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INVESTIGATION OF THE PHOTODISINTEGRATION OF THE O^{16} NUCLEUS

This article presents the results of studies concerning two questions in the photodisintegration of the O^{16} nucleus: 1) the probabilities of transition to various states of the final nucleus N^{15}, 2) the integral cross section for total absorption of γ quanta above the region of the giant resonance (up to 55 MeV). These questions were addressed by measuring and analyzing the energy spectra of photoprotons from the (γ, p) reaction in the range of values $E_{\gamma\,\max}$ from 21.3 to 55.0 MeV. In our experiments, protons were recorded at an angle of 90° relative to the direction of the bremsstrahlung beam by telescopes consisting of a front proportional counter and a rear scintillation counter with a NaJ(Tl) crystal. Details of the measurement method are set forth in work (^{1}). In different experiments, protons with energies 3.4-12.5, 5.5-15.0, and 5.0-30 MeV were recorded. The total number of all recorded protons exceeded 100,000. The bremsstrahlung energy flux was measured with a quantometer (^{2}), calibrated with an absolute accuracy of 2% at a relative accuracy of 0.1%. The calibration of the $E_{\gamma\,\max}$ scale had an accuracy of about 1%, and the accuracy of stabilizing the value of $E_{\gamma\,\max}$ during the experiments was about ±50 keV.

1. The study of the probabilities of transition to various states of the O^{15} and N^{15} nuclei as a result of the (γ, n) and (γ, p) reactions is of interest because two excited states of these nuclei that are situated close to one another (5.19 and 5.25 MeV for the O^{15} nucleus, 5.28 and 5.30 MeV for the N^{15} nucleus) have positive parity $I^{\pi} = 1/2^{+}$, $5/2^{+}$, whereas the ground and third excited states (6.15 MeV for O^{16} and 6.33 MeV for N^{15}) have negative parity $I^{\pi} = 1/2^{-}$, $3/2^{-}$. The positive-parity states are two-hole-one-particle states ($1p^{-2}1d$ or $1p^{-2}2s$), while the negative-parity states are single-hole states ($p_{1/2}^{-1}$ and $p_{3/2}^{-1}$). In the shell model, the dipole states of the O^{16} nucleus are described by configurations of the type $p^{-1}1d$ and $p^{-1}2s$, as, for example, in work (^{3}). If it is assumed that a nucleon is emitted from the $1d$ or $2s$ shell, as is usually implied, then the final nucleus

must remain in a state of negative parity. On this basis, some authors (^{4,5}) believe that transitions to states of positive parity would indicate the presence of correlations in the ground or excited states of the O^{16} nucleus. Recently performed theoretical calculations (^{6}) have shown that the presence of transitions to states of positive parity can be explained by the so-called "shaking" mechanism, when the nucleon is emitted from the p shell, forming a second hole, without invoking the concept of correlations in the ground or excited states. In view of this interest in transitions to positive-parity levels, a rigorous method was developed for determining the transition cross sections to the ground state $\sigma(\gamma, p_0)$, to the first + second $\sigma(\gamma, p_{1,2})$, and to the third excited state $\sigma(\gamma, p_3)$ of the N^{15} nucleus from proton spectra measured at different values of $E_{\gamma\,\max}$. This method was applied to spectra obtained in work (^{7}). Its essence is as follows. The proton spectra are divided into intervals of width $\Delta E_p = 200$ keV. The number of protons in each interval of the spectrum obtained at a given value of $E_{\gamma\,\max}$ is referred to the charge of the quantometer accumulated during measurement of the spectrum. If

denote this number by $Y(E_p, E_{\gamma\,\max})$, where E_p is the mean proton energy in the given interval; then, assuming that there are only transitions to states of the N^{15} nucleus no higher than the third, the quantity $Y(E_p, E_{\gamma\,\max})$ can be expressed as follows:

$$Y(E_{pE_{\gamma\,\max}}) = a_0 P(E_{\gamma_0}, E_{\gamma\,\max}) + a_1 P(E_{\gamma_1}, E_{\gamma\,\max}) + a_2 P(E_{\gamma_2}, E_{\gamma\,\max}).$$

Here $P(E_\gamma, E_{\gamma\,\max})$ is the number of γ-quanta in the energy interval $\Delta E_\gamma = {}^{16}/_{15}\Delta E_p$ of the bremsstrahlung spectrum with the given value of $E_{\gamma\,\max}$, incident on the target, with total energy corresponding to unit charge of the quantometer. $E_{\gamma_0}, E_{\gamma_1}, E_{\gamma_2}$ are the energies of the γ-quanta required so that, when protons of energy E'_p are formed, the final nucleus N^{15} would remain, respectively, in the ground, in the first + second, or in the third excited states, i.e.

$$E_{\gamma k} = {}^{16}/_{15}E'_p + E_k + Q,$$

where E_k is the energy of the given state of the N^{15} nucleus, and $Q = 12.11$ MeV is the threshold energy of the (γ, p) reaction. The coefficients a_0, a_1, a_2, which determine the relation between the number of protons in the given interval ΔE_p leaving the N^{15} nucleus in the three states under consideration, were calculated by the least-squares method for the first 5–8 values of $E_{\gamma\,\max}$, separated from one another by approximately 1 MeV. With the aid of the coefficients a_k, the cross sections $d\sigma(\gamma, p_0)/d\Omega$, $d\sigma(\gamma, p_{1,2})/d\Omega$, and $d\sigma(\gamma, p_3)/d\Omega$ were determined for protons emitted at an angle of 90° relative to the direction of the bremsstrahlung beam. For protons with energies below the detection threshold

Figure 1: Cross-section curves.

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(3.4 MeV), the cross sections of the reaction (γ, p_0) were found from the data of the inverse reaction (p, γ_0) (^{8,9}), while the cross sections of the reactions $(\gamma, p_{1,2})$ and (γ, p_3) were determined from analysis of the photoproton spectra of other works ($^{10-13}$) on the basis of the results of our measurements. Integration of the differential cross sections over angles was carried out with the aid of the separate components we had identified (corresponding to transitions to the ground state of N^{15} and to all excited states jointly) in the angular distributions of protons for individual energy groups, measured in other works (^{14}) at various values of $E_{\gamma\,\max}$. The cross section $\sigma(\gamma, p_0)$ for protons with energies above 12.5 MeV was determined from the proton spectra measured in works (^{13,15}), and also from the spectra of protons with energies up to 30 MeV measured by us.

Fig. 1. Cross-section curves. 1 –cross-section curve $\sigma(\gamma, p_0)$ (cross section for transition to the ground state of N^{15}); 2 –$\sigma(\gamma, p_3)$ (cross section for transition to the third excited state of N^{15}); 3 –$\sigma(\gamma, p_{1,2})$ (cross section for transition to the first + second excited state of the N^{15} nucleus); 4 –$\sigma(\gamma, p_0)+\sigma(\gamma, p_{1,2})+\sigma(\gamma, p_3)$; 5 –$\sigma_p$ (cross section for photoformation of protons with energies 3.4-30.0 MeV). The dashed curves show portions of curves 2, 3, and 4 obtained from analysis of works ($^{10-13}$) on the basis of the results of our measurements. The dotted curve is the curve of the cross section $\sigma(\gamma, p_0)$, calculated from the data of the inverse reaction $N^{15}(p, \gamma_0)O^{16}$ (^{8,9}).

In Fig. 1, curves 1, 2, 3, and 4 show, respectively, the cross-section curves $\sigma(\gamma, p_0)$, $\sigma(\gamma, p_3)$, $\sigma(\gamma, p_{1,2})$, and $\sigma(\gamma, p_0) + \sigma(\gamma, p_{1,2}) + \sigma(\gamma, p_3)$. The hatched portions of the curves are the result of analysis of the low-energy proton spectra according to data from other works already mentioned above. The dashed curve refers to the cross section $\sigma(\gamma, p_0)$, calculated from the cross section of the reaction $N^{15}(p, \gamma_0)O^{16}$ (^{8,9}).

The integral cross section of the reaction (γ, p_0) is

$$\int_{12.11}^{43} \sigma(\gamma, p_0)\, dE_\gamma = 47 \pm 6 \text{ MeV} \cdot \text{mb},$$

where the root-mean-square measurement error is indicated. The integral cross sections of the reactions $(\gamma, p_{1,2})$ and (γ, p_3), according to our measurements, are respectively

$$\int_{21.0}^{26.5} \sigma(\gamma, p_{1,2})\, dE_\gamma = 7.5 \pm 2.0 \text{ MeV} \cdot \text{mb}$$

and

$$\int_{22.0}^{27.5} \sigma(\gamma, p_3)\, dE_\gamma = 14.1 \pm 2.2 \text{ MeV} \cdot \text{mb},$$

where only the statistical errors characterizing the separation of the two cross sections are given. If the contribution to the integral cross sections from the region of lower γ-quantum energies is taken into account, corresponding to the dashed portions of the curves in Fig. 1, extrapolated to the thresholds of the reactions $(\gamma, p_{1,2})$—17.4 MeV and (γ, p_3)—18.4 MeV, then we obtain

$$\int_{17.4}^{26.5} \sigma(\gamma, p_{1,2})\, dE_\gamma \approx 10 \text{ MeV} \cdot \text{mb}$$

and

$$\int_{18.4}^{27.5} \sigma(\gamma, p_3)\, dE_\gamma \approx 22 \text{ MeV} \cdot \text{mb}.$$

The intensities of transitions in the decay of the main excited states of the ^{16}O nucleus into various states of the final ^{15}N nucleus in our work and in work (^{16}) agree well, as is seen from Table 1. These intensities in our work

Table 1

Relative intensities (in %) of transitions to various states of the ^{15}N nucleus and of the excited states of ^{16}O with energy E_i

E_i, MeV	Ground state of the ^{15}N nucleus —present work	Ground state of the ^{15}N nucleus —work (^{16})	First + second excited state of ^{15}N — present work	First + second excited state of ^{15}N — work (^{16})	Third excited state of ^{15}N — present work	Third excited state of ^{15}N — work (^{16})
22.3	56 ± 10	52 ± 10	12 ± 4	5 ± 5	32 ± 8	43 ± 10
23.1	35 ± 10	37 ± 10	7 ± 3	5 ± 5	58 ± 15	58 ± 10
24.3	53 ± 10	52 ± 10	13 ± 4	5 ± 5	34 ± 8	43 ± 10

were found by approximating the corresponding cross-section curves by a superposition of Gaussian curves with a half-width ~ 1 MeV. In doing so, the peaks of the Gaussian curves were chosen at those energies at which resonances of γ-quantum absorption by the ^{16}O nucleus were detected (^{14}). The analysis carried out showed that the intensities of transitions to the positive-parity levels (5.28 and 5.30 MeV) of the ^{15}N nucleus formed in the reaction $^{16}\text{O}(\gamma, p)^{15}\text{N}$ have a magnitude comparable with the intensities of transitions to negative-parity levels.

2. According to measurements ([17,18]) of the total absorption cross sections of γ-quanta by the ^{16}O nucleus in the energy region of the giant resonance, it was found that only about half of the integral cross section determined by the dipole sum rule lies in this region. To determine how the cross section is distributed at higher energies, the yield curves for individual energy intervals of the photoproton spectra were treated by the Penfold and Leiss method. Using the proton angular distributions mentioned above, a curve was obtained for the cross section σ_p of photoformation of protons with energies from 3.4 to 30 MeV (Fig. 1, 5). From Fig. 1 it is seen that the proton-formation cross section up to $E_\gamma \approx 50$ MeV has a significant magnitude. The integral cross section for proton formation is

$$\int_{12.1}^{55} \sigma_p \, dE_\gamma = 152 \pm 22 \text{ MeV} \cdot \text{mb},$$

with allowance (by extrapolation) for the contribution to the integral cross section of protons that were not registered (with energy less than 3.4 MeV and greater than 30 MeV).

The integrated cross section for total absorption was determined as follows:

$$\int \sigma \, dE_\gamma = \int [\sigma_p + \sigma(\gamma, n) + \sigma(\gamma, \alpha) + \sigma(\gamma, 4\alpha)] \, dE_\gamma.$$

The data on the cross section $\sigma(\gamma, n)$ up to $E_\gamma = 30$ MeV were taken from Ref. ([19]), and at higher energies—from the cross-section curve for the (γ, n) reaction in Ref. ([20]), normalized to the integrated cross section of the preceding work up to $E_\gamma = 30$ MeV. The data on the cross sections $\sigma(\gamma, \alpha)$ and $\sigma(\gamma, 4\alpha)$ were taken from Refs. ([21,22]). The integrated cross section up to 27 MeV was 127 MeV • mb, whereas in Ref. ([17]) it was 170 MeV • mb, and up to 35 MeV it was 166 MeV • mb, in good agreement with the value 179.5 MeV • mb ([18]). Up to 55 MeV the integrated cross section proved to be equal to 240 MeV, which coincides with the value for the classical dipole sum ($60\,NZ/A$ MeV • mb). Thus, whereas for heavy and medium nuclei in the region of the giant resonance almost the entire integrated photoabsorption cross section is contained, for the O^{16} nucleus more than half of the integrated cross section falls in the region of higher γ-quantum energies.

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