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

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

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In this paper we report the results of an experiment performed at Frascati with the
1.1 GeV electron-synchrotron, on the photoproduction of \( \eta \)-mesons in complex nuclei.
The reaction studied was

\[
\gamma + \text{nucleus} \rightarrow \eta + \text{residual nucleus} \tag{1}
\]

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

\[
\eta + \text{nucleon} \rightarrow \text{all channels} \tag{2}
\]

The average \( \eta \) momentum in the \( \eta \)-nucleon c.m.s. for reaction (2) is, in our case,
\( P^\star_\eta = (250 \pm 50) \text{ MeV}/c \). 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 \( \eta \) when going outside from inside the nuclear matter. This approximation does not alter

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our conclusions. On the other side we do not know yet the depth of the $\gamma$-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 $\gamma$ is greater than a nuclear diameter, it follows that, for nuclei with $A \gg 12$, $(d\sigma/d\Omega^*)/(1/A)$ were constant if the $\gamma$-nucleon interaction were small, and $(d\sigma/d\Omega^*)/A \propto A^{-1/2}$ were the $\gamma$-nucleon interaction large. The latter would lead to infer that detected $\gamma$'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.

![Diagram of experimental setup](image)

**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 quartz crystal. Each photon detector covers a typical laboratory solid angle of 12 mrad. a) side view, b) top view. Pb, 1/2” concrete.

The experimental arrangement (Fig. 1) is the same as that described in a previous paper (5). It is based on the detection of the two photons from the $\gamma \rightarrow \gamma \gamma$ 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 $\pi^0$ photoproduction and other backgrounds are the same as those described in ref. (5).

We have verified that for our kinematical conditions we may neglect: a) the interaction among the nucleons during the photoproduction step (5); b) the contribution


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

The detection efficiency for the $\eta$ 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

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

give very small contributions to process (1).

Our results are given in Fig. 2, where the quantity \( (d\sigma(A)/dQ^*)/A \) is plotted as a function of the quantity \( \ln A^2 \). We have assumed \( \rho_\gamma = 1.3 \cdot 10^{-15} \text{cm} \) in the expression for the nuclear radius \( R = \rho_\gamma A^4 \).

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

The points for H and D were taken from our previous results (5,7,8), 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 \( (d\sigma(A)/dQ^*)/A \) decreases rapidly with increasing $A$. According to what we said this result indicates a strong interaction of the $\eta$ in nuclear matter.

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

$$\left( \frac{d\sigma(A)}{dQ^*} \right)_x = \left( \frac{d\sigma}{dQ^*} \right)_x f_A,$$

where \( (d\sigma/dQ^*)_x \) is the eta photoproduction cross-section on free nucleons.

Measurements in deuterium indicate that the $\eta$ photoproduction cross-sections at $90^\circ$ c.m. on protons and neutrons 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 $\gamma$'s which survive absorption or scattering inside the nucleus.

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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 ($^*$):

$$f_A = \frac{1}{V} \int \exp \left[ - \frac{L}{\lambda_{\text{att}}} \right] dV,$$

where $V$ is the volume of the nucleus; $L$ is the path of the outgoing $\eta$ in the residual nucleus and $\lambda_{\text{att}}$ 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 $(d\sigma/d\Omega^*)_\nu f_A$ to our experimental values is shown in Fig. 2.

Some of the curves for this function for different values of $\lambda_{\text{att}}$ are shown also in the same figure.

The resultant best-fit value for $\lambda_{\text{att}}$ is

$$\lambda_{\text{att}} = (1.9 \pm 0.3) \times 10^{-15} \text{ cm}.$$

Given the small value of $\lambda_{\text{att}}$ and the fact that $f_A$ is insensitive to $\lambda_{\text{att}}$ for $\lambda_{\text{att}} \ll 10^{-15} \text{ cm}$ we are led to the conclusion that $\lambda_{\text{att}} \ll 1.9 \times 10^{-15} \text{ cm}$.

From $\lambda_{\text{att}}$ we can define a cross-section $\sigma_{\text{att}}$ by

$$\sigma_{\text{att}} = 1/q^2 \lambda_{\text{att}}.$$

Thus $\sigma_{\text{att}}$ is the cross-section per nucleon for those $\eta$-nucleon interactions which cause the eta to be undetected in our experimental apparatus; $q$ is the nuclear density which is assumed to be uniform.

From (5) and (6) we obtain

$$\sigma_{\text{att}} = (90 \pm 20) \text{ mb};$$

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

This value of $\sigma_{\text{att}}$ is close to the geometrical cross-section of the nucleon and it is indicative of a strong $\eta$-nucleon interaction at our momentum.

In an attempt to describe the interactions that give rise to $\sigma_{\text{att}}$, let us examine the nuclear processes due to which the $\eta$ is not detected by our apparatus. We will parametrize $\sigma_{\text{att}}$ in the following way:

$$\sigma_{\text{att}} = \sigma_r + K \sigma_{\text{esc}},$$

where $K$ is the fraction ($0 < K < 1$) of the produced $\eta$'s which escape detection due to the process of $\eta$-nucleon elastic scattering inside the nucleus whose cross-section is $\sigma_{\text{esc}}$; $\sigma_r$ is the sum of all inelastic reaction cross-sections as for instance

$$\eta + \text{nucleon} \rightarrow \pi + \text{nucleon},$$

$$\eta + \text{nucleon} \rightarrow \pi + \pi + \text{nucleon}.$$

From the knowledge of the inverse reaction ($^{*9}$)

$$\pi^- + p \rightarrow \eta + n$$


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:

\[
\sigma(\gamma pN \rightarrow \pi^+N) = \frac{3}{2} \sigma(\pi^- p \rightarrow \eta n) \left(\frac{P^2_{\pi}}{P^2_{\eta}}\right)^2 \approx 15 \text{ mb}.
\]

This value, when compared with our result, \(\sigma_{\text{tot}} > 50 \text{ mb}\), 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 \(\pi\)-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:

1. The most important contribution to \(\sigma\) comes from process (9), as 15 mb is very near the maximum value allowed by unitarity (\(\sim 19 \text{ mb}\));

2. When considering our experimental uncertainties the assumption of an S-wave is not inconsistent with the unitarity limit and with the value \(\sigma = 15 \text{ mb}\), if \(\sigma_{\text{tot}} > 50 \text{ mb}\).

This value of \(\sigma_{\text{tot}}\) 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 (9), then some other reaction channels, like channel (10), could contribute.

In conclusion we find a large \(\gamma\)-nucleon interaction cross-section \(\sigma\) at an \(\gamma\)-nucleon c.m.s. momentum of 250 MeV/c. This cross-section may be expressed by the relation \(\sigma = \sigma_\gamma + \sigma_{\text{nucl}} > 65 \text{ mb}\).

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