RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 38, NUMBER 6 DECEMBER 1988

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Energy dependence of pion inelastic scattering to the 1^+ states in ^{12}C

D. S. Oakley, R. J. Peterson, and D. J. Rilett
University of Colorado, Boulder, Colorado 80309-0446

C. L. Morris and S. J. Greene
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

B. Boyer, K. Johnson, A. H. Fuentes, J. W. McDonald, M. J. Smithson
A. L. Williams, S. H. Yoo, and C. Fred Moore
University of Texas at Austin, Austin, Texas 78712-1081

(Received 26 August 1988)

The energy dependence of cross sections for inelastic pion scattering to the $\Delta S=\Delta T=\Delta J=1$ transition at 15.11 MeV in ^{12}C is found to map very closely the $\Delta S=\Delta T=\Delta J=1$ π-nucleon scattering cross sections at beam energies from 50 to 295 MeV. This free π-nucleon energy dependence is due to the prominent $\Delta_{3/2,3/2}$ resonance, corresponding to the first excited nucleon state, which is mirrored in the π-nucleus system with little alteration.

Transitions from a nuclear ground state of zero spin and zero isospin to specific final states can be used to determine specific components of the interaction responsible for the excitation. In nucleon-nucleus reactions, for instance, the isovector spin and nonspin amplitudes are isolated by (p,n) reactions on ^{14}C to $1^+;0$ and $0^+;1$ final states.[1] In pion-nucleus interactions the $\Delta S=\Delta T=1$ reaction is of particular interest because these are also the quantum numbers for pion excitation of a free nucleon to a $\Delta_{3/2,3/2}$. This pion-nucleon excitation differs from the nucleon-nucleon interaction by proceeding through the prominent $\Delta_{3/2,3/2}$ resonance near a pion-beam energy of 180 MeV.

Here we discuss inelastic pion scattering on ^{12}C to excite the 1^+ $T=0$ state at 12.71 MeV and the 1^+ $T=1$ state at 15.11 MeV to isolate the isoscalar and isovector spin cross sections. While these two states have very similar structure and single-nucleon spectroscopic factors,[2,3] the 15.1-MeV state, unlike the 12.7-MeV state, has quantum numbers which mirror the excitation of a nucleon to a $\Delta_{3/2,3/2}$ and this makes their comparison particularly valuable.[4] It has been suggested that the 15.1-MeV state contains a $\Delta_{3/2,3/2}$ component in its wave function.[4] From the quantum numbers of the $\Delta_{3/2,3/2}$ resonance, a ratio of 4:1 is predicted for the $\Delta T=0$ over the $\Delta T=1$ π-nucleon cross sections. Hence, the impulse approximation, when applied to ^{12}C, will also yield a 4:1 ratio for the 12.71- and 15.11-MeV states, and this ratio should be constant with beam energy near the Δ resonance.

The measurement of these 1^+ cross sections has been the focus of several previous experiments at incident pion energies from 50 to 295 MeV.[4-7] There it can be seen that the ratios do not obey the 4:1 prediction and, in particular, we see energy-dependent ratios near 7 at 50 MeV (Ref. 7) and 1.4 at 180 MeV.[5] There are no reliable data significantly above the $\Delta_{3/2,3/2}$ resonance (180 MeV) from these studies, although this ratio appears to decline steadily.

We have measured, in a new experiment on the EPICS system at Los Alamos Meson Physics Facility (LAMPF), the differential cross sections for these 1^+ excitations at pion-beam energies from 80 to 295 MeV. With improved energy resolution (150 keV for most energies), a lower background, better statistical accuracy, smaller scattering angles with lower total counting rates, and a more sophisticated peak-fitting procedure, these data are much more reliable than the results previously obtained above resonance. By taking these data near the first maximum of the 1^+ angular distribution (constant q), no significant extrapolation is needed to find the exact maximum; this was not the case in Ref. 5. A sample fitted spectrum is shown in Fig. 1, showing the strong continuum and broad isoscalar states of natural parity known to underlie the peaks of interest.[8] The peaks were fit with a shape taken from the elastic peak using known excitation energies and widths.[8] Scattering angles were selected to be at the maximum of the differential cross-section angular distributions by an estimation employing the strong absorption

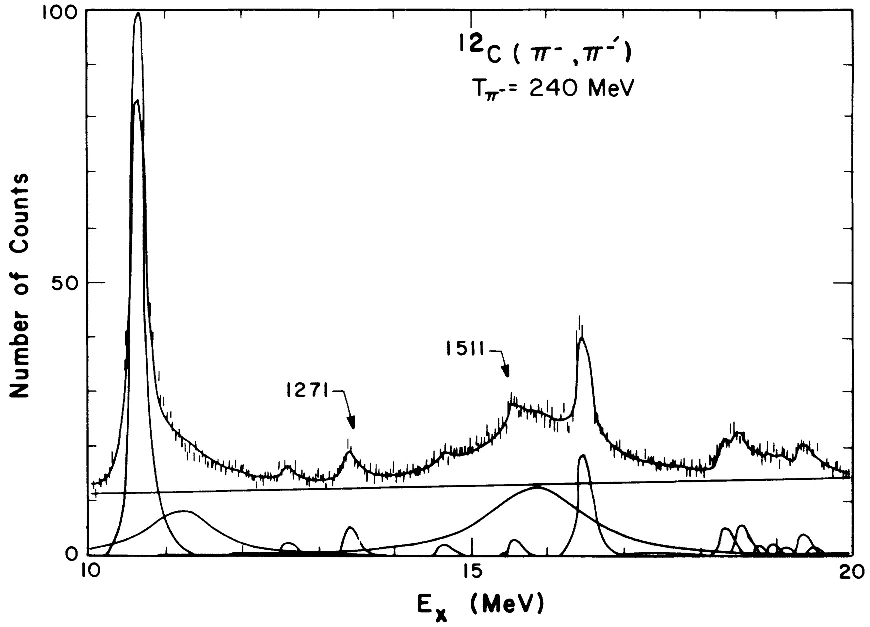

FIG. 1. A measured spectrum for π^- scattering on ^{12}C at $\theta_{cm}=22.7°$ (the expected 1^+ maximum) and $T_\pi=240$ MeV. Fitted peak shapes are shown by the indicated lines.

adiabatic model, as done in Refs. 5 and 7, which gives shapes similar to those from microscopic nuclear models as well.[6,9] Above 100 MeV, it has been shown that the angular dependences of the 12.71- and 15.11-MeV states are very similar, with shapes as assumed in the present study.[6] Below this beam energy, however, more subtle interference effects may cause these two shapes to differ, perhaps explaining the nonmonotonic behavior of the $T=0/T=1$ cross-section ratios at 50 and 80 MeV, as seen in Fig. 2.

These maximum differential cross sections and the $T=0/T=1$ ratios, together with those from earlier work, are shown in Figs. 2 and 3, with new values listed in Table I. The general features are the same as noted previously, but now the results extend reliably to both sides of the $\Delta_{3/2,3/2}$ resonance, centered near 180 MeV.

Possible isospin mixing between the 12.71- and 15.11-MeV states, which would yield different cross sections for π^+ and π^- scattering, has little significant energy dependence, and so these effects can be cancelled to first order by taking the π^+ and π^- average.[4] The resultant isospin-averaged values are the ones shown in Figs. 2 and 3, wherever possible, but give the same systematic behavior as the unaveraged results.

For the 12.71-MeV $(1^+;0)$ transition, the measurements show a smooth behavior very much like the $\sin^2\theta$ prediction,[10] where θ is the scattering angle at the maximum cross section (yielding $q \sim 0.60$ fm^{-1} at each energy). This prediction, shown as the solid curve in Fig. 2, is based upon the impulse approximation, where, below 100 MeV, the momentum terms cause the cross section to fall,[10] as also seen in the measurements. More sophisticated distorted-wave impulse approximations (DWIA) calculations, assuming predominantly $1p_{1/2}(1p_{3/2})^{-1}$ particle-hole configurations, also show this behavior and

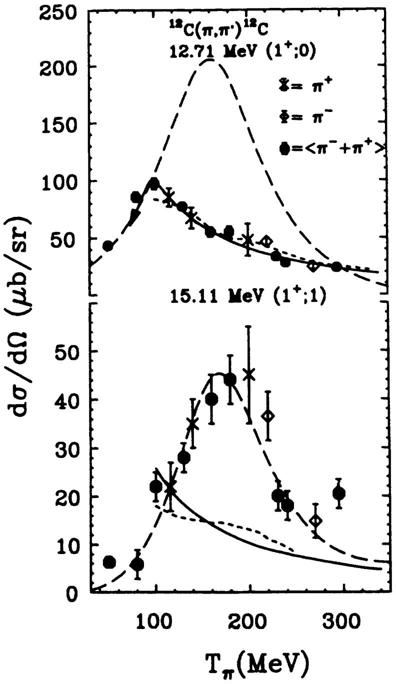

FIG. 2. Measured or interpolated maximum differential cross sections vs laboratory beam energy for pion scattering to the 1^+ states of ^{12}C, from Refs. 6, 7, and the present work. Where available, these are charge averages, as indicated. The solid curves show the impulse-approximation result from Ref. 10. The appropriate maximum π-nucleon isoscalar and isovector spin-differential cross sections are, as shown by the long-dashed curves, in excellent agreement with the data for the isovector transition. DWIA calculations using Cohen-Kurath p-shell wave functions are also shown by the short-dashed lines (Refs. 2, 4, 6, and 9).

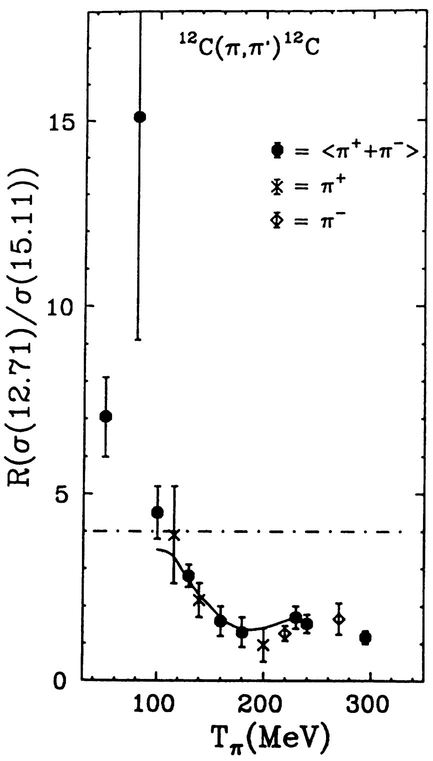

FIG. 3. Measured (or interpolated) ratios of $\sigma_{max}(12.7)/\sigma_{max}(15.1)$ from Refs. 6, 7, and this work. The dashed line shows the predicted 4:1 ratio while the solid line is from a phenomenological Δ-hole calculation (Ref. 14).

in some cases can give slightly better fits to the data.[4,6,9,10] A calculation of this kind is shown by the short-dashed lines in Fig. 2 where we have used one-body density-matrix elements taken from Cohen-Kurath wave functions.[2,9] It can, therefore, be concluded that the energy dependence of this state is well understood in the context of *p*-shell nuclear excitations.

For the 15.1-MeV isovector spin excitation, however, the differential cross sections show a definite peak near the $\Delta_{3/2,3/2}$ pion-nucleon resonance energy, a result not seen for the $T=0$ state and very different from that predicted from the DWIA calculations ($\sin^2\theta$). To emphasize the similarity between this energy dependence and the π-nucleon energy dependence, the long-dashed curve in Fig. 1 shows the free π-nucleon isovector (charge exchange) spin-flip cross sections taken at their maximum differential cross sections (around 90° for all lab energies). Here, we have used the scattering code SAID (Ref. 11) to calculate the cross sections using a current set of global phase shifts, separating out the isovector spin-flip piece and multiplying by 0.025 for the sake of comparison. A similar curve for the isoscalar spin flip free pion-nucleon cross sections is shown for the 12.7-MeV data, which is seen not to fit this shape. If the total, not maximum differential, π-nucleon cross sections had been used for these comparisons, the shapes would be very much the same. It should be pointed out that while the energy dependence of the cross sections is very different from that predicted from the DWIA calculations for this state, the angular dependences are not.[5,6]

Although the older data suggested this energy-dependent $T=1$ shape and a similar maximum is found over a small energy range for a spin-isospin pion excitation in ^{6}Li,[12] only the high quality of the present results shows the remarkably precise proportionality to the π-nucleon cross sections. That this energy dependence is not uniquely due to some feature of the 15.1-MeV state is shown by the similar result for ^{6}Li. Unfortunately, resolved 1^+ states are not common, and no other such excitation functions in pion scattering are available. Several 4^- states have been seen in ^{14}C,[13] but these show no evidence of the effect seen here, and while the 2^- 18.3- and 19.4-MeV $T=1$ states in ^{12}C are not resonance enhanced,[6] the strong isospin mixing confuses the interpretation.

Previous work has attempted to reproduce the anomalous $T=0/T=1$ ratios by a phenomenological altering of the Δ-nucleus potential until the observed ratio has been achieved.[14,15] Even though the results of these calculations were derived from fits to the data, there has been no success in reproducing the 12.7- and 15.1-MeV data simultaneously away from resonance. The lower-energy

TABLE I. Measured cross sections and those interpolated to the expected maximum from this work.

T_π (MeV)	State E_x (MeV)	$\frac{d\sigma}{d\Omega}(\pi^+)$ [a] (μb/sr)	$\frac{d\sigma}{d\Omega}(\pi^-)$ [a] (μb/sr)	θ_{cm} [b] (deg)	$\frac{d\sigma}{d\Omega}(\pi^+)$ [b] (μb/sr)	$\frac{d\sigma}{d\Omega}(\pi^-)$ [b] (μb/sr)
80	12.71	90.5(6.0)	80.4(5.8)	48.9	85.8(6.0)	74.4(5.8)
80	15.11	6.8(3.2)	4.8(3.0)	48.9	6.3(3.2)	4.5(3.1)
220	12.71	· · ·	46.5(3.3)	24.7	· · ·	42.3(3.3)
220	15.11	· · ·	36.5(5.0)	24.7	· · ·	33.4(5.0)
240	12.71	22.8(2.7)	33.6(2.1)	22.7	20.9(2.7)	30.3(2.1)
240	15.11	16.3(4.1)	20.3(3.0)	22.7	14.9(4.1)	18.6(3.0)
270	12.71	· · ·	24.5(2.4)	21.7	· · ·	21.5(2.4)
270	15.11	· · ·	14.8(3.5)	21.7	· · ·	13.0(3.5)
295	12.71	22.4(2.8)	25.1(2.8)	20.8	18.9(2.8)	21.1(2.8)
295	15.11	20.8(4.0)	20.1(3.6)	20.8	17.7(4.0)	16.9(3.6)

[a] Interpolated maximum values from $J_1(qR)^2$.
[b] Measured values from this work.

data, in particular, give much larger ratios than expected (Fig. 3) and these calculations do not single out the features of the $T=1$ state apart from the $T=0$. Two recent works have made comparisons of calculations to the $1^+;1$ angular distributions but these did not attempt to reproduce the entire excitation function.[16,17] It is now clear that this effect on the ratio is solely due to the isovector terms in the interaction and not the isoscalar, and that the isovector state is resonance enhanced.

We have thus observed a remarkably simple energy dependence for excitation of an isolated $\Delta J=1^+$, $\Delta T=\Delta S=1$ nuclear transition. This closely matches the shape observed in free π-nucleon scattering. The reason for such a simple result is not obvious, since only the quantum numbers are common to the two reactions. This energy dependence has only been observed for the 1^+ states in ^{12}C and perhaps in ^{6}Li.

This work was supported in part by the U.S. Department of Energy and the Robert A. Welch Foundation.

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