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SEARCH FOR η-MESIC NUCLEI IN THE REACTION $d+$C AT JINR

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Results of a search for quasi-bound states of the η meson and a target nucleus obtained during several years using the internal target at the Nuclotron d beam are presented. Formation of η-mesic nuclei was studied in the reaction $d+$C in the energy interval 1.5–2.2 GeV/nucleon Decay products of S_{11} resonances excited by η mesons captured by nucleons in the nuclear target have been analyzed. Measurements were performed with a scintillation spectrometer SCAN. Analysis of obtained data is presented.

Представлены некоторые результаты поиска квазисвязанного состояния η-мезона и ядра, полученные в течение нескольких лет на внутренней мишени нуклотрона ЛФВЭ ОИЯИ. Образование η-мезонных ядер исследовалось в реакции $d+$C в интервале энергий пучка от 1,5 до 2,2 ГэВ/нуклон. Анализировались продукты распада тех нуклонных резонансов S_{11}, которые образовывались при захвате η-мезона нуклоном мишени. Измерения выполнены на сцинтилляционном спектрометре SCAN. Представлен анализ полученных результатов.

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INTRODUCTION

Properties of hadrons in the nuclear medium is one of interesting topics in modern hadron and nuclear physics. All nuclei have essentially smaller masses than the sum of masses of neutrons and protons forming the nucleus. This mass difference is a result of strong interaction between hadrons that form the nuclear composite system. One can think that other particles distinct from nucleons, such as pions or η mesons, may also have smaller masses in the nuclear medium than those in the empty space. In the case of η, this feature is supported by many theoretical analyses of ηN interaction.

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Measurements of the meson masses and meson interactions in finite nuclei provide valuable data for our understanding of dynamical symmetry breaking in low energy QCD [1–9]. The SCAN experiment at JINR was designed to study possible formation of η-meson bound states inside nuclei [10]. The idea of that experiment is measurement of decays of the $S_{11}(1535)$ resonance at rest excited in a target nucleus after capturing (binding) the η meson. In the case of a recoilless reaction the rest of the target nucleus has a small momentum, so products of the $S_{11}(1535)$ resonance decay are emitted to nearly back-to-back directions. Detection of the emitted back-to-back particles is the main idea for separation of the wanted S_{11} decays in nuclei from another ones.

1. REQUIREMENTS FOR EXPERIMENT

Important prerequisite for a successful experiment is a right choice of reaction participants and optimization of initial parameters. In our case this is a right choice of the reaction of η-meson formation, finding an optimal energy for the primary beam, and a selection of a method for effective background separation.

A good candidate for the primary reaction is $d + {}^{13}$C interaction. ^{13}C is a halo nucleus. It has an outer neutron that can be easily removed from the nucleus. The reaction $d + {}^{13}\mathrm{C} = t + {}^{12}\mathrm{C} + \eta +$ Q has a positive energy balance Q and a big cross section.

We choose the primary deuteron energy to satisfy a recoilless kinematics for η-meson production in nuclei. In this kinematics the produced η mesons can be almost at rest in the nucleus.

In Fig. 1, we plot the minimal momentum transfer in the $A(d, X)(A-1)_\eta$ reaction as a function of the primary kinetic energy per nucleon. For the η momentum less than 100 MeV/c (this number is chosen according to a theoretically expected 100 MeV/c binding energy) that reaction with $\theta = 0°$ has a magic value for the nucleon energy when a recoilless condition is satisfied. Some wider region of the primary energy from 1.6 to 2.7 GeV/nucl. has been selected to take into account also a quasi-free nucleon reaction like $A(p, d)(A-1)_\eta$.

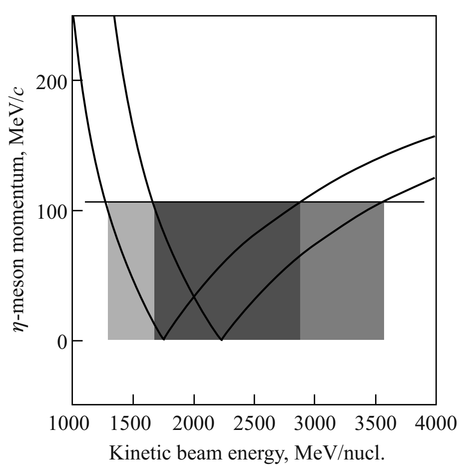

Fig. 1. Momentum transfer for the ^{13}C (p, d) ${}^{12}\mathrm{C}_\eta$ and ^{13}C (d, t) ${}^{12}\mathrm{C}_\eta$ reactions (right and left curves, respectively)

Theoretical predictions for the s-wave N scattering amplitude demonstrate an attraction between η and N at the kinetic energy of the η meson less than 70 MeV.

The captured η meson can decay through the S_{11} resonance to a πN pair that can be detected in the experiment. Such πN pairs emitted from nuclei are correlated over the opening angle $\theta(\pi, N) \sim 180°$.

In this paper we describe experimental results on a search for η-mesic nuclei at the internal deuteron beam of the Nuclotron in the reaction

$$d + \mathrm{C} \rightarrow (\mathrm{A}_2)_\eta + \ldots \rightarrow \pi + p \ldots, \quad (1)$$

where the A_2 nucleus is a part of ^{13}C formed in the $d + {}^{13}$C collision. Hadrons emitted in transverse directions are detected by a two-arm spectrometer. The flow of particles includes πp pairs which are products of η-nuclei decays. A bound state of η is expected to be seen as a peak in the total-energy spectrum of these pairs.

2. EXPERIMENTAL SETUP

The setup for studying η nuclei is shown in Fig. 2. It has two sets of counters located to the left (P arm) and right (K arm) side of the target for back-to-back coincidence measurements and also two-ring array of scintillators (H_M) near forward direction to cover a solid angle for particles emitted in the primary collision. Each of the coincidence counter sets consists of fast timing counters (P_1–P_3; K_1–K_3), a large-volume counter (P_4; K_4), a high-momentum particles detector (P_5; K_5), and a threshold Cherenkov counter (C_P; C_K) for pion separation. Four sets of counters (B_L, F_L, B_R, and F_R) are added to the setup for monitoring the interaction intensity.

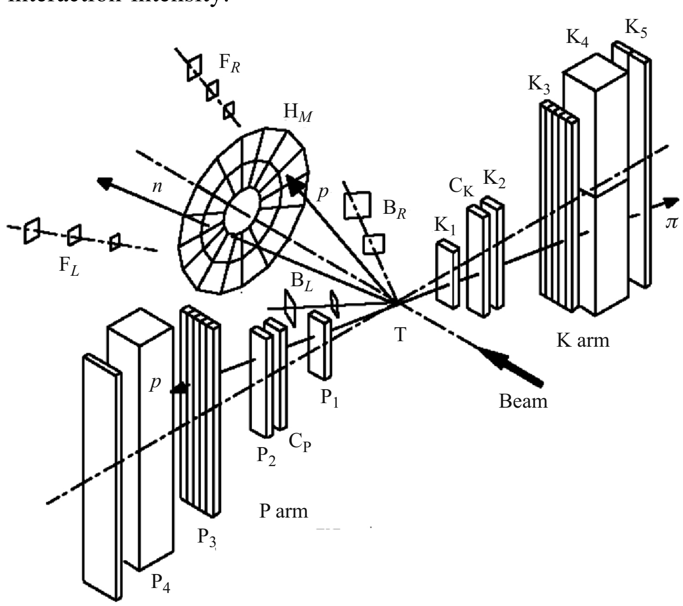

Fig. 2. The experimental setup for studying the in-medium properties of hadrons

Charged particles are identified using three measured quantities: 1) ΔE, the energy loss per unit length measured by all counters, 2) TOF, time of flight between $P_1(K_1)$ and $P_3(K_3)$, and 3) E, the ADC sum of sequentially fired counters. Protons and pions were clearly identified, and the proton contamination in the pion gate was less than 5%. The threshold Cherenkov counter reduces this contamination up to 10 times. Detection thresholds were 40 MeV/c for pions and 230 MeV/c for protons. Efficiency of the counter system was simulated using the Monte Carlo GEANT code. The particle counters are described in more detail in [11].

3. EVENT RECONSTRUCTION AND DATA SELECTION

The experiment was carried out at the internal deuteron beam of the accelerator Nuclotron with the primary beam energy T_d between 1.5 and 2.2 GeV/nucl. In order to achieve aims of the experiment it is important to unambiguously identify two-body decays of the S_{11} resonance. This identification has been realized by measuring velocities and angles of emitted particles. We measured in coincidence two charged particles emitted in back-to-back directions from the target, with the angle between two arms of the setup near the open angle ($\theta_{\rm PK} = 180°$). Also a background has been measured in another kinematics, with the angle $\theta_{\rm PK} = 170°$. Collected data have been converted to DST using a procedure described in [11] and then analyzed as follows. Types of particles were determined by evaluating their masses. The latter was done by measuring two independent kinematic quantities related to the particle mass, namely the velocity (β) and the kinetic energy (T). The velocity was found from the time of flight. The kinetic energy of a charged particle, being proportional to its ionization losses in detectors, was found through a light yield from detectors:

$$\beta = \frac{L_{\rm start-stop}}{t_{\rm tof}c}, \quad T = \sum_{i=1} k_i \left(\frac{dE}{dx}\right)_i, \tag{2}$$

Here c is the speed of light; $L_{\rm start-stop}$ is a time-of-flight base, and i is a number of an activated detector. Finally, the particle mass was reconstructed as

$$M_{\rm rec} = T\frac{\sqrt{1-\beta^2}}{1-\sqrt{1-\beta^2}}. \tag{3}$$

Two masses m_1 and m_2 of the two so-identified particles detected in coincidence by P and K arms have then been used for reconstruction of $M_{\rm eff}$, the effective mass (or the energy sum $E_{\rm sum}$) of the pair:

$$M_{\rm eff} = E_1 + E_2 = \frac{m_1}{\sqrt{1-\beta_1^2}} + \frac{m_2}{\sqrt{1-\beta_2^2}}. \tag{4}$$

A typical obtained distribution of $M_{\rm eff}$ is shown in Fig. 3 with the mass binning of 10 MeV/c^2. One can see three well separated tiles there which are formed by $\pi\pi$, πp, and pp pairs. Such distributions were not corrected for acceptance of the spectrometer because a procedure of background measurements allows one to take into account effects of the experimental acceptance.

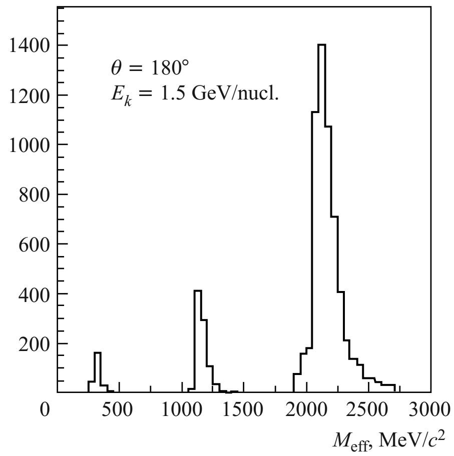

Fig. 3. Effective mass for coincidence of P and K arms

Acceptance in the region of the πp tile was estimated by Monte Carlo generating events corresponding to the reaction (1). This acceptance is increased near the opening angle $\theta = 180°$ of the pair due to a two-particle requirement in the trigger. We performed a coincidence measurement of two hadrons emitted from the decay of hadron resonances formed in the reaction (1). The energies and yield of the two hadrons events have been measured for two angles: $\theta = 180°$ and $\theta = 170°$.

The region of the effective masses of the pairs between 1300 and 1700 MeV/c^2 was further analyzed. The effective mass distribution in that region is shown in Figs. 4, 5 for two primary beam energies, 1.5 and 1.9 GeV/nucl. Only those pairs in which each particle has the energy above 50 MeV are counted there. In Fig. 4, plot a corresponds to back-to-back correlated pairs coming from two-body resonance decays with the opening angle $\theta = 180°$. Central plot b shows contaminations observed at the angle $\theta = 170°$. Plot c of Fig. 4 shows the difference between back-to-back ($\theta = 180°$) and contamination ($\theta = 170°$) measurements.

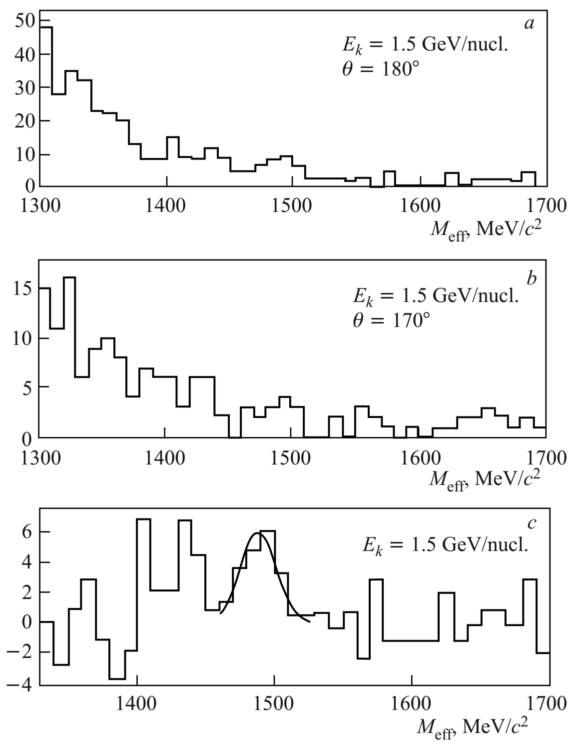

Fig. 4. The effective mass in the region of S_{11} resonance for the energy of primary beam 1.5 GeV/nucl.

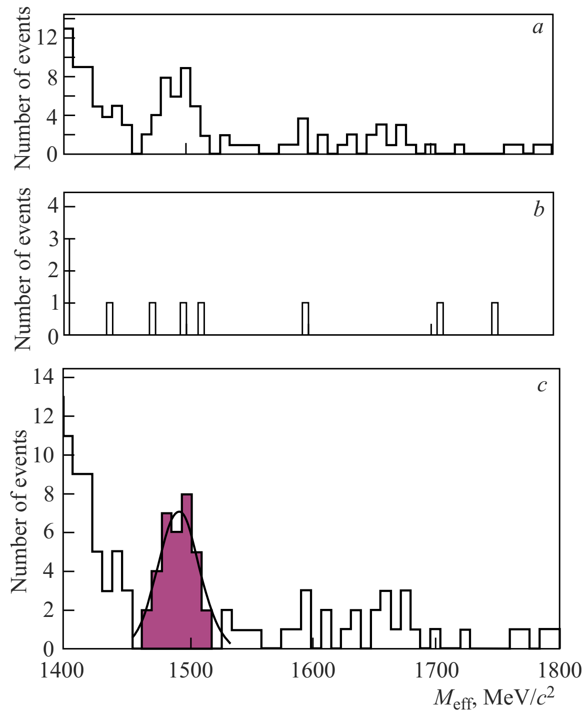

Fig. 5. The effective mass in the region of S_{11} resonance for the energy of primary beam 1.9 GeV/nucl.

Since the studied process is a two-body decay of the S_{11} resonance at rest and the emitted particles have momenta much higher than the nuclear Fermi momentum, one can expect that the two emitted particles are strongly back-to-back correlated in their opening angle ($175^\circ < |\theta_{NN}| \leqslant 180^\circ$) and that their total energy $M_{\rm eff}$ is close to 1500 MeV.

Actually the ratio of the pair yields with $\theta = 170^\circ$ and 180° was $N_{170}/N_{180} = 0.42 \pm 0.08$ (stat.) in the mass region of $1450 < M_{\rm eff} \leqslant 1550$ MeV/c^2 for data shown in Fig. 4, and $N_{170}/N_{180} = 0.1 \pm 0.04$ (stat.) for data of Fig. 5.

A Gaussian fit to bottom (difference) histograms gives $M_{\rm eff} = (1480 \pm 18)$ MeV/c^2 with the width of 23 MeV/c^2 for the data obtained at $T_d = 1.5$ GeV/nucl. and $M_{\rm eff} = (1496 \pm 4)$ MeV/c^2 with the width of 21 MeV/c^2 for $T_d = 1.9$ GeV/nucl. Both fits give practically identical mean values. The found widths are compatible with the energy sum resolution $\sigma(E_{\rm sum}) \approx 30$ MeV of the experimental setup for p pairs.

In the energy-sum spectrum of p pairs one can see a peak located at $E_{\rm sum} \approx 1500$ MeV as anticipated. Meanwhile, the free $S_{11}(1535)$ state is not clearly observed. We can only conclude that the number of events recorded in the open angle geometry greatly exceeds the number of events recorded in the background position of detectors.

The value of the total cross section can be estimated knowing the number of inelastic interactions $d + \mathrm{C}$. That number is determined from count rates of the monitor telescopes and their comparison with simulation results of the GEANT and RQMD codes. The histogram shown in Fig. 5 corresponds to $N_{\rm in} = 1.5 \cdot 2.2 \cdot 10^9$ inelastic interactions. Given the solid angle of the spectrometer ($\Omega \approx 8 \cdot 10^{-3}$ sr) and the cross section of inelastic $d_{\rm C}$ interaction ($\sigma_{\rm in} = (426 \pm 22)$ mb at $T_d = 2.1$ GeV/nucl.), one can roughly estimate the total cross section of η-nucleus formation and S_{11}-resonance excitation as

$$\sigma({}_\eta A) = \frac{4\pi}{\Omega} \frac{N_{\rm eff} - N_{\rm fon}}{N_{\rm in}} \sigma_{\rm in} \approx (11 \pm 8) \mu b. \qquad (5)$$

This value is ∼100 times smaller than expected [6].

4. SUMMARY

We have measured the energy-sum distribution of angular correlated πp pairs emitted in the $d + {\rm C}$ reaction. We have clearly observed a distinct πp back-to-back correlation that may be associated with the signature of the two-body S_{11}-resonance decay related with formation of an η-mesic nucleus. It was also found that the free resonance $S_{11}(1535)$ is not clearly observed. The investigated process deserves a further study using a more intense beam and the new spectrometer.

REFERENCES

1. *Hatsuda T., Lee S. H.* // Phys. Rev. C. 1992. V. 46. P. R34.
2. *Batty C. J. et al.* // Phys. Rep. 1997. V. 287. P. 385.
3. *Lvov A. I.* arXiv:nucl-th/9809054.
4. *Hayano R. S., Hirenzaki S., Gillitzer A.* // Eur. Phys. J. A. 1999. V. 6. P. 99.
5. *Pfeier M. et al.* // Phys. Rev. Lett. 2004. V. 92. P. 252001.
6. *Anikina M. Kh. et al.* arXiv:nucl-ex/0412036.
7. *Sokol G. A. et al.* arXiv :nucl-ex/0011005.
8. *Falter T. et al.* // Prog. Part. Nucl. Phys. 2004. V. 53. P. 25–44.
9. *Jido D., Nagahiro H., Hirenzaki S.* // Nucl. Phys. A. 2003. V. 721. P. 665–668.
10. *Afanasev S. V. et al.* // JINR Rapid. Commun. 1988. No. 5[91].
11. *Afanasev S. V., Dryablov D. K.* // Part. Nucl., Lett. 2005. V. 2, No. 2(125). P. 82–90.