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LETTER TO THE EDITOR

SEARCH FOR η-MESIC NUCLEI IN PHOTOPRODUCTION PROCESSES

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We present preliminary results of an experiment performed at the 1–GeV electron synchrotron of the Lebedev Physical Institute. Using the bremsstrahlung photon beam with the end-point energy of 650–850 MeV and the carbon target, correlated $\pi^+ n$ pairs with opening angle $\langle\theta_{\pi N}\rangle = 180^\circ$ and energies $\langle E_{\pi^+}\rangle = 300$ MeV, $\langle E_n\rangle = 100$ MeV have been observed. They arise from the process $\gamma + {}^{12}\mathrm{C} \to \mathrm{N} + {}_\eta(\mathrm{A}-1) \to \mathrm{N} + \pi^+ n + (\mathrm{A}-2)$ and provide evidence for the existence of ${}^{11}_{\eta}\mathrm{B}$ and ${}^{11}_{\eta}\mathrm{C}$ η-mesic nuclei.

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Eta-mesic nuclei ${}_\eta$A are a new sort of nuclear matter which is bound state of the η-meson and a nucleus [1]. Early attempts to discover the η-nuclei in pion-induced reactions [2,3] yielded negative results which excluded originally assumed properties of ${}_\eta$A [1] that were challenged later [4,5]. A new interest to study the hypothetical η-nuclei arose from an indirect evidence for a formation of the quasi-bound ηA state in the reactions $\mathrm{pp} \to {}^{3}_{\eta}\mathrm{He}$ and $\mathrm{dd} \to {}^{4}_{\eta}\mathrm{He}$ which would naturally explain [6,7] an experimentally observed near-threshold enhancement in the total cross section of those reaction [8,9].

Based on modern determinations of the T-matrix of ηN scattering [10,11], theoretical calculations of the η-nucleus scattering length $a_{\eta\mathrm{A}}$ were made [12], with the conclusion that η-nuclei ${}_\eta$A must exist for all $A \geq 3$.

It should be kept in mind that the purely experimental evidence from the reactions with η in the final state do not determine the *sign* of $a_{\eta\mathrm{A}}$ [8] and thus they cannot unambiguously prove that η-nuclei really exist as a bound rather than virtual state. Therefore, a crucial experiment would be to observe the bound η's. That is the aim of the present work. Specifically, we performed a search for η-nuclei in the reaction

$$\gamma + {}^{12}\mathrm{C} \rightarrow \mathrm{N} + {}_{\eta}(\mathrm{A}-1) \rightarrow \mathrm{N} + \pi^{+}\mathrm{n} + (\mathrm{A}-2), \qquad (1)$$

in which were detected decay products of the η-nuclei, viz. the correlated pions and nucleons emitted in opposite directions transversely to the beam (Fig. 1). The underlying idea [13] is that such πN pairs cannot be produced in quasi-free photoproduction at energies as high as $E_\gamma \sim 700$ MeV, whereas they naturally arise due to η's stopped and captured in the nucleus.

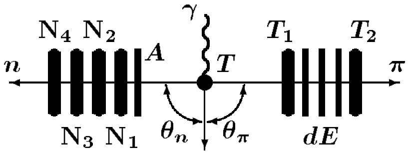

Fig. 1. Layout of the experimental setup. Shown are the time-of-flight pion and neutron spectrometers.

The process of the η-nucleus formation in the reaction (1) followed by its decay is shown schematically in Fig. 2a. There, both the first stage of the reaction, i.e. production of η by a photon, and the second stage, i.e. annihilation of η 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. Formation of the bound state of η and the nucleus becomes possible when the momentum of the produced η is small – typically less than 150 MeV/c (see Fig. 3). The kinematics suggests photon energies $E_\gamma = 650{-}850$ MeV as the most suitable for creating the η-nuclei. Due to the Fermi motion, πN pairs from η-nucleus decays have the characteristic opening angle $\langle\theta_{\pi\mathrm{N}}\rangle = 180^\circ$ with the width of $\simeq 25^\circ$. The kinetic energies are $\langle E_\pi\rangle \simeq 300$ MeV and $\langle E_n\rangle \simeq 100$ MeV. In the case when the momentum (or energy) of the produced η is high, the attraction between η and the nucleus is not essential, and the η-meson propagates freely (up to an absorption, see Fig. 2b). In this case, the final πN pairs also carry a high momentum and their kinematical characteristics are different from those of pairs produced through the stage of the η-nucleus formation.

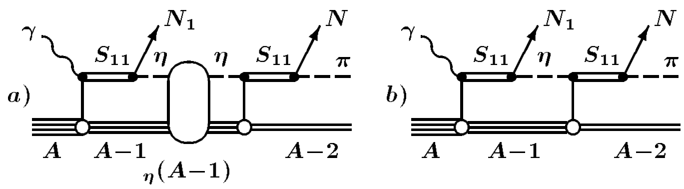

Fig. 2. (a) Mechanism of formation and decay of an η-nucleus. (b) Background production and decay of η's in the nucleus.

A systematic way to describe both the resonance (Fig. 2a) and background (Fig. 2b) processes consists in using the Green function $G(\mathbf{r}_1, \mathbf{r}_2, E)$ which gives an amplitude of η having the energy E to propagate between the creation and annihilation points in the nuclear mean-field described by an optical energy-dependent potential $U(r, E)$. In the vicinity of a bound level of a (complex) energy E_0, the Green function has a pole $\sim 1/(E-E_0)$, and this pole corresponds to the mechanism shown in Fig. 2a. The background process (Fig. 2b) corresponds to a non-pole part of G. A convenient measure of the relative role of the background and resonance processes is given by the spectral function $S(E) = \iint \rho(r_1)\,\rho(r_2)\,|G(\mathbf{r}_1, \mathbf{r}_2, E)|^2\,\mathrm{d}\mathbf{r}_1\,\mathrm{d}\mathbf{r}_2$ (cf. [14]), which characterizes a nuclear dependence of pion production through the two-step transition $\gamma \to \eta \to \pi$ in the nucleus. $S(E)$ depends on the binding potential U and it is proportional to the number of ηN collisions which η experiences when passes through the nucleus of the density $\rho(r)$ between the creation and annihilation points. The attractive potential U makes the produced η of a near-resonance energy E to pass several times through the nucleus before it decays or escapes, thus resulting in an enhanced number of collisions and in a resonance increasing the production rate of the correlated πN pairs.

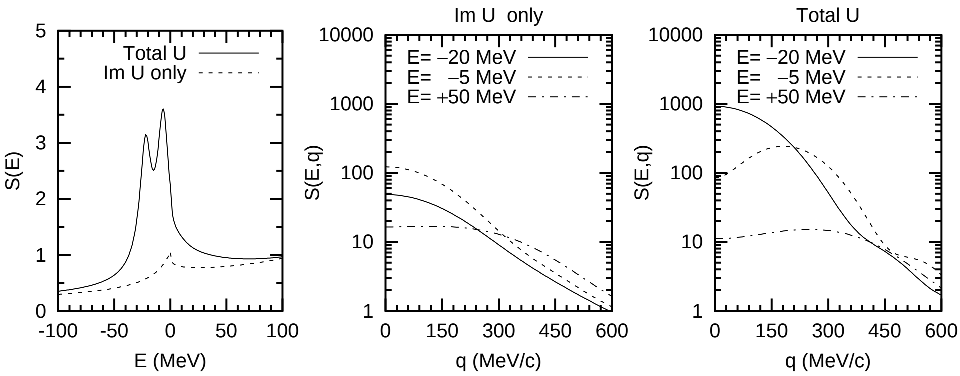

Fig. 3. Spectral functions $S(E)$ and $S(E, q)$ (in arbitrary units) calculated for a rectangular-well optical potential simulating the nucleus ^{12}C. *For a comparison, the results obtained by dropping out the attractive (i.e. real) part of the* ηA *potential* U *are also shown.*

A comparative role of the resonance and background contributions is illustrated in Fig. 3 [15], in which the spectral function $S(E)$ is shown for the case of a rectangular-well optical potential U simulating the ^{12}C nuclear density which is proportional to the elementary ηN-scattering amplitude [11]. The ηA attraction results in a prominent enhancement in the number of collisions when η has a negative energy between 0 and -30 MeV. The related spectral function $S(E, q)$ is is given by the Fourier components of the inner part of the Green function (viz. a part having an overlap with nucleons in the nucleus), describes a nuclear dependence of the energy-momentum distribution $\partial^2 N/\partial E \partial \mathbf{q}$ of the produced πN pairs over their total energy and momentum (which are $E + m_\eta + m_N$ and q, respectively, up to the Fermi smearing). As seen in Fig. 3, the η-nucleus attraction results in a strong enhancement in the momentum density at the resonance energies E and low q. This theoretical finding supports the starting point of the further analysis that the correlated πN pairs predominantly appear from decays of bound η's.

The experimental setup (Fig. 1) consisted of two scintillation time-of-flight spectrometers having the apparatus time-resolution of $\Delta\tau = 50$ ps. Both spectrometers were positioned around a 4 cm carbon target T at either $\theta = 50^\circ$ or 90° with respect to the photon beam (on its opposite sides), each covering a solid angle of ~ 0.06 sr. An anticoincidence-counter (A) for charged particles located in front of the neutron detectors had the rejection efficiency of 90%.

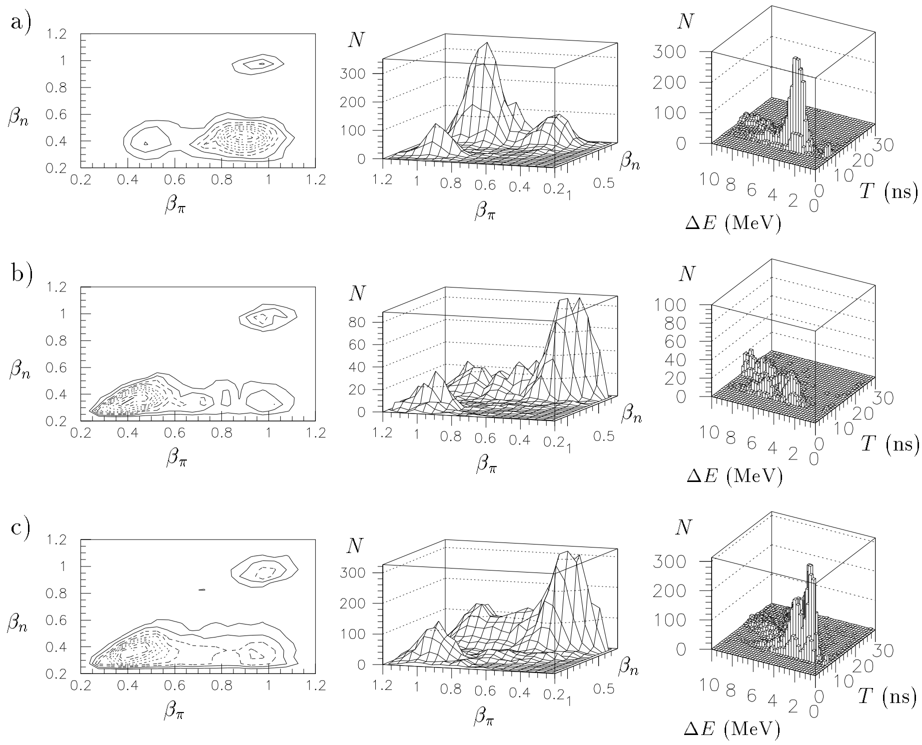

Fig. 4. Left and central panels: Distributions (the numbers of events N) over the pion and neutron velocities for (a) the "calibration", (b) "background" and (c) "effect+background" runs. Right panels: Distributions over the time-of-flight T and the energy losses ΔE in the pion spectrometer for the same runs; only events with a slow particle in the neutron spectrometer were selected for these plots.

Three runs were made in the present experiment with different positions $\theta = \theta_n = \theta_\pi$ of the spectrometers: (a) a "calibration", (b) "background", and (c) "effect + background" runs. In the "calibration" run (a), both spectrometers were placed at $\theta = 50^\circ$ with respect to the photon beam, and the end-point energy of the bremsstrahlung spectrum was $E_{\gamma\max} = 650$ MeV. In this run, mainly π^+n pairs from quasi-free production of pions on the carbon, $\gamma + {}^{12}\mathrm{C} \to \pi^+ + \mathrm{n} + \mathrm{X}$, were detected. In the "background" run (b), the spectrometers were moved to $\theta = 90^\circ$ with respect to the photon beam, i.e. to the position suitable for measuring the effect. The end-point energy was still $E_{\gamma\max} = 650$ MeV, i.e. well below the η photoproduction threshold off free nucleons which is 707 MeV. In the "effect+background" run (c), keeping the angle $\theta = 90°$, the beam energy was set above the threshold: $E_{\gamma\max} = 850$ MeV. The observed two-dimensional velocity spectra of the detected pairs are shown in Fig. 4 for all three runs.

According to the velocities of detected particles in the pion and neutron spectrometer, all events in each run were divided into three groups: fast-fast (FF), fast-slow (FS), and slow-slow (SS). The FF events with the extreme velocities close to the speed of the light correspond to a background (mainly e^+e^- pairs produced by π^0 from double-pion production). The FS events mostly correspond to πN pairs. In the "calibration" run ($\theta = 50°$, $E_{\gamma\max} = 650$ MeV), the quasi-free production of the π^+n pairs is seen as a prominent peak in the two-dimensional distribution (Fig. 4a). In the "background" run ($\theta = 90°$, $E_{\gamma\max} = 650$ MeV), the largest peak (SS events in Fig. 4b) is caused by $\pi\pi$ pairs from double-pion photoproduction off the nucleus. In the "effect+background" run ($\theta = 90°$ and $E_{\gamma\max} = 850$ MeV) (Fig. 4c), apart from the SS events, a clear excess of the FS events, as compared with the "background" run, is seen. This FS signal is interpreted as a result of production and annihilation of slow η's in the nucleus giving the π^+n pairs.

A further analysis of the events was done by using an information from three scintillation detectors which were positioned between the starting and finishing layers, T_1 and T_2, of the time-of-flight pion spectrometer (Fig. 1); they measured the energy losses ΔE of particles that passed through them. A selection of events with a minimal ΔE in the two-dimensional distributions over the time of flight T and the energy losses ΔE (Fig. 4) allows to discriminate events with a single pion from those with the e^+e^- pairs.

The counting rate of the π^+n events was evaluated as

$$N(\pi^+ n; 850) = N(\mathrm{FS_{min}}; 850) - N(\mathrm{FS_{min}}; 650) \times K(850/650)\,,$$

where $N(\mathrm{FS_{min}}; E_{\gamma\max})$ is the number of the observed FS events with the minimal ΔE and with the specific photon energy $E_{\gamma\max}$, and where the coefficient K(850/650) gives an increase of the FS-background due to double-pion photoproduction when $E_{\gamma\max}$ is increased from 650 MeV up to 850 MeV. Assuming that the same coefficient describes also an increase of the SS count rate, it was found from the SS events at 650 and 850 MeV that $K = 2.15$. Such a procedure gives $N(\pi^+\mathrm{n}; 850) = (61 \pm 7)$ events/hour. Assuming an isotropic distribution of the π^+n pairs, taking into account efficiencies of the pion and neutron spectrometers (80% and 30%, respectively) and evaluating a geometrical fraction f of the correlated π^+n pairs simultaneously detected by the pion and neutron detectors of a finite size ($f = 0.18$ was determined by a Monte Carlo simulation of the width of the angular correlation between π^+ and n caused by the Fermi motion of nucleons and η in the nucleus), we obtain the following estimate of the total photoproduction cross section of the correlated pairs from carbon averaged over the energy interval of 650–850 MeV $\langle\sigma(\pi^+\mathrm{n})\rangle = (12.2 \pm 1.3)$ μb (a statistical error only).

Summarizing, we have observed a clear excess of the correlated π^+n pairs with the opening angle close to 180° arising when the photon beam energy becomes higher than the η-production threshold. That is, we have observed production and decay of slow η's inside the nucleus. As was discussed above when describing Fig. 3, these pairs are expected to be mostly related with a formation and decay of η-nuclei in the intermediate state. The obtained total cross section of pair production (3) is close to the theoretical predictions [16] for the total cross section of η-nucleus formation in photo-reactions, what provides a further support for that expectation. For more direct arguments in favour of the observation of η-nuclei, angular and energy distributions of the components of the pairs have to be analyzed and a better statistics has to be achieved. This work is in progress now.

Acknowledgements

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References

1) L. Liu and Q. Haider, Phys. Rev. C **34** (1986) 1845;
2) R. Chrien et al., Phys. Rev. Lett. **60** (1988) 2595;
3) B. Leib and L. Liu, *LAMPF Progress Report*, LA-11670-PR (1988);
4) H.C. Chiang, E. Oset and L.C. Liu, Phys. Rev. C **44** (1988) 2595;
5) J. Kulpa, S. Wycech and A.M. Green, nucl-th/9807020;
6) C. Wilkin, Phys. Rev. C **47** (1993) R938;
7) L. Kondratyuk et al., In *Proc. of Int. Conf. Mesons and Nuclei at Intermediate Energies*, Dubna 1994 (World Scientific, Singapore, Eds. M.Kh. Khanhasayev and Zh.B. Kurmanov), p. 714;
8) B. Mayer et al., Phys. Rev. C **53** (1996) 2068;
9) N. Willis et al., Phys. Lett. B **406** (1997) 14;
10) M. Batinić et al., Phys. Rev. C **51** (1995) 2310; *ibid.* **57** (1998) 1004; Physica Scripta **56** (1997) 521; *ibid.* **58** (1998) 15;
11) A.M. Green and S. Wycech, Phys. Rev. C **55** (1997) R2167;
12) S.A. Rakityansky et al., Phys. Rev. C **53** (1996) R2043;
13) G.A. Sokol and V.A. Tryasuchev, Kratkie Soobsh. Fiz. [English transl.: Sov. Phys. – Lebedev Institute Reports] Issue No. 4 (1991) 23;
14) O. Morimatsu and K. Yazaki, Nucl. Phys. A **435** (1985) 727; A **483** (1988) 493;
15) A.I. L'vov, In: *Proc. 7th Int. Conf. Mesons and Light Nuclei*, Prague-Pruhonice 1998 (World Scientific, Singapore, in press) (nucl-th/9810032) and A.I. L'vov, in preparation;
16) A.I. Lebedev and V.A. Tryasuchev, Yad. Fiz. **58** (1995) 642;

TRAŽENJE η-MEZIČKIH JEZGRI FOTOTVORBENIM PROCESIMA

Snopovima kočnog zračenja najviše energije 650 i 850 MeV u Lebedevom fizičkom institutu opažale su se vezane tvorbe parova π^+n, koji su nastali procesom $\gamma+{}^{12}\mathrm{C} \rightarrow \mathrm{N} + {}_{\eta}(\mathrm{A}-1) \rightarrow \mathrm{N} + \pi^+\mathrm{n} + (\mathrm{A}-2)$. Ti su procesi potvrda postojanja ${}^{11}_{\eta}\mathrm{B}$ i ${}^{11}_{\eta}\mathrm{C}$ η-mezičkih jezgri.