pn-Pair Coupling in the (γ, pn) Reaction at 72 MeV

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The $^{16}\mathrm{O}(\gamma, pn)$ reaction was measured at $E_\gamma \sim 72$ MeV with resolution sufficient to distinguish the low-lying states of the residual ^{14}N nucleus. Cross sections averaged over the acceptance of the detector system were determined for each of the resolved states. The relative population of residual states indicates that proton-neutron pairs coupled to $(J^\pi, T) = (0^+, 1)$ play a minor role in the photon absorption process compared to $(1^+, 0)$ pairs and that both $L = 0$ and $L = 2$ pairs participate in the reaction.

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Photonuclear reactions provide an excellent tool for investigating the structure of atomic nuclei due to the high degree of accuracy with which the underlying electromagnetic interaction is described by the theory of quantum electrodynamics. Furthermore, the relative weakness of the interaction causes a minimal perturbation of the initial nuclear state, thus simplifying the description of the reaction process. However, in order to extract detailed nuclear structure information from photonuclear measurements the detailed reaction mechanism must be known, which is not the case for the energy region between the giant dipole resonance and the Δ resonance. In this region, early experimental results [1,2] pointed toward a reaction mechanism involving absorption on proton-neutron pairs. Levinger coined the term "quasideuterons" for these pairs and introduced a corresponding model [3], further elaborated by Gottfried [4], in which the relative wave function for a pair was approximated by the wave function for a free deuteron. Implicit in Levinger's model was the assumption that the pair had the same quantum numbers, $^3S_1$, as a free deuteron. The same assumption was used by Gottfried, who performed his calculation for higher photon energies (340 MeV). At these photon energies, the dominant reaction mechanism is expected to be absorption on Δ resonance currents, for which absorption on pairs coupled to the singlet $^1S_0$ state is suppressed by isospin and parity conservation. At lower photon energies the reaction mechanism is expected to be dominated by absorption on meson exchange currents, for which it has been suggested that $^1S_0$ pairs may contribute [5].

The present experiment aims primarily at determining the quantum numbers of the proton-neutron pairs on which $\sim$72 MeV photons are absorbed. This was accomplished by measuring the $^{16}\mathrm{O}(\gamma, pn)$ reaction with resolution sufficient to distinguish the low-lying states of the residual ^{14}N nucleus. The ground state of ^{16}O is characterized by quantum numbers $(J^\pi, T) = (0^+, 0)$, where J, π, and T are the angular momentum, parity, and isospin, respectively. Consequently, the quantum numbers of a proton-neutron pair on which a photon is absorbed are equal to those of the residual nucleus, assuming the latter has remained a spectator throughout the process. The quantum numbers for the ground state and second excited 3.95 MeV state of ^{14}N are $(J^\pi, T) = (1^+, 0)$, while those for the first excited 2.31 MeV state are $(0^+, 1)$. Hence, the population of the ground state and second excited state relative to the first excited state give an indication of the relative importance of absorption on proton-neutron pairs coupled to $^3S_1$ compared to $^1S_0$. The $\sim$1.5 MeV resolution in missing energy obtained in this measurement made it possible to distinguish these low-lying states. In the context of (γ, pn) experiments this is a high resolution, the best achieved in any previous experiment being $\sim$7 MeV [6,7].

The measurement was performed at the tagged-photon facility at the MAX-lab accelerator laboratory in Lund, Sweden [8–10]. A pulsed electron beam from a 100 MeV microtron was stretched in a pulse stretcher ring to give $\sim$50% duty cycle, and the $\sim$30 nA extracted beam produced bremsstrahlung in a 50 μm Al foil. Residual electrons corresponding to 67–76 MeV photons were detected by an array of 22 plastic scintillator detectors in the focal plane of a magnetic tagging spectrometer [11]. A tagged-photon intensity of $\sim 10^7\ \mathrm{s}^{-1}$ and a photon energy resolution of $\sim$400 keV were achieved. Because of collimation of the beam, the ratio of the number of tagged photons reaching the target to the number of residual electrons detected in the focal plane of the tagging spectrometer (the tagging efficiency) was $\sim$33%, determined by a separate measurement at low intensity in which photons were detected by a 100% efficiency scintillation-glass detector inserted in the beam.

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The photon beam impinged on a target consisting of 0.4 mm H_2O contained between two 12 μm stretched mylar foils [12]. Protons emitted from the target were detected by a ΔE-ΔE-E telescope with thin plastic scintillator ΔE elements and an E detector consisting of a 5×4 array of $25 \times 25 \times 30$ mm^3 CsI scintillators, read out by photodiodes [13]. A proton energy resolution of $\sim$800 keV was obtained, determined mainly by the uncertainty of the proton energy lost in the target, the intrinsic resolution of the detector being $\sim$300 keV. Neutrons were detected by an array of 36 NE110 plastic scintillator bars ($1.8 \times 0.2 \times 0.1$ m^3 and $3.0 \times 0.2 \times 0.05$ m^3) read out by photomultipliers at both ends [14,15]. The detectors were arranged in four walls, as shown in Fig. 1. The neutron energy was determined by the time-of-flight method, the start-signal being supplied by the proton detector. With a $\sim$0.8 ns time-resolution and a 3.7–4.9 m flight path, an energy resolution of $\sim$1 MeV was obtained for the neutron energies of interest. The neutron detection efficiency, determined with a Monte Carlo code [16], was $\sim$11%–13%, depending on the neutron energy and position in the detector. The data presented here show the results from the backward four columns of the CsI array, covering an angular range of 60°–100° with a solid angle of 354 msr, and the central neutron-detector wall, covering 81°–103° and 157 msr. This angular combination of the detectors follows the kinematics of the $D(\gamma, pn)$ reaction and the solid angles are sufficiently large to sample a substantial portion of the angular distribution of that reaction. Most of the yield from the $^{16}O(\gamma, pn)$ reaction was found in this quasideuteron configuration.

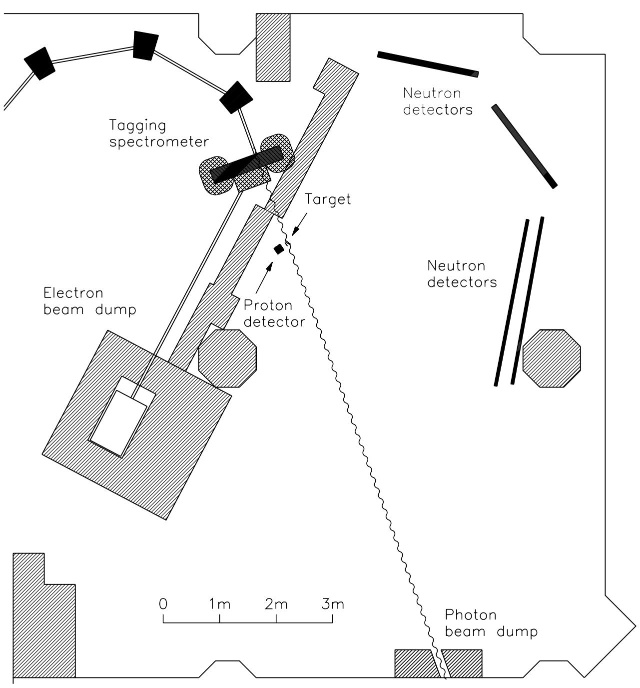

FIG. 1. Overview of the experimental area.

The analysis method is extensively reported in [17], and is briefly outlined in the following. For each event, the photon energy and the proton and neutron energies and directions were measured, enabling a determination of the *missing energy*, through the expression

$$E_{\rm miss} = \sqrt{(E_\gamma + m_{\rm target} - E_p - E_n)^2 - |\mathbf{k}_\gamma - \mathbf{k}_p - \mathbf{k}_n|^2} + m_p + m_n - m_{\rm target} \quad (1)$$

where $E, \mathbf{k}$, and m (with obvious indices) indicate energy, momentum and mass. A missing-energy spectrum for events characterized by a triple coincidence between the proton, neutron, and focal plane detectors was constructed, and random coincidences were subtracted. The resulting spectrum included events from the target-cell walls and surrounding air. Therefore, a background measurement with an empty target cell was subtracted from the foreground spectrum, yielding the contribution from the desired $^{16}O(\gamma, pn)$ events. In order to reduce background and avoid excessively large efficiency corrections, several conditions, such as energy thresholds, were imposed on the data. The resulting missing-energy spectrum is shown in Fig. 2, and the peaks are identified as the $(1^+, 0)$ ground state, $(1^+, 0)$ 3.95 MeV state and $(2^+, 0)$ 7.03 MeV state of the residual ^{14}N nucleus (the separation energy for the reaction is 23.0 MeV). These are the same states strongly populated in the $^{16}O(\pi^+, pp)^{14}N$ [18] and $^{16}O(d, \alpha)^{14}N$ [19] reactions. Cross sections were determined for each of the resolved states and are shown in Table I. Because of the energy thresholds and $<4\pi$ solid angle, these are not total cross sections but rather cross sections averaged over the acceptance of the detector system. The cross section for the 2.31 MeV state, not seen in the spectrum, is estimated to have an upper limit of

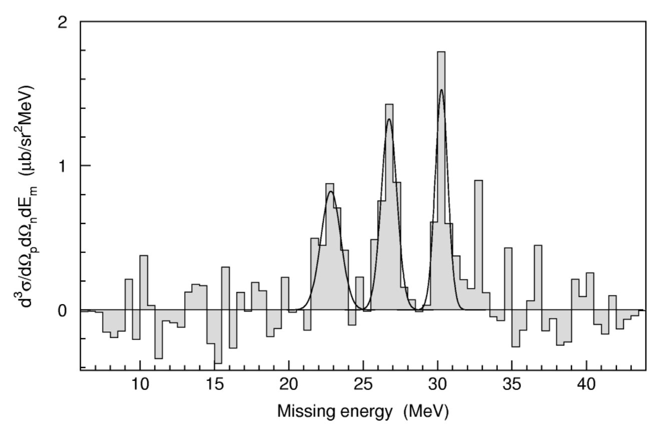

FIG. 2. Missing-energy spectrum for the $^{16}O(\gamma, pn)^{14}N$ reaction. The peaks are identified as the ground state, 3.95 MeV state and 7.03 MeV state of the residual ^{14}N nucleus (the separation energy for the reaction is 23.0 MeV). No population of the first excited state at 2.31 MeV is observed. The solid line shows a fit of three Gaussians to the data (used for obtaining the cross sections).

TABLE I. Measured and calculated [22] cross sections, averaged over the acceptance of the detector system, for the $^{16}O(\gamma, pn)^{14}N$ reaction leading to specific states of the residual ^{14}N nucleus. The uncertainties quoted in the table are statistical. The systematic uncertainty of the measurement is estimated to be $\sim$11%.

State	$(d^2\sigma/d\Omega_p d\Omega_n)_{\rm meas}$ (μb/sr^2)	$(d^2\sigma/d\Omega_p d\Omega_n)_{\rm calc}$ (μb/sr^2)
Ground state	1.4 $\pm$ 0.5	0.34
2.31 MeV	$<$0.1	0.09
3.95 MeV	1.7 $\pm$ 0.5	0.80
7.03 MeV	1.6 $\pm$ 0.4	0.15

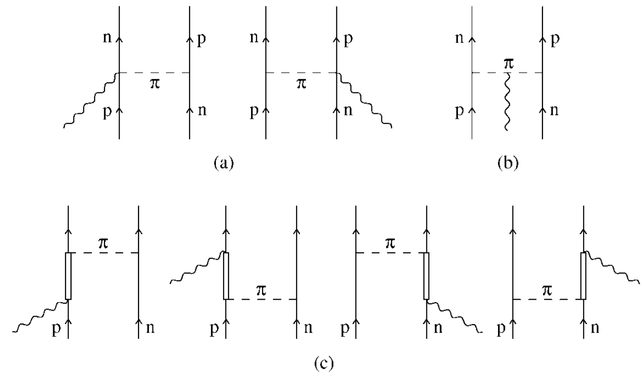

FIG. 3. Photon absorption mechanisms included in the (γ, pn) calculations of Ryckebusch *et al.* [5,22,23]: (a) seagull current; (b) pion-in-flight current; (c) Δ-resonance current.

0.1 μb/sr^2. Several corrections have been applied to the observed yield, including electronics and data acquisition dead time, neutron detection efficiency and tagging efficiency corrections. An overall check of the reliability of the measured cross sections was provided by a calibration measurement of the $D(\gamma, pn)$ reaction using a CD_2 target. The cross section obtained for the photodisintegration of the deuteron agrees with previous measurements [20] well within the 5% statistical and 11% systematic uncertainty of the present measurement.

The most notable feature of the relative population of states is the absence of the first excited state at 2.31 MeV, indicating that $(0^+, 1)$ proton-neutron pairs play a minor role in the photon absorption process. It may be noted that this result is compatible with the $^3S_1$-pair dominance assumed in the original "quasideuteron" models. However, a recent calculation, in which no explicit $^3S_1$ dominance is included, also predicts a small cross section for the 2.31 MeV state (see below). Furthermore, the fact that both the ground state and the second excited 3.95 MeV state are populated indicates that absorption takes place on both $L = 0$ and $L = 2$ proton-neutron pairs (where L is the orbital angular momentum for the center of mass of the pair), since the two states are known to have different structures, the ground state being dominated by $L = 2$ while the second excited state is mainly $L = 0$ [21].

A recent calculation of the cross sections for individual residual states in the $^{16}O(\gamma, pn)$ reaction has been performed by Ryckebusch [22] and the results are shown in Table I. The calculation was performed within a general shell-model framework, described in [23]. Bound- and continuum-state wave functions were generated in the same mean-field potential, thus guaranteeing orthogonal initial and final states and preventing spurious contributions from entering the calculation. The mean-field potential was determined through a Hartree-Fock calculation with an effective nucleon-nucleon interaction of the Skyrme type. A partial-wave expansion of the emitted nucleon waves was performed. A direct knockout reaction mechanism was assumed, with the two-nucleon current diagrams shown in Fig. 3 being considered. At photon energies near 72 MeV, the reaction mechanism is predicted to be dominated by the pion-exchange terms, with the Δ resonance contributing only marginally [5]. The pion-exchange terms were derived from the one-pion exchange potential in which pseudovector coupling was adopted, and are basically model independent. Thus, at these photon energies the calculation does not involve any free parameter. The residual nucleus was described by a superposition of two-hole states $|(hh')^{-1}J_R M_R\rangle$ with amplitudes taken from [21]. The major shell-model configurations are $(1p_{1/2})^{-2}$ for the ground state and 2.31 MeV state, and $(1p_{3/2})^{-1}(1p_{1/2})^{-1}$ for the 3.95 and 7.03 MeV states. As mentioned above, the detector system does not measure the entire (γ, pn) phase space. Therefore, in order to enable the comparison between measured and calculated cross sections, the latter were submitted to a Monte Carlo procedure in which the effects of the detector acceptances were accounted for (a similar procedure was applied to the deuteron photodisintegration cross sections obtained in previous measurements [20], thus enabling comparison with the cross section obtained in the present experiment and at the same time providing a check of the Monte Carlo procedure). The calculation predicts a significantly lower cross section for the $(0^+, 1,)$ 2.31 MeV state than for the $(1^+, 0)$ and $(2^+, 0)$ states, in agreement with the measurement, but substantially underestimates the measured cross sections for all observed states. It should be stressed, however, that the data were taken in the tail of the giant dipole resonance. In this energy region, where strong collective effects were observed in the (γ, p) and (γ, n) channels [24], the direct two-nucleon knockout mechanism as adopted in the calculations may not be justified. The unpredicted strong population of the lowest 2^+ state was also recently observed in high-resolution $^{16}O(e, e'pp)$ measurements [25]. Effects related to the strong core-excitation contributions to the nuclear structure of this state [26] might be at the origin of the unexpectedly high cross section.

In summary, a (γ, pn) experiment was performed in which, for the first time, it was possible to distinguish individual states of the residual nucleus. Cross sections were determined for each of the resolved states. The relative population of states indicates that $(J^\pi, T) = (0^+, 1)$ proton-neutron pairs play a minor role in the photon absorption process, compatible with a dominance of $^3S_1$ proton-neutron pairs as assumed in the original quasideuteron models [3,4]. However, the measured relative population is also predicted by a recent calculation based on pion-exchange currents, in which no explicit $^3S_1$ dominance is included [22]. The data further indicate that both $L = 0$ and $L = 2$ pairs participate in the reaction.

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