Search for and study of $\eta$-mesic nuclei in $pA$-collisions at the JINR LHE nuclotron

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An approved experiment at the internal proton beam of the JINR nuclotron on a search for $\eta$-mesic nuclei in the reaction $pA \rightarrow np + \eta(A - 1) \rightarrow np + \pi^- p + X$ is briefly presented.

Introduction

The present project is aimed at a search for and study of hadronic systems of a new kind, $\eta$-mesic nuclei, which are bound states of the $\eta$-meson and a nucleus. Such states were predicted long ago [1] after noticing that an interaction between a slow $\eta$-meson and the nuclear matter is attractive. At zero energy, an optical $\eta A$-potential is equal to $V(r) = -(2\pi \rho(r)/\mu)a_{\eta N}$, where $\mu$ is the reduced mass of $\eta$ and $N$, $\rho(r)$ is the nuclear density, and $a_{\eta N}$ is the $\eta N$-scattering length. Estimates of this scattering length are derived from analyses of $\pi N \rightarrow \pi N$ and $\pi N \rightarrow \eta N$ reactions (e.g. $a_{\eta N} = (0.75 - i0.27)$ fm according to [2]). The positive sign of Re $a_{\eta N}$ just means an attractive $\eta A$ optical potential.

Physics of $\eta$-mesic nuclei is a new field in nuclear and particle physics. A prominent feature of the $\eta N$ interaction is the strong inelastic mode $\eta N \rightarrow \pi N$ and a formation of the near-threshold $S_{11}(1535)$ resonance. The life-time of the $\eta$-nucleus is much shorter than the life-time of $\eta$ itself, and the wave function of an $\eta$-nucleus $\eta A$ is not a pure $\eta A$ state but rather a superposition involving the pure state, the $S_{11}$-resonance replacing a nucleon in the nucleus $A$, and a pion continuum.

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Investigations of $\nu$-nuclei open new possibilities for studying the $\nu N$ interaction. All data on $\nu N$ scattering are indirect and obtained from analyses of reactions in which $\nu N$ is produced in the final state. Results of such analyses suffer from large theoretical uncertainties. Depending on assumptions made, various results for $a_{\nu N}$ are derived in literature which are different by the factor of 4. On the other hand, the average $\nu A$ potential in $\nu$-nuclei is mainly formed by $\nu N$-scattering. Knowing the $\nu A$-potential or, at least, binding energies, one can learn more on the underlying $\nu N$ scattering.

One of aims in studies of $\nu$-nucleus systems is probing the $S_{11}(1535)$ resonance in the nuclear matter. Both the mass and the width of this resonance are changed — in particular, because new decay channels are opened in the nuclear matter, such as the collisional decay $S_{11} + N \rightarrow N + N$. Hadron masses are known to be closely related with the chiral condensate $q\bar{q}$. Understanding of the modification of the chiral condensate in the nuclear matter is an important and challenging problem. A presence of strange quarks in the $\nu$-meson allows to probe the strange condensate $s\bar{s}$ in addition to nonstrange condensates $u\bar{u}$ and $d\bar{d}$.

The first experiment on a search for $\nu$-mesic nuclei has been performed in Brookhaven \[4\]. Narrow peaks of a few-MeV width in the missing-mass spectrum of $\pi^+ A \rightarrow pX$ were then expected. However, no clean signal was found. Later it became clear that the peaks have not to be so narrow and that a better strategy of searching for $\nu$-nuclei is required. Instead of doing missing-mass experiments, it was proposed to detect decay products of $\nu$-nuclei \[5\]. Following this idea, an experiment was performed at the photon beam of the LPI electron synchrotron and for the first time a direct signal of formation of $\nu$-nuclei had been found \[6, 7\].

Last years further experiments on searching for $\nu$-nuclei are on their way – at the ion beam of GSI (Darmstadt) \[8\] and at the proton beam of COSY (Yulich) \[9\]. A possibility to use the photon beam in Grenoble is also considered \[10\]. Very recently, a collaboration working at the electron microtron MAMI-B (Mainz) observed a bound state of the $\nu$-meson in $^3\text{He}$ \[11\].

The present project is aimed at searching for $\nu$-nuclei at the internal proton beam of the JINR LHE nuclotron in reactions

\[
p + A \rightarrow n + p + \nu(A - 1) \rightarrow n + p + \pi^- + p + X, \\
p + A \rightarrow n + p + \nu(A - 1) \rightarrow n + p + p + p + X.
\]

(1)

(2)

An incident proton of the energy $\sim 2$ GeV hits a neutron in the nuclear target and produces a slow $\nu$-meson through the subprocess $p + n \rightarrow n + p + \nu$ yielding also two nucleons flying forward. These nucleons tag the created $\nu$-meson and they are included into the trigger. The slow $\nu$-meson is captured by the nucleus and forms an $\nu$-nucleus that then decays producing a $\pi^- p$ or $pp$ pair (see Fig. 1). A bound state of $\nu$ is expected to be seen as a peak in the energy spectrum of these pairs. Thus, predictions of numerous calculations for binding energies and widths can be tested. Moreover, relative probabilities of the $\pi N$ and $NN$ decay modes of $\nu$-nuclei can be measured.

**Kinematics of $\nu$-nucleus formation and decay**

Eta-nuclei are highly unstable. Their widths are typically $\sim 20-30$ MeV. When a slow $\nu$ travels in a nucleus, multiple $\nu N$-scattering occurs through excitations of intermediate $S_{11}(1535)$ resonances at different nucleons: $\nu + N_1 \rightarrow S_{11} \rightarrow \nu + N_1, \nu + N_2 \rightarrow S_{11} \rightarrow \nu + N_2,$
...\eta + N_k \rightarrow S_{11} \rightarrow \pi + N_k$. The last step here is a conversion of $\eta$ into an energetic $\pi N$ pair which escapes the nucleus. The final $\pi N$ pair carries the kinetic energy of about $m_\eta - m_\pi \simeq 400$ MeV and zero 3-momentum (up to Fermi-motion effects). That kinetic energy is shared between $\pi$ and $N$ as $T_\pi \simeq 310$ MeV and $T_N \simeq 90$ MeV. 3-momenta of the pion and nucleon are nearly opposite, $\theta_{\pi N} \simeq 180^\circ$. In the case of the $S_{11} N \rightarrow NN$ mode of the $\eta$-nucleus decay, nucleons in the $NN$ pair have energies of about $m_\eta/2 = 270$ MeV and again nearly opposite 3-momenta.

It is essential that $\pi N$ pairs with $\theta_{\pi N} \simeq 180^\circ$ and flying transversely to the beam cannot be easily produced in an alternative way. For example, pairs created in the process $N+N \rightarrow N + S_{11} \rightarrow N + \pi + N$ carry a large total 3-momentum needed to produce the $S_{11}$, and they have $\theta_{\pi N} \approx 100^\circ$. A thermalization or capture of $\eta$ is really needed to create transverse pairs.

Incident protons produce $\eta$-mesons through a pion exchange as shown in Fig. 2. Due to isotopic factors and antisymmetrization, $\eta$ is mainly produced in a $pn$ (rather than $pp$) charged-exchange reaction with emission of a leading forward neutron. This neutron has a low transverse momentum $\lesssim 200–300$ MeV/c and, at energies of our interest ($T_{\text{beam}} \sim 2$ GeV), travels at the angle $6^\circ–9^\circ$ with respect to the beam. The proton produced together with a slow $\eta$, has the momentum of about 800 MeV/c (or kinetic energy of 300 MeV). Its typical angle is $\sim 20–30^\circ$.

In the case of the carbon target, the total cross section of $\eta$-nucleus formation is expected to be $\sigma(\eta A) \sim 10$ $\mu$b, or 1% of the total $\eta$-production cross section. Meanwhile the inclusive cross section of inelastic processes in $pC$ collisions is much bigger ($\simeq 250$ mb) thus leading to dangerous backgrounds. That is why it is absolutely necessary to include into the trigger both the $\pi N$ pair and the forward-flying nucleon(s). In the proposed experiment isotopic modes with charged particles will be detected: the transverse $\pi^- p$ or $pp$ pair from the $\eta$-nucleus decay, the proton $p_1$ from the formation stage, and optionally the forward-flying neutron.

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Experimental setup

The planned experimental setup (Fig. 3) includes a two-arm spectrometer for detecting $\pi^- p$ and $pp$ pairs from $\eta$-nucleus decays and ring spectrometers for detecting $p$ and $n$ emitted at the first stage of the reactions (1), (2). The setup will include the following systems:

1) A monitor system consisting of 4 scintillator telescopes — two triple monitors ($F_L$, $F_R$) and two double monitors ($B_L$, $B_R$).

2) A 32-channel scintillator hodoscope $H_M$ for detection of forward-flying protons.

3) A two-arm spectrometer that serves for detecting $\pi^- p$ and $pp$ pairs and measuring particle momenta (time-of-flight) and kinetic energies ($dE/dx$). One arm of this spectrometer already exists: that is the spectrometer SCAN [12]. Its time-of-flight part includes scintillator detectors P1 and P3 (P3 consists of 4 segments) and a solid-state threshold Cherenkov counter P2. The $dE/dx$ part consists of two thick scintillators P4 and two counters P5 which select high-energy particles passing through all layers. Each of these detectors has two phototubes at top and bottom edges. The second arm of the spectrometer is yet to be built.

4) A neutron detector (Fig. 3) will be built and installed beyond the vacuum tube at $\sim 3$ m from the target. That will be a segmented ring of large-volume scintillator covered with veto counters excluding charged particles. A cryogenic shell of the accelerator serves as an absorber of charged particles that reduces a overall load of the detector.

In order to select useful events from the expected flow of $10^4$ triggers/s, a fast two-level trigger will be used. At the first level, events with transverse $180^\circ$ pairs will be selected. Fast identification of particles will be performed using the Cherenkov counter. At the second level, the selected events will be checked using information from the proton and neutron detectors.

The experiment will be performed at the internal proton beam of the JINR nuclotron. Thin filament (or film) targets of various $A$ (Be, C, Al) and thickness $10-20$ $\mu$m will be used. Targets are placed into a target block which enables one to remotely move targets transversely to the beam having the size $\sigma_b = 0.75$ mm. This allows to maintain a constant collision rate during $\sim 5$ s and reduce an average load of detectors what is important for coincidence experiments. Multiple passes of proton bunches through the target ($6 \cdot 10^6$ times during 5 s) result in a sufficient luminosity of the setup: up to $L \simeq 0.5 \cdot 10^{32}$ cm$^{-2}$ s$^{-1}$ in average per one accelerator cycle (10 s) with $10^9$ initially accelerated protons. There is
practically no background caused by secondary interactions of particles produced in a very thin target with the target material.

**Signal and background**

Expected count rates of the setup for signal and background are summarized in the Table 1 for several variants of coincidences with a 10 $\mu$m carbon filament target and $10^9$ initial protons at the accelerator orbit.

| coincidences | signal events/hour | background events/hour |
|--------------|-------------------|------------------------|
| $Y(p\pi^-)$ (\(\theta_{p\pi}\)) = 180° | 1400 | 6500 |
| $Y(pp)$ (\(\theta_{pp}\)) = 180° | 230 |  |
| $Y(p\pi^-, p_1)$ (\(\theta_{p\pi}\)) = 180° \(\theta_{p_1} = (15-20)^\circ\) | 250 | 960 |
| $Y(pp, p_1)$ (\(\theta_{pp}\)) = 180° \(\theta_{p_1} = (15-20)^\circ\) | 40 |  |
| $Y(p\pi^-, p_1n)$ (\(\theta_{p\pi}\)) = 180° \(\theta_{p_1} = (15-20)^\circ\) \(\theta_{n} = (7-11)^\circ\) | 35 | 1 |
| $Y(pp, p_1n)$ (\(\theta_{pp}\)) = 180° \(\theta_{p_1} = (15-20)^\circ\) \(\theta_{n} = (7-11)^\circ\) | 6 |  |

Yields of the double-coincidence events $p\pi^-$ and $pp$ from the reaction of formation of $\eta$-nuclei are determined by the expected cross section $\sigma(\eta A) \approx 10$ $\mu$b of $\eta$-nucleus formation in $p$C-collisions, branching ratios $\text{Br}(p\pi^-) \approx 0.15$ and $\text{Br}(pp) \approx 0.025$ of the $\eta$-nucleus to decay through the $p\pi^-$ and $pp$ modes, respectively, the solid angle $\Omega_\pi = 0.1$ sr of the two-arm spectrometer, and the geometric probability $g_p \approx 0.2$ of the proton to hit the second arm provided another particle of the correlated pair hits the first arm (this probability is determined by a theoretically expected width of the angular correlation).

Addition of the proton $p_1$ to the coincidences reduces count rates by the geometric probability $g_{p_1} \approx 0.18$ of the proton $p_1$ emitted in the reaction of slow-$\eta$ production to fly in the angular range $(15-20)^\circ$ covered by the hodoscope $H_M$. Addition of the neutron further reduces count rates by the neutron detector efficiency $\epsilon_n \approx 0.3$ (as determined by GEANT simulation) and the geometric probability $g_n \approx 0.5$ of the neutron emitted in the same reaction to fly in the angular range $(7-11)^\circ$ covered by the neutron detector (this probability is determined by a simulation of processes shown in Fig. 2).

GEANT simulation of $3 \cdot 10^8$ $p$C-collisions (ignoring the possibility of $\eta$-nucleus formation) found no events with two charged particles $\pi^\pm$ or $p$ flying at $\sim 90^\circ$ and one proton flying forward in the kinematical range of interest. Therefore backgrounds for triple and 4-fold coincidences are only related with random coincidences. Those backgrounds were found as follows.

Using earlier Dubna data obtained with a propane chamber at $T_p = 3.3$ GeV, average loads of elements of the hodoscope $H_M$ positioned at 1.5 m from the target and detectors of the two-arm spectrometer have been estimated and found to be $< 5 \cdot 10^5$ s$^{-1}$ in conditions of the planned experiment. Consistent results were also obtained via GEANT simulation.
which also gave information on loads with neutral particles. Moreover, a test run with carbon and polyethylene targets was done in December 2003 at the JINR nuclotron and the SCAN spectrometer. In that run, the beam energy was 1.5 GeV, 2 GeV, 3 GeV and 4.2 GeV and the beam intensity was $I_p = (0.6-1) \cdot 10^{10} \text{ s}^{-1}$. Loads of all detector elements were measured and found to be less than $2 \cdot 10^{5} \text{ s}^{-1}$. Random coincidences obtained with such loads and the time resolution of the coincidence scheme, $\tau = 20 \text{ ns}$, are given in the Table 1.

At the full intensity created by $10^9$ protons, only 4-fold coincidences clearly select signal events from the background, whereas the rate of triple coincidences is bigger for the background than that for the signal. Such an unfavorable situation can be cured by a reduction of the luminosity — via a reduction of the beam intensity or placing the target more away from the beam axis. When the luminosity is decreased by $N = 10$ times, the rate of the signal is reduced by the factor of $N = 10$ too, whereas the rate of random 2-coincidences is reduced by $N^2 = 100$ and that of triple coincidences is reduced by $N^3 = 1000$. Such a $N = 10$ reduction of the luminosity still makes it possible to obtain a sufficient number of events with double and triple coincidences for a further analysis and determination of energy distributions.

**Conclusions**

The above estimates show that the main aims of the proposed experiment can be achieved. Among them are:
- search for $\eta$-mesic nuclei formed in $pA$ collisions and their separation from background;
- measurement of the total cross section $\sigma(\eta A)$ of $\eta$-nucleus production in $pA$ collisions and its energy and $A$-dependence;
- measurement of the total energy distribution for $p\pi^-$ pairs arising from decays of $\eta$-nuclei and determination of the energy level and the width of the formed $\eta$-nucleus;
- measurement of the branching ratios of $p\pi^-$ and $pp$ modes of $\eta$-nucleus decays.

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