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[13]By partial lifetime into a specific decay mode we mean total lifetime divided by the branching ratio into that mode.

[14]These numbers are the result of general consensus of some of the theoretical calculations of Ref. 7, T. J. Goldman (private communication), and our own estimates.

[15]These are obtained by one of us (A. S.) by a reasonable variation of the proportions of X into a spinless meson, a vector meson, or two spinless mesons.

[16]By using the measured absorption cross sections of π^+ on nuclei we estimate that about $\frac{1}{2}$ of the π^+ would result into μ^+.

[17]Final states with η, as opposed to π^0 in (a)–(c), are likely to be suppressed relative to π^0's. Since η and ω have substantial branching ratios for decays to π^0 their inclusion will enhance the inequality $(N\to e^+ +\pi^0 +X)/(N\to e^+ +X) \gtrsim \frac{1}{2}$ and the resulting limit (9).

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[19]An amusing limit on nucleon decays of the form $N \to \nu_\mu + X$, $N\to 3\nu_\mu$ can be obtained at the level of (2–5) $\times 10^{26}$ yr by attributing the entire observed ν_μ flux to decays of all the baryons in the earth. For details see Ref. 10.

Experimental Test of One-Pion Exchange and Partial Conservation of Axial-Vector Current in Proton-Nucleus Charge-Exchange Reactions at 144 MeV

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We have measured the differential cross sections of the (p,n) reaction on ^{6}Li, ^{12}C, and ^{14}N to the ground state of the final nucleus ($\Delta J=1$, $\Delta I=1$, $\Delta P=0$) at $E_p=144$ MeV and $0° < \theta_{\rm lab} < 20°$. We treat the nuclei as elementary particles, extract the initial-nucleus–pion–final-nucleus coupling constants, and compare them with predictions based on the partial conservation of axial-vector current hypothesis. The calculations, which have no free parameters, agree with the data for ^{6}Li and ^{12}C, but not for ^{14}N.

A common feature of the three reactions, $p + {}^6\text{Li} \to n + {}^6\text{Be}$, $p + {}^{12}\text{C} \to n + {}^{12}\text{N}$, and $p + {}^{14}\text{N} \to n + {}^{14}\text{O}$ is that the change in nuclear angular momentum (J), isospin (I), and parity (P) is the same; namely, $\Delta J = 1$, $\Delta I = 1$, and $\Delta P = 0$. These nuclei undergo the same change in their quantum numbers in the (p,n) reaction as in an allowed Gamow-Teller β decay, which is also the quantum-number change required of a one-pion exchange mechanism. We therefore *conjectured* that the reactions are dominated by *one-pion* exchange for small momentum transfer ($q^2 \lesssim m_\pi{}^2$) and intermediate-energy protons ($E_p = 144$ MeV).

The experiment was carried out at the Indiana

University Cyclotron Facility. The incident proton beam had an energy of 144 MeV, which was chosen to take advantage of existing elastic-scattering data.[1] The target, with an areal density of ~50 mg/cm^2, is located at the entrance of a large-gap dipole magnet, which swept the proton beam into a well-shielded dump. The neutrons passed between the pole faces of the magnet and exited from the vacuum chamber through a thin Kapton window. Adjustable lead and concrete collimators permitted the remote detector to view only the target. Although background arising from scattering off the collimators was negligible, a small correction for attenuation in air along the 20-m flight path was made.

The detector consisted of a thin plastic scintillator to identify charged particles (mostly elastically scattered protons), followed by two plastic scintillator timing rods,[2] and a liquid scintillator vat,[3] used for setting the energy threshold. A valid neutron event consisted of a coincidence between one of the rods and the vat, with no signal in the charged-particle identifier. Elastically scattered protons provided both a time and a pulse-height reference. A phototube was placed on each end of the rods, and the time difference between each phototube pulse and the subsequent cyclotron rf pulse was recorded. The neutron time-of-flight spectrum for each rod was then obtained by averaging the time differences from each of its ends. Sample spectra are shown in Fig. 1. The efficiency of this detector was determined by comparing its yield to that of a simpler detector,[4] which was calibrated in an independent experiment using the associated-particle method. The tagged 130-MeV neutron beam was produced with the reaction $p + {}^7\text{Li} \to n + {}^7\text{Be}$.

The differential cross sections are plotted in Fig. 2. We estimate that the absolute normalization, including the efficiency and target thickness, has an accuracy of ± 7%; the errors indicated are statistical. The fact that our ^{6}Li data are in good agreement with the data of Measday and Palmieri[5] on the analog reaction $n + {}^6\text{Li} \to p + {}^6\text{He}$ is a good cross check on our experimental results.

The contribution of one-pion exchange to these reactions is calculated in a formalism treating the nucleus as an elementary particle.[6] The initial-nucleus (N), pion (π), final-nucleus (N') vertex function, $g_{N\pi N'}(q^2)$, is obtained from the partially conserved axial-vector current hypothesis (PCAC) in conjunction with β decay (which gives the value at $q^2 = 0$) and inelastic electron scattering (which gives the momentum-transfer dependence). In this manner, we may examine the application of PCAC and one-pion exchange to nuclei. Although the application of PCAC to nuclei has a growing literature,[7] this particular comparison, which includes zero momentum transfer, has not been previously attempted. The (p,n) reaction can also be described by the distorted-wave impulse approximation with use of a one-pion exchange potential.[8] The results are in good agreement with what is presented in this Letter.

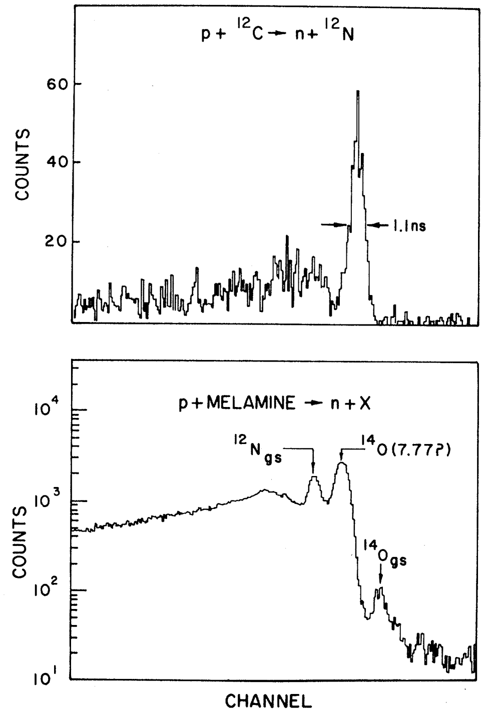

FIG. 1. Sample neutron time-of-flight spectra.

Our theoretical calculations were done in the framework of an absorption-modified one-pion exchange model.[9] The form of the six independent pion-exchange Born helicity amplitudes for a $\Delta J = 1$, $\Delta I = 1$, $\Delta P = 0$ transition is given in Ref. 10. The magnitude and momentum-transfer dependence of the above amplitude is, of course, governed by the vertex functions $g_{p\pi n}(q^2)$ and $g_{N\pi N'}(q^2)$. As pointed out by Kim and Primakoff,[6] the value of these functions at $q^2 = 0$ are given by applying PCAC to nuclei to obtain a nuclear Goldberger-Treiman relation,[11]

$$g_{N\pi N'}(0) = (M_N M_{N'})^{1/2} F_A(0)/a_\pi .$$

In this equation M_N, $M_{N'}$, and $a_\pi = 0.131$ GeV denote the masses of the initial and final nuclear states, and the pion decay constant, respectively. The axial-vector matrix element $F_A(0)$ is ob-

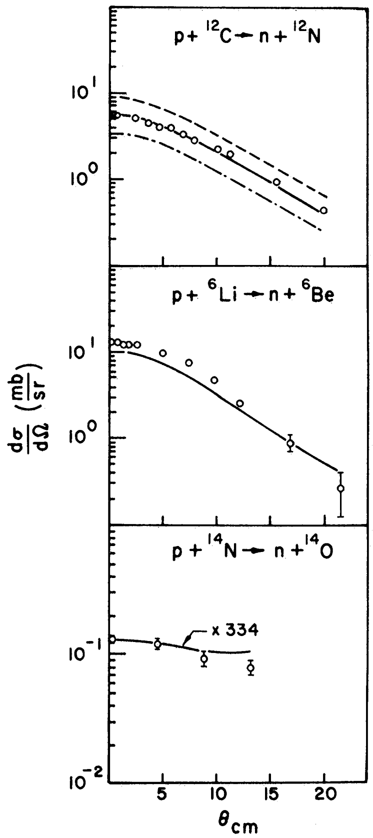

FIG. 2. Differential cross sections. For ^{12}C the three calculations are, as described in the text, plane-wave Born approximation with extraordinary terms removed (dashed curve), the usual absorption model (dash-dotted curve), and our approximation (solid curve). For ^{6}Li and ^{14}N only our approximation is indicated. The ^{14}N calculation is multiplied by a factor of 334 to produce agreement at 0°.

tained from the ft value[12] in nuclear β decay, $N' \to N + e + \nu$ (for $A = 6$ we use the ^{6}He decay), so that

$$F_A^2(0) = \frac{2\pi^3 \ln[2(2J_{N'}+1)]}{3G^2\cos^2\theta_C m_e^5 ft}.$$

From this, one sees that $g_{N\pi N'}^2(0)$, and hence the Born cross sections, are inversely proportional to the β-decay ft value.

It is necessary to modify the helicity amplitudes in three ways before a sensible comparison with experiment is made:

(a) First of all, the term $B_{\lambda'\lambda}(x)$ in Ref. 10, labeled "extraordinary" in the literature, is removed. By this procedure, the Born amplitudes are made to have a smoothly varying partial-wave expansion,[13] an expansion which is made with the technique given by Hogaasen and Hogaasen.[10]

(b) Secondly, vertex functions are chosen to provide the correct momentum-transfer dependence. Assuming that the momentum-transfer (q^2) dependence of $F_A(q^2)$ is identical to that measured in inelastic electron scattering, Kim,[14] and Kim and Townsend[14] find that

$$g_{N\pi N'}(q^2) = \frac{1 - q^2/25m_\pi^a}{(1+q^2/M_A^2)^2} g_{N\pi N'}(0),$$

where $M_A = 2m_\pi^2$ and $2.6m_\pi^2$ for $A = 6$ and 12, respectively.[15] For $A = 14$, $F_A(0)$ is so small that the usual method of obtaining $F_A(q^2)$ may not be valid. Lacking anything else, we use the usual approximations. The result is given in Ref. 15. The momentum dependence for F_M was taken from Goulard *et al.*[16] Nucleon β decay and neutrino scattering yield the equation[17]

$$g_{p\pi n}(q^2) = g_{p\pi n}(0)/(1 + q^2/24.1m_\pi^2)^2.$$

(c) The third modification takes cognizance of the distortions from initial-state and final-state interactions. To introduce absorption, each partial wave was multiplied by the product of the elastic-scattering phase shifts of the initial and final channels,

$$T_{\lambda'\lambda}{}^j \to (S_f{}^j)^{1/2} T_{\lambda'\lambda}{}^j (S_i{}^j)^{1/2},$$

where S^j are the elastic-scattering matrix elements from an optical-model calculation.

The theoretical prediction for the differential cross section with and without absorption is shown in Fig. 2. The prediction is low compared to the data. This is understandable since this form is justified for the case where the range of the inelastic scattering is much less than that of the elastic scattering. Thus the dashed and dashed-dotted curves in Fig. 2 serve as limits within which absorption modifications could affect our results.

Since, at $q^2 = 0$, no form factors enter into the PCAC comparison, the magnitude of the $g_{N\pi N'}(0)$ have been extracted from the 0° cross sections with the absorption model, assuming that they are dominated by one-pion exchange. The results are compared to those predicted by PCAC in Table I. The agreement is excellent for ^{12}C and within 15% for ^{6}Li, indicating that these reactions are indeed dominated by one-pion exchange. The failure of the model to predict the magnitude of the ^{14}N cross sections could be due to a vertex function, which has a minimum at $q^2 = 0$, in which case the absorption model may be grossly inadequate. Or, it could be that the reaction is not dominated by one-pion exchange. The success of

TABLE I. The initial-nucleus (N), pion (π), final-nucleus vertex function, $g_{N\pi N'}(0)$, as calculated from nuclear β decay, assuming the validity of the modified Goldberger-Treiman relation. It is compared to $g_{N\pi N'}(0)$, extracted from our zero-degree differential cross sections, using our absorption-modified one-pion-exchange model.

Target	$g_{N\pi N'}(0)$ (PCAC)	$g_{N\pi N'}$ (expt.)	$d\sigma/d\Omega\vert_{0°}$ (mb/sr)
^{6}Li	69.2	60.9	13.1
^{12}C	59.5	59.9	5.56
^{14}N	0.994	18.0	0.13

PCAC in predicting both the magnitude and shape of the (p,n) cross sections for ^{6}Li and ^{12}C is evidence that these reactions are dominated by one-pion exchange, and shows the power of applying PCAC to nuclei treated as elementary particles.

It is a pleasure to acknowledge the assistance of Dr. C. C. Foster in the design and construction of the neutron beam line and shielding arrangements. The support of Professor R. E. Pollock and Professor G. T. Emery throughout this work has been appreciated. We would like to thank Professor K. Vasavada for his theoretical assistance during the proposal and analysis stage. Professor H. Primakoff, Professor B. Goulard, and Professor F. Petrovich were kind enough to elucidate the problems in ^{14}N. Finally, we thank Dr. H. Foelsche of the Accelerator Division of Brookhaven National Laboratory for arranging the loan of the sweeping magnet without which our experiment would not have been possible.

This work has been supported by the U. S. Department of Energy and the National Science Foundation.

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[2]The rods, made from NE102, had a diameter of 4.44 cm and were 45.7 cm long. Their time resolution was better than 400 ps.

[3]This detector was 50.8 cm long, 25.4 cm high, and 15.2 cm deep, with 0.32-cm walls of Pyrex. It was filled with NE213 liquid scintillator and viewed by two phototubes.

[4]This detector was 12.7 cm deep and 12.7 cm in diameter. It was filled with NE213 liquid scintillator and viewed by one phototube.

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[15]Our equation is obtained by combining the nuclear PCAC relation [Ref. 13b, Eq. (6)] with the impulse approximation for the pseudoscalar form factor [Ref. 13a, Eq. (56)]; and Ref. 13b, Eq. (16), with the q^2 dependence of the axial-vector matrix element [Ref. 13a, Eqs. (59) and (60)]. We then obtain $g_{N\pi N'}(q^2) = (1-q^2/25m_\pi^2)(1+q^2/m_\pi^2)\exp(-0.38q^2/m_\pi^2)\exp(-0.38q^2/m_\pi^2)$.

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