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Study of η-nucleus interaction through the formation of η-nucleus bound state

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Abstract. The question of possible existence of η-mesic nuclei is quite intriguing. Answer to this question will deeply enrich our understanding of η-nucleus interaction which is not so well-understood. We review the experimental efforts for the search of η-mesic nuclei and describe the physics motivation behind it. We present the description of an experiment for the search of η-nucleus bound state using the GeV proton beam, currently being performed at COSY.

Keywords. η-mesic nuclei; η-nucleus interaction.

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1. Introduction

There is an ongoing interest in the possible formation of the η-mesic nuclei [1,2], the bound state of η meson in nucleus. This is because these studies provide a unique way of understanding the η-nucleus interaction, which is very poorly understood. In the absence of any η-meson beam due to their short-lived nature, this interaction can only be studied through the production of η as the final state particles and possible creation of η-nucleus bound states. In contrast to the pion–nucleon interaction, which is quite weak at low momenta, η-nucleon interaction at small momenta is sufficiently strong. The η-N interaction at low energies is strongly influenced by the presence of the s-wave nucleon resonance $S_{11}(1535)$ which lies close to the η production threshold and couples strongly to the ηN channel. The experimental studies of such bound states of various η–A systems will elucidate on the nature of elementary η-nucleon interaction in the presence of medium. The in-medium properties and the possible mass shift in N^* at the nuclear density if observed, can be related to partial restoration of chiral symmetry in the hadronic medium. The η-mesic nuclei by themselves, are very interesting objects of study since they represent a nuclear system with very high excitation energy (η mass = 547.3 MeV).

Though there has been strong theoretical prediction of the existence of the η-mesic nuclei, concrete experimental proof of their existence is still missing. In spite of failure of early experiments to detect the η-mesic nuclei, a number of experiments are being carried out or proposed in different laboratories around the world. In this work we provide the physics motivation for such efforts. We also describe the experiment proposed by us at COSY for the search of η-nucleus bound states.

2. The η-nucleus interaction

The η meson is a member of $SU(3)$ octet of psuedoscalar spinless mesons having isospin $I = 0$. Although it does not contain any open strangeness it has 50% strangeness content which gives it a heavier mass (~547 MeV) compared to the pion (140 MeV). Due to the large mass of η meson, N^* $S_{11}(1535)$ resonance is very close to the η-N threshold. As a result, the interaction of nucleons with η meson in this energy region, where the S-wave contribution dominates, is much stronger than with pions. The large width of this resonance ($\Gamma \sim 150$ MeV) means that it covers almost the entire low energy of the η-nucleon interaction. The $N^*(1535)$ resonance has dominant decay in the η-N channel in addition to the π-N channel. Thus the interaction of η meson with a nucleon at low energies can be considered as a series of creation and decay of the intermediate $N^*(1535)$ resonance. This creation and annihilation of η through N^* inside the nuclear medium can lead to the binding of η inside the nucleus if the S_{11}-induced η-N interaction is strong enough. However, such an η-nucleus bound state will have finite lifetime and nonzero width due to alternate decay mode of N^*, i.e. into the π-N channel.

The existence of the η-A bound states can be related to the positive values of real part of the scattering length $a_{\eta N}$. However, a wide range of values of $a_{\eta N}$ have been deduced by different models [2]. Initial calculations by Bhalerao and Liu [3] from the coupled channel analysis extracted a value $a_{\eta N} = (0.27 + i0.22)$ fm, signifying the presence of an average attractive s-wave interaction between an η meson and a nucleon. Based on these values the authors of ref. [1] predicted the existence of η-nucleus bound states for nuclei with mass number $A \geq 10$. Recent analyses of the scattering length however, predict a value up to three times larger for $\mathrm{Re}(a\eta N)$ with most values lying in the region of 0.5–0.8 fm. These results led to speculations that η-nucleus bound state may be possible for all nuclei with $A \geq 2$. However, very recent calculations of ref. [4] using the techniques of unitarized chiral perturbation theory predict that it is only in the region of $A = 24$ that bound state peaks with widths comparable to binding energy can be observed. In summary, the results of these calculations and analyses indicate that the suitable nuclei where the bound state peaks can be observed experimentally, is still uncertain. The calculated binding energies and the associated widths calculated by few models are summarized in table 1.

3. Previous and current η-mesic nucleus searches

On the experimental side, there has been few attempts to search for the η-mesic nuclei. Earliest measurements for the search of bound η-meson states with the (π^+, p) reaction at Brookhaven AGS and LAMPF could not confirm their existence

Table 1. Calculated binding energy and half-widths (in MeV) of the η-mesic nucleus.

Nucleus	Orbital	Ref. [2]	Ref. [4]
^{12}C	1s	−(1.19, 3.67)	−(9.71, 17.5)
^{16}O	1s	−(3.45, 5.38)	–
^{24}Mg	1s	–	−(12.57, 16.7)
^{26}Mg	1s	−(6.39, 6.60)	–
^{27}Al	1s	–	−(16.65, 17.98)
	1p	–	−(2.9, 20.47)
^{40}Ca	1s	−(8.91, 6.80)	−(17.88, 17.19)
	1p	–	−(7.04, 19.30)
^{208}Pb	1s	−(18.46, 10.11)	−(21.25, 15.88)
	1p	−(12.28, 9.28)	−(17.19, 16.58)
	2s	−(2.37, 5.82)	−(10.43, 17.99)
	1d	−(3.99, 6.90)	−(12.29, 17.74)

[5]. From the experimental measurements of hadron-induced η-production reactions, e.g. $pd \rightarrow\ ^3\mathrm{He}\,\eta$, $dd \rightarrow\ ^4\mathrm{He}\,\eta$ etc. close to threshold there has been indirect evidence of the enhanced ηN attraction. However, it is difficult to say from these measurements whether the final state ηN interaction is sufficiently strong to form a quasi-bound state.

Recently there have been some positive results from the photon-induced η production reactions. Sokol *et al* [6] have claimed the creation of η-mesic nuclei in the $\gamma+^{12}$C reaction with the measurement of $\gamma + A \rightarrow p(n) + (A-1)_\eta \rightarrow p(n) + (\pi^+ + n) + (A-1)$. Here, π^+–n correlation spectra is assumed to arise through stages of formation of the η-mesic nuclei and a peak in the π^0–n invariant mass distribution is seen. However, measurements with better statistics are required for drawing any further conclusion. In a more recent work on the photoproduction of η-mesons in ^{3}He [7], an enhancement of yield is observed when the excitation function of correlated π^0 and proton production for opening angles 170–180° is compared to opening angles of 150–170°. This enhancement seen near the η production threshold has been construed as the observation of an η-nucleus quasi-bound state. However, as is claimed in ref. [8], the enhancement could as well be due to a virtual state near the η-threshold.

4. The experiment to be perormed at COSY

An experiment for η-mesic nucleus search using the (p,^{3}He) reaction on various targets is proposed at COSY. It is planned to use a ^{27}Al target based on the binding energy and width considerations following the calculations of ref. [4]. The signature for the η-mesic nucleus production in this experiment is a peak in the spectrum of ^{3}He at the momentum corresponding to the production of negative energy η's in two-body kinematics. The beam momentum for the experiment is chosen to make use of recoilless kinematics so that the slow η produced in elementary reaction gets embedded inside the nuclear medium. Also, at these sub-threshold energies

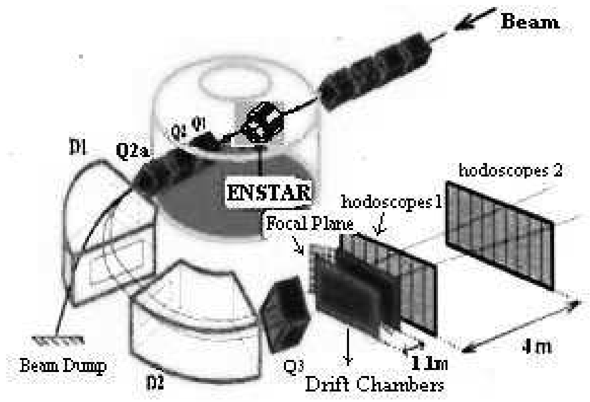

Figure 1. Experimental set-up for the proposed search of η-mesic nucleus at COSY by GEM Collaboration. The set-up uses Big Karl magnetic spectrometer (consisting of dipoles D1, D2 and quadrupoles Q1, Q2, Q2a and Q3), drift chambers and scintillator hodoscopes together with ENSTAR detector.

the quasi-free continuum η production is suppressed. The outgoing ^{3}He particles will be detected by the magnetic spectrometer Big Karl along with its focal plane detectors as shown in figure 1. Because the cross-section is sharply peaked in the forward direction, a major part of the total cross-section can be detected in the angular acceptance of BK. Further, for the background reduction the decay products of the η-mesic nuclei are measured in coincidence with the outgoing ^{3}He particles. These decay products are measured in the large acceptance plastic scintillator detector ENSTAR [9]. The sensitivity of the measurement is enhanced as the missing mass technique has been supplemented with the detection of decay products of the η-mesic nuclei.

5. Summary

Study of η-bound states of nuclei is a fascinating field with profound physics implications. A dedicated experiment is being performed at COSY, Juelich for the search of η-mesic nucleus.

References

[1] Q Haider and L C Liu, *Phys. Lett.* **B172**, 257 (1986)
[2] Q Haider and L C Liu, *Phys. Rev.* **C66**, 045208 (2002)
[3] R S Bhalerao and L C Liu, *Phys. Rev. Lett.* **54**, 865 (1985)
[4] C Garcia-Recio, T Inoue, J Nieves and E Oset, *Phys. Lett.* **B550**, 47 (2002)
[5] R E Cherien *et al*, *Phys. Rev. Lett.* **60**, 2595 (1988)
[6] G A Sokol *et al*, *Fizika* **B8**, 81 (1998)
[7] M Pfeiffer *et al*, *Phys. Rev. Lett.* **92**, 252001 (2004)
[8] C Hanhart, *Comment Phys. Rev. Lett.* **94**, 049101 (2005)
[9] A Chatterjee, B J Roy, V Jha, P Shukla and H Machner for GEM Collaboration, *Pramana – J. Phys.* **66**, 885 (2006)