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First observation of absorption of real photons by $T=1$ p-n pairs in the (γ,p) reaction

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Excitation energy spectra resulting from the ^{12}C, ^{16}O, and ^{40}Ca(γ,p) reactions at 90° have been measured with tagged photons of about 61 and 77 MeV. Decay to several discrete states is discussed. Evidence is shown for an absorption process where the photon interacts with a $T=1$ proton-neutron pair, instead of the $T=0$ p-n pair implicit in the quasideuteron model.

A long time ago it was suggested[1] that a real photon with energy between 40 and 140 MeV predominantly interacts with correlated proton-neutron pairs in the nucleus, which have a relative wave function similar to the free deuteron wave function. Models based upon this quasideuteron picture yield a satisfactory description of total absorption cross sections[2] and provide a natural framework for (γ,pn) reactions.[3] Also, only such models seem to be able to account for the near equality of (γ,p) and (γ,n) cross sections in light nuclei.[4] Only recently, clear experimental indications for a reaction mechanism other than a pure single-particle knockout have been found in the (γ,p) reaction. In ^{12}C, a large transition probability was observed[5] towards states in ^{11}B at an excitation energy of $\simeq$6.8 MeV, which are only very weakly excited in the quasifree $(e,e'p)$ reaction.[6] It was proposed[5] that the (γ,p) reaction mechanism leading to these states is a so-called modified quasideuteron process:[4] The incoming photon interacts with a correlated proton-neutron pair, the proton of which is emitted. The neutron merely helps to share the large momentum mismatch ($\simeq$250–300 MeV/c) between the incoming photon and the outgoing proton. In the course of this reaction the neutron may or may not remain in the same single-particle orbit.[5]

In a series of experiments the (γ,p) reaction was studied with good energy resolution ($\Delta E_m \simeq 750$ keV) in several light nuclei. The aim was to investigate the modified quasideuteron mechanism in more detail, and to try to obtain information on the structure of the proton-neutron pair which absorbs the incoming photon.

The experiments were performed at the tagged photon facility of the MAX-laboratory in Lund.[7–9] The available 80–100% duty cycle electron beam with a nominal energy of 75 or 95 MeV, allows the production of "tagged" photons. The focal plane of the tagging spectrometer[9] covers an energy range between 13% and 21% of the incoming electron energy, and is equipped with 18 scintillators. With an average electron current of around 50 nA on the radiator, the number of "monoenergetic" photons was typically 5×10^5 s^{-1}MeV^{-1}. The targets used in the present experiment are listed in Table I. Charged particles were detected in a ΔE-E telescope consisting of a 500 μm thick, 900 mm^2 Si detector and a 15 mm thick, 800 mm^2 LN-cooled hyperpure Ge detector. This detector system, placed at a fixed angle of 90° with respect to the photon beam, covers a solid angle of about 80 msr with a corresponding angular acceptance of $\pm$9° full width at half maximum. The detectors were energy calibrated with a ^{228}Th α source. From the pulse heights in the ΔE and E detectors, it is possible to accurately separate contributions from electrons, protons, deuterons, and tritons. Prompt and random coincidences are determined from the time-of-flight information relative to the focal plane scintillators. The experiment was performed with two incident electron energies: 75 MeV (^{12}C, ^{16}O, and ^{40}Ca) and 95 MeV (^{12}C). The average photon energies corresponding to these electron energies are 61.0 and 77.3 MeV, respectively. A full account of the experimental procedure will be given in a forthcoming paper.[10]

Figure 1 shows the (γ,p) spectra for the three nuclei discussed here. Comparing the present spectra with results obtained in the quasifree $(e,e'p)$ reaction,[6,11,12] some interesting differences appear. In the case of ^{12}C an important transition is found to states in ^{11}B with an excitation energy around 7 MeV, only weakly excited in $(e,e'p)$. The present data at $E_\gamma \simeq 61$ MeV confirms the results of Ref. 5. In this energy region, there are three states which could possibly contribute: $\frac{7}{2}^-$ (6.74 MeV), $\frac{1}{2}^+$ (6.79 MeV), and $\frac{5}{2}^+$ (7.29 MeV). With the presently achiev-

TABLE I. Specifications of targets used in this experiment.

Target	Thickness (mg/cm^2)	Composition
^{12}C	26[a]	$(C_8H_8)_n$
^{12}C	43	$(C_8H_8)_n$
^{16}O	57.3	BeO[b]
^{40}Ca	45	^{nat}Ca

[a]Used in the 75 MeV runs.
[b]The Be background was determined in a separate run on a Be target (Ref. 10). The subtraction does not affect the ^{16}O spectrum for $E_x < 6.0$ MeV.

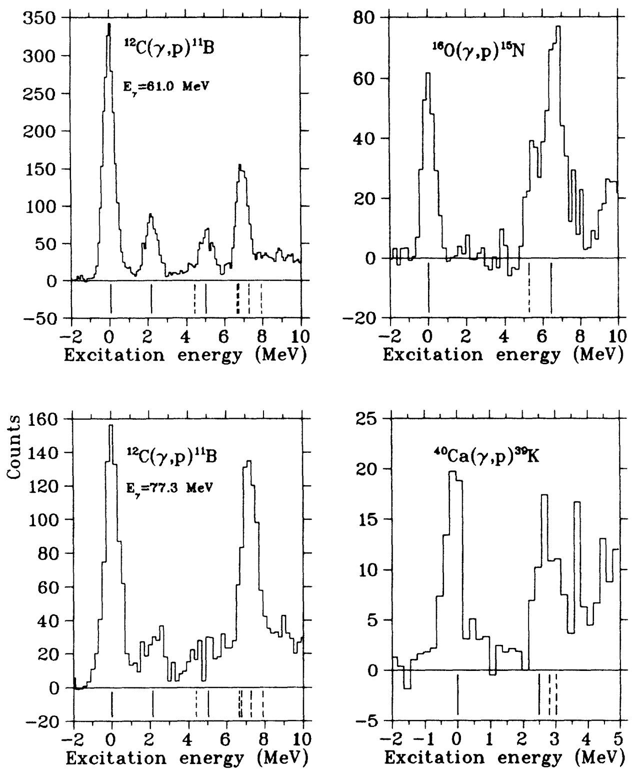

FIG. 1. The net (γ,p) spectrum for ^{12}C, ^{16}O, and ^{40}Ca. The proton detection angle is 90°. Low-lying states in the residual nuclei ^{11}B, ^{15}N, and ^{39}K are indicated by solid ($1h$ states) and dashed lines. The photon energy for ^{16}O and ^{40}Ca is about 61 MeV.

able energy resolution in (γ,p) reactions it is not possible to separate the 6.7 MeV doublet from the 7.3 MeV state. However, from Fig. 1 it is clear that there also must be a sizable contribution from the $\frac{5}{2}^+$ state at 7.3 MeV. In ^{16}O, we observe a non-negligible decay to the doublet of positive-parity states at an excitation energy of 5.3 MeV in ^{15}N, with a strength much larger than what is found in a single-particle knockout reaction.[11] In the $^{40}Ca(\gamma,p)$ reaction, population of the ground state and a group of states around 2.5–3.0 MeV is seen. It is clear from Fig. 1 that in the latter case not only the $\frac{1}{2}^+$ (2.52 MeV) state is excited, but also the $\frac{7}{2}^-$ (2.81 MeV) and $\frac{3}{2}^-$ (3.02 MeV) states. In $(e,e'p)$ reactions these negative-parity states are again only very weakly excited.[12] In Fig. 1, solid lines indicate the states with a dominant one-hole structure, as they were identified in the $(e,e'p)$ reactions. This paper is mainly concerned with the strength going towards the complex states indicated by the dashed lines in Fig. 1.

There are several possible reasons why the (γ,p) and quasifree $(e,e'p)$ reactions should excite states differently. First, the values for the missing momentum for the relevant (γ,p) transitions ($\simeq$300 MeV/c) are well above the missing momenta now studied in the corresponding $(e,e'p)$ reactions. Still, the single-particle spectroscopic factors found in $(e,e'p)$ are very small for all states discussed here. Another possibility is the excitation of these states in a two-step reaction process, involving absorption of the photon by a single proton, and a subsequent inelastic scattering of the proton. Such a mechanism should, however, also excite the $\frac{5}{2}^-$ (4.45 MeV) state in ^{11}B, as it does in $(p,2p)$ and $(d,{}^3He)$ reactions.[13,14] Decay to this state is very small, indicating that such a mechanism contributes little[15] to the present spectra. The states discussed above all have an important $1p$-$2h$ structure with respect to the target nucleus ground state. This was also found in other light nuclei, in particular ^6Li, where large differences between $(e,e'p)$ and (γ,p) spectra are due to the population of $1p$-$2h$ states in the latter reaction.[10] Such observation lends strong support to the idea that the reaction mechanism appropriate for these transitions involves a two-nucleon absorption of the photon. Exactly as a single-particle absorption of the photon singles out $1h$ states in the residual nucleus [as it does in the $(e,e'p)$ reaction], the two-nucleon mode of absorption will enhance the transition strength to $1p$-$2h$ states. It also should be

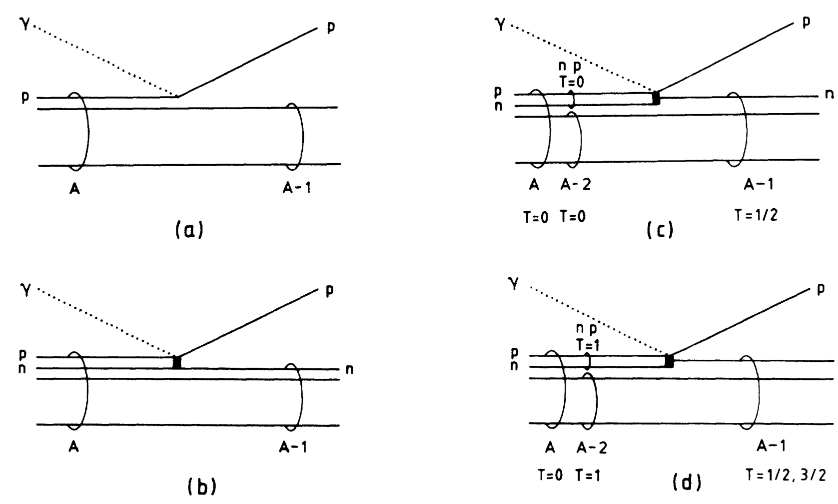

FIG. 2. Reaction processes relevant to (γ,p) reactions at intermediate photon energies. (a) The direct knockout mechanism. (b) The modified quasideuteron process. This process is further divided in Figs. (c) and (d) into the two cases with the np pair; (c) configurations $S=1$, $T=0$ and (d) $S=0$, $T=1$.

pointed out here that the decay to $1h$ states can acquire a sizable contribution from such a "modified quasideuteron" reaction mechanism.[4,5] In the latter case, the neutron remains in its own single-particle orbit, while in the former it gets excited to another level.

In the following, we will interpret the transition to the states indicated by the dashed lines in Fig. 1 as being the result of a two-nucleon absorption process. First consider the ^{16}O target. The structure of the two states at 5.27 MeV $\frac{5}{2}^+$ and 5.30 MeV $\frac{1}{2}^+$ is dominantly[16] $d_{5/2}(p_{1/2}^{-2})$ and $2s_{1/2}(p_{1/2}^{-2})$. Interestingly, the $2h$-parent state in ^{14}N is not the $(1^+,T=0)$ ground state, but the $(0^+,T=1)$ excited state at 2.31 MeV.[16] Similar observations can be made for the other target nuclei. The structure of the $\frac{7}{2}^-$ state at 6.74 MeV in ^{11}B is $p_{1/2}(p_{3/2}^{-2})$, while the 6.79 MeV $\frac{1}{2}^+$ and 7.29 MeV $\frac{5}{2}^+$ states have a $2s_{1/2}(p_{3/2}^{-2})$ character. However, the nature of the $(p_{3/2}^{-2})$ $2h$-parent states is quite different in the two cases. For the $\frac{7}{2}^-$ state this is the $(3^+,T=0)$ ground state of ^{10}B. In the case of the $\frac{1}{2}^+$ and the $\frac{5}{2}^+$ states,[17] it is the $(0^+,T=1)$ state at 1.74 MeV and the $(2^+,T=1)$ state at 5.16 MeV in ^{10}B, respectively. In Ref. 5, the decay to the ^{11}B $\frac{7}{2}^-$ state is described in terms of a modified quasideuteron model: the proton is emitted from the $p_{3/2}$ shell to the continuum, while the neutron makes a transition from the $p_{3/2}$ to the $p_{1/2}$ shell. Also, the decay to the $\frac{1}{2}^+$ and $\frac{5}{2}^+$ states in ^{15}N and ^{11}B now can be considered to proceed in such a way: in this case the neutron makes a transition to the $2s_{1/2}$ or the $d_{5/2}$ shell. The reaction mechanisms leading to the excitation of these states are schematically depicted in Fig. 2. It is seen that these positive-parity states can be excited only if the photon is absorbed by a $T=1$ proton-neutron pair, rather than the $T=0$ p-n pair implicit in the (modified) quasideuteron model.

The relative importance of the absorption on a $T=1$ p-n pair for the transitions discussed here can also be seen from the following: coupling of a $2s_{1/2}$ neutron to the $(3^+,T=0)$ ^{10}B ground state yields the positive-parity $(\frac{7}{2}^+,\frac{5}{2}^+)$ states around 9 MeV in ^{11}B (Ref. 17). Similarly, coupling of a $2s_{1/2}$ or $d_{5/2}$ neutron to the $(1^+,T=0)$ ground state of ^{14}N leads to the positive-parity states between 7 and 8.5 MeV excitation energy in ^{15}N (Ref. 16). No clear indications of decay to these states are observed in the experiment, certainly not if one compares this to the huge population of the 6.7–7.3 MeV states in the ^{12}C(γ,p) reaction.

The situation in ^{40}Ca is similar to the one found in ^{12}C and ^{16}O. While the $\frac{3}{2}^+$ (ground state) and $\frac{1}{2}^+$ (2.52 MeV) states in ^{39}K have a strong $1h$ character with respect to the ^{40}Ca ground state, this is not so for the $\frac{7}{2}^-$ (2.81 MeV) and $\frac{3}{2}^-$ (3.02 MeV) states. The structure of the latter states can, to a great extent, be described[18] as that of an $f_{7/2}$ neutron $(2p_{3/2})$ coupled to the $(0^+,T=1)$ state at 0.13 MeV in ^{38}K, rather than to the $(3^+,T=0)$ ground state. Such a structure is the most important component in the $\frac{7}{2}^-$ wave function, but probably less so for the $\frac{3}{2}^-$ state. (However, decay to this state presumably occurs through this component in its wave function.)

From the reaction mechanism depicted in Fig. 2(d) one also expects a sizable excitation of $T=\frac{3}{2}$ states. Indeed, the lowest-lying $T=\frac{3}{2}$ states have a structure which is close to that of the $T=\frac{1}{2}$ states discussed above. In ^{11}B, the first $\frac{1}{2}^+$, $T=\frac{3}{2}$ state is situated at an excitation energy of 12.6 MeV. In ^{39}K, the $\frac{7}{2}^-$ and $\frac{3}{2}^-$, $T=\frac{3}{2}$ states are found at 6.5 and 7.7 MeV, respectively. It is interesting to note that in both cases (Fig. 3) structure is observed in the (γ,p) spectra at these excitation energies. This is most obvious in the ^{12}C(γ,p) spectrum, where definite strength is seen at about 12 MeV, especially at the highest photon energy, where also the strength going to the $\frac{5}{2}^+$ states was found to increase. Also in the ^{40}Ca(γ,p) reaction a peak is found at the expected excitation energy. Although the much higher density of levels which can be excited in this

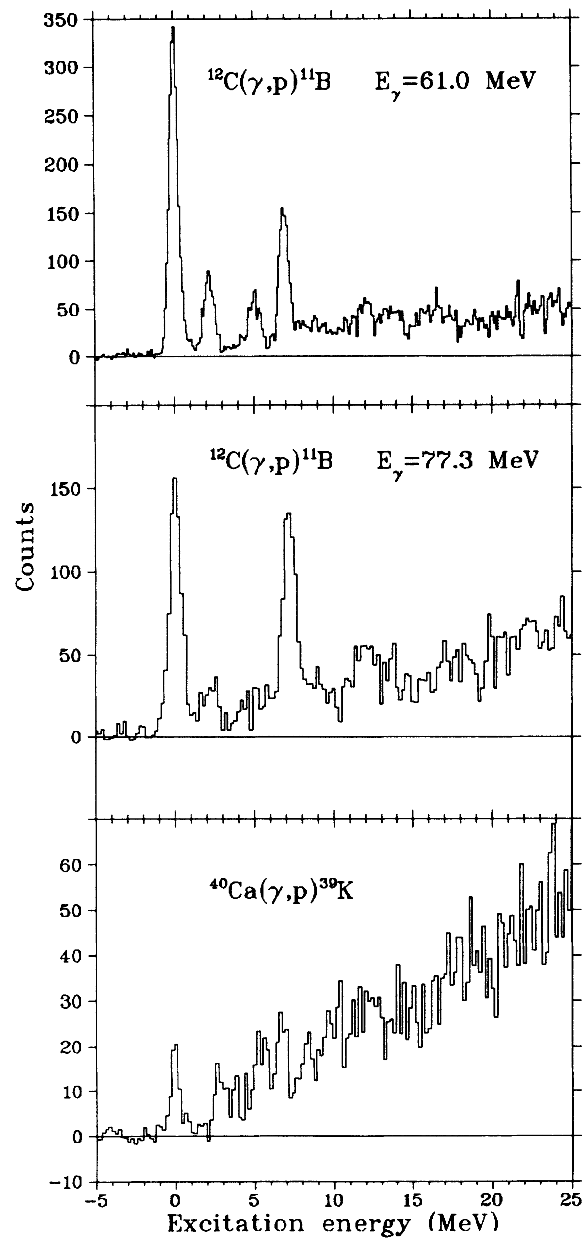

FIG. 3. Same as Fig. 1 for ^{12}C and ^{40}Ca, over a wider energy range.

case makes the identification less clear, both observations are consistent with the picture we have outlined above. [The uncertainties involving the Be-background subtraction are too large to discuss the structure found in the $^{16}O(\gamma,p)$ spectrum above $E_x \simeq 10$ MeV.]

Recent data[19] on the $^{12}C(e,e'd)$ reaction show a surprisingly large decay strength to the $(0^+,T=1)$ state in ^{10}B. This transition is, in principle, isospin forbidden, but was shown to proceed via the absorption of the virtual photon on a $T=1$ p-n pair, with a subsequent "integration" of the emitted deuteron. Interestingly, the $(e,e'd)$ spectrum of Ref. 19 also exhibits strength at an excitation energy of $\simeq 5.2$ MeV, where the $(2^+,T=1)$ state is situated. This observation of the occurrence of $T=1$ p-n pairs in the ^{12}C ground state concurs with the present results for the (γ,p) reaction.

Summarizing, in all three nuclei studied here a clear indication of the population of final states with a strong parentage to $T=1$, $2h$ states in the A-2 nucleus seems to be present. As such, this is the first direct evidence for the interaction of an intermediate energy photon with a $T=1$ p-n pair in the target nucleus. Such a mechanism is not unlike the usual quasideuteron formulation of photon absorption in that it also implies an absorption of the photon on a two-nucleon cluster. However, the relative wave function of the particles involved is quite different. It was already known that absorption by $T=0$ pairs plays an important role in the (γ,p) reaction where it enhances the cross section for decay to, e.g., the $\frac{7}{2}^-$ state[5] in ^{11}B. The present data suggest that in specific (γ,p) transitions, absorption by $T=1$ pairs may also significantly contribute. Further experimental and theoretical work are necessary to determine the overall importance of this mechanism.

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