally noted that the experimental value of σ_k' is slightly higher than this theoretical prediction, which constitutes, as said before, the limiting case of the model.

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(7) R. R. WILSON: *Phys. Rev.*, **86**, 125 (1952).
(8) I. REFF: *Phys. Rev.*, **91**, 150 (1953).
(9) G. BERNARDINI: *Kiev Conference* (1959).
(10) J. M. SELLEN, G. COCCONI, V. T. COCCONI and E. L. HART: *Phys. Rev.*, **113**, 1323 (1959).
(11) V. Z. PETERSON: private communication.

However, the rather large cross-section, especially at high energies (1000 ÷ 1100 MeV) could be an indication of higher multiplicities in the pion production contributing to the photostar process. This last point would find support in the steady rise of the mean prong number with increasing energy, as shown in Fig. 4.

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RIASSUNTO

Si presentano i risultati ottenuti sulla fotoproduzione di stelle in emulsioni nucleari irraggiate con raggi γ di bremsstrahlung di energia massima compresa tra 500 e 1100 MeV. Vengono calcolate le sezioni d'urto per quanto equivalente e per fotone. I risultati vengono confrontati con quelli di precedenti autori ad energie inferiori e con quelli deducibili dai valori noti per fotoproduzione singola o multipla di π, e si trova un buon accordo.