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NEW STATUS OF THE PROJECT "η-NUCLEI" AT THE NUCLOTRON

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Abstract

We review status and perspectives of the search of the η-mesic nuclei at the synchrotron NUCLOTRON. This article present the results obtained at the spectrometer "SCAN" and the plans to study the interaction of eta-meson with nucleon and modification of the particle properties in the nuclear matter.

Keywords: eta-nuclei, particle properties, experiment, exotic nuclei

1. Introduction

A bound system of strongly interacting particles in a nucleus have provided variable information about various aspects of hadron-nucleon interaction in a nucleon environment. In the past, the intensive studies of the η meson are predict of the existence of a bound state of η meson in a nucleus. This phenomenon has been termed as η-mesic nucleus [1]. At the present moment, the experimental status of η-mesic states in nuclei, same measurements give a positive indication of the existence of such states [2]-[6].

2. Formation and decay of η-nuclei

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The predictions of the η-meson nuclear bound state based on the analysis of the η-nucleon scattering length $a_{\eta N}$ and the solutions with ηN potentials. Both approaches give a positive prediction. Experimental researches are currently limited unavailability of the meson beams. As a result, multi-step reactions are investigated. Where the initial stage is formed meson with is reacted the remainder of the nucleus. In the final stage of the η-meson decays mainly through a resonant state S_{11} and the products of this decay is analyzed. The random walk inside the nucleus allow of η-meson has independent multiple scatterings on different nucleons $\eta + N_1 \to \eta + N_1 \cdots \eta + N_m \to \eta + N_m$. This chain of rescattering ended conversion η-meson-nucleon to energetic π N or NN-pair which escapes from the nucleus. The η-mesic nuclei in very unstable short lived formation. The width of this process is estimated at the level $\Gamma \approx 10 \div 20$MeV [7]-[8]

It is important to recognize that if we register πN pair with approximately equal but opposite momentum components, even with some total energy $E_\pi + E_N \approx m_\eta + m_N$ ($1487 \div 1489$ MeV/C^2), it does not mean that we have registered the decay products of the η-mesic nucleus. The pair with a small total momentum can be pro-

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duced from the annihilation of slow unbound η-meson and slow intranuclear nucleon. The criterion of a bound η-meson is two factors: the total energy of the πN pair's should be below the threshold ($E_\pi + E_N < m_\eta + m_N$) and a narrow mass distribution of the πN pairs. The energy and width of this distribution will give information about the energy level of meson bound in a nucleus.

Theoretical predictions for the binding energy and width of the η-nuclear levels are highly dependent on the assumed nuclear potential ηA and nucleus size. For example, for the carbon core is predict a binding energy according to 1-10 MeV and a level width is according to 7 MeV and 35 MeV.

These peculiarities the formation of eta-mesic nuclei formed the basis of the experiment performed at JINR LHEP . The idea of this experiment is in observing decays of resonances excited in a target nucleus after capturing the η-meson. In the case of a recoilless reaction the rest of the target nucleus has a small momentum, so products of the resonance decay are emitted to nearly back-to-back directions. Detection of the particles emitted in opposite direction is the good method for separation of the explored decays from another ones.

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

$$d + \mathrm{C} \to (A_2)_\eta + \ldots \to \pi + p + \ldots \tag{1}$$

where the A_2-nucleus is part of C formed in the $d + C$ 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.

3. Experimental results

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. The setup for study of η-nuclei is shown in Fig. 1. 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 measurement. One arm have fixed position and second one (K-arm) was rotable in the angle range $85^0 \div 120^0$. The identification of the resonance has been realized by measuring velocities, masses and angles of emitted particles. Two charged particles emitted from the target have been measured in coincidence in two conditions. First one is the angle between two arms of the setup was near the open angle ($\Theta_{PK} = 180°$). Second one has the angle $\Theta_{PK} = 170°$. This position of the arms is called as background. Collected data have been analyzed. Types of particles were determined by means procedure of mass reconstruction (m_1 and m_2). The time of flight is produced velocity of registered particles (β_1 and β_2). Finally, the effective mass of resonance M_{eff} was reconstructed as combination thise variables [10]:

$$M_{\mathrm{eff}} = \frac{m_1}{\sqrt{1-\beta_1^2}} + \frac{m_2}{\sqrt{1-\beta_2^2}}.$$

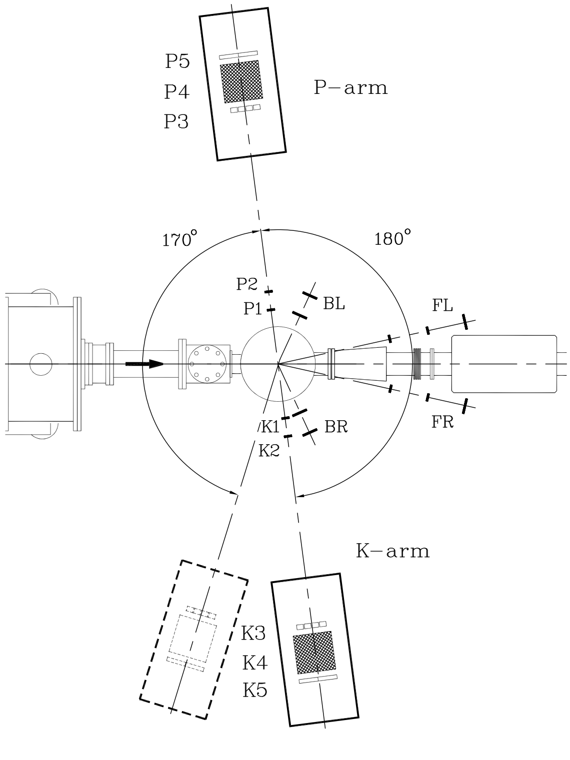

Figure 1: The geometry of the experiment.

The set of experiment were carried out at the internal deuteron beam of the Nuclotron with the primary beam energy range T_d between 1.5 and 2.2 GeV/nucl. A much more statistically significant results were recently obtained for $d+A$ reactions at the beam energy $T_d = 2.1$ GeV/nucl. Analysis of these data used dE-E and TOF techniques and also information from Cherenkov counters. In the region of $M_{\mathrm{eff}} \approx 1450$ MeV/c^2 a visible peak has been registered. A fit of the data with an exponent plus a gaussian functions gives the peak position at 1447.8 ± 3.6 MeV/c^2 with the width 38.8 ± 10.4 MeV/c^2. Fig. 2 shows these data after subtraction of background. Given the energy resolution of the spectrometer, $\sigma(M_{\mathrm{eff}}) = 10$ MeV/c^2, and systematic errors estimated as 10 MeV/c^2, we find these results consistent with those obtained previously at a lower energy of the accelerated beam.

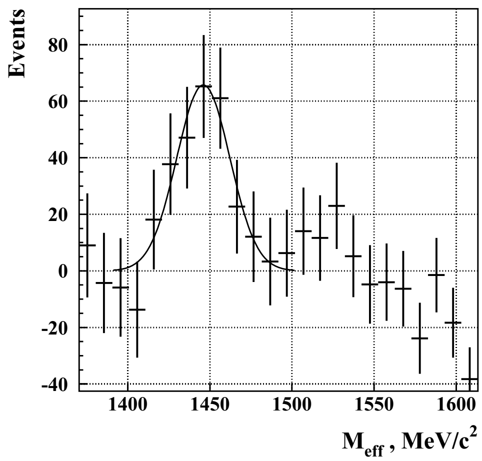

Figure 2: The effective mass of correlated πp pairs after background subtraction for T_d = 2.1 GeV/nucl.

The value of the total cross section can be estimated from the number of inelastic interactions d + C. This number is determined from counts of the monitor telescopes and comparison with simulation results of the GEANT and RQMD codes. Using the solid angle of the spectrometer ($\Omega \approx 8 \times 10^{-3}$ sr) and the cross section of inelastic dC interaction ($\sigma_{\text{in}} = 426 \pm 22$ mb for the energy 2.1 GeV/nucleon), one can roughly estimate the total cross section of πN production through intermediate η-nucleus formation as

$$\sigma(A_\eta) \approx \frac{4\pi}{\Omega}\frac{N_{\text{effect}} - N_{\text{backgr}}}{N_{\text{in}}}\sigma_{\text{in}} \approx 11 \pm 8\ \mu\text{b}.$$

Also, narrow peaks in a spectrum of masses were observed experimentally in Mainz [2] (for a nucleus 3He: a binding energy is about 4 MeV, width is about 25 MeV; the peak was observed in a spectrum of π^0p-pairs) and recently in COSY [3] (for a nucleus 25Mg: a binding energy is about 13 MeV, width is about 10 MeV).

4. The new experimental setup

Based on the experience we can formulate the basic criteria for an optimal spectrometer. The task of the experiment is the allocation and measurement of the narrow peak in the energy distribution of pairs, which are products of η-nucleus decay. It should assume that the peak width will be about 10 MeV, and therefore the future experiment should provide accurate measurements of particle energies not worse than 3.5 MeV, so that the accuracy of the total energy of the pair will be at least 5-7 MeV.

If we consider the process $\eta + N_i \to \pi + \text{N}$ with initial particles at rest, the kinetic energy, momentum and velocity of the secondary particles must be equal (if we ignore the effect of binding and Fermi motion): E_π = 313 MeV, E_N = 94 MeV, $p_{pi} = p_N$ = 431 MeV/c, β_π = 0.95, β_N = 0.42. Accordingly, experiment performance demands precisions of measurement of kinetic energy at level of 1% for pions and 3 % for nucleons

It is necessary to point that besides decay on channel πN η-nuclei can decay with emission NN pair. It occurs at the expense of an η-meson annihilation on pair of the intra nuclear nucleons $\eta + N_i + N_j \to N_1 + N_2$.

Channel NN has a relatively low background. If to consider background processes, it is possible to expect that knocking-out of two nucleons with high energy (≈270 MeV) and transverse to the beam is less probable, than knocking-out of πN-pair where the nucleon has energy ≈94 MeV and the pion energy is ≈300 MeV. At comparable outputs of πN and NN pairs from decay of η-nucleus it means essential increase in the relation of a signal/background.

It should be noted that the energy release in the reaction $\eta N_i N_j \to N_1 N_2$. is m_η = 547 MeV/c^2, so the kinetic energy, momentum and velocity of the emitted nucleons are about $E_1 = E_2$ = 273 MeV, $p_1 = p_2$ = 767 MeV/c, $\beta_1 = \beta_2$= 0.63. Accordingly, experiment performance at the declared level demands accuracy in measuring of kinetic energies of such nucleons at level of 1% It is possible to achieve the required accuracy only by magnetic analysis and study NN-channel of reaction only neutron spectrometry.

The new project performed in JINR provides a significant increase of the energy resolution. This upgrade is include the modernization of one arm to magnetic spectrometer and increasing the time-of-flight base. It allow to measure sign of pions and momentum with good precision. In addition, the neutron registration will be realise in the new project. This modification will expand the number of investigated channels of the reaction and, in particular, it will allow to obtain and analyze data on the decays of η-mesic nuclei into the proton-neutron channel.

A schematic view of the upgraded spectrometer is presented in Fig. 3 Taking into account the above assessment the new setup is planned as three arm spectrometer. The one arm is been constructing as a magnetic arm for charged particles and another two are time-of-flight spectrometers for registration of the neutrons and protons. This combination of detectors can register π^+n ,

π^-p, pn and pp pairs. All arm are located in plane. Two are horizontal and one is vertical. This disposition will be used for determination the studied processes and the background simultaneously.

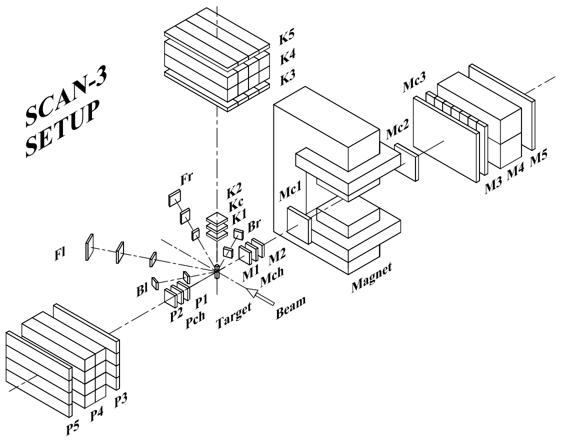

Figure 3: The experimental setup for studying η-mesic nucleai.

The required energy resolution of resonance $\delta E = \delta(E_\pi + E_N) \leq 10$ MeV means the same requirement to energy resolution for each registered particle. If we propose what $\delta E_\pi = \delta E_N \leq 10/\sqrt{2}$ MeV it is require for time-of-flight measurement $\delta\beta_{TOF} \leq 10^{-2}$ and for the magnetic analyser is $\delta\beta_{MAG} \leq 10^{-3}$. The value $\delta\beta_{TOF}$ is limited of time resolution of detectors (δt) and base of flight (L). The values of $\delta t \leq 1$ns and $L \leq 3$m are satisfy it.

The accuracy of measured velocity in magnetic analyse $\delta\beta_{MAG}$ is a function of a curvature. It is measured as a transverse deflection of trajectory of particles in a magnetic field. For the charged pion this deflection is equal to X $\approx$ 15cm and δX should be $\leq$ 0.15 mm. The modern detectors have space resolution in ten times better and δX is limited of a multiple scattering of registered particle. We are planning use drift chamber (the space resolution better 0.1 mm) and helium bag for reduction of the multiple scattering to the level 0.1 mm. It allow us to make $\delta X \leq 0.15$ mm and $\delta\beta_{MAG} \leq 10^{-3}$.

5. Summary

The set of experimental runs were carried out at the internal deuteron beam of the Nuclotron gave data on πp pairs formation. Analysis of these data shown what in the region of $M_{\mathrm{eff}} \approx 1450$ MeV/c^2 a visible peak has been found. The obtained data is a good base for further studies of η-mesic nuclei at the internal beam of the Nuclotron. For this studies the existing spectrometer should be upgraded. Such modernization is planed.

The main objectives of the experiment are:

- detection of the η-mesic nuclei in dA-collisions as resonance peak in a spectrum of a total energy of the correlated pairs;

- definition of the cross-sections of η-nuclei formation;

- measurements of the energy and A-dependence of the cross-section $\sigma({}_\eta A)$ in the dA-collisions ;

- definition of a binding energy of η-meson in a nucleus, it is key parameter characterising potential of an attraction of the η-meson and nucleons at low energies;

- measuring of the ratio of output of (π-p) and (pn)-events;

- definition of the ratio of resonances widths $\Gamma(\pi N)$ and $\Gamma(NN)$.

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