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# *CROSS SECTION FOR GAMMA-RAY ABSORPTION BY $O^{16}$ IN THE GIANT-RESONANCE REGION*

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The cross section for $\gamma$-ray absorption by $O^{16}$ was measured by the absorption method with a high-resolution pair magnetic $\gamma$ spectrometer as detector, in the range $h\nu = 18.9—26.6$ MeV. The cross-section curve has four resonance peaks each several hundred keV wide, at 22.3, 23.05, 24.3, and 25.15 MeV. The integral cross section in the given range is $150^{+30}_{-10}$ MeV-mb.

AMPLE experimental information is now available regarding the structure of cross sections for individual photonuclear reactions in light nuclei, obtained through measurements of the yield curves of $(\gamma, n)$ reactions, photoproton and photoneutron energy spectra, and cross sections for inverse $(p, \gamma_0)$ photonuclear reactions. The $O^{16}$ nucleus has been the object of especially intensive investigation [1-15] because the light, doubly-magic $O^{16}$ nucleus should have more sharply separated levels, and because theoretical calculations based on the shell model are most nearly correct for this nucleus. These circumstances enabled the most reliable comparison of experimental data with the available theoretical calculations. [16,17]

It should be noted, however, that whereas the theory of the giant resonance considers the total cross section for nuclear absorption of $\gamma$ rays, the experimental data furnish information regarding the structure of cross sections for individual partial photodisintegration processes.

Detailed measurements of the shapes of absorption cross-section curves for light nuclei have been practically nonexistent for the following reasons. Direct measurements of $\gamma$-ray absorption give the total absorption cross section, which is the sum of the cross sections for nuclear absorption, pair production, and the Compton effect. The nuclear cross section comprises only a few percent of the total cross section. Therefore an investigation of the structure of the nuclear-absorption cross section requires, above all, a very high statistical accuracy of the measurements.

For this purpose it is most reasonable to use monochromatic $\gamma$ rays resulting from proton capture in the $Li(p, \gamma)$ and $T(p, \gamma)$ reactions. Despite the rather low intensity of these $\gamma$ lines, the use of highly sensitive detectors permits measurements of the required accuracy on electrostatic generators producing a $\sim 50\ \mu A$ current. [18,19] These measurements are confined to a very narrow energy range, and tandem Van de Graaff accelerators cannot be used to expand the possibilities of the technique because of the low resultant $\gamma$-ray intensity ($\sim 1\ \mu A$ current).

Difficulties are encountered when measurements are performed with $\gamma$ bremsstrahlung for the purpose of varying the energy over a very broad range. In order to discriminate narrow energy intervals from the continuous spectrum a high-resolution $\gamma$ detector is required. At the present time the maximum resolution attained with pair magnetic and Compton spectrometers in the 20-MeV region is 0.5—1%, which is several times worse than the resolution attained in work with monochromatic $\gamma$ lines. Such $\gamma$ spectrometers are marked by very low transmission; therefore despite the relatively high intensity of radiation from betatrons and synchrotrons it is extremely difficult to obtain highly accurate measurements. This obviously accounts for the fact that the first investigations performed with $\gamma$ bremsstrahlung [20-22] did not yield quantitative results regarding the structure of the nuclear cross section.

In the present work the total cross section for nuclear absorption by $O^{16}$ was measured in the range 18.9—26.6 MeV by the absorption method, with a high-resolution pair magnetic spectrometer as $\gamma$ detector. The experiment was performed with the 250-MeV synchrotron of the Physics Institute of the Academy of Sciences at 200-MeV peak x-ray energy. The use of this accelerator, instead of the synchrotrons and betatrons usually employed to investigate giant resonance at 25—30 MeV, increased the counting rate by a factor of ~ 25 and enabled the desired measurements. Because of the time spread of the beam, the accidental coincidences did not comprise an appreciable percentage, despite considerably increased loads in individual circuits.

## 1. EXPERIMENTAL TECHNIQUE

The apparatus is represented schematically in Fig. 1. The absorber was distilled water of thickness of 100 g/cm², which corresponded to $\gamma$-ray attenuation in the measured energy range by a factor of about six.

The collimated x-ray beam entering the absorber was measured with a thin-walled integrating ionization chamber (monitor) positioned in the beam 0.5 m ahead of the absorber. The $\gamma$ rays traversing the absorber reached the $\gamma$ spectrometer through collimators placed immediately behind the absorber.

The parameters of the pair magnetic spectrometer were:

| | |
|---|---|
| Thickness of gold radiator | 10 mg/cm |
| Effective area of radiator | 60 × 50 mm |
| Width of tungsten slits (in plane of radiator) | 2 mm |
| Height of slits | 60 mm |
| Distance between inner edges of slits | 40 cm |
| Magnetic field homogeneity in working region | ~0.05% |
| Magnetic field stability (maintained by proton resonance) | <0.01% |

The inside dimensions of the rectangular spectrometer vacuum chamber were 70 × 70 × 10 cm. The walls, bottom, and lid of the chamber were lined with polyethylene 2 mm thick.

Electron-positron pairs were registered by two 60 × 6 × 3 mm plastic scintillators placed behind the slits. The scintillators were cemented to conical clear plastic light pipes 20 cm long, which were in optical contact with FÉU-3 photomultipliers located outside the spectrometer chamber. The photomultipliers were thoroughly protected against stray magnetic fields by multilayered iron and permalloy shields.

Pulses from the photomultipliers were transmitted through UR-1M broadband amplifiers to a diode coincidence circuit[23] having the resolving time $\tau \approx 4 \times 10^{-9}$ sec. A second similar coincidence circuit with the delay time $\Delta t = 2 \times 10^{-8}$ sec in one of its channels was connected parallel to the first circuit for simultaneous registration of accidental coincidences. The identity of the channels was checked several times a day. Measurements were performed with time spread of the beam up to 3000 $\mu$sec, for which the accidental coincidences comprised ~ 15% without the absorber and ~ 0.4% with the absorber.

The spectrometer resolution was measured at $h\nu = 9.716$ MeV for the $\gamma$ line resulting from thermal neutron capture by $Cr^{53}$. A heavy-water reactor was used; the instrumental curve is shown in Fig. 2. At 9.716 MeV the resolution was 63 keV, in good agreement with the value 60 keV calculated for this energy. On the basis of the foregoing data it was calculated that the resolving power of the spectrometer did not exceed 110—120 keV for 20—25 MeV $\gamma$ rays.

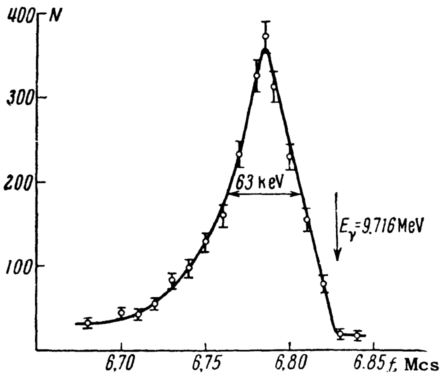

FIG. 2. Instrumental curve for monochromatic 9.716-MeV $\gamma$ rays.

In order to reduce errors associated with a possible sensitivity drift of the detecting apparatus and with small changes in the x-ray spectrum (because of unstable time spread of the beam), we determined in each separate measurement the ratio of the number of coincidences without an absorber ($N_0$) to the number with an absorber (N) in the x-ray beam path. The values of $N_0$ and N were obtained for the same monitor reading; each measurement of $N_0/N$ required about 10 min.

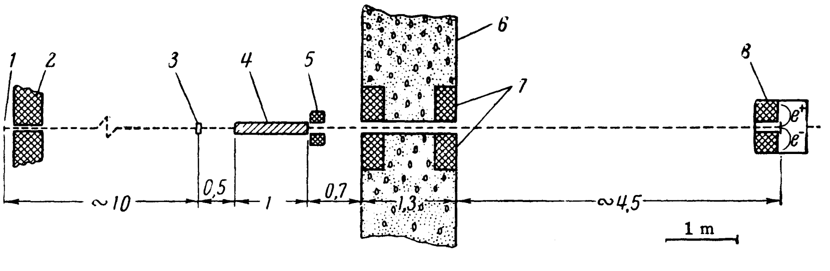

FIG. 1. Experimental scheme. 1 — synchrotron target, 2 — lead collimator, 3 — thin-walled integrating ionization chamber (monitor), 4 — absorber, 5 — second lead collimator, 6 — concrete wall, 7 — lead shield against scattered radiation, 8 — pair magnetic $\gamma$ spectrometer.

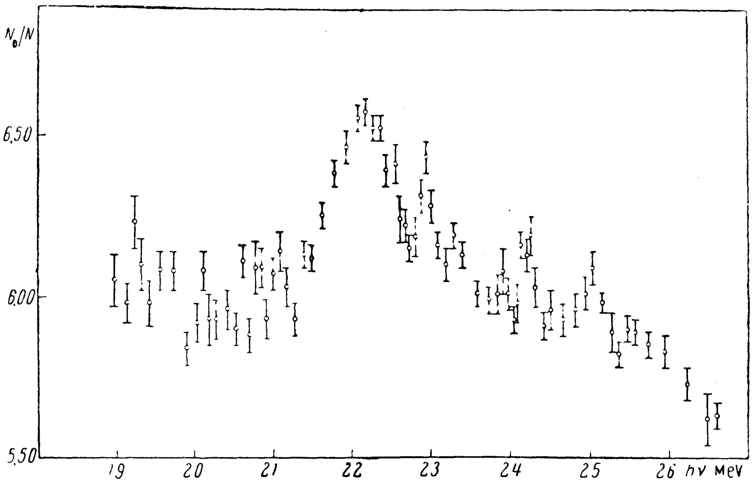

FIG. 3. Ratio of number of coincidences without absorber ($N_0$) and with absorber (N) in the range hν = 18.9 – 26.6 MeV.

The absorber was moved by means of a remotely controlled motor.

The measurements were performed within intervals about 500 keV wide; the energy was varied in ~ 50-keV steps (with subsequent averaging of neighboring points). A run in the investigated interval included on the average 15 periodically alternating measurements at each point. Independent runs were repeated three to six times for each interval.

## 2. EXPERIMENTAL RESULTS

Figure 3 shows the ratio $N_0/N$ in the range 18.9—26.6 MeV with the rms errors indicated. The statistical accuracy of each point is about 1%. The measured ratio $N_0/N$ gives the total cross section for absorption in water:

$$\sigma_{\text{tot}} = (M/A\rho L)\ \ln(N_0/N) \qquad (1)$$

where M is the molecular weight, A is Avogadro's number, and ρ and L are the intensity and length of the absorber. In order to obtain the cross section for absorption by oxygen nuclei the experimental value of $\sigma_{\text{tot}}$ must be reduced by the pair-production cross section $\sigma_{\text{pair}}$ and the Compton-effect cross section $\sigma_{\text{Comp}}$ for water. The cross section for elastic scattering of γ rays by protons at these energies is ~ $10^{-31}$ $\text{cm}^2$ and can be completely neglected. It might therefore seem most reasonable to use the theoretical cross sections for pair production and Compton scattering, but this could not be done for the following reasons:

1. In water the number of pairs produced on electrons is ~ 10% of the total number. Theoretical calculations for triplet production[24-26] in water at ~ 20 MeV yield cross sections differing by a factor of $1\frac{1}{2}$ to 2; for $\sigma_{\text{tot}} \approx 520$ mb and hν = 20 MeV we find 15 mb,[24] 22.6 mb,[25] and 32.1 mb.[26] This uncertainty of 17 mb in the pair-production cross section results in a very large uncertainty of the nuclear-absorption cross section, which is a few percent of the total absorption cross section.

2. The measurements were performed at 200-MeV peak γ bremsstrahlung energy. With an absorber in the beam path the number of γ rays in the investigated energy interval was necessarily increased somewhat by cascade multiplication of high-energy photons. This effect must have reduced the measured ratio $N_0/N$, with a corresponding reduction of $\sigma_{\text{tot}}$. The calculation showed that with good experimental geometry (careful collimation of the x-ray beam behind the absorber and large absorber-spectrometer separation) the photon increase in the investigated energy range did not exceed 0.5% of the photons with the same energy which impinged on the absorber. On this basis the values obtained for $\sigma_{\text{tot}}$ were reduced by not more than 1.7% (~ 9 mb). Since the correction cannot be calculated exactly, the uncertainty in the total cross section as a result of cascade multiplication is a few millibarns.

The nuclear part of the cross section was determined as follows. From data on the cross sections for the reactions $O^{16}(\gamma, n)$[27,28] and $O^{16}(\gamma, p)$[7,8,10] the giant-resonance peak for $O^{16}$ is located at 22—23 MeV; the resonance half-width is ~ 3.5 MeV. In the range 18.9—20 MeV the mean nuclear cross section is about one order of magnitude smaller than the mean cross section at the giant resonance peak. The presence of other reactions should not appreciably change the observed giant-resonance shape.

On the basis of the foregoing, the ($\sigma_{\text{pair}} + \sigma_{\text{Comp}}$) curve was normalized to make the nuclear cross section satisfy the given mean-value ratio in the intervals 18.9—20 and 22—23 MeV. The lowest points of the $\sigma_{\text{tot}}$ curve for 18.9—20 MeV were used to fix the zero point of the nuclear

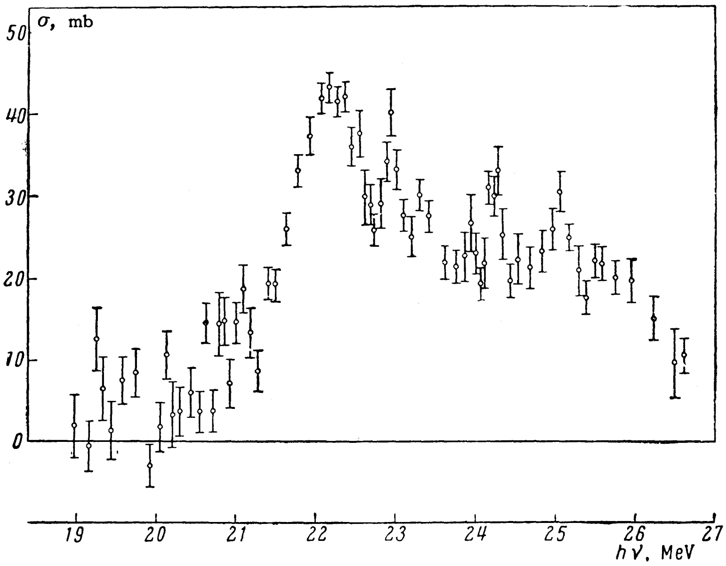

FIG. 4. Cross section for nuclear absorption by $O^{16}$.

cross-section scale. The underestimation of the nuclear part of the cross section should in this case not exceed the mean cross section ~ 4 mb observed in this energy interval. If the correction for cascade photon multiplication is considerably smaller than the upper limit obtained for the given effect, the normalized ($\sigma_{\text{pair}} + \sigma_{\text{Comp}}$) curve coincides with the theoretical curve for which the pair-production cross section on electrons was calculated from Votruba's data.[24] If the correction is of the order 1.5%, good agreement is obtained with the theoretical curve for which the triplet-production cross section was taken from [25].

Figure 4 shows the resulting cross section for nuclear absorption by $O^{16}$. Taking into account the measurement errors and the procedure used in subtracting the non-nuclear part of the absorption cross section, the position of the scale zero was determined within the limits −4 to +1.5 mb.

## 3. DISCUSSION OF RESULTS

The first conclusion derived from an analysis of the curve in Fig. 4 is that the nuclear absorption cross section has a structure. Four peaks having widths of a few keV are clearly observed at 22.2, 22.95, 24.2, and 25.05 MeV. The observed peaks are shifted to lower energies than the true resonances in the absorption cross section by an amount of the order of the γ-spectrometer energy resolution in this region. Following the correction for spectrometer resolution, resonance levels of $O^{16}$ are obtained at 22.3, 23.05, 24.3, and 25.15 MeV. The 19—21 MeV region has resonances at 19.4 and 21.2 MeV. However, since measurements in this region were performed for normalization of the ($\sigma_{\text{pair}} + \sigma_{\text{Comp}}$) curve, they are not accurate enough to provide a basis for discussion of the cross-section structure.

The table gives the available experimental data on $O^{16}$ levels in the 21—28 MeV region; the first column contains results of the present work. Special note should be taken of the excellent agreement with [15] regarding the cross section for the inverse reaction $N^{15}(p, \gamma_0)O^{16}$ (fifth column).

The cross sections for $N^{15}(p, \gamma_0)O^{16}$ and the corresponding direct reaction $O^{16}(\gamma, p_0)N^{15}$ with the ejected proton leaving the $N^{15}$ nucleus in the ground state are, according to the principle of detailed balancing, associated with the here considered excitation energy region by the relation $\sigma(\gamma, p_0) \approx 77\sigma(p, \gamma_0)$. The cross section for $O^{16}(\gamma, p_0)$ calculated in this way from the data of [15] in the giant-resonance region is found to be about one-half of the total $(\gamma, p)$ cross section of oxygen. Since this is such a large fraction of the total $(\gamma, p)$ cross section it is reasonable to assume that the resonances observed in [15] should also be observed in the $(\gamma, p)$ cross section. The available information regarding the structure of the $(\gamma, p)$ cross section, obtained by analyzing the photoproton spectrum (the third column of the table) are still very qualitative in character. Therefore the absence of photoproton peaks corresponding to $(\gamma, p)$ resonances at 23 and 25.1 MeV apparently results only from the insufficient accuracy of these results. The same applies to the data for the $(\gamma, n)$ cross section in the fourth column.

The second column gives the positions of sharp "breaks" observed on the $(\gamma, n)$ yield curve above 21 MeV. Four such breaks are observed on a broad peak of the nuclear absorption cross section

Energy levels of $O^{16}$ in the range 21—28 MeV

| Experimental | | | | | | Theoretical | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | [17] | |
| $\sigma_{tot}$ | $O^{16}(\gamma,n)$ yield curve [3]* | Photoproton spectrum[10] | Photoneutron spectrum[11] | $[N^{15}(p,\gamma_0)O^{16}]$ [15]*** | Cross section for reaction with charged particles[29] | [16] | Ordinary forces | Soper forces |
| | 20.91 | | | | | | | |
| | 21.17 | | | | | | | |
| | | | | | | | 21.5 | |
| | 21.87 | 21.9 ± 0.2** | 21.8 ± 0.3 | | | | | |
| | 22.01 | | | | | | | |
| 22.3 | 22.19 | 22.2 ± 0.2** | | 22.35 | 22.05 $(d, n)$ | | | 22.2 |
| | 22.41 | | | | | | | |
| | | | | | | 22.6 | | |
| 23.05 | | | 22.8 ± 0.3 | 23.08 | 23.05 $(d, n)$ | | | |
| | | | | | 23.54 $(\alpha, \alpha')$ | | | |
| 24.3 | | 24.0 ± 0.2** | 24.1 ± 0.4 | 24.43 | 24.38 $(d, n)$ | | | |
| 25.15 | | | | 25.11 | | 25.2 | | 25.0 |
| | | 25.7±0.2 | 26.0 ± 0.3 | | 25.7 $(He^3, \alpha)$<br>$(He^3, p)$ | | 25.6 | |
| | | | | | 26.4 $(He^3, p)$ | | | |
| | | 27.3 ± 0.2 | 27.9 ± 0.5 | | | | | |

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*The data of [3] were recalculated following improvement of the $O^{16}(\gamma, n)$ and $C^{12}(\gamma, n)$ thresholds used here to calibrate the betatron energy scale (private communication from B. Spicer).

**Corresponding peaks in the proton spectrum from $O^{16}$ photodisintegration have also been observed elsewhere: for hν = 21.9 MeV in [8,9], for 22.2 MeV in [7], and for 24.0 MeV in [9,12].

***The same resonances, but not well resolved, have apparently been observed in [14].

at 22.3 MeV. The fact that resonances corresponding to these breaks were not even partially resolved at a γ-spectrometer resolution ~ 120 keV obviously indicates that their width is considerably greater than the 25 keV assumed in [3].

Theoretical shell-model calculations for dipole transitions in γ-ray absorption by $O^{16}$ show [16,17] that the absorption cross section should consist of five resonances at about 13.5, 17.5, 20, 22, and 25 MeV. The table gives the more exact locations obtained in [16,17] for the last two resonances. According to these calculations almost the entire contribution to the absorption cross section should come from transitions to ~ 22- and 25-MeV levels. According to [16] the dipole-transition intensities to the 22- and 25-MeV levels are in approximately a 2 : 1 ratio. According to [17] a 2 : 1 ratio is calculated with Soper forces; for ordinary nuclear forces the ratio is increased to 5 : 1.

The presence of at least four experimental resonances in the 21—26 MeV region shows that the theoretical analysis in [16,17] underestimates the number of transitions in this region. Since the theoretical calculations considered only dipole transitions, the discrepancy can possibly be accounted for by assuming that some of the experimental resonances represent transitions having different multipolarity. An indication of quadrupole emission character for the 24.3-MeV level is found in [30], which is concerned with inelastic $O^{16}(e, e')$ scattering. A second possible explanation, given in [16], is that when mixtures of states corresponding to higher configurations are taken into account, each of the five levels should be transformed into a band of more or less closely located compound-nucleus levels. If the latter explanation is adopted, it is reasonable to assume that the 22-MeV transition is associated with the first two resonances observed in the absorption cross section, corresponding to 22.3- and 23.05-MeV levels. The 25-MeV transition would then be associated with the remainder of the cross section in the 23.5—26.6 MeV interval, including two resonances at 24.3 and 25.15 MeV, and an apparently unresolved resonance at ~ 25.8 MeV. The total intensity of the dipole absorption corresponding to transitions to all states in the given band should, according to [16], agree with that expected for a single pure state. Thus the integral cross section of the first group of levels in the 21—23.5 MeV interval should be approximately twice as great as the integral cross section in the 23.5—26.6 MeV interval. An estimate of this ratio based on the experimental cross section curve gives a ratio of the order of unity, in contradiction to the theory.

From the present work we obtain the integral cross section for nuclear absorption by $O^{16}$ in the giant resonance region. It is well known that for light nuclei the sum of the integral cross sections

$\sigma(\gamma, n)$ and $\sigma(\gamma, p)$ for the main reactions in the giant-resonance region amounts to an integral absorption cross section that is about one-half as large as it should be according to the sum rule. For oxygen, instead of the theoretical result 336 MeV-mb, the sum of the integral cross sections for $O^{16}(\gamma, n)O^{15}$ and $O^{16}(\gamma, p)N^{15}$ is 150-175 MeV-mb according to different authors.[31,32] This can be accounted for either by underestimation of the cross sections for other reactions that are possible in the giant resonance region, or by the fact that an insufficient part of the absorption cross section is associated with energies above the giant resonance. The integral absorption cross section in the interval 18.9—26.6 MeV, as calculated from the data in Fig. 4, is $150^{+30}_{-10}$ MeV-mb, which agrees within experimental error limits with the sum of the integral cross sections for $O^{16}(\gamma, n)$ and $O^{16}(\gamma, p)$. This result shows that the cross sections for other reactions in the giant resonance region are relatively small; therefore the missing portion of the integral absorption cross section lies in the region of higher energies. This conclusion has recently been confirmed by cloud chamber measurements[32] of the partial cross sections for different reactions in the photodisintegration of $O^{16}$ up to 170 MeV.

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