Coincidence Measurements of (p,n) Reactions at 1.5 GeV/c on C and H in the Δ Excitation Region

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Coincidence measurements of (p,n) reactions at 1.5 GeV/c in the Δ excitation region have been carried out for the first time. The location of the Δ peak in the neutron spectrum is found to be dependent on the coincident particles. The peak in coincidence with $p\pi^+$ is shifted to lower momenta compared to the free case, in contrast to the inclusive spectrum and the coincidence with other particles where it is shifted to higher momenta. The $p\pi^+$ invariant-mass distribution for C is significantly lower and broader than that for H. The coincidence data set stringent constraints on theoretical models introduced to interpret the peak shift in inclusive spectra.

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The observation of peak shifts in the region of Δ excitation in the inclusive $(^3\text{He},t)$ reaction on nuclear targets [1,2] has attracted much attention. The Δ peak appears at an excitation energy about 70 MeV lower than expected. Such a shift is seen also in inclusive (p,n) reactions at 1.5 GeV/c [3-5], but only small shifts have been observed in inclusive (e,e') reactions [6] and these are often in the opposite direction. This difference suggests the possibility that spin-longitudinal (pionic) nuclear correlations might be important in explaining the hadronic shifts, since they are invisible to electrons. Indeed, several recent detailed theoretical calculations [7,8] propose that such correlations are responsible for at least some of the shift. This very interesting conclusion is surprising in view of the strong absorption of the hadrons and should be tested with a more thorough investigation of the reactions. There are also various kinematic and reaction mechanism effects which must be considered and which require study with more exclusive measurements to be understood.

We present here the first results of coincidence experiments in the Δ region for the (p,n) reaction on nuclear targets (C and CH_2) at 1.5 GeV/c. The cross section for Δ production is maximum around 1.5 GeV/c. The nucleon charge-exchange reaction avoids some of the theoretical complications and is likely to view more of the nuclear interior than the $(^3\text{He},t)$ reaction. Initial results from coincidence measurements with the $(^3\text{He},t)$ reaction have been discussed recently [9]. Coincidence measurements have previously been carried out for the $(p,p'\Delta^0)$ reaction on nuclear targets (C, Al, and Cu) at 4 GeV/c [10] where the inclusive spectra do not show a clear Δ peak because the Δ^{++} which dominates (p,n) is absent in (p,p'). The position and width of the Δ^0 peak in proton spectra in coincidence with $p\pi^-$ were well reproduced with the mass and width of the Δ in free space. Comparable experiments for electron scattering have not yet been reported.

Experiments were performed at the $\pi2$ beam line of the 12-GeV proton synchrotron (PS) at the National Laboratory for High Energy Physics (KEK) using a time-of-flight (TOF) neutron spectrometer and a large-acceptance spectrometer called FANCY for coincidence particle detection. The neutron spectrometer consisted of fifty scintillators in a 10×5 array at a distance of about 10 m. Individual scintillators were 3 cm thick and 20 cm wide with heights varying from 100 to 150 cm, giving a total width of 200 cm and a thickness of 15 cm. The array was surrounded by veto scintillators with a thickness of 1 cm to reject charged particles. The usable range of polar angles covered by the neutron spectrometer was $0°-6°$. FANCY is a cylindrical spectrometer [11] composed of a solenoid (3-kG magnetic field), a cylindrical drift chamber, and a cylindrical hodoscope. A momentum resolution σ_p/p of 10% at 1 GeV/c was achieved. Particle identification by dE/dx was possible for momenta up to 800 MeV/c.

An unseparated beam with an intensity of $(1-2)\times10^5$

particles per 0.5-sec beam spill was delivered from the internal target of the PS to the experimental target. The beam momentum measured by time of flight over a 12-m path was 1.49 GeV/c with a momentum spread of 0.02 GeV/c. An event trigger consisted of a coincidence of a beam proton and a hit in any neutron detector and anticoincidence with the veto scintillators. Since the cylindrical hodoscope was not used in the trigger logic, the acceptance of the cylindrical spectrometer was very large (between 12° and 141° covering a solid angle of 88% of 4π). Tracking efficiency was more than 95% in this angular range. Energy loss in the target material limited the lowest detectable momenta to 70 and 240 MeV/c for pions and protons, respectively. Targets were carbon and polyethylene (CH_2) with thicknesses of 0.87 and 0.94 g/cm^2, respectively. H-target data were deduced by subtraction.

The detection efficiency of the neutron detector was calculated by a Monte Carlo program in which the detector geometry including veto scintillators was realistically treated. The efficiency estimated by the Monte Carlo was $(5.5\pm1)\%$, almost independent of the neutron momentum in the Δ region, with a pulse-height cut at 11 MeV energy deposit. Long-term time drift was monitored and corrected using laser pulses, giving an overall TOF resolution of 350 psec (rms) for a 5-month data-taking period. The corresponding momentum resolution was 15 MeV/c at 1.0 GeV/c and 50 MeV/c at 1.5 GeV/c.

All events were classified into six types according to the combination of particles detected in the cylindrical spectrometer (CDC): none (hereafter called none event), only a π^+ (π event), only a proton (p event), a proton and a π^+ ($p\pi$ event), two protons ($2p$ event), and others. All types except none events were almost free from background. Inclusive cross sections were thus obtained as a sum of all six event types. Using the calculated neutron efficiency mentioned above, the peak position in the inclusive cross section agreed well with previous measurements at LAMPF [12] but the cross section at the peak was 15% less. Figure 1 shows the inclusive double-differential cross section for the C(p,n) reaction (bottom), together with bands corresponding to the fractions of each event type in the Δ excitation energy region (top). Note that the detector acceptance is so large that at least one charged particle is detected in 80% of all (p,n) events. No acceptance corrections have been made for this or succeeding figures; these corrections must certainly be model dependent. The fraction of $2p$ events remains constant at about 15% throughout the Δ region. These events, forbidden for the H target, might naturally arise from the $\Delta N \rightarrow NN$ process in nuclei, possibly with intermediate steps. The $p\pi$ fraction is roughly similar to the π fraction at low neutron momenta, but the π fraction becomes dominant at higher momenta. For H, where $p\pi^+$ is the only allowed decay mode for the Δ, the fractions of $p\pi$, π, none, and p events observed are about 65:20:10:5,

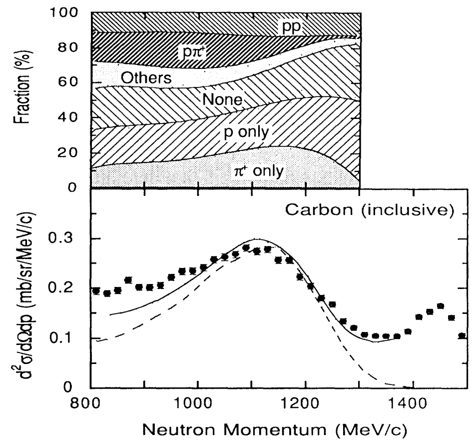

FIG. 1. Bottom: Double-differential cross sections for (p,n) reactions at 1.5 GeV/c on C between 0° and 6°. The solid line shows cross sections (×0.85) for the same reaction at 1.46 GeV/c at 4° [12] with a shift of -35 MeV/c to account for the difference in incident momentum. A calculation of quasifree Δ (with a mass of 1207 MeV and a width of 190 MeV) production is shown by the dashed line. Top: The fraction of each event type.

in reasonable agreement with Monte Carlo calculations accounting for the detector acceptance. At least part of the relative increase in π events for C can be attributed to production of the Δ^+ on the neutrons in the target, but this would be expected to be a constant percentage of $p\pi$ events.

Now we turn our discussion to a detailed study of the $p\pi$ events. Figure 2(a) shows differential cross sections for the (p,$np\pi^+$) reaction on C and H. The peak in the C spectrum is significantly broadened and shifted somewhat toward lower momenta (higher excitation energy). Such changes are the result of many possible dynamical factors. To get a feeling for their magnitude, the C spectrum can be fitted by naively introducing an effective binding energy of 40 MeV and a Fermi motion of Gaussian form with a width (σ_F) of 120 MeV/c (solid line). The centroid of this fitted peak is thus shifted by about 100 MeV/c lower than the inclusive C peak. The dashed line shows the results for H with the standard mass (1232 MeV) and width (115 MeV) of the Δ. The ratio of the C and H cross sections here is 1.22 ± 0.04. This agrees well with the (p,$p'\Delta^0$) data at 4 GeV/c [10], where the target-mass dependence of the cross section was discussed based on an intranuclear cascade model.

While the position of the Δ peak found here in the neutron spectrum in coincidence with $p\pi^+$ is similar to that found in the 4-GeV/c Δ^0 experiment, the distribution of the invariant mass ($M_{p\pi^+}$) of a proton and a π^+ does not yield the standard free-space values. Figure 2(b) shows $M_{p\pi^+}$ distributions for the C and H targets. The distribution for the H target is well expressed by a Breit-Wigner function with standard mass and width (solid line). But

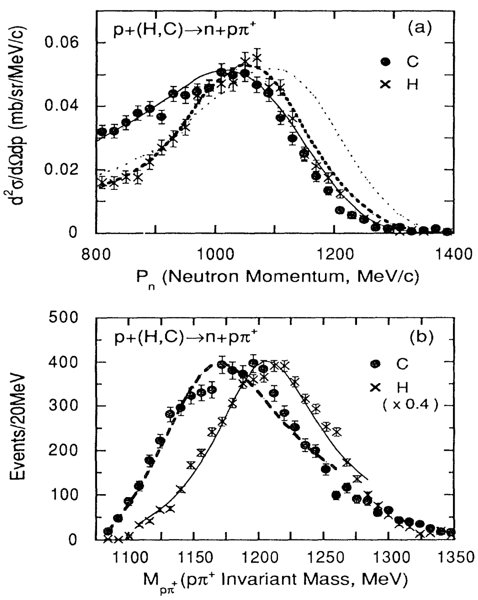

FIG. 2. (a) Momentum spectra of forward neutrons for $p\pi$ events on C and H targets. The lines show our model calculation with the mass and width of the Δ the same as those in free space ($M=1232$ MeV and $\Gamma=115$ MeV). The binding energy (Q) and Fermi motion (σ_F) are $Q=40$ MeV, $\sigma_F=120$ MeV/c (solid line), $Q=0$, $\sigma_F=0$ (dashed line), and $Q=0$, $\sigma_F=120$ MeV/c (dotted line), respectively. (b) Distributions of $p\pi^+$ invariant mass for C and H targets. Breit-Wigner functions with $M=1225$ MeV and $\Gamma=115$ MeV (solid) and $M=1207$ MeV and $\Gamma=190$ MeV (dashed) are also shown.

the C data yield a mass of 1207 ± 7 MeV and a width of 190 ± 25 MeV (dashed line) and the fit is not very good. This value of the mass would be expected to yield a peak at a higher neutron momentum than observed in Fig. 2(a). The effect of distortions on the outgoing proton and pion should be the first thing to consider in explaining this apparent discrepancy.

Figure 3 compares cross sections on C for π and $2p$ events with those for the $p\pi$ events shown above. Both the π and $2p$ events peak at a much higher neutron momentum than the $p\pi$ events, and their peak positions are similar to the peak position in the inclusive C spectrum. These events thus contribute in a major way to the shift in the inclusive spectrum relative to H. (Roughly 30 MeV/c of the shift in the π spectrum can be attributed to the CDC acceptance; this can be seen in the H data and is reproduced by the Monte Carlo calculations.) It is worth noting that the distribution of total energy detected for π events is maximum close to the beam energy. Pure π events are particularly interesting, since they can occur, for example, if the nucleon from Δ decay is reabsorbed in an empty nuclear orbit. Coherent pion production corresponds to such events with no missing energy. Other π events can arise from acceptance or energy threshold losses of accompanying protons, or from target or projectile excitation to Δ^+ and subsequent decay into neutron and π^+. Projectile excitation in fact has been suggested as a possible explanation of the shift in the inclusive peak [13].

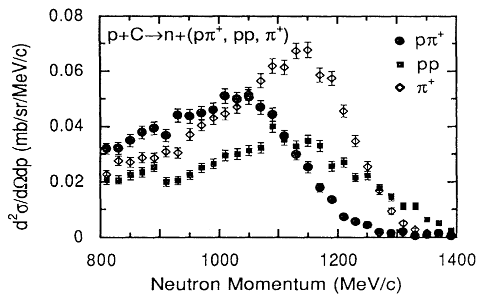

FIG. 3. Momentum spectra of forward neutrons for π, $2p$, and $p\pi$ events on C targets.

Contour plots of invariant cross sections ($E\,d^3\sigma/dp^3 = d^2\sigma/2\pi p_t\,dp_t\,dy$, where y is rapidity and p_t is transverse momentum) of pions for events with neutron momentum greater than and less than 1.05 GeV/c (the momentum corresponding to the H inclusive peak) are shown in Fig. 4. Such plots suggest many interesting features of Δ excitation in (p,n) reactions. (1) For example, the centroid of the entire distribution in each plot occurs around $y\sim0.4$, as expected if the pions arise from Δ's created in a single nucleon-nucleon collision. If the incoming nucleon interacted with a two-nucleon cluster to create the Δ, the rapidity of this source of pions would be about 0.2. (2) The plot suggests that projectile excitation is not dominant for events with $p_n > 1.05$ GeV/c, as suggested in Ref. [13]. In this case, in order to detect a high-momentum forward neutron as required, the pion would have to be emitted backward in the Δ frame from a Δ moving forward. This would give an enhancement around $y\sim0$. Yet the two plots are quite similar in this region. (3) Both plots show peaks in the cross sections for pions moving forward and backward relative to the Δ source velocity. This forward-backward peaking of the pion angular distribution in the Δ frame may indicate an alignment of the Δ's as previously observed in free pp collisions [14]. The fact that we see no significant changes as a function of neutron momentum in the pion angular distribution puts constraints on theoretical models based on proposed medium modifications of the longitudinal response.

In summary, these first coincidence measurements for (p,n) reactions in the Δ region contain a wealth of information on the production and propagation of Δ's in the nuclear medium. They require a thorough experimental analysis to compare the multidimensional data for C and H in a convenient manner, appropriate for comparison with theory. Our initial analysis has revealed several striking features. The position of the Δ-production peak in the neutron spectrum for C depends critically on the

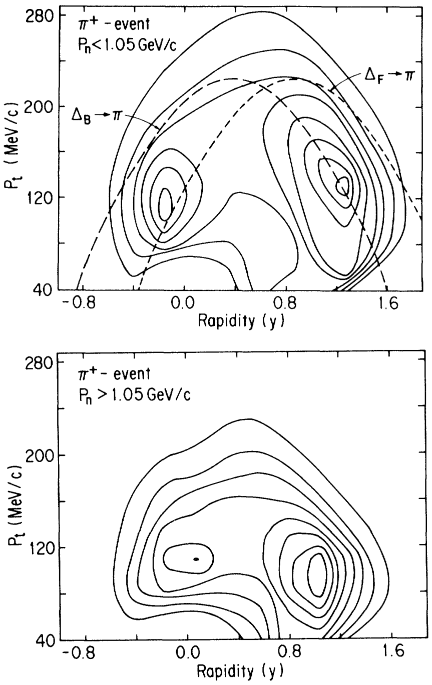

FIG. 4. Contour plots of invariant cross sections ($E\,d^3\sigma/dp^3 = d^2\sigma/2\pi p_t\,dp_t\,dy$, where y is rapidity and p_t is transverse momentum) of pions for π events. Events with $p_n < 1.05$ GeV/c were used for the top figure and with $p_n > 1.05$ GeV/c for the bottom. Each contour is drawn at a constant step, $\frac{1}{9}$ of the peak values, the ratio of which is 1(top):2.4(bottom). Dashed lines present kinematical lines for pions decaying from a Δ with the mass of 1232 MeV produced at 0° (F) and 180° (B), respectively.

particles observed in coincidence with the neutrons. While the $p\pi^+$ decay yields a peak shifted somewhat toward higher excitation energy compared to the free position, observation of a single pion or of two protons in coincidence with the neutron yields a peak strongly shifted in the opposite direction. Nevertheless, the invariant mass of the Δ determined from the $p\pi^+$ decays is lower than the mass of the free Δ, and the width of the Δ determined in this way is also larger than the free width. A rapidity analysis of the cross section for neutron-single pion events suggests that the pion is created in a collision with a single nucleon, and that projectile excitation is not large enough to account for the shift in the observed spectrum. It is possible to speculate at length on the basis for these observations, but it is better to await detailed predictions of theoretical models.

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[1] V. G. Ableev *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **40**, 35 (1984) [JETP Lett. **40**, 763 (1984)].

[2] D. Contardo *et al.*, Phys. Lett. **168B**, 331 (1986).

[3] B. E. Bonner *et al.*, Phys. Rev. C **18**, 1418 (1978).

[4] P. J. Riley *et al.*, Phys. Lett. **68B**, 217 (1977).

[5] J. Chiba, Nucl. Phys. **A478**, 491c (1988).

[6] R. M. Sealock *et al.*, Phys. Rev. Lett. **62**, 1350 (1989), and references therein.

[7] T. Udagawa, S.-W. Hong, and F. Osterfeld, Phys. Lett. B **245**, 1 (1990).

[8] J. Delorme, in *Proceedings of the Seventh International Conference on Polarization Phenomena in Nuclear Physics, Paris, 1990,* edited by A. Boudard and Y. Terrien (Les Editions de Physique, Paris, 1990), p. C6-125.

[9] T. Hennino, Nucl. Phys. **A527**, 399c (1991); B. Ramstein *et al.*, in Proceedings of the Conference on Spin and Isospin in Nuclear Interactions, Telluride, Colorado, 1991 (Plenum, New York, to be published).

[10] T. Nagae *et al.*, Phys. Lett. B **191**, 31 (1987).

[11] H. En'yo, Ph.D. thesis, University of Tokyo, 1984 (unpublished); K. Ichimaru *et al.*, Nucl. Instrum Methods Phys. Res., Sect. A **237**, 559 (1985).

[12] R. G. Jeppesen, Ph.D. thesis, University of Colorado, 1986 (unpublished).

[13] E. Oset, E. Shiino, and H. Toki, Phys. Lett. B **224**, 249 (1989).

[14] E. Colton and A. R. Kirschbaum, Phys. Rev. D **6**, 95 (1972); A. B. Wicklund *et al.*, Phys. Rev. D **35**, 2670 (1987).