ticle motion depending on λg_{ab} and an equation governing measurements (and therefore clock rates) depending on g_{ab}. (This is precisely the structure of the so-called two-metric theories of gravity.) EEP is only satisfied if λ is constant.

Further analysis within the framework of the principle of UGR does indeed show that λ must be constant. This analysis takes the following form: (a) Solar-system experiments involving test-particle motion and clock measurements show that λ is constant (at least within the parametrized post-Newtonian approximation[8]); (b) if the theory is to yield consistent predictions for the gravitational red shift, which are independent of the nature of the clocks used, λ must be constant.[3,8] Consequently, we find that WEP + UGR $\rightarrow$ EEP.

The following conclusions can be drawn from the analysis. Although the WEP severely constrains the possible form of any theory of gravity, in general it does not imply EEP (thus disproving Schiff's original formulation of the conjecture). We do find, however, that for the class of theories under investigation WEP + UGR $\rightarrow$ EEP. Consequently the analysis supports Will's current version of Schiff's conjecture.

[1]L. I. Schiff, Am. J. Phys. 28, 340 (1960).
[2]For definitions of these terms, see K. S. Thorne, D. L. Lee, and A. P. Lightman, Phys. Rev. D 7, 3563 (1973), or C. M. Will, in *General Relativity*, edited by S. W. Hawking and W. Israel (Cambridge Univ. Press, London, 1979).
[3]Will, Ref. 2.
[4]In another version of the conjecture W.-T. Ni, Phys. Rev. Lett. 38, 301 (1976), postulates the need for the added restriction that for a given initial rotation state, the subsequent rotation state of a polarized test body must be independent of the test body's internal composition.
[5]The two principles, WEP and UGR, are not completely independent; a violation of one may imply a violation of the other—see K. Nordtvedt, Jr., Phys. Rev. D 11, 245 (1975).
[6]A. P. Lightman and D. L. Lee, Phys. Rev. D 8, 364 (1973); M. P. Haugen and C. M. Will, Phys. Rev. D 15, 2711 (1977).
[7]C. M. Will, Phys. Rev. D 10, 2330 (1974).
[8]To be published.

Evidence for Two-Nucleon Processes in $A(p_{\rm pol}, \pi^-)A+1$

W. W. Jacobs, T. G. Throwe, S. E. Vigdor, M. C. Green, J. R. Hall, H. O. Meyer, and W. K. Pitts
Indiana University Cyclotron Facility, Bloomington, Indiana 47405

and

M. Dillig
Institut fur Theoretische Physik, Universität Erlangen-Nürnberg, D-8520 Erlangen, West Germany

(Received 24 May 1982)

Possible signatures of two-nucleon pion production processes in reactions $A(p_{\rm pol}, \pi^-)A+1$ near threshold are identified: a dependence of the analyzing power on the total angular momentum, and a simple scaling of the cross section with subshell occupancy for the struck target neutron. Measurements for $^{12,13,14}C(p_{\rm pol}, \pi^-)$ exhibit these expected features, supporting the view that the fundamental $NN \rightarrow NN\pi$ processes dominate in nuclear pion production.

PACS numbers: 25.40.Rb, 24.70.+s, 27.20.+n

Nuclear pion production, specifically reactions of the type $A(p, \pi)A+1$, is the object of continued study, not only because of intrinsic interest in understanding an unusual, high-momentum-transfer reaction, but also because of its expected close relationship to more general aspects of meson-nucleon interactions in the nucleus. To date, however, there are few clear systematic trends apparent in the available data, and it remains uncertain which, if any, reaction mechanism dominates near-threshold pion production. Recent progress, both theoretical and experimental, has been reviewed by several authors.[1,2]

In the currently favored, so-called "two-nucleon" models of (p, π) reactions,[1,2] the pion production mechanism involves the explicit interaction of the incident nucleon with a target nucleon, which facilitates (compared to single-particle "pionic stripping") sharing of the large momentum transfer in the residual nucleus. To date there have been no clearly posed experimental tests of the general validity of the assumed two-nucleon (N-N) character of the production process, although there are suggestions in the data that N-N processes play a significant role. For example, similarities with experimental results for the fundamental $p+p \to d+\pi^+$ process have been observed for at least some (p, π^+) transitions on nuclei, in the near-threshold energy dependence of the total cross section[3] and in the analyzing power (see Auld *et al.*,[4] but also Sjoreen *et al.*[5] and Lolos *et al.*[6] for counterexamples). On the other hand, studies of inclusive π^+ and π^- absorption processes on nuclei have been presented as evidence of an important role for mechanisms involving considerably more than two active nucleons[7] (although the same data have been alternatively interpreted in a simple two-nucleon volume absorption model[8]). The ambiguity concerning the reaction mechanism has prompted us to identify simple, yet general, signatures of N-N production processes which might be exhibited experimentally in selected (p, π) transitions to discrete nuclear final states.

The possible *free* N-N charged-pion production processes are (a) $p+p \to d+\pi^+$, (b) $p+p \to p+n+\pi^+$, (c) $p+n \to n+n+\pi^+$, and (d) $p+n \to p+p+\pi^-$. In contrast to the situation for (p, π^+) reactions, we note that only a single two-nucleon process (d), involving the interaction with a target *neutron*, can contribute to (p, π^-). When the configurations of the initial and final [2-particle (protons), 1-hole (neutron)] states are known, the shell-model orbital of the struck target neutron is uniquely determined. If N-N processes do indeed play a dominant role in nuclear pion production, the above restrictions may serve to make (p, π^-) reactions simpler to understand than (p, π^+). In particular, we predict on general grounds a systematic difference in near-threshold (p_{pol}, π^-) analyzing powers between transitions involving target neutrons from $j_> = l + \frac{1}{2}$ vs $j_< = l - \frac{1}{2}$ orbitals. Under more stringent assumptions, a simple scaling of the (p, π^-) cross section across an isotopic series of targets is also expected. Neither of these features would be expected to apply in general for (p, π^-) mechanisms involving more than two nucleons, nor for (p, π^+) even in a pure two-nucleon model. These predictions are discussed below and compared with measurements for the $^{12,13,14}\text{C}(p_{\text{pol}}, \pi^-)^{13,14,15}\text{O}_{\text{g.s.}}$ transitions.

The measurements were performed with polarized proton beams from the Indiana University Cyclotron Facility. The pions were detected with the new Indiana University Cyclotron Facility quadrupole-quadrupole split-pole (QQSP) pion spectrometer,[9] a device combining large solid angle and momentum range with a short flight path and good energy resolution, making systematic studies of near-threshold (p_{pol}, π^-) reactions feasible despite cross sections of typically only ~1 nb/sr. The QQSP focal-plane detection system consists of a vertical drift chamber,[10] allowing for simultaneous measurement of charged-particle position and angle, followed by three plastic scintillation detectors. Pion identification was based on flight time and energy loss. Background levels obtained for π^- detection were ≤ 50 pb/sr in the region of a peak in the position spectrum. A typical π^- spectrum from the reaction $^{14}\text{C}(p, \pi^-)^{15}\text{O}$, acquired with an enriched 30-mg/cm^2 ^{14}C target and corrected for horizontal aberrations of the spectrometer, is shown in Fig. 1. The energy resolution was typically ≤ 120 keV full width at half maximum, arising largely from the spread in beam energy.

Cross sections $\sigma(\theta)$ and analyzing powers $A_y(\theta)$ were measured in the angular range $31° \leq \theta_{\text{cm}} \leq 153°$ for $^{12}\text{C}(p_{\text{pol}}, \pi^-)^{13}\text{O}$, $^{13}\text{C}(p_{\text{pol}}, \pi^-)^{14}\text{O}$, and $^{14}\text{C}(p_{\text{pol}}, \pi^-)^{15}\text{O}$, at $E_p = 205$, 190, and 183 MeV,

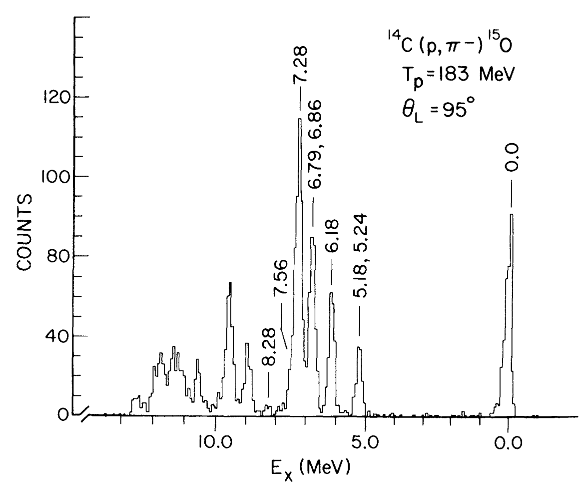

FIG. 1. Representative (p, π^-) spectrum (spin averaged) from an enriched ^{14}C target showing low background, broad range, and good (120-keV full width at half maximum) resolution obtainable with the QQSP pion spectrometer.

respectively. These bombarding energies were chosen to produce the same nominal center-of-mass pion energy (40 MeV) for the ground-state transitions so as to minimize differences arising from possible changes in pion distortions. The results for $\sigma(\theta)$ and $A_y(\theta)$ are plotted in Fig. 2, with error bars reflecting statistical uncertainties only. The thicknesses of the natural ^{12}C and 95%-enriched ^{13}C targets ranged from 48 to 98 mg/cm^2 and were determined to ±10% uncertainty by weighing. The ^{14}C target enrichment was only 67%, and relative isotopic abundances were determined by comparing 200-MeV proton elastic-scattering data with previously measured $^{12,13}C(p,p)$ cross sections.[11] Systematics of the $^{12,13,14}C$ elastic-scattering distributions as a function of momentum transfer were used to infer a ^{14}C thickness of 20 mg/cm^2 to an estimated uncertainty of ±15%. The normalization errors for the $\sigma(\theta)$ data are dominated by these target thickness uncertainties.

Our expectations and interpretation of the results for $\sigma(\theta)$ and $A_y(\theta)$ are most readily understood in the context of a simple shell model picture for $^{12,13,14}C$ and $^{13,14,15}O$. For example, a (p,π^-) reaction between the dominant ground-state configurations in $^{13}C(\frac{1}{2}^-)$ and $^{14}O(0^+)$ [or between $^{14}C(0^+)$ and $^{15}O(\frac{1}{2}^-)$] can be mediated by two-nucleon process (d) above only if the incident proton interacts with a $p_{1/2}$ target neutron. (Note that as the two final-state $p_{1/2}$ protons produced are coupled to spin 0 Δj is equal to the total j_n of the struck neutron.) In contrast, the $\Delta j=\frac{3}{2}$ transition between ^{12}C and ^{13}O would involve a $p_{3/2}$ target neutron. While N-N processes involving target neutrons from other subshells are conceivable, they would join configurations which are only weakly admixed in the states of interest.[12]

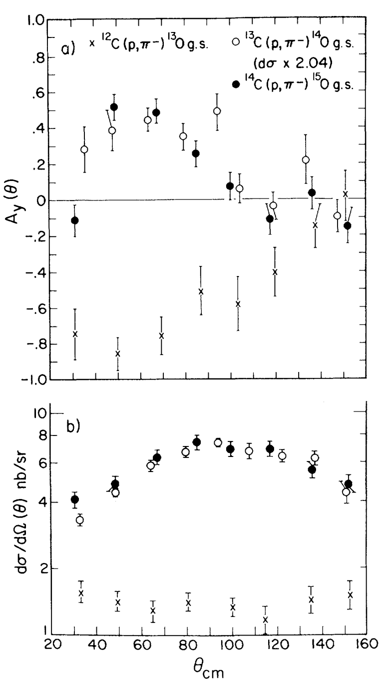

FIG. 2. Cross section and analyzing power angular distributions for $^{12}C(p_{pol},\pi^-)\,^{13}O_{g.s.}$ $(\Delta j=\frac{3}{2}^-)$, $^{13}C(p_{pol},\pi^-)\,^{14}O_{g.s.}$ $(\Delta j=\frac{1}{2}^-)$ and $^{14}C(p_{pol},\pi^-)\,^{15}O_{g.s.}$ $(\Delta j=\frac{1}{2}^-)$.

It is seen in Fig. 2(a) that there is a particularly striking difference in the (p_{pol},π^-) analyzing power between the $\Delta j=\frac{3}{2}$ transition and the $\Delta j=\frac{1}{2}$ transitions, with $A_y(\theta)$ in the forward hemisphere being large and negative for the former and positive for the latter transitions. Previous results[13] for another $\Delta j=\frac{3}{2}$ p-shell case, $^9Be(p_{pol},\pi^-)^{10}C_{g.s.}$, also show a negative $A_y(\theta)$ at forward angles. This clear j-dependent difference in $A_y(\theta)$ was in fact predicted from N-N process (d) on the following general semiclassical grounds. For nuclear final states where the two residual protons are coupled to spin 0, angular momentum and parity conservation require (1) the interacting proton and neutron in the process $p+n\to(pp)_0+\pi^-$ to be in a relative *spin-triplet state* (i.e., $J_{pn}=l_{pn}\pm1$ because $J^\pi=0^-$ for the pion), and (2) the struck neutron to be in a state of uniquely defined spin and parity within the target nucleus (i.e., $j_n=\Delta j$ as discussed above). In addition pion production below the threshold for the free N-N process requires the Fermi motion of the struck nucleon to be directed predominantly toward the incident nucleon. As a result of these conditions (see Fig. 3), $j_>$ target neutrons will interact preferentially with spin-up incident protons on one "side" of the

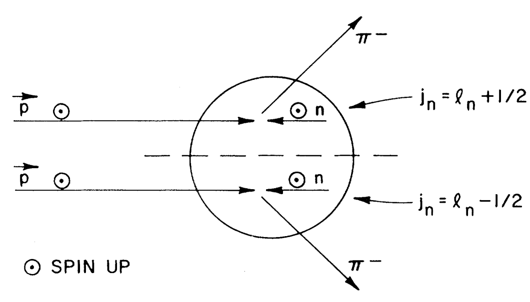

FIG. 3. Schematic illustration of the expected j dependence in near-threshold (p_{pol},π^-) analyzing powers, viewed in a two-nucleon picture. Spin-up protons interact primarily with spin-up neutrons, producing pions preferentially on different sides of the nucleus for struck neutrons with $j=l\pm\frac{1}{2}$. Further details in text.

nucleus and with spin-down protons on the other, with the preferred sides reversed for $j_<$ neutrons. Distortions generally introduce a further "sidedness" to nuclear reactions[14]; e.g., they might cause the π^- to emerge preferentially on the same side of the nucleus as the projectile (as assumed arbitrarily in Fig. 3) or, alternatively, on the opposite side [as suggested by the measured $A_y(\theta)$ in Fig. 2(a)]. The combination of these arguments leads to the prediction of a systematic difference in the sign of $A_y(\theta)$ for (p_{pol}, π^-) reactions involving $j_>$ and $j_<$ target neutrons.[15] This j-dependent effect should be superimposed on a common contribution to $A_y(\theta)$ arising from any analyzing power in the fundamental process $p_{\text{pol}}+n \to (pp)_0+\pi^-$ itself [it is apparent from Fig. 2(a) that this latter contribution is in fact small]. No such j dependence would be expected, nor indeed has been observed, for (p, π^+), where conditions (1) and (2) above are not satisfied, and the spin system of the interacting nucleons is thus far less constrained. These predictions for the behavior of $A_y(\theta)$ follow almost directly from an assumed dominant role of the fundamental N-N processes; hence the (p, π^-) data in Fig. 2(a) support the validity of this assumption.

Turning now to the $\sigma(\theta)$ data in Fig. 2(b), we note that for ^{13,14}C(p, π^-), which both involve interaction with neutrons from the same orbital $(p_{1/2})$, the $\sigma(\theta)$ [and $A_y(\theta)$] distributions are expectedly very similar, whereas the ^{12}C(p, π^-) distribution ($p_{3/2}$ neutron) has a different character. The observed (angle-independent) ratio of absolute cross sections for ^{13,14}C(p, π^-) may also be understood from simple considerations of N-N processes, without more detailed knowledge of the production mechanism, provided we ignore energy differences among, and invoke closure over, the intermediate states reached for the two targets. Then we expect a simple scaling of $\sigma(\theta)$ with occupancy of the relevant neutron subshell $(p_{1/2})$, i.e., by a factor of 2 in the simplest shell-model picture.[16] Better estimates of the $p_{1/2}$ neutron occupancy, based on theoretical $1p$-shell wave functions,[12] modify the expected ratio only slightly (to 2.04). The excellent agreement of $2.04\times\sigma^{13}(\theta)$ with $\sigma^{14}(\theta)$ for the ^{13,14}C(p, π^-) distributions, well within uncertainties over the full angular range [Fig. 2(b)], supports the simple scaling prediction and validates the assumptions leading to this N-N process signature.

In summary, we have proposed and made simple experimental tests for N-N signatures in nuclear pion production, signatures not expected in general for processes involving more than two nucleons. The results obtained support the view that it is two-nucleon processes which dominate in (p, π) near threshold. In particular, the similarity in shape of $\sigma(\theta)$ and $A_y(\theta)$ data for ^{13,14}C-(p_{pol}, π^-) and the prediction, borne out by the ^{12,13,14}C(p_{pol}, π^-) data, of a *j dependence* for (p_{pol}, π^-) analyzing powers, follow directly and generally from an assumed dominance of fundamental $NN \to NN\pi$ processes for pion production in the nuclear environment. Although more sensitive in principle to the detailed nature of the two-nucleon mechanism involved, the observed *scaling* of the ^{13,14}C(p, π^-) cross sections agrees well with the result expected in the simplest shell model picture. Clearly, $\sigma(\theta)$ and $A_y(\theta)$ data of this type will be of use in constraining future calculations within the framework of specific two-nucleon models.[2] Further measurements for selected (p_{pol}, π^-) transitions are needed to determine if the systematics based on these initial cases will persist.

We acknowledge fruitful discussions with Professor G. T. Emery. This research was supported in part by the National Science Foundation and NATO (No. 23381).

[1]B. Hoistad, in *Advances in Nuclear Physics*, edited by J. Negele and E. Vogt (Plenum, New York, 1979), Vol. 11, p. 135; D. F. Measday and G. A. Miller, Ann. Rev. Nucl. Part. Sci. 29, 121 (1979); H. W. Fearing, in *Progress in Particle and Nuclear Physics*, edited by D. H. Wilkinson (Pergamon, Oxford, 1981), Vol. 7, p. 113.

[2]*Pion Production and Absorption in Nuclei—1982*, edited by R. D. Bent, AIP Conference Proceedings No. 79 (American Institute of Physics, New York, 1982).

[3]R. E. Marrs, R. E. Pollock, and W. W. Jacobs, Phys. Rev. C 20, 2308 (1979).

[4]E. G. Auld *et al.*, Phys. Rev. Lett. 41, 462 (1978).

[5]T. P. Sjoreen *et al.*, Phys. Rev. C 24, 1135 (1981).

[6]G. J. Lolos *et al.*, Phys. Rev. C 25, 1086 (1982).

[7]R. D. McKeown *et al.*, Phys. Rev. Lett. 44, 1033 (1980).

[8]K. G. R. Doss and W. R. Wharton, Phys. Rev. C 22, 1219 (1980).

[9]M. C. Green, in *Pion Production and Absorption in Nuclei—1982*, edited by R. D. Bent, AIP Conference Proceedings No. 79 (American Institute of Physics, New York, 1982), p. 131.

[10]W. Bertozzi *et al.*, Nucl. Instrum. Methods 141, 457 (1977).

[11]H. O. Meyer, P. Schwandt, G. L. Moake, and P. P. Singh, Phys. Rev. C 23, 616 (1981); H. O. Meyer *et al.*, to be published.

[12]S. Cohen and D. Kurath, Nucl. Phys. A101, 1 (1967).

[13]T. P. Sjoreen *et al.*, Phys. Rev. Lett. 45, 1769 (1980).

[14]H. C. Newns, Proc. Phys. Soc., London, Sect. A 66, 477 (1953).

[15]The actual sign of A_y could be calculated, but requires a detailed treatment of the channel distortions, which goes beyond the scope of this report.

[16]Spin and/or isospin coupling coefficients may differ for specific intermediate states reached in the reactions on ^{13,14}C, but in the summation over all such states these differences are subsumed in the scaling with occupancy.

High-Precision Muonic X-Ray Measurement of the rms Charge Radius of ^{12}C with a Crystal Spectrometer

W. Ruckstuhl, B. Aas, W. Beer, and I. Beltrami
Laboratorium für Hochenergiephysik der Eidgenössische Technische Hochschule Zürich, c/o Schweizerisches Institut für Nuklearforschung, CH-5234 Villigen, Switzerland

and

F. W. N. de Boer
Institut de Physique de l'Université de Fribourg, CH-1700 Fribourg, Switzerland

and

K. Bos
Laboratorium für Hochenergiephysik der Eidgenössische Technische Hochschule Zürich, c/o Schweizerisches Institut für Nuklearforschung, CH-5234 Villigen, Switzerland

and

P. F. A. Goudsmit
Laboratorium für Hochenergiephysik der Eidgenössische Technische Hochschule Zürich, c/o Schweizerisches Institut für Nuklearforschung, CH-5234 Villigen, Switzerland, and Nationaal Instituut voor Kernfysica en Hoge-Energiefysica, Amsterdam, The Netherlands

and

U. Kiebele
Institut de Physique de l'Université de Fribourg, CH-1700 Fribourg, Switzerland

and

H. J. Leisi, G. Strassner, and A. Vacchi
Laboratorium für Hochenergiephysik der Eidgenössische Technische Hochschule Zürich, c/o Schweizerisches Institut für Nuklearforschung, CH-5234 Villigen, Switzerland

and

R. Weber
Institut de Physique de l'Université de Fribourg, CH-1700 Fribourg, Switzerland

(Received 5 May 1982)

A precision measurement with the SIN bent-crystal spectrometer of the wavelength of the $2p_{3/2}$-$1s_{1/2}$ transition in muonic ^{12}C yields $\lambda = 16.473\,766(89)$ pm, the accuracy being an order of magnitude higher than that of earlier investigations. The rms charge radius of ^{12}C is deduced as $\langle r^2\rangle^{1/2} = 2.4832(18)$ fm, differing by 2.4 standard deviations from the most accurate electron-scattering results. Consequences of attributing this discrepancy to a μ-N interaction beyond QED are discussed.

PACS numbers: 21.10.Ft, 14.60.Ef, 36.10.Dr

The work described in this paper was carried out with the purpose of determining the charge radius of ^{12}C with the highest precision available at present. Moreover, a comparison of the charge radius determined in the muonic atom with the one derived from elastic electron-scattering