$^{12}C(\pi^{\pm},\pi^{\pm\prime}p)^{11}B$ Reaction near the Giant Dipole Region

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Cross sections for the $^{12}C(\pi^{\pm},\pi^{\pm\prime}p)^{11}B$ reaction have been measured and compared with the results of distorted-wave impulse-approximation calculations that employ the factorization approximation for quasifree scattering. Near the giant dipole resonance of ^{12}C the calculations underestimate the cross sections for $(\pi^-,\pi^{-\prime}p)$. The angular distributions for $(\pi^+,\pi^{+\prime}p)$ and $(\pi^-,\pi^{-\prime}p)$ are different and indicate that in this region there is interference between direct decay and semidirect decay.

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The response of the continuum of nuclear states above nucleon breakup threshold to inelastic scattering has been the subject of intensive research.[1] Transitions to the giant resonances (GR's) can proceed in competition with the quasielastic scattering process. Thus, a detailed understanding of the reaction mechanism is needed in order to unravel the structure of the continuum. For example, the extent to which isospin is a good quantum number for the giant resonances is of great importance in the study of nuclear structure.[2] We believe that coincidence measurements between inelastically scattered probes and emitted secondary particles provide a powerful tool for these investigations. The isospin selectivity of π^+ and π^- scattering makes pion probes particularly useful in a study of the continuum.

Coincidence experiments involving pions as a probe can be divided into two groups: experiments in the region where quasielastic scattering dominates [E_x(target) ≥ 40 MeV and backward angles][3-7] and experiments in the region of the giant resonances [E_x(target) ≤ 40 MeV and forward angles].[8,9] Indeed, Chant, Rees, and Roos[10] have shown that quasifree single-nucleon knockout calculations, carried out with the code THREEDEE[11] are in good agreement with the measured $^{12}C(\pi^+,\pi^{+\prime}p)^{11}B$(g.s.) cross sections of Ziock *et al.*[4] at large momentum transfer and high $E_x(^{12}C)$. These calculations use a factorized form of the distorted-wave impulse approximation (DWIA), and include optical-model distortions of the incoming pion, outgoing pion, and final-state proton. The processes that contribute to the lower E_x(target) of the continuum, however, are more complicated. It has been suggested[9,12] that, in this GR region, direct decay (due to quasifree-knockout scattering) and semidirect decay (due to resonant inelastic scattering to states of good isospin) compete with each other in a coherent way.

The current study is aimed at the excitation region near the giant dipole resonance (GDR) of ^{12}C. In this Letter, we compare cross sections for the $^{12}C(\pi^{\pm},\pi^{\pm\prime}p)$ reaction with DWIA calculations performed with the code THREEDEE in order to evaluate the importance of quasifree-knockout scattering in the excitation-energy region near the GDR. We also present values for the ratio $R=\sigma(\pi^+,\pi^{+\prime}p)/\sigma(\pi^-,\pi^{-\prime}p)$, which may provide information on the isospin structure of the continuum.

The experiment was performed on the Energetic Pion Channel and Spectrometer (EPICS)[13] at Los Alamos National Laboratory. Scattered pions were detected in the focal plane of the high-resolution EPICS spectrometer. Protons were detected in coincidence with the scattered pions using five plastic-BGO (bismuth-germanate) "phoswich" detectors mounted in the vacuum scattering chamber. Measurements were made at an incident pion energy of 180 MeV. The target was a carbon foil of natural isotopic composition and of areal density 91 mg/cm^2 mounted at 60° with respect to the beam direction. The energy loss in the detector entrance foil and in the target limited the minimum detectable proton energy to about 4 MeV (at the center of the target). The pion scattering angle θ_{lab} was chosen to be 20°, near the maximum in the angular distribution for the GDR in ^{12}C.[14] Protons were detected at laboratory scattering angles $\theta_p = -120°, -90°, -60°, 60°$, and 90° with respect to the incident beam. A relative measure of the pion beam intensity was provided by a toroidal pickoff upstream of the pion production target which measured the primary proton beam current. Typical average pion fluxes were $\approx 2.8\times 10^7$/sec for π^+ and 1.5×10^7/sec for π^-. The data were normalized by comparing yields measured for π^+ and π^- scattering from hydrogen (using a CH_2 target of areal density 73 mg/cm^2) to cross sections calculated using the π-N phase shifts of Rowe, Salomon, and Landau.[15] The energy resolution in the (π,π') and $(\pi,\pi' p)$ reactions is about 200 keV and 4 MeV, respectively.

Missing-mass spectra for π^+ and π^- scattering are shown in Fig. 1. Singles spectra for π^+ (red) and π^- (blue) are presented in the upper portion. The π^+ and π^- cross sections are nearly equal everywhere as expected for a self-conjugate nucleus because of charge symmetry except for a known isospin-mixed doublet near 19 MeV.[16]

Figure 1(b) shows the pion missing-mass spectrum, gated by the requirement of detecting a coincident proton at an energy which implies that the excitation energy of the residual nucleus, ^{11}B, is less than 10 MeV, and summed over all proton detectors. In contrast to the singles spectra, the $(\pi,\pi' p)$ coincidence yields are larger for π^+ than π^- throughout the spectrum. The missing-mass spectrum gated by detecting a proton leading to excited states of ^{11}B higher than 10 MeV is plotted in Fig. 1(c). In this case, which includes multiparticle breakup states, the $(\pi^+,\pi^{+\prime} p)$ and $(\pi^-,\pi^{-\prime} p)$ cross sections are about the same at all energies. The 4-MeV threshold for proton detection in our phoswich detectors seems to have a minimal effect on the results of our coincidence data, since we are considering the decay of ^{12}C* states above $E_x = 20$ MeV.

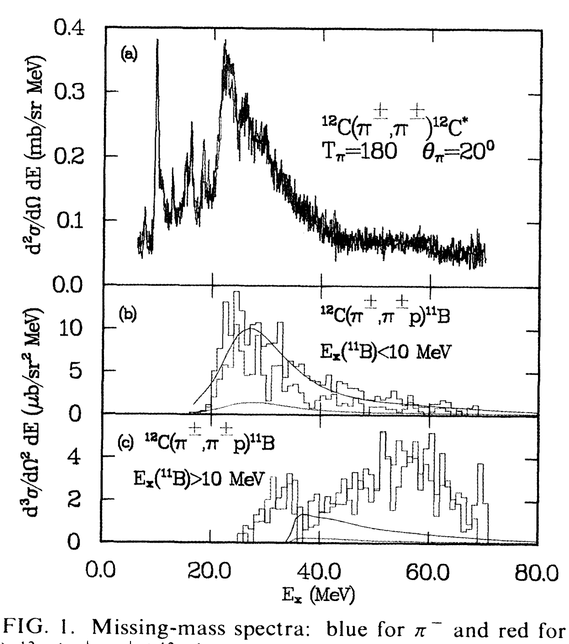

FIG. 1. Missing-mass spectra: blue for π^- and red for π^+. (a) $^{12}C(\pi^\pm,\pi^{\pm\prime})^{12}C^*$ singles spectra at $\theta_\pi = 20°$ and $T_\pi = 180$ MeV. (b) $^{12}C(\pi^\pm,\pi^{\pm\prime}p)^{11}B$ coincidence spectra, gated by $E_x(^{11}B) < 10$ MeV. Red (blue) solid curve is a DWIA calculation of π^+ (π^-) $1p$-shell knockout. (c) $^{12}C(\pi^\pm,\pi^{\pm\prime}p)^{11}B$ reaction, gated by $E_x(^{11}B) \geq 10$ MeV. Red (blue) solid curve is a DWIA calculation of π^+ (π^-) $1s$-shell knockout.

The inequality of the $(\pi^-,\pi^{-\prime} p)$ and $(\pi^+,\pi^{+\prime} p)$ cross sections for $E_x(^{11}B) < 10$ MeV can be qualitatively understood by simple arguments. If the reaction process is quasifree knockout, we expect a ratio R close to 9 as for π^+ and π^- scattering from free protons. Nearly as large a ratio is obtained from the factorized DWIA calculations performed with the code THREEDEE. The curves plotted in Fig. 1(b) correspond to scattering from a proton bound in the $1p$ shell. A spectroscopic factor $C^2S = 3.98$, the summed $1p$-shell spectroscopic factor predicted by Cohen and Kurath,[17] and a separation energy $S_p = 15.8$ MeV were assumed. The calculations in Fig. 1(c) are for scattering from a $1s$-shell proton with $C^2S = 2.0$, the value of the shell-model limit, and $S_p = 34.3$ MeV. Both sets of calculations show π^+ scattering to be larger than π^- by nearly the free π-p ratio (for example, we calculate $R \sim 7.36$ for $1p$ knockout near the GDR). However, the experimental ratio is only 1.59 on the average (Table I).

Both the shape and magnitude of the $(\pi^+,\pi^{+\prime} p)$ spectrum gated by $E_x(^{11}B) < 10$ MeV are well described by the DWIA. However, the $(\pi^-,\pi^{-\prime} p)$ data for the same gate are much larger than the predicted values [Fig. 1(b)]. This discrepancy would be larger if we had used the $1p$-shell spectroscopic factor of 2.9 and $1s$-shell spectroscopic factor of 1.8 reported in Ref. 10. For the data from $E_x(^{11}B) > 10$ MeV gate, the agreement between experiment and the DWIA prediction is poor for both π^+ and π^- scattering [Fig. 1(c)].

The angular distributions of the emitted protons are plotted in Fig. 2 as a function of the outgoing proton angle in the center-of-mass system of the recoil ^{12}C. The cross section for events leading to the ground state or the low-excitation states of ^{11}B, i.e., $E_x(^{11}B) < 10$ MeV, summed over $E_x(^{12}C)$ from 20 to 30 MeV, is shown in

TABLE I. The ratios $R = \sigma(\pi^+,\pi^+p)/\sigma(\pi^-,\pi^-p)$ at each proton detector and the ratio of summed cross section. The $\sigma(\pi^\pm,\pi^{\pm\prime}p)$ data were obtained by summing cross sections from 20 to 30 MeV in $E_x(^{12}C)$ with the $E_x(^{11}B) < 10$ MeV gate, at $T_\pi = 180$ MeV and $\theta_{lab} = 20°$.

$\theta_{p\,c.m.}$	R (DWIA)	R (Experiment)
−60.3°	8.59	1.99 ± 0.41
−28.5°	7.89	3.09 ± 0.62
3.9°	6.75	2.50 ± 0.61
127.3°	5.29	0.47 ± 0.12
155.5°	6.02	0.33 ± 0.11
R of summed σ	7.36	1.59 ± 0.16

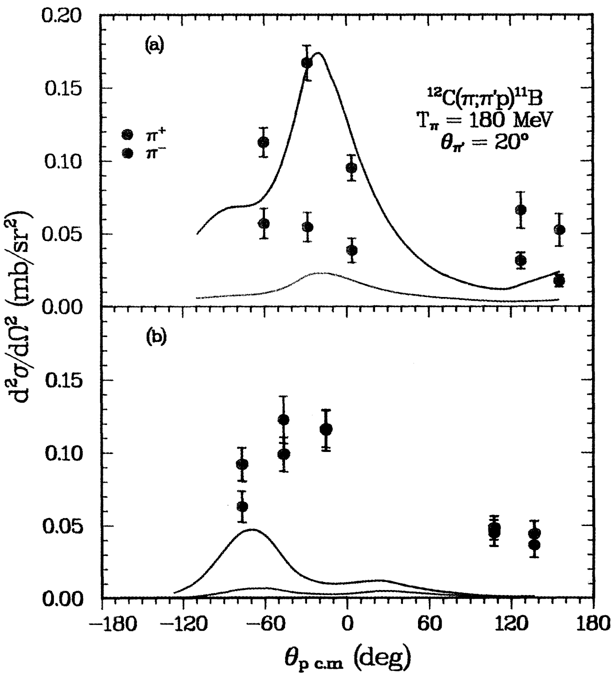

FIG. 2. Angular distribution in the center-of-mass system of the recoil $^{12}C^*$. (a) The missing-mass spectra were summed over $E_x(^{12}C) = 20$ to 30 MeV and $E_x(^{11}B) < 10$ MeV. Red (blue) solid curve is a DWIA calculation of π^+ (π^-) $1p$-shell knockout. (b) The missing-mass spectra were summed over $E_x(^{12}C) = 41$ to 70 MeV and $E_x(^{11}B) \geq 10$ MeV. Red (blue) solid curve is a DWIA calculation of π^+ (π^-) $1s$-shell knockout calculations.

Fig. 2(a). In Fig. 2(b) data for the higher-excitation states of ^{11}B, $E_x(^{11}B) \geq 10$ MeV, were summed over $E_x(^{12}C)$ from 41 to 70 MeV. The curves are the DWIA calculations described earlier. The $(\pi^+,\pi^{+\prime}p)$ data with the $E_x(^{11}B) < 10$ MeV gate are reasonably well described by the DWIA. However, the $(\pi^-,\pi^{-\prime}p)$ data exhibit no clear peak in the recoil direction in contradiction to the DWIA. In Table I we present the ratio R of the data leading to $E_x(^{11}B) < 10$ MeV and the DWIA predictions for $1p$-shell knockout summed from 20 to 30 MeV of $E_x(^{12}C)$. The experimental value of R varies from a maximum of $R = 3.09 \pm 0.62$ near the quasifree-knockout direction to a minimum of $R = 0.33 \pm 0.11$ in the opposite direction. However, the calculations give $R = 8$ and 6 at these two angles, respectively.

The calculations discussed so far include only the quasifree-knockout process. Another process that can contribute to this $(\pi^\pm,\pi^{\pm\prime}p)$ reaction in the GR region is a semidirect one where the pion excites a state of ^{12}C in the GR region that subsequently decays through emission of a proton. If the state in ^{12}C has good isospin and if the difference between the neutron and proton penetrabilities is neglected, R must be equal to 1 at all emitted proton angles. In this case the decay of the state is governed by branching ratios and these are independent of the manner in which the state was created. Furthermore, the angular distribution should be symmetric about 90°. The data for $20 \leq E_x(^{12}C) \leq 30$ MeV with the $E_x(^{11}B) < 10$ MeV gate could be qualitatively explained by a mixture of these two processes: direct (due to quasifree knockout) and semidirect (due to inelastic scattering to states of good isospin). The angular distributions of the decay proton indicate that the $(\pi^+,\pi^{+\prime}p)$ is dominated by the direct decay whereas, at least, the $(\pi^-,\pi^{-\prime}p)$ must have a strong contribution from the semidirect process. This process must, of course, also contribute to $(\pi^+,\pi^{+\prime}p)$, although the good agreement between absolute experimental cross sections and THREEDEE predictions suggests a predominance of the quasifree process. We propose that the observed strong angle dependence of R is probably due to an interference between the amplitudes for these two processes.

In order to describe a situation which lies between the limits of quasifree knockout and the excitation and decay of states of good isospin, one may use a form of the doorway model.[18] In this model, the interaction of the pion probe with the nucleus leads to proton particle-hole and neutron particle-hole states in the continuum with amplitudes approximately in the ratio of the free pion-nucleon couplings. These continuum states couple either to the GR states with width Γ_R, or they decay directly into a potential scattering state with width Γ_D (the quasifree process). The decay of the GR states would lead to equal amplitudes for proton and neutron emission, i.e., $R = 1$, but the interference with the quasifree process causes π^+/π^- asymmetries. The enhancement of the proton decay observed in the current $(\pi^-,\pi^{-\prime}p)$ data above the DWIA calculations indicates that Γ_R and Γ_D must be comparable in size for the continuum near the GR region of ^{12}C. This interference would be less important for $(\pi^+,\pi^{+\prime}p)$ because the direct amplitude is 3 times larger than for $(\pi^-,\pi^{-\prime}p)$. Therefore, the decay of the continuum in the region of the GR is largely governed by how it was excited. The absolute cross sections predicted by THREEDEE depend on the choice of spectroscopic factors, but not on the ratio R. Thus, we base our conclusion on the failure of simple DWIA calculations to reproduce R. We have made no attempt to include higher-order effects in the π-nucleus scattering such as those which have been predicted to arise from the Δ-hole model.[7]

These observations in the region of the GDR in ^{12}C can be contrasted with the result obtained at higher excitations energies in ^{12}C [Figs. 1(c) and 2(b)]. In this high-excitation region, $40 \leq E_x(^{12}C) \leq 70$ MeV, we find that more than half of the cross section seen in the coincidence spectrum corresponds to the data leading to $E_x(^{11}B) \geq 10$ MeV. For these events we observe a broad bump in Fig. 1(c) centered near 55 MeV of excitation in ^{12}C. The angular distribution of protons associated with this bump also appears to peak near the recoil direction but the ratio R [Fig. 2(b)] is near unity at all angles. The DWIA calculations for 1s-shell knockout do not resemble these data at all. The near equality of the $(\pi^+,\pi^{+\prime}p)$ and $(\pi^-,\pi^{-\prime}p)$ cross sections suggests that protons and neutrons are involved equally in the reaction. However, we do not believe that, for $E_x(^{12}\mathrm{C}) \geq 40$ MeV, states of good isospin would play a major role except for possible double resonances.[19] It is also possible that direct two-, three-, and four-nucleon removal are important here. Lourie *et al.*[20] also observed considerable strength in this region of $E_x(^{12}\mathrm{C})$ in the $^{12}\mathrm{C}(e,e'p)$ reaction. They interpreted this strength as due to multinucleon reaction mechanisms. The failure of the one-nucleon-knockout calculations with THREEDEE to reproduce the magnitude and the near equality of the π^+ and π^- data suggests the importance of one of these processes for $(\pi,\pi'p)$.

In summary, we have measured cross sections for the $^{12}\mathrm{C}(\pi^\pm,\pi^{\pm\prime}p)$ reactions, and have compared the results with the factorized DWIA calculations. Neither the DWIA calculations, which assume a quasifree-knockout process, nor the assumption that the reaction is dominated by states of good isospin in ^{12}C (the GDR) can explain the data. This leads to the speculation that inelastic scattering to the giant dipole region in ^{12}C contains two components, one of which is direct (quasifree), the other being semidirect (resonance). The ratio R shows an angular dependence that indicates coherent interference between these amplitudes.

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[1]C. C. Chang, in *Giant Multiple Resonance,* edited by F. E. Bertrand (Harwood-Academic, Chur, Switzerland, 1979), p. 191.

[2]S. S. Hanna, in Ref. 1, p. 1.

[3]H. J. Ziock, R. J. Ellis, K. O. H. Ziock, J. Bolger, E. Boschitz, J. Arvieux, R. Corfu, and J. Piffaretti, Phys. Rev. Lett. **43**, 1919 (1979).

[4]H. J. Ziock, R. J. Ellis, K. O. H. Ziock, J. Bolger, E. Boschitz, J. Arvieux, R. Corfu, and J. Piffaretti, Phys. Rev. C **24**, 2674 (1981).

[5]E. Piasetzky, D. Ashery, A. Altman, A. I. Yavin, F. W. Schlepütz, R. J. Powers, W. Bertl, L. Felawka, H. K. Walter, R. F. Winter, and J. v. d. Pluym, Phys. Rev. Lett. **46**, 1271 (1981); Phys. Rev. C **25**, 2687 (1982).

[6]J. R. Hurd, J. S. Boswell, R. C. Minehart, L. B. Rees, Y. Tzeng, H. J. Ziock, and K. O. H. Ziock, Nucl. Phys. **A462**, 605 (1987).

[7]G. S. Kyle, P.-A. Amaudruz, Th. S. Bauer, J. J. Domingo, C. H. Q. Ingram, J. Jansen, D. Renker, J. Zichy, R. Stamminger, and F. Vogler, Phys. Rev. Lett. **52**, 974 (1984).

[8]M. Jones, Ph.D. thesis, University of Minnesota, 1989 (unpublished).

[9]Christopher L. Morris, Bull. Am. Phys. Soc. **33**, 1093 (1988).

[10]N. A. Chant. L. Rees, and P. G. Roos, Phys. Rev. Lett. **48**, 1784 (1982).

[11]N. S. Chant, computer code THREEDEE; L. Rees, N. S. Chant, and P. G. Roos, Phys. Rev. C **26**, 1580 (1982).

[12]H. Überall, *Electron Scattering from Complex Nuclei* (Academic, New York, 1979), Vol. B, p. 729.

[13]H. A. Thiessen and S. Sobottka, Los Alamos National Laboratory Report No. LA-4534-MS (unpublished).

[14]L. C. Bland, Ph.D. thesis, University of Pennsylvania, 1984 (unpublished); Los Alamos National Laboratory Report No. LA-9960-T, 1984 (unpublished).

[15]G. Rowe, M. Salomon, and R. H. Landau, Phys. Rev. C **18**, 584 (1978).

[16]W. B. Cottingame, K. G. Boyer, W. J. Braithwaite, S. J. Green, C. J. Harvey, R. J. Joseph, D. B. Holtkamp, C. Fred Moore, J. J. Kraushaar, R. J. Peterson, R. A. Ristinen, J. R. Shepard, G. R. Smith, R. L. Boudrie, N. S. P. King, C. L. Morris, J. Piffaretti, and H. A. Thiessen, Phys. Rev. C **36**, 230 (1987).

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

[18]H. Feshbach, A. K. Kerman, and R. H. Lemmer, Annu. Rev. Phys. **41**, 230 (1967).

[19]S. Mordechai, N. Auerbach, M. G. Burlein, H. T. Fortune, S. J. Greene, C. Fred Moore, C. L. Morris, J. M. O'Donnell, M. W. Rawool, J. D. Silk, D. L. Watson, S. H. Yoo, and J. D. Zunbro, Phys. Rev. Lett. **61**, 531 (1988).

[20]R. W. Lourie *et al.*, Phys. Rev. Lett. **56**, 2364 (1986).

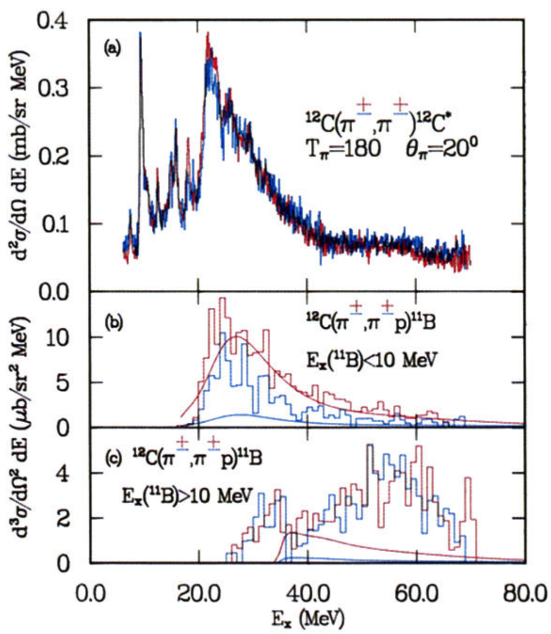
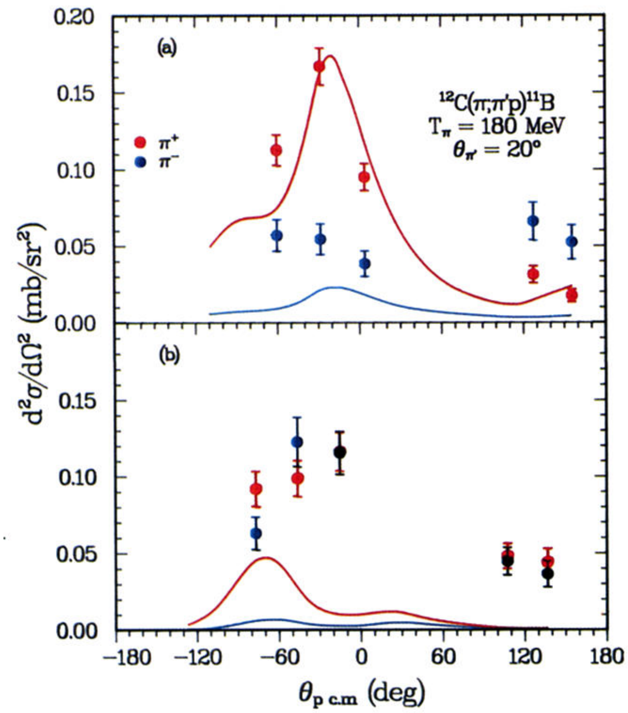


FIG. 1. Missing-mass spectra: blue for π^- and red for π^+. (a) $^{12}C(\pi^{\pm},\pi^{\pm\prime})^{12}C^*$ singles spectra at $\theta_\pi = 20°$ and $T_\pi = 180$ MeV. (b) $^{12}C(\pi^{\pm},\pi^{\pm\prime}p)^{11}B$ coincidence spectra, gated by $E_x(^{11}B) < 10$ MeV. Red (blue) solid curve is a DWIA calculation of π^+ (π^-) 1p-shell knockout. (c) $^{12}C(\pi^{\pm},\pi^{\pm\prime}p)^{11}B$ reaction, gated by $E_x(^{11}B) \geq 10$ MeV. Red (blue) solid curve is a DWIA calculation of π^+ (π^-) 1s-shell knockout.



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