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$^{16}O(\pi^+,2p)$ reaction at 165 MeV

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New data for the $^{16}O(\pi^+,2p)$ reaction at $T_\pi=165$ MeV are presented. Significant differences with previously published data are discussed. It is found that below 20 MeV excitation approximately 14% of the total absorption cross section is due to a two-nucleon mechanism. Evidence for direct two-nucleon absorption at higher excitation energy is also presented. Including estimates for final state interactions, the present results suggest that about 50% of the absorption cross section is due to two-nucleon processes.

One of the surprising recent developments in pion physics is the suggestion that multinucleon absorption modes in nuclei have unexpectedly large importance. By the term "multinucleon absorption" we refer to processes in which the pion total energy is shared directly by three or more nucleons, rather than a two-nucleon absorption preceded (initial state interaction) or followed (final state interaction) by sequential inelastic collisions. Most of the speculations concerning the importance of multinucleon absorption were stimulated by inclusive $A(\pi^\pm,p)$ measurements[1] and by the extensive semiexclusive $A(\pi^+,2p)$ measurements of Altman and co-workers[2,3] In the latter experiments, two-proton angular correlations were measured for nuclei ranging from ^{12}C to ^{209}Bi at 165 and 245 MeV pion kinetic energy. These data confirmed earlier evidence[4] for absorption on n-p pairs in the nucleus in a quasideuteron configuration. Specifically, on decomposing the angular correlation data into a sum of two Gaussian terms, the authors extracted angular distributions for the narrow Gaussian, which they associated with two-nucleon absorption, and which followed the $\pi^+ + d \rightarrow 2p$ angular distribution. However, integration of these angular distributions produced the rather surprising result that this part of the two-nucleon absorption cross section was $<10\%$ of the total pion absorption cross section. Even with the inclusion of an estimate for final state interaction effects, the authors concluded that less than 30% of the absorption cross section can be attributed to direct two-nucleon absorption.

In this paper we present new measurements of the $^{16}O(\pi^+,2p)$ reaction at 165 MeV. We obtain both significantly larger cross sections than Refs. 2 and 3 and a substantially larger two-nucleon absorption component.

The measurement was carried out at the $\pi M1$ channel of Schweizerisches Institut für Nuklearforschung (SIN). A pion flux of approximately 9×10^6 π^+/sec, measured by an in-beam scintillator, was incident upon a 4 mm thick H_2O target. Protons emerging from the $^{16}O(\pi^+,2p)$ reaction were detected with the SUSI magnetic spectrometer[5] in coincidence with a large (~600 msr) wire chamber and plastic scintillator array.[6] The combined system gave an excitation energy resolution of ~6 MeV.

Measurements were carried out for five angle settings of the spectrometer ($\theta_1 = 30°$, 50°, 76°, 105°, 132°) with magnetic field settings covering a proton energy range of $T_1 = 53$ to 233 MeV. When physically possible, three partially overlapping angle settings of the scintillator array were used to measure coincident protons. These provided an angular coverage of approximately $\Delta\theta_2 = \pm 58°$ centered about the conjugate angle for the $\pi^+ + d \rightarrow 2p$ reaction. The angle θ_2 is the angle of the second proton measured in the reaction plane defined by $\hat{n} = \hat{k}_\pi \times \hat{k}_1$, the momenta of the beam and the proton detected by the spectrometer, respectively. For all settings, the scintillator array covered a range $\Delta\beta_2 = \pm 23°$, where β_2 is the angle of noncoplanarity measured in a plane normal to the reaction plane (defined by $\hat{k}_2 \times \hat{n}$, where $\hat{k}_2$ is the momentum of the second proton). The low energy cutoff of the array was 35 MeV for protons. Further details of the experimental setup and measurements can be found in Ref. 7.

Absolute cross sections were obtained using the measured pion flux, target thickness, solid angles, and efficiencies. The various components of the cross section calculation were carefully checked with measurements of elastic π^+ scattering from ^1H and ^{16}O and numerous measurements of $\pi^+ + d \rightarrow 2p$ using a similar D_2O target. Based on the consistency of these checks, we estimate that the absolute cross sections are determined with an uncertainty of less than 8%.

In Fig. 1 we show typical excitation energy spectra for two angle and spectrometer momentum ranges which emphasize different recoil momenta. At the quasifree angle pair [corresponding to $\pi^+ + d \rightarrow 2p$ kinematics, see Fig. 1(a)] the low excitation energy region dominates. From our previous high resolution measurements[8] we know that the bulk of this low excitation energy cross section corresponds to absorption on $(1p)^2$ pairs leading to the 1^+ (ground and 3.95 MeV), 2^+ (7.03 MeV), and 3^+ (11.0 MeV) states in ^{14}N. In Fig. 1(b) we show the excitation energy spectrum when the angles and energies of the outgoing protons are constrained to "off-quasifree" kinematics that require higher nuclear recoil momenta, thereby favoring absorption on *n-p* pairs with center-of-mass angular momentum $L > 0$. We observe in the spectrum [Fig. 1(b)] a broad peak centered at about 35 MeV of excitation. Based on its location in excitation energy, its dependence on recoil momentum, and expectations that the $(1s)$-$(1p)$ yield should be comparable to the $(1p)^2$ yield,[9] we attribute this broad peak to absorption on $(1s)$-$(1p)$ pairs with orbital angular momentum $L = 1$. This peak is also observed[7,8] at a pion energy of 115 MeV.

In Fig. 2 we present angular correlation data for a spectrometer angle of $\theta_1 = 132°$ and different excitation energy regions. Note that these cross sections are integrated over proton energies ($T_1 = 53$ to 233 MeV, $T_2 = 35$ to 225 MeV) and averaged over the scintillator array solid angle with acceptances of $\Delta\theta_2 = \pm 1.5°$ and $\Delta\beta_2 = \pm 20°$. From the excitation energy spectra and the narrow angular correlations, we conclude that there is a substantial two-nucleon absorption yield up to at least 45 MeV in excitation energy.

In Fig. 3 we present a similar angular correlation for the full excitation energy range, but with angular ranges

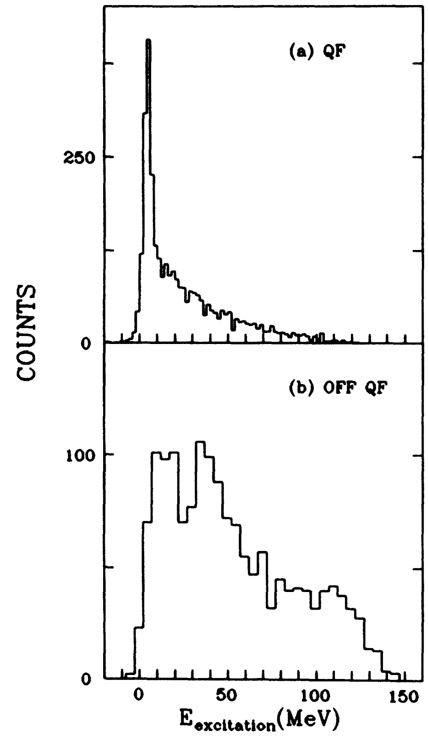

FIG. 1. Excitation energy spectra for $^{16}O(\pi^+,2p)\,^{14}N$ at 165 MeV. Panel (a) corresponds to proton angles centered at $\langle\theta_1\rangle = 50°$, $\langle\theta_2\rangle = -105°$ and a spectrometer momentum bite of 557 MeV/c ($\pm 12\%$), reaction parameters which emphasize low recoil momenta. Panel (b) corresponds to proton angles centered at $\langle\theta_1\rangle = 50°$, $\langle\theta_2\rangle = -87.5°$, and an out-of-plane angle in the range $8° \leq |\beta_2| \leq 23°$. The momentum bite is 471 MeV/c ($\pm 7.4\%$). These reaction parameters emphasize higher recoil momenta ($>$ 100 MeV/c).

of $\Delta\theta_2 = \pm 1.5°$ and $\Delta\beta_2 = \pm 6°$. These angle bins are similar to those used by Altman *et al.*[3] as are our proton energy thresholds, so that we may compare the two sets of data. We note that the energy thresholds for the backward angle detector ($\theta \sim 130°$) are stated to be 30 MeV for Ref. 3, whereas in the present experiment the threshold is higher at about 53 MeV. For the forward angle detector ($\theta \sim 30°$) Altman *et al.*[3] quoted a threshold of 80–100 MeV below the peak of the energy spectrum, corresponding to a proton energy threshold of 90–110 MeV. This is to be compared with our forward angle detector threshold of 35 MeV. We have examined the effect of increasing the threshold to 100 MeV on the scintillator array and find that the angular correlation cross sections presented in Fig. 2 are reduced by $< 1\%$ for 0–20 MeV of excitation energy, $< 3\%$ for 20–45 MeV, and $< 15\%$ for the full excitation energy range. Note that the effect of the energy threshold is not nearly as severe as in the case of the $^{58}Ni(\pi^+2p)$ study of Burger *et al.*[10] where the fraction of strength at low excitation energy is much smaller than in the present case. Given this small change and the off-setting correction arising from the fact that we have a higher energy threshold for the 132° detector (53 MeV vs 30 MeV) which measures the lower energy protons, we feel justified in making a direct comparison with

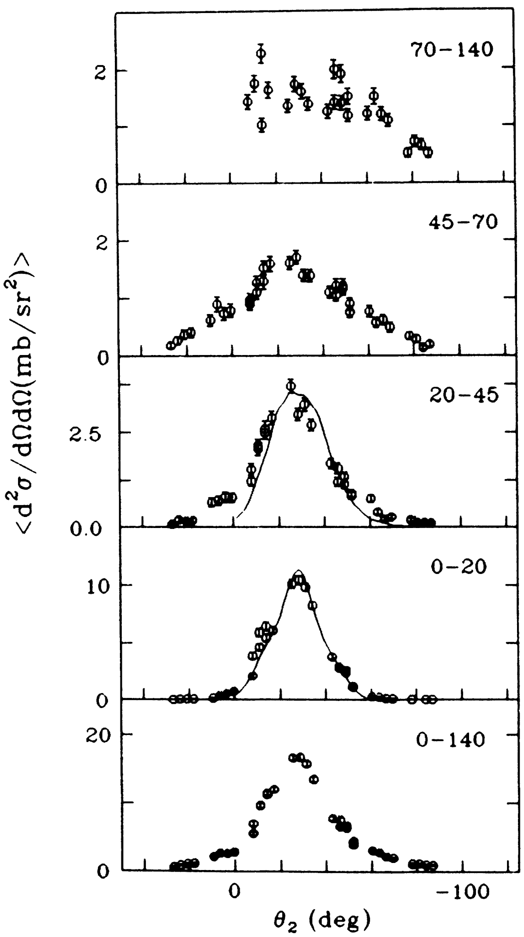

FIG. 2. Angular correlation data for $^{16}O(\pi^+,2p)$ ^{14}N at 165 MeV with $\theta_1 = 132°$. These data have been integrated over proton energies ($T_1 = 53 \rightarrow 233$ MeV) and averaged over a solid angle of $\Omega \simeq 36$ msr ($\Delta\theta_2 = \pm 1.5°$ and $\Delta\beta_2 = \pm 20°$). Each panel corresponds to a different range of excitation energy as indicated. The large solid angle average has a significant effect on vertical cross section scale. Only statistical errors are indicated. The curves represent DWIA (0-20 MeV) and DWIA plus phase space (20-45 MeV) calculations.

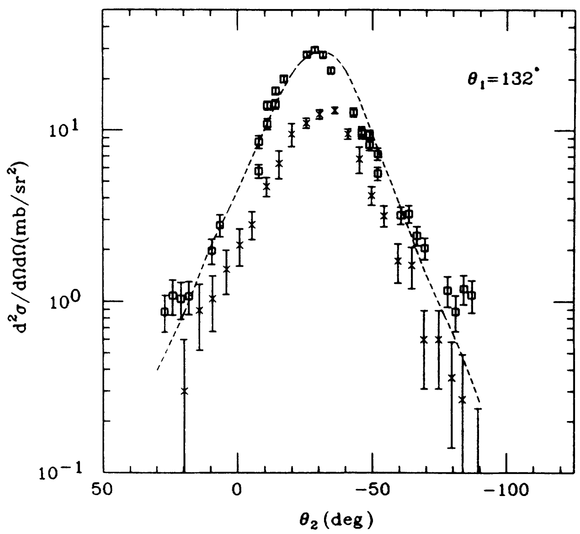

FIG. 3. Angular correlation data for $^{16}O(\pi^+,2p)$ ^{14}N at 165 MeV. These data are as in Fig. 2, but with the data constrained to $\Delta\beta_2 = \pm 6°$ ($\Omega \simeq 11$ msr). The squares are data from the present experiment for $\theta_1 = 132°$ and the full excitation energy range 0-140 MeV. The crosses are from Ref. 3 for $\theta_1 = 130°$ shifted by 2°. The dashed curve is a smooth curve through the data of Ref. 3 and renormalized by a factor of 2.3

the data of Ref. 3.

The comparison of the two sets of data is made in Fig. 3 where the data of Ref. 3 have been shifted by 2° to adjust for the fact that this measurement was made at $\theta_1 = 130°$. Clearly, a large discrepancy in magnitude exists. The dashed curve, a smooth curve through the data of Ref. 3 renormalized by a factor of 2.3, agrees quite well with our data. Based on our comparisons with other measured cross sections ($\pi^+ + {}^1H$ and $\pi^+ + {}^{16}O$ elastic scattering and $\pi^+ + d \rightarrow 2p$) and the consistency of our results obtained from three measurements over an eighteen-month period, one of which (Ref. 8) used NaI detectors instead of the plastic scintillator array, we believe that our present cross section measurements are correct. Note that the agreement in shape suggests that the differences in cross sections are due primarily to the overall normalization.

To obtain an estimate of the total yield for two-nucleon absorption, we have chosen to divide the data into two excitation energy regions to emphasize the contributions from the different shell model orbitals in ^{16}O. Note that the use of a simple two Gaussian analysis of the full excitation energy range, such as that used in Ref. 3, is guaranteed to produce an integrated cross section of more than twice that extracted in Ref. 3, since the shape of our angular correlation data is essentially the same, whereas our peak cross section is a factor of 2.3 larger. Below 20 MeV excitation, a region corresponding to absorption on $(1p)^2$ pairs, we extrapolated our angular correlation data to the unmeasured regions using distorted-wave impulse approximation (DWIA) calculations[7,8,11] which provided excellent fits to the measured 0-20 MeV data; the extrapolations contain only 10-25% of the cross sections. The normalized DWIA calculation is shown in Fig. 2. Fits at other angles with the same normalization are comparable. Integrating the data we obtain an angular distribution [presented in Fig. 4(a)] whose shape is identical (within errors) to the $\pi^+ + d \rightarrow 2p$ angular distribution and leads to an integrated cross section of 26.1 ± 1.6 mb. This is approximately 14% of the total pion absorption cross section[12] of 188 ± 36 mb.

In this excitation energy region below 20 MeV the contribution from processes involving initial and final state rescattering should be very small. We therefore used DWIA calculations[7,8,11] to estimate that final state interactions reduce the yield in the excitation energy region below 20 MeV by a factor of 2.2. These DWIA calculations use optical model potentials which predict the ratios[13] of $(e,e'p)$ exclusive to $A(e,e')$ inclusive cross sections at the quasifree peak to better than 15%. This factor of 2.2 is significantly smaller than that of 3.3 used in Ref. 3 based on intranuclear cascade code (INC) calculations which tend to use effective mean free paths which are too

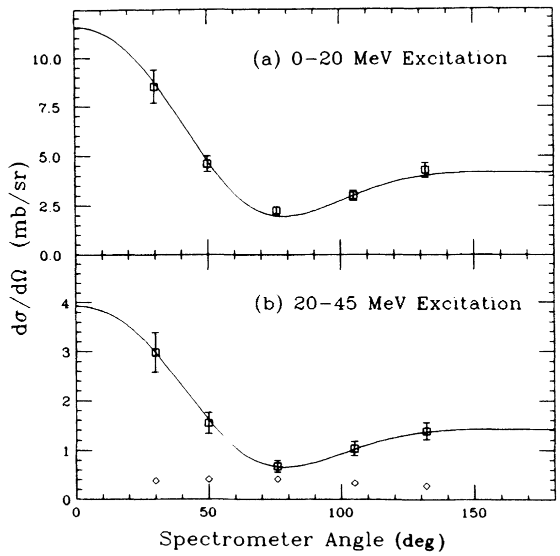

FIG. 4. Angular distributions obtained for (a) the 0–20 MeV and (b) the 20–45 MeV excitation regions. In panel (a) the data have been integrated and extrapolated using DWIA calculations. In panel (b) a background component (diamonds) obtained from spectator model phase space calculations was subtracted and the resultant extrapolated again using DWIA. The solid lines represent the shape of the $\pi^+ + D \rightarrow 2p$ angular distribution arbitrarily normalized at 105°. The error bars reflect the uncertainties in the efficiency and acceptance corrections and in the separate normalizations to $D(\pi^+,pp)$ data obtained at each angle. Not included is an additional overall error of $\pm 16\%$ assigned to the 20–45 MeV cross sections for the uncertainty in the background determination.

short.[14] Using our estimates, we determine that 57.4 mb or 31% of the total absorption cross section proceeds via the first 20 MeV of excitation energy.

To evaluate the two-nucleon absorption component at higher excitation energies in the region of four-body (or more) final states is much more difficult. Here one can no longer cleanly separate direct two-nucleon absorption on more tightly bound nucleons from an underlying background resulting from absorption preceded or followed by inelastic collisions which remove an additional nucleon, or for that matter from multinucleon absorption. However, the narrow angular correlations observed for the 20–45 MeV excitation energy region and the presence of a broad peak at 35 MeV excitation with the characteristics expected for absorption on a $(1s)$-$(1p)$ pair leads us to conclude that there is significant direct two-nucleon absorption yield in this excitation energy range. To obtain a reasonable estimate of this yield in the 20–45 MeV excitation energy region, we have carried out an analysis of the data using a combination of DWIA and multinucleon phase space calculations. In particular we assume that the absorption on a $(1s)$-$(1p)$ pair can be adequately described by the DWIA calculations. For the underlying "background," whether from multinucleon absorption or initial and final state interactions, we assume that these can be described by four-body phase space calculations in which three nucleons are emitted while the fourth body, the residual nucleus, is confined to a Gaussian momentum distribution with a width given by $\sqrt{3}\times 80$ MeV/c; i.e., effectively a spectator model for absorption on a three-nucleon cluster. The choice of this phase space calculation is justified by the remarkable success obtained by Tacik *et al.*[15] in using the same model to describe their extensive $^{12}C(\pi^+,3p)$ data.

The phase space calculations for our detector acceptances were carried out with the European Organization for Nuclear Research (CERN) codes FOWL/GENBOD.[16] Integrating these calculations leads to a background angular distribution which was normalized and subtracted from the experimental angular distribution for the 20–45 MeV region. The resultant was then extrapolated to unmeasured regions of phase space using the DWIA calculations. The normalization of the background phase space calculation was angle independent and was adjusted until the extrapolated resultant reproduced the $\pi^+ + d \rightarrow 2p$ angular distribution. This result is presented in Fig. 4(b) along with the normalized background phase space angular distribution. A comparison of the calculation to the angular correlation data is shown in Fig. 2. Integration of the resultant angular distribution leads to a total two-nucleon absorption cross section of 8.6 ± 1.5 mb, where the error represents the variation in the background normalization which provides an acceptable fit to the $\pi^+ + d \rightarrow 2p$ angular distribution. Again using the DWIA calculations to estimate final state interactions, we obtain 21.6 mb or 12% of the total absorption cross section to be associated with $(1s)$-$(1p)$ absorption ($L=1$ quasideuterons). A similar analysis was used to extract an additional 11.4 mb of possible direct yield present in the 45–70 MeV excitation range.

The inclusion of the 20–45 MeV region of excitation energy increases our directly measured fraction of the total absorption cross section arising from two-nucleon absorption to $\sim 19\%$ or about twice that reported in Ref. 3. A comparable discrepancy would also appear to exist with the work of Yokota *et al.*[17] who extract two-nucleon absorption cross sections for $^{12}C(\pi^+2p)$ which are similar to Ref. 3. After correcting our cross sections for final state interactions the two-nucleon absorption fraction increases to about 42%. One should presumably add to this a contribution of roughly 2% of the total absorption cross section from the weak (π^+,pn) channel which is about $\frac{1}{24}$ of the $(\pi^+,2p)$ yield.[3] Thus, taking into account the uncertainty in absorption cross section, we would attribute a fraction of between 35% and 53% of the total absorption cross section to two-nucleon absorption (or 40% to 60% with the inclusion of the yield from the 45–70 MeV excitation region). These results neglect any contributions from initial state interactions which have not been quantitatively established experimentally.[10,18–20]

In conclusion, we believe that the earlier reported $^{16}O(\pi^+,2p)$ cross sections are too small and thus underestimate the two-nucleon absorption mechanism. We note that a comparable discrepancy in cross section is observed between the $^{58}Ni(\pi^+,2p)$ data of Burger *et al.*[10] and the $Fe(\pi^+,2p)$ data of Ref. 3. We thus believe that the data of Altman *et al.* should be renormalized by approximately the factor of 2.3 found here. We have also identified direct two-nucleon absorption strength in the excitation energy range of 20–45 MeV, which we attribute to absorption on $(1s)$-$(1p)$ pairs. Based on the present work the fraction of the total absorption cross section which can be attributed to a two-nucleon absorption mechanism is approximately 50%. This value was obtained using a phase space calculation to estimate the background in the higher excitation energy regions. We again note that a simple two Gaussian analysis of our data would lead to a comparable value. More refined estimates of the yield will be presented in a future publication. However, we expect a significant fraction of the absorption cross section will remain unexplained and could be attributable to multinucleon absorption.

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