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The (γ, N) Reaction Mechanism at Intermediate Energies

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The cross sections of the $^{16}O(\gamma$,n) reaction were measured with tagged photons of 50-70 MeV and compared with the equivalent (γ,p) reaction and various theoretical calculations. The implications for the dependence of the (γ,N) cross section on meson exchange currents and final state rescattering are discussed.

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At intermediate energies, E_γ = 50-150 MeV, the single arm (γ, N) reaction $(N = p, n)$ provides a very important message about nuclear structure, provided the photon absorption mechanism is known. In this energy range it is expected that the photon will interact, in a simplified picture, either with a single nucleon current (Fig. 1A) in a quasi-free knockout process (QFK) or with meson-exchange currents (MEC) between correlated nucleons (Fig. 1BCD). The QFK process leaves the residual nucleus in a one-hole ($1h$) state relative to the target nucleus (Fig. 1A). The high missing momentum of the photon with respect to the ejected nucleon, typically ~ 300 MeV/c for $E_\gamma \sim 60$ MeV, tends to suppress the QFK process in (γ, N) reactions. Since the photon can only couple weakly to the magnetic moment of the uncharged neutron, the QFK predicts that the cross-section of (γ, n_0) is much smaller than the corresponding (γ, p_0) cross-section. The zero subscript denotes that the residual A-1 system is left in the ground state. However early bremsstrahlung measurements have shown, surprisingly, that cross-sections for the (γ, n_0) [2] and (γ, p_0) [1] reactions are similar in magnitude, and this has been confirmed by the recent high resolution tagged photon measurements [4, 6, 7, 9]. The prediction of the QFK for the ratio of the (γ,N) reaction cross section and the ratio of the measured tagged photon data are displayed in Fig. 2. This similarity has been explained in a phenomenological way by Schoch [3] in terms of the modified quasi-deuteron mechanism (MQD), in which the photon is absorbed on a $p - n$ pair (MEC) and one of them is reabsorbed into the residual nucleus (Fig. 1B). The more microscopic Hartree-Fock (HF) Random-Phase-Approximation (RPA) approach [11], which considers photon absorption on MEC and multi-step processes (MSP), thus including the effects of long and medium range N-N correlations, also predicts the approximate equality of the cross-sections. Absorption of photons by correlated nucleon pairs (MEC) leaving the residual nucleus in a two-hole ($2h$) state (Fig. 1D) is thought to be the dominant mechanism at intermediate energy. However for the case of the (γ,N) reaction, one of the nucleons is reabsorbed into the initial or to another orbital leaving the residual nucleus in a $1h$ or two-hole, one-particle ($2h - 1p$) state (Fig. 1C, B

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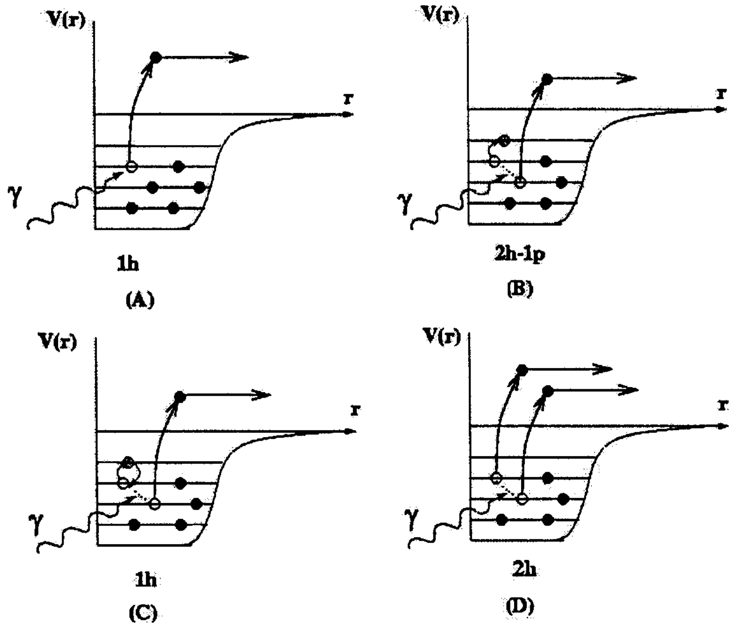

FIG. 1. Possible reaction mechanisms at intermediate energy.

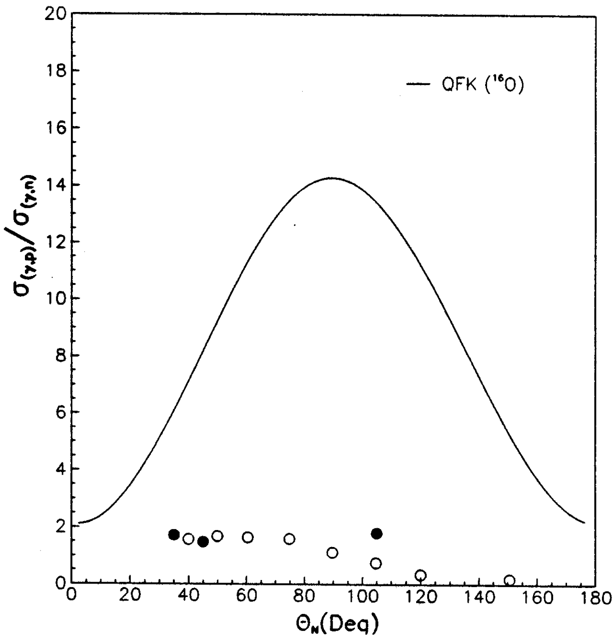

FIG. 2. QFK prediction of the cross section ratio for the $^{16}\text{O}(\gamma, N_0)$ reaction (solid curve) and comparison with data [7]. (solid line: QFK, prediction, filled circles: neutron data from present data and Andersson *et al.* [4] and proton data from Miller *et al.* [6], open circles: neutron data from Goringer *et al.* [2] and proton data from Findlay *et al.* [1]).

respectively). For all these processes the knocked-out nucleons interact strongly with the residual system. Final state interactions (FSI), sometimes referred to as rescattering, may have a large effect on the cross-section.

In order to clarify the reaction mechanism in this energy range a broad body of (γ, N) data should be studied :

1. Both (γ, n) and (γ, p) are needed to be measured, because the QFK of a single proton should be much stronger than single uncharged neutron knockout. On the other hand, γ - absorption on a $p-n$ pair should lead to comparable (γ, n) and (γ, p) cross-sections.

2. Measure over a broad range of photon energy and missing momentum, as the different reaction mechanisms have different photon energy and momentum dependence.

3. Make measurements in which discrete states are identical in the mass A-1 nucleus, because different reaction mechanisms can populate excited states of different structure.

4. Measure over a range of A, because FSI effects can change with A.

The development of tagged photon facilities, following on from high-duty-factor electron accelerators, has resulted in a number of (γ, N) experiments [4, 6, 7, 9] with good enough energy resolution for resolving different individual residual states in light nuclei(A=4-40). As the detection of a charged particle (proton) is much easier than a neutral particle (neutron), most of the measurements have focused on the (γ, p) reaction. The neutron energy is measured by time-of-flight (TOF), and thus the energy resolution depends on the neutron flight path. A first attempt to get high resolution was made by Andersson *et al.* [4], using a 6 meter flight path at Maxlab; this gave $\sim 1MeV$ resolution, which is not good enough for this purpose. Alternatively, decay-γ-rays from 5.2 and 6.2 MeV states in the ^{15}O residual nucleus have been measured in coincidence with the knocked out neutron for the first time [7]. The $^{16}O(\gamma, n)$ reaction leaves ^{15}O in excited states, where the ground state $(\frac{1}{2}^{-})$ and 6.2 MeV $(\frac{3}{2}^{-})$ states are $1h$ in character and the 5.2 MeV doublet $(\frac{1}{2}^{+}, \frac{5}{2}^{+})$ are $2h-1p$ in character.

The experiment was performed at the Maxlab tagged photon facility [8] and Glasgow time-of-flight (TOF) spectrometer [10]. The Maxlab offers very good energy resolution (300 keV) and a well-known beam intensity. It produces a maximum 100 MeV electron beam, and a maximum 80 MeV photon beam can be obtained from thin Aluminum (Al) foil through a bremmstrahlung process. The neutrons are detected by two neutron detector arrays, which constitutes a considerable advance over the previous generation of photonuclear experiments [4, 9]. Each array consists of an NE213 liquid scintillator filled tank of internal dimensions $60 \times 60 \times 10$ cm [10]. Here the outgoing neutrons were produced from a water target, held in a cylindrical aluminium cell of dimensions 9 cm × 6 cm diameter, and detected at the 45° and 105° detection angle after travelling 2.5 meter, from target to the detector. This flight path gives ~ 3 MeV resolution, which is not important as the states were resolved by measuring decay-γ-rays [7].

The differential cross section for the ^{16}O(γ, n_0) reaction to the ground $(\frac{1}{2}^{-})$ state of the ^{15}O nucleus is displayed in Fig. 3A and for the ^{16}O(γ, p_0) reaction [6] in Fig. 3B, where it is compared with previous (γ, N_0) data [2, 4, 5] and also with the results of coupled-channels calculations, which were performed within a consistent, continuum HF, RPA framework [11]. In the description of the initial photoabsorption mechanism, the current operator, obtained by minimal substitution

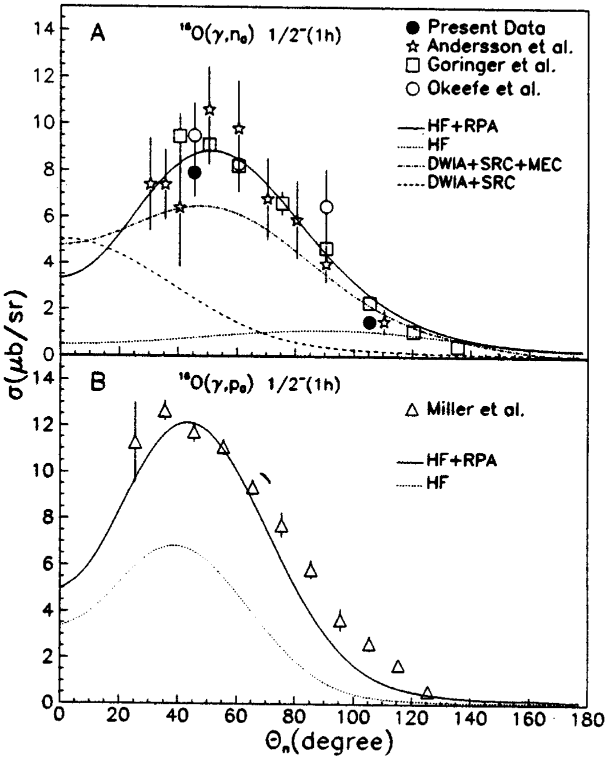

FIG. 3. Measured cross section for the $^{16}O(\gamma, n_0)$ reaction and comparison with previous $^{16}O(\gamma, N_0)$ data and theoretical calculations.

in the Hamiltonian, includes both one-body and two-body terms. The latter was essentially determined by the momentum-dependent-force component of the extended Skyrme-type effective $N - N$ interaction, also used for the coupled channels calculations. The full calculation is labellled HF+RPA in Fig. 3, but to asses the importance of final state rescattering and coupling to collective modes of the nucleus, equivalent direct-knockout calculations were made using the same Skyrme interaction with two-body (HF, Fig. 3) current terms included. The other calculations for the $^{16}O(\gamma, n_0)$ reactions, shown in Fig. 3A use an extension of the Pavia DWIA approach [12]. Here short-range correlation effects are crudely modelled in the nuclear wavefunction and the current operator has a two-body part, derived from the one-pion-exchange potantial, where only the seagull term has been retained. Calculations with and without the two-body term are labelled DWIA+SRC+MEC and DWIA+SRC in Fig. 3, respectively. The extended DWIA calculation gives a fair description of the (γ, n_0) cross section, and predicts a dominant MEC effect, in disagreement with the HF+RPA calculation. However the former lacks the degree of self-consistency of the latter, and is extremely sensitive to the choice of optical potential. Differential cross sections for the $1h$ states excited in the $^{16}O(\gamma, N_3)$ reaction are displayed in Fig. 4A, 4B and compared with previous measurements [4] and the coupled-channels calculations [11] described above. The consistency of the data with the HF+RPA calculation shows the importance of the MEC effects. Differential cross sections for the largely $2h1p$ states excited in $^{16}O(\gamma, N_{12})$ is displayed in

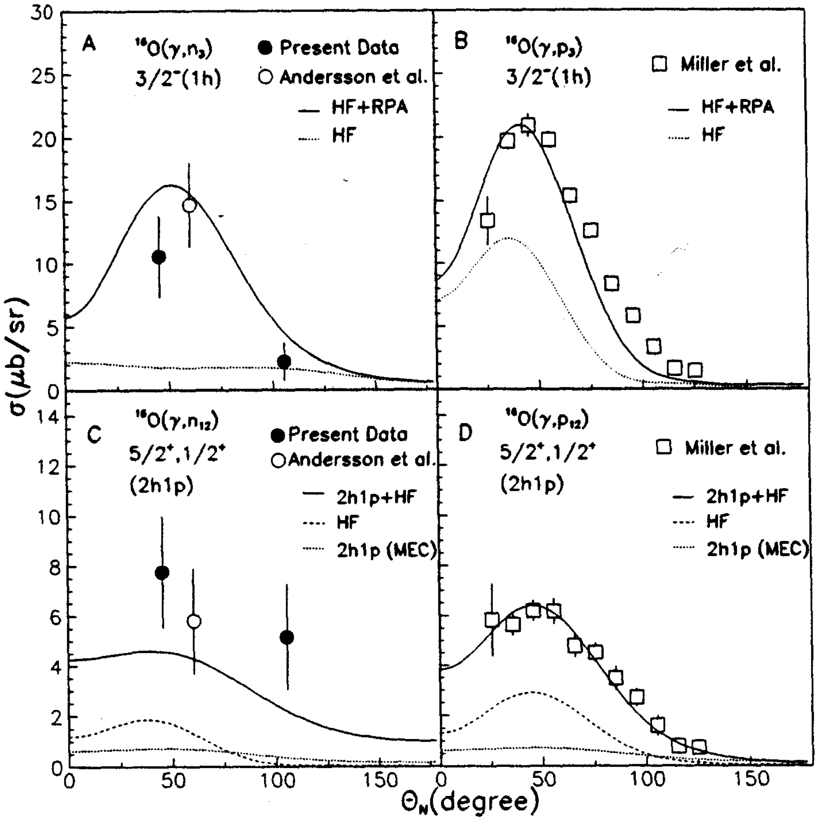

FIG. 4. Measured cross sections and comparison with theoretical calculations for the 6.2 MeV (A,B) and 5.2 MeV (C,D) states in A=15.

Fig. 4C, 4D. The calculations come from a direct knockout model [13] (RPA handles only $1h$ states), where MEC effects are assumed to be fully responsible for the observed cross section, these being implemented through a non-relativistic reduction of two-body currents derived from the one-pion-exchange potential. The cross section to the $\frac{5}{2}^+$, $\frac{1}{2}^+$ doublet the explicit MEC calculation [13] ($2h1p$ Fig. 4C, 4D, note the cross section of the $\frac{1}{2}^+$ state is much lower then the cross section of the $\frac{5}{2}^+$ states) falls far below the measured cross section. However the ground state of ^{16}O is impure, having an admixture of the $2s1d$-shell, from which the doublet states can be reached by QFK or $2N$ absorption, where one nucleon returns to its original orbital. Processes of this type were calculated (HF, Fig. 4C, 4D) using the model described above (HF in Fig. 3), and when added coherently to the MEC calculation ($2h1p$+HF, Fig. 4C, 4D) a reasonable description of the data is obtained. The consistency of the present data with the equvialent (γ, p) measurements is very good, lending confidence that the photon absorption on nucleon pair (MEC) and FSI are very important in this energy range.

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