Interference Effects in $^{16}O(\pi^\pm, \pi^\pm p)^{15}N$ and Δ-Nucleus Interactions

G. S. Kyle, P.-A. Amaudruz, Th. S. Bauer, J. J. Domingo, C. H. Q. Ingram,
J. Jansen, D. Renker, and J. Zichy
Schweizerisches Institut für Nuklearforschung, CH-5234 Villigen, Switzerland

and

R. Stamminger and F. Vogler
Physikalisches Institut, Universität Erlangen-Nuernberg, D-852 Erlangen, Germany
(Received 7 November 1983)

First results for $^{16}O(\pi^\pm, \pi^\pm p)^{15}N_{g.s.}$ at 240 MeV for $\theta_\pi = 35°$, 60°, and 130° in quasifree kinematics are reported. π^+/π^- cross-section ratios much greater than for scattering by free protons are interpreted as due to a Δ-*N* interaction interfering with the quasifree process.

PACS numbers: 25.80.Ls, 21.30.+y

The quasifree pion-nucleon interaction, which has an important role in the pion-nucleus reaction dynamics, is substantially modified in the region of the Δ(1232) resonance by the surrounding nuclear medium.[1] The dominance of the Δ and the nonlocality of the interaction through its recoil provide a natural framework to describe the medium modifications through Δ-nucleus interactions. The validity of such a description has been demonstrated in the analysis of total and elastic cross sections.[2] Thus studying the pion-nucleus reaction dynamics provides the opportunity to examine the interaction of a strong baryon resonance with the nuclear medium.

Modifications to the pion-nucleon interaction may be studied more directly with quasielastic scattering than in coherent processes like elastic scattering. A systematic study of this reaction in the resonance region was recently provided in a one-arm measurement of $^{16}O(\pi^+, \pi^{+\prime})$.[3] Calculations in the Δ-hole model[4] reproduce these results well and emphasize the importance of the effects of the nuclear medium on the Δ and its propagation.

We report here first results from a kinematically complete experiment surveying the reaction $^{16}O(\pi, \pi p)^{15}N$, in which the quasifree π^+-*p* and π^--*p* reactions have been compared. In this experiment the kinematics of the interaction is better defined than in one-arm experiments, and so the interaction may be examined in more explicit detail. With sufficient energy resolution, the direct process may be identified free from incoherent multistep backgrounds. Further, by the requiring of a knockout proton, it is possible to compare the weak π^--*p* interaction with the π^+-*p* one (which is about 8 times stronger at 240 MeV because of the $I = \frac{3}{2}$ resonance). The weak channel might generally be expected to be more affected by the nuclear medium, and so the ratio of π^+-*p* to π^--*p* quasielastic scattering may be a useful investigative tool. π^+/π^- ratios very different from those for free π-*p* scattering may be a good indicator of medium effects.

Deviations from free ratios have previously been reported by Piasetzky *et al.*[5] in the reaction $^{12}C(\pi^\pm, \pi^\pm p)$ at 245 MeV. They identified the direct knockout strength from the π-*p* angular correlation only. While unseparated incoherent backgrounds might add to both reactions and depress the π^+/π^- ratio, at the peak of the angular correlation enhancements of up to 50% were reported.

In the experiment reported here, the particles' energies and angles have been measured, so that the excitation and recoil momentum of the residual ^{15}N nucleus are known. The 3-MeV resolution is sufficient to identify the ^{15}N ground state, which is dominantly populated by direct $p_{1/2}$-shell proton knockout.

The experiment was performed at the Schweizerisches Institut für Nuklearforschung with the πM1 beam line and spectrometer,[3] and a proton detector built for this purpose. A second quadrupole was added to the spectrometer for this experiment to enlarge the transverse acceptance. The incident flux was 10^7 π^+/sec and 3×10^6 π^-/sec with a 100% macro duty cycle. 3.5- and 8.5-mm-thick rectangular water targets with 30-μm Mylar windows were used at angles chosen to maintain the ^{15}N excitation-energy resolution. Data were taken at 35°, 60°, and 130° pion angles (by which the data sets are identified in this text), with the proton arm near the corresponding quasifree angle. Measurements were made for a range of spectrometer momentum settings over the quasifree peak. The geometry was unchanged for the π^+/π^- comparison.

The proton arm consisted of three plastic scintillator telescopes placed 500 mm from the target in a cylindrical geometry with 17.5° spacing. Each had a 5-mm-thick dE/dx counter followed by two 150-mm-thick E counters and a veto counter, and subtended 15° horizontally by 50° vertically. The proton angle was measured with two multiwire proportional chambers. Protons were identified by time-of-flight, dE/dx, and E analysis. Energies from 35 to 200 MeV were analyzed with 3% resolution at 100 MeV, and a typical efficiency of 75%.

For the 130° data, the proton arm was placed with one of the telescopes in the incident beam, but with a tungsten alloy beam stopper in front of it. This enabled a π^+ beam of 5×10^6/sec to be used, but obscurred a $\pm 8°$ square angular bin. No substantial backgrounds were caused by this beam stopper.

Pileup flags were set if a particle was detected in a large proton counter less than 150 nsec before an event, which was then rejected; for the 35° and 60° data these comprised $< 5\%$ of all triggers, and for the 130° data $< 15\%$ of triggers in each telescope. Accidental coincidences were monitored and negligible, except at 130° where up to 6% of the triggers were caused by two simultaneous incident particles, one of which passed directly into the proton arm. Such triggers were eliminated before determination of efficiencies for true events. A few target-empty runs were taken and raw rates found to be $< 5\%$ of full-target rates.

The corrections for efficiencies and acceptances needed to determine the $(\pi, \pi p)$ cross sections were calibrated by free π^+-p scattering and will be described elsewhere.[6] The cross sections shown here are preliminary. However, in the π^+/π^- ratios most of these corrections identically cancel, or are easily measured. At 60° and 130° the free $\pi^\pm$-p cross sections were measured with the water targets, and the ratios agreed with those given by phase shifts[7] to $< 5\%$.

Figure 1 shows ^{15}N excitation spectra for $(\pi^+, \pi^+ p)$ and $(\pi^-, \pi^- p)$ near the quasifree kinematics; both spectra are dominated by two peaks at 0 and $6\frac{1}{2}$-MeV excitation. Since both peaks behave similarly, falling off away from the quasifree kinematics, we attribute them to direct $p_{1/2}$ and $p_{3/2}$ shell proton removal, the peak at $6\frac{1}{2}$ MeV excitation being mainly the $\frac{3}{2}^-$ one-hole state at 6.32 MeV. We present here only cross sections and ratios for the ground-state reaction, selected by a cut applied at 3–4 MeV. At 130° the resolution was 5 MeV full width at half maximum, and so this cut did not select the ground state cleanly, but the results are dominantly for p-shell knockout.

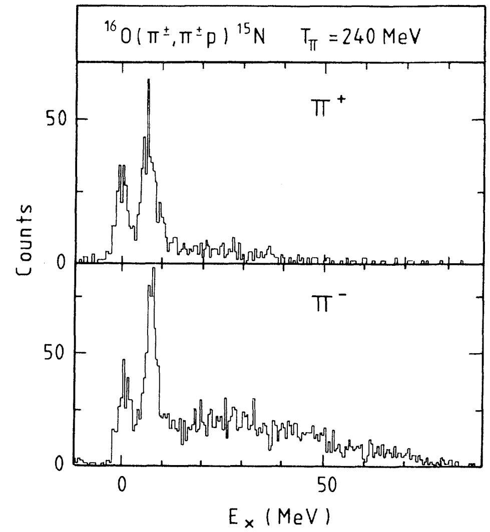

FIG. 1. Excitation-energy spectra of the residual $^{15}N_{g.s.}$ nucleus for π^+- and π^--induced reactions, for $\theta_\pi = 60°$, $\theta_p = -35°$, and $T_{\pi'} = 110$–170 MeV.

In Figure 2(a) we show cross sections for the reaction $^{16}O(\pi^\pm, \pi^\pm p)^{15}N_{g.s.}$ as a function of outgoing pion energy, for protons in our detector which covered about 75% of the quasifree yield. The minimum knockout proton energy was 35 MeV. A $\pm 8°$-wide square around the beam is excluded from the 130° data. The cross sections should be reliable to $< 20\%$: Only statistical uncertainties are shown. The cross sections peak near the energy for free π-p scattering, showing a Fermi-broadened quasifree bump as already seen in the one-arm results.[3]

In Fig. 2(b) we show ratios of the π^+ cross sections of Fig. 2(a) to π^--induced ones. The uncertainties shown are statistical, but others should be less than 10%. In Fig. 2(b) we include a comparison with estimates of the ratio in the plane-wave impulse approximation (PWIA). For simple quasifree scattering the ratios should be given fairly well by the PWIA since optical distortions should be similar for the nearly charge-symmetric system and Coulomb effects will be small. At 130° the measured ratios are similar to or smaller than the PWIA ratio, but at the forward angles ratios over three times the PWIA ones are observed. It should be noted that the large ratios occur in the vicinity of the peak of the quasifree cross section., and are not artifacts of phenomena occurring in low-cross-section tails. For the $p_{3/2}$ shell knockout peak simi-

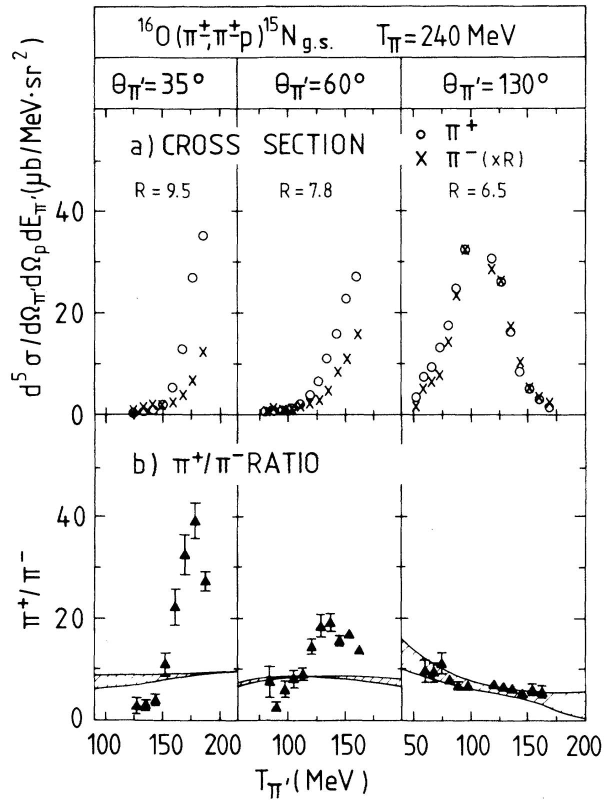

FIG. 2. (a) Differential cross sections for $^{16}O(\pi^{\pm}, \pi^{\pm}p)^{15}N_{g.s.}$ for each pion angle, and for the full proton acceptance, as a function of $T_{\pi'}$. The π^- data are multiplied by R, the free π^+p/π^-p cross-section ratio. (b) Ratios of π^+- to π^--induced cross sections for the conditions in (a); the hatched areas show the range of PWIA estimates using the initial- or final-state kinematics to define the interaction.

lar behavior is seen, but at high ^{15}N excitations ratios less than the PWIA value are usual, presumably because of a strong contribution from incoherent two-step processes in the (π^-, π^-p) reaction. In Fig. 3 we show ratios of cross sections measured in each of the three telescopes; the yields in the side telescopes were typically 50% of that in the central one.

The large ratios seen imply that the quasielastic process itself is substantially modified since they cannot be understood in the simple impulse-approximation picture. Since the strong π^+-p cross section is unlikely to be enhanced by a factor of 3, the primary effect must be from a reduction of the π^--p quasifree amplitude through destructive interference with another process. The reduced π^--p cross section and the substantial kinematic sensitivity of the ratio suggest that not many processes are involved.

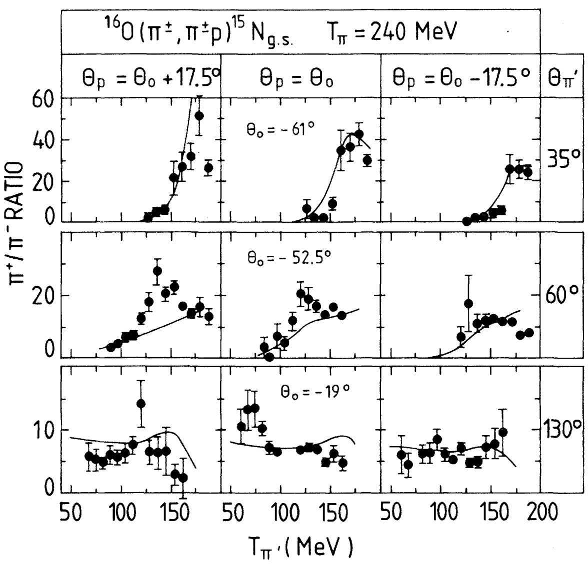

FIG. 3. Ratios of π^+- to π^--induced cross sections to the $^{15}N_{g.s.}$ in each proton telescope, compared to the estimates (solid curves) including Δ-N knockout described in the text (Ref. 8).

Hirata, Lenz, and Thies[9] have suggested that the Δ-nucleus interaction can cause such large changes in the π^+/π^- quasifree ratio. They estimate that an interaction of the Δ, which knocks out another nucleon while its decay nucleon is recaptured in the nucleus, could be a process of comparable strength to π^--p scattering. It may be noted that these hard Δ-N collisons are not contained in the Δ-hole calculations of Thies,[4] which only include effects which may be described by a Δ-nucleus spreading potential. This is inadequate for processes where two nucleons are explicitly involved, as is the case when the knocked-out nucleon is not that of the decaying Δ.

By comparing an amplitude for this Δ-N knockout to an impulse-approximation one, we have made calculations of π^+/π^- ratios,[8] which are also shown in Fig. 3. These Δ-N knockout processes can only affect the π^+/π^- ratios strongly if there is a substantial isospin-1 ($I=1$) Δ-N interaction. ($I=2$ Δ-N states can only lead to $I=\frac{3}{2}$ states of the detected π-p pair, retaining the usual overall isospin structure, and thus alone they cannot alter the π^+/π^- ratio.) We note that pion absorption from Δ-N states also must occur in the $I=1$ channel. These calculations[8] were based on Eq. (61) of Ref. 9 which describes an amplitude containing the direct resonant (P_{33}) πN knockout and a Δ-N knockout process in the $I=1$, $S=2$, s-wave channel. These processes are illustrated in

Fig. 7 of Ref. 9. In these calculations the amplitude of Eq. (61) was evaluated with more appropriate kinematics than indicated in Ref. 9. Relative π-N momenta reconstructed from the final state were used, and the effect on the Δ propagation energy of the recoil of the knocked-out proton was included. These calculations are only estimates since Pauli blocking, distortions, nonresonant π-N amplitudes, interactions in other Δ-N channels, and effects such as coherent (n,p) final-state interactions have been ignored.

The $I=1$ transition strength, V_α, which is the only free parameter of Eq. (61), was chosen to give simultaneous agreement with the ratios at all angle pairs shown in Fig. 3, with a value $V_\alpha = -(4\pi)^2(800+i1300)$ MeV fm^3. This strength is consistent with that due to the total Δ-nucleus potential, $V \approx -(4\pi)^2(1000+i1000)$ MeV fm^3.[2,9] The agreement of this rough calculation with the data is surprisingly good, the qualitative trends of the ratios being well represented.

We conclude that the very large $(\pi^+, \pi^+p)/(\pi^-, \pi^-p)$ ratios we have observed are due to an interference with the π^--p amplitude, by a process we identify as Δ-N knockout. This appears to be the most direct manifestation of a Δ-nucleus interaction yet reported. Comparison of these data with more complete calculations, together with analysis of elastic scattering and pion absorption, may lead to determination of the isospin structure of the Δ-N interaction in the nucleus. Further data at this and lower energies are being analyzed.

It is a pleasure to thank Dr. J. Beveridge, Dr. P. A. M. Gram, Dr. R. E. Mischke, and Dr. P. Gheno for assistance in mounting this experiment, and Dr. F. Lenz for his continued interest in it.

[1]See, e.g., C. H. Q. Ingram, Nucl. Phys. A374, 319c (1982), and in Proceedings of the Symposium on Δ-Nucleus Dynamics, Argonne, 1983 (to be published).

[2]Y. Horikawa, M. Thies, and F. Lenz, Nucl. Phys. A345, 386 (1980), and references therein.

[3]C. H. Q. Ingram, P. A. M. Gram, J. Jansen, R. E. Mischke, J. Zichy, J. Bolger, E. T. Boschitz, G. Proebstle, and J. Arvieux, Phys. Rev. C 27, 1578 (1983).

[4]M. Thies, Nucl. Phys. A382, 434 (1982).

[5]E. Piasetzky, D. Ashery, A. Altman, A. I. Yavin, F. W. Schlepuetz, R. J. Powers, W. Bertl, L. Felawaka, H. K. Walter, R. G. Winter, and J. v. d. Pluym, Phys. Rev. C 25, 2687 (1982).

[6]G. Kyle *et al.*, to be published.

[7]J. B. Walter and G. A. Rebka, Los Alamos National Laboratory Report No. LA-7731-MS, 1979 (unpublished); J. R. Carter *et al.*, Nucl. Phys. B58, 378 (1973).

[8]R. Stamminger and F. Lenz, private communication.

[9]M. Hirata, F. Lenz, and M. Thies, Phys. Rev. C 28, 785 (1983).