Spin and isospin transfer in the $^{12}C(\pi^+,\pi^{+\prime})$ reaction

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Inelastic scattering cross sections from ^{12}C were measured for the 12.7 MeV (1^+;0), 15.1 MeV (1^+;1), and 16.1 MeV (2^+;1) levels for positive pion beam energies of 100, 116, 140, 160, 180, 200, 230, 260, and 291 MeV. Clearly oscillatory angular distributions were measured for the 1^+ states, and these are shown to be explained by very general considerations of the scattering amplitudes. The 16.1 MeV data show little structure at the lower beam energies, but the falling angular dependence at the higher beam energies is very like that observed for the 4.4 MeV (2^+;0) state. A prediction for the ratio of the $T=0$ and $T=1$ 1^+ cross sections is derived from a specific two-step calculation, and found to agree with the data at the 3-3 resonance.

[NUCLEAR REACTIONS $^{12}C(\pi^+,\pi^{+\prime})^{12}C$, E_{π^+}=100, 116, 140, 160, 180, 200, 230, 260, 291 MeV. Measured $\sigma(\theta)$ for 12.7, 15.1, and 16.1 MeV states.]

I. INTRODUCTION

The understanding of pi-meson scattering by complex nuclei is hindered by the lack of a clear distinction between the features of the reaction mechanism peculiar to pions and those of nuclear structure, which may again manifest sensitivities particular to pions. The aim of the present study of inelastic π^+ scattering on ^{12}C is to understand better the reaction mechanism for exciting states of reasonably well-known structure.

Inelastic pion scattering data[1] are presently limited largely to the strongly excited low-lying collective states. The nuclear matrix elements are largely of an isoscalar ($\Delta T=0$) nature, with little involvement of the spin-flip ($\Delta S=1$) degree of freedom. A decomposition of the pion-nucleon scattering amplitude[2] is shown in Fig. 1, expressed as the isospin and spin transfers to the struck nucleon. In a quasifree picture of pion scattering from bound nucleons to populate excited states of nuclei,[3] these four energy-dependent amplitudes are the driving terms for the inelastic scattering. Since excitation of the low-lying collective states largely involves[4] $\Delta T=\Delta S=0$, only one of the four pion-nucleus terms has been heretofore extensively examined. Two well-known[5] 1^+ states in ^{12}C may be resolved with a good pion scattering system. The 12.71 MeV 1^+ state has an isoscalar excitation ($\Delta T=0$), while the 15.1 MeV 1^+ state has an isovector excitation ($\Delta T=1$), both with spin flip ($\Delta S=1$). The small

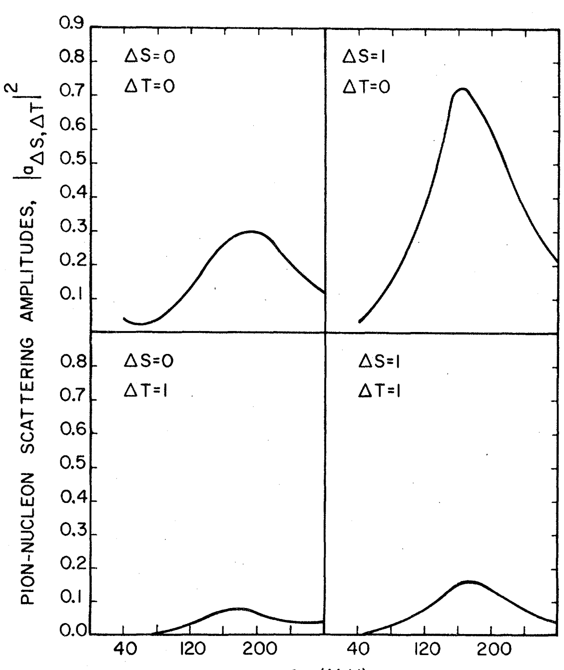

FIG. 1. The pion-nucleon scattering amplitudes are shown separated by the spin and isospin transfers to the struck nucleon, using the Roper 350 set (Ref. 2).

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isospin mixing between these states[6] will be ignored in the present work. It is also worth noting that the 16.1 MeV 2^+ state is, in part, excited via the $\Delta S=0$, $\Delta T=1$ amplitude, thus the three states considered in this work reflect the influence of all three previously unexamined amplitudes.

The good energy resolution that can be obtained with the pion spectrometer (EPICS) used in this experiment permits the individual $T=1$ states to be resolved readily, whereas the pion charge exchange $(\pi^\pm, \pi^0)$ experiments, which could provide much of the same information, are not able to resolve the individual states. In addition, the $(\pi^\pm, \pi^0)$ reactions cannot provide information on the $\Delta S=1$, $\Delta T=0$ transition, as the 12.71 MeV state has no analog. An understanding of $\Delta T=1$ transitions in ^{12}C will be of great assistance in interpreting $(\pi^\pm, \pi^0)$ data on targets where isovector scattering data cannot be obtained.

Electron scattering experiments[7] show the transition form factor for the 15.1 MeV state to have the shape, if not the magnitude, expected from a very simple p shell particle-hole excitation from the ground state. Since the spectroscopic factors for the 12.7 and 15.1 MeV states in the $^{11}B(^3He, d)^{12}C$ reaction[8] and in the $^{13}C(p, d)^{12}C$ and $^{13}C(d, t)^{12}C$ reactions[9] are similar, these two states may be regarded as nearly identical in structure,[10,11] differing only in their isospin symmetry. The existence of identical 1^+ states this close in energy allows a very simple test of an impulse approximation model for the pion scattering; the 12.7 MeV state should be four times more strongly excited than the 15.1 MeV state[3] if the π-N interaction is pure P_{33}. No other 1^+ states are known in ^{12}C but a second $T=1$ 1^+ level is expected near 20.1 MeV by analogy to the level structure of ^{12}B.[5] The role of the nuclear wave functions in pion scattering is not investigated in this work, but some idea of the sensitivity of the results may be gained by studies of the analogous $^{12}C(\gamma, \pi^-)^{12}N$ (g.s.) and $^{12}C(\mu, \nu)^{12}B$ transitions.[12] A better fit to the energy dependence of the (γ, π^-) reaction is obtained for a transition density matrix element of -0.34 for the transition between the $p_{1/2}$ and $p_{3/2}$ orbitals, whereas the present assumption neglecting transitions from $p_{1/2}$ to $p_{1/2}$ or $p_{3/2}$ to $p_{3/2}$ orbitals takes this matrix element to be -0.44. The effects of such mixing can only be addressed in a true microscopic calculation, not attempted for this work.

If the pionic excitation of the 1^+ states proceeds by a quasifree process, as it does in electron scattering, the relative yield could be expected to exhibit the 3-3 resonance in the form of Fig. 1. These states thus provide several tests of pion inelastic scattering models due to their single-particle nature. A number of calculations have investigated the $\Delta S=1$ mode[13-15] but not for the transitions being studied. A simple scheme of particle-hole excitations within the $1p$ shell also allows two 2^+ states.[11,16] Single nucleon transfer data point to the 4.4 MeV ($\Delta T=0$) and 16.1 MeV ($\Delta T=1$) states as largely of this nature,[8,9] but the high collectivity of the 4.4 MeV state precludes any simple direct comparison to the 16.1 MeV data. In general, these 2^+ states seem to exhibit a more complex structure than shown for the 1^+ states.[17]

II. EXPERIMENTAL PROCEDURE

The experiment was performed with the EPICS system of the Clinton P. Anderson Meson Physics Facility of the Los Alamos Scientific Laboratory. The targets were of natural carbon with thicknesses of 110 and 227 mg/cm^2. The overall energy resolution at all incident energies was 250 keV for the thin target at scattering angles forward of 40° and 400 keV for the thicker target used at the backward angles. Incident positive pion energies of 100, 116, 140, 160, 180, 200, 230, 260, and 291 MeV were used.

The spectrometer field was set to keep the 12 to 16 MeV excitation region in the center of the focal plane. The acceptance of the spectrometer as a function of focal plane position was determined by sweeping the elastic peak across the focal plane. Corrections no larger than 30% were needed for a momentum bite $(\Delta p/p)$ of ±6%, and the uncertainty in cross sections from this correction does not exceed ±5%. This momentum bite corresponds to an excitation region of 10 MeV for incident pions of 100 MeV and a 23 MeV excitation region for 291 MeV pions.

At forward angles where the elastic cross section dominates, the fractional momentum spread $(\Delta p/p)$ of the incident beam was reduced to ±0.25%, whereas it normally was ±1.0%. This reduction permitted the use of a scintillator at one end of the focal plane to veto elastic events and thus reduce the computer dead time. It was not feasible to take data forward of 15° lab due to the high singles rate in the front wire chambers.

A sample spectrum at 180 MeV is shown in Fig. 2, where only the region of interest is displayed. The energy calibration is based on the very well-known and sharp energy levels in ^{12}C. Relative normalization of the cross section at each incident energy was determined by ion chambers at the pion production target and after the scattering target. The two chambers gave consistent results. Absolute cross sections were

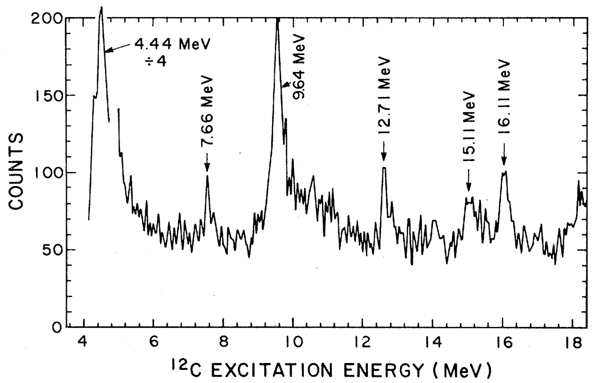

FIG. 2. A sample spectrum at 180 MeV at 25° is shown, with the states discussed in the present work noted. Most of the background is due to muons.

obtained by inserting a polyethylene target and normalizing at each incident energy to published[18] π^+-p cross sections.

Two prominent background problems were present in most of the spectra: muon contamination and a false peak at about 10 MeV in excitation higher than the elastic peak and each strongly populated low-lying energy level. This peak was about 3 MeV wide and was produced by energy loss in protruding vacuum flanges in the quadrupole magnets. At the forward angles the 12.7 MeV state sits on the shoulder of this peak, but because of the 3 MeV width and the much sharper energy resolution of the system, the extraction of the 12.7 MeV state cross section was not complicated. Muon contamination from pion decay produced a very large and continuous background. Peak area extraction for the 15.1 MeV state was difficult for most of the runs and impossible for any runs with poor statistics.

Some evidence for structure in the spectra at an excitation energy 200–300 keV higher than the 15.1 MeV state was present. This could possibly be from structure previously noted[19] near 15.4 MeV excitation in ^{12}C and reported to be broad ($\approx$2 MeV). Great care was taken to use the known location and narrow width of the 15.1 MeV state in extracting the area. Since a state is known to exist at 15.4 MeV, some contribution from this state may have been included in the cross sections for the 15.1 MeV state. If this were the case, the 15.1 MeV cross sections would be lower than those presented here. Tables of cross sections measured in this work are available, and may be obtained from the Physics Auxiliary Publication Service.[41]

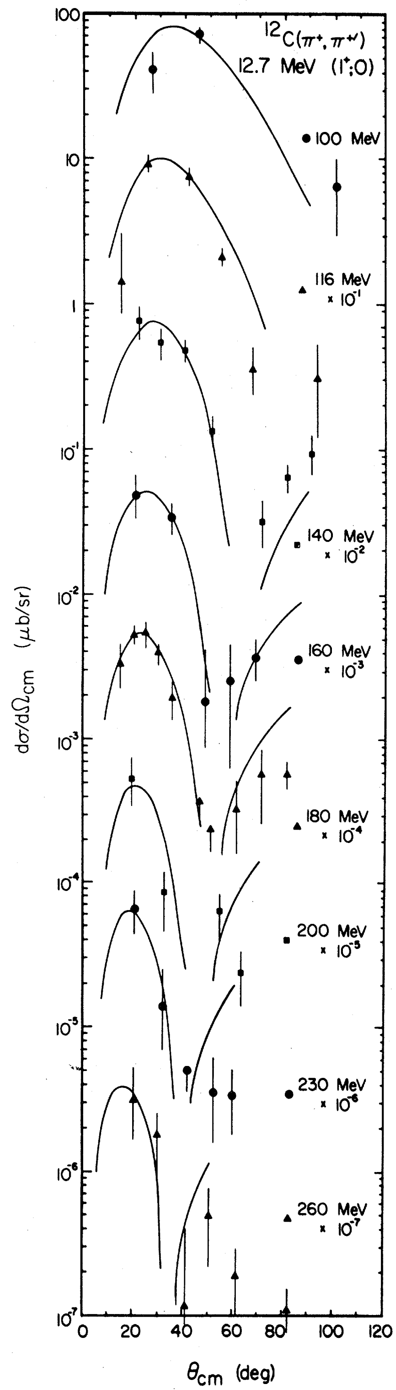

FIG. 3. Data at eight pion energies for exciting the 12.7 MeV state of ^{12}C are compared to Bessel function curves as described in the text.

III. THE 12.7 AND 15.1 MeV STATES

The data for the 1$^+$ states at 12.7 and 15.1 MeV are shown in Figs. 3 and 4. The data at some energies are sparse, but they are presented to

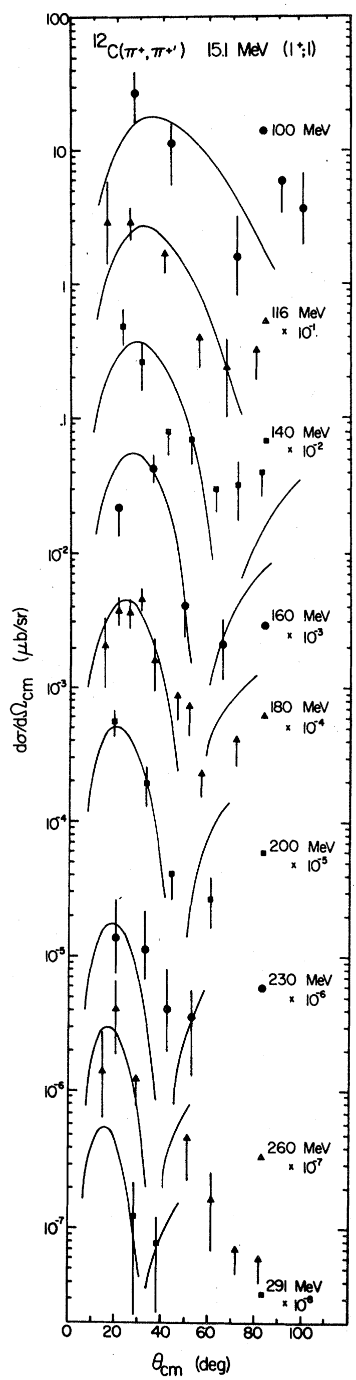

FIG. 4. Data at nine pion energies for the $(1^+;1)$ excitation in ^{12}C are compared to Bessel functions, as in Fig. 3.

establish the dependence on the pion beam energy. The 180 MeV data, the most complete, show a structured angular distribution for both 1^+ states, with a forward angle minimum, a minimum near 50°, and indications of a second maximum. At all energies, the shapes of the angular distributions for the two states appear to be identical.

The differential cross section for positive pion scattering to the 15.1 MeV 1^+ level has been reported at 148 MeV and 58° (Ref. 20) as 40 μb/sr. This is much greater than the result obtained in the present work. It appears from the features of the spectra shown in Ref. 20, as compared to our data, that this state was misidentified in the earlier work. The data reported were actually for the 16.1 MeV 2^+ level, although the present work measures a cross section for that state of about half the strength reported in Ref. 20 at similar beam energies and angles. The cross sections for the stronger states also seen in the present experiment may be compared to data of previous studies. At 160 MeV the cross sections to the 9.6 MeV $(3^-;0)$ state are found to agree in shape and magnitude with the data of Chabloz *et al.*[21] to within the estimated uncertainty in the overall normalization of ±15%.

The structured angular dependence for the 1^+ data would seem to be informative. Conservation of angular momentum and parity for a spin zero projectile leads, however, to the demand for zero cross section at zero degrees for scattering to these 1^+ states for any single-step reaction mechanism.[22] Moreover, if the beam energy is sufficiently greater than the excitation energy to allow for the adiabatic approximation, the cross section must be zero at all angles. This adiabatic limit is very closely approached by pion scattering near the 3-3 resonance.[23]

A relaxation of the adiabatic approximation permits a specific prediction for the angular dependence of the 1^+ cross sections. For strongly absorbed particles such as pions of greater than 100 MeV, a semiclassical theory[24] yields a differential cross section for a 1^+ state (at small angles) proportional[22] to

$$\frac{d\sigma}{d\Omega}(\theta)\sim|J_1(kR\sin\theta)|^2.$$

The use of $\sin\theta$ in this expression allows this prediction to be effective at larger angles than would the use of θ alone. This is also the prediction for the scattering of alpha particles. The radius R was thus taken from the sharply oscillatory angular distribution for alpha scattering to the 12.7 MeV 1^+ state,[25] and determined to be 3.38 fm or 1.47 $A^{1/3}$ fm. The predictions at each energy are compared to the data in Figs. 3 and 4. The first point to note is that the shape of the first maximum is reproduced, just as was the case for the alpha particle data of Ref. 25. The second feature is that the same radius is adequate for both the pion and alpha particle scattering. As was demonstrated in Ref. 25, all calculations will also generally reflect this small angle behavior, and we must conclude that the angular distributions of the present pion data will not constrain any calculations.

The energy dependence of the magnitude of these 1^+ data is taken at the first maximum, determined by matching the $|J_1(kR\sin\theta)|^2$ curves to the data, even where only one data point exists. These data are shown in Fig. 5. The 3-3 resonance is not apparent in these results. The magnitudes of these $\Delta S=1$ cross sections are far below the yields to the 4.4 MeV state,[19,26,27] indicating the importance of the nuclear matrix elements in reducing the role of the strong $\Delta S=1$ pion-nucleon amplitudes. A further sign of the failure of the simple impulse approximation at the 3-3 resonance energy is noted in the essentially equal cross sections, rather than the four to one enhancement of the 12.7 MeV state over the 15.1 MeV data expected from Fig. 1 or Ref. 3. These data thus exhibit none of the signatures expected for a simple quasifree scattering reaction. Other options for the reaction will be treated in Sec. V.

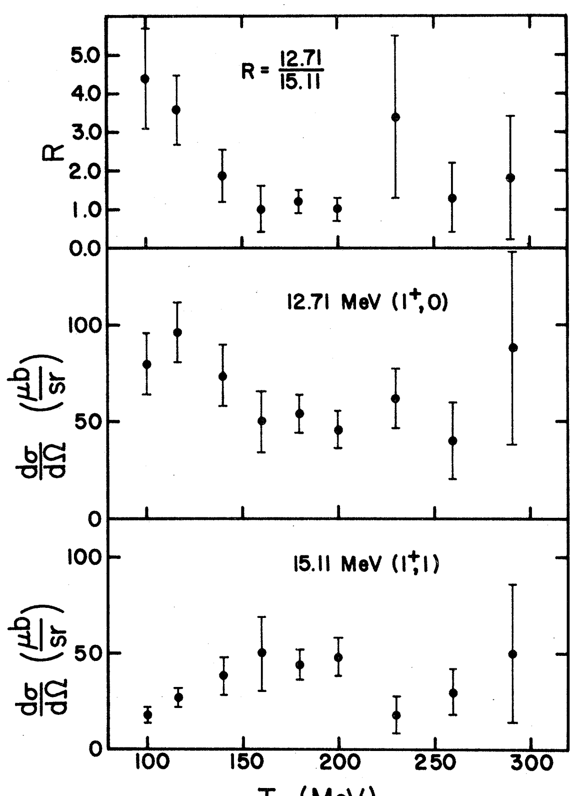

FIG. 5. The magnitudes of the differential cross sections of the ^{12}C 1^+ states at their forward maxima are compared. These are obtained with the Bessel function shapes shown in Figs. 3 and 4.

The peak cross sections shown in Fig. 5 may be compared to charge exchange total cross sections[28] for ^7Li and ^{13}C, which are dominated by the quasielastic or analog mechanism, which is largely of a $\Delta S=0$ nature.[15,29] The lack of a sharp energy dependence appears to be common to both the present data and to the data and predictions for the charge exchange reaction. Theoretical angular distributions for the (π^+,π^0) reaction on ^7Li, ^{10}B, and ^{13}C exhibit a variety of shapes.[15,30]

Two sets of predictions are compared in Fig. 6 to data for excitation of the 15.1 MeV state at several pion energies. The dashed curves represent the calculations of Huber and Klingenbeck,[31] carried out in a hole-delta model.[32] These predictions are substantially greater than the data at 120, 150, and 180 MeV. The predicted minimum occurs well beyond that observed.

The solid and dotted curves in Fig. 6 are the predictions of Wilkin,[13] which include a convection current term (for the dotted curve) interfering constructively with the direct spin-flip amplitude below the 3-3 resonance and destructively above. The striking energy dependence predicted by this interference is definitely not seen in the data. Calculations with the direct term only (solid curves) fit the magnitude of the data at 120 MeV, but are low by about a factor of 2 at 200 MeV and appear to be appreciably below the sparse data at 280 MeV.

As pointed out earlier, the general features of the predicted angular distributions are constrained to a shape similar to that for a first-order Bessel function. Little can be claimed for the general success of the calculations in fitting the shape of the experimental angular distribution since the radius of the form factor assumed will determine the locations of the minima.

IV. THE 16.1 MeV $(2^+;1)$ STATE

Angular distributions for the isospin changing excitation of the natural parity 16.1 MeV $(2^+;1)$ state are shown in Fig. 7. Much less structure is exhibited by these data, with no sharp minima in the angular range covered. The solid lines in Fig. 7 are representations (21), (26), and (27) of pion scattering data to the 4.4 MeV 2^+ state at beam energies near those of the present experiment as well as data from the present work. At the higher beam energies the fall in cross section is similar to that found for the 4.4 MeV state,[26] but below 160 MeV the cross sections to the 16.1 MeV state become much flatter than would be expected from the 4.4 MeV results.

The differential cross sections at the forward angle maximum are plotted for the $(2^+;0)$ and

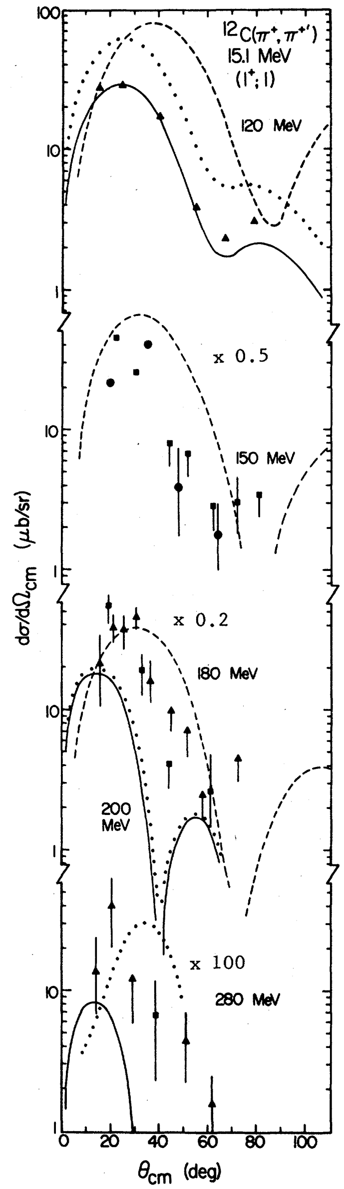

FIG. 6. Data from the present experiment are compared to the predictions of Huber and Klingenbeck (Ref. 31) as the dashed curves and to the predictions of Wilkin (Ref. 13) for a direct spin flip only for the solid curves. The dotted curves are the predictions of Wilkin (Ref. 13) including the interference of a convection current term. Data at 116 MeV (triangles) are used for comparison to the 120 MeV calculations. Data at 140 MeV (squares) and 160 MeV (circles) are compared to a calculation at 150 MeV. Data at 180 MeV (triangles) and 200 MeV (squares) are compared to the 180 MeV prediction (Ref. 31) and 200 MeV predictions (Ref. 13), and data at 260 MeV (triangles) and 291 MeV (squares) are compared to the 280 MeV calculation. The dotted prediction of Wilkin at 280 MeV has been multiplied by 100, while the broken curves show the Huber and Klingenbeck predictions multiplied by 0.2 at 180 MeV and 0.5 at 150 MeV.

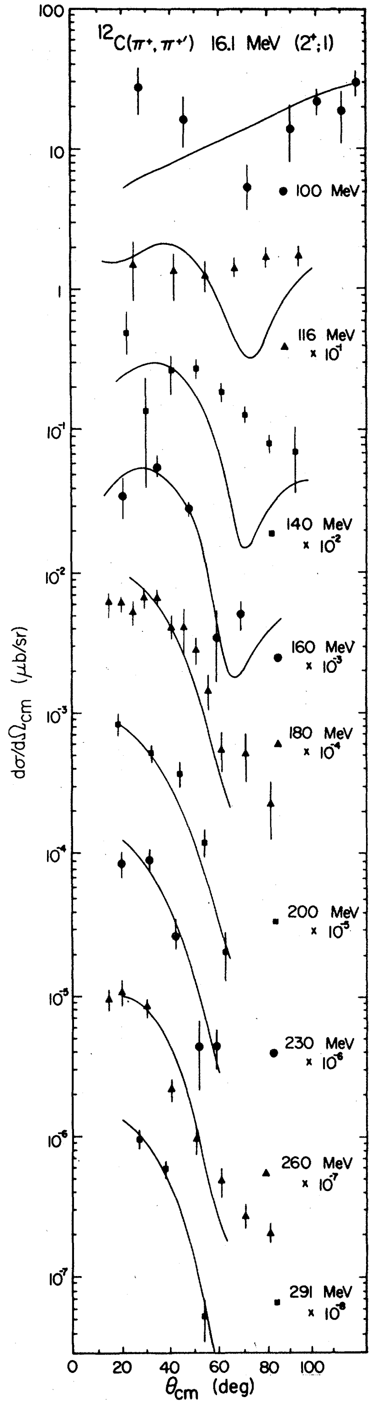

FIG. 7. Data for the 16.1 MeV $(2^+;1)$ excitation in ^{12}C are compared to the shape of the angular distributions observed for the 4.4 MeV $(2^+;0)$ excitation in this and previous experiments.

$(2^+;1)$ states in Fig. 8. The yields to the 2^+ states are similar and differ from the energy-dependent yield to either 1^+ state.

A collective model distorted-wave Born approx-

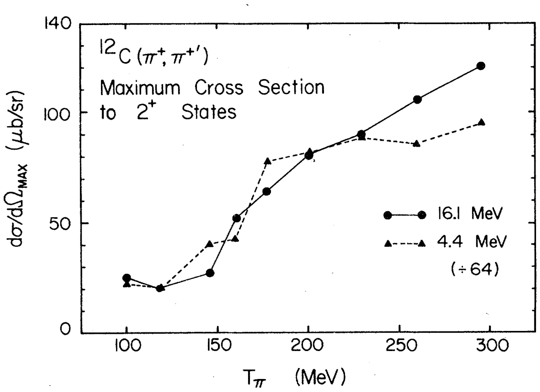

FIG. 8. The peak differential cross sections for the 2^+ states of ^{12}C are compared for nine positive pion beam energies. These excitation curves for the 4.4 and 16.1 states are much the same, but they both are distinctly different from the 1^+ excitation curves shown in Fig. 5.

imation (DWBA) prediction[33] using conventional optical model parameters[34] fits the shape of the 4.4 MeV data adequately with pion energies of 120 to 280 MeV and the magnitude agrees with the conventional value of 0.6 for the deformation parameter. A value of $\beta_2 = 0.07$ accounts roughly for the magnitude of the 16.1 MeV data and, although the shapes of these data are as predicted at higher beam energies, a discrepancy is found at 100 and 116 MeV, as shown in Fig. 7. This is perhaps due to a change in the interference between the s wave and p wave terms in the deformed optical potential for the isovector excitation.

It was pointed out in the previous section that the 1^+ cross sections are expected to be very weak from the effects of parity conservation and the adiabatic approximation. These conditions do not hold for the 16.1 MeV 2^+ data and yet the cross sections for this state are not much larger than those found for the 1^+ states. Evidently some fairly strong selection rule is retarding the transition to the $(2^+;1)$ state. This may be due to the isovector nature of the excitation.

V. TWO-STEP MECHANISMS FOR THE 1^+ DATA

Since the cross sections for populating the two 1^+ states are comparable to those for the 14.1 MeV 4^+ state, which is thought to be populated by two-step processes, a similar mechanism must be investigated for the 1^+ excitations as well. The role of collective intermediate states for analog charge exchange processes was investigated by Warszawski and Auerbach.[30] The first expectation is that the very strong 4.4 MeV state would be the first excitation. The quadrupole coupling from the 4.4 MeV state to either 1^+ state is very weak, however. This has been checked with the realistic L-S coupled wave functions of Ref. 35; in the simple $p_{3/2}^{-1}p_{1/2}$ single-particle model of greatest symmetry or in the SU3 limit of a harmonic oscillator model, the quadrupole 2^+ to 1^+ coupling vanishes identically.

It is not clear[36] if a giant quadrupole state exists in ^{12}C, but there do exist wave functions for high-lying 2^+ states with both $T=0$ and $T=1$.[35] In fact, appreciable isoscalar $E2$ strength has been observed at excitation energies between 15 and 27 MeV in (α,α') measurements at 150 MeV.[37] Two-step calculations proceeding through these states to the 1^+ states have been presented,[38] in the form of a double quadrupole calculation as performed for the population of the 7.6 MeV 0^+ state.[39] The shape agrees with the general expectations, but, thus far, calculations of the absolute magnitude have not been made. Other two-step pathways are also possible, perhaps through such strongly excited levels as the 9.64 MeV 3^-,[21,27] or the strongly excited levels at ~20 MeV excitation.[40]

Even without an actual calculation specifying the exact structure of the intermediate levels, the isospin symmetry of the final and intermediate states of interest allows a prediction for the expected ratio of two-step yields to the 1^+ states through the intermediate particle-hole states. All nuclear structure and reaction mechanism information is then separated from the isospin dependent terms by the Wigner-Eckart theorem.

Let A_0, A_1 be the $\Delta T=0$, $\Delta T=1$ amplitudes exciting the intermediate states and B_0, B_1 the ($\Delta T=0$ and $\Delta T=1$) amplitudes for decay to the final states of $T_f=0,1$. The intermediate states may be in ^{12}C or ^{12}N. For the 12.7 MeV $T_f=0$ state, the two-step amplitude is

$$C_0 = (00\ 00\,|\,00)A_0B_0 + (11\ 00\,|\,00)A_1B_1 + (11\text{-}11\,|\,00)A_1B_1 = A_0B_0$$

and for the 15.1 MeV $T_f=1$ state is

$$C_1 = (11\ 00\,|\,10)A_1B_1 + (10\ 00\,|\,10)A_1B_0 + (01\ 00\,|\,10)A_0B_1 + (11\text{-}11\,|\,10)A_1B_1 = A_1B_0 + A_0B_1 - \frac{1}{\sqrt{2}}A_1B_1 .$$

On the 3-3 resonance, where the present data are available, $A_0 = 2A_1$, $B_0 = 2B_1$ for $\Delta S = 1$ transitions[3] and the ratio of cross section

$$R = \frac{|C_0|^2}{|C_1|^2} = 1.476 .$$

The data of Fig. 5 show the cross sections to the 12.7 MeV state to be about 1.3 times the strength of the 15.1 MeV cross sections at 120 MeV, in good agreement with the simple prediction on the 3-3 resonance. An interesting energy dependence remains to be addressed.

This success does not depend upon any particular set of intermediate states, but only upon the existence of a symmetric set of both $T=0$ and $T=1$ levels. A crucial feature neglected in this picture is the possible difference in the radial wave functions. The similar binding energies of the 1^+ states and the fairly tight cluster of strength near 20 MeV seen in Ref. 38 are reassuring in this regard. Since similar isospin pairs of particle-hole states are known throughout the light nuclei, the mechanism here described would be effective for all simple spin-flip $0^+ \rightarrow 1^+$ transitions of the Gamow-Teller form. A more varied range of possibilities would be found for targets with a neutron excess.

This two-step model for the excitation of two particular states of ^{12}C is similar to, but more specific than, doorway models for pion scattering,[32] in that the intermediate state is viewed as a well-determined nuclear eigenstate and a pion. The advantage of a particular set of intermediate nuclear states is that the first stage of a coupled-channel Born approximation (CCBA) calculation may be constrained by existing data.[38]

VI. CONCLUSIONS

Although positive pion scattering from ^{12}C near 150 MeV shows oscillatory angular distributions for the two known 1^+ states, this angular dependence is required by very general conservation laws. This measured property is not a constraint to any calculation. The yield to the 1^+ states exhibits no sign of the 3-3 pion-nucleon resonance and the isovector excitation is about equal to the isoscalar strength at the resonance, rather than one-fourth as observed in the pion-nucleon system. These results indicate that the reaction mechanism responsible for populating these 1^+ states is far removed from the simple quasifree mechanism. A prediction for the ratio of isoscalar to isovector strengths was obtained by a two-step process through intermediate states symmetric between $T=0$ and $T=1$. This model did account for the observed ratio.

Several predictions of the absolute magnitude of the single-step 1^+ cross sections in ^{12}C have been published and come near to accounting for the data. The present work has not included effects due to isospin mixing of the two 1^+ states, which may have a particularly strong role, due to the different nucleon binding energies for the two states. No detailed comparison of the isovector 2^+ and 1^+ states has been attempted, but that also is worthy of further theoretical study.

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