Study of continuum nuclear structure of $^{12}$C via $(p, p'X)$ at intermediate energies

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The inclusive $^{12}$C$(p, p')$ and exclusive $^{12}$C$(p, p'X)$ reactions have been studied with a beam energy of 156 MeV and for $X = p$ and $\alpha$. The study focuses on the $(p, p'X)$ reaction mechanism and on the structure of $^{12}$C just above the particle-emission threshold, $14 \leq E_x \leq 28$ MeV. Cross sections were simultaneously measured for all three reactions. The exclusive data were analyzed by making multiple-peak fits of the spectra and by Legendre-polynomial fits of the angular correlations. Multiple-peak fits were also made of the inclusive spectra. The resultant cross sections were compared to theoretical calculations. An analysis of the results shows that this region of $E_x$ consists predominantly of resonant excitations, in contradiction to the findings of previous analyses.

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Studies of structure in the nuclear continuum suffer from difficulties in interpreting inelastic-scattering data. The biggest problems are that the resonance

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peaks in the cross-section spectra are often broad and poorly separated, and
the amount of nonresonant “background” cross section underlying the res-
onance peaks is difficult to determine. Observation of the continuum decay
products in coincidence with the inelastically-scattered probe can reduce these
difficulties in two ways. First, since specific decay modes are accessible to only
a subset of the excited states, the density of states seen in a particular decay
channel is lower than that seen in inclusive measurements. Second, the angu-
lar distribution of the decay products contains information about the reaction
dynamics and can be used to judge the relative importance of non-resonant vs.
resonant continuum excitation; for the latter, information about the angular
momentum of the resonance excitations can be deduced.

These features have been beautifully realized in \((e, e'X)\) and \((\alpha, \alpha'X)\) experiments, but only a few \((p, p'X)\) experiments of this type have been
reported. Coincidence studies on \(^{12}\text{C}\) - \((\alpha, \alpha'X)\), \((p, p'\alpha)\), \((e, e'p_0)\) and \((e, e'\alpha)\) - have concentrated on searches for isoscalar giant resonance
strength. Since intermediate-energy proton inelastic scattering is an important
source of our knowledge of nuclear single-particle excitations, it is useful to
examine the \((p, p'X)\) reaction to gain a better understanding of the continuum
excited by the \((p, p')\) reaction. This letter describes the first such intermediate-
energy experiment on a complex nucleus, \(^{12}\text{C}\). For states, or groups of states,
up to 20.6 MeV, these results may be compared with those from the reactions
\(^{11}\text{B}(d, nX)\), where \(X = p \) or \(\alpha \).

Data were accumulated for the reactions \(^{12}\text{C}(p, p'X)\), where \(X = p \) or \(\alpha \), at
the Indiana University Cyclotron Facility. Inclusive \((p, p')\) data were measured
simultaneously. A beam of 156 MeV protons with a DC current of 25–70 nA
was focussed on a 2.0 mg/cm\(^2\) natural-carbon target foil. Scattered protons
were detected in the IUCF K600 spectrometer at central scattering-angle
settings of 14.3, 19, and 24 deg (momentum transfers \(q_{cm}\) of 0.71, 0.93, and
1.16 fm\(^{-1}\).) An energy resolution of 140 keV FWHM was obtained, which is
dominated by the energy spread of the incident beam. The proton scattering
angle was reconstructed for each event to an accuracy of 0.1\(^\circ\). Coincident low-
energy charged particles were detected in an array of eight silicon detector
telescopes arranged to provide maximal coverage of the in-plane angular range.
The residual-nucleus mass resolution was better than 250 keV FWHM. For
\(^{12}\text{C}\) excitation energies \(14 \leq E_x \leq 28\) MeV, \(\alpha\)-particle emission to both the
ground and first-excited states of \(^{8}\text{Be}\) were observed, and proton emission was
observed to the ground state and several excited states of \(^{11}\text{B}\). Only the two
most prominent decay channels — \(\alpha_1\) (to the \(J^\pi = 2^+\) first excited state of
\(^{8}\text{Be}\)) and \(p_0\) (to the \(J^\pi = 3/2^-\) \(^{11}\text{B}\) ground state) — are discussed below.

Fig. shows representative spectra for the inclusive and exclusive reactions
at \(q = 0.7\) fm\(^{-1}\). Two observations are apparent from these spectra. The first
is that the separation of the continuum spectrum into specific decay chan-
nels, by requiring the detection of specific coincident decay products, gives the expected reduction of level density. The $p_0$ and $\alpha_1$ gated spectra are both less complex than the inclusive spectrum and have few common features. The second observation is that the coincidence spectra do not display the large nonresonant backgrounds which are normally associated with inclusive spectra. There is little evidence in the coincidence data for any background for $E_x \leq 24$ MeV. A similar observation has been made in the study of the $^{12}\text{C}(e, e'p)$ reaction [11]. These observations led us to two conjectures: 1) the $^{12}\text{C}$ continuum at low excitation energy is less complex than commonly believed and can be analyzed in terms of individual excitations, and 2) the common assumption of large nonresonant contributions to the $^{12}\text{C}(p, p')$ spectrum in the low-energy (15–25 MeV) continuum is incorrect.

The level-density reduction is best demonstrated in the $(p, p'\alpha_1)$ spectrum. One can clearly see four peaks below 24 MeV: the well-known states [12] at $E_x = 15.4$ MeV ($J^\pi = 2^+, T = 0$), 16.1 MeV ($J^\pi = 2^+, T = 1$), 18.3 MeV ($J^\pi = 2^-, T = 0$), and 21.6 MeV ($J^\pi = 2^+, T = 0$). The 16.1 MeV $T = 1$ state is known to be isospin-mixed and to decay mainly into the $\alpha_1$ channel [12].

The $(p, p'p_0)$ spectrum in the inset of Fig. 1 shows the result of a least-squares fit which assumed the presence of only these three peaks, without inclusion of any background. The inclusive spectrum, on the other hand, suggests the presence of significant nonresonant backgrounds. Large backgrounds have been included in earlier analyses of $(p, p')$ spectra in this region of excitation [13–17] (see especially [19]).

The $(p, p'\alpha_1)$ spectrum suggests a possible resolution of this background disparity. The long Lorentzian tails of the broad states at 15.4 and 21.6 MeV are clearly visible, and contribute significantly to the yield under the peak at 18.3 MeV. Failure to properly represent these broad resonances when fitting the inclusive spectrum would lead to a false identification of a large nonresonant background. This conclusion might even be drawn if these resonances were included but had incorrect widths. The studies [16,17,20], in which gaussian shapes have been used, provide examples of this effect and result in underestimation of the cross section.

One of the motivations for this experiment was to measure the angular correlation functions (ACFs) and to determine the extent of their sensitivity to the angular momentum of the resonance excitations. The ACF is simply the cross section $d^3\sigma/d\Omega_{p'}d\Omega_XdE_X$ plotted as a function of $\theta_{X}^{c.m.}$ (at fixed $\theta_{p'}$), defined in the center-of-mass frame of the recoiling $A = 12$ system. This is the natural frame for a multipole decomposition of the ACF. The angle $\theta_{X}^{c.m.} = 0$ corre-
sponds to the \((p,p')\) momentum-transfer direction \(\hat{q}\). Under the assumptions that the reaction proceeds by sequential resonance excitation and decay, and that the ACFs are independent of the azimuthal angle \(\phi_{X}^{m}\), the ACFs can be described by a Legendre-polynomial \((P_{\ell})\) series \([21]\). In regions dominated by a single resonance, this model predicts that only even-\(\ell\) terms with \(\ell_{\text{max}} \leq 2J\), where \(J\) is the total angular momentum of the resonance, are needed in the fit.

Fig. 2 displays several ACFs, for the \(p_0\) and \(\alpha_1\) channels, for \(E_x\)(12C) values centered on three of the observed resonances. The ACFs are different for the three regions, indicating a sensitivity to nuclear structure. A single resonance appears to dominate the region around 21.6 MeV in the \((p,p'\alpha_1)\) channel. Several experiments \([4,5,8]\) and references therein) assign \(J^\pi = 2^+\), \(T = 0\) to this level. The Legendre polynomial fit shown in the figure has large reduced coefficients \((b_{\ell})\) for \(P_2\) and \(P_4\), and those for \(P_1\) and \(P_3\) are an order of magnitude smaller, consistent with the \(2^+\) assignment. The other prominent peak in the \((p,p'\alpha_1)\) spectrum at \(E_x = 24.4\) MeV has an ACF similar in shape to the 21.6 MeV resonance, suggesting that it too is a \(J^\pi = 2^+, T = 0\) level.

The experiments of \([2,22]\) have demonstrated that significant quasi-free knock-out strength leads to large fore-aft asymmetries in the ACFs. No such asymmetry is seen in the two ACFs at lower \(E_x\). This further supports the conjecture that little nonresonant background exists in this region.

The channel cross section at a given \(E_x\) is given by the integral over \(d\Omega_X\) of the ACF. If the assumption of \(\phi_{X}^{m}\)-independence for the ACFs holds, this cross section is given by \(4\pi a_0\), where \(a_0\) is the coefficient of \(P_0(\theta)\) in the Legendre-polynomial fit to the data. These cross sections in turn indicate the channel composition of the continuum seen by inclusive \(^{12}\text{C}(p,p')\). The deduced angle-integrated cross sections for \(\alpha_1\) and for \(p_0\) account for respectively 24\% and 36\% of the inclusive cross section for \(17 \leq E_x \leq 24\) MeV. The corresponding \(n_0\) contribution over this region cannot be deduced from the data; only \(s\)-wave emission will be important close to the threshold at 18.72 MeV, with \(d\)-wave emission rising to 50\% of \(p_0\) at about 22.7 MeV. However, estimates can be made for specific cases. For the peak at 19.4 MeV, \(p_0\) and \(\alpha_1\) emission account for 48\% and 20\% of the inclusive cross section at low \(q\), where \(2^-\) strength is known to dominate. The shell-model \(n_0\) width for this \(2^-\) state should be enhanced by the isospin mixing observed in pion scattering \([13]\). A 5\% isospin mixing by intensity, chosen to fit the ratio of \((e,e')\) cross sections \([18]\), of the second \(2^-\) shell-model states with \(T = 0\) and \(T = 1\) raises the \(n_0\) contribution from 16\% to 40\%, which means that all the inclusive cross section is accounted for. The measured width for this state (see Table 1) is well reproduced by the calculated nucleon decay width of 468 keV \((\Gamma_{p_0}(d) = 86\text{ keV}, \Gamma_{p_0}(s) = 168\text{ keV and }\Gamma_{n_0}(s) = 214\text{ keV})\) and the measured \(\alpha_1\) width \((\sim 100\text{ keV})\).
The conjectures about the \((p,p')\) continuum, reinforced by this quantitative analysis of the \((p,p'X)\) coincidence data, necessitate a reanalysis of the inclusive data. This analysis was performed on the present \((p,p')\) data sorted into twelve spectra, each corresponding to a one-degree bin of scattering angle \(\theta_{p'}\). The twelve spectra were fit simultaneously using identical peak centroids and widths. The background contribution was represented in the fit by a lorentzian function whose centroid, width, and area varied freely at each angle. It is likely that this background represents the low-energy tails of higher-excitation resonances. Broader resonance structures are clearly evident in the \((p,p'\alpha_1)\) spectrum in Fig. 1. A more quantitative treatment of this excitation region would require response functions from a continuum shell model calculation since the broad structure near 25 MeV cannot be represented by a single lorentzian lineshape. Fig. 3 shows the results of this analysis for one of the twelve spectra. Comparable representations were obtained for all spectra using a fit that includes thirteen resonances and one background function. The peak parameters for the most prominent of these resonances are tabulated in Table 1. Also listed are the corresponding data of [15] for comparison. The errors on the peak positions and widths are small since a weighted mean has been made of the results for each of the twelve spectra for most cases. The correlations between the parameters in the fit are only partially included in these errors.

A comparison of the current inclusive analysis with previous data provides information about the effect of background overestimation on the extracted cross sections. Only the pioneering work of Buenerd et al. [15] reports cross sections over the range 14–25 MeV, although the data of Comfort et al. [16,23] extend to the lower edge of the current experiment’s energy acceptance.

Fig. 3 displays cross section results for several states along with results from the previous experiments. The data of [16] for the states at 18.3, 19.4, and 19.7 MeV are from a 200 MeV experiment; Comfort has shown previously [23] that \((p,p')\) cross sections over the range 120-200 MeV have a weak beam-energy dependence. The three datasets are in good agreement for the sharp states at 15.1 \((J^\pi = 1^+, T = 1)\) and 16.1 \((J^\pi = 2^+, T = 1)\) MeV (not shown), and with half the cross sections for the corresponding states in \((p,n)\) and \((n,p)\) reactions (25 and references therein). For both states, the current data are identical within errors to that of [23], while those of [16] agree in shape but are lower by a factor 1.6. For the remaining states, the data of [16] agree well in shape with the current results, but usually not in magnitude. Since Comfort et al. [16] made no attempt to decompose the strong peak at 19.7 MeV into \(2^-\) and \(4^-\) components, comparisons should be made for the summed strength in the 19.4-MeV and 19.7-MeV panels in Fig. 4. The figure illustrates nicely how resonance cross-section results depend strongly on the assumptions of the peak-fitting procedure, and how previous experiments have tended to underestimate the cross sections. With two exceptions, our cross sections are everywhere larger or equal to those of the other two experiments.
A comparison with the results of nucleon charge-exchange reactions corroborates the conclusions reached above. Simple isospin-symmetry arguments predict that the \((p,p')\) cross sections for a given peak should be at least half that of the corresponding peak in \((p,n)\) or \((n,p)\) reactions. For the region around 19.5 MeV at the lowest \(q\) measured, near the maximum for the \(2^-\) \(T=1\) state which dominates, the \((p,n)\) cross section of \[25\], also extracted using Lorentzian lineshapes, is equal to twice the summed cross section for the 19.4-MeV and 19.7-MeV peaks in Fig. 4. The cross sections of Comfort at 200 MeV \[14\] and Jones \[17\] at higher energies fall well short of expectations based on the charge-exchange data, the more so of other recent data \[26\] and several older data sets (see references in \[25\]). Given the similar backgrounds subtracted for the 19.4-MeV and 18.3-MeV peaks \[19\], the discrepancies seen in Fig. 4 for the 18.3-MeV peak are not surprising.

DWIA calculations were compared with the new inclusive cross sections in order to associate the resonances with levels from shell-model calculations \[18,24,25\] using interactions from \[27,28\]. Calculations were performed using the code DW86 \[29\], the NN effective interaction of \[30\], the shell-model one-body density-matrix elements with harmonic oscillator wave functions \((b_0 = 1.669 \text{ fm or } b_{rel} = 1.743 \text{ fm \[24,25\]}) and the \(^{12}\text{C}\) optical potential of \[31\]. The results of the calculations are displayed in Fig. 4; any normalization factors by which the curves are scaled are shown in parentheses. The normalization factors are also listed in Table 1. When a specific transition density is identified with a peak, the subscript indicates which of the several states for each \((J^\pi,T)\) was used. The agreement in most cases is good, and the normalization factors have reasonable sizes in the sense that quenching of the shell-model transition densities is expected for all the cases listed in Table 1 \[24,25\].

Two curves for \(J^\pi = 4^-\) excitation are shown with the data for the state at 19.7 MeV. Individually, the normalization factors for these curves are twice as large as those characteristic of the other states but the normalization factor of 0.55 for the sum of the \(T=0\) and \(T=1\) \(4^-\) states is consistent with that required for the \(T=1\) state in the \((p,n)\) reaction \[25\]. A strongly isospin-mixed \(J^\pi = 4^-\) doublet, with peaks at 19.25 and 19.65 MeV, was observed in a \(\pi^+ / \pi^-\) inelastic-scattering experiment \[13\]. No peak at 19.25 MeV was observed in the current experiment. Its absence suggests that the isospin mixing results in all of the \((p,p')\) strength going to the 19.7 MeV state. However, DWIA calculations for a more proton-like lower state do not support this hypothesis. The fact that the \(4^-_2\) and \(4^-_3\) \(T=0\) shell-model states are closely spaced and share the \(L = 3\) \(S = 1\) excitation strength may complicate the isospin mixing calculation.

The level at 20.6 MeV has been one of the most difficult states to explain in \(^{12}\text{C}\) (see \[14,16,18,25\] and references therein.) States with \(J^\pi = 3^+\) and \(3^-\), both with \(T = 1\), are certainly present \[12\] but the \((p,n)\) results of \[25\]...
suggest that T=1 states account for only 25% of the cross section shown in Fig. 4. Neither of these states can account for the large $^{11}$B($d$, $n$) cross section for the 20.6-MeV peak [14]. However, the $J^\pi = 3_1^-$, T = 0 state included in Fig. 4 is predicted to lie in the energy region and has a large ground-state spectroscopic factor of 0.56 (mainly $d_{3/2}$). None of these calculations reproduce the data alone, although the sum of the three has at least the correct order of magnitude. Recent ($\vec{d}$, $\vec{d}$') experiments [32] indicate an isoscalar $J^\pi = 1^+$ resonance at 20.5 MeV, but none of the unassigned $1^+$, T = 0 wavefunctions of [27] have significant ($p$, $p'$) strength. The nature of the states in this region remains unclear.

Evidence was presented above which was consistent with a $J^\pi = 2^+$ T = 0 assignment for the 21.6 MeV state. For this state, as well as for the 15.4-MeV $2^+$ T=0 state, neither the large inclusive cross section nor the large positive analysing power (not shown) over the $q$ range measured can be reproduced by a $0\hbar\omega$ [27] shell-model wavefunction. Essentially all the $0\hbar\omega$ E2 strength is contained in one state, which corresponds to the 4.44-MeV level. A modest fraction of the $2\hbar\omega$ giant-quadrupole strength built on the $0\hbar\omega$ ground state is required to explain the cross sections and analysing powers - roughly 16% in the case of the of the 21.6 MeV state.

In summary, a $^{12}$C($p$, $p'$X) experiment has been performed at a beam energy of 156 MeV. Analysis of the coincidence data indicates that the nonresonant component of the low-energy (14 ≤ $E_x$ < 24 MeV) continuum is much smaller than commonly accepted. The measured angular correlation functions follow the pattern expected for a resonance excitation-decay process, which also points to relatively small nonresonant contributions. The ACFs display sensitivity to nuclear structure.

The inclusive ($p$, $p'$) data, measured simultaneously in this experiment, were analyzed using more physically motivated peak shapes than used in earlier analyses. This reanalysis produces cross sections that are, in general, much larger than deduced from previous $^{12}$C($p$, $p'$) experiments. Theoretical calculations agree quite well with the present data and require renormalization factors which are qualitatively in line with the quenching expected and to those needed for the corresponding T=1 states excited in recent charge-exchange reactions. At the low momentum transfers probed in the present experiment, we have deduced that the low-energy (21 < $E_x$ < 24 MeV) continuum of $^{12}$C is dominated by $1^-$, T=1 resonances which decay primarily by single-nucleon emission, and $2^+$, T=0 resonances which decay primarily by alpha emission. There is little, if any, non-resonant background in the spectrum. This is a qualitatively different view of the continuum than has been presented in earlier works. Instead of viewing the continuum as giant resonances sitting atop a sizable non-resonant background, the present analysis suggests that most of the continuum cross section is due to resonance excitation, with clear peak
structures melting into the familiar smooth continuum as the width of the overlapping resonances increases with increasing excitation energy.

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Fig. 1. Representative $^{12}\text{C}(p,p')$ and $^{12}\text{C}(p,p'X)$ spectra (counts vs. excitation energy $E_x$) at proton scattering angle $\theta_{p'} = 14.3^\circ$. The coincidence data shown are for a correlation angle $\theta_X^{\text{cm}} = 0^\circ$ (along $\vec{q}$).

Fig. 2. Representative ACFs for the $p_0$ and $\alpha_1$ decay channels. The solid curves are Legendre-polynomial fits. In all cases $\ell_{\text{max}} \leq 4$. Coefficients of polynomials with larger $\ell$ values are not sufficiently constrained by the data’s $25^\circ$ spacing in $\theta_X^{\text{cm}}$. The first two sets of ACFs correspond to the $J^\pi = 2^-, T = 0$ (18.3 MeV), $J^\pi = 2^+, T = 0$ (21.8 MeV) resonances. Reduced coefficients for the Legendre-polynomial fit are shown for the 21.8 MeV $(p,p'\alpha)$ ACF, with the estimated errors in parentheses. The third set is centered about a resonance at 24.4 MeV which is only seen in the $(p,p'\alpha_1)$ channel.

Fig. 3. Multiple-peak fit of the inclusive spectrum for $\theta_{p'} = 14.3^\circ$ (lab). The area under the curve labelled B is the background contribution.

Fig. 4. Differential cross sections for selected transitions. The curves are DWIA calculations discussed in the text. For the 15.1-MeV $1^+$ state, the curve labelled FIT uses a $p$-shell transition density optimized to fit the measured $(e,e')$ form factor [24]. The error bars are smaller than the symbols for some data points. Filled circles: present experiment; diamonds: Comfort et al. [16,23]; squares: Buenerd et al. [15].
Table 1
Comparison of current and previous continuum $^{12}$C$(p,p')$ results (see text.) The subscripts on the spin $J$ indicate the specific wavefunction of $^{27,28}$ which gave the best fit to the data in the DWIA calculation. Quantum numbers without a subscripted $J$ are suggested by systematics or determined in other experiments $^{12}$. “DWIA Scaling” refers to the best-fit multiplicative factor applied to DWIA calculations.

| Current Experiment | Ref. $^{15}$ |
|--------------------|-------------|
| $E_x$ (MeV ± keV) | $\Gamma$ (keV) | $J^\pi$ ($T$) | DWIA | Scaling | $E_x$ (MeV ± keV) | $\Gamma$ (keV) |
| 15.38 ± 30 | 2800 ± 170 | $2^+$ (0) | — | — | 15.3 ± 200 | 2000 ± 200 |
| 16.62 ± 10 | 280 ± 30 | $2^-$ (1) | — | — | — | — |
| 18.292 ± 4 | 486 ± 10 | $2^-$ (0) | 0.80 | 18.35 ± 50 | 400 ± 100 |
| 19.394 ± 10 | 520 ± 30 | $2^-$ (1) | 0.38 | 19.4 ± 50 | 530 ± 100 |
| 19.671 ± 6 | 490 ± 20 | $4^-$ (0 + 1) | 0.58 | 19.6 ± 50 | 500 ± 100 |
| 20.584 ± 5 | 440 ± 11 | — | — | 20.6 ± 80 | 450 ± 150 |
| 21.61 ± 20 | 1450 ± 90 | $2^+$ (0) | — | 21.3 ± 250 | 950 ± 300 |
| 21.99 ± 20 | 550 ± 90 | $1^-$ (1) | 0.78 | 21.95 ± 150 | 800 ± 100 |
| 22.72 ± 30 | 1200 ± 130 | $1^-$ (1) | 0.60 | 22.6 ± 150 | 900 ± 100 |
| 23.57 ± 20 | 238 ± 34 | $1^-$ (1) | — | 23.50 | 230 |
| 24.04 ± 18 | 659 ± 48 | $1^-$ (1) | — | 23.92 | 400 |
| 24.38 ± 10 | 671 ± 49 | $2^+$ (0) | — | — | — |
$^{12}\text{C}(p,p'p_0)$

$^{12}\text{C}(p,p'\alpha_1)$

$\phi_{\text{c.m.}} = 0$

$\phi_{\text{c.m.}} = \pi$

$18.3\text{ MeV}$

$b_1: 0.196 (083)$

$b_2: 0.918 (121)$

$b_3: 0.039 (118)$

$b_4: 2.203 (173)$

$21.8\text{ MeV}$

$24.4\text{ MeV}$
