50 MeV π^+ and π^- scattering from ^{12}C

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Differential cross sections were measured for 50 MeV π^+ and π^- elastic scattering from ^{12}C and for 50 MeV π^+ inelastic scattering to the (4.44 MeV, 2^+), (7.65 MeV, 0_2^+), (9.64 MeV, 3^-), (12.71 MeV, 1^+), and (15.11 MeV, 1^+) levels in ^{12}C. Comparisons of the data obtained in this study to data taken previously for these states resolve discrepancies between the earlier data sets. Using a recently discussed procedure, one-step and coupled-channels calculations using a modified MSU potential were performed. The results of both one-step and coupled-channels calculations describe the data for the ground, first, and third excited states, indicative of the collective isoscalar structure of those states. The one-step analysis fails to describe the excitation of the 0_2^+ state. The coupled-channels calculations are more successful in describing those data, indicating that the failure of the one-step calculations may be attributed to coupled-channels effects.

I. INTRODUCTION

Studies of pion-nucleus reactions at energies below the delta resonance have been pursued because of the vast difference in the underlying pion-nucleon reaction dynamics between low and resonance energies.[1] The long mean free path of the pion at lower energies results in the pion probing the nuclear interior, with consequent sensitivity to the treatment of nuclear correlations in pion optical model treatments of the associated phenomena. While a detailed understanding of the phenomena involved in low-energy pion-nucleus scattering requires data on a variety of nuclei and on a variety of states within those nuclei, data obtained in the past have primarily been for pion elastic scattering from nuclei with relatively simple structure because of the constraints dictated by the poor energy resolution of the devices used in those experiments

Recently, investigations of low-energy pion-nucleus scattering have been greatly enhanced by the development of a new generation of low-energy pion spectrometers with good energy resolution. The development of these devices has provided an opportunity to study low-energy pion scattering to nuclear levels that were previously inaccessible. In a previous Rapid Communication,[2] we reported the results of an experiment using such a device, a study of the pair of 1^+ states at 12.7 ($T=0$) and 15.1 ($T=1$) MeV in ^{12}C using 50 MeV pions. In this paper we discuss the results of measurements on other levels in ^{12}C at 50 MeV.

Elastic scattering data were taken for both π^+ and π^- during our measurements of the cross sections for the ^{12}C 1^+ doublet. Optical model descriptions of pion-nucleus scattering frequently use 50 MeV pion elastic scattering on ^{12}C as a test case. Previous measurements[3-6] of the elastic scattering of positive pions from ^{12}C at 50 MeV were in significant disagreement for pion-scattering angles beyond 90 deg. Thus, the elastic scattering data taken during this experiment are of considerable interest in resolving this discrepancy. Studies of the inelastic excitations in ^{12}C can provide a test of the applicability of simple models of the transition densities and the effects of coupled reaction channels. The results from previous pion inelastic scattering experiments have presented cross sections for several of the excited states of ^{12}C, but in some cases no confirmation of those results was available or the confirmation has been ambiguous. To clarify the experimental situation, we report here differential cross sections for 50 MeV positive pion scattering from ^{12}C for all states where sufficient statistical accuracy was obtained to generate a reasonably complete angular distribution situation. Finally, since the cross sections for the

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excitation of the 1^+ doublet were not tabulated in Ref. 2, we tabulate them here.

II. EXPERIMENT

All measurements reported here were made using the Low Energy Pion (LEP) Channel at the Clinton P. Anderson Meson Physics Facility (LAMPF) and the LAMPF low-energy pion "Clamshell" spectrometer. The LEP channel and Clamshell spectrometer are discussed elsewhere;[7,8] only those details particular to this experiment are discussed here.

The LEP channel was tuned to deliver 50 MeV pions to the Clamshell spectrometer target with a beam momentum spread of $\Delta p/p = 0.4\%$. The pion beam position and spot size were optimized by measuring the beam spot profile with an integrating strip ionization chamber. The target was a self-supporting pressed sheet of graphite of thickness 223.42 mg/cm.^{2} Data were taken with the target in transmission geometry for all angles less than 120 deg, and in reflection geometry for scattering angles of 120 deg or greater to minimize the contribution of energy straggling within the target to the overall system energy resolution.

Relative monitoring of the pion beam flux was accomplished using three pairs of scintillator telescopes which detected muons arising from the decay of pions within the pion beam. The decay telescope geometry was such that the muons detected were in the plateau region of the phase space Jacobian for the decay muons. The decay telescopes also provided an indirect monitor of the pion beam position via the constancy of the ratio of counts observed in each. Additionally, the primary proton production beam current of the LAMPF linac was monitored during data collection by toroid an ion chamber monitors present at the pion production target. The primary production beam and pion decay monitors agreed to within 2% for all periods of data acquisition.

Measurements of the focal plane acceptance and efficiency were made to determine those factors directly by using π-p scattering and varying the spectrometer magnetic field to move the scattered pion peak to various positions on the spectrometer focal plane. A series of runs using rod targets was also undertaken to optimize the energy resolution of the system. A thin plastic scintillator was positioned at the entrance to the spectrometer to assist in particle identification and background rejection. The overall energy resolution of the Clamshell-LEP system with the target described above was approximately 400 keV FWHM for the states discussed here.

Absolute normalization of the relative pion flux monitors for the π^+ beam was obtained by measuring π-p

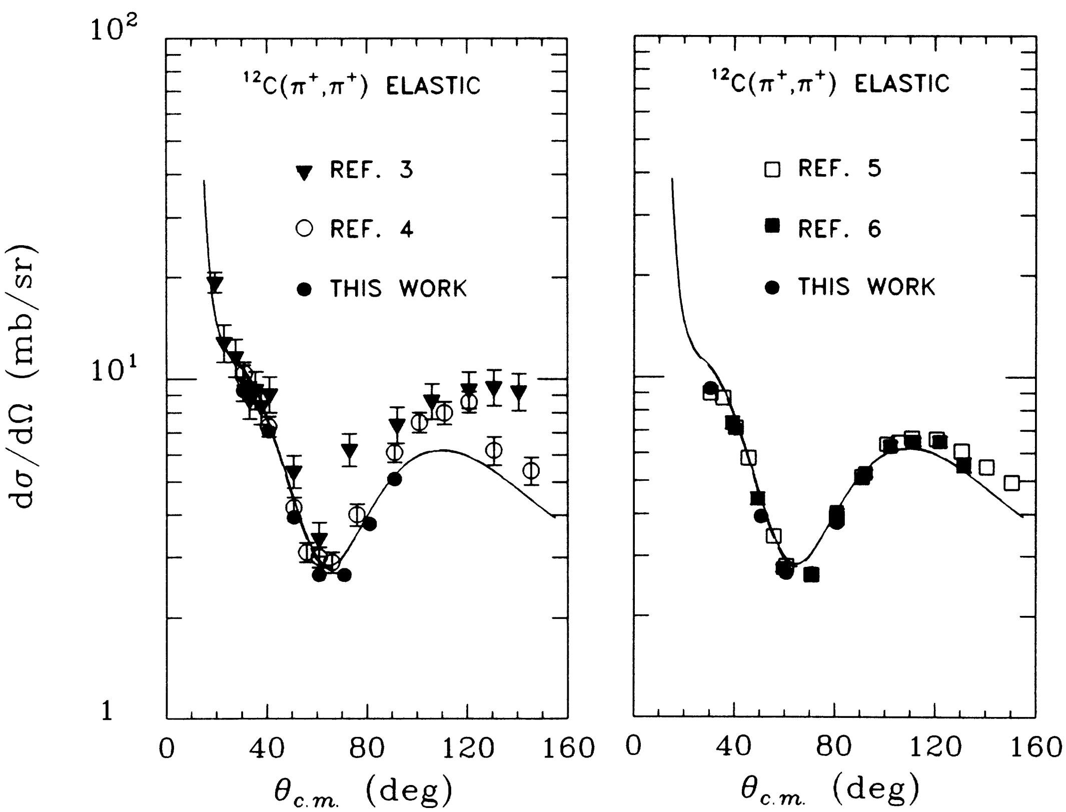

FIG. 1. Measured differential cross sections for elastic scattering of positive pions at 50 MeV from ^{12}C. Data are from this work and from Ref. 3–6. Error bars shown include statistical error only. The solid line indicates the results of the one-step calculation described in the text. The coupled-channels calculation discussed in the text is indistinguishable from the one-step calculation.

TABLE I. Differential cross sections $d\sigma/d\Omega$ and uncertainties for 50 MeV $^{12}C(\pi^+,\pi^+)$ scattering measured in this work. Statistical uncertainties are given in parentheses for the least significant digits of each tabulated cross section. Normalization uncertainties of ±10% are not included in the stated uncertainties.

θ_{lab} (deg)	Ground state (mb/sr)	4.44 MeV (mb/sr)	7.65 MeV (μb/sr)	9.64 MeV (μb/sr)	12.71 MeV (μb/sr)	15.11 MeV (μb/sr)
30.0	9.27(6)	0.233(13)	73(13)			
40.0	7.07(3)	0.170(6)	38(4)		45(4)	12(5)
50.0	3.93(2)	0.139(3)	32(2)	9(2)	41(3)	
60.0	2.66(1)	0.124(2)	27(1)	14(1)	38(1)	5(1)
70.0	2.66(1)	0.142(2)	40(1)	22(1)	35(2)	6(1)
80.0	3.75(1)	0.208(3)	48(1)	46(3)	29(2)	5(2)
90.0	5.09(2)	0.315(4)	56(2)	70(3)	25(2)	4(2)

scattering and normalizing the observed scattering cross sections to previously measured cross sections for π-p scattering.[9] (It should be noted that all previous π^+ elastic experiments[3–6] discussed below used this same set of cross section data for absolute normalization of positive pion scattering.) The normalization uncertainty of the π^+ measurements was determined to be better than or equal to 10% for all data reported here. Absolute normalization of the relative pion flux monitors for the π^- beam was obtained using predictions from phase shifts.[10] The calculated normalization uncertainty for the π^- cross sections was approximately 10%.

Data were taken for laboratory scattering angles of 30–90 deg for π^+ elastic and inelastic scattering. For π^- elastic scattering, data were taken for laboratory scattering angles of 30–130 deg. Additional cross section measurements for the inelastic scattering of negative pions were made at a laboratory scattering angle of 60 deg for the 1^+ doublet; as noted above, those results are analyzed elsewhere,[2] but we tabulate those results here. All cross sections were corrected for spectrometer acceptance, efficiency, and finite angle binning, and for pion decay within the spectrometer. Substantial improvement in background rejection was accomplished by using pulse height information from the scintillator at the entrance to the spectrometer.

TABLE II. Differential cross sections $d\sigma/d\Omega$ and uncertainties for 50 MeV $^{12}C(\pi^-,\pi^-)$ elastic scattering measured in this work. Statistical uncertainties for the least significant figures of the tabulated cross sections are given in parentheses. Normalization uncertainties of ±10% are not included in the stated uncertainties.

$\theta_{c.m.}$ (deg)	$d\sigma/d\Omega$ (mb/sr)
30.5	43.6(11)
40.6	20.1(7)
50.7	8.2(3)
60.8	3.2(1)
70.9	2.05(7)
81.0	3.4(1)
91.0	5.0(2)
101.0	5.8(1)
111.0	6.2(2)
121.0	5.7(1)
131.0	4.9(1)

III. RESULTS

The differential cross sections for the states studied in this work are given in Tables I and II. The results for each state are discussed below.

The data for elastic positive pion scattering from ^{12}C are shown in Fig. 1, along with data taken previously.[3–6] The data taken in this study strongly favor the measurements of Preedom et al.[5] and Sobie et al.[6] within the angular range studied. The disagreement between the data taken here and those of Dytman et al.,[4] though within

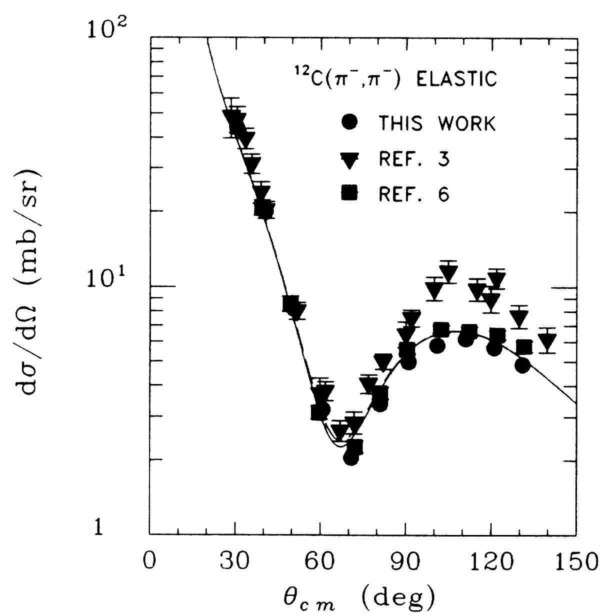

FIG. 2. Measured differential cross sections for elastic scattering of negative pions at 50 MeV from ^{12}C. Data are from this work and from Refs. 3 and 6. Error bars shown include statistical error only. The solid line indicates the results of the one-step calculation described in the text. The coupled-channels calculation discussed in the text is indistinguishable from the one-step calculation.

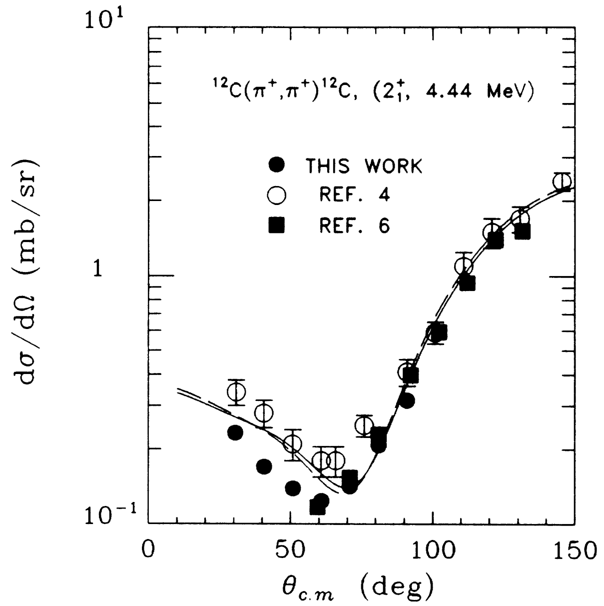

FIG. 3. Measured differential cross sections for excitation of the 4.44 MeV 2^+ level of ^{12}C by positive pions at 50 MeV. Data are from this work and from Refs. 4 and 6. Error bars shown in include statistical error only. The solid (dashed) line indicates the results of the one-step (coupled-channels) calculation described in the text.

the quoted normalization error for that work (15%), is seen in all comparisons with states measured here and in that work. The discrepancy between this work and that of Johnson *et al.*[3] is more serious, with disagreement in both the position of the minimum and the magnitude of the cross sections at all but the smallest angles. We conclude that the measurements reported in Refs. 5 and 6 correctly describe the cross sections for elastic scattering of positive pions from ^{12}C at 50 MeV. With some renormalization, the data from Ref. 4 are substantially in agreement as well. The elastic differential cross sections for negative pion scattering from ^{12}C at 50 MeV obtained in this work are shown in Fig. 2, again compared to previous data. The data obtained here are in general agreement with the data reported in Ref. 6, disagreeing by little more than the normalization errors. However, the data taken here again seriously disagree with the data of Ref. 3, particularly at large scattering angles.

The differential cross sections for the excitation of the first excited state of ^{12}C at 4.44 MeV by positive pions as determined in this study are shown in Fig. 3, along with data reported previously in Refs. 4 and 6. Once again, the data taken here are in excellent agreement with the data of Ref. 6, and disagree with the data of Ref. 4 mainly in overall normalization by approximately the same factor as seen in the elastic angular distribution.

The data obtained here for positive pion excitation of the 7.65 MeV, 0_2^+ state in ^{12}C are shown in Fig. 4, along with data taken previously[4,11] for that state. The data of Lee *et al.*[11] are in excellent agreement with the data obtained in our studies. The data of Ref. 4, while in disagreement, have very large uncertainties.

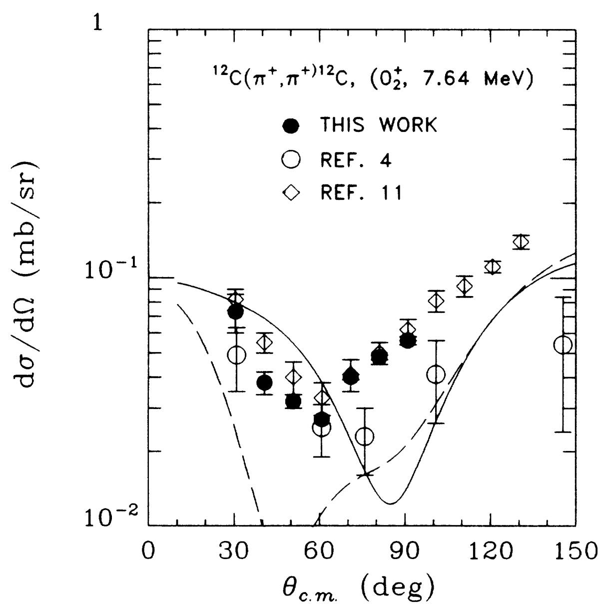

FIG. 4. Measured differential cross sections for excitation of the 7.65 MeV, 0_2^+ level of ^{12}C by 50 MeV positive pions. Data are from this work and from Refs. 4 and 11. Error bars shown include statistical error only. The solid (dashed) line indicates the results of the one-step (coupled-channels) calculation described in the text.

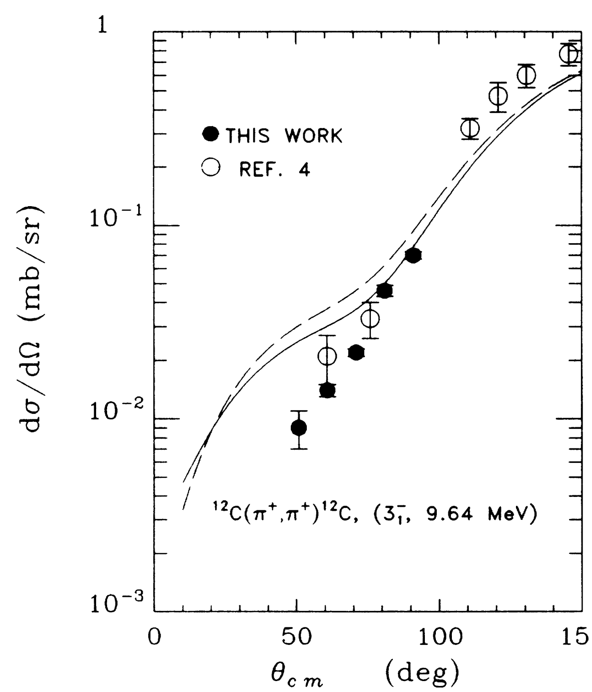

FIG. 5. Measured differential cross sections for excitation of the 9.64 MeV, 3^- level of ^{12}C by 50 MeV positive pions. Data are from this work and from Ref. 4. Error bars shown include statistical error only. The solid (dashed) line indicates the results of the one-step (coupled-channels) calculation described in the text.

Data obtained here for the excitation of the 9.64 MeV, 3^- state are displayed in Fig. 5, along with the data reported in Ref. 4. The previously reported data again appear to be in disagreement in overall normalization, but since the angular ranges in that work and this study are for the most part different, it is not unambiguously clear that the difference is significant.

As noted above, the preliminary data for the 1^+ doublet were discussed in Ref. 2. Subsequent analysis has not changed the 60 deg cross sections reported there, though slight changes in the cross sections at other angles for the 12.71 MeV data were determined. The values for those cross sections after final analysis are given in Table I along with those determined for the 15.11 MeV state. No other data for these states exist at or near 50 MeV at this time, though recently data were obtained at 80 MeV and above.[12]

IV. DISCUSSION

The results of the measurements reported in this study primarily concern states in ^{12}C which are believed to be essentially collective isoscalar excitations. However, the excitation of the 0_2^+ state is generally not explained well with the use of simple one-step collective transition densities. To confirm these observations, predictions for the cross sections of the excited states made using the method discussed in a systematic analysis[13] of data obtained for pion scattering at 50 and 65 MeV are compared with the data discussed in the preceding section. A full discussion of the procedure used in arriving at the predictions discussed below may be found in that work. Both one-step (OS) and coupled-channels (CC) calculations were performed using a modification of the MSU potential[14] by Wienands *et al.*;[15] this modified potential is denoted as MSUT in Ref. 13. The CC calculation included the effects of two-step excitation of the 0_2^+ and 3^- states through the first excited state, the 2^+ state at 4.44 MeV, with deformation lengths of $\beta_2 R = 1.24$ fm and $\beta_3 R = 0.90$ fm, as found in Refs. 13 and 16, respectively; a discussion of those deformation lengths may be found in Ref. 13. The one-step transition density to the 0_2^+ state was based on the fit to the electron scattering data by Sparrow and Gerace.[17] In the comparisons of the results of the calculations in Fig. 1–6, the OS results are indicated by solid lines, while the CC results are shown with broken lines.

For elastic scattering of both positive and negative pions, the OS and CC calculations were indistinguishable. The resulting OS calculation is compared with the data for π^+ elastic scattering from this and previous studies in Fig. 1, with a similar comparison for the π^- elastic scattering data in Fig. 2. In both figures, it is seen that the calculation gives an excellent description of the data reported in this work. The results of the OS and CC calculations are compared to the angular distributions for π^+ scattering to the 2^+, 4.44 MeV state in Fig. 3, and again it is seen that the results of the two calculations are nearly indistinguishable and both describe the data very well. While angular distributions for the excitation of the 4.44 MeV state by negative pions were not measured in this study, data from Ref. 6 for such an excitation are shown in Fig. 6 and compared with the results of the calculations. The agreement is seen to be very satisfactory for both. Shown in Fig. 5 are predictions for the excitation of the 9.64 MeV 3^- state by positive pions. Qualitatively, both calculations describe the data obtained here and in Ref. 4, though the data appear to require a steeper angular dependence than either calculation provides. Since the calculations performed used a spherical vibrational model for the nucleus, better agreement might be obtained by removing that assumption.

Overall, the strong agreement between the OS and CC calculations and the agreement of the results of the OS calculation with the data presented in Figs. 1, 2, 3, 5, and 6 provide strong confirmation that the dominant components in each of the transition matrix elements to the ground, first excited, and third excited states are those given by a simple one-step derivative collective transition density with little evidence for coupled-channels effects. This is presumably due to the small pion-nucleon cross sections found at this low beam energy.

The results obtained for the 0_2^+ state are shown in Fig. 4. As may be seen in the figure, the data for the 0_2^+ data are not well described by the OS calculations. Though Jennings and Takacsy[18] attributed this failure to the Lorentz-Lorenz-Ericson-Ericson effect, Ref. 13 argues that this lack of agreement can be interpreted as a manifestation of coupled-channels effects in the excitation of that state, particularly coupling through the first excited state. These effects are very pronounced, and proper treatment is crucial in achieving agreement between the calculation and the data obtained here. The CC calcula-

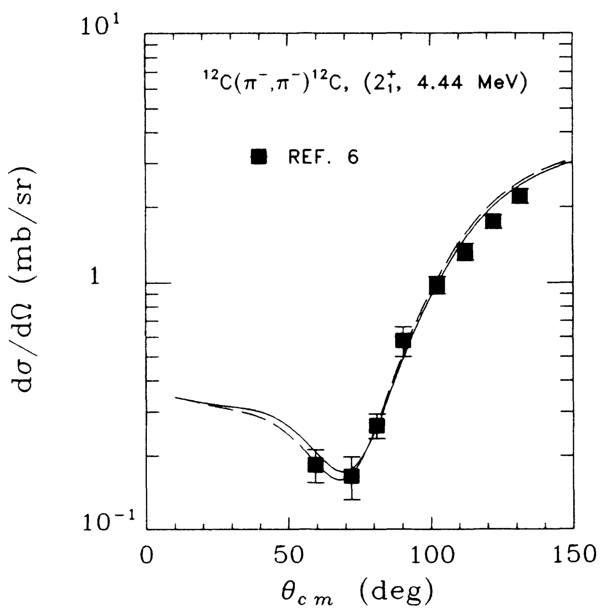

FIG. 6. Comparison of the measured differential cross sections of the excitation of the 4.44 MeV 1^+ level of ^{12}C by negative pions reported in Ref. 6 with the calculations discussed in the text. The solid (dashed) line indicates the results of the one-stem (coupled channels) calculation described in the text.

tion, though disagreeing in overall magnitude, is qualitatively better in its description of the data. A thorough discussion of the ramifications of this comparison may be found in Ref. 13.

A discussion of the results for the 1^+ doublet has been presented in Ref. 2. We note here that the average value for the ratio $R_+ = \sigma(12.71\text{ MeV})/\sigma\ (15.11\text{ MeV})$ for the entire angular distribution is 5.8 ± 0.7, which is in agreement within uncertainties with the value of 7.1 ± 1.1 reported in Ref. 2.

V. CONCLUSIONS

Data obtained here for the elastic scattering of positive and negative pions at 50 MeV from ^{12}C support the measurements of Refs. 4–6 for this important test case widely used for tests of low-energy pion optical models. Data obtained for inelastic scattering in general support the collection of measurements for those states described above by Refs. 4, 6, and 11. The results of the one-step calculation provided an excellent description of the ground, first excited, and third excited states in ^{12}C, supporting a simple collective isoscalar nature for those states. The failure to describe the 0_2^+ excitation has been addressed in Ref. 13, and is indicative of coupled-channels effects in the excitation of that state.

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