Creation and Decay of $\eta$-Mesic Nuclei

G.A. Sokol, T.A. Aibergenov, A.V. Koltsov, A.V. Kravtsov, Yu.I. Krutov, A.I. L'vov, L.N. Pavlyuchenko, V.P. Pavlyuchenko, S.S. Sidorin

P.N. Lebedev Physical Institute, Leninsky Prospect 53, Moscow 117924, Russia

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 subthreshold 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 $\text{Re} a_{\eta N} > 0$, 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]. Modern calculations [4,5] predict a rather strong $\eta N$ attraction which is sufficient for binding $\eta$ in all nuclei with $A \geq 4$.

The very first experiments on searching for the $\eta$-mesic nuclei performed at BNL [6] and LAMPF [7] gave negative results. Meantime, studies of the reactions $p(d,^3\text{He})\eta$ [8,9], $^{18}\text{O}(\pi^+,\pi^-)^{18}\text{Ne}$ [10], and $d(d,^4\text{He})\eta$ [11] suggest that a quasi-bound $\eta A$ state is formed in these reactions [12,13].

In the present work we report on first results concerning formation of $\eta$-mesic nuclei in photoreactions. A very efficient trigger for searching for $\eta$-mesic nuclei [15] consists in detecting decay products of the $\eta$-mesic nucleus, viz. a $\pi N$ pair produced in the reaction $\eta N \rightarrow \pi N$ inside the nucleus. Here $\eta$ itself is produced at an earlier stage, in the reaction $\gamma N \rightarrow \eta N$ in our case. Both these reactions are mediated by the $S_{11}(1535)$ resonance which affects also a propagation of the

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1) Talk given at CIPANP-2000 (May 22-28, 2000, Quebec). E-mail: gsokol@x4u.lebedev.ru
intermediate $\eta$ in the medium (via multiple $\eta N$ rescattering) and leads to capturing slow $\eta$ into a bound state (Fig. 1). 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). This requirement suggests photon energies $E_\gamma = 650$–850 MeV as most suitable for creating $\eta$-nuclei.

$\pi N$ pairs emerging from $\eta$-mesic nucleus decays have an opening angle $\langle \theta_{\pi N} \rangle = 180^\circ$ and specific kinetic energies of their components (though smeared by the Fermi motion), $\langle E_\pi \rangle \simeq 300$ MeV, $\langle E_n \rangle \simeq 100$ MeV. Among four possible isotopic combinations $\pi^+ n$, $\pi^- p$, $\pi^0 n$, $\pi^0 p$ the first one is quite suitable for measuring energies of the particles.

Accordingly, in an experiment performed at the 1 GeV electron synchrotron of the Lebedev Physical Institute, correlated $\pi^+ n$ pairs arising from the reaction

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

have been searched for. An experimental setup (Fig. 2) consisted of a carbon target $\varnothing 4$ 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.

$$\begin{align*}
\text{FIGURE 1.} & \quad \text{Mechanism of creation and decay of } \eta\text{-mesic nuclei.} \\
\pi N \text{ pairs emerging from } \eta\text{-mesic nucleus decays have an opening angle } & \langle \theta_{\pi N} \rangle = 180^\circ \text{ and specific kinetic energies of their components (though smeared by the Fermi motion), } \\
& \langle E_\pi \rangle \simeq 300 \text{ MeV, } \langle E_n \rangle \simeq 100 \text{ MeV. Among four possible isotopic combinations } \\
& \pi^+ n, \pi^- p, \pi^0 n, \pi^0 p \text{ the first one is quite suitable for measuring energies of the particles.} \\
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& \text{identification of particles.} \\
\end{align*}$$
production threshold on the free nucleon which is 707 MeV. The first, “calibration” run was performed at 650 MeV with the spectrometers positioned at angles $\theta_n = \theta_\pi = 50^\circ$ around the beam. In that run, this was a quasi-free photoproduction $\gamma p \rightarrow \pi^+ n$ which dominated the observed yield of the $\pi^+ n$ pairs. Then, at the same “low” energy 650 MeV, the spectrometers were positioned at $\theta_n = \theta_\pi = 90^\circ$ (the “background” run). In such a kinematics, the quasi-free production did not contribute and the observed count was presumably dominated by double-pion production. At last, the third run (the “effect+background” run) was performed at the same $90^\circ/90^\circ$ position, however with the higher photon beam energy of 850 MeV, at which $\eta$ mesons are produced too.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig3.png}
\caption{Raw $\pi^+ n$ event distributions over the particle velocities $\beta_n$ and $\beta_\pi$ for the “calibration” run (a), “background” run (b), and “effect+background” run (c).}
\end{figure}

In accordance with measured velocities of particles detected by the spectrometers, all candidates to the $\pi^+ n$ events were separated into three classes: fast-fast (FF), fast-slow (FS), and slow-slow (SS) events. The FF events mostly correspond to $\pi^0 \pi^0$ production which results in hitting detectors by photons or $e^+/e^-$. The FS events mostly emerge from the $\pi^+ n$ pairs. Comparing yields and time spectra in these runs (and, in particular, using the SS events for extrapolating and subtracting a background), we have found a clear excess of the FS events which appeared when the photon energy exceeded $\eta$ production threshold. The total cross section
of photoproduction of such excess pairs, averaged over the photon energy range 650–850 MeV, was found to be about $\sigma_{\text{tot}}(\pi^+n) \simeq 10 \, \mu\text{b}$. See Ref. [14] for more details. In the present work a further analysis of the excess FS events is done and their energy characteristics are determined.

In order to find kinetic energies of the neutron and pion, the velocities $\beta_i = L_i/c\tau_i$ of both the particles have to 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. 3). 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. [16], one can unfold the experimental spectrum, obtain a smooth velocity distribution in the physical region $\beta_i < 1$ (Fig. 4), 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.

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 $\sim 50–70$ MeV (see, e.g., [14,17]). 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. 6. 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 $\eta N \to \pi N$, 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.

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. 7. 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 $\pi N \rightarrow \eta N$. 

**FIGURE 5.** 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.

**FIGURE 6.** 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 $\eta N \rightarrow \pi N$ [5] is shown with the dashed line (in arbitrary units).
FIGURE 7. 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).

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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REFERENCES

1. J.C. Peng, AIP Conference Proceedings 133, 255 (1985).
2. R.S. Bhalerao and L.C. Liu, Phys. Rev. Lett. 54, 865 (1985).
3. L.C. Liu and Q. Haider, Phys. Rev. C 34 (1986) 1845.
4. M. Batinić et al., Phys. Rev. C 57 (1998) 1004.
5. A.M. Green and S. Wycech, Phys. Rev. C 55 (1997) R2167.
6. R.E. Chrien et al., Phys. Rev. Lett. 60 (1988) 2595.
7. B.J. Lieb and L.C. Liu, LAMPF Progress Report, LA-11670-PR (1988).
8. J. Berger et al., Phys. Rev. Lett. 61 (1988) 919.
9. B. Mayer et al., Phys. Rev. C 53 (1996) 2068.
10. J.D. Johnson et al., Phys. Rev. C 47 (1993) 2571.
11. N. Willis et al., Phys. Lett. B 406 (1997) 14.
12. C. Wilkin, Phys. Rev. C 47 (1993) R938.
13. L. Kondratyuk et al., Proc. Int. Conf. “Mesons and Nuclei at Intermediate Energies”, Dubna 1994 (World Scientific, Singapore, Eds. M.Kh. Khanhasayev and Zh.B. Kurmanov), p. 714.
14. G.A. Sokol et al., Fizika B 8 (1998) 81.
15. G.A. Sokol and V.A. Tryasuchev, Kratk. Soobsh. Fiz. [Sov. Phys. – Lebedev Institute Reports] 4 (1991) 23.
16. V.P. Pavlyuchenko, Vopr. Atom. Nauki i Tekhn, ser. Tekh. Fiz. Eksp. 1/13 (1983) 39.
17. A.I. L’vov, nucl-th/9810054 and Proc. 7th Int. Conf. “Mesons and Light Nuclei”, Pruhonice, Prague, Czech Republic, 1998 (World Scientific, eds. J. Adam et al.), p. 469.