Search for Bound States of the η Meson in Light Nuclei

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A search for nuclear-bound states of the η meson has been carried out. Targets of lithium, carbon, oxygen, and aluminum were placed in a π^+ beam at 800 MeV/c. A predicted η bound state in $^{15}O^*$ ($E_x \approx 540$ MeV) with a width of ≈ 9 MeV was not observed. A bound state of a size $\frac{1}{3}$ of the predicted cross section would have been seen in this experiment at a confidence level of 3σ ($P > 0.9987$).

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This Letter describes a search for a novel nuclear excitation involving the creation of a bound η meson in the nuclear medium. The concept is similar in spirit to a number of ideas which have recently been vigorously pursued. Some familiar examples are Λ hypernuclear states, Σ hypernuclear states, antiprotonic nuclear states, and various dibaryon resonances. In each case an attractive particle-nucleus potential is required together with some mechanism to inhibit the decay process, such as strangeness conservation in the case of the Λ.

Several suggestions of the existence of bound states of the η meson in a wide range of nuclei have recently been published.[1-3] The suggestions of this novel nuclear excitation are based on bound-state formation through the attractive N-η channel of the $N^*(1535)$, where $N^*(1535)$ is the (πN) resonance with $(I,J^\pi)=(\frac{1}{2},\frac{1}{2}^-)$ and mass 1535 MeV/c^2. This resonance dominates η production near threshold. Bhalerao and Liu[4] have shown, by a coupled-channels analysis, that the low-energy ηN interaction is attractive with a scattering length of $0.28+0.202i$ fm. The attractive interaction is a consequence of the threshold being below the $N^*(1535)$ resonance.

Liu and his collaborators have examined the consequences of this attractive interaction in the formation of a bound-η state as a function of mass number. Their study indicates that nuclear bound states could exist for mass numbers larger than $A \approx 10$. At low mass numbers, only s-state bound η's are predicted. At larger mass numbers, p and d states could become bound. Both binding energies and widths increase with A. The optimum case, in their analysis, is $^{15}_{\eta}O$, formed from the (π^+,p) reaction on ^{16}O at a momentum near 740 MeV/c.[3] At an angle near 15°, the momentum transfer is favorable for the transition involving the conversion of a p-shell neutron to an s-shell η. For higher mass numbers, the increase in predicted width would make this excitation more difficult to see over the continuum (π^+,p) background which is present.

An experiment to test these predictions was devised with the positive pion beam available at the low-energy separated beam I at the Brookhaven alternating-gradient synchrotron (AGS), and the Moby Dick spectrometer. The experimental arrangement is virtually identical with that used for the production and measurement of hypernuclei, and it has been described in detail in a number of publications (see Milner *et al.*[5] and related references). The only differences involve the selection of pions, rather than kaons, in the incident particle channel and protons in the exiting particle channel.

The spectrometer was set at 15° to be near the maximum for bound η production as predicted in the analysis of Liu and Haider.[1,3] For example, Ref. 3 predicts the production of an η excitation of width of 9 MeV (FWHM) and a peak cross section of about 30 μb/sr-MeV for an incident pion momentum of 800 MeV/c on an ^{16}O target. The peak would appear near zero binding energy in the $^{15}\mathrm{O}+\eta$ missing-mass spectrum corresponding to the emission of protons with 248 MeV kinetic energy in the laboratory frame, and an excitation of 540 MeV in the ^{15}O system.

Four targets were selected for examination; the target parameters are listed in Table I. The oxygen target was in the form of water. For lithium, no η bound states are predicted, while for carbon the binding is predicted to be marginal. Oxygen is expected to display the largest bound-state cross section; for aluminum and for larger A, the cross sections are smaller, while the widths grow larger.

To confirm a cross-section scale and to measure a spectrometer momentum acceptance function, the reaction $p(\pi^+,p)\pi^+$ was measured for a π^+ momentum of 525 MeV/c. This reaction has been measured by Gordeev *et al.*,[6] and their reported cross sections were in reasonable agreement ($\approx 20\%$) with our measurements. To establish the acceptance function, the nominal momentum setting of the proton spectrometer was varied from 620 to 780 MeV/c, and the strength of the observed π^+ missing-mass peak was used to determine the acceptance. It was desirable to limit the spectrometer acceptance correction to no more than 30% of the central value over the entire spectrum. With this criterion, an acceptance range of ≈ 80 MeV/c was obtainable; i.e., the relative acceptance is everywhere larger than 0.7 throughout the range. To obtain a sufficiently broad range in outgoing proton momenta, overlapping runs were taken for spectrometer central values of 657, 700, and 740 MeV/c.

The spectrometer resolution was measured by analysis of (p,p') events for ^{12}C, recorded simultaneously with the (π^+,p) events. The missing-mass resolution was studied in two separate ways: by use of TRANSPORT[7] matrix elements to calculate the particle momenta, and also by use of the program RAYTRACE,[8] which includes magnetic corrections to all orders. The spectrometer resolution was measured to be 4 MeV (FWHM) with use of the TRANSPORT analysis and 2.5 MeV (FWHM) with RAYTRACE. For either mode of analysis, the resolution is sufficient to detect the predicted η states without serious resolution broadening of the peak.

These (p,p') studies also serve to confirm the energy scale and the energy losses in the target and beam windows of the experiment.

The results of the experiment on the four targets are shown in the composite diagram of Fig. 1. The inclusive proton spectra of this experiment show a qualitative similarity to recent $(\bar{p},p)$ reaction studies on various nuclei by Garreta *et al.*[9] We know of no comparable (π^+,p) data at these pion energies. The data for each target show a smooth (π^+,p) cross section down to an energy corresponding to the η-production threshold. At lower energies, the cross section appears to increase, and it is plausible to attribute this increase to the quasifree η-production process. For the aluminum, oxygen, and possibly carbon cases, an η peak would be expected to

TABLE I. The target thicknesses and the total dead-time-corrected pion irradiations for the spectra obtained in this experiment.

Target	Thickness (g/cm^2)	Dead-time-corrected pion irradiation
Li	2.23	2.92×10^{10}
C	1.59	2.99×10^{10}
Water	2.15	4.57×10^{10}
Al	2.03	1.66×10^{10}
Polyethylene[a]	2.15	1.40×10^{10}

[a]Calibration.

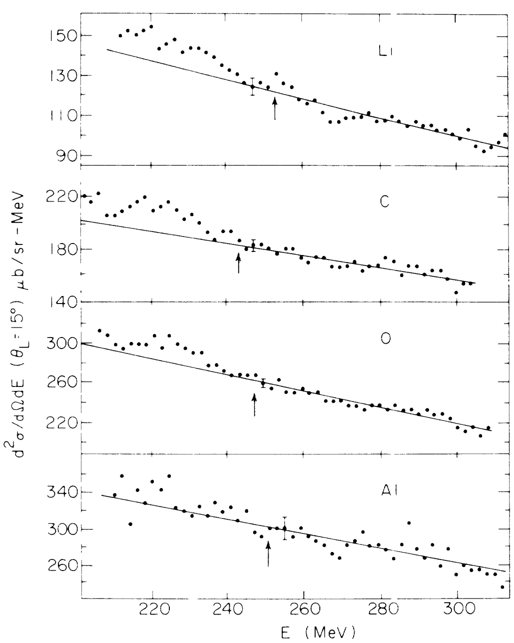

FIG. 1. The proton kinetic-energy spectra obtained for the targets examined in this experiment at 800 MeV/c incident π^+. In each case, a Maxwellian function was fitted to the (π^+,p) inclusive proton energy above the η production threshold. The arrows indicate that threshold for each target. The error bar indicates the standard deviation for a typical datum near threshold.

appear near the position of the arrow.

The sensitivity of this experiment to narrow η bound-state peaks is obviously compromised by the large proton continuum background observed in this experiment. This background is presumably attributable to nuclear protons ejected by the incident pions through various processes, including quasifree knockout, multiple pion and proton scattering, and pion absorption. To establish the experimental sensitivity quantitatively, a statistical analysis was carried out in detail. The analysis was made on data that were not corrected for momentum acceptance, since the correction process increased the spread of the data points significantly. Fluctuations about a polynomial fit to the uncorrected data were analyzed with a standard least-squares fitting code.

The quantitative statement of the experimental sensitivity, based on the largest observed fluctuation in the data, is the following: The detection of a peak with a full width at half maximum of 9 MeV in the ^{16}O data occurs at a confidence level of 3σ (0.9987) for a peak height of 8.7 μb/sr MeV. This size is about one-third of the prediction of Ref. 3. The ^{16}O target was predicted in Ref. 3 to be the most favorable case, i.e., the one displaying the largest cross section. Similar sensitivities obtain for the lithium and carbon cases, while for aluminum the size of the fluctuations, due to a poorer statistical accuracy, preclude any strong statements.

It is interesting to remark on the similarities of the spectra shown in Fig. 1 with the spectra obtained in the experiment of Garreta *et al.*[9]—both of which experiments were designed to search for narrow states located near the onset of a quasifree process. In the latter the search is for $\bar{p}$ states, while in our work we are searching for a structure due to bound η states.

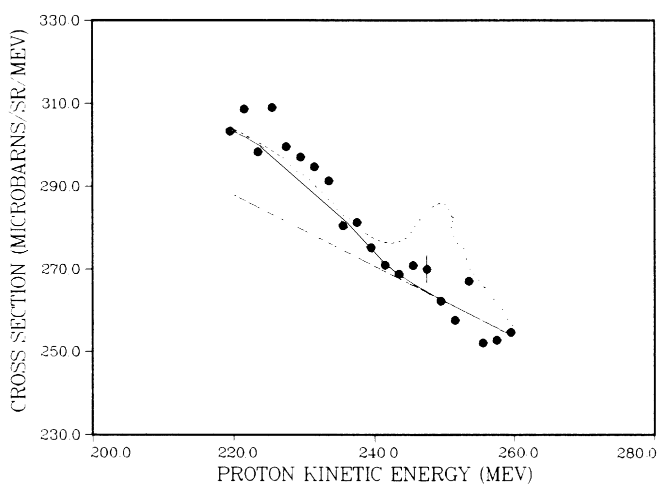

FIG. 2. The region of the oxygen spectrum in which an η bound state would appear. The long-dashed curve shows the extrapolated Maxwellian fit to the inclusive (π,p) background, and the solid curve shows the quasifree η production added to the (π,p) background. The short-dashed curve indicates a state in which a $p_{1/2}$-shell neutron has been transformed into a bound η, with the size, width, and binding predicted by Ref. 3. The data are clearly inconsistent with that prediction.

The $(\bar{p},p)$ process is thought to proceed via the annihilation of the $\bar{p}$ with a target nucleon to produce, on average, five pions which subsequently interact with the $A-1$ target nucleons and eject protons. Thus the subsequent stages of the process are similar to the (π^+,p) reaction. Reference 9 documents the fact that over a very wide range of proton momenta, the cross section has a Maxwellian shape:

$$d^2\sigma/d\Omega\, dE = C(E)^{1/2}\exp(-E/T),$$

where E represents proton kinetic energy.

We adopted the same parametrization to characterize the (π^+,p) data. For the fitting procedure, it was necessary to exclude the η quasifree region; hence, only data outside the allowed kinematical range of η production were used. The resulting fits were then extrapolated into the η quasifree region; these fits are indicated in Fig. 1. We believe that the obvious excess which occurs near the onset of the η threshold is attributed to η quasifree processes.

An expanded region near the η threshold is shown in Fig. 2 for the oxygen target. To indicate the various reaction mechanisms more explicitly, three curves are shown: The long-dashed curve is the Maxwellian fit to the (π^+,p) inclusive process, the solid curve shows an estimate of the quasifree η production added to the Maxwellian, and the short-dashed curve shows the p-shell bound η state predicted by Liu and Haider.[1,3] It should be clear from the figure that a peak of the predicted size would be visible in the experiment; it is not seen.

The size of the quasifree production observed in the ^{16}O data is roughly in line with the observations of Peng and collaborators[10] at a somewhat lower beam momentum of 680 MeV/c. An estimate of the magnitude of the expected quasifree η production was based on the elementary cross sections of Litchfield[11] and Brown *et al.*[12] [the latter for the charge-conjugate (π^-,n) reaction]. The shape of the onset of the quasifree process near threshold was taken from Ref. 3, and that result was arbitrarily normalized to our data as shown in Fig. 1. From this normalization, a result for the effective number of scatterers, defined as

$$N_{\text{eff}} = \frac{d\sigma(\text{nuclear})}{d\sigma(\text{elementary})},$$

can be obtained. The preliminary estimate of the quasifree cross section, derived from the fit of Fig. 2 and integrated over the spectrum shape presented by Ref. 3, leads to a value $d\sigma(\text{QF})/d\Omega \simeq 150$ μb as compared with a value 191 μb derived from Ref. 11. We estimate therefore that N_{eff} is of the order of unity (≈ 0.8). This is quite comparable to the value characteristic of hypernuclear cross sections and an order of magnitude higher than N_{eff} deduced from $(\bar{p},p)$ nuclear interactions.

In summary, the search for a narrow η-nuclear bound state has produced negative results. A peak one-third the size predicted would have been seen in oxygen at a confidence level of 3σ. The conclusion is either that widths for such excitations are much larger than predicted, or that the production cross sections are much smaller than predicted, or both.

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