PHYSICAL REVIEW C VOLUME 24, NUMBER 3 SEPTEMBER 1981

Rapid Communications

^{16}O$(\gamma,p)^{15}$N reaction with linearly polarized photons

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(Received 8 May 1981)

The ^{16}O(γ,p_0) reaction has been studied with linearly polarized bremsstrahlung photons in and below the giant $E1$ resonance. The parity of the absorbed radiation was determined from the observed azimuthal asymmetry of the emitted protons. Combined with unpolarized measurements the polarized results determine the proton decay amplitudes of the $M1$ resonance at $E_x = 16.2$ MeV in ^{16}O. The shape of the unpolarized ^{16}O(γ,p_3) angular distribution in the giant $E1$ resonance was derived from the measured analyzing power.

NUCLEAR REACTIONS ^{16}O(γ,p), $E = 15-25$ MeV; measured analyzing power $\theta = 90°$ linearly polarized bremsstrahlung; ^{16}O dipole levels deduced π; 16.2 MeV 1^+ resonance deduced p_0 decay amplitudes; ^{16}O GEDR deduced p_3 angular distribution.

Investigations of photonuclear reactions with linearly polarized photons will become possible on a large scale in the near future. A monoenergetic almost completely polarized photon beam is available now at Frascati.[1] The new generation of high duty factor electron accelerators presently under construction allow tagging the linearly polarized off-axis bremsstrahlung. Also the synchrotron radiation from the planned large electron positron storage ring LEP will be highly polarized and could be used for nuclear physics experiments.[2] In this Communication we show that studies of photonuclear reactions with linearly polarized photons provide additional information about the excited nuclear states and their decay: (i) The parity of the absorbed radiation is determined in an unambiguous and completely model independent way. (ii) The decay amplitudes of overlapping resonances with different parities can be separated. (iii) The (γ, particle)-angular distribution for a dipole transition of known parity can be derived from a polarization measurement at only one angle. To exemplify this, we report here on a study of the ^{16}O(γ,p_0) and ^{16}O(γ,p_3) reactions with linearly polarized bremsstrahlung photons in and below the region of the giant electric dipole resonance (GEDR).

Measurements with linearly polarized photons yield the analyzing power A, which is defined as

$$A(\theta,E_\gamma) = \frac{1}{P_\gamma(E_\gamma)} \frac{\sigma_\perp(\theta,E_\gamma) - \sigma_\parallel(\theta,E_\gamma)}{\sigma_\perp(\theta,E_\gamma) + \sigma_\parallel(\theta,E_\gamma)} \quad . \tag{1}$$

$P_\gamma(E_\gamma)$ is the photon polarization, $\sigma_\perp(\theta,E_\gamma)$ and $\sigma_\parallel(\theta,E_\gamma)$ are the (γ,p) cross sections at scattering angle θ and excitation energy E_γ for polarized photons with the electric vector perpendicular and parallel to the (γ,p) reaction plane, respectively.

Linearly polarized photons from the off-axis electron bremsstrahlung were selected by a narrow collimator. Two polarization sensitive reactions, the photodisintegration of the deuteron and nuclear resonance fluorescence scattering from the $J^\pi = 1^+$ level at 11.445 MeV in ^{28}Si were used to measure and to monitor continuously the photon polarization. Figure 1 shows the measured photon intensity and photon polarization as function of photon energy for 30 MeV electrons hitting a 50 μm thick aluminum radiator and an off-axis angle of 1.4°. A detailed description of the whole setup will be given elsewhere.[3]

Protons from the ^{16}O(γ,p) reaction were detected in a scattering chamber filled with 0.40 bars oxygen gas. Four $\Delta E - E$ surface barrier detector telescopes were arranged symmetrically around the photon beam at a scattering angle $\theta = 90°$ and at azimuthal angles of $\Phi = 0°$, 90°, 180°, and 270°. Data were taken with two perpendicular directions of the photon polarization to cancel experimental asymmetries.

Measurements were done at bremsstrahlung endpoint energies of 22 and 30 MeV. These energies were chosen to get maximum photon polarization in the excitation regions of interest and to be able to distinguish between proton transitions to the ground

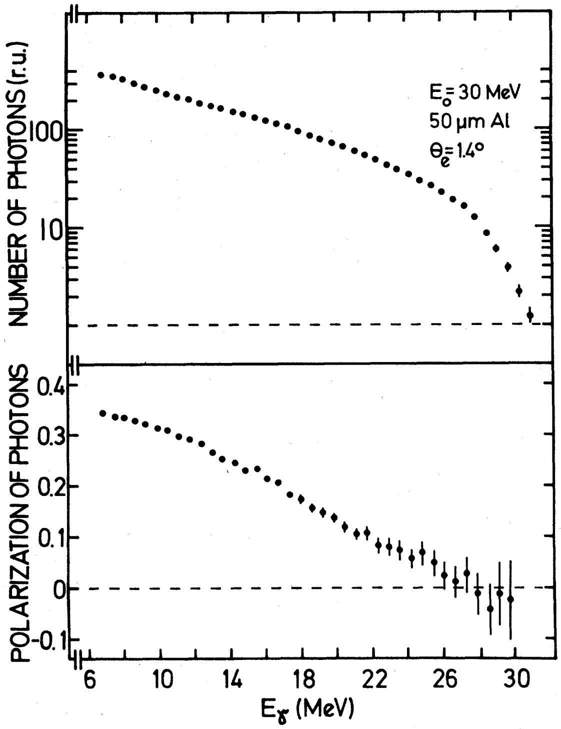

FIG. 1. Photon intensity and polarization as function of photon energy for 30 MeV bremsstrahlung.

and excited states in ^{15}N. From the 22 MeV run we derived the analyzing power for the $^{16}O(\gamma,p_0)$ reaction between 15 and 18 MeV excitation energy since there is no significant contribution of non-ground-state proton decay in the proton spectra in this energy region. From the 30 MeV run we obtained the analyzing power for the p_0 decay between 20 and 25 MeV excitation energy by assuming that all protons stem from ground-state transitions in the corresponding energy range of the proton spectra. This assumption seems to be justified since the known $^{16}O(\gamma,p\gamma')$ and $^{16}O(\gamma,p_3)$ cross sections[4,5] and a comparison of our proton spectra with the $^{16}O(\gamma,p_0)$ cross section[6] show that only a small amount of non-ground-state protons from excitation energies above 26 MeV contribute to the corresponding p_0-proton energies in the measured proton spectra.

In $^{16}O(\gamma,p_0)$ only electric and magnetic dipole and electric quadrupole absorption are present below 29 MeV excitation energy[6] and its unpolarized angular distribution can be expressed in terms of Legendre polynomials

$$\sigma(\theta) = A_0\left[1 + \sum_{\nu=1}^{4} a_\nu P_\nu(\cos\theta)\right] . \tag{2}$$

Then the analyzing power for linearly polarized photons at $\theta = 90°$ is given by[7]

$$A(\theta=90°) = \frac{3a_2(E1) - 3a_2(M1) - 3a_2(E2) + a_2(M1,E2) - \frac{5}{4}a_4}{2 - a_2 + \frac{3}{4}a_4} , \tag{3}$$

where $a_2 = [a_2(E1) + a_2(M1) + a_2(E2) + a_2(M1,E2)]$ and $a_4 = a_4(E2)$ are the even Legendre polynomial coefficients of the unpolarized angular distribution. $a_2(E1)$, $a_2(M1)$, and $a_2(E2)$ designate the $E1$, $M1$, and $E2$ terms and $a_2(M1,E2)$ the $M1-E2$ interference term in the a_2 coefficient.

Since in $^{16}O(\gamma,p)$ the most dominant feature is the GEDR, we first consider a pure electric dipole transition, i.e., $a_2 = a_2(E1)$. Then the analyzing power at $\theta = 90°$ reduces to

$$A(\theta=90°) = \frac{3a_2}{2-a_2} . \tag{4}$$

Since the a_2 coefficient is known from angular distribution measurements with unpolarized photons the analyzing power can be calculated with Eq. (4). Any measured deviation from that calculated value is direct evidence for the presence of absorption other than electric dipole. The upper part of Fig. 2 presents the total $^{16}O(\gamma,p_0)$ cross section from Earle and Tanner[8] as a function of excitation energy. Below, our measured proton energy spectra are shown for comparison. The lower part depicts the measured analyzing power as bold error bars together with values for the analyzing power calculated from the a_2 coefficients as given by Earle and Tanner[8] (open circles), by Snover *et al.*[9] (dashed curve), and by O'Connell and Hanna[6] (dotted curve) assuming pure $E1$ absorption. At the peaks of the cross section the measured values for the analyzing power were averaged over an energy interval equal to their observed half-width, between peaks the data were averaged over 0.5 MeV.

Except for the narrow resonance at 16.2 MeV, the measured analyzing power follows closely the curve for pure $E1$ absorption. This clearly shows that all these resonances (excepting the $E_x = 16.2$ MeV resonance) are predominantly electric dipole. The only previous measurements with linearly polarized photons[10] suggested already dominant electric dipole absorption for the 17.3 MeV region. As can be seen from the cross section displayed at the top of Fig. 2 there are actually two resonances at this energy. For the weaker one at 17.15 MeV a $M1$ assignment was proposed.[9] In our experiment, this state was not resolved from the stronger neighboring 1^- state at 17.3 MeV.

A clear deviation of the analyzing power from the

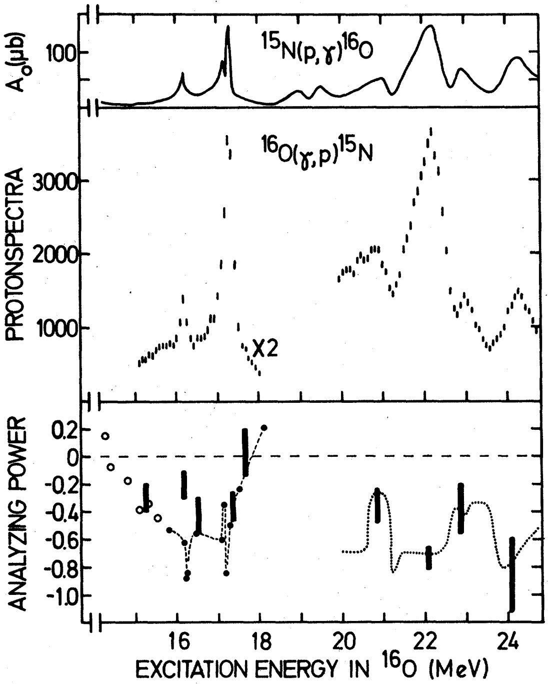

FIG. 2. The upper part shows the total $^{15}N(p,\gamma)^{16}O$ cross section from Ref. 8. The middle part gives the original proton energy spectra from this measurement. In the lower part the measured analyzing power at 90° is presented as error bars together with calculated values taking a_2 coefficients from the literature and assuming only $E1$ excitation.

pure $E1$ value is obvious at the 16.2 MeV resonance. The measurement gives $A=-0.21\pm0.09$ whereas the large negative a_2 coefficient observed in this resonance[8,9] would infer a much larger negative value for an electric dipole state. The large negative a_2 coefficient observed in unpolarized[8,9] (γ,p) excludes $J^\pi=2^+$ for the 16.2 MeV resonance, therefore, the analyzing power gives direct evidence that this state has $J^\pi=1^+$ and overlaps with a broad $E1$ resonance.[8] The $J^\pi=1^+$ assignment confirms previous[11] (e,e') and polarized[9] (p,γ) studies. However, the magnitude of the analyzing power provides new additional information about the decay amplitudes of this 1^+ state. For overlapping electric and magnetic dipole states the analyzing power at $\theta=90°$ is given by

$$A(\theta=90°)=\frac{3a_2(E1)-3a_2(M1)}{2-a_2}\ , \qquad (5)$$

where $a_2=a_2(E1)+a_2(M1)$. From the energy averaged (±100 keV) measured value $A(\theta=90°)=-0.21\pm0.09$ together with the energy averaged value[8,9] of $a_2=-0.7\pm0.1$, we obtain for the $E1$ and $M1$ parts in the a_2 coefficient $a_2(E1)=-0.45\pm0.10$ and $a_2(M1)=-0.25\pm0.10$. In the channel spin formalism, $E1$ absorption in ^{16}O is associated with ^3S and ^3D waves and $M1$ absorption with ^1P and ^3P waves for proton decay to the ground state of ^{15}N.

With the normalization $|^1P|^2+|^3P|^2+|^3S|^2+|^3D|^2=1$ we obtain $|^1P|^2+|^3P|^2=0.35\pm0.10$ by taking the ratio of the peak cross section of the 16.2 MeV resonance to the underlying broad $E1$ resonance from the total cross section of Ref. 8 and averaging over our experimental energy resolution using resonance parameters[9] for the 16.2 MeV resonance. Together with $a_2(M1)=-|^1P|^2+0.5|^3P|^2=-0.25\pm0.10$ we derive $|^1P|^2=0.28\pm0.10$ and $|^3P|^2=0.07\pm0.13$ for the singlet and triplet amplitudes of the 16.2 MeV resonance for the proton decay to the ground state of ^{15}N.

In the 30 MeV data, protons, primarily from transitions to the third excited $\frac{3}{2}^-$ state in ^{15}N contributed to the lower energy part of the spectrum.[4] The total $^{16}O(\gamma,p_3)$ cross section has been measured,[5] but nothing is known about the angular distribution. Protons from the (γ,p_3) decay of the main peak of the ^{16}O GEDR at 22.2 MeV were identified and their analyzing power measured. The analyzing power in Fig. 2 shows that for the 22.2 MeV resonance electric dipole absorption is dominant. Therefore we can derive the a_2 coefficient of the angular distribution for the $^{16}O(\gamma,p_3)$ reaction from its measured value of the analyzing power at $\theta=90°$. From

$$A_{(\gamma,p_3)}(\theta=90°)=\frac{3a_2}{2-a_2}=-0.20\pm0.27$$

we obtain $a_2=-0.14^{+0.19}_{-0.23}$. Despite the large error this indicates that in the main peak of the ^{16}O GEDR the (γ,p_3) angular distribution is less strongly peaked around 90° than for the ground-state decay for which $a_2\approx-0.55$.[6]

In conclusion this study of the $^{16}O(\gamma,p)$ reaction shows that new important information about the parities and the decay of states excited in photonuclear reactions can be obtained from measurements with linearly polarized photons. Especially, for overlapping radiation of different parity or/and different multipolarity the analyzing power provides information about the decay amplitudes which is in addition to that obtainable from unpolarized measurements.

We thank W. Arnold and his linac staff for the help in producing polarized bremsstrahlung. This work was supported by the Deutsche Forschungsgemeinschaft.

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