(p,π^+) reaction on 1p shell nuclei at $E_p = 200$ MeV

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Energy spectra of pions produced by the (p,π^+) reaction on ^{10}B, ^{11}B, ^{12}C, and ^{13}C leading to discrete final states have been measured with 170–210 keV resolution. Except for ^{12}C, final states that can be reached by the simple transfer of a neutron tend to be favored compared to final states of more complicated structure, which is suggestive of a one-step reaction mechanism. These (p,π^+) spectra are surprisingly similar to (d,p) spectra at much lower momentum transfer. For ^{12}C, single-particle and 2p-1h final states are populated about equally and there is little similarity between the (p,π^+) and (d,p) spectra.

[NUCLEAR REACTIONS ^{10}B$(p,\pi^+)^{11}$B, ^{11}B$(p,\pi^+)^{12}$B, ^{12}C$(p,\pi^+)^{13}$C, ^{13}C$(p,\pi^+)^{14}$C, $E_p = 200$ MeV; measured $\sigma(E_\pi)$ at $\theta_{\text{lab}} = 25°$.]

The mechanism of pion production in proton-nucleus collisions near threshold has been the subject of a good deal of experimental and theoretical work during the past several years. The essential feature of pion production and absorption is that the reaction takes place at a very high momentum transfer, which is several times larger than the average momentum of bound nucleons. Therefore, a central problem is to understand how this large transferred momentum is shared among the constituents of the nucleus. The theoretical interpretation of experimental results has turned out to be difficult because of interrelated questions regarding the reaction mechanism and nuclear structure. Most calculations are carried out within the framework of either the distorted-wave Born approximation (DWBA) pion stripping model or the two-nucleon model.[1] In both of these models pion rescattering plays an important role and is a major source of difficulty.

Because not even the leading term for the (p,π) reaction mechanism has been established, the reaction at present is not a useful probe of nuclear structure. The aim of the present work is to investigate the state dependence of the (p,π^+) reaction for a variety of target and final state configurations in order to gain information about the reaction mechanism. This work complements earlier studies carried out in this laboratory[2] of the energy dependence of the (p,π^+) reaction.

Data on (p,π^+) and (π^+,p) reactions to discrete final states are meager, because the energy resolution in past experiments has not been adequate to resolve more than a few of the low-lying levels in the residual nucleus. In the present work, an overall energy resolution of 170 keV was achieved in the (p,π^+) experiments at the Indiana University Cyclotron Facility by using a quadrupole-dipole-dipole-multipole (QDDM) magnetic spectrograph.[3] Angular distributions were not measured because of the prohibitive amount of beam time required using the QDDM spectrograph, which has a small solid angle (3.3 msr), narrow momentum bite (3%) requiring several magnetic field settings to record a broad energy spectrum, and long flight path in which most of the pions decay before being detected. Consequently, the measurements were made at a single forward angle [θ(lab) = 25°] where the cross sections were expected to be large. The highest proton energy available at IUCF (200 MeV) was chosen in order to maximize the energy range covered by the spectrograph focal plane. The results, when combined with other data and systematics of the (p,π^+) reaction in the 1p shell, allow reasonable inferences to be made about relative transition strengths to different nuclear states.

The spectra obtained at 25° (lab) for ^{10}B and ^{11}B targets are shown in Fig. 1. All of the levels below 9 MeV excitation in ^{11}B are resolved except for the doublet at 6.7 MeV. The five low-lying states of odd parity are believed to arise mainly from configurations comprised of $p_{3/2}$ and $p_{1/2}$ nucleons. The ground ($\frac{3}{2}^-$), 4.44 ($\frac{5}{2}^-$), and 6.74 ($\frac{7}{2}^-$) MeV states in ^{11}B, and the ground (1^+) and 0.95 (2^+) MeV states in ^{12}B are well described by the shell model based on the intermediate coupling scheme.[4] The negative parity states at 1.67(2^-) and 2.62(1^-) MeV in ^{12}B can be formed by coupling a $s_{1/2}$ neutron to the ground state ($\frac{3}{2}^-$) in ^{11}B.

In Figs. 2(a) and 2(b), the relative intensities of the (p,π^+) and (d,p) reactions to final states in ^{11}B and ^{12}B are compared. A strong correlation between the two reactions can be seen. All the states quoted above, which have large single nucleon spectroscopic factors, are strongly excited in both reactions. This common feature of selectivity is suggestive of a stripping process as a dominant mechanism in the (p,π^+) reaction, at

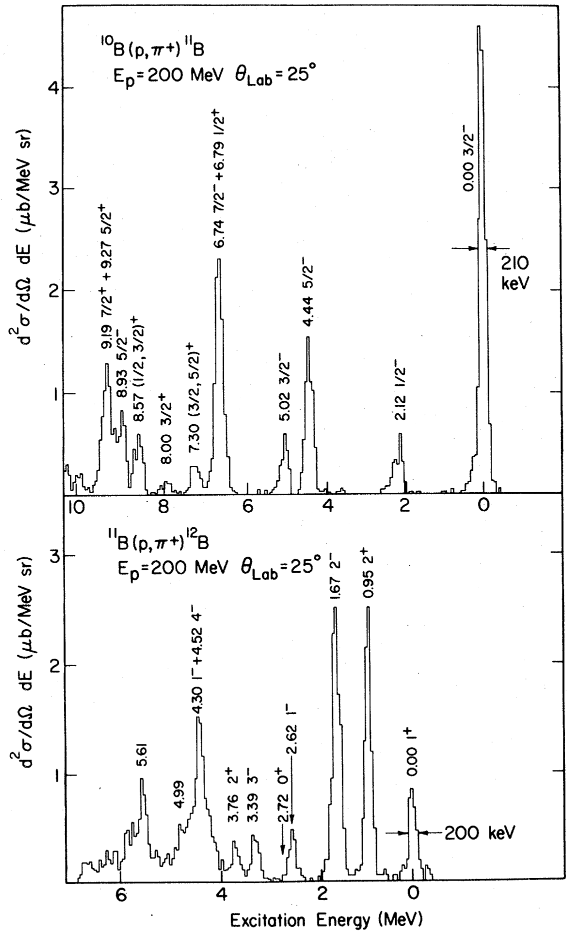

FIG. 1. The $^{10}B(p,\pi^+)^{11}B$ and $^{11}B(p,\pi^+)^{12}B$ spectra at E_p = 200 MeV, obtained with the QDDM magnetic spectrometer positioned at θ_π(lab) = 25°. Each spectrum in this and the succeeding figures is a composite of several field settings of the QDDM.

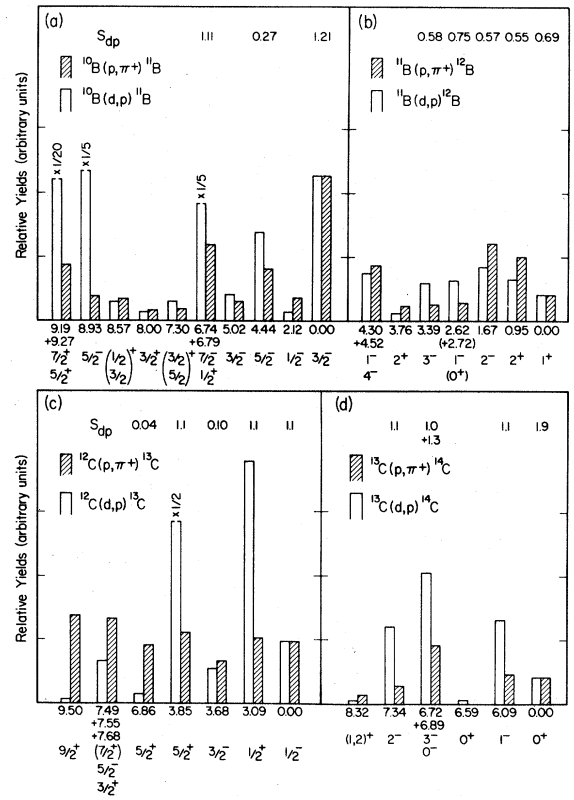

FIG. 2. Relative (p,π^+) yields at θ_π(lab) = 25°. The (d,p) yields at the forward maximum of the angular distributions are normalized to the (p,π^+) ground state transition for each reaction. Yields in the (d,p) reactions are from (a) Ref. 13 (E_d = 10.1 MeV), (b) Ref. 14 (E_d = 5.5 MeV), and Ref. 19 (E_d = 8 MeV), (c) Ref. 18 (E_d = 14.8 MeV), and (d) Ref. 18 (E_d = 14.8 MeV). Spectroscopic factors deduced from DWBA analysis of the (d,p) reactions are indicated on the top of figures. These values are from (a) Ref. 16 (E_d = 12.0 MeV), (b) Ref. 17 (E_d = 12.0 MeV), (c) Ref. 20 (E_d = 15 MeV), and (d) Ref. 15 (E_d = 12 MeV) and Ref. 20 (E_d = 15 MeV). The spectroscopic factor above the 6.7-MeV state in ^{11}B is the value for the 6.74-MeV state.

least at the forward angles.[5] The 2.12($\frac{1}{2}^-$) MeV state, which is forbidden by a one-step mechanism, and the 5.02($\frac{3}{2}^-$) MeV state, which is predicted by the intermediate-coupling model to have little single particle overlap with the ^{10}B ground state, are both populated weakly in the (p,π^+) and (d,p) reactions. There are three even parity states at 7.30, 8.00, and 8.57 MeV in ^{11}B that are characterized by weak (d,p) intensities suggestive of highly mixed configurations. These states are also populated weakly in the (p,π^+) reaction. Accordingly, excitation of these states in the (p,π^+) reaction probably involves multiple step processes. The two states of even parity near 9 MeV in ^{11}B have very large (d,p) stripping amplitudes characteristic of direct neutron capture into the 2s or 1d shell. Transitions to these states, as well as the 6.7 MeV doublet state (presumably, 6.74 MeV single-particle state dominates), are accordingly enhanced in the (p,π^+) reaction but to a much lesser extent. The small yield to the 2.72(0^+) MeV state of ^{12}B can be interpreted as being due to the recoupling of core nucleons together with the transfer of a neutron and hence a multistep mechanism.

Although this simple comparison of the cross sections does not take into account differences between the two reactions in Q values, linear momentum transfers, angular momentum matching conditions, and the interaction Hamiltonian, the correlations in selectivity of the (d,p) and (p,π^+) reactions on ^{10}B and ^{11}B targets indicate that both reactions are sensitive to the nuclear structure in a similar way. This result is surprising considering the fact that the momentum transfer in the (p,π^+) reaction is about 500 MeV/c, whereas that of the (d,p) reactions is smaller by an order of magnitude. This consequence must be interpreted with some caution in view of the absence of angular distributions; however, previous investigations of the (p,π^+) reaction in the $1p$ shell[6-9] have shown a lack of strong features in the angular distributions. In every case observed, the differential cross sections are large at forward angles and either decrease monotonically with increasing angle or decrease monotonically in the forward hemisphere and rise again in the backward hemisphere. Therefore, the forward angle differential cross sections are expected to be a good indication of the relative transition strengths.

Figure 3 shows the pion spectra for ^{12}C and ^{13}C targets taken at 25°(lab). For ^{12}C$(p,\pi^+)^{13}$C, though the triplet at 7.5 MeV is not resolved, the centroid of this peak is at 7.53 ± 0.03 MeV, indicating that the main contribution is from the 7.55 and/or 7.49 MeV state(s) and not the 7.68-MeV state. All of the states above 4.94 MeV in ^{13}C are unstable to breakup into ^{12}C $+n$, but only the 8.4 MeV state has a natural width (1 MeV) greater than the instrumental resolution. Angular distributions for several low-lying states have been measured at 185 MeV and the present energy.[7] Unlike the cases of ^{10}B and ^{11}B targets, there appears to be no preference for the single-particle final states at $0.0(p_{1/2})$, $3.09(s_{1/2})$, $3.85(d_{5/2})$, and $8.4(d_{3/2})$ MeV in the ^{12}C$(p,\pi^+)^{13}$C reaction. The strong transitions to 2p-1h final states[10] at $6.86(\frac{5}{2}^+)$ and $9.50(\frac{9}{2}^+)$ MeV (Ref. 11) confirm the multistep (or multinucleon) nature of the (p,π^+) reaction, which presumably is related to the relative ease with which the strongly deformed ^{12}C core can be excited. Transitions to the 2p-1h states at $3.68(\frac{3}{2}^-)$ and probably $7.55(\frac{5}{2}^-)$ MeV could be due in part to 2p-2h components in the ^{12}C ground state wave function. Figure 2(c) shows that there is little correspondence of enhancements in the (d,p) and (p,π^+) reactions on a ^{12}C target.

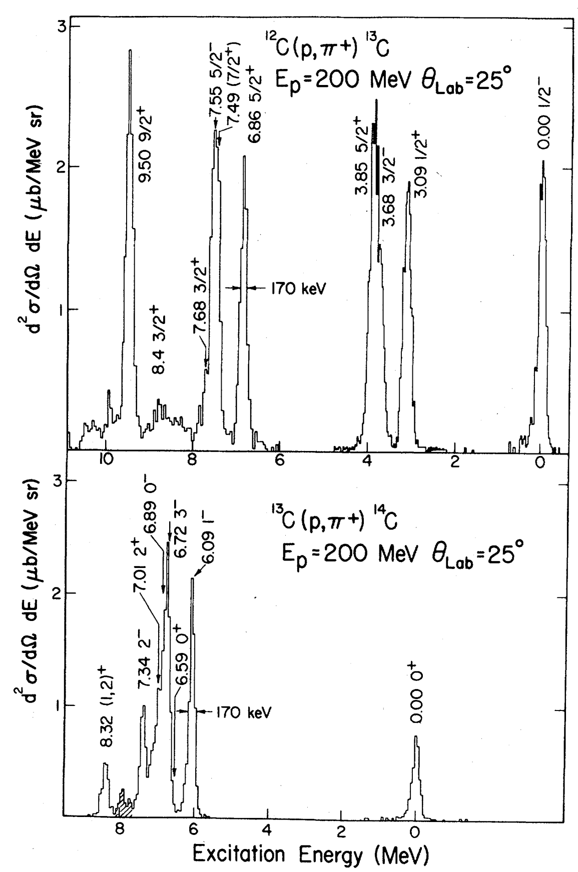

FIG. 3. The ^{12}C$(p,\pi^+)^{13}$C and ^{13}C$(p,\pi^+)^{14}$C spectra at $E_p = 200$ MeV and $\theta_\pi(\text{lab}) = 25°$. The peak areas in the ^{13}C(p,π^+) spectrum denoted by hatch marks belong to the 3.68–3.85 MeV doublet in ^{13}C from ^{12}C contamination. The region corresponding to the ground state in ^{13}C was not sampled in this measurement.

For ^{13}C$(p,\pi^+)^{14}$C, there are four states which lie between 6.59 and 7.01 MeV excitation. The peak in this region lies at 6.75 ± 0.04 MeV and probably is due mainly to the 6.72 MeV (3^-) MeV state. The high-energy tail of the 6.7 MeV peak shows that the $6.89(0^-)$ and/or $7.01(2^+)$ MeV states are populated with significant intensity but more weakly than the 6.72-MeV state. Since the ^{13}C ground state is predominantly a $p_{1/2}$ single particle state, the 0^+ ground state and the low-lying negative parity states of ^{14}C at 6.09-, 6.72-, 6.89-, and 7.34-MeV can be formed by coupling a $p_{1/2}$, $s_{1/2}$ or $d_{5/2}$ neutron to the ground state of ^{13}C. Transitions to the 6.59- and 7.01-MeV states involve capture of a neutron together with excitation or recoupling of core nucleons. In Fig. 2(d), there is a qualitative correspondence of enhancements in the (d,p) and (p,π^+) reactions.

Calculations of the (p,π^+) reaction based on the DWBA stripping model[12] were attempted for several single-particle final states in order to extract relative spectroscopic factors for comparison with theoretical values[4] and experimental values deduced from the (d,p) reaction. Unfortunately, the DWBA calculations are very sensitive to the choice of parameters describing the proton and pion optical potentials and the bound state neutron wave function, and meaningful comparisons of this kind cannot be made until the present uncertainties and ambiguities in these parameters are resolved.

In summary, for targets of ^{10}B, ^{11}B, and ^{13}C the (p,π^+) reaction populates preferentially final states that can be formed by coupling a neutron to the target nucleus in its ground state. This is suggestive of a one-step reaction mechanism. If this is the case, then the observed similarity of the (p,π^+) and (d,p) spectra at very different momentum transfers is noteworthy, since the two reactions probe entirely different momentum regions of the captured neutron wave function. A quite different behavior is observed for the $^{12}C(p,\pi^+)^{13}C$ reaction; for this case single-particle and 2p-1h final states are populated about equally, suggesting a multistep reaction mechanism. Thus, while a strong coupling between nuclear structure and the reaction mechanism is indicated by the data, it seems likely that pionic stripping makes an important contribution to the (p,π^+) process near threshold.

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[1]B. Höistad, in *Advances in Nuclear Physics*, edited by J. Negele and E. Vogt (Plenum, New York, 1979), Vol. II, p. 135; D. F. Measday and G. A. Miller, Annu. Rev. Nucl. Part. Sci. 29, 121 (1979), and references therein.

[2]P. H. Pile, R. D. Bent, R. E. Pollock, P. T. Debevec, R. E. Marrs, M. C. Green, T. P. Sjoreen, and F. Soga, Phys. Rev. Lett. 42, 1461 (1979).

[3]R. D. Bent, P. T. Debevec, P. H. Pile, R. E. Pollock, R. E. Marrs, and M. C. Green, Phys. Rev. Lett. 40, 495 (1978).

[4]S. Cohen and D. Kurath, Nucl. Phys. A101, 1 (1967).

[5]J. V. Noble, in *Meson-Nuclear Physics—1976*, Proceedings of the Carnegie-Mellon Conference, edited by P. D. Barnes, R. A. Eisenstein, and L. S. Kisslinger (AIP, New York, 1976), p. 221.

[6]S. Dahlgren and P. Grafström, Phys. Scr. 10, 104 (1974); S. Dahlgren, P. Grafström, B. Höistad, and A. Asberg, Nucl. Phys. A204, 53 (1973).

[7]S. Dahlgren, P. Grafström, B. Höistad, and A. Asberg, Nucl. Phys. A211, 243 (1973); B. Höistad, P. H. Pile, T. P. Sjoreen, R. D. Bent, M. C. Green, and F. Soga, Phys. Lett (to be published).

[8]S. Dahlgren, P. Grafström, B. Höistad, and A. Asberg, Phys. Lett. 47B, 439 (1973).

[9]P. H. Pile, R. E. Pollock, T. P. Sjoreen, W. W. Jacobs, M. C. Green, F. Soga, R. D. Bent, H. O. Meyer, and R. E. Marrs, IUCF Technical and Scientific Report, p. 2 (1978), and unpublished.

[10]K. Hosono, J. Phys. Soc. Jpn. 25, 36 (1968).

[11]D. Dehnhard, S. J. Tripp, M. A. Franey, G. S. Kyle, C. L. Morris, R. L. Boudrie, J. Piffaretti, and H. A. Thiessen, Phys. Rev. Lett. 43, 1091 (1979).

[12]M. Tsangarides, Ph.D. thesis, Indiana University, 1979 (unpublished).

[13]S. Hinds and R. Middleton, Nucl. Phys. 38, 114 (1962).

[14]A. Gallmann, F. Hibou, P. Fintz, P. E. Hodgson, and E. K. Warburton, Phys. Rev. 138, 560 (1964).

[15]R. N. Glover and A. D. W. Jones, Nucl. Phys. 84, 673 (1966).

[16]J. P. Schiffer, G. C. Morrison, R. H. Siemssen, and B. Zeidman, Phys. Rev. 164, 1274 (1967).

[17]J. E. Monahan, H. T. Fortune, and C. M. Vincent, Phys. Rev. C 3, 2192 (1971).

[18]J. N. McGruer, E. K. Warburton, and R. S. Bender, Phys. Rev. 100, 235 (1955).

[19]J. R. Holt and T. N. Marsham, Proc. Phys. Soc. London A66, 1032 (1953).

[20]S. E. Darden, S. Sen, H. R. Hiddleston, J. A. Aymar, and W. A. Yoh, Nucl. Phys. A208, 77 (1973).