Status of experimental investigations of $\eta$-mesic nuclei

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Abstract

Short history of ideas concerning a possible existence of bound states of the $\eta$-meson and a nucleus is considered. First experiments at BNL and LAMPF on searching for these states are discussed. Another recent experiment using the photon beam of the 1 GeV electron synchrotron of LPI is described. Possible experiments on studying $\eta$-mesic nuclei using a proton beam (at Nuclotron of Dubna) and a $\gamma$-beam (CEBAF, JLAB) are suggested.

Key words: $\eta$-meson, $\eta$-mesic nuclei, $a_{\eta N}$-scattering length, $S_{11}(1535)$ nucleon resonance, $E_{\text{g}}(\eta)$-bounding energy of $\eta$-meson into nucleus, time of flight method, bremsstrahlung photons.

I. INTRODUCTION

This report has the aim to discuss of the states at studying a new objects of nuclear physics - $\eta$-mesic nuclei, $\eta A$, a bound system of $\eta$-meson and nucleus (fig. 1). The $\eta$-nuclei are a new kind of the atomic nuclei and their research has the fundamental significance in studying the interaction of the $\eta$-meson with nucleons and nucleon resonances into the nucleus.

FIG. 1. $\eta$-nuclei as $\eta$-meson in nuclei field (left) and as $S_{11}$-resonance inside nuclei (right).

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A. Short history.

Beams of the $\eta$-mesons cannot be obtained because of very short life-time of the $\eta$-mesons ($t_{1/2} \sim 5, 5 \cdot 10^{-19}$ sec). So the study of the interactions of the $\eta$-mesons with nucleons in elementary processes of $\eta N \rightarrow \eta N \eta N \rightarrow \pi N$ type is not possible. The interaction $\eta N$ can be investigated only in the final state of the elementary processes, for example $\pi N \rightarrow \eta N, \gamma N \rightarrow \eta N$.

The $\eta$-mesic nuclei give us unique possibility for study $\eta N$-interaction in nuclear matter. The possibility of the existence of the $\eta$-meson and nucleus bound state was firstly noted by J.C. Peng [1] in connection with the analysis of the $\pi N \rightarrow \eta N$ reaction. As one noted, this reaction is characterized by nonrecoil kinematics for a $\eta$-meson. Then assuming that the reaction proceeds on a nuclear nucleon providing that:
- the $\eta N$-interaction has attractive character in a s-wave and
- the reaction time of $\eta$-meson in the nucleus is not small
the $\eta$-mesic nuclei can be formed.

B. The scattering length $a_{\eta N}$

The interaction of the $\eta$-meson in a s-wave with nucleon can be describe by $a_{\eta N}$. The analysis of the scattering lengths of reactions $\pi N \rightarrow \pi N; \pi N \rightarrow \pi \pi N$ and $\pi N \rightarrow \eta N$ carried out by R. Bhalerao and L. Liu [2] has shown that scattering length $a_{\eta N}$ calculated for the reaction $\eta N \rightarrow \eta N$ is equal to:

$$a_{\eta N} = (0, 27 + i \cdot 0, 22) \text{fm} \quad (1.1)$$

A positive value of $Rea_{\eta N}$ means that
- the interaction in s-wave has attractive character and
- the existence of quasi-bound states of the $\eta$-meson with a nucleus for $A \geq 11$ is possible at this value $Rea_{\eta N}$.

The widths of these levels were estimated by Q. Haider and L. Liu [3]. The calculated values of width $\Gamma_g(\eta) \approx 10$ MeV mean that the life-time of these states is approximately 10 times larger then the "characteristic" nucleus time ($10^{-23}$ sec), corresponding to the flight of relativistic particle through the nucleus.

The values of $\Gamma_g(\eta) \approx 30 \div 80$ MeV for the widths of the bound states of the $\eta$-nuclei are obtained by E. Oset et. al [4].

New calculations [5] of the scattering length $a_{\eta N}$ for the $\eta N \rightarrow \eta N$ reaction were then carried out and the values of $Rea_{\eta N}$ were found to be 3 times larger then those from paper [2]. This means that the existence of the $\eta$-meson bound states with lighter nuclei having atomic number $A = 4 \div 5$ [6] and even $A=2$ [7] is possible.

Fig. 2 shows energy dependence of $Rea_{\eta N}$ and $Ima_{\eta N}$ [5].

C. The first experiments for search of the $\eta$-nuclei.

First experiments on direct research for $\eta$-nuclei were undertaked just after calculation of $a_{\eta N}$ [2] with using $\pi^+$ beams at BNL [8] and LAMPF [9]. The criterion of $\eta$-nuclei selection
FIG. 2. Energy dependence of Rea and Ima of $a_{\eta N}$ for process $\eta N \rightarrow \eta N$ [5].

in the BNL experiment was the observation of narrow kinematic peak ($\Gamma_g \sim 9$ MeV) in the spectrum of proton arising in the final state of the 2-particle reaction:

$$\pi^+ + A \rightarrow p + \eta (A - 1)$$  \hspace{1cm} (1.2)

The peak width $\Gamma_g(\eta)$ corresponded to the width of the $\eta$ bound state in $\eta(A - 1)$ nuclei [3]. The trigger of the events was detection only one particle-proton. The experiment was carried out on a $\pi^+$ meson beam with momentum of 800 MeV/c ising Li, C, O and Al targets. A narrow peak, 9 MeV in width, was assumed to be observed in the spectrum of protons for $\Theta_p = 15^0$. However, no narrow kinematic peak was observed for any target in the spectrum p in the expected area. The authors of paper [8] would like to note that these negative results can be explained by:
- a larger width of the expected peak than it was assumed.
- a smaller cross section, that it was assumed.
- a very bad relation: effect/background < 1.
- a too high energy of primary $\pi^+$-mesons.

As noted in [6] $\text{Re}a_{\eta N}$ is decreased with energy and can become negative at higher energies. This means that ”attraction” in the $\eta N$ system can be replased by ”repulsion”.

Of course, all risons above are important, but in our opinion, the negative results in [8] can be due in principle the fermi-motion of nucleons in the nucleus. Really, a reaction of the (1.2) type at a fixed energy of $\pi$-mesons but with the nucleon mowing in the nucleus (fermi-motion) is equivalent that on the nucleon at rest, but with energy ”spread” of $\pi$-beam. This naturally leads to a sharp energy spread of protons detected at fixed angle $\Theta_p$.

An experiment [9] was carried out on a $\pi^+$-meson beam with a momentum of 640 MeV/c and a harder trigger for event selection corresponding to the production of $\eta$-nuclei was used: proton $p$ was detected on coincidences with $\pi$-meson from the decay of the $S_{11}(1535)$ resonance in the $\eta$-nucleus. As noted in report [9], in this experiment an excess of counts was observed in the expected area for a kinematic peak of protons. However, the experiment was not completed, as so the results are not published.

Thus, first direct experiments on the discovery of the $\eta$-nuclei have not given the expected results. At the same time, some results were obtained in the study of reaction $p+d \rightarrow^3 He + \eta$ [10]. There interpretation required to use of the representations of nucleus interaction of $\eta$-meson with the nucleus in the intermediate stage of the reaction [10]. The characteristic properties of this reaction was:
- a very large cross section in a 10 MeV interval at threshold, by two orders greater then the cross section of the reaction with $\pi^0$-meson production.

- practically an isotropic angular distribution of $\eta$-mesons over this energy range (at threshold), which assumed a multiplicity of interaction of $\eta$-mesons with nucleons inside the nucleus.

An indication of nuclear interaction of $\eta$-meson with the nucleus in the intermediate stage of the reaction was also obtained in the analysis of double charge-exchange reaction $^{18}\text{O}(\pi^+, \pi^-)^{18}\text{Ne}$ [12], where a peak was observed in the excitation curve at energy $E_{\pi^+} = 410$ MeV corresponding to $\eta$-meson production threshold.

II. FIRST RESULTS CONCERNING FORMATION OF $\eta$-MESIC NUCLEI IN PHOTOREACTIONS.

The problem of the $\eta$-nuclei existence for long time ($\sim 10$ years) remained open after experiments at BNL and LAMPF with negative results. Only in 1998 in the experiment carried out on the 1 GeV electron synchrotron at Lebedev Physical Institute the results were obtained which can be interpreted as a direct experimental evidence for the existence of bound $\eta$-meson-nucleus states [13].

A. Method of the identification $\eta$-nuclei.

The experiment was performed on a bremsstrahlung photon beam and correlated $\pi^+ n$ pairs, arising from the reaction

$$\gamma + ^{12}\text{C} \rightarrow p(n) + n\eta \rightarrow \eta N$$

have been search for.

The experiment was carried out at 2 energies $E_{\gamma\text{max}} = 650$ and 850 MeV, i.e. lower and above $\eta$-meson production threshold. As noted earlier in paper [14], the registration of $(\pi N)$-pairs and the analysis of angular and energy characteristics can be a good criterion of production and consequent decay of quasi-bound state of $\eta$-meson and nucleus in an intermediate stage of reaction (2.1).

The $\eta$-nucleus formation in the reaction (2.1) followed by its decay is shown schematically in fig. 3. There, the first stage of the reaction, i.e. production of $\eta$ by photon, second stage i.e. formation of bound state $\eta$-meson with nucleus, and the third stage, i.e. annihilation of $\eta$ and creation of 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. According to modern representations, the bound state of $\eta$-meson and nucleus can be considered as a sequence of production and decay into $\eta N$-pairs of the $S_{11}(1535)$ resonanse in the nucleus

$$\eta + N \rightarrow S_{11} \rightarrow \eta + N \rightarrow S_{11} \rightarrow \eta + N$$

were $N$ is nucleon, proton or neutron.

As result, the full averaging of the energy and angular characteristics of pair components
are arised. The decay of the $\eta$-nucleus is via the decay of the “last” practically “termalized” $S_{11}(1535)$ resonance in this nucleus into $\pi N$-pair.

$$\eta N \to S_{11}(1535) \to \pi N$$ (2.3)

Due to the Fermi motion, $\pi N$ pairs from $\eta$-nucleus decays have the characteristic opening angle $<\Theta_{\pi N}> = 180^\circ$ with the width of $\simeq 25^\circ$. The kinetic energies $<E_{\pi}> = 300$ MeV and $<E_N> = 100$ MeV with the widths of $\simeq 10\%$. It should be noted that the average energies $<E_{\pi}>$ and $<E_N>$ of the decay components were estimated for the $S_{11}(1535)$ resonance bound in the nucleus. Its energy is reduced to binding energy $E_g(S_{11})$ which can reach $20 \div 30$ MeV.

In the case when the momentum (or energy) of produced $\eta$ is high ($> 150$ MeV/c), the attraction between $\eta$ and the nucleus is not essential and the $\eta$-meson propagates freely (up to an absorprion, see Fig. 3b).

![Diagram](image)

**FIG. 3.** (left) Mechanism of formation and decay of an $\eta$-nuclei in photoproduction process. ($E_\gamma \leq 70$) MeV. (right) Mechanism of production and annigilation of $\eta$’s in the nucleus. ($E_\eta > 70$ MeV.)

In this case, the final $\pi N$-pairs also carry a high momentum and their kinematic characteristics, such as the opening angle $<\Theta_{\pi N}>$ and average energies $<E_{\pi}, <E_N>$, are different from those for pairs produced through the stage of the $\eta$-nucleus formation. The kinematics suggests photon energies $E_\gamma = 650 \div 850$ Mev as the most suitable for creating the $\eta$-mesic nuclei.

**B. Experimental set-up.**

An experimental set-up consisted of two the time of flight scintillator spectrometers having a time resolution of $d\tau \simeq 0.1$ ns (fig. 4). Carbon target $\varnothing 4 \times 4$ was used. 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. The time of flight spectra in the pion and neutron spectrometers shown in fig. 4. Two-dimentional distributions over the time of flight particles were obtained for ($\pi^+ n$)-coincidence by combination their individual distribution events.
C. Procedure of measurements.

Strategy of measurements was as follows. Two bremsstrahlung-beam energies were used, $E_{γmax} = 650$ MeV and $850$ MeV, i.e. well below and well above $η$ production threshold (707 MeV on the free nucleon). The first "calibration" run was performed at 650 MeV with spectrometers positioned at angles $Θ_π = Θ_η = 50^0$ around the beam. In that run, this was a quasi-free photoproduction $γp → π^+n$ which dominated, the observed yield of the $(π^+n)$ pairs. Then, at the same "low" energy 650 MeV, the spectrometers were positioned at $Θ_π = Θ_η = 90^0$ (the "background" run), In such kinematics the quasi-free production did not contribute and the observed counts were presumably dominated by double pion production. At last, the third run (the "effect + background") was performed at the same $90^0/90^0$ position, however with the higher photon beam energy of 850 MeV, at with $η$ mesons are produced too.

D. Handling of raw results.

In accordance with measured velosities of particles detected by the spectrometers all candidates to the $(π^+n)$-events were separated into three classes: fast-fast (FF), fast-slow (FS), and slow-slow (SS) events. The FF events mostly correspond to $π^0π^0$ production with results in hitting detectors by photons or $e^+/e^-$. The FS events mostly emerge from $(ππ) + (π^+n)$-pairs. The SS events arised from $(ππ)$ pairs. Comparing yields and time spectra in these runs we have found a clear excess of the FS events which appeared when the photon energy exceeded $η$ production threshold. (see [13] for more details). The raw experimental spectrum over the particles velocities had unphysical region with $β_i > 1$. So happened the velocities $β_i = L_i/t_i$ are subject to fluctuations stemming from errors $δt_i$ and $δL_i$ 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. Therefore, an experimental $β$-resolution of the set-up can be directly inferred from the FF events. Then, using this information and applying an inverse-problem statistical method described in Ref [15], one can unfold the experimental spectrum, obtain a smooth velocity distribution on the physical region $β_i ≤ 1$. (fig. 5), and eventually find a distribution of the particle’s kinetic energies $E_i = M_i[(1 − β_i^2)^{-1/2} − 1]$. Finding $E_i$, we introduced corrections related with every energy losses of particles in absorbers and in the detector matter. It is worth to say that the number of the $(π^+n)$ FS events visibly increases when the photon beam energy becomes sufficient for producing $η$ mesons.

E. Results.

Of the most interest is the distribution of the $(π^+n)$-events over their total energy $E_{tot} = E_n + E_π$, because creation and decay of $η$-mesic nuclei is expected to produce a relatively narrow peak in $E_{tot}$ (see [13, 16]. Such a peak was indeed observed.

At fig. 6 we see an excess of the FS events appears when the photon energy exceeds the $η$-production threshold. These $(π^+n)$ pairs arise from creation and decay of captured bound $η$ in the nucleus, i.e. they arise through the stage of formation of an $η$-mesic nucleus.
The second important result is a "shift" of the position of $S_{11}(1535)$ resonance decayed into nuclei.

On fig. 7 we have a 1-dimensional energy distribution of the $(\pi^+ n)$ events presumably coming from bound $\eta$ decaying in the nuclei. 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 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.

F. Conclusions.

The first results which gives the evidence for existence of the bound state of $\eta$-meson and nucleus in intermediate stage photomesonic processes are obtained at LPI [13].

III. STUDY FOR THE $\eta$-MESIC NUCLEI IN PA-COLLISIONS AT JINR NUCLOTRON (PROPOSAL)

A. Experimental conditions.

The use of intensive monochromatic beams of protons with energies of some GeV may look promising to study $\eta$-mesic nuclei. The possibility of the $\eta$-nuclei production in the reaction

$$p_0 + A \rightarrow p_1 + p_2 + \eta (A - 1) \rightarrow p_1 + p_2 + p_3 + \pi^- + X$$

(3.1)

for light nuclei with $A \geq 12$($^{12}C, ^{14}N, ^{16}O$) is considered in this suggestion.

Fig. 8(a) presents a diagram of process describing the stage of $\eta$-meson production in nucleus with formation of the bound state of $\eta$-meson and nucleus and at last the stage of the $\eta$-nucleus decay. The diagram corresponding to process where the $\eta$-mesic nucleus is not production is shown in fig. 8(b). One can assume that the kinetic energy of the $\eta$-meson is rather great ($T_\eta > 70$ MeV) in this case and there is not attraction between $\eta$-meson and nucleon [6].

The production cross sections of $\eta$-meson in elementary processes $\pi p \rightarrow \eta p$ and $pp \rightarrow \eta pp$ are practicaly similar. However, the advantage of $p$-beams consist in their much greater intensity (by 2-3 orders) in comparing with $\pi$-meson beams (the latter are secondary beams of proton accelerators). This circumstance is important as the production cross sections of $\eta$-nuclei in $pA$-collisions are expected at a level of some tens microbarns.

The event selections of $\eta$-mesic nuclei production in $pA$-collisions are assumed to be made by registrating 4 particles: $p_1$ and $p_2$ protons produced in the 1-st stage of the reaction (3.1) and $(\pi^-, p_3)$ pairs from the decay of the $\eta$-mesic nucleus (fig. 8). To separate from the process shown by the diagram in fig. 8b should be detected the 4 particles in the corresponding energy and angular intervals.
For a bound state of η-meson and nucleus the angular distribution of the (π−, p3) components from the S_{11}(1535) resonance decay is characterized by isotropy at an average angle of < Θ_{πp} > ≃ 180° and an increased yield of such pairs a 3-5 times fold in comparison with the case without ηA-interaction.

B. Experimental setup.

The experiment is supposed to be performed on an internal beam of protons at the JINR NUCLOTRON.
The use of the internal beam affords unique opportunities to study processes with small cross sections through the full interaction of the beam with a "wire" target so the total intensity can reach ∼ 10^{14} p/hours and a low noise level since the background particles are not practically multiplied into the target.

The scheme of the experimental setup and its deposition on the ring of the accelerator is shown in fig. 9. According to the chosen algorithm of event selection of the η-nuclei production in pA-collisions, the setup consists of 3 types detectors. All the detectors are made of the plastic scintillation counters. This is determined by the necessity of the realization of fast coincidences and the measurement of the time-of-flight of particles in the picosecond range. The detectors of p_{1} and p_{2} represents an assembly of counters W1-W8 placed around the axis of an incident beam at an angle < Θ > of ∼ 10°. The function of detectors p_{1} and p_{2} is to measure the coordinate of the detected protons, angle Θ(p) and time-of-flight. The detector used to register the proton p_{3} is a scintillation telescope of the ΔE − E tipe. The detector of π−-mesons is scintillation telescope of 2 counters TC1 and TC2. The time resolution of all detectors is about 150-170 psec. The first counter of the π−-spectrometer is used as a "start" counter for all the time-of-flight system.

C. Estimates of the ΔY(p₁,p₂,p₃,π⁻) yield.

As the production of the η-nuclei is preferable for slow η-mesons (E_η ≤ 70 MeV) the reaction yield is determined by threshold values of the cross sections for elementary processes of the η-meson production. A favourable circumstance is that production cross sections are rather significant. It is due to the disposition of the η-meson production threshold inside the energy region of the S_{11}(1535) resonance, having a large width of Γ ∼ 150 MeV in an elementary pp → pS_{11}(1535) → ppη reaction. The total production cross section of η-meson near threshold is equal to [17, 18]:

\[ \sigma_t(pp \rightarrow ηpp) ≃ 100 \mu{kb}(10^{-28} cm^2) \]  

(3.3.1)
The yield of the 4 multiple coincidences $\Delta Y(p_1, p_2, p_3, \pi^-)$ for 50 $\mu m^{12}C$ target wire can be estimated from the following relation:

$$\Delta Y(p_1, p_2, p_3, \pi^-) = \sigma_t(p^{12}C \rightarrow p_1p_2^{11}B) \cdot N_n \cdot N_p \cdot Br(\pi, N) \cdot \xi \cdot \Omega_{\pi} \cdot f(\Omega_p/\Omega_{\pi}) \cdot \eta_{\pi} \cdot \eta_{p} \cdot \chi_{p1} \cdot \chi_{p2}$$  

(3.3.2)

In this expression:

$\sigma_t(p^{12}C \rightarrow p_1p_2^{11}B)$ is taken as part of $\sigma_t$ for the $\eta$-meson production on the $^{12}C$ nucleus. This part is the same as for photoreactions, i.e. $\sim 5\%$. Then the production cross section of the $\eta$-nuclei in the interaction of p-beam with the $^{12}C$ nucleus is equal:

$\sigma_t(p^{12}C \rightarrow p_1p_2^{11}B) = [6 \cdot \sigma(pp \rightarrow \eta pp) \cdot F^{(11)B}] \cdot 0.05 = 3 \cdot 10^{-3}mb = 3 \mu kb$

where $F^{(11)B}$ is the form factor of the nucleus $^{11}B$, assumed to be $\sim 0.1$.

$N_n = \frac{N_A}{A} \cdot \rho(g/cm^3) \cdot \Delta x(cm) = \frac{6 \cdot 10^{23} \cdot 1.7 \cdot 5 \cdot 10^{-3}}{12} = 4.25 \cdot 10^{20}nucleus/cm^3$

$N_p = I_p \cdot n \cdot K = 10^{11} \cdot 800 \cdot 2 = 1.6 \cdot 10^{14}p/hour$

Where n=800 -number of acceleration cycles per hour, k=2 is the average multiplicity of the passages of the proton beam through the target.

- $\Omega_{\pi} = \left(\frac{50}{150}\right)^2 \frac{1}{4\pi} = 9 \cdot 10^{-3}$
- $Br(\pi,N) = 0,5$
- $\xi = 1/3$ - the part $(\pi^-p)$ decay $S_{11}$ of all kind decay.
- $f(\Omega_p/\Omega_{\pi})$ - is the correlation function = 0,2
- $\eta_{\pi} = 0.8$ - efficiency of $\pi$-detection
- $\eta_{p} = 0.8$ - efficiency of $p$-detection
- $\chi(p_1)$ and $\chi(p_2)$ are the geometric factors describing the fraction over angle interval of $\Delta \Theta = 10 \pm 5^\circ$.

This fraction is registered by the $p_1$ and $p_2$ detectors of the total number of $p_1$ and $p_2$ produced in the $pp \rightarrow \eta pp$ reaction. The kinematic calculations give the following values:

$$\chi(p_1) = 0,185; \chi(p_2) = 0,233$$

Substituting these numerical values to formula (3.3.2) we obtained:

$$\Delta Y(p_1p_2p_3\pi^-) \ approximate \ 4 \frac{events}{hour} \ approximate \ 100 \frac{events}{day}$$

The value of the expected yield can be considered as rather high under the condition of the small background level.

D. Conclusion.

The research of the $\eta$-mesic nuclei in pA-collisions can be interest from point of view of development of the presentations about interaction adrons $(\eta$-meson) with nuclear matter and a research of the new kind of atomic nucleus - $\eta$-mesic nuclei. In these research one can have possibility to formation two-$\eta$-mesic nuclei and mesic nuclei with other mesons $(\rho, \omega, \varphi)$.

IV. SEARCH FOR A FEW-BODY $\eta$-MESIC NUCLEI AT JLAB (CEBAF)
A. Experimental conditions.

Performance of study for $\eta$-mesic nuclei at CEBAF can be very favourable consequently high intensity and continuous e-beam of accelerator. The experiment can be performed at bremsstrahlung photons in region of energy $E_{\gamma \text{max}} = 600 \div 1000 \text{ Mev}$.

The main task of experiment may be to measure of energy and A-dependence cross section for photoproduction of light $\eta$-mesic nuclei (up A=12 to A=3).

The method of $\eta$-nuclei identification consist of the detection 3-particles: one particle, from first stage of reaction (see fig.10) (n or p) and two-particles from second stage -decay of $\eta$-mesic nuclei: $(\pi^+ n)$ or $(\pi^- p)$-pairs. Detection of 3-ple coincidence is guarantee of selection of events connecting with formation $\eta$-mesic nuclei. The experimental set-up must have 3 type scintillation time-of-flight spectrometers (Fig. 10). The yield of 3-ple councedence events can be to compose about 10 events/hour. One can receive the experimental results about energy bounding $E_g S_{11}(1535)$ resonance in light nuclei.

One of interested results can be evidence of existence lightest $\eta$-mesic nuclei ($^3_\eta H, ^3_\eta He, ^4_\eta He$).

V. CONCLUSIONS.

Study of the $\eta$-mesic nuclei is new very interesting field of nuclear physics and particle physics. One can be received a new information for interaction of the $\eta$-meson with nucleon and nucleon resonance in the nuclear matter. The measurement of the bonding energy $E_g(\eta)$ and $E_g(S_{11})$ can be used in chiral symmetry theories in problem for origion of the elementary particle masses.

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FIG. 4. Layout of the experimental setup. Shown also time-of-flight spectra in the π (left) and n (right) spectrometers.
FIG. 5. Corrected two-dimensional distributions over the velocities ($\beta$) for the ($\pi^+n$)-events with end-point energy of the bremsstrahlung spectrum $E_{\gamma\text{max}} = 650$ and 850 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 “fon” run (the right panel) obtained after unfolding raw spectra.
FIG. 7. Distribution over the total kinetic energy of the \((\pi^+ n)\) pairs after subtraction of the background. An arrow indicates the threshold of 408 MeV (see in the text). For a comparison, a product of free-particle cross sections of \(\gamma N \to nN\) and \(nN \to \pi N\) is shown with the dashed line.

FIG. 8. (left) Mechanism of formation and decay of an \(\eta\)-nuclei in pA-collisions. \((E_\eta \leq 70)\) MeV. (right) Mechanism of production and annihilation of \(\eta\)’s in the nucleus. \((E_\eta > 70\) MeV.)

FIG. 9. The scheme of the experimental setup and its deposition on the ring of the accelerator.
FIG. 9. Scheme of the experimental setup.