Letter of Intent

Study of creation and decay of light η-mesic nuclei in photoreactions

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1. Introduction: ηN interaction and η-nuclei

Eta-mesic nuclei, ${}_\eta A$, are analogues of ordinary atomic nuclei, which consist of both ordinary particles, protons and neutrons (nucleons), and a lighter one, the η-meson, which is bound by nuclear forces. The η-nuclei have a resemblance with better-studied Λ and Σ hypernuclei which consist of ordinary nucleons and a Λ or Σ, respectively.

The Λ and Σ hyperons are close analogues of the nucleons as for their quark content and masses. Like nucleons, they consist of 3 constituent quarks, one of them being the strange (s) quark. The η-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 η is 547.5 MeV, i.e. about 1/2 of the nucleon mass.

The possibility that a bound state of the η-meson and nucleus can exist in nature was suggested by J.C. Peng [1], who relied on the first estimate of the ηN scattering length $a_{\eta N}$,

$$a_{\eta N} = (0.27 + i \cdot 0.22)\ \text{fm}, \tag{1}$$

derived by Bhalerao and Liu [2] from a coupled-channel analysis of the reactions $\pi N \to \pi N$, $\pi N \to \eta N$ and $\pi N \to \pi\pi N$. Owing to $\mathrm{Re}\, a_{\eta N} > 0$, there is an average attractive s-wave potential between a slow η-meson and a nucleon. For extended nuclei, such 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 L. Liu and Q. Haider [3] and based on the ηN potential corresponding to Eq. (1) predicted that bound states of the η-meson and a nucleus A must exist for $A \geq 11$. Later on, this conclusion was strengthened. More sofisticated coupled-channel analysis [4,5] taking into account both resonance and nonresonance contributions arrived at very different results, giving the scattering length $\mathrm{Re}\, a_{\eta N}$ about 3 times larger than the very first estimate (1) [5]:

$$a_{\eta N} = (0.75 + i \cdot 0.29)\ \text{fm}. \tag{2}$$

For such $a_{\eta N}$, η-mesic nuclei should exist for all nuclei with $A \geq 4$. With slightly larger $a_{\eta N}$, η-bound states would even be possible for $A = 3$ and even for $A = 2$ [6].

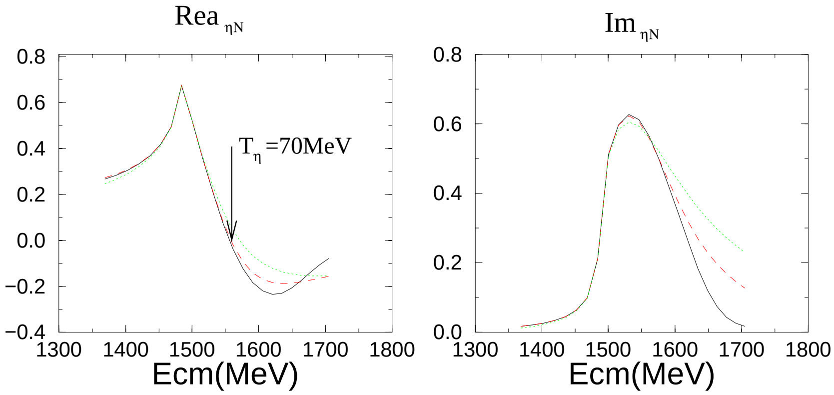

FIG. 1. *Energy dependence of Re* $f_{\eta N}$ *and Im* $f_{\eta N}$ *for the process* $\eta N \to \eta N$ *[5].*

The 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 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, $\Delta E_\eta \approx 0{-}70$ MeV. The attractive forces in the final state should 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 $p(d,{}^3\mathrm{He})\eta$ [7,8] and $d(d,{}^4\mathrm{He})\eta$ [9], thus supporting the existence of the ηA attraction even for the lightest nuclei. Nevertheless, all these experiments which have deal with η in the final state cannot directly prove that bound ηA states do really exist. A well-known counter-example is provided by the NN system in the ${}^1\mathrm{S}_0$ state, which has a virtual, not real level described by a *negative*, not positive scattering length.

It is worth to emphasize that elementary ηN scattering amplitudes are theoretically derived from other reactions like $\pi N \to \pi N$ and $\pi N \to \eta N$ 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 these extrapolations (missing are, e.g., $\pi N \to K\Lambda$ and $\eta N \to K\Lambda$ which are important according to [10]), it is not clear how reliable are the obtained results. A difference between Eq. (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 and, more generally, to an understanding of meson-baryon interactions in the second nucleon-resonance region.

2. How to search for η-mesic nuclei: a previous experience

Two attempts to discover η-nuclei in the missing mass spectrum of the reaction $\pi^+ A \to pX$ were performed at BNL [11] and LAMPF [12] soon after the first theoretical suggestions [1,3]. Both the experiments failed to find a signal of η-nuclei, perhaps owing to their bigger width than then expected.

We propose to search for η-nuclei in photoreactions in which a smaller cross section of η production by photons, as compared with that by pions, is nearly compensated by a higher intensity of the photon beam, as compared with that available for pion beams. A major difference with the previous attempts [11,12] is that decay products of the η-nuclei are to be detected too, what drastically reduces a background.

First results of searching for η-nuclei in photoreactions were recently obtained in [13]. That experiment was performed at the bremsstrahlung photon beam of the 1 GeV electron synchrotron of Lebedev Physical Institute. The reaction studied was

$$\gamma + {}^{12}C \to p(n) + {}^{11}_{\eta}B\ ({}^{11}_{\eta}C) \to p(n) + \pi^+ + n + X \to \pi^+ + n + X'. \quad (3)$$

The η-meson was produced through an elementary subprocess $\gamma + N \to S_{11}(1535) \to N + \eta$ which may yield slow η. The participating nucleon escapes the nucleus, whereas the η is captured into a quasi-bound state and then it annihilates inside the nucleus giving a $\pi^+ n$ pair through the subprocess $\eta + p \to S_{11}(1535) \to \pi^+ + n$ (Fig. 2). Note that $\pi^+ n$ pairs flying

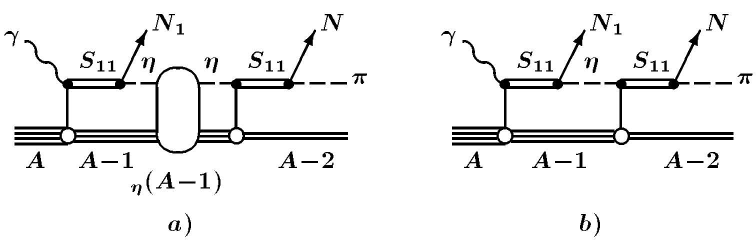

FIG. 2. *Left: Mechanism of formation and decay of an η-nuclei in a photoproduction process. Right: Background production and annihilation of η in the nucleus.*

transversely to the photon beam cannot be produced via the one-step reaction $\gamma p \to \pi^+ n$ in the nucleus, whereas they naturally appear due to an intermediate η agent. Such transverse pairs have indeed been seen in the experiment [13].

The $S_{11}(1535)$ nucleon resonance plays a fundamental role in all that dynamics. It ensures creation and annihilation of η and is also makes the η-meson bound in the nucleus due to an effective ηN attraction caused by multiple rescattering, $\eta + N \to S_{11}(1535) \to \eta + N \to S_{11}(1535) \to \eta N \to \dots$.

Theoretical estimates given in [13,14] show that binding effects lead to a full dominance of the reaction mechanism related with a formation of the intermediate η-nucleus (Fig. 2, left) over a nonresonance, background production of the pairs in the subthreshold invariant-mass region $\sqrt{s_{\pi^+ n}} < m_\eta + m_N$, where a peak in the mass distribution is theoretically expected.

A resonance peak in the total energy $E_{\rm tot}$ of the $\pi^+ n$ pairs was indeed observed just when the photon energy exceeded the η-production threshold (Fig. 3). This peak was interpreted as a manifestation of decays of bound etas in the nucleus, i.e. a result of the formation of η-mesic nuclei.

After a substraction of a smooth background, a 1-dimentional energy distribution of the $\pi^+ n$ pairs have been found (Fig. 4). The experimental width of this distribution is about 100 MeV. Its center lies by $\Delta E = 40 \pm 15$ MeV below the ηN threshold and by 90 MeV below the $S_{11}(1535)$ resonance. This energy shift ΔE is partly related with the binding of η in the nucleus.

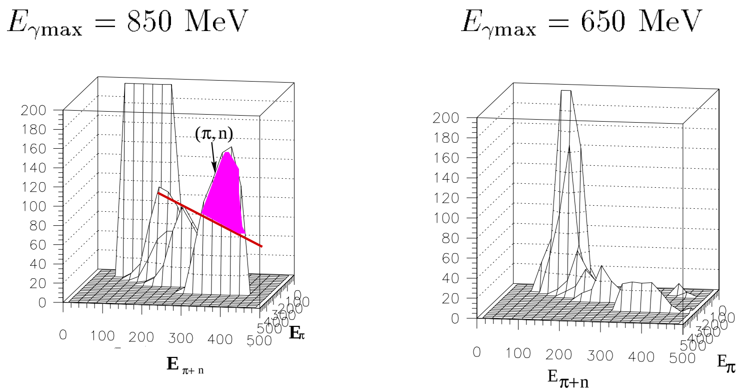

FIG. 3. *Distribution over the total kinetic energy of the π^+n pairs for the "effect+background" run (the left panel) and for the "background" run (the right panel) obtained after unfolding raw spectra [13].*

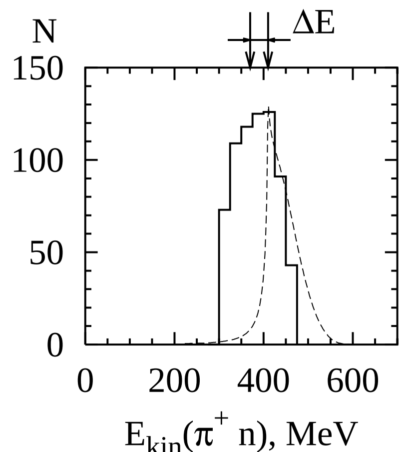

FIG. 4. *Distribution over the total kinetic energy of the π^+n pairs after a subtraction of the background. An arrow indicates the threshold energy $m_\eta - m_\pi = 408$ MeV. For a comparison, a product of free-particle cross sections of $\gamma N \to \eta N$ and $\eta N \to \pi N$ is shown with the dashed line (in arbitrary units).*

3. A sketch of a new experiment

The performance for studying η-mesic nuclei at CEBAF can be very favourable due to intense and continuous-in-time electron beam. The experiment can be performed at bremsstrahlung photons in region of energies $E_{\gamma \max} = 600-1000$ MeV.

The main task of the experiment may be in measuring an energy and A-dependence of the cross section of photoproductuon of light η-mesic nuclei (between $A = 16$ and $A = 3$) and to measure the η-binding energy and its width for different A.

The method of identification of η-nuclei consists of a detection of 3 particles: one particle (n or p) from the first stage of the reaction of η-meson photoproduction and two particles from the second stage (a decay of the η-mesic nucleus), π^+n or π^-p pairs. Triple coincidences should guarantee a reliable selection of events related with a formation of η-mesic nuclei. The experimental setup may, for example, have 3 spectrometers (Fig. 5).

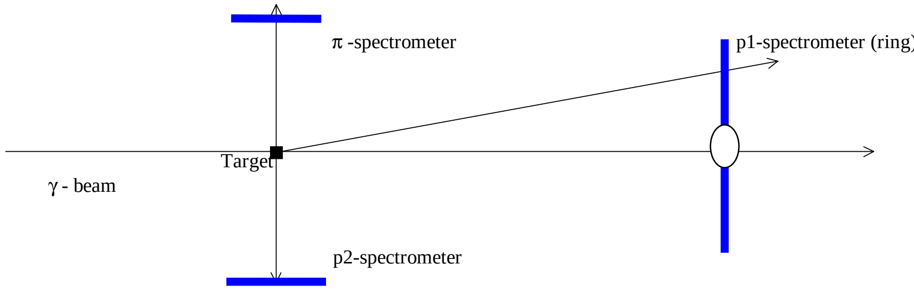

FIG. 5. *Sketch of the experimental setup.*

Assuming $\langle E_\gamma \rangle \sim 800$ MeV and $\langle \theta_{p_1} \rangle \sim 15°$, the mean energies of the particles p_1, p_2 and π^- particles can be estimated as

$$\langle E_{p_1} \rangle \sim 200 \text{ MeV}, \quad \langle E_{p_2} \rangle \sim 85 \text{ MeV}, \quad , \langle E_{\pi^-} \rangle \sim 300 \text{ MeV}.$$

The yield of the triple coincidences can be calculated from the following relation:

$$Y(p_1 p_2 \pi^-) = \frac{d\sigma}{d\Omega}(p_1, p_2, \pi^-, \Delta E_\gamma) \cdot N(\Delta E_\gamma) \cdot N_{\rm nucl} \cdot \Delta\Omega_\pi \cdot f(p_1) \cdot f(p_2). \tag{4}$$

Realistic values (based on the experiment [13] and assuming that the geometrical fraction of detection of p_1 emitted at the stage of low η-meson production, is about 0.1) are as follows:

- $d\sigma/d\Omega_\pi(p_1, p_2, \pi^-, \Delta E_\gamma) = 1\mu$b/sr is the characteristic cross section of η-nucleus production [15],
- $N(\Delta E_\gamma = 200 \text{ MeV}) \sim 2 \cdot 10^8 \gamma/\text{sec}$ is the number of (untagged) photons,
- $N_{\rm nucl} = 3 \cdot 10^{23}$ cm^{-2} is the target density,
- $\Delta\Omega_\pi = 6 \cdot 10^{-2}$ sr is the solid angle of the pion spectrometer,
- $f(p_1) = 0.1$ is the geometrical fraction of detection of p_1 (these p_1 provide a reliable kinematical selection of slow η-mesons),
- $f(p_2) = 0.2$ is the geometrical fraction of detection of p_2 from of the correlated $\pi^- p_2$ pairs.

With these numbers Eq. (4) gives the yield

$$Y(p_1 p_2 \pi^-) \simeq 250 \ \frac{\text{events}}{\text{hour}}, \tag{5}$$

which can be considered reasonably high in view of a small background expected. More realistic estimates pertinent to experimental conditions at CEBAF are planned to be done in future.

4. Summary of aims and perspectives

In conclusion, studies of η-mesic nuclei lie at the interception between the nuclear physics and the physics of hadrons and they promise to bring new information important for both the fields. Such studies are quite feasible at CEBAF. Main aims of the proposed experiment can be summarized as follows.

- Finding whether the lightest η-mesic nuclei (i.e. ${}^3_\eta$H, ${}^3_\eta$He, ${}^4_\eta$He) exist, is a very interesting result itself which crucially confronts the modern predictions for the ηN scattering amplitude.

- We expect to bring experimental information on the binding energy of η in different nuclei in the $A = 3-16$ mass range. It is expected that the η levels and their widths in nuclei depend on such medium effects as the self-energy of $S_{11}(1535)$ in the medium. Interpreted in the framework of the chiral-symmetry models, data can shed more light on the problem of masses of free and bound hadrons.

- The data on energies and widths of η-nuclei levels will be useful for further progress in existing theories of exotic nuclear systems, η-nuclei being a specific example of them.

- Studies of η-nuclei can open a way towards wider investigations of (ρ, ω, φ)-nucleus systems which are presently discussed in literature [16].

- Due to impossibility to have η-meson beams, η-nuclei provide an almost unique possibility to learn interactions of η-mesons with nucleons and nucleon resonances, including those in the nuclear matter. Detecting and measuring the energy of the nucleon knocked out in the process of quasi-free η-production on nucleons in the nucleus, one can tag the energy of η staying in the nucleus (with accuracy up to Fermi motion). When used with tagged photons, this opens a possibility to study an energy dependence of interactions between η and nuclear constituents.

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