First experimental results on creation and decay of $\eta$-mesic nuclei

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Abstract

First experimental results on photoproduction of $\eta$-mesic nuclei are analyzed. In an experiment performed at the 1 GeV electron synchrotron of the Lebedev Physical Institute, correlated $\pi^+n$ pairs arising from the reaction
\[ \gamma + ^{12}\text{C} \rightarrow N + \eta(A-1) \rightarrow N + \pi^+ + n + (A-2) \]
and flying transversely to the photon beam have been observed. When the photon energy exceeds the $\eta$-meson production threshold, a distribution of the $\pi^+n$ pairs over their total energy is found to have a peak in the sub-threshold region of the internal-conversion process $\eta p \rightarrow \pi^+ n$ which signals about formation of $\eta$-mesic nuclei.

The idea that a bound state of the $\eta$-meson and a nucleus (the so-called $\eta$-mesic nucleus) can exist in Nature was put forward long ago by Peng [1] who relied on the first estimates of the $\eta N$ scattering length $a_{\eta N}$ obtained by Bhalerao and Liu [2]. Owing to Re $a_{\eta N} > 0$, an average attractive potential exists between slow $\eta$ and nucleons. This can result in binding $\eta A$ systems, provided the life time of $\eta$ in nuclei is long enough [3].

Two attempts to discover $\eta$-nuclei were performed soon after the first theoretical suggestions. They were based on using $\pi^+$-meson beams at BNL [4] and LAMPF [5] and both failed, thus excluding properties of $\eta A$ assumed in the first works and challenged later [6,7]. A new interest in studying the hypothetical $\eta$-nuclei arose out of an indirect evidence for a formation of a quasi-bound $\eta^3\text{He}$ state in the reaction $pd \rightarrow \eta^3\text{He}$ which would naturally explain [8,9] an experimentally observed near-threshold enhancement in the total cross section of the reaction [10]. A similar enhancement was found in the reaction $dd \rightarrow \eta^4\text{He}$ as well [11]. Based on modern determinations of the $T$-matrix of $\eta N$ scattering [12,13], theoretical calculations of the $\eta$-nucleus scattering length $a_{\eta A}$ were fulfilled [14] which suggested that $\eta$-nuclei $\eta A$ indeed exist for all $A \geq 3$.

It should be kept in mind, however, that the above experimental evidences from the reactions with $\eta$ in the final state do not determine the sign of $a_{\eta A}$ [10] and thus cannot

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unambiguously prove that \( \eta \)-nuclei really exist as bound rather than virtual states. Therefore, a crucial experiment would be in an observation of bound \( \eta \)'s, and the present work is aimed at doing that.

Specifically, in the present work a search for \( \eta \)-nuclei is performed in the photo-mesonic reaction

\[
\gamma + ^{12}\text{C} \rightarrow N + \eta(A - 1) \rightarrow N + \pi^+ n + (A - 2),
\]

in which decay products of the \( \eta \)-nuclei are detected, viz. correlated pions and nucleons emitted in opposite directions transversely to the beam. The underlying idea is that such \( \pi N \) pairs cannot be produced in quasi-free photoproduction at energies as high as \( E_\gamma \sim 700 \text{ MeV} \), whereas they naturally appear due to \( \eta \)'s stopped (captured) in the nucleus.

![Diagram](image)

FIG. 1. (a) Mechanism of formation and decay of an \( \eta \)-nucleus. (b) Background production and decay of \( \eta \)'s in the nucleus.

The process of the \( \eta \)-nucleus formation in the reaction (1) followed by the decay is shown schematically in Fig. 1a. There, both the first stage of the reaction, i.e. production of \( \eta \) by a photon, and the second stage, i.e. annihilation of \( \eta \) and creating a 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, see below in Fig. 2). This requirement suggests photon energies \( E_\gamma = 650-850 \text{ MeV} \) as most suitable for creating \( \eta \)-nuclei. Due to the Fermi motion, \( \pi N \) pairs from \( \eta \)-nuclei decays with characteristic opening angle \( \langle \theta_{\pi N} \rangle = 180^\circ \) have the width of \( \approx 25^\circ \). Their kinetic energies are \( \langle E_\pi \rangle \approx 300 \text{ MeV} \) and \( \langle E_n \rangle \approx 100 \text{ MeV} \). In the case 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 (up to an absorption), see Fig. 1b. 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.

A systematic way to describe both the resonance (Fig. 1a) and background (Fig. 1b) processes consists in using the Green function \( G(r_1, r_2, E) \) which gives an amplitude of \( \eta \) having an energy \( E \) to propagate between the creation and annihilation points in the nuclear mean-field described by an optical energy-dependent potential \( U(r, E) \). In the vicinity of a bound level of a (complex) energy \( E_0 \), the Green function has a pole \( \sim 1/(E - E_0) \), and this pole corresponds to the mechanism shown in Fig. 1a. The background process (Fig. 1b) corresponds
FIG. 2. Spectral functions $S(E)$ and $S(E, q)$ (in arbitrary units) found with a rectangular-well optical potential simulating the nucleus $^{12}\text{C}$. For a comparison, shown also are results obtained with dropping out the attractive (i.e. real) part of the $\eta A$ potential.

to a non-pole part of $G$. A convenient measure of the relative role of the background and resonance processes is given by the spectral function $S(E) = \iint \rho(r_1) \rho(r_2) |G(r_1, r_2, E)|^2 \, dr_1 \, dr_2$, which characterizes a nuclear dependence of pion production through the two-step transition $\gamma \rightarrow \eta \rightarrow \pi$ in the nucleus. $S(E)$ depends on the binding potential $U$ and is proportional to the number of $\eta N$ collisions which $\eta$ experiences when travels through the nucleus of the density $\rho(r)$ between the creation and annihilation points. An attractive potential $U$ makes the produced $\eta$ of a near-resonance energy $E$ to pass several times through the nucleus before it decays or escapes, thus resulting in enhancing the number of collisions and in a resonance increasing the production rate of the correlated $\pi N$ pairs.

A comparative role of the resonance and background contributions is illustrated in Fig. 2 [16,17], in which the spectral function $S(E)$ is shown for the case of a rectangular-well optical potential $U$ simulating the $^{12}\text{C}$ nuclear density and proportional to the elementary $\eta N$-scattering amplitude by Green and Wycech [13]. The $\eta A$ attraction results in a prominent enhancement in the number of collisions when $\eta$ has a negative energy in between 0 and $-30$ MeV. A related spectral function $S(E, q) = \int \rho(r) |G_{r_2 < R}(r, q, E)|^2 \, dr$, which is given by Fourier components of the inner part of the Green function (viz. a part having an overlap with nucleons in the nucleus), describes a nuclear dependence of the energy-momentum distribution $\partial^2 N/\partial E \partial q$ of the produced $\pi N$ pairs over their total energy and momentum (which are $E + m_\eta + m_N$ and $q$, respectively, up to the Fermi smearing). As seen in Fig. 2, the $\eta$-nucleus attraction results in a strong enhancement in the momentum density at the resonance energies $E$ and low $q$. This theoretical finding supports the starting point of the further analysis that the correlated $\pi N$ pairs predominantly appear from decays of bound $\eta$'s.

An experimental setup (Fig. 3) consisted of a carbon target 4 cm $\times$ 4 cm and two time-of-flight scintillator spectrometers having a time resolution of $\delta \tau \simeq 0.1$ ns. A plastic anticounter $A$ of charged particles (of the 90% efficiency), placed in front of the neutron detectors, and $dE/dx$ layers, placed between start and stop detectors in the pion spectrometer, were used for a better identification of particles.

Strategy of measurements was as follows. There were three runs in the present experiment with different positions of the spectrometers: (a) “calibration”, (b) “background”, and (c)
“effect + background” runs. 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, \( \gamma + {^{12}}C \rightarrow \pi^+ + n + X \), were detected. 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 (which is 707 MeV). In the “effect+background” run (c), keeping the angle \( \theta = 90^\circ \), the beam energy was set above the threshold: \( E_{\gamma\text{max}} = 850 \text{ MeV} \). The observed two-dimensional velocity spectra of the detected pairs are shown in Fig. 4 for all three runs.

In accordance with the velocities of particles in the pion and neutron spectrometer, 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 \( (\theta = 50^\circ, E_{\gamma\text{max}} = 650 \text{ MeV}) \), the quasi-free production of the \( \pi^+n \) pairs is seen as a prominent peak in the two-dimensional distribution (Fig. 4a). In the “background” run \( (\theta = 90^\circ, E_{\gamma\text{max}} = 650 \text{ MeV}) \), 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 \( (\theta = 90^\circ \text{ and } E_{\gamma\text{max}} = 850 \text{ MeV}) \) (Fig. 4c), 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 annihilation of slow \( \eta \)'s in the nucleus giving the \( \pi^+n \) pairs.

A further analysis of the events was done using an information from three scintillation detectors which were positioned between the start- and stop-layers of the time-of-flight pion spectrometer. They measured the energy losses \( \Delta E \) of particles passed through. A selection of events with a minimal \( \Delta E \) in two-dimensional distributions over the time of flight \( T \) and the energy losses \( \Delta E \) (Fig. 4) allows to discriminate events with a single pion from those with the \( e^+e^- \) pairs.
FIG. 4. Left and central panels: Distributions (the number of events \(N\)) over the pion and neutron velocities for the “calibration” (a), “background” (b), and “effect+background” (c) runs. Right panels: Distributions over the time-of-flight \(T\) and the energy losses \(\Delta E\) in the pion spectrometer for the same runs; only events with a slow particle in the neutron spectrometer were selected for these plots.

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

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

where \(N(\text{FS}_{\text{min}}; E_{\gamma_{\text{max}}})\) is the number of the observed FS events with the minimal \(\Delta E\) and with the specific photon energy \(E_{\gamma_{\text{max}}}\), and the coefficient \(K(850/650)\) gives an increase of the FS-background due to double-pion photoproduction when \(E_{\gamma_{\text{max}}}\) grows from 650 MeV up to 850 MeV. Assuming that the same coefficient describes an increase of the SS count rate as well, it was found from the SS events at 650 and 850 MeV that \(K = 2.15\). Such a procedure gives \(N(\pi^+n; 850) = (61 \pm 7)\) events/hour. Assuming an isotropic distribution of the \(\pi^+n\) pairs, taking into account efficiencies of the pion and neutron spectrometers (80% and 30%, respectively) and evaluating a geometrical fraction \(f\) of the correlated \(\pi^+n\) pairs simultaneously detected by the pion and neutron detectors of a finite size (this fraction,
\( f = 0.18 \), was determined by a Monte Carlo simulation of the width of the angular correlation between \( \pi^+ \) and \( n \) caused by the Fermi motion of nucleons and \( \eta \) in the nucleus), we obtain the following estimate of the total photoproduction cross section of the correlated pairs from the carbon averaged over the energy interval of 650–850 MeV:

\[
\langle \sigma(\pi^+n) \rangle = (12.2 \pm 1.3) \text{ b}
\]

(a statistical error only).

Summarizing, we have observed a clear excess of the correlated \( \pi^+n \) pairs with the opening angle close to 180° arising when the photon beam energy becomes higher than \( \eta \)-production threshold. That is, we have observed production and decay of slow \( \eta \)'s inside the nucleus. As was discussed above in relation with Fig. 2, these pairs are expected to be mostly related with a formation and decay of \( \eta \)-nuclei in the intermediate state. The obtained total cross section of pair production \((3)\) is close to theoretical predictions \([18]\) for the total cross section of \( \eta \)-nuclei formation in the photo-reaction, what provides a further support for that expectation.

\[
E_{\gamma_{\text{max}}} = 850 \text{ MeV} \quad \text{and} \quad E_{\gamma_{\text{max}}} = 650 \text{ MeV}
\]

FIG. 5. Corrected two-dimensional distributions over the velocities \( \beta \) of the \( \pi^+n \) events with the end-point energy of the bremsstrahlung spectrum \( E_{\gamma_{\text{max}}} = 850 \) and 650 MeV.

In a further analysis of the excess FS events, their energy characteristics have been studied. In order to find kinetic energies of the neutron and pion, the velocities \( \beta_i = L_i/ct_i \) of both the particles must be determined. They are subject to fluctuations stemming from errors \( \delta t_i \) and \( \delta L_i \) in the time-of-flight \( t_i \) and the flight base \( L_i \). Such fluctuations are clearly seen in the case of the ultra-relativistic FF events which have experimentally observed velocities close but not equal to 1 (see Fig. 4). Therefore, an experimental \( \beta \)-resolution of the setup can be directly inferred from the FF events. Then, using this information and applying an inverse-problem statistical method described in Ref. \([19]\), one can unfold the experimental spectrum, obtain a smooth velocity distribution in the physical region \( \beta_i < 1 \) (Fig. 5), and
eventually find a distribution of the particle’s kinetic energies \( E_i = M_i[(1 - \beta_i^2)^{-1/2} - 1] \). Finding \( E_i \), we introduced corrections related with average energy losses of particles in absorbers and in the detector matter. It is worth to say that the number of the \( \pi^+ n \) FS events visibly increases when the photon beam energy becomes sufficient for producing \( \eta \) mesons.

\[
E_{\gamma \text{max}} = 850 \text{ MeV} \quad \text{and} \quad E_{\gamma \text{max}} = 650 \text{ MeV}
\]

**FIG. 6.** Distribution over the total kinetic energy of the \( \pi^+ n \) pairs for the “effect+background” run (the left panel) and for the “background” run (the right panel) obtained after unfolding the raw spectra.

\[
E_{\text{kin}(\pi^+ n), \text{MeV}}
\]

**FIG. 7.** Distribution over the total kinetic energy of the \( \pi^+ n \) pairs after subtraction of the background. Arrows indicate threshold in the reaction \( \eta N \rightarrow \pi N \), i.e. 408 MeV, and the weighted center of the histogram. For a comparison, a product of free-particle cross sections of \( \gamma N \rightarrow \eta N \) and \( \eta N \rightarrow \pi N \) is shown with the dashed line (in arbitrary units).

Of the most interest is the distribution of the \( \pi^+ n \) events over their total energy \( E_{\text{tot}} = E_n + E_\pi \), because creation and decay of \( \eta \)-mesic nuclei is expected to produce a relatively narrow peak in \( E_{\text{tot}} \) of the width \( \sim 50-70 \text{ MeV} \) (see, e.g., [14]). Such a peak was indeed observed: see Fig. [5] in which an excess of the FS events appears when the photon energy
exceeds the $\eta$-production threshold. Subtracting a smooth background, we have found a 1-dimensional energy distribution of the $\pi^+ n$ events presumably coming from (bound) $\eta$ decaying in the nucleus, see Fig. 7.

The experimental width of this distribution is about 100 MeV, including the apparatus resolution. Its center lies by $\Delta E = 40$ MeV below the energy excess $m_\eta - m_\pi = 408$ MeV in the reaction $\eta N \rightarrow \pi N$, and it is well below the position of the $S_{11}(1535)$ resonance too. Up to effects of binding of protons annihilated in the decay subprocess $\eta p \rightarrow \pi^+ n$, the value $\Delta E$ characterizes the binding energy of $\eta$ in the nucleus. The width of that peak is determined both by the width of the $\eta$-bound state and by the Fermi motion.

\[
E_{\gamma\text{max}} = 850 \text{ MeV} \quad E_{\gamma\text{max}} = 650 \text{ MeV}
\]

**FIG. 8.** Distribution over the total transverse momentum $p_\perp$ of $\pi^+ n$ pairs for the “effect+background” run (the left panel) and for the “calibration” run (the right panel).

Whereas the fixed opening angle $\theta_{\pi n} = 180^\circ$ chosen in the kinematics with $\theta_n = \theta_\pi = 90^\circ$ selects $\pi^+ n$ pairs carrying a low total momentum in the direction of the photon beam, an independent check of the transverse momentum $p_\perp = p_\pi - p_n$ is meaningful. The corresponding distribution is shown in Fig. 8. On the top of a background, there is a narrower peak in $p_\perp$ having a width compatible with the Fermi momentum of nucleons in the nucleus.

In conclusion, an excess of correlated $\pi^+ n$ pairs with the opening angle $\langle \theta_{\pi N} \rangle = 180^\circ$ has been experimentally observed when the energy of photons exceeded the $\eta$-production threshold. A distribution of the pairs over their total kinetic energy was found to have a peak lying below threshold of the elementary process $\pi N \rightarrow \eta N$. A narrow peak is also found in the pair’s distribution over their total transverse momentum. All that suggests that these $\pi^+ n$ pairs arise from creation and decay of captured bound $\eta$ in the nucleus, i.e., they arise through the stage of formation of an $\eta$-mesic nucleus.

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