Laboratori Nazionali di Frascati

LNF-69/24

C. Bacci, G. Salvini, R. Baldini-Celio, V?N. Eponenshnikov, C. Mencuccini, A. Reale, M. Spinetti and A. Zallo : TOTAL ETA-NUCLEON CROSS-SECTION BY PHOTOPRODUCTION OF ETA-MESONS IN COMPLEX NUCLEI

Estratto da : Lett. Nuovo Cimento 1, 391 (1969)

C. BACCI, *et al.*
11 Marzo 1969
Lettere al Nuovo Cimento
Serie I, Vol. 1, pag. 391-395

Total Eta-Nucleon Cross-Section by Photoproduction of Eta-Mesons in Complex Nuclei.

C. BACCI and G. SALVINI
Istituto Nazionale di Fisica Nucleare - Sezione di Roma

R. BALDINI-CELIO, V. N. EPONESHNIKOV (*), C. MENCUCCINI, A. REALE, M. SPINETTI and A. ZALLO
Laboratori Nazionali di Frascati del Comitato Nazionale per l'Energia Nucleare - Frascati

(ricevuto il 30 Gennaio 1969)

In this paper we report the results of an experiment performed at Frascati with the 1.1 GeV electron-synchrotron, on the photoproduction of η-mesons in complex nuclei.

The reaction studied was

$$\gamma + \text{nucleus} \to \eta + \text{residual nucleus}\,, \tag{1}$$

for nuclei of different atomic weight A, by measuring the differential cross-section $\mathrm{d}\sigma(A)/\mathrm{d}\Omega^*$ for this process. The measurements were made at a total energy in the center of mass $E^* = (1600 \pm 35)$ MeV and an angle of the outgoing η around 90° in the center-of-mass system (c.m.s.) of the γ-ray and target nucleon. Under these conditions the momentum transfer in reaction (1) is sufficiently high to virtually exclude coherent η production. Due to the interaction of the produced η with nucleons inside the nucleus, the dependence of $\mathrm{d}\sigma(A)/\mathrm{d}\Omega^*$ on A is strictly related to the total cross-section for the process

$$\eta + \text{nucleon} \to \text{all channels}\,. \tag{2}$$

The average η momentum in the η-nucleon c.m.s. for reaction (2) is, in our case, $P^*_\eta = (250 \pm 50)$ MeV/c. The aim of the present experiment is the measurement of the interaction cross-section of process (2). We assume no change in momentum of the η when going outside from inside the nuclear matter. This approximation does not alter

(*) Present adress: Polytechnical Institute of Tomsk, Tomsk.

our conclusions. On the other side we do not know yet the depth of the η-nucleus potential.

Our indirect method of measuring reaction (2) is practically the only one available considering the decay time ([1]) of the eta. As the incident photon has a long interaction length in nuclear matter, and as the mean decay length of the η is greater than a nuclear diameter, it follows that, for nuclei with $A \geqslant 12$, $(\mathrm{d}\sigma(A)/\mathrm{d}\Omega^*)(1/A)$ were constant if the η-nucleon interaction were small, and $(\mathrm{d}\sigma(A)/\mathrm{d}\Omega^*)/A \propto A^{-\frac{1}{3}}$ were the η-nucleon interaction large. The latter would lead to infer that detected η's would have been produced close to the nuclear surface.

We have measured the dependence of the photoproduction cross-section on the mass number A for H, D, Li, C, Al, Cu, Ag and Pb.

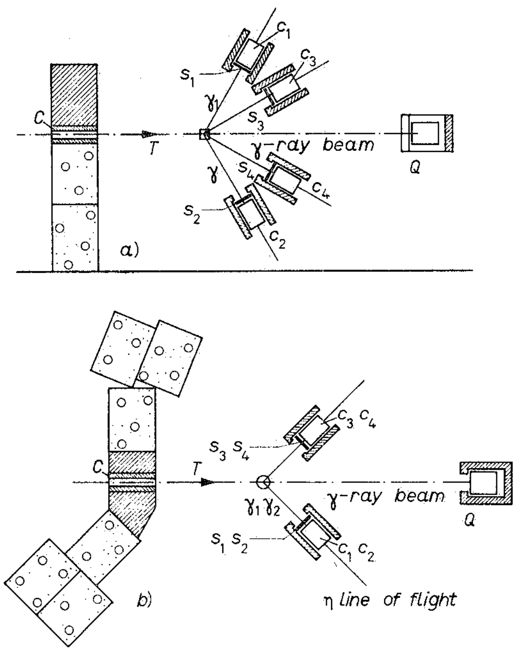

Fig. 1. – Experimental arrangement. C_1, C_2, C_3 and C_4 are two pairs of lead-glass Čerenkov counters; S_1, S_2, S_3, S_4 are veto scintillation counters, C is the collimator, T the target and Q the quantameter. Each photon detector covers a typical laboratory solid angle of 12 msr. *a*) side view, *b*) top view. [hatched] Pb, [dotted] concrete.

The experimental arrangement (Fig. 1) is the same as that described in a previous paper ([2]). It is based on the detection of the two photons from the $\eta \to \gamma\gamma$ decay mode by use of two total-absorption Čerenkov counters. The recoil nucleon was not observed. The methods used to separate reaction (1) from double π^0 photoproduction and other backgrounds are the same as those decribed in ref. ([2]).

We have verified that for our kinematical conditions we may neglect: *a*) the interaction among the nucleons during the photoproduction step ([3]); *b*) the contribution

---

([1]) G. Bellettini, C. Bemporad, P. L. Braccini and L. Foà: *Phys. Lett.*, **18**, 333 (1965).

([2]) C. Bacci, R. Baldini-Celio, C. Mencuccini, A. Reale, M. Spinetti and A. Zallo: *Phys. Rev. Lett.*, **20**, 571 (1968).

([3]) M. L. Goldberger and K. M. Watson: *Collision Theory* (New York, 1965), p. 687.

of coherent production ($\leqslant 2\%$) [4]; and *c*) the influence of the exclusion principle for final-state nucleons in reactions (1) and (2).

The detection efficiency for the η has been calculated by the Monte Carlo method, assuming different models for the Fermi motion of the nucleons [5]. The results were found to be practically model-independent.

We estimated also that two-step processes such as

$$\gamma + \text{nucleus} \to \pi + \text{nucleus} \to \eta + \text{nucleus}$$

give very small contributions to process (1).

Our results are given in Fig. 2, where the quantity $(\mathrm{d}\sigma(A)/\mathrm{d}\Omega^*)/A$ is plotted as a function of the quantity $\ln A^{\frac{1}{3}}$. We have assumed [6] $r_0 = 1.3 \cdot 10^{-13}$ cm in the expression for the nuclear radius $R = r_0 A^{\frac{1}{3}}$.

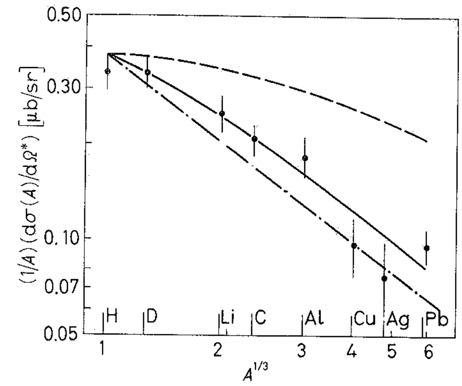

Fig. 2. – The quantity $(\mathrm{d}\sigma(A)/\mathrm{d}\Omega^*)/A$ as a function of $A^{\frac{1}{3}}$ in a logarithmic scale. $(\mathrm{d}\sigma(A)/\mathrm{d}\Omega^*)/A$ is the differential cross-section for photoproduction of η in a nucleus at $\theta^*_\eta = 90°$ in the γ-nucleon c.m.s. The full line is the best-fit curve for eq. (4), $\lambda_{\text{eff}} = 10^{-13}$ cm. The dashed line is the expected behaviour if we consider only the contribution of the process $\eta + \text{nucleon} \to \pi + \text{nucleon}$ as deduced from process (12) by detailed balance, $\lambda_{\text{eff}} = 6 \cdot 10^{-13}$ cm. The dot-dashed line represents the expected behaviour for $\lambda_{\text{eff}} \ll 10^{-13}$ cm.

The absolute value of $\mathrm{d}\sigma(A)/\mathrm{d}\Omega^*$ depends on the apparatus which, in our case, is moderately insensitive to the scattering of the η's inside nuclear matter. This point is made clearer in the following.

The points for H and D were taken from our previous results [2,7,8], but the photon energy was corrected to correspond to the same average c.m.s. energy of the photon-nucleon interaction in the nucleus.

The data of Fig. 2 show that the quantity $(\mathrm{d}\sigma(A)/\mathrm{d}\Omega^*)/A$ decreases rapidly with increasing A. According to what we said this result indicates a strong interaction of the η in nuclear matter.

We will now attempt to put this conclusions in a more quantitative form. One can write

$$\left(\frac{\mathrm{d}\sigma(A)}{\mathrm{d}\Omega^*}\right)\Big/ A = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega^*}\right)_N f_A \,, \tag{3}$$

where $(\mathrm{d}\sigma/\mathrm{d}\Omega^*)_N$ is the eta photoproduction cross-section on free nucleons.

Measurements in deuterium indicate that the η photoproduction cross-sections at 90° c.m. on neutrons and protons are approximately equal [7], so our results should be quite independent of the relative distribution of protons and neutrons inside the nucleus. f_A is the fraction of the η's which survive absorption or scattering inside the nucleus

---

(4) M. Lax and H. Feshbach: *Phys. Rev.*, **81**, 189 (1951); S. M. Berman: *Nuovo Cimento*, **21**, 1020 (1961).

(5) A. Wattenberg: *Hand. d. Phys*, **40**, 450 (1957).

(6) R. Herman and R. Hofstadter: *High-Energy Electron Scattering* (Stanford, Cal., 1960), p. 62.

(7) C. Bacci, R. Baldini-Celio, C. Mencuccini, A. Reale, M. Spinetti and A. Zallo: to be published.

(8) C. Bacci, G. Penso, G. Salvini, C. Mencuccini and V. Silvestrini: *Phys. Rev. Lett.*, **16**, 157 (1966).

and are detected by the apparatus. f_A is directly related to the mean free path of the eta in nuclear matter and is the function of direct interest in our study.

We assume f_A as follows [9]:

$$f_A = \frac{1}{V}\int_V \exp\left[-l'/\lambda_{\text{eff}}\right] \mathrm{d}V\,, \tag{4}$$

where V is the volume of the nucleus; l' is the path of the outgoing η in the residual nucleus and λ_{eff} is the mean free path of the eta for those interactions which cause the eta to be undetected by our experimental apparatus. The best fit of $(\mathrm{d}\sigma/\mathrm{d}\Omega^*)_N \cdot f_A$ to our experimental values is shown in Fig. 2.

Some of the curves for this function for different values of λ_{eff} are shown also in the same figure.

The resultant best-fit value for λ_{eff} is

$$\lambda_{\text{eff}} = (1^{+0.9}_{-0.5}) \cdot 10^{-13}\ \text{cm}\,. \tag{5}$$

Given the small value of λ_{eff} and the fact that f_A is insensitive to λ_{eff} for $\lambda_{\text{eff}} \leqslant 10^{-13}$ cm we are led to the conclusion that $\lambda_{\text{eff}} \leqslant 1.9 \cdot 10^{-13}$ cm.

From λ_{eff} we can define a cross-section σ_{eff} by

$$\sigma_{\text{eff}} = 1/\varrho\lambda_{\text{eff}}\,. \tag{6}$$

Thus σ_{eff} is the cross-section per nucleon for those η-nucleon interactions which cause the eta to be undetected in our experimental apparatus; ϱ is the nuclear density which is assumed to be uniform.

From (5) and (6) we obtain

$$\sigma_{\text{eff}} = (90^{+90}_{-40})\ \text{mb}\,; \tag{7}$$

a χ^2 analysis of our data gives $\sigma_{\text{eff}} \geqslant 50$ mb, with a confidence level $\sim 85\%$.

This value of σ_{eff} is close to the geometrical cross-section of the nucleon and it is indicative of a strong η-nucleon interaction at our momentum.

In an attempt to describe the interactions that give rise to σ_{eff}, let us examine the nuclear processes due to which the η is not detected by our apparatus. We will parametrize σ_{eff} in the following way:

$$\sigma_{\text{eff}} = \sigma_r + K\sigma_{\text{sc}}\,, \tag{8}$$

where K is the fraction $(0 \leqslant K \leqslant 1)$ of the produced η's which escape detection due to the process of η-nucleon elastic scattering inside the nucleus whose cross-section is σ_{sc}; σ_r is the sum of all inelastic reaction cross-sections as for instance

$$\eta + \text{nucleon} \to \pi + \text{nucleon}\,, \tag{9}$$

$$\eta + \text{nucleon} \to \pi + \pi + \text{nucleon}\,. \tag{10}$$

From the knowledge of the inverse reaction [10]

$$\pi^- + \text{p} \to \eta + \text{n} \tag{11}$$

---

[9] S. Fernbach, R. Serber and T. B. Taylor: *Phys. Rev.*, **75**, 1352 (1949).

[10] W. B. Richards, C. B. Chiu, R. D. Eandi, A. C. Helmoltz, R. W. Kenney, N. J. Moyer, J. A. Poirier, R. J. Cence, V. Z. Peterson, N. K. Sehgal and V. J. Stenger: *Phys. Rev. Lett.*, **16**, 1221 (1966).

one can establish, by detailed balance and isospin conservation, the value of the cross-section for processes (9), at the same center-of-mass energy. In fact the following relation holds at our energies:

$$(12)\qquad \sigma(\eta\mathcal{N}\to\pi\mathcal{N}) = \frac{3}{2}\,\sigma(\pi^-\mathrm{p}\to\eta\mathrm{n})\cdot\left(\frac{P^*_\pi}{P^*_\eta}\right)^2 \approx 15\ \mathrm{mb}\ .$$

This value, when compared with our result, $\sigma_{\text{eff}} \geqslant 50$ mb, shows that we require contributions other than reaction (9) to explain our experimental results.

Let us examine these contributions under the hypothesis that all channels are dominated by an S-wave interaction. This is suggested by the analysis of the total and differential cross-sections for reaction (11) and by the phase-shift analysis of π-nucleon scattering ([11]). In this hypothesis we find a value $K = 0.6$.

Taking into account the unitarity condition for an S-wave and the relation (8), one arrives to the following conclusions, which are illustrated in Fig. 3:

a) the most important contribution to σ_r comes from process (9), as 15 mb is very near the maximum value allowed by unitarity (~ 19 mb);

b) when considering our experimental uncertainties the assumption of an S-wave is not inconsistent with the unitarity limit and with the value $\sigma_r = 15$ mb, if $\sigma_{\text{sc}} \simeq 50$ mb.

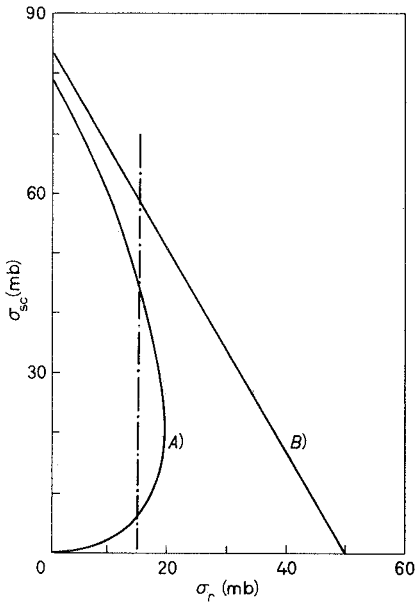

Fig. 3. – Relation between σ_r, the reaction cross-section, and σ_{sc}, the elastic cross-section, for the η-nucleon interaction. Line A) is the boundary imposed by unitarity if only S-wave is present in the η-nucleon interaction. The straight line B) is obtained using the lower limit $\sigma_{\text{eff}} = 50$ mb and relation (8), with $K = 0.6$. The dot-dashed vertical line is the value of σ_r due to η+nucleon $\to\pi$+nucleon, as deduced from reaction $\pi^-+\mathrm{p}\to\eta+\mathrm{n}$ ([10]).

This value of σ_{sc} is somewhat higher than the value which can be deduced ([11]) in the analysis of process (11).

If, contrary to the conclusions of this analysis ([11]), P and D waves contribute to process (2), then some other reaction channels, like channel (10), could contribute.

In conclusion we find a large η-nucleon interaction cross-section σ at an η-nucleon c.m.s. momentum of 250 MeV/c. This cross-section may be expressed by the relation $\sigma = \sigma_r + \sigma_{\text{sc}} \geqslant 65$ mb.

* * *

We would like to thank Prof. G. T. Zorn for his critical comments and Prof. M. Coli for his helpful assistance in setting up our electronic equipment. Thanks are also due to our technicians Messrs. V. Bidoli and I. Bruno.

([11]) A. T. Davies and R. G. Moorhouse: *Nuovo Cimento*, **52** A, 1112 (1967); F. Uchiyama-Campbell and R. K. Logan: *Phys. Rev.*, **149**, 1220 (1966).