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$^{12}C(p,p')^{12}C$ reaction at 155 and 200 MeV and precritical phenomena

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Cross-section and analyzing-power data are presented for the $^{12}C(p,p')^{12}C$ reaction at bombarding energies of 155 and 200 MeV. Comparisons are made with the systematics of data from other energies. Distorted-wave impulse-approximation calculations for the "pion-like" 1^+, $T = 1$ transition to the 15.11-MeV state are successful for $q < 280$ MeV/c, but are substantially smaller than the data at larger momentum transfers. The implications of the data regarding precritical behavior associated with the pion-condensation threshold are discussed.

NUCLEAR REACTIONS $^{12}C(p,p')$, $E=155$ MeV, measured $\sigma(E,\theta)$; $E=200$ MeV, measured $\sigma(E,\theta)$, $A_y(\theta)$; $\theta=6-50°$, $\Delta\theta=2-3°$, $E_x=11-17$ MeV. DWIA analysis. Precritical phenomena near pion-condensation threshhold.

I. INTRODUCTION

The recent suggestion[1,2] that precritical phenomena associated with the pion-condensation threshhold might be observable in (p,p') reactions has focused attention on the inelastic excitation of the 1^+, $T=1$ state at 15.11 MeV in ^{12}C. This transition is said to be "pion-like" in that the transfer of a virtual pseudoscalar pion requires both spin transfer and isospin transfer ($\Delta S=\Delta T=1$). If nuclei are sufficiently close to the critical point for pion condensation, the polarization of the medium by the pion field will produce special collective effects. These should appear as enhancements of (p,p') differential cross sections for isovector unnatural-parity transitions in the range of momentum transfer q near 300–450 MeV/c.[1,2]

Existing data for the 15.11-MeV transition at $E_p=155$ MeV indeed show a minimum near $q=250$ MeV/c followed by a prominent second maximum.[3,4] Microscopic effective-interaction calculations were unable to describe this shape.[4] However, these features are absent in recent data at $E_p=122$ MeV (Ref. 5), where the large-q region of the angular distribution is characterized by a shoulder. Microscopic calculations [5] were quite successful in reproducing the absolute cross sections for $q<300$ MeV/c; above this point they fell significantly below the data.

Arguments have also been advanced, based on the large-q behavior of the (e,e') transverse form factor for the same transition, that ^{12}C might actually be close to the pion-condensation threshhold.[6-8] Analysis of elastic electron scattering data from ^{13}C seems to support this interpretation.[9] It has been noted, however,[6-8] that the (p,p') reaction may be a more sensitive probe of pion phenomena than (e,e') reactions. The reasons are related to the longitudinal $(\vec{\sigma}\cdot\vec{q})$ nature of the dominant one-pion-exchange process as opposed to the transverse $(\vec{\sigma}\times\vec{q})$ nature of virtual photon transfer, although these distinctions are blurred by surface effects for light nuclei.[6-8]

In order to obtain new and detailed data on this issue, cross sections for the $^{12}C(p,p')^{12}C$ reaction to the 15.11-MeV and nearby states have been remeasured at 155 MeV with particular attention given to the region $q>200$ MeV/c. These will be discussed and compared with additional data, including analyzing-power data, at 120 MeV (Refs. 5,10) and 200 MeV.[11] The transitions of prime concern here are those most closely related to the issue of precritical phenomena.

Comparisons of the data with microscopic distorted-wave impulse-approximation (DWIA) calculations at 155 MeV are also made in order to establish a reference point for discussions regarding the pionic polarization of the medium.[12] Calculations that incorporate these pionic effects are given in separate articles.[12,13] More complete discussions of the 120-MeV analyzing-power data and the full set of 200-MeV data will appear in forthcoming publications.

II. EXPERIMENTAL PROCEDURES

The experiments were carried out at the Indiana University Cyclotron Facility with natural graphite targets and at bombarding energies near 155 and 200 MeV. Scattered protons were detected in a helical-cathode proportional chamber[14] located in the focal plane of a magnetic spectrograph. The chamber was backed by two plastic scintillator detectors for purposes of particle identification. Data acquisition and analysis procedures were similar to those described elsewhere.[5]

A. 155 MeV data

Data were taken with an unpolarized proton beam of energy 155.05 ± 0.05 MeV. The target was 10.0 ± 0.4 mg/cm^2 thick in the region of the beam spot. Data were obtained over the angular range 7–50°. The relative scattering angle is believed to be correct to 0.04° and the angular offset is known to 0.2° or better. The angular resolution was about 1° in the scattering plane. A few spectra in the important angular region near 25° (or $q \sim 240$ MeV/c) were obtained with an angular resolution of about 0.5°.

The momentum bite of the spectrograph is rather narrow (3%) so that data could be obtained only over a limited range of excitation. Since the states of principal interest were near 15-MeV excitation, cross sections were extracted for five states between 11 and 17 MeV. These were the 1^+ states at 12.71 ($T=0$) and 15.11 ($T=1$) MeV, the 2^- states at 11.83 ($T=0$) and 16.58 ($T=1$) MeV, and the 2^+, $T=1$ state at 16.11 MeV. A representative spectrum is shown in Fig. 1.

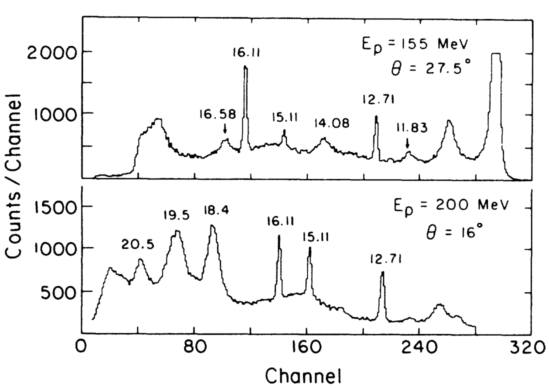

FIG. 1. Representative spectra of the $^{12}C(p,p')^{12}C$ reaction at 27.5° for 155-MeV protons and at 16° for 200-MeV protons. States are labeled with their excitation energies in MeV.

The Faraday cup was internal to the scattering chamber. It was split down the middle into electrically isolated sections and the two currents were used to stabilize the centering of the beam. It was also preceded with extra undivided absorber in order to degrade the 155-MeV protons to appropriate energies. Previous experience with this cup and with proton beams near 155 MeV has indicated that it typically loses about 4% of the beam charge, thus producing cross sections that are too large by this amount. No corrections for this possibility have been made. Although some of the data were affected by a nonuniform efficiency across the helix detector, corrections were possible. The overall uncertainty of the absolute cross-section scale is believed to be less than 10%. A more thorough description of the experimental details with a tabulation of the cross sections has been deposited with the Physics Auxiliary Publications Service.[15]

B. 200 MeV data

Data were taken with polarized proton beams of energies 200.1 and 199.8 MeV. The targets were 3.74 and 21.5 mg/cm^2 thick. Data were obtained in two separate momentum bites and spanned the entire excitation range 0–21 MeV. Data in the higher-excitation bite covered the angular range 6–50° in 2° steps. A spectrum is shown in Fig. 1.

The helix detector performed very well in this part of the experiment. An undivided external Faraday cup could be used for angles greater than 23° and this reduced room background substantially. For forward angles a split internal Faraday cup was used. It was found to have an insufficient amount of extra absorber so that about one-third of the total beam charge was lost. Nevertheless, the relative normalization of the data at forward angles appeared to be very good. Several runs at angles overlapping those of the external cup permitted the determination of the overall absolute cross-section scale to better than 10%. The relative cross sections are believed to be correct to better than 3%, in addition to the indicated errors due mainly to statistics.

Differential cross sections and analyzing powers were obtained simultaneously. The spin orientation of the proton beam and the active spectra for data acquisition were switched at about 60-sec intervals under automatic computer control, thus eliminating most of the possible time-dependent systematic errors from the analyzing-power data. The polarization of the beam was about 70% and was determined to about 2–3%. It was checked periodically with a ^{4}He polarimeter and was found to vary quite slowly with time.

III. DISCUSSION OF EXPERIMENTAL RESULTS

A. Presentation of results

Differential cross sections for the states above 12 MeV are plotted against momentum transfer $|\vec{q}|$ in Figs. 2–5. Analyzing powers for the 1^+ states are shown in Fig. 6. The present data are supplemented in Figs. 2–6 with additional data at 65 MeV,[16] 120 MeV,[5,10] and 800 MeV.[17]

The shapes of the angular distributions from the present 155-MeV experiment generally agree very well with the measurements of Buenerd *et al.*[3,4] However, the absolute cross sections in the present work are consistently larger by about a factor of 1.5. The new data are seen to be in good accord with the systematics of other energies. They are also in excellent agreement with cross sections measured for 156-MeV inelastic proton scattering from ^{12}C.[18] The reasons for the discrepancies between the data reported in Refs. 4 and 18, taken at the same laboratory, are not apparent.

Of particular importance to the issue of precritical phenomena (see Sec. IV) is the oscillatory structure in the angular distribution of the 15.11-MeV transition (Fig. 3). The 155- and 200-MeV data are nearly indistinguishable and both sets have a second maximum near $q = 320$ MeV/c, where enhancements due to precritical behavior could be expected. Data at both lower[5,16]

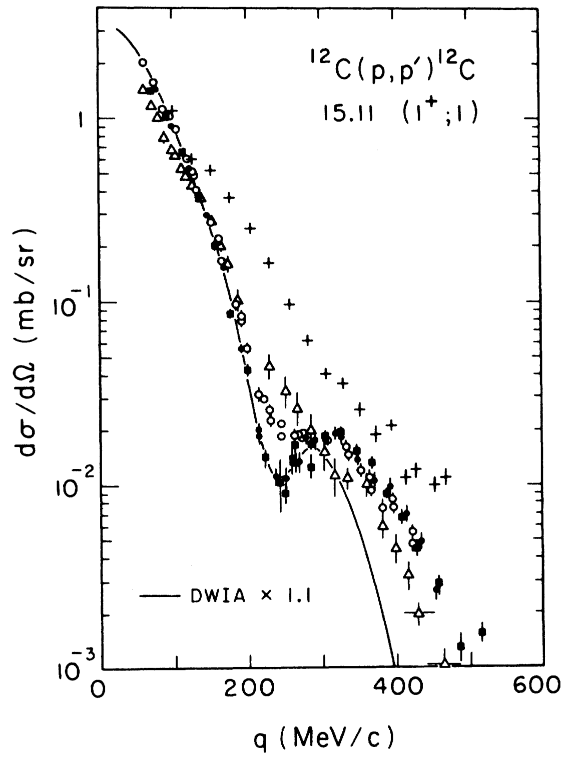

FIG. 3. Cross sections for the 15.11-MeV state in ^{12}C. See also the caption for Fig. 2. The triangles are for data at 800 MeV. The DWIA calculation has been multiplied by 1.1.

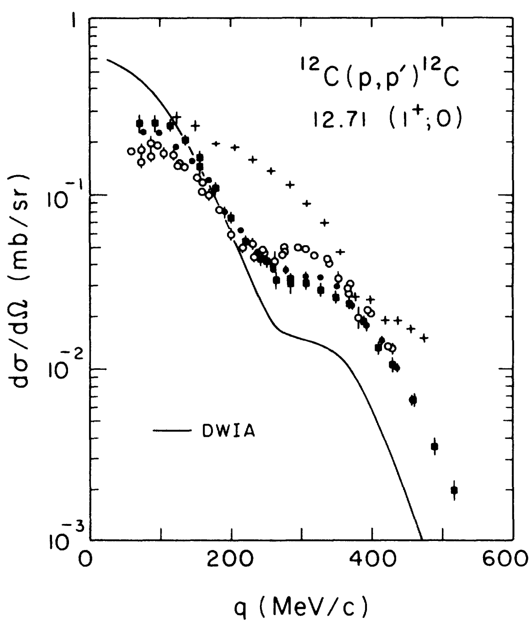

FIG. 2. Cross sections for the 12.71-MeV state in ^{12}C for proton energies 65 MeV (pluses), 122 MeV (open circles), 155 MeV (solid circles), and 200 MeV (solid squares). The curve is a DWIA calculation for 155 MeV.

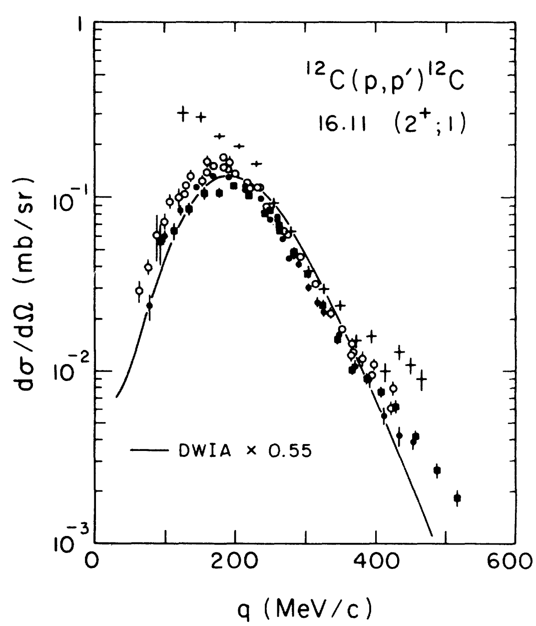

FIG. 4. Cross sections for the 16.11-MeV state in ^{12}C. See also the caption for Fig. 2. The DWIA calculation has been multiplied by 0.55.

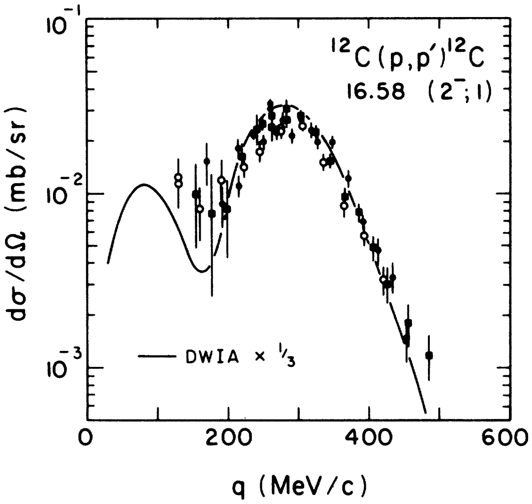

FIG. 5. Cross sections for the 16.58-MeV state in ^{12}C. See also the caption for Fig. 2. The DWIA calculation has been divided by 3.

and higher[17,19] energies do not show such a maximum. However, it is apparent in Fig. 3 that between 120 and 800 MeV the cross sections at both low q (<200 MeV/c) and high q (>300 MeV/c) are approximately independent of bombarding energy and that the 155/200-MeV data differ primarily in the formation of a minimum at intermediate momentum transfer. The important question here is the extent of possible enhancements at large q in each of the data sets.

B. Energy systematics

In recent studies[5,20] of the applicability of the impulse approximation[21] between 100–200 MeV, it was found that the effective interaction for isovector spin-transfer processes could be reasonably well described, while the interaction for isoscalar $\Delta S=1$ transitions was poorly determined and resulted in poor agreement with data. The energy systematics of the data shown in Figs. 2–6 shed additional light on the subject. Each of the isovector transitions is dominated by spin-transfer processes[5,12] and their respective momentum-transfer distributions are quite similar at all the energies above 100 MeV in spite of energy changes by factors of about 2–7. Although the cross sections for the 12.71-MeV transition between 120 and 200 MeV are also similar, the distributions become systematically steeper as the energy is increased (a trend that appears to continue to higher energies[17,19]) and the analyzing powers change sign over the entire range of momentum transfer.

Some reasons for the features can be outlined briefly. Calculations have been made in which

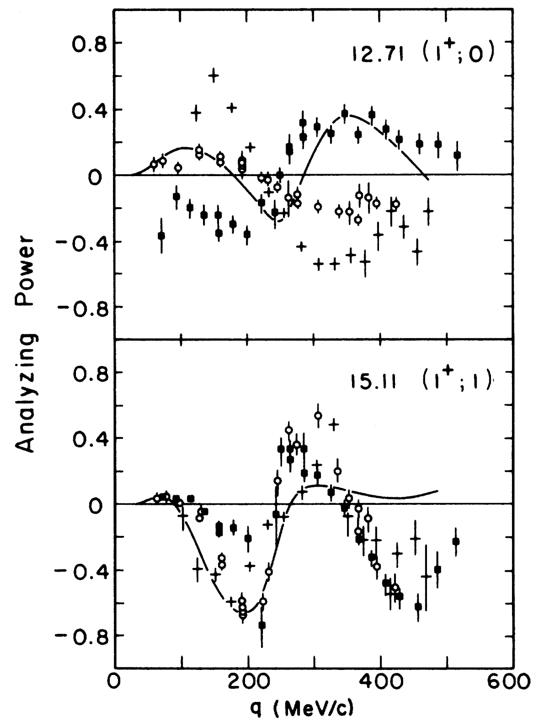

FIG. 6. Analyzing powers for the 1^+ states in ^{12}C. See also the caption for Fig. 2. The curve is a DWIA calculation for 120 MeV.

the optical potential[22] for proton scattering at one energy was used to compute the (p,p') cross sections at a different energy. It was found, for example, that the main reason for the changes in the data for the 15.11-MeV transition between 65 and 120 MeV is the decreasing importance of the refractive part of the optical potential. There is much less sensitivity between 120 and 200 MeV to further changes in this part. At the same time, it is known that the interaction for the isovector transitions does not change appreciably over the entire energy range.[20] For the 12.71-MeV transition, on the other hand, the difficulty in reproducing the data[5] (see also Sec. III D) suggests that the reaction mechanism is not completely understood. At present, the detailed validity of the impulse approximation cannot be assured for any transition.

C. Distorted-wave calculations

Calculations in the distorted-wave impulse approximation have been carried out for a bombarding energy of 155 MeV. The effective two-nucleon interaction was taken to be a coordinate-space representation of the free N-N t matrix at 140 MeV and consisted of central, spin-orbit, and tensor terms.[20] Knockon exchange was treated exactly. Transition densities were constructed from the p-shell interaction of Cohen and Kurath (CK).[23] In this regard it should be noted that since the CK wave functions are restricted to the $1p$ shell, they may be inadequate for describing reactions at high momentum transfer. Details of the calculations are described in Ref. 5; the optical potentials for 155-MeV proton scattering were interpolated from the systematics given in Ref. 22.

In principle these calculations have no free parameters. In practice some adjustments are possible. The single-particle wave functions were taken to be harmonic-oscillator functions and the size parameters, listed in Ref. 5, were adjusted to give the best fit to the (e,e') form factors. It has been found[5] that finite-well wave functions, with the same constraint, give very similar results.

The results of the calculations for the cross sections are shown in Figs. 2–5. Calculations of the analyzing powers for the 15.11-MeV transition at 120 MeV (Refs. 5,10) are shown in Fig. 6.

D. Comparisons with the data

The absolute normalizations of the calculations have been adjusted for the best fit to the data. Such adjustments may reflect the anticipated deficiencies of the CK spectroscopic amplitudes.[5,23] A factor of 1.1 is needed for the 15.11-MeV transition. This is consistent with the renormalization needed for β-decay rates.[5,23] The factor of 0.55 for the 16.11-MeV transition is smaller than the factor of 0.7 at 122 MeV.

The calculations fit the cross sections for the 15.11-MeV transition quite well out to about 280 MeV/c. Beyond this value they fall considerably below the data, as was also the case at 122 MeV.[5] The region between 200–280 MeV/c, which is the only region where the data change appreciably between 122 and 155 MeV, is well reproduced by the DWIA calculations at both energies. The calculations for the 120-MeV analyzing powers are fairly successful in reproducing the negative lobe for $q < 250$ MeV/c. However, for larger momentum transfers the curve has very little structure, in contrast with the data. Reasonable changes in the optical potentials or the transition densities were found to have very little effect on the calculations for either the cross sections or the analyzing powers in this large-q region.[12]

The shape of the 16.58-MeV angular distribution, which is also a pion-like transition, is well described by the calculations. As was the case at 122 MeV,[12] the theoretical magnitude is too large by about a factor of 3. The transition is an inhibited one that carries very little of the $M2$ sum rule. The amplitudes are dominated by the tensor interaction, including its knockon-exchange part, so that small changes in the interaction or the wave functions[24] might have a substantial effect on the normalization.

The cross sections for the isoscalar 1^+ transition to the 12.71-MeV state are poorly reproduced, although there is some improvement relative to the 122-MeV results.[5] This transition is dominated largely by the isovector part of the tensor force which contributes through the knockon-exchange terms.

IV. PRECRITICAL PHENOMENA

It is apparent from the preceding discussion that the DWIA calculations are unable to account for all of the features of the isovector unnatural-parity transitions. For the important 1^+ state at 15.11 MeV, the calculations are especially unsatisfactory for both the cross sections and the analyzing powers in the region with $q > 280$ MeV/c. For the 2^- transition, which is dominated by the tensor interaction but which has a more uncertain transition density,[12] the calculated cross sections are too large. Since the one-pion-exchange (OPE) process is an important contribution to these transitions,[5,12,25] the discrepancies could reflect a modification of the scattering amplitudes in the nuclear medium such as that associated with precritical behavior.[1,2] The evidence regarding this phenomenon is ambiguous.

In Figs. 2 and 3 one sees that the data for the two 1^+ states are distinctively different from each other. The isovector transition shows a second maximum at the momentum transfer where enhancements due to precritical behavior are expected,[1,2] while the isoscalar transition merely decreases monotonically. However, such differences need not suggest any unusual phenomena but could simply reflect the underlying differences between the isoscalar and isovector spin-transfer operators. The long-range OPE interaction is very important for the isovector 15.11-MeV transition,[5,25] but does not contribute to the direct amplitude of the isoscalar transition. The location of the second maximum is close to the maximum of the momentum-space distribution of the tensor interaction,[20] which also arises primarily from the OPE interaction.[5]

Some independent information is available regarding the high-momentum components of the tensor part of the interaction through the excitation of isovector high-spin unnatural-parity states with "stretched" configurations.[26] The high spin strongly inhibits the possible influence of precritical phenomena in light nuclei.[1,2] Analyses of

(e,e') and (p,p') data for the same transitions indicate that the tensor term used in the DWIA calculations of Sec. III has about the right strength and momentum dependence.[26] Seen in this light, the discrepancies between the DWIA calculations and the data for the 15.11-MeV transition are especially noteworthy.

Although the impulse approximation relates the effective interaction for (p,p') reactions to the free N-N scattering amplitudes,[21] the modeling of this interaction is not unique.[20] It is possible, therefore, that the discrepancies cited above are consequences of such ambiguities, particularly for the high Fourier components of the interaction. Support for this interpretation may be found in the analyzing-power data for the 15.11-MeV transition. If the sensitivity to optical distortion is not large, modifications of the OPE (or $\vec{\sigma}\cdot\vec{q}$) parts of the interaction by the nuclear medium should have only a small effect on the analyzing powers.[21] Consequently, the large discrepancies with the analyzing-power data at large q suggest that some other cause may be responsible for the discrepancies with the cross-section data. Additional discussion on this issue will be given in Ref. 13.

It has been argued elsewhere[12,13] that the proposed models for the pionic effects[1,2] appear to be inconsistent with the (p,p') data unless the response of the medium is moved substantially away from the critical point. Notably, near the critical point, the good agreement between DWIA calculations and data at 122 MeV for the 15.11-MeV transition in the region $q < 250$ MeV/c is seriously impaired. Large discrepancies between the predicted effects[8] and data at 800 MeV have also been reported.[17] Moreover, enhancements of the data above theoretical predictions often occur for channels where the pionic effects should not be present, such as for isoscalar transitions.[12]

Finally, it may be noted that conventional core-polarization processes[27] may help to remove the observed discrepancies. Since they bring in virtual processes through higher oscillator shells, they are expected to be most significant at high momentum transfers, but are less collective than precritical phenomena. It must be concluded, therefore, that the experimental data cannot presently be interpreted unambiguously with respect to the issue of precritical phenomena.

V. SUMMARY AND CONCLUSIONS

Differential cross-section and analyzing-power data have been presented for the $^{12}C(p,p')^{12}C$ reaction at energies between 120 and 200 MeV and discussed with respect to conventional DWIA calculations and the issue of precritical phenomena. When applicable, the impulse approximation considerably simplifies the interpretation of inelastic scattering reactions. Some justification for its use at bombarding energies near 200 MeV and beyond was found in the energy systematics of the data shown here. The DWIA calculations for the 155-MeV data were generally as successful as those at 122 MeV.[5,12] The least satisfactory result was for the 12.71-MeV transition, as is also true at lower energies.[5]

The study of precritical phenomena by searching for enhancements of one-pion-exchange processes is complicated by the presence of other pieces of the nuclear force (e.g., rho exchange), particularly at high momentum transfer.[7,8] The most important transition in ^{12}C for the issue is the excitation of the 1^+, $T=1$ state at 15.11 MeV. The 16.58-MeV state, also excited by a pion-like transition, is less well understood theoretically. The DWIA calculations are in very good agreement with both the cross-section and analyzing-power data for the 15.11-MeV state in the region with $q < 280$ MeV/c, but deviate substantially from the data at higher momentum transfers.

Although the differences between the calculations and experimental data offer the possibility that precritical phenomena are being observed, the pionic effects seem to be too small to be identified unambiguously. The discrepancies of such calculations with the data for other types of transitions, particularly at large momentum transfer, suggest that much remains to be understood regarding nuclear wave functions and interaction processes for (p,p') reactions.

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