SEARCH FOR $\eta$-MESIC NUCLEI
IN PHOTO-MESONIC PROCESSES

G.A. Sokol†, T.A. Aibergenov, A.V. Kravtsov, Yu.I. Krutov, A.I. L’vov, L.N. Pavlyuchenko, S.S. Sidorin

P.N. Lebedev Physical Institute of the Russian Academy of Sciences
Leninsky Prospect 53, Moscow 117924, Russia
† E-mail: gsokol@sgi.lpi.msk.su

Abstract

Results of an experiment performed at the Lebedev Physical Institute with the bremsstrahlung photon beams of the end-point energies 650 and 850 MeV are presented. Correlated $\pi^+n$ pairs with the opening angle $\langle \theta_{\pi N} \rangle = 180^\circ$ and the energies $\langle E_{\pi^+} \rangle = 300$ MeV and $\langle E_n \rangle = 100$ MeV from the process $\gamma + ^{12}\text{C} \rightarrow N + \eta(A - 1) \rightarrow N + \pi^+n + (A - 2)$ were observed. They provide an evidence for the existence of the $^{11}\eta\text{B}$ and $^{11}\eta\text{C}$ $\eta$-mesic nuclei.

Key-words: $\eta$-meson, $\eta N$-interaction, $\eta$-mesic nuclei, $S_{11}(1535)$ resonance, scattering length, bremsstrahlung photon beam, reaction trigger, correlated $\pi N$ pairs

1 Introduction

Eta-mesic nuclei $\eta A$ are a new form of the nuclear matter which represents bound states of the $\eta$-meson and a nucleus. Till now, the eta-mesic nuclei were not discovered despite theoretical works of more than 10 years old which suggested an existence of such exotic objects of the nuclear physics [1, 2]. Two attempts to discover the $\eta$-nuclei were performed soon after the first theoretical suggestions. They were based on using $\pi^+$-meson beams at BNL [3] and LAMPF [4]. Both of these experiments failed to find $\eta$-nuclei, what is probably related with non-optimal experimental conditions and not quite adequate interpretation of experimental data.

The negative result of the first experiments cooled significantly an interest in solving the $\eta$-nuclei problem and conducting direct searches for $\eta$-nuclei. Meanwhile, experimental studies of the reactions $d(p, ^3\text{He})\eta$ [5] and $^{18}\text{O}(\pi^+, \pi^-)^{18}\text{Ne}$ [6] did provide an evidence for formation of a strongly-bound state of the $\eta$-meson and the nucleus in the intermediate stage of the reactions [7]. Moreover, recent re-evaluations [8] of the s-wave scattering length of $\eta N$ scattering, $a_{\eta N}$, give a significantly larger (by $\sim 3$ times) value of Re$a_{\eta N}$ which makes feasible to exist $\eta$-nuclei at all $A \geq 3$ and, perhaps, even at $A = 2$ [9].

These later experimental and theoretical works stimulated new searches for $\eta$-mesic nuclei. Among new proposals is an idea to search for $\eta$-mesic nuclei in photo-mesonic reactions from nuclei [10] which is based on a method of identifying $\eta$-nuclei suggested in Ref. [11]. In the present work, given are the first (preliminary) data of the experiment on a search for $\eta$-nuclei in photo-reactions with the bremsstrahlung photon beam of the 1-GeV electron synchrotron of the Lebedev Physical Institute. They provide an evidence for an existence of $\eta$-mesic nuclei.
2 Search for $\eta$-nuclei in photo-mesonic reactions

The use of photons rather than pions to produce $\eta$-nuclei may provide some advantages. Photon beams are far more intense, and this quite compensates a lower cross section of $\eta$ production in electromagnetic vs. strong interactions. Also, photons freely penetrate into the nucleus and make all nucleons to participate in the $\eta$-nucleus production.

The process of the $\eta$-nucleus formation in a photo-reaction followed by a decay is depicted in Fig. 1. It is assumed that both the first stage of the reaction, i.e. production of the $\eta$ by the photon, and the second stage, i.e. annihilation of the $\eta$ and creating the pion, proceeds through single-nucleon interactions (either with a proton or a neutron in the nucleus) mediated by the $S_{11}(1535)$ nucleon resonance. Formation of the bound state of the $\eta$ and the nucleus becomes possible when the momentum of the produced $\eta$ is small (typically less than 150 MeV/c). Note that the $\eta N$ interaction is attractive when the kinetic energy of the free $\eta$ is $T_\eta \leq 50$ MeV \[8\]. These restrictions suggest the energies of photons, $E_\gamma = 650−850$ MeV, as most suitable for creating $\eta$-nuclei.

In cases when the momentum (or energy) of the produced $\eta$ is high, the attraction between the $\eta$ and the nucleus is not essential, and the $\eta$ propagates freely, see Fig. 2. In this case the final $\pi N$ pairs carry a high momentum too and their kinematical characteristics, such as an opening angle, are different from those of pairs produced through the stage of the $\eta$-nucleus formation.

3 Identification of $\eta$-nuclei

In the present experiment, detection of the $\pi N$ pairs from the decay of the second-stage $S_{11}$ resonance was selected as a trigger \[11\]. Such pairs have an (almost) isotropic distribution. When the energy and the momentum of the intermediate $\eta$ are low (as in the case of the mechanism shown in Fig. 1), the characteristic opening angle of the pair is $\langle \theta_{\pi N} \rangle = 180^\circ$ with the width of $\simeq 25^\circ$ due to Fermi motion, and the kinetic energies are distributed around $\langle E_\pi \rangle \simeq 300$ MeV and $\langle E_n \rangle \simeq 100$ MeV. In the case of a higher momentum of $\eta$ (diagram in Fig. 2), the opening angle is smaller.

Thus, identification of $\eta$-nuclei can be realized by analyzing angular and energy distributions of the $\pi N$ pairs. Spectrum of the total energy of the pairs is expected to form a peak at $E_{\text{tot}} \simeq 1460$ MeV of the total width 25–50 MeV \[12\]. The reduction of the total energy of the pairs vs. $m_\eta + m_N = 1486$ MeV is related with formation of the quasi-bound $\eta$-nucleus state(s) and with an excitation of the rest of the nucleus. Analysis of spectra observed in the actual experiment was done with taking into account energy losses in absorbers and detectors.
4 Performance of the experiment

The experiment was performed at the bremsstrahlung photon beam of the electron synchrotron “Pakhra” of the Lebedev Physical Institute. Parameters of the beam are: \( E_{\text{e,max}} = 1.2 \text{ GeV} \), \( f = 50 \text{ Hz} \), \( I_{e} = 10^{12} \text{s}^{-1} \), \( \Delta \tau_{\gamma} = 2 \text{ ms} \) (duration of the photon beam bunch), the duty factor = 0.1.

The experimental setup consisted of two scintillation time-of-flight spectrometers with the apparatus time resolution (the channel acceptance) of \( \Delta \tau = 50 \text{ ps} \). Both spectrometers were positioned around a 4 cm carbon target at either \( \theta = 50^\circ \) or \( 90^\circ \) with respect to the photon beam (on its opposite sides). Among four possible charge combinations of \( \pi N \) pairs produced from \( \eta \)-meson collisions inside the nucleus, i.e. \( \pi^+ n \), \( \pi^- p \), \( \pi^0 p \) and \( \pi^0 n \), the first one was chosen as the most suitable for effective detection and identification. In Fig. 3, a layout of the \( \pi^+ \) and \( n \) spectrometers is shown with typical time-of-flight spectra for \( \pi^+ n \) coincidences. The spectrometers were build of scintillator blocks of \( 500 \times 500 \times 100 \text{ mm}^3 \) and \( 500 \times 500 \times 20 \text{ mm}^3 \) with four photo-tubes FEU-63 and FEU-143 located at corners of the scintillator plates. Coordinates of particles passed through the detectors were determined via a time difference of the light collection by the photo-tubes. This procedure gave a space resolution \( \sigma_x = \sigma_y \simeq 5 \text{ mm} \). The time-of-flight base between the first (\( T1 \)) and last (\( T2 \)) detectors of the pion spectrometer was 1 m. The start signal was formed by the \( T1 \) detector. The trigger was a coincidence of two signals from the \( \pi \) spectrometer (\( T1 \land T2 \)) with a signal from any detector of the \( n \) spectrometer (\( N_i \)) and an anti-coincidence with the anti-counter \( A \) of charged particles located in front of the neutron detectors and having the efficiency of 90%.

There were three runs in the present experiment with different positions of the spectrometers: a) “calibration”, b) “background”, and c) “effect + background”. In the “calibration” run a), both spectrometers were placed at \( \theta = 50^\circ \) with respect to the photon beam, and the end-point energy of the bremsstrahlung spectrum was \( E_{\gamma,\text{max}} = 650 \text{ MeV} \). In this run, mainly \( \pi^+ n \) pairs from quasi-free production of pions from the carbon were detected:

\[
\gamma + ^{12}\text{C} \rightarrow \pi^+ + n + X.
\]

Since energy characteristics of pions and neutrons in the reaction (1) at \( \theta = 50^\circ \) are similar to those expected for the decay products of \( \eta \)'s in the nucleus, this run was used to calibrate the setup and to adjust time delays for the spectrometers.

In the ”background” run b), the spectrometers were moved at \( \theta = 90^\circ \) with respect to
the photon beam, i.e. to the position suitable for measuring the effect. However, the end-point energy still was $E_{\gamma \text{max}} = 650 \text{ MeV}$, i.e. well below the $\eta$ photoproduction threshold off free nucleons (707 MeV), so that $\eta$’s were not produced.

In the last run c), keeping the angle $\theta = 90^\circ$, the beam energy was increased up to $E_{\gamma \text{max}} = 850 \text{ MeV}$, i.e. above the $\eta$ threshold. Then a large excess of the correlated $\pi^+n$ pairs was experimentally observed.

5 Data analysis

The observed two-dimensional velocity spectra of the detected pairs are shown in Fig. 4 for all three runs. In accordance with the velocities, all events in each run can be assembled into three groups: fast-fast (FF), fast-slow (FS), and slow-slow (SS).

The FF events with the extreme velocities close to the speed of the light correspond to a background (mainly $e^+e^-$ pairs produced by $\pi^0$ from double-pion production).

The FS events mostly correspond to $\pi N$ pairs.

In the “calibration” run ($\theta = 50^\circ$, $E_{\gamma \text{max}} = 650$), the quasi-free production of the $\pi^+n$ pairs is seen as a prominent peak in the two-dimensional distribution (see Fig. 4a).

In the “background” run ($\theta = 90^\circ$, $E_{\gamma \text{max}} = 650$), the largest peak (SS events in Fig. 4b) is caused by $\pi\pi$ pairs from double-pion photoproduction off the nucleus.

In the “effect+background” run ($\theta = 90^\circ$ and $E_{\gamma \text{max}} = 850 \text{ MeV}$), apart from the SS events, a clear excess of the FS events as compared with the “background” run is seen. This FS signal is interpreted as a result of production and decay of slow etas in the nucleus giving the $\pi^+n$ pairs.

In order to reduce a mis-identification of an $e^+e^-$ pair as a single pion, a further analysis of the events was done by using information from three scintillation detectors which were positioned between $T_1$ and $T_2$ and measuring the energy losses $\Delta E$. The two-dimensional distribution over the time-of-flight $T$ and the energy loss $\Delta E$ (see Fig. 5) allows to discriminate the events with a single pion from the $e^+e^-$ background by selecting events with minimal $\Delta E$.

The count rate of the $\pi^+n$ events was evaluated as

$$N(\pi^+n; 850) = N(\text{FS}; 850) - N(\text{FS}; 650) \times K(850/650),$$

where $N(\text{FS}; E_{\gamma \text{max}})$ was a number of the observed FS events at the specified energy $E_{\gamma \text{max}}$ and the coefficient $K(850/650)$ was an increase of the FS-background due to the double-pion photoproduction when $E_{\gamma \text{max}}$ was growing from 650 MeV up to 850 MeV. This coefficient was determined by using the SS events at 650 and 850 MeV. It was equal to $K = 2.15$. This procedure gave $N(\pi^+n; 850) = (61 \pm 7) \text{ events/hour}$.

The differential cross section of producing the correlated $\pi^+n$ pairs in the reaction (1) in the energy range $\Delta E_\gamma = 650$–850 MeV is found as

$$\frac{d\sigma}{d\Omega}(\pi^+n; \Delta E_\gamma) = \frac{N(\pi^+n)}{N_\gamma N_{\text{nucl}} \Delta \Omega_\pi \xi_{\pi}\xi_n f},$$

where $N(\pi^+n) = (61 \pm 7) \text{ hour}^{-1}$ is the number of events, $N_\gamma = 0.75 \cdot 10^{11} \text{ hour}^{-1}$ is the photon flux in the energy interval $\Delta E_\gamma$, $N_{\text{nucl}} = 3.4 \cdot 10^{23} \text{ cm}^{-2}$ is the nuclear density of the target, $\Delta \Omega_\pi = 5.8 \cdot 10^{-2} \text{ sr}$ is the solid angle of the $\pi$-telescope, $\xi_{\pi} = 0.8$ is the detection efficiency of the pions, $\xi_n = 0.3$ is the detection efficiency of the neutrons (by any of the four neutron detectors), and $f = 0.18$ is the geometrical fraction of the correlated $\pi^+n$
pairs simultaneously detected by the pion and neutron detectors. The last number is determined by smearing the angular correlations between the pion and neutron momenta due to Fermi motion and was determined by a Monte Carlo simulation.

Using these number, we get the differential cross section

$$\frac{d\sigma}{d\Omega} (\pi^+ n; \Delta E_\gamma) = (0.97 \pm 0.11) \, \mu\text{b/sr}$$

and, assuming an isotropic distribution of the pairs, the total cross section

$$\sigma (\pi^+ n; \Delta E_\gamma) = 4\pi \frac{d\sigma}{d\Omega} (\pi^+ n; \Delta E_\gamma) = (12.2 \pm 1.3) \, \mu\text{b}.$$ (2)

6 Conclusions

The observation of the excess of the correlated $\pi^+ n$ pairs when the photon energy becomes higher than the $\eta$-meson production threshold provides an evidence for production and
decay of $\eta$’s inside the nucleus. The obtained total photoproduction cross section for such pairs (2) is close to theoretical predictions [13] for the total cross section of formation of $\eta$-nuclei. This provides a confirmation that the observed events are related with the formation of $\eta$-nuclei. For more direct arguments, angular and energy distributions of the components of the pairs have to be analyzed. This work is in progress now.

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