DISCOVERY OF $\eta$-MESIC NUCLEI

G.A. Sokol$^a$, L.N. Pavlyuchenko
P.N. Lebedev Physical Institute, Moscow, Russia

Abstract. First experimental results from a photoreaction which confirm an existence of eta-mesic nuclei are discussed. The experiment was performed at the 1 GeV electron synchrotron of LPI. Two values of the end-point energy of the bremsstrahlung beam were used, 650 and 850 MeV (below and above $\eta$-photoproduction threshold on the nucleon). Correlated $\pi^+n$ pairs flying from the $^{12}$C target were detected by two TOF scintillator spectrometers placed in opposite directions and transversely to the $\gamma$ beam. Measured energy spectra provide a strong evidence for a creation of eta-mesic nuclei as intermediate states of the reaction studied.

1 Introduction

A modern view of the structure of atomic nuclei as a system of protons and neutrons appeared in 30s years of the 20th century after the discovery of the neutron. Since then many new particles and their resonance states were found which led in 60s to a development of the conception of quarks. Accordingly, a question arose of a possible existence of nuclear bound systems including, apart from protons and neutrons (nucleons), new particles too.

In 50s years, hypernuclei — a new sort of nuclei consisted of $\Lambda$ or $\Sigma$ hyperons (apart from the nucleons) — were discovered. The $\Lambda$ and $\Sigma$ hyperons are close analogues of nucleons as for their masses and the quark content. Their masses are only bigger by $\sim 200$ MeV than the nucleon mass ($\sim 940$ MeV) and they consist of 3 constituent quarks as the nucleons do, one of them being however the strange ($s$) quark.

2 $\eta N$ interaction and $\eta$-nuclei

An 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]. The $\eta$-meson does not have an open strangeness. It consists of 2 quarks (more exactly, a quark and antiquark with the total isospin 0) of different flavors, of which $\approx 50\%$ is an $s\bar{s}$ pair. The mass of $\eta$ is 547.5 MeV, i.e. about 1/2 of the nucleon mass. The suggestion of J.C. Peng was based on the first estimate of the $\eta N$ scattering length $a_{\eta N}$,

$$a_{\eta N} = (0.27 + i \cdot 0.22) \text{ fm},$$

derived by Bhalerao and Liu [2] from a coupled-channel analysis of the reactions $\pi N \rightarrow \pi N$, $\pi N \rightarrow \eta N$ and $\pi N \rightarrow \pi\pi N$. Owing to $\text{Re} a_{\eta N} > 0$, there

\[a\text{-mail: gsokol@x4u.lpi.ruhep.ru} \]
is an average attractive s-wave potential between a slow η and a nucleon. For extended nuclei, such an attraction should be sufficient for making the η-meson bound, provided the life-time of the η-meson in the nucleus is not too short. A quantum-mechanical consideration done by Liu and Haider [3] and based on the ηN potential corresponding to Eq. (1) predicted that bound states of the η-meson and a nucleus A exist for all A ≥ 11. Later on, this conclusion was strengthened. More sophisticated coupled-channel analysis [4,5] taking into account both resonance and nonresonance contributions arrived to the scattering length \(\text{Re } a_{\eta N}\) which is about 3 times bigger than the very first estimate (1):

\[
a_{\eta N} = (0.75 + i \cdot 0.29) \text{ fm} \quad [5].
\]

For such a large \(a_{\eta N}\), η-mesic nuclei are predicted to exist for all nuclei with \(A \geq 4\). With slightly larger \(a_{\eta N}\), η-bound states are to be possible for \(A = 3\) and even for \(A = 2\) [6]. It is worth emphasizing that elementary ηN scattering amplitudes are theoretically derived from other reactions like \(\pi N \rightarrow \pi N\) and \(\pi N \rightarrow \eta N\) through extrapolations based on a factorization [2] or, in the latest works, on unitarity constraints [4,5]. Since, however, not all important channels are involved into those extrapolations (missing are, e.g., \(\pi N \rightarrow K\Lambda\) and \(\eta N \rightarrow K\Lambda\)), it is not clear how reliable are the obtained results. A difference between Eqs. (1) and (2) may give a hint about real uncertainties. Therefore, experimental studies of bound states of various ηA systems would greatly contribute to learning elementary ηN scattering.

![Figure 1](image-url)  
Figure 1: Energy dependence of the amplitude \(f_{\eta N}\) for the process \(\eta N \rightarrow \eta N\) [5].

Real part of the ηN scattering amplitude \(f_{\eta N}\), the threshold value of which is just equal to the scattering length \(a_{\eta N}\), remains positive up to the kinetic energies of η below 70 MeV [5] (Fig. 1). This means that an effective ηA attraction exists in a wide near-threshold energy region \(E_{\text{kin}}^\eta \approx 0 \div 70\) MeV. The attractive forces in the final state have to lead to a near-threshold enhancement in the total and differential cross section of real-η production by different beams. Such an enhancement was indeed observed in several reactions including \(p(d,^{3}\text{He})\eta\) [7,8] and \(d(d,^{4}\text{He})\eta\) [9,10], thus supporting the existence of the ηA attraction even for the lightest nuclei. Nevertheless, all these experiments
which have deal with $\eta$ in the final state cannot directly prove that bound $\eta A$ states do really exist. A well-known counter example is provided by the $NN$ system in the $^1S_0$ state which has a virtual rather than a real level and it has a negative rather than positive scattering length.

3 A previous experience

Two attempts to find $\eta$-nuclei in the missing mass spectrum of the reaction $\pi^+ A \rightarrow pX$ were performed at BNL [11] and LAMPF [12] soon after the first theoretical suggestions [1,2]. Both the experiments failed to find a signal of the $\eta$-nuclei, perhaps owing to their much bigger total widths than then expected.

A new experiment started in 1994 at the 1 GeV electron synchrotron of Lebedev Physical Institute aiming at a search for $\eta$-nucleus bound states in photoreactions. In 1998, the first experimental data were obtained [13] which indicated that a bound state of the $\eta$-meson and a nucleus $A = 11$ does exist.

4 LPI experiment

Below we describe in some details a method used in [13] for identification of the bound states of the $\eta$-meson and a nucleus, as well as a procedure of measurements and data analysis.

As a preliminary remark note that the use of the photon beam for forming $\eta$-nuclei has certain advantages when compared with the use of the pion beam. The reason is that

- photons interact with nucleons throughout the whole nuclear volume whereas pions strongly interact only with nucleons near the nuclear surface;
- high photon flux of order $10^9 - 10^{10}$ s$^{-1}$ in the energy range of $\Delta E_\gamma \approx 200$ MeV provides quite an adequate reaction rate.

5 Method of identification of $\eta$-mesic nuclei

An important idea of the work [13] was in searching for decay products of $\eta$-nuclei which are $\pi N$ pairs arising from decays of the $S_{11}(1535)$ resonance inside a nucleus [14]. A mechanism of $\eta$-nuclei production and decay in photoreactions is schematically shown on Fig. 2. At the first stage, the incoming photon produces a slow $\eta$-meson and a fast nucleon, the latter leaving the nucleus. Then, in the nuclear medium, the $\eta$-meson undergoes multiple elastic scattering, $\eta N \rightarrow S_{11} \rightarrow \eta N \rightarrow S_{11} \ldots$. At the last stage, the $\eta$-meson annihilates after interaction with a nucleon, $\eta N \rightarrow S_{11} \rightarrow \pi N$, so that a $\pi N$ pair emerges which leaves the nucleus too. The $S_{11}(1535)$ resonance plays a fundamental role in this dynamics. It provides production and annihilation of the $\eta$-meson and it also predetermines an attractive $\eta$-nucleus interaction. The chain of
elastic processes $\eta N \rightarrow S_{11} \rightarrow \eta N \rightarrow \ldots S_{11}$ in the nuclear medium results in randomizing momenta of the $S_{11}(1535)$ resonance and the $\eta$-meson. Fermi motion of nucleons is important for this randomization because the $\eta$-meson scatters on nucleons having random velocities and directions. The most important result of the randomization is the isotropic momentum distribution of decaying $S_{11}(1535)$ resonances. It leads to an isotropic distribution of the $\pi N$ pairs and, since the momentum of $S_{11}(1535)$ in the nucleus is small, to the opening angle $\theta_{\pi N}$ close to $180^\circ$. This is a basic idea of the method of $\eta$-nuclei identification suggested in [14]. The method consists in detection and energy measurements of components of $\pi N$ pairs from $S_{11}$-resonance decays in the nuclear medium. It is worth mentioning that $\pi^+ n$ pairs flying transversely to the photon beam cannot be produced via the one-step reaction $\gamma p \rightarrow \pi^+ n$ in the nucleus when the photon energy is as high as 700–800 MeV.

6 Simulation of $\pi N$ events

Theoretical estimates [13,15] show that the binding effects lead to a full dominance of the reaction mechanism related with multiple rescattering of $\eta$ and with a formation of the intermediate $\eta$-nucleus over a mechanism of non-resonance (background) production of the $\pi N$ pairs in the subthreshold region of the invariant mass $\sqrt{s_{\pi N}} < m_\eta + m_N$ for the subprocess $\eta + N \rightarrow \pi + N$. A peak in the mass distribution of $\pi N$ is theoretically expected in this region.

This is illustrated in Fig. 3 where the spectral function $S(E)$ of the (kinetic) energy $E$ of $\eta$ in the nucleus is shown which is proportional to the number of $\eta N$ collisions that the $\eta$ undergoes when travels through the nucleus. Another spectral function, $S(E, q)$, shows a distribution of the produced $\pi N$ pairs over their total energy $E + m_\eta + m_N$ and the total momentum $q$. A presence of the $\eta N$ attractive potential $U$ produces strong enhancements in these spectral functions in the energy-momentum region corresponding to the bound $\eta A$ states.
Figure 3: Spectral functions $S(E)$ and $S(E, q)$ (in arbitrary units) of the kinetic energy $E$ and momentum $q$ of $\eta$ in the nucleus. They are found with a rectangular-well optical potential simulating the nucleus $^{12}$C. For a comparison results obtained with dropping out the attractive (i.e. real) part of the $\eta A$ potential $U$ are also shown.

Figure 4: Layout of the experimental setup. Shown also are the time-of-flight spectra in the $\pi$ (left) and $n$ (right) spectrometers.

7 Experimental setup and procedure of measurements

The reaction studied in our work was

$$\gamma + ^{12}\text{C} \rightarrow p(n) + ^{11}_1\text{B} \ (^{11}_1\text{C}) \rightarrow \pi^+ + n + X,$$

in which energies and momenta of of $\pi^+$ and $n$ are correlated. Among four different $\pi N$ channels of $S_{11}(1535)$ decays we have chosen the $\pi^+ n$ channel because:

- detection of the $\pi^0$-decay modes is more expensive since this requires a use of the 4$\pi$ geometry of the $\gamma$-spectrometer;
- detection of the $\pi^- p$ pairs with proton energies of about 100 MeV dictates a use of rather thin targets and leads therefore to a reduced count rate.

At the same time the selected decay channel ($\pi^+ n$) allows the use of thick targets and a rather simple setup. Average energies of $\pi n$ pair’s components are $\langle E_\pi \rangle = 300$ MeV and $\langle E_n \rangle = 100$ MeV. The setup used included two arms of
time-of-flight (TOF) scintillator spectrometers (Fig. 4). The pion spectrometer contained two scintillator blocks of $50 \times 50 \times 2 \text{ cm}^3$ and $50 \times 50 \times 5 \text{ cm}^3$. The neutron spectrometer contained an anti-coincidence scintillator detector of the size $50 \times 50 \times 2 \text{ cm}^3$ and four scintillator detectors of the size $50 \times 50 \times 10 \text{ cm}^3$. Efficiency of the anti-coincidence (veto) detector was 90%. Efficiency of the neutron detecting was about $8 \div 10\%$. Each scintillator detector had four photo-tubes FEU-63 placed on the edges of the scintillator block; they were used for determination of the coordinates of particles passed through the detector using time differences of light signals coming to the photo-tubes. An accuracy of the coordinate determination was about $\Delta x = \Delta y = 1.5 \text{ cm}$. An accuracy of the determination of time was $\Delta t = 250 \text{ ps}$. Measurements in

![Diagram](image-url)

Figure 5: Raw $\pi^+ n$-event distributions over the particle velocities $\beta_n$ and $\beta_\pi$ for the “calibration” (a), “background” (b) and “effect+background” (c) runs.

the experiment were made in three different runs. In the “calibration” run (a) both $\pi^+$ and $n$ spectrometers were positioned at angles $\langle \theta_\pi \rangle = +50^\circ$ and $\langle \theta_n \rangle = -50^\circ$ with respect to the photon beam direction and the bremsstrahlung
beam end-energy $E_{\gamma\text{max}} = 650$ MeV was used. This configuration is suitable for measuring quasi-free single-pion photoproduction $\gamma p \rightarrow \pi^+ n$ on protons in the nuclear target. It was used for final tests of both arms of the setup since energies of the detected particles were close to expected energies of $\pi^+ n$ pairs arising from the $S_{11}(1535)$ decays. In the “background” run (b) the spectrometers were shifted to $\langle \theta_\pi \rangle = +90^\circ$ and $\langle \theta_n \rangle = -90^\circ$ and the beam energy was still $E_{\gamma\text{max}} = 650$ MeV. In such a configuration single-pion production events were eliminated and most of the detected events were related to a quasi-free double-pion photoproduction $\gamma N \rightarrow \pi\pi N$. In the last, “effect+background” run (c) the configuration of the setup was as in the “background” run (b) with the except for the end-point energy which was increased to $E_{\gamma\text{max}} = 850$ MeV thus making $\eta$ production possible.

8 Data analysis and results

Fig. 5 shows a two-dimensional spectrum of the detected particle’s velocities $\beta$ for all three runs. The measured velocities $\beta_i = L_i/c t_i$ 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 $L_i$ measured in the experiment. Such fluctuations are clearly seen in the case when $\pi^0\pi^0$ (actually photons or relativistic electrons or positrons) hit scintillators. Therefore, experimentally observed velocities are close but not equal to 1 (see in Fig. 5). Therefore, an experimental $\beta$-resolution of the setup can be directly inferred from the $\pi^0\pi^0$ events. Then, using this information and applying a statistical method of solving the inverse problem described in [16],
one can unfold the experimental spectrum, obtain a smooth velocity distribution in the physical region $\beta_i \leq 1$ (Fig. 6) and eventually find a distribution of the particle’s kinetic energies $E_i = M_i [(1 - \beta^2_i)^{-1/2} - 1]$. Finding $E_i$, we introduced corrections related with average energy losses of particles in absorbers and in the detector matter. Fig. 7 shows a two-dimensional energy distribution of $\pi^+n$ pairs obtained through the above data evaluation for two runs at the beam energies of 650 and 850 MeV. At 650 MeV, Figure 7 shows a smooth decrease of the number of $\pi^+n$ pairs with the total energy of the pair. At 850 MeV, a resonance structure is observed in the kinematical region of the $S_{11}(1535)$ resonance. We believe that such a structure is directly related to $\eta$-nuclei formation and decay.

Of the most interest is the distribution of the $\pi^+n$ events over their total energy $E_{\text{tot}} = E_n + E_\pi$. Subtracting a smooth background (Fig. 7), we have found a 1-dimensional energy distribution of the $\pi^+n$ events presumably coming from bound $\eta$-mesons decaying in the nucleus (Fig. 8). The experimental width of this distribution is about 150 MeV. Its center lies by $\Delta E \approx 90 \pm 15$ MeV below the position of the $S_{11}(1535)$ resonance and even below the threshold energy $m_\eta + m_N = 1485$ MeV, thus indicating a presence of binding effects, i.e. a formation of $\eta$-mesic nuclei.

9 Prospects

Studies of $\eta$-mesic nuclei which lie at the intersection of the nuclear physics and physics of hadrons promise us to bring a new information important for both
the fields. $\eta$-mesic nuclei provide a unique possibility to learn interactions of $\eta$-mesons with nucleons and nucleon resonances in the nuclear matter. Data on the self-energy of $S_{11}(1535)$ in the medium, being interpreted in the framework of the chiral-symmetry models, can shed more light on the problem of masses of free and bound hadrons [17].

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