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50 MeV pion inelastic scattering to the 1^+ doublet in ^{12}C

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Cross sections have been measured for the excitation of the 12.71 MeV, $T=0$, and 15.11 MeV, $T=1$, 1^+ states in ^{12}C by 50 MeV $\pi^{\pm}$ scattering. The cross section ratio, $R=\sigma(12.7 \text{ MeV})/\sigma(15.1 \text{ MeV})$, was found to be 7.5 ± 1.5 for π^+ and 6.6 ± 1.5 for π^- at 50 MeV, giving an isospin averaged value of $R=7.05 \pm 1.06$. These results indicate that the anomalous behavior of R is attributable to the energy dependence of the $T=1$ 1^+ level. The data also indicate that the impulse approximation is probably invalid at 50 MeV, contrary to the conclusions of a recent study at 65 MeV.

Studies of pion inelastic scattering to nuclear states of simple, well-known structure provide a powerful tool for unraveling the details of the pion-nucleus reaction mechanism. Although numerous studies of this nature have been performed for resonance energy pions, the extension of those studies to low energies has been hampered by the available experimental energy resolution for the scattered pions. Because of this limitation, low-energy pion-nucleus studies have been almost exclusively measurements of elastic scattering on very light or even-even nuclei, with very few data on inelastic scattering. Consequently, the reaction information gained from the low-energy studies thus far has been restricted to isoscalar, non-spin-flip excitations.[1,2] With the advent of new, moderate resolution low-energy pion spectrometers at the "meson factories," more detailed studies of inelastic scattering of low-energy pions from nuclei have become feasible, and the remaining components of the pion-nucleus reaction mechanism may now be explored.

One commonly studied pair of states with relatively simple nuclear structure is the ^{12}C 1^+ doublet, which consists of the 12.71 MeV, $T=0$ state and the 15.11 $T=1$ state. The structure of these states has been extensively examined with a number of probes, including resonance energy pions.[3-5] The dominant component for the doublet wave functions under discussion is the $(1p_{3/2}^{-1}-1p_{1/2})$ configuration, representing a spin flip of one of the $p_{3/2}$ nucleons. Thus, a pion spectrometer capable of resolving these states can provide a straightforward measurement of the isoscalar and isovector spin-flip transition amplitudes for the reaction mechanism.

If the pion reaction exciting the 1^+ doublet is dominated by delta formation, then, in the impulse approximation, at resonance energies the ratio of the cross sections for exciting the states, $R=\sigma(12.71 \text{ MeV})/\sigma(15.11 \text{ MeV})$, would be 4, by simple isospin arguments.[6] Previous measurements[3-5] have shown, however, that this ratio is not only very energy dependent, but is nearly 1 rather than 4 at resonance energies, and approaches 4 only at about 100 MeV. Calculations of R by Lee and Kurath,[7] taking into account isospin mixing, predicted essentially the same value for R as the simple isospin impulse approximation arguments (i.e., about 4) for incident pion energies from 100 MeV through resonance, with only a small energy dependence. Interestingly, predictions by Carr[8] also gave similar results for R at energies lower than 100 MeV. To date, the best attempt at explaining the magnitude and energy dependence of R was made by Hirata, Lenz, and Thies[9] using the delta-hole model. Within that model, the $T=1$ transition strength was enhanced and the $T=0$ transition strength reduced. The predicted value of R at resonance was in fair agreement with measurements, but the value at 100 MeV was too small. In summary, no wholly satisfactory explanation of the energy dependence and magnitude of R exists.[10]

We report here the first measurements of the cross sections for the excitation of the ^{12}C 1^+ doublet with π^+ and π^- at low energies, specifically, 50 MeV. The measurements were made using the "Clamshell" low-energy pion spectrometer[11] at the Clinton P. Anderson Meson Physics Facility (LAMPF). The pion beam was provided by the low-energy pion channel at LAMPF with $\Delta p/p=0.4\%$.

The ^{12}C target had a thickness of 236 mg/cm^2. An energy resolution of about 450 keV (FWHM) was obtained. Normalization for solid angle and pion flux was obtained by measuring πp scattering at several scattering angles and comparing to the values of Bertin *et al.* for the pion-nucleon cross section.[12] At each of these scattering angles, data were taken in several runs with spectrometer field settings chosen to place the scattered pion peak at different positions of the focal plane, thereby providing a check on the detection system efficiency and solid angle, as well as providing the normalization for pion flux.

The data were taken in 10° steps for laboratory scattering angles from 30° to 90° for π^+ and π^-; however, for π^-, sufficient statistics for the 1^+ doublet were only obtained at 60°. Though data were taken for many states, only the results for the 1^+ states will be discussed here; the remainder will be described in a forthcoming article.[13] The data indicate that the angular distribution is simple in structure, as shown in Fig. 1 for the 12.71 MeV state. The peak in the angular distribution is located at about 50° at a momentum transfer $q = 101$ MeV/c. As shown in the figure, the distribution is well described by a semiclassical prediction[14] for a 1^+ state, where the shape is given by $[J_1(qr)]^2$, where $r = 3.38$ fm as in Ref. 3. The use of q rather than kr or $2kr\sin(\theta/2)$ in this expression permits extension of the semiclassical adiabatic prediction discussed in Ref. 14 to the significant energy loss and large angles studied here.

The excitation region of interest is shown in Fig. 2 for π^+ at 60°. The states of interest are seen clearly; the peaks correspond to differential cross sections of 37.7 ± 1.4 and 5.0 ± 1.0 μb/sr for the 12.71 and 15.11 MeV states, respectively, giving a ratio of 7.5 ± 1.5, which we denote as R_+. For π^-, the cross sections were found to be 49.2 ± 2.4 and 7.4 ± 1.6 μb/sr for the 12.71 and 15.11 MeV states, respectively, giving a ratio $R_- = 6.6 \pm 1.5$. The normalization uncertainty of 10% is not included in the values given for the cross sections, and *cancels in the ratios.*

From R_+ and R_-, an isospin-averaged ratio $R = 7.05 \pm 1.06$ is obtained. The trend of the ratio R with pion energy is shown in Fig. 3, which includes the results of Ref. 5. R shows no sign of saturation at lower energies, which gives convincing evidence that the agreement between the simple delta dominance value of 4 with the measured value of about 4 at 100 MeV is coincidental and that the reaction mechanism is more complicated.

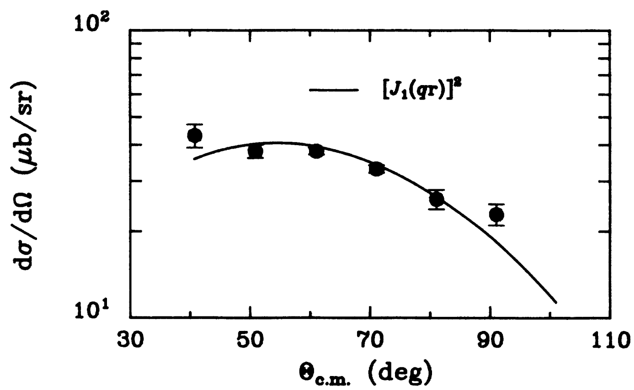

FIG. 1. Angular distribution for 12.71 MeV state in ^{12}C excited by 50 MeV π^+. The curve is a prediction based on a semiclassical reaction model, as described in the text.

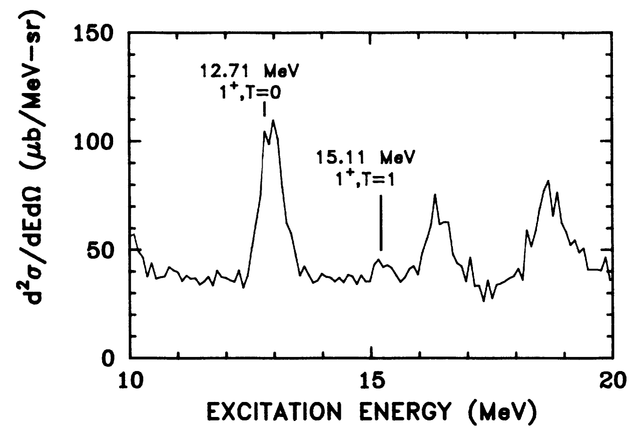

FIG. 2. Missing mass spectrum for ^{12}C for π^+ at 50 MeV highlighting the region near the 1^+ doublet. The laboratory angle at which the spectrum was taken, 60°, is near the maximum for the cross section for the 1^+ states.

Morris *et al.*[4] presented a formalism for extracting the isospin mixing between the states studied here and the magnitude of the spin-flip amplitude. The difference of R_+ and R_- is proportional to the isospin-mixing matrix element H_{01}. The sum yields the isospin averaged R, which reflects the strength of the p-wave spin-flip amplitude X independent of isospin. The assumption of the validity of the impulse approximation is crucial for obtaining results for both H_{01} and X within that formalism. It would not be expected that the impulse approximation would be valid at an energy as low as 50 MeV. However, a recent study[15] of pion inelastic scattering from ^{13}C suggests that the impulse approximation is still valid for a simple spin-flip transition at 65 MeV. By using the formalism of Ref. 4, as outlined below, the present work strongly suggests that this is not the case at 50 MeV.

Since the values of R_+ and R_- are very close (indeed,

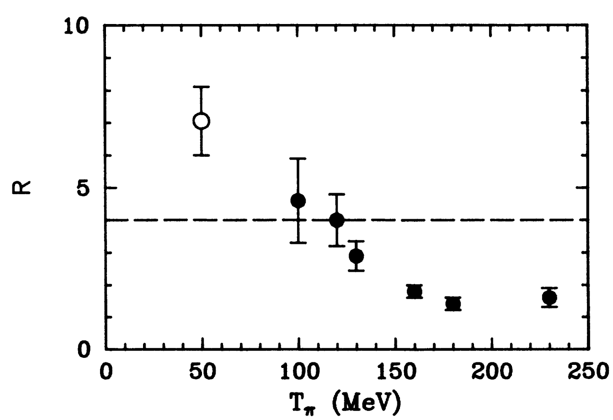

FIG. 3. The isospin averaged ratio $R = \sigma(12.71)/\sigma(15.11)$ determined in this work (open circles) and in Ref. 5 (closed circles). The dashed line indicates the delta-dominance impulse approximation value of $R = 4$.

the same to within errors), these measurements do not provide a sensitive measure of the small degree of isospin mixing present in the 1^+ doublet. Nonetheless, using the results given above, a value of 25 ± 58 keV was obtained for the charge-dependent matrix element H_{01}. This value is significantly lower than the average value of 148 ± 29 keV obtained in Ref. 4 for pions for several energies near resonance. Since this matrix element should not exhibit such an energy dependence, this difference indicates that the formalism of Ref. 4 is inapplicable at 50 MeV. The best explanation for this failure would be that the crucial assumption underlying this formalism, the validity of the impulse approximation, is unjustified.

The isospin averaged ratio R provides a measure of the parameter $X = [\sigma(\pi^+p)/\sigma(\pi^+n)]^{1/2}$ noted in Ref. 4, which relates the cross sections for p-wave spin-flip processes to the cross sections for pion-nucleon scattering. The value extracted for X here based on the isospin averaged R would be 2.21 ± 0.16, which is considerably higher than the value which would be given by simply utilizing phase-shift values for the pion-nucleon cross sections evaluated at the incident pion energy of 50 MeV (about 1.4). As indicated in the discussion above, this discrepancy represents a failure of the formalism of Ref. 4 *independent* of the failure to predict correctly predict H_{01}. This discrepancy and the failure of the formalism to yield an energy-independent isospin-mixing matrix element both point to a failure of the impulse approximation for the reaction studied.

Siciliano and Walker (SW)[16] have argued that the excitation of an unnatural parity state should involve a vector operator. In a one-step process, the simplest vector operator leads to a $\sin^2\theta$ dependence for the reaction amplitude at fixed momentum transfer, where θ is the angle between the incident and outgoing pion momenta in the center of mass system. Such a dependence will yield an excitation function which decreases as the incident pion energy is increased. SW also predict that the cross section at fixed momentum transfer should drop abruptly below 100 MeV. SW found satisfactory agreement between this prediction and the measured cross sections for the 1^+ 12.71 MeV, the 2^- 18.36 MeV, and the 4^- 19.25 MeV levels in ^{12}C, but no data existed at that time for comparison below 100 MeV.

In Fig. 4, the SW prediction for $q = 130$ MeV/c is shown for pion energies from 80 to 250 MeV; the curve is normalized such that the value predicted at 100 MeV is 100 μb/sr. Also plotted in Fig. 4 are the results of this study and Ref. 5. As seen in the figure, the cross-section measurements support the SW mechanism for exciting the $T = 0$ state, including the prediction of an abrupt drop below 100 MeV. However, the observed energy dependence for the $T = 1$ state clearly is in disagreement with the prediction. This sharp disagreement with the prediction of Siciliano and Walker provides strong evidence that the source of the anomaly in the behavior of R is attributable to features of the 15.11 MeV level.

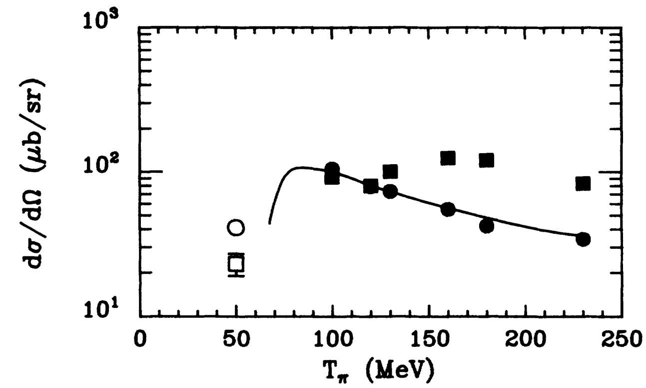

FIG. 4. Cross sections determined in this work (open symbols) and Ref. 5 (closed symbols) for the 12.71 MeV (circles) and 15.11 MeV (squares) states. The 15.11 MeV cross sections have been multiplied by 4. The curve illustrates the prediction of Ref. 16, as discussed in the text.

In conclusion, the data presented here indicate that the ratio R does not saturate at 4 at low incident pion energies. While the behavior of the $T = 0$ state seems understandable, the behavior of the $T = 1$ state remains puzzling. Evaluation of the effects of isospin mixing indicate that the impulse approximation is inapplicable at 50 MeV. Given that the ratio R shows no indication of reaching a limiting value of 50 MeV, future measurements at lower energy might find that the ratio increases considerably.

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