Single-Proton Emission Following Positive Pion Absorption in Carbon*

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Pions are usually absorbed by a pair of nucleons in complex nuclei. It is, however, possible for the pion to be absorbed by a single nucleon, leading to the emission of only one nucleon. Letourneux and Eisenberg have pointed out that this latter reaction would be useful in studying single-nucleon states within nuclei and as a test of the validity of perturbation theory for low-energy pion-nucleus interactions. Accordingly, we have searched for the reaction $C^{12}(\pi^+,p)C^{11}$ at 68-MeV pion energy and 11° proton emission angle. The observed cross section of 640 ± 130 μb/sr for absorption by $1p_{3/2}$ neutrons is more than eight times larger than the theoretical value.

PION absorption by nuclei results predominantely in the emission of a pair of nucleons.[1] In the past, such reactions have been studied to obtain information on the correlations of pairs of nucleons within the nucleus. Letourneux and Eisenberg[2] have pointed out that in order to investigate single-nucleon states within nuclei and also to test the validity of perturbation theory as applied to low-energy pion-nucleus interaction, it is more appropriate to study single-nucleon emission. We have, accordingly, measured the cross section for the reaction $C^{12}(\pi^+,p)C^{11}$ by detecting very energetic protons emitted at an angle of 11° with respect to the incident 68-MeV pions. We find the cross section for absorption by $1p_{3/2}$ neutrons to be much larger than the theoretical prediction.

The experimental setup is shown in Fig. 1. An 86-MeV positive pion beam is produced with an internal target in the synchrocyclotron of the NASA Space Radiation Effects Laboratory. Muons compose about 25% of the beam and positrons less than 1%. To eliminate proton contamination in the beam, a Lucite Čerenkov counter C_1 is operated in coincidence with the beam telescope. A 2.12-g/cm^2 graphite target is located inside a bending magnet so as to make a rough momentum selection of the particles coming from the target. One advantage of this method is that protons produced at small angles, where the theoretical cross section is largest, can be observed. The energies of the protons thus selected are measured by total absorption in a 5-in.×4-in.-thick NaI crystal. C_2 is a 2-in.-thick Čerenkov counter in anticoincidence to further prevent stray pions and muons from being measured. Also, a pulse from the NaI crystal is rejected if it is followed within 10 μsec by another pulse. This would occur if a pion or muon stopped in the NaI crystal and eventually decayed into an electron.

The NaI crystal was calibrated in a proton beam and also in the pion beam. The measurements agreed after corrections were made for light output as a function of dE/dx. The absolute energy scale is uncertain by an estimated amount of 2–3 MeV.

The result is shown in Fig. 2. The arrows indicate the expected positions for single protons produced from neutrons in the $1s_{1/2}$ and $1p_{3/2}$ shells of C^{12}, assuming binding energies of 34 and 19 MeV, respectively. Since the $1s_{1/2}$ neutron-binding energy is not known, the value for $1s_{1/2}$ protons is used.

The solid curve centered at the expected $1p_{3/2}$ position is a Gaussian curve with a standard deviation of 6 MeV, which corresponds to our energy resolution. It is normalized to the number of counts between 168 and 200 MeV. The curve below 170 MeV is the phase space for two-nucleon emission using an expected total binding energy of 35 MeV. The curve is normalized to the number of counts in the region from 138 to 168 MeV. Our energy resolution has been folded in. Above 170 MeV it is kinematically impossible for two nucleons to be emitted.

Our energy resolution is a combination of a 10-MeV full width at half-maximum (FWHM) spread in the incident pion energy, a 7-MeV (FWHM) minimum resolution of the NaI counter itself, and a 4-MeV spread due to finite target thickness.

There is some uncertainty in the background (target out) subtraction. It is difficult to know what fraction of the background protons are produced in material before or after the target. Therefore, it is assumed that one-half are produced before and the other half produced after the target. However, this uncertainty makes no qualitative difference in the results and corresponds

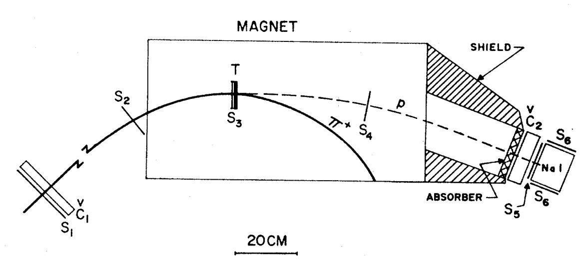

FIG. 1. Experimental apparatus: S, scintillation counters; C, Lucite Čerenkov counters. The event and monitor counters are S_1, C_1, S_2, S_3, S_4, $\bar{C}_2$, S_5, $\bar{S}_6$, and NaI, and S_1, C_1, S_2, and S_3, respectively.

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[1] J. Favier, T. Bressani, G. Charpak, L. Massonet, W. Meyerhof, and C. Zupancic, Phys. Letters **25B**, 409 (1967).
[2] J. Letourneux and J. M. Eisenberg, Nucl. Phys. **87**, 331 (1966).

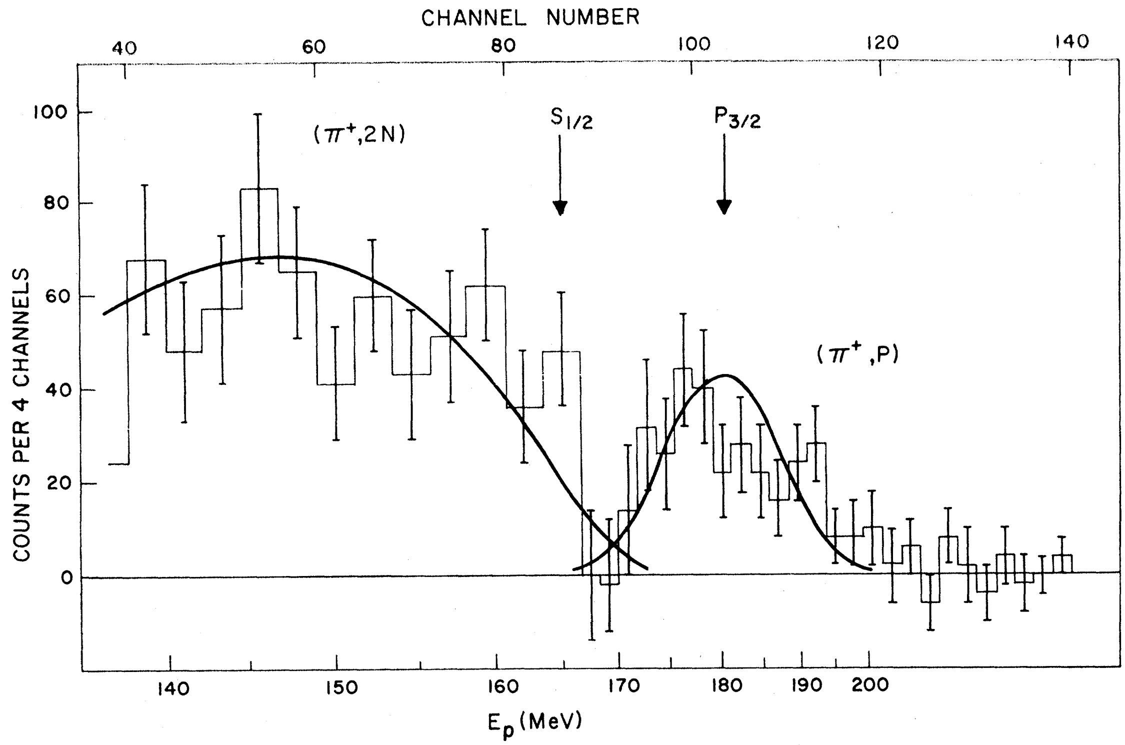

FIG. 2. Proton energy spectrum for 68±5-MeV positive pions on C^{12}. The energy scale is for protons at the center of the target. The average emission angle is 11° with a spread of 6° (FWHM).

to a maximum of 12% difference in the calculation of the cross section.

From the data with C_1 turned off, and knowing the accidental rate of C_1 with the telescope, it is deduced that the possible contribution from the proton contamination in the incident beam is less than 3% for any part of the observed energy spectrum.

In addition to the already described methods of eliminating pions and muons in the energy measurement, there are further reasons why the particles must be protons. A pion or lighter particle cannot lose as much energy as we have observed by direct ionization in the NaI crystal, regardless of its initial energy. Also we have data taken with a smaller amount of absorber in front of the NaI counter. The spectral shift was consistant with that expected from the known dE/dx values for protons. Deutrons or heavier particles produced by 68-MeV pions on C^{12} cannot have sufficient energy to pass through the material in front of the NaI counter.

We identify the observed peak at 180 MeV as protons resulting from π^+ absorption by $1p_{3/2}$ shell neutrons in the C^{12} nucleus. The observed events give the cross section for this reaction to be 640±130 μb/sr. This includes a 25% correction for loss of protons due to inelastic scattering in the absorber and in the NaI crystal itself. The error quoted is the probable error due to statistics, uncertainty in subtracting background, and uncertainty in the muon flux in the beam.

With the present resolution, it is impossible to determine whether the C^{11} nucleus is left in the ground state or in one of its low-energy excited states of 2.0 or 4.3 MeV. The data is consistent with the assumption that the C^{11} nucleus is always left in its ground state, which we have assumed in the data analysis. In our experiment, it is not possible to obtain data for the $1s_{1/2}$ shell since it overlaps the spectrum of two-nucleon emission.

For two-nucleon emission we obtain a rough estimate of the cross section of 25 mb/sr at 11° for detecting one proton of two-nucleon pairs. The assumptions made here are that all protons detected below 168 MeV come from this reaction and that the energy spectrum follows phase space.

The cross section for single-nucleon emission has been calculated by Letourneux and Eisenberg.[2] Using their theory, we calculate the theoretical value of the cross section for protons from the $1p_{3/2}$ shell neutrons. We obtain 19 μb/sr at 11° using relativistic pion and proton kinematics and 80 μb/sr for relativistic pions and nonrelativistic protons. The latter set of kinematics gives values of the cross section that agree with those in Ref. 2. The results are also very sensitive to the harmonic-oscillator parameter α in the C^{12} wave function, for which we use 125 MeV/c.[2] From electron scattering data[3] α is given as 1.52×10^{-13} cm or 130 MeV/c. A 10% increase in α gives a sixfold increase in the cross section.

[3] P. F. Cooper and R. Wilson, Nucl. Phys. **15**, 373 (1960), especially p. 385.

Several corrections to the theory are now being made, which hopefully will account for the difference between theory and experiment. They are (1) corrections for the effect of the (3,3) resonance,[4] (2) initial- and final-state interactions,[5] and (3) corrections to the harmonic-oscillator wave function for large momentum transfer.[5]

[4] D. K. Anderson (private communication).
[5] J. M. Eisenberg (private communication).

We plan to continue this experiment for different nuclei and hopefully with better energy resolution.

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Many-Body Theory of Nuclear Reactions

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The localization of composite projectiles in the many-body theory of nuclear reactions is studied within the single-particle shell model with configuration mixing. Difficulties are pointed out in extending the existing theory of nucleon–heavy-nucleus scattering to more general reaction processes, and it is shown that an improved treatment of the collective variables corresponding to the c.m. motion of clusters is necessary in order to generalize the theory. Multiple, deformed single-particle (shell-model) potentials, modified to incorporate the c.m. motion, are introduced to spatially localize the composite particles in the continuum. The total c.m. motion gives rise to a physically trivial degeneracy, while the relative motion of clusters is the very scattering process being solved. Double sets of redundant variables are introduced to describe the reactions involving two-cluster channels, and the correct scattering functions are obtained by the double-projection method of Peierls and Thouless.

I. INTRODUCTION

THE single-particle shell model with configuration mixing has been used extensively in the past in the study of nuclear bound states,[1] and, more recently, the method has been extended to nucleon–heavy-nucleus scattering.[2–4] This extension, to be referred to as the continuum shell model (CSM), was made simply by including a single set of continuum configurations in the truncated subset of determinantal single-particle wave functions. The simplicity of the Hartree-Fock (HF) basis with full exchange symmetry is then retained, but otherwise the method is of very limited applicability. Some of the difficulties are

(a) The usual HF basis functions formed by the product of single-particle wave functions are by definition not the eigenstates of the total linear and angular momenta of the system, so that the states generated by a fixed potential are not invarient under the translation, rotation, and Galilean transformations. The localized HF basis functions are spuriously degenerate, and this property has been used earlier[5,6] to generate, for example, the collective rotational states of deformed nuclei. Multiple spurious degeneracies occur in the scattering problem; the c.m. motion of the entire system gives rise to a trivial degeneracy when all the particle coordinates and momenta are taken to be independent. The c.m. coordinates **X** and momentum **P** can be introduced as redundant variables and be eliminated by the double-projection method of Peierls and Thouless.[7,8] On the other hand, the relative c.m. motion of clusters gives rise to a nontrivial dynamical problem. The CSM method completely ignores this problem, and thus is restricted to scatterings by an *infinitely heavy target.*

(b) As is well known, the product of single-particle basis sets is not suitable for incorporating the strong long-range correlations,[9] unless each set is itself cor-

[1] See, e.g., V. Gillet, in *Proceedings of the International School of Physics*, edited by C. Bloch (Academic Press Inc., New York, 1966), Course 36.
[2] U. Fano, Phys. Rev. **124**, 1866 (1961).
[3] C. Bloch and V. Gillet, Phys. Letters **16**, 62 (1965); V. Gillet and C. Bloch, *ibid.* **18**, 58 (1965); C. Bloch, in *Proceedings of the International School of Physics*, edited by C. Bloch (Academic Press Inc., New York, 1966), Course 36.
[4] H. A. Weidenmüller, Nucl. Phys. **75**, 189 (1966); H. A. Weidenmüller and K. Dietrich, *ibid.* **83**, 332 (1966).
[5] D. J. Thouless and J. G. Valatin, Nucl. Phys. **31**, 211 (1962).
[6] J. G. Valatin, in *Lectures in Theoretical Physics*, edited by W. E. Brittin *et al.* (Interscience Publishers, Inc., New York, 1962), Vol 4; M. Baranger, in *Cargese Lectures in Theoretical Physics*, edited by M. Lévy (W. A. Benjamin, Inc., New York, 1963); G. E. Brown, *Unified Theory of Nuclear Models* (North-Holland Publishing Company, Amsterdam, 1964); F. Villars, in *Proceedings of the International School of Physics*, edited by C. Bloch (Academic Press Inc., New York, 1966), Course 36.
[7] R. E. Peierls and D. J. Thouless, Nucl. Phys. **38**, 154 (1962); R. E. Peierls and J. Yoccoz, Proc. Phys. Soc. (London) **A70**, 381 (1957).
[8] J. J. Griffin and J. A. Wheeler, Phys. Rev. **108**, 311 (1957); E. P. Gross, Nucl. Phys. **14**, 389 (1959).
[9] H. J. Lipkin, Phys. Rev. **110**, 1395 (1958); Ann. Phys. (N. Y.) **9**, 212 (1960); **12**, 452 (1961); also in *Lectures at Brandeis Summer Institute in Theoretical Physics* (Brandeis University, Waltham, Massachusetts, 1959), Vol. 2.