

Search for η -mesic nuclei in a recoil-free transfer reaction

A. Budzanowski,¹ A. Chatterjee,² P. Hawranek,³ R. Jahn,⁴ B. K. Jain,⁵ V. Jha,^{2,*} S. Kailas,² K. Kilian,⁶ S. Kliczewski,¹ Da. Kirillov,^{6,7} Di. Kirillov,⁸ D. Kolev,⁹ M. Kravcikova,¹⁰ M. Lesiak,^{3,6} J. Lieb,¹¹ L. C. Liu,¹² H. Machner,^{6,7,†} A. Magiera,³ R. Maier,⁶ G. Martinska,¹³ S. Nedeв,¹⁴ N. Piskunov,⁸ D. Protić,⁶ J. Ritman,⁶ P. von Rossen,⁶ B. J. Roy,² P. Shukla,² I. Sitnik,⁸ R. Siudak,¹ R. Tsenov,⁹ J. Urban,¹³ and G. Vankova^{6,9}

(COSY-GEM Collaboration)

¹*Institute of Nuclear Physics, PAN, Krakow, Poland*

²*Nuclear Physics Division, BARC, Mumbai, India*

³*Institute of Physics, Jagellonian University, Krakow, Poland*

⁴*Helmholtz-Institut für Strahlen- und Kernphysik der Universität Bonn, D-53115 Bonn, Germany*

⁵*Mumbai University, Mumbai, India*

⁶*Institut für Kernphysik, Forschungszentrum Jülich, Jülich, Germany*

⁷*Fachbereich Physik, Universität Duisburg-Essen, Duisburg, Germany*

⁸*Laboratory for High Energies, JINR, Dubna, Russia*

⁹*Physics Faculty, University of Sofia, Sofia, Bulgaria*

¹⁰*Technical University, Kosice, Kosice, Slovakia*

¹¹*Physics Department, George Mason University, Fairfax, Virginia, USA*

¹²*Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*

¹³*P. J. Safarik University, Kosice, Slovakia*

¹⁴*University of Chemical Technology and Metallurgy, Sofia, Bulgaria*

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We have studied the reaction $p + {}^{27}\text{Al} \rightarrow {}^3\text{He} + p + \pi^- + X$ at recoil-free kinematics. An η meson possibly produced in this reaction would be thus almost at rest in the laboratory system and could therefore be bound with high probability, if nuclear η states exist. The decay of such a state through the $N^*(1535)$ resonance would lead to a proton- π^- pair emitted in opposite directions. For these conditions we find some indication of such a bound state. An upper limit of ≈ 0.5 nb is found.

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The study of Λ and Σ hypernuclei, which are nuclear bound systems of short-lived hadrons, has proved to be a very useful tool for gaining information about Λ - N and Σ - N interactions in nuclei. Also, studies of π^- and K^- atomic levels have provided useful information about π - N and K - N interactions in nuclei. However, there has never been, to the best of our knowledge, an observation of a neutral pseudoscalar meson bound strongly in the nucleus. Observation of such bound states would open new possibilities in nuclear and particle physics with respect to the structure of such nuclei, the ηNN^* coupling constant, and the behavior of the S_{11} nucleon resonance in nuclei.

In contrast to the pion-nucleon interaction, the η -nucleon interaction at small momenta is attractive and sufficiently strong. This attraction can be seen from the fact that the η threshold (1488 MeV) is situated just below the $N^*(1535)$ resonance, which couples strongly to the η - N channel. In initial calculations, Bhalerao and Liu [1] obtained attractive s -wave η - N scattering lengths of $a_{\eta N} = (0.28 + 0.19i)$ fm and $a_{\eta N} = (0.27 + 0.22i)$ fm, using the π - N phase shifts calculated by Arndt and the CERN theory group, respectively. With these phase shifts, Haider and Liu [2] have shown that

the η can be bound in nuclei with $A \geq 10$. Other groups have also obtained similar results [3–5]. Recent analyses of the experimental data and different theoretical calculations predict a range of values for the η - N scattering length from 0.2 to 1.0 fm for the real part and from 0.2 to 0.35 fm for the imaginary part. The higher values for the real part of $a_{\eta N}$ have led to speculations that the η bound state might be possible even for lighter nuclei. An overview of this topic is given in Ref. [6].

There have been previous searches for the proposed η -mesic nucleus. The first experiments searching for η -mesic nuclei at BNL [7] and LAMPF [8] by using a missing-mass technique in the (π^+, p) reaction came to negative or inconclusive results. Later it became clear that the peaks are not necessarily narrow and that a better strategy of searching for η nuclei is required. Furthermore, the BNL experiment was in a region far from the recoilless kinematics, in which the cross section is substantially reduced [9]. More recently, the existence of η -mesic ${}^3\text{He}$ was claimed to have been observed in the reaction $\gamma^3\text{He} \rightarrow \pi^0 p X$ by using the photon beam at MAMI [10]. It has, however, been pointed out in Ref. [11] that the data of Ref. [10] does not permit an unambiguous determination of the existence of a ${}^3\text{He} \eta$ bound state. The suggestion that ${}^3\text{He} \eta$ is not bound is also supported by the theoretical studies of Refs. [6,12].

The present experiment makes use of the transfer reaction

$$p + {}^A Z \rightarrow {}^3\text{He} + {}^{A-2}(Z-1) \otimes \eta. \quad (1)$$

*Present address: Institut für Kernphysik, Forschungszentrum Jülich, Jülich, Germany.

†Corresponding author: h.machner@fz-juelich.de

The ^3He nuclei were measured at zero degrees with the magnetic spectrograph Big Karl [13] by ray tracing in the focal plane with two packs of multiwire chambers. This was followed by two hodoscope layers, separated by 4 m, that provided an additional time-of-flight measurement. The beam momentum ($p_{\text{beam}} = 1745 \text{ MeV}/c$) and the setting of the spectrograph were chosen such that, for binding energies in the range 0–20 MeV, the η is produced almost at rest. The ^3He spectrum is expected to be dominated by particles being emitted during the nuclear cascade process. To reduce this background a coincidence was required among ^3He and events produced through a second step,



Because the overall ηn system (or N^*) is almost at rest, energy and momentum conservation require the two charged particles to be emitted back to back to each other with energies of $\approx 100 \text{ MeV}$ for the proton and $\approx 348 \text{ MeV}$ for the pion. Such a clear pattern is smeared out by Fermi motion, resulting in a distribution around $\approx 150^\circ$ with a width of 40° . For the measurement of these particles a dedicated detector ENSTAR was built, the details of which are described in Ref. [14]. Briefly, it consists of three cylindrical layers of scintillating material surrounding the target. Each layer is divided into long bars, thus allowing a measurement of the azimuthal emission angle. The bars of the middle layer are further divided along the length to measure the polar emission angle. Whereas the protons of interest are stopped in the middle layer of the detector, pions pass through all layers, giving only ΔE information.

Although, some calculations predict ^4He to be large enough to bind η mesons, Garcia-Recio *et al.* [5] expect more medium-mass nuclei ($A \sim 24$) to show stronger binding. However, heavier nuclei will have broader states, making them harder to detect on a smooth background. Furthermore, the final nucleus should not have too many excited states, which is the case for even-even nuclei. The ideal target should thus be odd-odd, but such a nucleus does not exist as a solid target so we were limited to an odd-even system. As a compromise among these different factors we choose ^{27}Al . The target thickness of 1 mm, corresponding to a resolution of 2 MeV, was chosen in order not to spoil the natural width of the bound state. Two runs were performed with different spectrometer momentum settings ($p_0 = 859 \text{ MeV}/c$ and $897 \text{ MeV}/c$). An integrated luminosity of $0.50 \pm 0.05 \text{ pb}^{-1}$ was accumulated for each run.

Prior to the experiment, the ENSTAR detector was calibrated as described in Ref. [14]. Because of the high-brilliance proton beam the experiment was performed with minimal background even though the ^3He nuclei were measured in the forward direction.

In Fig. 1 the energy loss in the first hodoscope layer is shown as a function of the time of flight. Different particle groups can be clearly identified. Beam particles do not enter the focal plane because their charges differ by a factor of 2. This would not be the case in a deuteron-induced reaction where breakup protons would flood the focal plane detectors. The inclusive ^3He spectra are uniformly distributed when the data are corrected for the acceptance of the spectrograph. ^3He

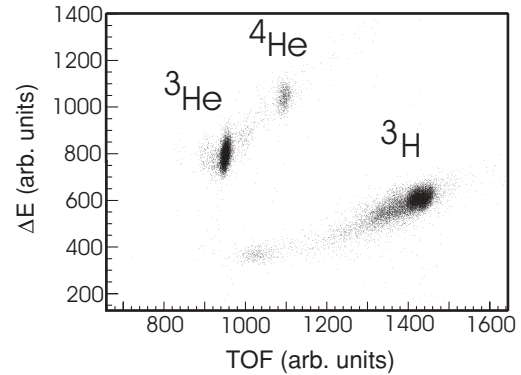


FIG. 1. Energy loss ΔE as function of the time of flight (TOF) for particles in the focal plane area of the magnetic spectrograph.

nuclei within angles of $\approx 3^\circ$ in the vertical and $\approx 0.6^\circ$ in the horizontal direction were recorded by the spectrograph focal plane detectors.

The coincidence required between the focal plane detectors and the ENSTAR detector was achieved by measuring the time between the first hodoscope layer and one of the individual ENSTAR elements. A peak-to-background ratio of 3.2:1 was obtained and the background was subtracted.

For the beam momenta used, the selection of ^3He means that the residual system is at rest with an excitation energy of $\approx 550 \text{ MeV}$. The only background that could give the same pattern as the N^* decay would be a deuteron, stopping in the middle layer in association with a higher energy proton punching through all detectors. A gate was therefore put on pions on a ΔE - E spectrum for events going through all layers. With such geometrical selections we obtain the missing-mass spectra for the two spectrograph settings shown in Fig. 2. The counts have been corrected for the acceptances of the spectrograph for the two settings. To minimize systematical uncertainties in areas of small acceptance, only the regions with acceptance of 4% around the central momentum value have been retained. This eliminated data in less than 5% of the missing-mass range. Applying the cuts from ENSTAR corresponding to $\eta + n \rightarrow \pi^- + p$ leads to reduction in yield by a factor of $\sim 10^3$.

Positive values of the binding energy BE correspond to the free or unbound η production. Owing to the large width of the N^* resonance of 100 to 200 MeV [15], the yield should rise with phase space, but at the η -mesic formation threshold it is expected to be zero. An indication of such a rise is somewhat seen in the data as demonstrated by the fitted polynomial shown in the insert of Fig. 3, which gives a better χ^2 value than the one that is obtained by a fit with a constant.

For both settings, there appears to be an enhancement from the threshold for $^{25}\text{Mg} \otimes \eta$, which is -23.8145 to $\approx -23.79 \text{ GeV}$. One may attribute all the counts to background. However, background should be randomly distributed and hence it is very unlikely for two different measurements to show the same structure. We, therefore, conclude that the structures could be from the bound η .

To elucidate this point further we discuss the spectra in more detail. In Fig. 3 we show the binding energy spectra combined

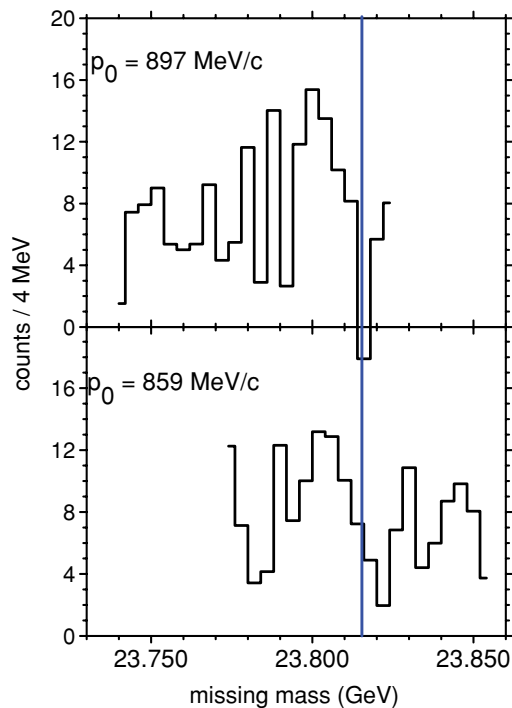


FIG. 2. (Color online) Missing mass spectra for two spectrograph settings indicated in the figure. The counts were generated from acceptance-corrected ^3He spectra measured in the magnetic spectrograph with two charged particles detected in the ENSTAR detector, which show the decay pattern of an N^* . The solid line indicates zero excitation energy of a $^{25}\text{Mg} \otimes \eta$ system (i.e., binding is to the left of the line).

for the two settings. Since for both settings the same luminosity was acquired, the weighted arithmetic mean was used in the overlapping region. The figure shows the data without the strong back-to-back correlation requirement (upper panel) and with the requirement (lower panel). The unconstrained data do not show any structure and can be well described by a constant. For the data in the lower spectrum, the N^* decay pattern is required. The counts are typically lower by an order of magnitude than that in the unconstrained case. Although, the $N^*(1535)$ can also decay with two-pion emission, this branch is small compared to the $p\pi^-$ channel [15].

The data show an enhancement around $BE \approx -13$ MeV. The significance of this structure is extracted according to the two methods given in Refs. [16] and [17], respectively. At first, we test the hypothesis of peak structure being fluctuation of background (i.e., the origin of the background is taken to be independent of the signal). The background outside the peak region, for simplicity approximated by a constant, was found to be 5.8 ± 0.64 . The significance [16] is then given by $(N - BG)/\sqrt{BG + \sigma_{BG}^2}$, where N is the total counts in the region of interest, BG is the total background in this region as determined from the fit to the outside region, and σ_{BG} is error in the estimation of background value as taken from the fit. This yields a value of significance of 5.3σ . Here we have assumed Gaussian errors. For the assumption of Poisson errors with asymmetric error bars (see Fig. 3) the background is 6.2 ± 1.0 . This larger value is typical for Poisson distribution

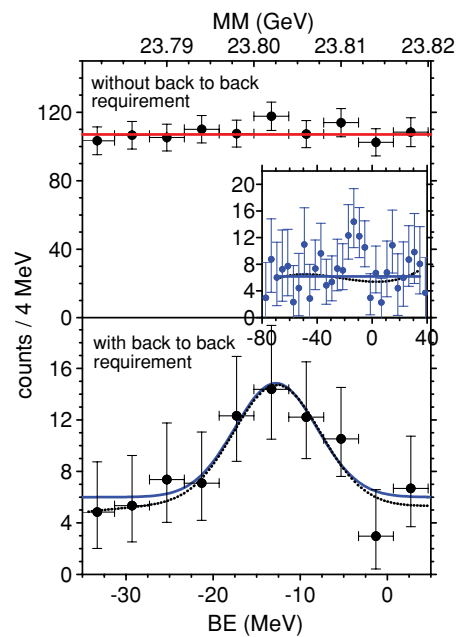


FIG. 3. (Color online) Data in the peak region as function of the missing mass (upper abscissa) or the corresponding binding energy (lower abscissa). The upper panel shows the data without the back-to-back correlation. The solid line in the upper panel is a fitted constant to the whole data set. The solid curve in the lower panel is a constant fitted as background and a Gaussian on top of this background. The dotted curve is a fitted polynomial as background and a Gaussian on top of this background. The insert shows the total data set for the back-to-back condition and two different background fits to the data outside the peak region. The errors are asymmetric because of the underlying Poisson statistics.

and hence the significance reduces to 4.9σ . Finally, a Gaussian on top of the background was fitted to the whole data set. This yielded for the case of Poisson statistics 6.4 ± 0.96 for the background, 8.3 ± 3.6 for the amplitude, -12.0 ± 2.2 MeV for the centroid, and 4.7 ± 1.7 MeV for the width. The corresponding curves are shown in Fig. 3. Also a third-order polynomial was fitted to the data. The resulting curves are also shown in Fig. 3.

In the second method, the statistical significance is extracted by assuming the background events as well as the peak events on top of the background being Poisson distributed. Again a constant background and a Gaussian were assumed. A fit was performed by using the maximum likelihood method. The significance is then defined as $\sqrt{-2\Delta \ln L}$, where $\Delta \ln L$ is the difference in the values of the logarithm likelihood function with signal fixed to zero and at the best-fit value. In this way, we obtain a value of 6.20σ for the significance, assuming a simultaneous determination of amplitude, centroid, and width of the signal. The fit gives 6.38 ± 0.53 for the linear background together with the values 8.55 ± 3.05 for the signal amplitude, -13.13 ± 1.64 MeV for the centroid, and 4.35 ± 1.27 MeV for the width corresponding to a FWHM of 10.22 ± 2.98 MeV. These results compare favorably with those from the first method. We, therefore, consider the present

experimental results to provide a strong hint of a nuclear η bound state.

This allows us to give an upper bound for the cross section. With an estimated efficiency from detector geometry and analysis selections of 0.70 ± 0.07 we find $\sigma = 0.152 \pm 0.054(\text{stat}) \pm 0.021(\text{syst})$ nb. If this “structure” corresponds to a bound η decaying via the reaction of Eq. (2), the cross section would be $0.46 \pm 0.16(\text{stat}) \pm 0.06(\text{syst})$ nb, assuming an isospin branching ratio of 1/3. This cross section value can be compared with the “elementary” $pd \rightarrow {}^3\text{He} \eta$ reaction, which, for the present beam energy, has a cross section integrated over the spectrograph acceptance of $\approx 39 \mu\text{b}$ [18,19].

In summary, we have measured the reaction $p + {}^{27}\text{Al} \rightarrow {}^3\text{He} + \pi^- + p + X$. The ${}^3\text{He}$ ions, which were detected at zero degrees with a magnetic spectrograph, carried the beam momentum (recoilless kinematics). The remaining system has the mass $m({}^{25}\text{Al}) + m(\eta) + BE$ with BE the binding energy. The $\pi^- + p$ system, measured with the ENSTAR detector, decays almost back to back with energies corresponding to an $N^*(1535)$ at rest. The most probable scenario for the η decay is through forming an in-medium N^* resonance, which decays into p and π^- . In this case, the remaining system is $m({}^{24}\text{Al}) + m[N^*(1535)_{\text{in medium}}]$, although instead of an η

a pion could be produced in the intermediate step, forming another N^* nearby, which could lead to the back-to-back $\pi^- p$ events. However, simple kinematical calculations show that this would require the momentum of a target nucleon to at least 210 MeV/c, for which the probability is very low. In two spectra, taken at different spectrograph settings, an enhancement was found for negative binding energies close to the free production threshold. This is exactly what is expected from the bound ηN system. The enhancement may not be purely a result of binding in the ground state only but may also result from an excited ${}^{25}\text{Mg}$ state. However, this requires pickup of more deeply lying nucleons, which may be less likely than pickup of the least-bound nucleons. Binding energy spectra without strong N^* constraint do not show the enhancement.

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