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WIDE ANGULAR RANGE STUDY OF THE REACTION

$^{16}\text{O}(\pi^-, 2n)^{14}\text{N}$ WITH STOPPED PIONS^{*}

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ABSTRACT

A first kinematically complete investigation of the reaction $^{16}\text{O}(\pi^-, 2n)^{14}\text{N}$ with stopped pions has been performed at the CERN SC over a wide angular range.

Measured distributions in excitation energy of the residual nucleus, recoil momentum, and angle between the two neutrons are presented. They are compared with theoretical predictions on two-hole states and with detailed calculations on the quasi-free two nucleon absorption process.

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1. INTRODUCTION

The results of a systematic study of the $(\pi^-, 2n)$ reaction with stopped pions in light nuclei have been reported in a series of recent publications [1-4]. The general motivation for this study had two major aspects: namely, to explore the reaction mechanism, and to gain nuclear structure information.

The emphasis was on the former aspect. Concentrating on the absorption by a nucleon pair, we have studied the influence of the two-nucleon quantum numbers -- such as orbital angular momentum, spin, and isospin -- on the πNN interaction. Also, a careful investigation of the importance of the direct, quasi-free mechanism seemed to us to be necessary. The latter aspect was centred around the characteristics of nucleon pairs, such as separation energies, momentum distributions, and angular momentum structure.

The present paper completes the survey of this reaction type with the data obtained with an ^{16}O target. We laid special emphasis on this nucleus for the following reasons. It is a closed-shell double-magic nucleus, and the removal of two nucleons from the different shells and subshells is expected to produce a large variety of two-hole states (e.g. $p_{1/2}^{-2}$, $p_{1/2}^{-1} p_{3/2}^{-1}$, $p_{3/2}^{-2}$, $p_{1/2}^{-1} s^{-1}$, s^{-2}) with fairly pure configurations. On the other hand, ^{16}O is still a light enough nucleus to expect the direct quasi-free reaction mechanism to be of significant importance.

Many theoretical calculations for pion absorption have been published, virtually all of them being restricted to the quasi-free two nucleon process [5-7] (for references, see also [8]). Several effects such as short-range correlations, final-state interactions, and rescattering have been considered. In a more recent investigation [9] several of these effects are taken into account simultaneously, and explicit recoil momentum distributions and opening angle distributions have been calculated for specific final states. The numbers are given for the absorption of bound pions in ^{16}O . Detailed comparisons with respective experimental data of high resolution seem to be very attractive.

On the experimental side, surprisingly little information is available on the $(\pi^-, 2n)$ reaction in ^{16}O . For instance, no excitation energy spectrum has yet been reported. Only data from the charge symmetric $(\pi^+, 2p)$ reaction are known [10, 11] which, on the other hand, offer also an interesting possibility for comparisons with $(\pi^-, 2n)$ data.

A particular aspect of the $(\pi^-, 2n)$ reaction is the possibility to study also deep-lying two-hole states, i.e. configurations with at least one hole in the 1s-shell. So far, very little is known about such states. They could, however, manifest themselves as structures at higher energies in the excitation spectra of the residual nuclei, provided there are quasi-free 2N processes involving s-shell nucleons, and that the lifetime of the respective two-hole states is long enough. The competition of reactions with more than two emitted nucleons has to be considered in this range of excitation energies.

Deep-lying states as well as states with higher angular momenta should both have broad angular distributions. Therefore considerable effort has been spent on extending the angle spanned by the two neutron momenta from the "quasi-deuteron" angle of 180° down to 125° . In this way considerably more information on events with large recoil momenta was obtained (see Section 2).

2. KINEMATICAL AND DYNAMICAL ASPECTS

For every event, the kinetic energies of both neutrons and their relative angle were determined. This allows us to calculate variables which are more directly related to the data interpretation:

- a) Excitation energy E_x of the residual nucleus, defined by $E_x = Q - E_1 - E_2 - E_R$, where Q is the Q-value of the reaction, and $E_{1,2}$ and E_R are the neutron and recoil nucleus kinetic energies, respectively. This quantity, sometimes referred to as the 'missing mass', is (except for an additive constant) identical with $E_S^*)$, the separation energy of a free deuteron. Provided

*) $E_S = E_x + M_B - M_A + m_d$, where M_A , M_B , and m_d are the masses of the target nucleus, recoil nucleus, and the free deuteron, respectively.

there is a quasi-free two-nucleon absorption process, the E_x distribution gives important information on the position of two-hole states and their population by this special reaction. Any deviation of experimentally observed population from calculations of coefficients of fractional parentage (c.f.p.) contains pion-specific information. Unfortunately, c.f.p. calculations are only available for p-shell holes [12].

- b) Recoil momentum q , $q = |\vec{p}_1 + \vec{p}_2|$, where $\vec{p}_1$ and $\vec{p}_2$ are the momenta of the two emitted neutrons. The particular importance of this quantity lies in the fact that it reflects the momentum of nucleon pairs inside the nucleus. In the quasi-free model the pion is absorbed by two nucleons, with the rest of the nucleus acting as a spectator. In this picture the recoil momentum is equal to the momentum of the nucleon pair prior to the absorption. Geometrical and phase-space factors have to be taken into account, of course. In addition, the gross shape of the q -distribution gives an indication of the angular momentum L of the pair c.m. with respect to the target c.m. within the direct quasi-free two-nucleon absorption picture (two-nucleon impulse approximation). The q -distributions are essentially given by the Fourier transform squared of the two-nucleon c.m. wave function. In this case one expects, for $L = 0$, to have q -distributions with a maximum at $q = 0$ MeV/c, and for $L \neq 0$ the q -distributions should fall to zero at $q = 0$ MeV/c (see also ref. 2). Up to now, the effects of the pion absorption mechanism have been neglected in these considerations. They will at least in principle, modify the measured distributions.
- c) Relative momentum p , $2\vec{p} = \vec{p}_1 - \vec{p}_2$, see fig. 1. For a given excitation energy, p is a function of q . Therefore p and q give essentially the same information.
- d) Opening angle ω , spanned by $\vec{p}_1$ and $\vec{p}_2$. This quantity is closely related to q (e.g. for $q = 0$ it follows that $\omega = 180^\circ$).
- e) Angle Θ (see fig. 1), spanned by $\vec{q}$ and $\vec{p}$. The importance of this quantity has been pointed out by Koltun [13], and recently, corresponding distributions

were measured for the first time [2,4]. It has been shown [4] that under certain assumptions a direct quasi-free mechanism will produce an isotropic Θ -distribution. The assumptions consist of a π -nucleon interaction operator of the form $\nabla_{\pi} - a \nabla_N$, a relative s-state ($\ell=0$) of the absorbing nucleon pair, or a single value of the initial state c.m. angular momentum L . In general, the Θ -distributions contain information on reaction mechanism and on angular momentum structure of the nucleon pairs involved in the absorption.

The theoretical description of pion-induced two-nucleon emission is complicated by the necessary inclusion of various effects such as pion rescattering, initial-state two-nucleon correlation, and various final-state interactions. Despite many theoretical efforts [5-7,14] the relative weight of these various parts does not yet seem to be clear. A detailed theoretical investigation has recently been made [9], taking into account the quantum numbers of the absorbing pair and producing momentum and angular distributions for certain residual states or groups of states.

The interpretation of our data is usually done within the framework of a two-nucleon impulse approximation. In this case the transition matrix element factorizes into a two-nucleon and a residual nucleus part [15]:

$$M_{fi} \propto \sum_{\alpha} S_{\alpha}(A, B^*) \phi_{\alpha}(\vec{q}) \langle \vec{p} | T | \psi_{\alpha} \rangle .$$

Here $S_{\alpha}(A, B^*)$ is the spectroscopic factor (c.f.p.) connecting the target state A with the residual nucleus state B^* and the two-nucleon state α ; $\phi_{\alpha}(\vec{q})$ describes the momentum distribution of the two nucleons. The matrix element of T involves only relative coordinates of the two absorbing nucleons.

3. THE EXPERIMENT

Negative pions from the CERN-SC II low-energy pion channel were stopped in a D_2O target of 4.5 g/cm^2 thickness. The monoenergetic neutrons from absorption by the deuterium served as check of the energy calibration. A counter telescope in the beam contained the start counter for the two neutron time-of-flight (TOF)

measurements and a hodoscope providing position information on the pion before entering the target.

The internal proton beam intensity was 1-2 μA , and the resulting pion stopping rate was of the order of $1.5 \times 10^5 \text{ s}^{-1}$.

For the detection of the two neutrons, two large-area, position-sensitive, TOF counters ($200 \text{ cm} \times 48 \text{ cm} \times 9 \text{ cm}$) made of NE 110 were used. Each counter was subdivided into 4 modules of 12 individual rods each. Eight photomultipliers (56 DVP) were used for pulse-height and timing signals. In addition, 30 small tubes (XP 1110) gave information on the rods that had emitted light for each event.

The position of the neutron impact along the counter was determined from the time difference between the arrivals of the light signals at both ends.

A typical time resolution for minimum ionizing particles traversing the counter in the centre was 800 ps FWHM. This includes ~ 300 ps FWHM from the start counter. We finally obtained an excitation energy resolution of 3-6 MeV FWHM, depending on pulse-height threshold, flight path, and E_x . This constitutes a significant improvement over previous measurements, which had ~ 10 -15 MeV FWHM.

A more detailed description of the experimental set-up can be found in ref. 16.

Two independent, overlapping measurements were performed, one with a flight path of 5.8 m and an angle between the centre of the two counters of 169° , and a second one with 4.5 m and 140° . The range covered in angle ω was 150° - 180° and 125° - 160° , respectively. The first measurement will be referred to as I and the second one as II.

The data were recorded via a CAMAC system and a PDP-8L computer. All events were written on magnetic tape for extensive off-line analysis, which was done at the CERN CDC 7600.

With respect to a comparison between the experimental results and theoretical predictions, it is very important to measure absolute rates and have no geometrical

bias. Within the angular range covered, our data are corrected for neutron counter efficiencies and geometrical acceptance. We give the population of residual states as the number of events per stopped pion. The geometrical acceptance was determined by a Monte Carlo simulation program. The neutron counter efficiency was calculated according to the Kurz code [17]; it had been tested experimentally on a prototype counter [18].

4. RESULTS AND DISCUSSION

4.1 Population of two-hole states

In figs. 2 to 4 the excitation energy spectra of the residual nucleus ^{14}N are presented for different regions of the opening angle ω and recoil momentum q . Whereas fig. 2 shows the total of all events obtained in measurement I ($\omega \geq 155^\circ$) and II ($160^\circ \geq \omega \geq 125^\circ$), the spectra of fig. 3 contain additional windows in q .

The spectra exhibit a structure which has to be interpreted as transitions into discrete two-hole states. The arrows at the E_x axis indicate the position of known two-hole states in ^{14}N with $T = 0$. The states are compiled in table 1 [19], together with their spectroscopic factors obtained in $(p, {}^3\text{He})$ [20] and (d, α) [21] reactions and the results of c.f.p. calculations of Cohen and Kurath [12], including the quantum numbers isospin T and angular momentum L . The states listed cover all possible configurations of two p-shell holes. No information is available for two-hole states involving s-nucleons.

All measured spectra show a peak at 4 MeV, which is most pronounced at large ω (fig. 2, lower curve) and small q (fig. 3, lower curve). This peak has been attributed to transitions into the second excited state at 3.95 MeV, which has a large transition strength according to table 1. The exact excitation energy of this dominant transition is also confirmed by two (π^-, γ) -measurements [22,23].

At the energies of the four remaining arrows, virtually no structure can be found in the above-mentioned lower curves of figs. 2 and 3. This is, however, different in the two upper curves, where the relative rates are drastically increased at just these energies. Especially the upper curve of fig. 3 shows clearly

the excitations at the marked energies of 0 MeV, 7 MeV and around 11 MeV. The conclusion that states at all three energies are populated is justified, the transitions into these states, however, being correlated with high recoil momenta.

Such a preference for large q -values must be interpreted with an orbital angular momentum L having a value different from zero (see Section 2). As we consider p -nucleons only, the conclusion can only be $L = 2$. In contrast, the peak at 4 MeV shows opposite behaviour. There the preference for small recoil momenta clearly indicates $L = 0$.

All these conclusions are in full agreement with the L -values given in table 1: the only $L = 0$ state with a large strength is at 3.9 MeV, whereas $L = 2$ states are known to be at 0 MeV, 7.03 MeV, and 11.05 MeV. An additional state at 11.5 MeV has much a smaller strength and is predicted as $L=0 / L=2$ admixture. This state is, of course, too close to the 11.05 MeV state to be resolved experimentally. Nevertheless, a small peak around this energy in the lower curves 2 and 3 could indicate the presence of some $L = 0$ strength from the 11.5 MeV state.

So far, the $T = 1$ states in table 1 have not been considered. The reason is that measurements on π^- absorption with the neighbouring target nuclei ^{14}N [1], ^{12}C , ^{10}B , and ^9Be [2] showed a clear preference for $T = 0$ np pairs. Moreover, the absorption on $T = 1$ pairs is excluded by the Pauli principle under the following assumptions:

- a) $\Delta L = 0$, i.e. no change in the angular momentum of the centre of mass of the pair during pion absorption. This is plausible, as the pion brings in very little momentum.
- b) P -wave absorption, i.e. the pion is absorbed from the atomic $1P$ orbit.
- c) $\ell = 0$, i.e. the relative angular momentum of the two nucleons is zero. This condition seems justified in view of the close correlation of the nucleons required in the absorption process.

For an ^{16}O target, assumption (b) seems to be even better fulfilled than for the nuclei studied in refs. 1 and 2. Hence we did not expect to see strong population of $T = 1$ states.

Experimentally, however, we cannot exclude weaker transitions into $T = 1$ states. Three such states with large strengths are given in table 1. The first one, at 2.31 MeV, is in the close vicinity of the strongly populated $T = 0$ state at 3.9 MeV. A possible contribution of this state to the 4 MeV peak is hard to distinguish; however, from (π^-, γ) measurements it is known to be small [22,23]. The second state, at 9.17 MeV and 10.43 MeV, should have $L = 2$, and it is hard to distinguish it from $L = 2$, $T = 0$ state at 11.05 MeV. The third one has a predicted energy of 17.88 MeV, which coincides with an observed peak at 18 MeV. Since the theoretical energy given in table 1 does not yet seem to be confirmed by any other experiment, and since the observed peak at 18 MeV can also indicate a two-hole state involving s-nucleons, this coincidence should not be overestimated.

Summarizing the region in excitation energy that corresponds to the removal of two p-shell nucleons, we can state that most of the predicted strong two-hole states in ^{14}N are populated. Within a few MeV the strength lies where it is expected to according to table 1. Also the angular momentum assignments have been verified. The expectation of strong $T = 0$ absorption has been fulfilled. The role of the $T = 1$ part must remain less clear until an excitation energy resolution of < 2 MeV is achieved.

A point of considerable interest is the search for deep-lying two-hole states i.e. states involving s-shell nucleons. If the two-hole strength for such states were concentrated in a few places, then it would show up in the experimental results as structure at high excitation energies. Because of the large separation energy, wider q - and ω -distributions for transitions into these states are expected.

Figure 4 shows again the data from measurement II. In order to distinguish more clearly between the true and the statistical structure, the data have been smoothed and plotted for normal (10 MeV) and higher (25 MeV) off-line threshold. The high-threshold data should have better resolution; they have less efficiency, however, especially at high excitation energies. In this energy range two peaks are visible at 31 MeV and 54 MeV, which are good candidates for two-hole states involving s-nucleons.

Estimates of the energies of two-hole states can be made using the energies of known one-hole states. In ref. 2 a surprisingly simple similarity is reported between single and two-nucleon separation energies in ^9Be , ^{10}B , ^{12}C , and ^{14}N , obtained from $(p,2p)$ and $(\pi^-,2n)$ measurements, respectively. The most strongly populated two-hole states seem to have a separation energy which is higher by an empirical factor of 1.62 than that of the most strongly populated single-hole states. For ^{16}O the most strongly populated level in ^{14}N at 3.9 MeV has a separation energy of 24.7 MeV. On the other hand, the $^{16}\text{O}(p,2p)^{15}\text{N}$ reaction has shown two strong peaks at approximately 12 MeV and 18.5 MeV separation energy [24], corresponding to $p_{1/2}^-$ and $p_{3/2}^-$ -removal, respectively. Scaling by the factor 1.62 places our two-nucleon separation energy as lying exactly in the middle between the two single-nucleon separation energies, as if it were a $(p_{3/2}^1 p_{1/2}^1)$ removal. The 3.9 MeV level in ^{14}N is known to have a strong $(p_{3/2}^{-1} p_{1/2}^{-1})$ configuration [20]; thus also the separation energies mentioned above furnish a confirmation of this multiplication factor connecting single- and two-nucleon removal.

Using this factor, our peaks at 31 MeV and 54 MeV excitation energy would correspond to one-particle separation energies of 32.5 MeV and 46 MeV, respectively. It is again surprising to find a peak at 33 MeV in the separation energy spectrum of the $^{16}\text{O}(pd)^{15}\text{O}$ [25], and a broad peak centred around 40-50 MeV in both the $(p,2p)$ and the (p,d) reaction in ^{16}O .

The observed excitation energy spectra can also be compared with results from the $^{16}\text{O}(\pi^+,2p)^{14}\text{N}$ reaction with $E_\pi \approx 70$ MeV [10,11]. The π^+ data show our prominent peak at 4 MeV and little population of the ground state of ^{14}N . Thus π^+ and π^- data show the same kind of similarities that have already been observed for other target nuclei [2,4].

Although the two reactions are connected via charge symmetry, this result is not trivial. Differences in the observed transitions between a π^+ in flight and a bound π^- are expected because of the different initial quantum state of the pion. Also the pion mean free path varies strongly with energy because of the (3,3) resonance. More detailed investigations with higher resolution and at different

pion energies might reveal differences and thus show new aspects of the reaction mechanism.

4.2 Distributions for the variables q , ω , Θ , and E_n

Measured q - and ω -distributions are given in Section 4.3 together with the respective theoretical curves. Figure 9 shows the recoil momentum distributions for the ground state and the 3.95 MeV state. Because of its weak population, the error for the ground-state distribution is rather large. Nevertheless the curve shows the fall-off towards $q = 0$, consistent with an $L = 2$ transition. Note that both parts of the figure have the same arbitrary units.

The recoil momentum distribution of the 3.95 MeV transition being peaked at $q = 0$ MeV/c clearly demonstrates the $L = 0$ character of this transition. Its shape is in good agreement with the reported $(\pi^+, 2p)$ results [11], and in qualitative agreement with (π^-, γ) data [22,23] where this distribution has been obtained via Doppler-broadening of the de-excitation γ -ray. A quantitative comparison shows that the reported distribution from the γ -data is wider than our result by about 20% [22] and 50% [23], respectively.

Figure 10 shows the recoil momentum distribution for excitation energies between 10 MeV and 12 MeV. According to table 1, much of the $L = 2$ strength should be concentrated in this region. Because structure is less pronounced, simple cuts in excitation energy have been used for this q -distribution. The result obtained clearly shows the presence of $L = 0$ contributions, also to be expected according to table 1. The $L = 2$ component is only weakly indicated.

We have already stressed the fact that wide momentum distributions for increasing nucleon-pair separation energies [4] can be expected in the quasi-free absorption mechanism. In fig. 5 we summarize our results for the most prominent $L = 0$ transitions from refs. 1, 2 and 4 by adding the point corresponding to the $^{16}\text{O} \rightarrow ^{14}\text{N}$ (3.95 MeV) transition. The general trend is clearly established and the ^{16}O point fits in very well.

In fig. 11 we present the opening angle ω -distributions integrated over all excitation energies and for the region of the 3.95 MeV state. Measurements I and II have been joined together. The importance of the direct quasi-free reaction mechanism manifests itself in the observed peaking at 180° . This is particularly evident for the 3.95 MeV case. At smaller angles ω and higher excitation energies the contribution of non-direct processes involving more than two nucleons will become more important. Therefore more isotropic ω -distributions are expected there, in agreement with the experiment.

The relevance of the angle Θ spanned by centre of mass and relative momenta of the two nucleons has already been discussed in refs. 4 and 13. In Fig. 6 we present results from the present measurement, for different excitation energies. The distributions are consistent with isotropy, although some fine structure cannot be excluded, particularly in the region of higher E_x (lower part of fig. 6). The observed isotropy for the 3.95 MeV transition is consistent with a direct quasi-free reaction mechanism under the assumptions mentioned in Section 2.

For completeness and for possible future comparisons with theoretical results, we show in fig. 7 the neutron energy distribution for the 3.95 MeV transition. It exhibits a symmetric peak, centred at half the available energy for the two neutrons in the corresponding excitation energy range. The width of the distribution reflects the momentum distribution of the absorbing nucleon pair.

The corresponding relative momentum distribution ($|\vec{p}| = \frac{1}{2}|\vec{p}_1 - \vec{p}_2|$) is given in fig. 8. The way in which the two neutrons share the available energy leads to a very narrow p -distribution centred at rather high relative momenta, thus showing how this process is sensitive to high components of the relative two-nucleon wave function. It should be pointed out that because of momentum exchange between the two nucleons, the measured quantity p is not necessarily the initial relative momentum.

4.3 Comparisons with theoretical calculations

Several theoretical calculations for the quasi-free 2N-absorption in ^{16}O have been reported. They include total absolute rates [26,27] as well as the population

of different final states, taking account of the absorption from atomic S-orbits and that from the P-orbits [28]. Also, distributions for neutron energy [27,29,30] and the angle between the neutrons [27,30,31] in the $(\pi^-, 2n)$ reaction have been given. The most detailed calculations have been made by Shimizu and Faessler [9], who considered absolute rates as well as q - and ω -distributions for specific states populated by P-absorption. Hence these calculations offer the best possibilities for comparisons with our experimental data.

The population of different final states and the corresponding q - (and ω -) distribution are primarily determined by the c.f.p. coefficients and the momentum distribution of the NN pair prior to absorption, respectively. The pion interaction mechanism, however, causes strong modifications of both observables; therefore corresponding theoretical results depend markedly on the assumptions concerning the pion interaction.

Figures 9 and 10 show the already mentioned data points for different q -distributions together with the respective theoretical curves from ref. 9. Normalization has been made at one point only, namely at $q = 50$ MeV/c in the 3.95 MeV distribution. All experimental and theoretical rates are given in the same arbitrary units for both figures.

The 3.95 MeV transition (upper part of fig. 9) shows remarkably nice agreement between theory and experiment. The agreement is less good for the ground-state transition (lower part of fig. 9). There the theoretical curve has a maximum around 200 MeV/c, whereas the data points seem to peak around 100 MeV/c. Nevertheless, the experimental curve also shows the fall-off towards $q = 0$ as expected for a $L = 2$ transition and seems to be compatible with the theoretical result, within the rather large error bars.

Figure 10 shows the q -distribution for the range of 10-12 MeV excitation energy. Theoretically, two final states should be populated in this region, namely an $L = 0$ state at 11.05 MeV and an $L = 2$ state at 11.5 MeV. The data points exhibit an $L = 0$ shape in general; however, a shoulder around 100-200 MeV is visible.

Another comparison between the 3.95 MeV and the ground-state transition can be made on the basis of the total population of these states. By measuring over a wider angular range, we attempted to avoid the usual geometrical preference of small recoil momenta q and hence $L = 0$ transitions. The ratio obtained for transition probability to the 3.95 MeV and ground state is 5.7 ± 2.0 , for $\omega > 125^\circ$. This is in reasonable agreement with the respective theoretical result of 4.3. It should be noted that the ratio of the c.f.p. coefficients is 1.0 (see Table 1) and the observed enhancement of the $L = 0$ transitions is pion-specific.

Also the observed absolute rates for transitions into different final states can be compared with calculations of ref. 9. For the 3.95 MeV state, we observe a total rate of $(2.5 \pm 0.7)\%$ per stopped pion. This value lies between the two (π^-, γ) results of 1.8% [23] and $(4.8 \pm 0.9)\%$ [22]. According to data from pionic atoms, more than 80% of the pions are captured from atomic P-orbits [32,33].

Assuming pure P absorption and using an experimentally observed 2P width of 5 eV $\cong 7.6 \times 10^{15} \text{ s}^{-1}$ [34], we can convert the observed percentage into absolute transition probability. The result is $19 \times 10^{13} \text{ s}^{-1}$. The corresponding theoretical value is $52.4 \times 10^{13} \text{ s}^{-1}$, with 48.7 or $41.1 \times 10^{13} \text{ s}^{-1}$ for modified calculations. Hence the theory agrees within a factor of 2 with the experiment.

In fig. 11 the theoretical curves for the opening angle distribution are compared with our data. Normalization has been made for the 3.95 MeV transition (upper part of the figure) at large angles; here the agreement between the experimental and theoretical distribution is rather good. At smaller angles the data points are systematically higher, indicating a more isotropic distribution. This flat part of the distribution is even more pronounced in the lower part of fig. 11, which contains data integrated over all excitation energies. Two theoretical curves are shown: the lower one is the corresponding distribution using the normalization from the 3.95 MeV transition, whereas the higher one is multiplied by an empirical factor of 1.45.

This seems to suggest that the measured spectra contain an appreciable amount of non-quasi-free events, which are predominantly at smaller opening angles. At high excitation energies, however, they are even present at 180° .

5. CONCLUSIONS

We reported results from the first kinematically complete measurement of the excitation energy distribution in the $^{16}\text{O}(\pi^-, 2n)^{14}\text{N}$ reaction with good resolution, high statistics, and over a wide angular range.

The excitation energy spectrum is dominated by transitions to low excited states that are populated in a direct, quasi-free mechanism. We find peaks in excitation energy where there are states with large $T = 0$ p-shell two-hole strength predicted. In addition, we observed indications of two peaks at high excitation energies, that might be attributed to absorption involving s-shell nucleus.

Data taken at opening angles ω that were considerably smaller than the "deuteron angle" of 180° , were shown to be very important for conclusions on the relative transition strength involving angular momentum $L = 0$ and $L = 2$ nucleon pairs. Compared with c.f.p. predictions, the $L = 0$ transitions seem to enhance relative to $L = 2$ in the $(\pi^-, 2n)$ reaction.

A recent theoretical calculation for bound 2P absorption involving various rescattering terms as well as initial and final-state interactions has been used for comparison with our data. It gave good agreement for the recoil momentum distribution of the dominant transition but a less satisfactory description of our data at higher excitation energies.

As in the other light nuclei, we found many events leading to high excitation energies in the residual nucleus. This feature was enhanced at smaller opening angles.

Within the present resolution, there is a great similarity between the missing-mass spectra from $(\pi^-, 2n)$ with stopped π^- and $(\pi^+, 2p)$ with π^+ in flight.

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Table 1

Compilation of known two-hole states in ^{14}N ($\ell = 0$ coupled)

	$E_x(\text{exp.})$ a)	$J^\pi T$	$\sigma(\rho^3, \text{He})$ b)	$S(d, \alpha)$ c)	E_x d)	Configuration	Strength for states with (τ, L) c)		
							(0,0)	(0,2)	(1,0) (1,2)
1	0	1^+0	195	5.5	0	$P_{1/2}^{-2}$	0.016	<u>2.704</u>	
2	2.313	0^+1	185	-	2.69	$P_{1/2}^{-2}$			<u>2.212</u>
3	3.948	1^+0	295	6	3.62	$P_{3/2}^{-1} P_{1/2}^{-1}$	<u>2.675</u>	0.081	
4	7.028	2^+0	205	7	6.99	$P_{3/2}^{-1} P_{1/2}^{-1}$		<u>5.0</u>	
5	9.17	2^+1	145	-	} 9.52	$P_{3/2}^{-1} P_{1/2}^{-1} + (P_{3/2}^{-2})$			<u>12.721</u>
6	10.43	2^+1	160	-					
7	11.05 e)	3^+0	130	6	10.14 c)	$P_{3/2}^{-2}$		<u>6.6</u>	
8	11.5 f)	1^+0		fairly large	15.24	$P_{3/2}^{-2}$	0.308	0.214	
9	13.2	? 0		"					
10	13.7	? 0		"					
11	?	0^+1			16.32	$P_{3/2}^{-2}$			0.788
12	?	2^+1			17.88	$P_{3/2}^{-2} + (P_{3/2}^{-1} P_{1/2}^{-1})$			<u>2.277</u>

- a) ref. 19 d) ref. 12
b) ref. 20 e) Identified in refs. 20 and 21.
c) ref. 21 f) $E_x = 11.07$ according to ref. 19

Figure captions

- Fig. 1 : Kinematical variables used in the text.
- Fig. 2 : Measured excitation energy distributions for $125^\circ \leq \omega \leq 160^\circ$ (upper curve) and $\omega > 155^\circ$ (lower curve). The arrows at the E_x axis indicate the position of $T = 0$ states in ^{14}N with large two-hole strength, according to Table I.
- Fig. 3 : Excitation energy distributions for different ranges in recoil momentum q . Upper curve: $q > 250$ MeV/c; lower curve: $60 \leq q \leq 100$ MeV/c. The arrows at the E_x axis are as in fig. 2.
- Fig. 4 : Smoothed excitation energy spectra for $125^\circ \leq \omega \leq 160^\circ$ with 15 MeV (upper curve) and 25 MeV (lower curve) off-line threshold on the pulse height of the neutron counters. The arrows at the E_x axis are as in fig. 2.
- Fig. 5 : Width of the q distribution of the most prominent $L = 0$ transitions for ^{16}O and target nuclei from previous measurements as a function of the pair separation energy.
- Fig. 6 : θ distributions for $2 < E_x < 7$ MeV (upper curve) and $10 < E_x < 15$ MeV (lower curve). The data points refer to measurement I ($\omega > 155^\circ$).
- Fig. 7 : Neutron energy distributions for $2 < E_x < 7$ MeV. Upper curve: measurement I ($\omega > 155^\circ$); lower curve: measurement II ($125^\circ < \omega < 160^\circ$).
- Fig. 8 : Distributions in relative momentum of the two neutrons for $2 < E_x < 7$ MeV and $10 < E_x < 15$ MeV. Points are from measurement I, triangles from measurement II. The solid line is just a guide to the eye.
- Fig. 9 : Measured recoil momentum distributions (crosses) for transitions into the 3.9 MeV state (top) and ground state (bottom) of ^{14}N compared with calculations (solid curve) of Shimizu and Faessler (ref. 9). Both parts of the figure have the same units; normalization has been made at $q = 50$ MeV/c with the 3.9 MeV state transition.

The data points were obtained by fitting the excitation energy distribution in each recoil momentum bin. For the fit, a sum of two Gaussians plus a small constant background has been used.

Fig. 10 : Same as fig. 9 for a window in excitation energy $10 \leq E_x \leq 12$ MeV. Units and normalization are the same as in fig. 9. See also text.

Fig. 11 : Angular distribution of the two neutrons for a window in excitation energy $2 < E_x < 7$ MeV (upper curve) and the total of all events. The data points are from measurements I and II. The curves are calculations from ref. 9. See also text.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11