LA-UR -86-1863

CONF-860575 - - 3

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LA-UR--86-1863

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SUBMITTED TO: Proceedings of the 2nd Conference on
Intersections of particle and nuclear physics
(American Institute of Physics, New York)

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THE ETA-MESIC NUCLEUS: A NEW NUCLEAR SPECIES?

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ABSTRACT

The strong-interaction dynamics of the ηN system can cause the η meson to be captured into nuclear orbitals in nuclei with mass numbers greater than 10. We present our prediction for what should be the experimental signature of the formation of an η -mesic nucleus and describe briefly a forthcoming experiment at Brookhaven. The scientific significance of the η -mesic nuclei is also discussed.

INTRODUCTION

Searching for new forms of matter constitutes one of the most rewarding endeavors in sciences, as every successful discovery generates inevitably quantum leaps in our understanding of the nature. Familiar examples in nuclear physics are the use of Λ - and Σ -hypernuclei to advance our knowledge of the ΛN and ΣN interactions. While meson clouds and meson-exchange currents have since long become an integral part of the theoretical description of known nuclear systems, formation of a mesonic nucleus by capturing a physical meson into a nuclear orbital has not yet been discovered. However, the existence of a mesic nucleus cannot be readily investigated with pions or kaons. Low-energy s-wave pion-nucleus interaction is weak and repulsive. Although the p-wave pion-nucleus interaction is attractive, its strength depends critically on the local pion momentum that theoretical estimates indicate is very small. The K^+ meson is not suitable because low-energy K^+N interaction is repulsive. Although the low-energy K^-N interaction is attractive, the use of a stopped K^- beam could be hampered by the presence of Coulomb interaction that would cause K^- to form preferentially the mesic atom. Furthermore, because of strangeness conservation, K^- will be produced in nuclear reactions only through K^+K^- pair-production that has a small cross section. We show that η -mesic nucleus can exist¹ and can be studied experimentally.

There are currently extensive theoretical and experimental efforts devoted towards achieving a better understanding of the η and η' mesons. Studying η -nucleon interactions can yield additional important information on the nature of the η meson. Because it is nearly impossible to produce an η beam, the nucleus provides a natural laboratory for such investigations.

EVIDENCE AND SEARCH FOR ETA-MESIC NUCLEUS

Recent coupled-channel analysis² of $\pi N \rightarrow \pi N$, $\pi N \rightarrow \pi \pi N$, and $\pi N \rightarrow \eta N$ reactions indicates that pionic η production on a nucleon in the threshold region proceeds mainly through the formation of the $N^*(1535)(S_{11})$ resonance and that low-energy ηN interaction is

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attractive with a scattering length $(0.28 + 0.20i)$ fm. It is easy to prove that this attractive interaction is a necessary consequence of the fact that the threshold for ηN scattering is below $N^*(1535)$, the lowest resonance in the s-wave channel.

Our recent theoretical study¹ indeed indicates that nuclear bound states of the η meson can exist in nuclei with mass number $A > 10$. Such a bound system, termed the η -mesic nucleus, is caused by the strong interaction between the electrically neutral η meson and all the nucleons in the nucleus. In Fig. 1, we present the predicted A-dependence of the binding energies of η . The underlying dynamics that gives rise to this systematics has been discussed in Ref. 1.

As can be seen from Fig. 1, in light nuclei the η is bound in the s-state for which the bound-state wave function is peaked at low momenta. The production of a low-momenta η meson will, therefore, favor the formation of η -mesic nucleus. Because of the kinematics of the $\pi N \rightarrow \eta N$ reaction, a low-momentum η is associated with a high-momentum nucleon in the laboratory frame. We conclude that the reaction $A(\pi^+, p)\eta B$ leading to the emission of a high-energy outgoing proton is favorable to the search for the η -mesic nucleus. An experiment along this line of consideration will soon be carried out at Brookhaven.³ Pions of momentum ~ 740 MeV/c will be used to bombard three nuclear targets: ^{12}C , ^{16}O , and ^{28}Si . The reaction kinematics of the experiment is illustrated in Fig. 2, where we also show, as an example, the predicted proton energy spectrum for the reaction $^{16}\text{O}(\pi^+, p)X$. The two peaks situated at outgoing proton kinetic energies 185 and 158 MeV correspond, respectively, to the formation of the mesic nucleus $^{15}\text{O}_\eta$ after the removal of 1p- and 1s-shell neutron in the ^{16}O target.⁴ The background events at $T_p > 185$ MeV are due mainly to $(\pi, \pi xp)$ and $(\pi, 2\pi xp)$ reactions. The background at lower proton energies contains also a component arising from the $(\pi, \eta xp)$ reactions. To facilitate the determination of systematic errors, nuclear target ^7Li that cannot bind an η meson will also be used.

The calculated widths of η bound-states are ~ 10 to 13 MeV in nuclei with $A < 30$ and are ~ 15 to 20 MeV for nuclei with higher A . About 95% of the width is due to the decay of the η -mesic nucleus with the emission of one pion and one nucleon. The remaining 5% is related to the emission of two pions. The η absorption, being strongly suppressed, does not contribute significantly to the width. Details of medium effects on the binding energies and widths of the η -mesic nucleus can be found in Ref. 4. We stress that the order of magnitude of the above-mentioned widths represents an upper limit. This is because our calculations of were based on the η interacting with one and/or two nucleons at a time. It is conceivable that the large wave length of the bound η meson could favor genuine η -3N interaction. In such a case, the η will share its energy and momentum with three nucleons and the pion emissions will be completely blocked by Pauli principle. As a result, widths of the order of keV may be possible. Consequently, if the widths observed at Brookhaven are comparable to the energy resolution of the experiment, then a better measurement of the widths should be seriously considered in future.

IMPLICATIONS OF ETA-MESIC NUCLEUS

The magnitude of the η binding energies depends on the magnitude of the ηNN^* coupling constant. Since $N^*(1535)$ is not a ground state of the quarks, the ηNN^* coupling constant depends not only on the quark content of the η meson but also on the quark excitation mechanism in N^* . Thus, studies of η -mesic nuclei will improve our understanding of the η and N^* . It is further noteworthy that the η -mesic nuclear levels correspond to an average excitation energy of ~ 540 MeV (Fig. 3), to be compared with an average excitation energy of ~ 200 MeV associated with the Λ - and Σ -hypernuclei. We anticipate that the existence of nuclear bound states with such high excitation energies will trigger many new fundamental studies in nuclear structure theory.

We thank the INC Division at Los Alamos for constant encouragement. One of us (LCL) wishes to express his deep gratitude to Drs. H. O. Funsten, R. E. Chrien, P. Pile, and C. B. Dover for stimulating discussions on various aspects of the Brookhaven experiment. This work was supported by the US DOE.

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