[15]This assumes, of course, the $c \to s$ transition to be dominant. If on the other hand the higher Kobayashi-Maskawa angles are large, the $c \to b$ transition would be enhanced at the cost of $c \to s$; and the 5% rise from intrinsic charm would be spread over even a wider range of energy.

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Strong Cancellations of Neutron and Proton Transition Amplitudes Observed in Pion Inelastic Scattering from ^{14}C

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Differential cross sections were measured for inelastic scattering of 164-MeV π^+ and π^- from ^{14}C. Large cross-section ratios, $R = \sigma(\pi^+)/\sigma(\pi^-)$ (or R^{-1}), were observed, two being significantly larger than the free π-nucleon value. Lower limits are $R > 26$, $R^{-1} > 17$, and $R > 11$ for states at 8.32 MeV (2^+), 11.67 MeV (4^-), and 17.26 MeV (4^-), respectively. These values are interpreted as being due to strong cancellations of the neutron and proton components of the transition amplitudes.

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At energies near the (3, 3) π-N (pion-nucleon) resonance, the ratio, $R = \sigma(\pi^+)/\sigma(\pi^-)$, of the cross sections for π^+ and π^- scattering from free protons (neutrons) is about 9 ($\frac{1}{9}$). Thus, comparisons of π^+ and π^- inelastic scattering from nuclei should provide a sensitive method of separating the proton and neutron components of inelastic transitions. Cross-section ratios near the free π-N values are expected for pure proton or pure neutron particle-hole (p-h) excitations if the impulse approximation is valid. However, in previous studies on even-A, $N > Z$ nuclei, such as ^{18}O (Ref. 1) and ^{26}Mg (Ref. 2), values of R (or R^{-1}) in the range of 1.0 to 2.0 were found. These small values have been attributed to the large amount of core excitation present in these nuclei. Deviations from $R = 1$ for $N = Z$ nuclei, which arise from charge symmetry violation (e.g., due to the Coulomb force), have been observed and interpreted successfully as due to transitions to an isospin-mixed doublet in ^{12}C (Ref. 3) and a triplet in ^{16}O (Ref. 4). The free π-neutron value of $R^{-1} \simeq 9$ was detected[5] so far only for a transition in the odd-A nucleus ^{13}C and was interpreted as the result of a pure neutron p-h transition to a "stretched" state.

In this Letter, we report on the first observation of ratios R significantly larger than 9 in a measurement of inelastic pion scattering on ^{14}C at an incident energy $T_\pi = 164$ MeV. The large differences in π^+ and π^- cross sections are seen to provide unusually transparent signatures of the shell-model structure of the transitions. As discussed in detail below, the near vanishing of either π^+ or π^- cross sections (but not both) for a specific state comes about from the strong cancellation of the proton and neutron transition amplitudes.

The experiment was performed at the Clinton P. Anderson Meson Physics Facility with the

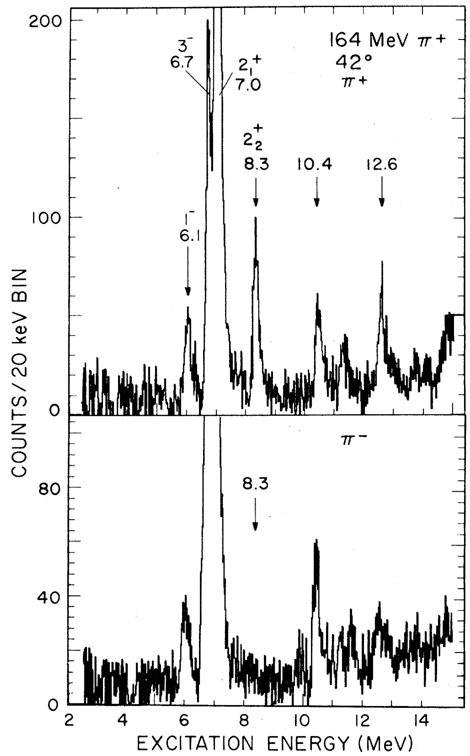

FIG. 1. Energy loss spectra for π^+ and π^- scattering from ^{14}C at $\theta_{1ab} = 42°$ and $T_\pi = 164$ MeV.

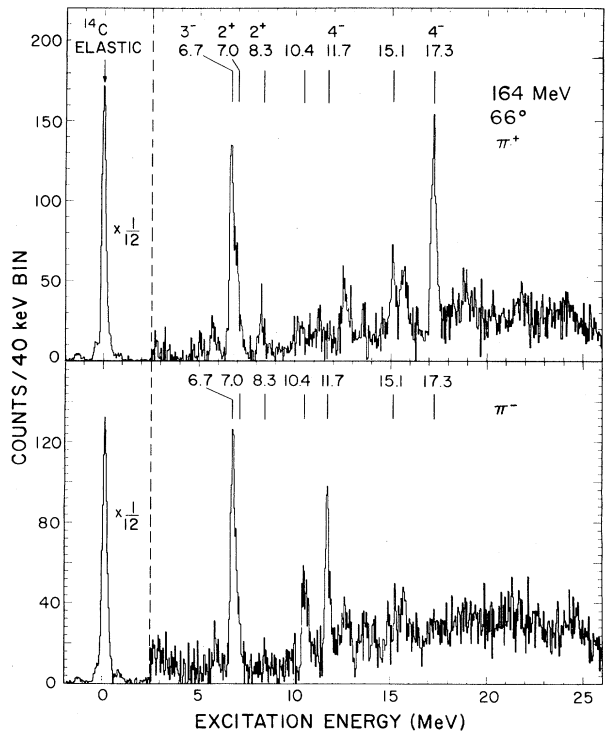

FIG. 2. Same as Fig. 1, but at 66°.

energetic pion channel and spectrometer which has been described in detail elsewhere.[6] The target consisted of ~9 g of carbon powder enriched to 83% in ^{14}C. The $^{14}C/^{12}C$ atom ratio was 4.87 ± 0.24.[7] The carbon powder was pressed to a thickness of ~0.10 g/cm^2 into six target cells, each consisting of a U-shaped stainless-steel frame covered with 0.025-mm-thick windows made of stainless steel. Since the ^{14}C target was smaller than the beam spot size, strips of natural graphite were placed above and below the ^{14}C target cells in order to obtain ^{12}C and ^{14}C spectra simultaneously. Additional spectra were taken from stainless-steel foils as target. These spectra enabled us to derive "clean" spectra via a channel-by-channel subtraction, shown in Figs. 1 and 2. The energy resolution obtained was about 200 keV (full width at half maximum).

Cross sections at 42° and 66° for selected states are presented in Table I. The ^{14}C cross sections were normalized with use of the $\pi^{\pm}$ cross sections for the 4.44-MeV state in ^{12}C, the ^{12}C (4.44 MeV) yield from the ^{14}C target, and the known $^{14}C/^{12}C$ atom ratio. We employed this method of normalization since it does not rely on the assumption of uniform target thickness. The absolute normalization was obtained by comparing $\pi^{\pm}$-hydrogen yields with the π-proton cross sections of Dodder.[8] The ^{12}C cross sections (Table I), which were measured using the graphite strips, are in good agreement with previous work.[9]

The most surprising feature of the present data is the sharp contrast between the near equality of $\sigma(\pi^+)$ and $\sigma(\pi^-)$ for the 2_1^+ state at 7.01 MeV and the highly asymmetric cross sections for the 2_2^+ state at 8.32 MeV. At $\theta_{1ab} = 42°$, which is near the first maximum of known $\Delta l = 2$ angular distributions, no π^- yield could be detected above background (Fig. 1). The experimental cross sections and errors (Table I) yield a lower limit of $R > 26$ for the 2_2^+ state. This is dramatically larger than the free π-proton value of 9.

Similarly, at $\theta_{1ab} = 66°$ (Fig. 2), a state at 11.67 MeV is observed only in $(\pi^-, \pi^{-\prime})$ and a state at 17.26 MeV is seen essentially only in $(\pi^+, \pi^{+\prime})$. The lower limits for the cross-section ratios are $R^{-1} > 17$ and $R > 11$, respectively. Angular distributions for these states (not shown) have maxima near 66° and shapes similar to those of previously measured $\Delta J = 4$ transitions in ^{12}C (Ref. 3), ^{13}C (Ref. 5), and ^{16}O (Ref. 4), all of which are due to excitations of the "stretched" $(d_{5/2}, p_{3/2}^{-1})$

TABLE I. The measured π^+ and π^- differential cross sections (lab),[a] cross-section ratios R, and asymmetries A [b] for states in ^{14}C and the 4.44-MeV state in ^{12}C.

Target	E_x (MeV)	J^π	θ_{lab} (deg)	$d\sigma/d\Omega_{\pi^+}$ (mb/sr)	$d\sigma/d\Omega_{\pi^-}$ (mb/sr)	R	A
^{14}C	7.01	2^+	42°	1.01±0.08	0.90±0.07	1.12±0.07	−0.06±0.03
^{14}C	8.32	2^+	42°	0.14±0.01	< 0.0054 [c]	> 26 [c]	$-0.99^{+0.09}_{-0.01}$
^{14}C	11.67 [d]	(4^-)	66°	<0.0028 [c]	0.049±0.005	< 1/17 [c]	$0.96^{+0.04}_{-0.10}$
^{14}C	17.26 [d]	(4^-)	66°	0.094±0.008	0.005±0.003	>11 [c]	−0.89±0.06
^{12}C	4.44	2^+	42°	2.85±0.17	2.88±0.18	0.99±0.06	0.006±0.03

[a] The errors quoted are based on an estimate of all known uncertainties but do not include a ±20% error in the overall normalization. In calculating R and A, the cancellation of some errors which are common to π^+ and π^- was taken into account.

[b] $A \equiv [\sigma(\pi^-) - \sigma(\pi^+)] / [\sigma(\pi^-) + \sigma(\pi^+)]$.

[c] At the 90% confidence level.

[d] The estimated uncertainty in the energies of these states is ±0.1 MeV.

p-h configuration. On the basis of this similarity to previous pion data, we suggest a J^π assignment of 4^- for these states.

It has been known for some time that the p-shell model[10] predicts only one low-lying 2^+ state, yet the two experimental 2^+ states at 7.01 and 8.32 MeV share the p-shell strength for transfer reactions,[11] electromagnetic transitions,[11] and the (π^-, γ) reaction.[12] On the basis of previous work[13,14] a reasonable approximation to the wave functions of the two 2^+ states ($i=1, 2$) is

$$|^{14}\mathrm{C}; 2_i^+, T=1\rangle = \alpha_i |(p^{-2p})_{2^+}\rangle + \beta_i |(p^{-4})_{0^+}(sd^{2n})_{2^+}\rangle,$$

with $\alpha_1 = \alpha_2 = 1/\sqrt{2}$ and $\beta_1 = -\beta_2 = -1/\sqrt{2}$, and for the ground state (g.s.)

$$|^{14}\mathrm{C}; 0_1^+, T=1\rangle = \alpha_0 |(p^{-2p})_{0^+}\rangle + \beta_0 |(p^{-4})_{0^+}(sd^{2n})_{0^+}\rangle.$$

The relative phases of the p-shell (proton) and s-d–shell (neutron) parts of the 2^+ states indicate constructive interference of the proton and neutron components in the transition from the g.s. to the 2_1^+ state and destructive interference for the 2_2^+ state. This destructive interference could result in a near vanishing of $\sigma(\pi^-, 2_2^+)$ even if β_0 is relatively small because of the enhancement of the neutron part of the transition amplitude in π^- scattering.

To prove this point quantitatively, we performed momentum-space distorted-wave impulse-approximation[15] calculations. The p-h matrix elements for the p-shell proton holes and the s-d–shell neutron particles were obtained from the work of Ellis and Engeland[16] and the coefficient α_0 [$\beta_0 = -(1-\alpha_0^2)^{1/2}$] was taken as an adjustable parameter. Harmonic-oscillator radial wave functions were used for the bound states of the active nucleons with an oscillator parameter $b = 1.7$ fm for both protons and neutrons.[13] Both spin transfer values of $\Delta S = 0$ and $\Delta S = 1$ were included in calculating the scattering amplitudes. To account for the truncation of the model space, effective charges for both protons and neutrons were used to enhance the $\Delta S = 0$ piece of the nuclear transition matrix elements.[15] The polarization charges for the protons and neutrons were set equal ($\delta_p = \delta_n$) and treated as a second adjustable parameter. Further details of the calculation will be presented in a subsequent publication.

With $\delta_p = \delta_n = 0.4$, $\alpha_0 = 0.81$, and $\beta_0 = -0.19$, the calculations yield (in mb/sr at 42°) $\sigma(\pi^+, 2_1^+) = 1.04$, $\sigma(\pi^-, 2_1^+) = 0.80$, $\sigma(\pi^+, 2_2^+) = 0.21$, and $\sigma(\pi^-, 2_2^+) = 0.008$. The data indicate an even more complete cancellation for the 2_2^+ than these calculations do. Possible reasons for the remaining discrepancies are presently being investigated. Nevertheless, the basic features of the data are correctly described as due to an interference of the neutron and proton parts of the transition amplitude.

The data for the two proposed 4^- states at 11.67 and 17.26 MeV are also suggestive of cancellation effects. In any simple model, several 4^-, $T=1$ states are expected with large components of the "stretched" $(d_{5/2}, p_{3/2}^{-1})$ configuration. The 4^- state lowest in energy should have a large overlap with a state formed by a $d_{5/2}$ neutron coupled to a $\frac{3}{2}^-$, $T=\frac{1}{2}$ ^{13}C core.[13] This state would be reached mainly by a neutron p-h excitation from a $T=\frac{1}{2}$ core component in the ground state of ^{14}C. The experimental ratio for the 4_1^- state at 11.67 MeV, $R^{-1}>17$, is larger than the free π-neutron value of $R^{-1}\simeq 9$, indicating the presence of small contributions from proton p-h excitations to the transition density amplitude with a sign opposite to the one of the principal neutron p-h excitation.

Although the lower limit of $R>11$ for the other prominent 4^- state at 17.26 MeV is essentially consistent with a pure proton excitation ($R\simeq 9$), such an interpretation is unlikely since it would imply a transition to a state strongly mixed in isospin. Cross-section ratios estimated from a shell-model calculation by Kurath[17] for 4^- model states at 12.7 and 16.9 MeV are in good agreement with our data, although the estimated absolute cross sections are about a factor of 2 too large. A complete comparison of all the data with these predictions will be presented in a forthcoming publication.

In summary, our measurements on ^{14}C have shown for the first time that π^+/π^- cross-section ratios for nuclear excitations can be considerably larger than the value of 9 for scattering from free nucleons at the (3, 3) resonance. In addition, candidates for the first 4^- states of "stretched" $(d_{5/2}, p_{3/2}{}^{-1})$ configuration in ^{14}C have been located. We have interpreted the extraordinarily large π^+/π^- ratios as being due to cancellations of the neutron and proton components of the transition amplitudes. The direct manifestation of such cancellation phenomena in a simple comparison of the measured π^+ and π^- spectra demonstrates the value of pion scattering for elucidating the structure of nuclear states.

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