Proton-induced inclusive pion production from light nuclei in the region of the Δ_{1232} resonance

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(Received 2 December 1987)

Proton-induced pion production to the continuum was investigated via the reactions ^{13}C(p,π^-)X, ^{13}C(p,π^+)X, and ^{16}O($\vec{p}$,π^+)X at bombarding proton energies of 250, 354, and 489 MeV, in the kinematic region where the pion has nearly its maximum allowable kinetic energy. Results from the ^{16}O($\vec{p}$,π^+)X reaction indicate that at small missing momenta the analyzing powers can be adequately described by a quasi-free $\vec{p}p \rightarrow d\pi^+$ process, but as the missing momentum is increased this description becomes less accurate. The energy dependence of the cross section for the inclusive (p,π^+) reactions is very similar to that of previously published exclusive (p,π^+) data from the same target nuclei. The double differential cross sections for the π^- data, however, exhibit an energy dependence different from that of the exclusive (p,π^-) reaction.

I. INTRODUCTION

Exclusive A(p,π)A + 1 reactions, in which the recoil nucleus is left in its ground state, or in a specific excited state, have been investigated for many years both experimentally and theoretically.[1–4] The study of these reactions has been motivated by the hope of extracting information about the high momentum components of nuclear wave functions once the interplay of reaction mechanism and nuclear structure effects has been understood. The dynamics of the reaction process (eg., Δ production and propagation in the nuclear medium) are also of intrinsic interest. Despite the effort of the last 15 years, there is still considerable controversy as to the identification of the dominant processes in the exclusive (p,π) reaction mechanism. A simplifying feature of inclusive A(p,π)X reactions is that they do not require the residual nucleus to remain intact. Consequently, these reactions should, in principle, be less sensitive to nuclear structure effects, thus providing a clearer picture of the reaction mechanism. The combination of inclusive and exclusive pion production studies may help in reaching the eventual goal of understanding the effects of nuclear structure in the (p,π) reaction.

Unlike the exclusive process, there are few results available on inclusive pion production at intermediate energies. Two comprehensive sets of information on inclusive π^+ and π^- production, from a wide range of target nuclei at bombarding energies of 585 (Ref. 5) and 730 (Ref. 6) MeV, were motivated by the need for data for the optimal design of pion beam lines at the meson factories. Recent inclusive measurements have also been performed on ^{12}C, ^{89}Y, and ^{nat}Pb at bombarding energies of 180 and 201 MeV,[7] on ^{12}C and ^{238}U at 330, 400, and 500 MeV,[8] and on ^{12}C at 400 and 450 MeV.[9] In each of these references, however, the double differential cross section ($d^2\sigma/d\Omega\, dT_\pi$) results have been presented as a function of the pion lab energy for a set of constant pion lab angles. This makes it inconvenient to relate the results of these studies to the exclusive pion production case. The reason for this is that the exclusive reaction $d\sigma/d\Omega$ results are presented for the population of a particular nuclear final state versus pion scattering angle, and hence, the pion lab energy varies within a data set as the pion scattering angle changes.

More recently, Korkmaz *et al.*[10] and Throwe *et al.*[11] have published some inclusive ($\vec{p}$,π) analyzing powers taken during two exclusive ($\vec{p}$,π) experiments. These inclusive data were presented for a 1 MeV wide slice of pion continuum centered about some specified equivalent excitation energy as if there was a two body final state in which the recoil nucleus remained intact. By comparing data at a constant excitation energy, the internal total energy of the recoil nucleus is fixed, and a comparison of these data to the exclusive pion production data may help elucidate the nature of the reaction mechanism.

II. THE EXPERIMENT

Proton beam energies of 250, 354, and 489 MeV were chosen for this experiment because in this region the effects of the Δ_{1232} resonance should be the most pronounced. A simple calculation shows that the peak of the Δ_{1232} resonance should occur at $T_p = 315$ MeV, if the beam proton and ^{16}O target combine to form an intermediate mass 17 nucleus state in which one nucleon is excited to a mass of 1232 MeV. The inclusive data presented here were taken during investigations of exclusive pion production recently completed at TRIUMF.[12,13] The experiments were performed with the medium resolution spectrometer (MRS) (Ref. 14) at TRIUMF using a polarized proton beam for the $^{16}O(\vec{p},\pi^+)X$ experiment, and an unpolarized proton beam for the $^{13}C(p,\pi^{\pm})X$ experiment. Details of the experimental procedure have already been described in Refs. 12 and 13. In Fig. 1 are three representative spectra taken at $T_p = 250$ MeV, in Fig. 2 are three spectra at 354 MeV, and in Fig. 3 are three spectra taken at 489 MeV.

III. RESULTS

Each of the (p,π^+) spectra in Figs. 1–3 are characterized by a large number of populated states superimposed upon an inclusive pion production continuum. This continuum starts near 8 MeV excitation and increases linearly in strength with excitation energy. The $p + A \rightarrow A_{g.s.} + n + \pi^+$ reaction has a threshold of 8.18 MeV excitation in the $^{13}C(p,\pi^+)$ reaction, and has a threshold of 4.15 MeV excitation in the $^{16}O(p,\pi^+)$ reaction. On the other hand, the $p + A \rightarrow (A-1)_{g.s.} + d + \pi^+$ reaction does not contribute until 23.49 MeV excitation in the $^{13}C(p,\pi^+)$ reaction, and does not contribute until 14.05 MeV excitation in the $^{16}O(p,\pi^+)$ reaction. Since the slope of the continuum does not increase at the onset of (p,π^+d) contributions in the $^{13}C(p,\pi^+)^{14}C$ spectrum (23.49 MeV) in Figs. 2 and 3, this must indicate that the $(A\text{-}1) + d + \pi^+$ final state does not contribute significantly to the continuum at this range of pion momenta.

In Figs. 2 and 3 only a weakly populated cluster of

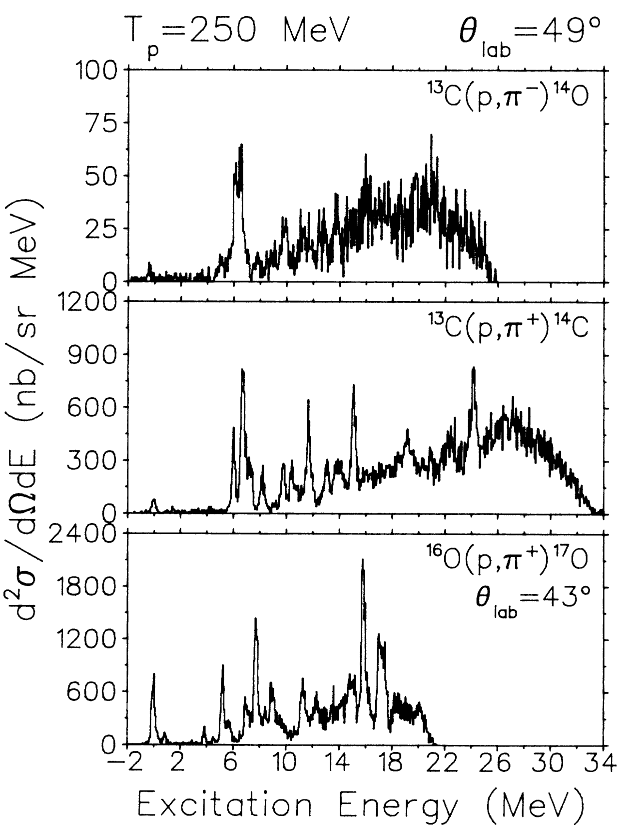

FIG. 1. Three pion spectra taken at an incident proton energy of 250 MeV. The pion spectra are plotted vs excitation energy for the two body reactions listed. The $^{13}C(p,\pi^+)^{14}C$ spectrum is a composite of three spectra obtained with different settings of the MRS dipole magnet, and the other spectra are composites of spectra obtained with two different settings of the MRS dipole magnet.

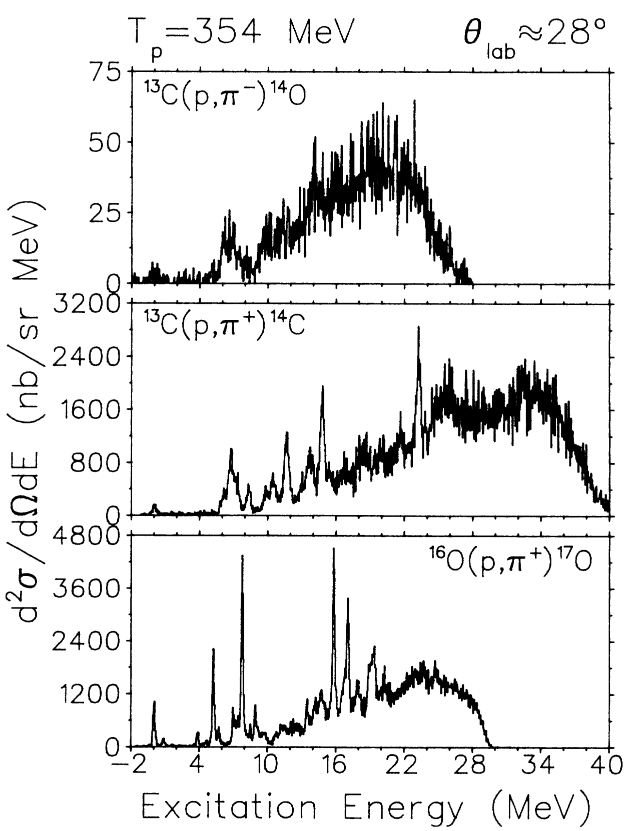

FIG. 2. Three pion spectra taken at an incident proton energy of 354 MeV. The MRS spectrometer angle was 28° for the two ^{13}C spectra and was 30° for the ^{16}O spectrum. The $^{13}C(p,\pi^+)^{14}C$ spectrum is a composite of two spectra obtained with different settings of the MRS dipole magnet. The broad states from 17 to 22 MeV excitation in the $^{16}O(p,\pi^+)^{17}O$ spectrum are from the $^7Li(p,\pi^+)^8Li$ reaction due to the LiOH target.

states near 6 MeV excitation stands out in the 354 and 489 MeV (p,π^-) spectra. These (p,π^-) spectra are strikingly different from those obtained at 200 MeV in Ref. 10 and at 250 MeV in Fig. 1. At these lower energies the ^{13}C(p,π^-)^{14}O reaction exhibits a striking selectivity for the population of a cluster of discrete states near 6 MeV excitation. While the ratio of π^+/π^- cross sections leading to discrete states at 489 MeV is approximately 60, this ratio for the continuum is only 30. A similar suppression can also be seen at 354 MeV in Fig. 2. This compares with a π^+/π^- ratio of approximately 10 for both the inclusive and exclusive reactions at 250 MeV in Fig. 1. Thus, at 354 and 489 MeV the (p,π^-) reaction leading to discrete states is suppressed in relation to the (p,π^-) reaction leading to the continuum. This may result from Pauli blocking effects that are more restrictive in exclusive π^- production, due to the identity of the final two nucleons in the elementary pn$\rightarrow$ppπ^- process, than in exclusive π^- production, which involves the elementary pp$\rightarrow$pnπ^+ process. This argument does not explain, however, why the π^+/π^- ratio is approximately the same for both the inclusive and exclusive reactions at 200 and 250 MeV.

Note in Fig. 3 that there is a broad structure of about 4 MeV width in the ^{13}C(p,π^-) spectrum near 23 MeV excitation. This structure is prominent in a previously published spectrum obtained at 200 MeV.[10] There are similar structures near 25 MeV excitation energy in the ^{13}C(p,π^+) spectra shown in Figs. 2 and 3. A broad structure has also been seen previously at 19 MeV excitation in the ^{9}Be(p,π^-)^{10}C reaction.[15] The nature of these broad structures at high excitation, as well as the reason for the narrowness of the 23.2 MeV state strongly excited in the ^{13}C(p,π^+)^{14}C* reaction, are not known.

A. Energy dependence of the double differential cross sections

Figure 4 shows the energy dependence of the double differential cross sections of the continuum, at an equivalent excitation energy of 19 MeV, for three different reactions at a constant missing four momentum squared of $t=0.50$ GeV$^2/c^2$. The choice of the relativistically invariant Mandelstam variables s and t is dictated by the fact that the unpolarized scattering amplitude is only a function of s and t, as far as the dynamical

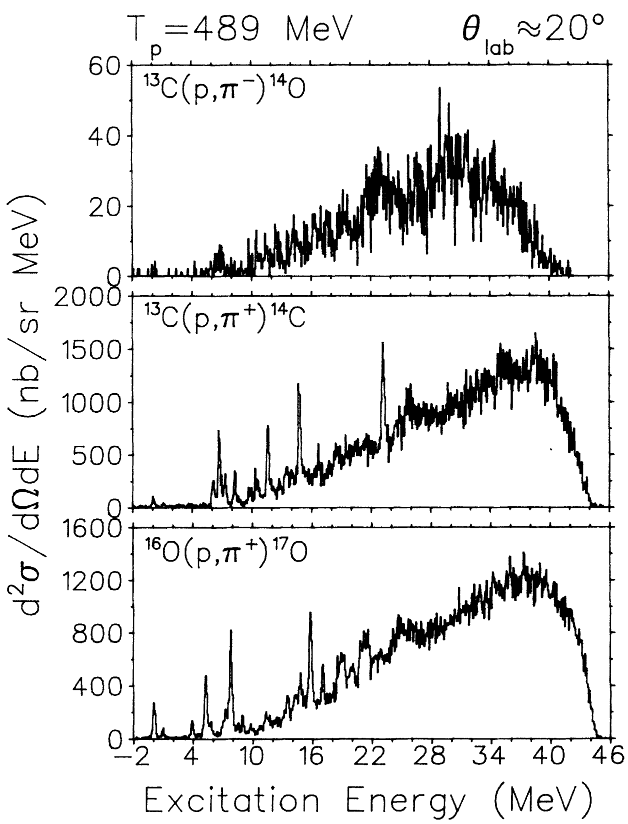

FIG. 3. Three pion spectra taken at an incident proton energy of 489 MeV. The MRS spectrometer angle was 20° for the two ^{13}C spectra and was 23° for the ^{16}O spectrum. The broad states near 20, 22, and 25 MeV excitation in the ^{16}O(p,π^+)^{17}O spectrum are from the ^{7}Li(p,π^+)^{8}Li reaction due to the LiOH target.

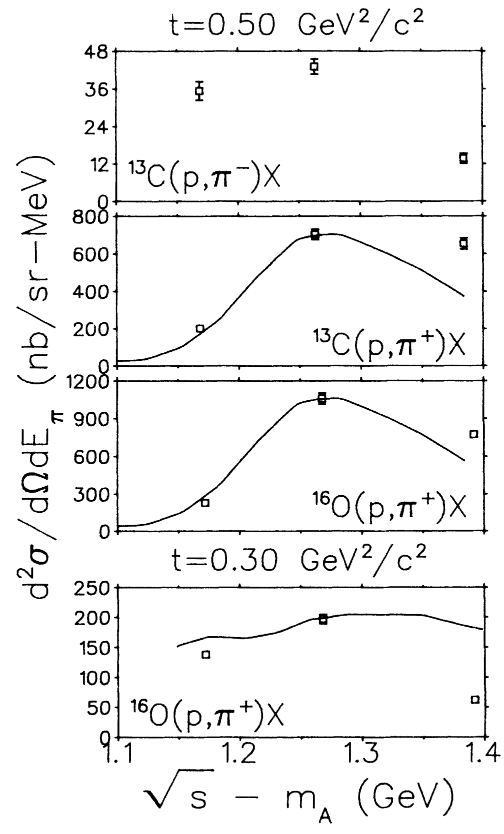

FIG. 4. Energy dependence of the double differential cross section for a 1 MeV wide slice of pion continuum at 19 MeV excitation for three different reactions at a constant missing four momentum of $t=0.50$ GeV$^2/c^2$, and for one reaction at a missing four momentum of $t=0.30$ GeV$^2/c^2$. The solid line is the differential cross section for the two-body pp$\rightarrow$dπ^+ reaction at equivalent missing four momentum squared after transformation to nuclear kinematics and solid angle and normalized to the 354 MeV data point.

variables are concerned. The quantity $\sqrt{s}-m_A$ is a measure of the excitation energy available for one nucleon; the invariant mass of the Δ_{1232} resonance occurs at an $\sqrt{s}-m_A$ value of 1.232 GeV.

Also shown in Fig. 4, by the solid line, is the differential cross section of the two-body $pp \rightarrow d\pi^+$ reaction normalized to the 354 MeV data point, transformed to nuclear kinematics via the method of Korkmaz *et al.*,[10] and referred to the nucleon-nucleus frame. The transformation assumes that the nucleus emits a proton directly into the incident beam. Using the constraint that the $pp \rightarrow d\pi^+$ reaction between this emitted proton and the beam proton must create a pion with the same momentum and scattering angle (in the p-A lab frame) as that produced by the $A(p,\pi^+)A+1$ reaction, conservation of momentum conditions are used to solve for the energy of the proton emitted by the nucleus. The residual nucleus is off-shell. The incident proton energy and pion lab angle are then transformed from the p-A lab frame to the p-p lab frame so that the $pp \rightarrow d\pi^+$ differential cross section may be calculated from published fits to the data. Finally, the $pp \rightarrow d\pi^+$ differential cross section is corrected for the nuclear body Jacobian instead of the p-p frame Jacobian.

At energies close to pion production threshold, the assumption that the target nucleus emits a proton directly into the incident beam is clearly valid. This is because the reaction must utilize the Fermi momentum of the nuclear proton if it is to proceed at energies below that of the free $NN \rightarrow NN\pi^+$ threshold. At incident proton energies above this threshold (approximately 280 MeV), it is no longer necessary for the reaction to utilize the Fermi momentum of the nuclear protons. Nevertheless, the assumption that the nucleus emits a proton directly into the incident beam maximizes the p-p center of mass energy, and as a result, this configuration is expected to still play an important role above the free $NN \rightarrow NN\pi^+$ threshold, although all other configurations in which the beam proton and the nuclear proton do not collide head-on will become increasingly important. For the $^{16}O(p,\pi^+)$ reaction to 23 MeV excitation in the continuum, this transformation requires the nuclear proton to have a momentum of 203 ± 2 MeV/c at $t=0.5$ GeV$^2/c^2$ for all incident proton energies from 200 to 489 MeV. At $t=0.4$ GeV$^2/c^2$ the transformation requires a nuclear proton momentum of 238 ± 4 MeV/c, and for $t=0.2$ GeV$^2/c^2$ the transformation requires a nuclear proton momentum of 297 ± 9 MeV/c for incident proton energies between 250 and 489 MeV. Thus, as the momentum transfer is increased, it becomes less likely to find a proton in the nucleus with the required momentum, and the model loses validity. As such, the model is only meant to describe the qualitative trends of the nuclear (p,π) data, and not the details.

In Fig. 4 the $t=0.50$ GeV$^2/c^2$ double differential cross section of the inclusive (p,π^+) reactions increase with energy up to the Δ_{1232} invariant mass at a rate that is identical to that of the $pp \rightarrow d\pi^+$ reaction. Above this invariant mass, however, the $^{13}C(p,\pi^+)X$ and $^{16}O(p,\pi^+)X$ reactions do not fall as fast with energy as the elementary $pp \rightarrow d\pi^+$ process. This behavior is expected since the cross section of the $pp \rightarrow pn\pi^+$ reaction is known to level off at energies well above the Δ_{1232} resonance.[16]

Plotted at the bottom of Fig. 4 is the $t=0.30$ GeV$^2/c^2$ energy dependence of the $^{16}O(p,\pi^+)X$ reaction at an equivalent excitation energy of 19 MeV, as well as that of the $pp \rightarrow d\pi^+$ reaction after transformation to the nucleon-nucleus frame. The choice of $t=0.30$ GeV$^2/c^2$ emphasizes the energy dependence at larger pion scattering angles than the 0.50 GeV$^2/c^2$ data referred to above. As shown in Fig. 4, the energy dependence of the $^{16}O(p,\pi^+)X$ reaction is much flatter between 250 and 354 MeV than it was at $t=0.5$ GeV$^2/c^2$. However, the $pp \rightarrow d\pi^+$ process qualitatively describes this flatter energy dependence, just as it does in the exclusive case.[13] The very small double differential cross section that the inclusive reaction exhibits at 489 MeV ($\sqrt{s}-m_A=1.4$ GeV) is not understood.

Plotted at the top of Fig. 4 is the energy dependence of the $^{13}C(p,\pi^-)X$ reaction at $t=0.50$ GeV$^2/c^2$. The energy dependence of this reaction is different from that observed at $t=0.50$ GeV$^2/c^2$ for either the inclusive (p,π^+) or the $pp \rightarrow d\pi^+$ reactions. This difference may indicate that the Δ_{1232} resonance plays different roles in π^+ and π^- production. It should be pointed out, however, that the maximum differential cross section of the exclusive $^{13}C(p,\pi^-)^{14}O$ reaction occurs in the 200–250 MeV region,[12] whereas the maximum double differential cross section shown for the $^{13}C(p,\pi^-)X$ reaction in Fig. 4 occurs near 350 MeV. Thus, the energy dependence at a constant t value is different depending on whether the residual nucleus is left in its ground state, an excited state, or is left unbound. Since holding t constant should minimize nuclear structure effects, it is not clear what is the dynamical effect causing the different (p,π^-) energy dependences. In contrast, the (p,π^+) energy dependences for the inclusive and exclusive reactions are very similar.

B. Energy dependence of the angle integrated differential cross sections

Figure 5 shows the energy dependence of the angle integrated differential cross section of the $^{16}O(p,\pi^+)X$ reaction for two, 1 MeV wide slices of pion energy corresponding to excitation energies of 19 and 21 MeV. The energy dependence shown here is very similar to that of the total cross section for exclusive $^{16}O(p,\pi^+)^{17}O$ reactions leading to discrete states.[13] This behavior is expected since these data were obtained at the maximum momentum end of the pion's kinematical range. Thus, the neutron and recoil nucleus are restricted to small values of momentum, and the inclusive reaction is forced to mimic the large momentum transfer seen in exclusive (p,π) reactions. If one took continuum data such that both the pion and the neutron could share the increase in available energy as the incident proton energy is increased (perhaps by holding the difference between the neutron and pion energy constant), then the maximum cross section might occur closer to the Δ_{1232} invariant mass ($\sqrt{s}-m_A=1.232$ GeV) and not near 250 MeV. A $^{16}O(p,\pi^+n)^{16}O$ coincidence experiment in which both the π^+ and the neutron are observed, and their energies measured, would have to be performed to confirm this hypothesis.

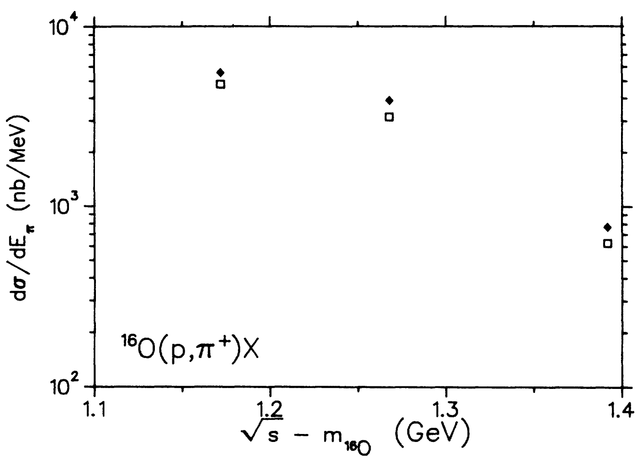

FIG. 5. Angle integrated differential cross section of the $^{16}O(p,\pi^+)X$ continuum vs center of mass energy for two, 1 MeV slices of continuum. Plotting symbols indicate the equivalent excitation energy as follows: □ 19 MeV; ♦ 21 MeV.

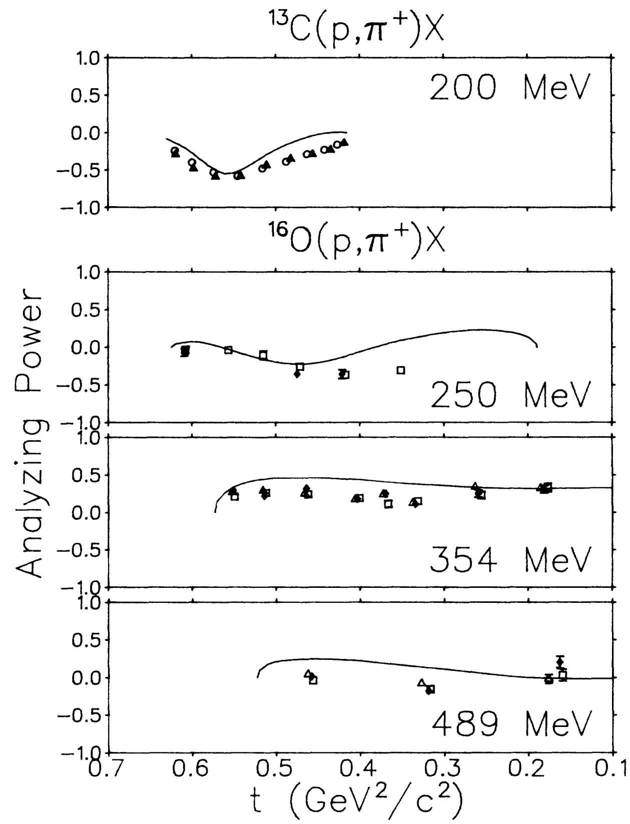

FIG. 6. Analyzing power vs missing four momentum squared (t) at four incident proton energies compared to the $\vec{p}p \rightarrow d\pi^+$ reaction (solid line). The 200 MeV data is from Ref. 10. For the 200 MeV data, the circles are for 20 MeV excitation and the solid triangles are for 22 MeV excitation. For the higher energy data, the open squares are for 19 MeV excitation, the solid diamonds are for 21 MeV excitation, and the open triangles are for 23 MeV excitation.

C. Analyzing powers of the continuum

Figure 6 shows the analyzing power of the $^{16}O(\vec{p},\pi^+)X$ reaction plotted versus the missing four momentum squared at incident proton energies of 250, 354, and 489 MeV. Also shown for comparison are the previously published $^{13}C(\vec{p},\pi^+)X$ analyzing powers[10] at 200 MeV, as well as the $\vec{p}p \rightarrow d\pi^+$ analyzing powers transformed to the nucleon-nucleus kinematical frame (solid lines). At each incident energy, analyzing powers for several 1 MeV wide slices of the continuum near 20 MeV excitation energy are plotted. The analyzing powers shown do not change very much within the range of excitation energies plotted. The analyzing powers are best described by the $\vec{p}p \rightarrow d\pi^+$ curve at low missing momenta squared ($t > 0.45$ GeV^2/c^2) and this description becomes less accurate as the square of the missing momentum is increased (smaller t). However, the $\vec{p}p \rightarrow d\pi^+$ analyzing power still provides a qualitative description of the 489 MeV data.

Korkmaz *et al.*[10] interpreted the exceptionally good description of the 200 MeV forward angle analyzing powers by the $\vec{p}p \rightarrow d\pi^+$ curve as evidence that π^+ production within the nucleus can be viewed as a quasifree two-body process. Falk *et al.*[9] also noted that the 400 and 450 MeV forward angle $^{12}C(\vec{p},\pi^+)X$ analyzing powers are very close to what would be observed via a $\vec{p}p \rightarrow d\pi^+$ quasifree process. As the square of the missing momentum is increased, nuclear distortions presumably play a larger role and the quasifree model is no longer relevant. Also, it is not unreasonable to expect that more nucleons may become involved in the momentum sharing process at the higher momentum transfers. This hypothesis may be supported in fact by measurements of the inverse reaction, pion absorption on nuclei leading to multinucleon emission.

IV. SUMMARY AND CONCLUSIONS

In summary, we have studied proton induced pion production to the continuum via the reactions $^{13}C(p,\pi^-)X$, $^{13}C(p,\pi^+)X$, and $^{16}O(\vec{p},\pi^+)X$ in a kinematic region where the pion has nearly its maximum allowable kinetic energy. Bombarding proton energies of 250, 354, and 489 MeV were chosen because at these energies one spans the region in which the effects of the Δ_{1232} should be pronounced. The energy dependence of the double differential cross section for the inclusive (p,π^+) reactions is very similar to that of the exclusive (p,π^+) data from the same target nuclei.[12,13] This energy dependence has been previously interpreted as evidence of a $NN \rightarrow N\Delta \rightarrow NN\pi^+$ reaction mechanism. The energy dependence of the angle integrated differential cross section for the $^{16}O(p,\pi^+)X$ reaction is also similar to what has been observed previously for exclusive π^+ production data.

Analyzing power results from the $^{16}O(\vec{p},\pi^+)X$ reaction indicate that at small missing momenta squared the analyzing powers can be adequately described by a quasifree $\vec{p}p \rightarrow d\pi^+$ process, but as the missing momentum squared is increased, this description becomes less valid. The energy dependence of the (p,π^-) reaction to the continuum is different from that of the exclusive (p,π^-) reaction, and from that of the $pp \rightarrow d\pi^+$ reaction after transformation to the nuclear kinematical frame. These results, therefore, support the hypothesis[12] that the dynamical role of the Δ_{1232} resonance is different in the (p,π^-) and (p,π^+) reactions.

This work has been supported by a grant from the Natural Sciences and Engineering Research Council of Canada (NSERC).

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