SOVIET PHYSICS

JETP

A translation of the Zhurnal Eksperimental'noĭ i Teoreticheskoĭ Fiziki.

Vol. 18, No. 5, pp. 1159-1465 (Russ. Orig. Vol. 45, No. 6, pp. 1693-2115, December 1963) May 1964

CROSS SECTION FOR GAMMA-RAY ABSORPTION BY CARBON IN THE GIANT RESONANCE REGION

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Submitted to JETP editor March 25, 1936; resubmitted July 3, 1963

J. Exptl. Theoret. Phys. (U.S.S.R.) 45, 1693-1703 (December, 1963)

The cross section for nuclear absorption of γ rays by carbon in the 13—27 MeV region was measured by the absorption method. A pair magnetic spectrometer was used as γ detector. Measurements were performed at the 250-MeV synchrotron of the Lebedev Physics Institute. The cross section curve has five peaks, at 16.5, 17.6, 19.1, 23, and 25.6 MeV. The integral cross section in the given energy region is 84 ± 10 MeV-mb. The measured C^{12} nuclear absorption cross section in the giant resonance region is compared with theoretical calculations and with experimental photonucleon spectra and cross sections for $C^{12}(\gamma, n)$ and $C^{12}(\gamma, p)$ in the same energy region.

INFORMATION about high-lying excited levels of light nuclei and the γ-ray interaction mechanism can be obtained by studying in detail the structure of the γ-ray absorption cross sections of these nuclei in the giant resonance regions. Recent publications have reported the first detailed investigations of the absorption cross sections for several light nuclei.[1-5]

Giant resonance in C^{12} has been investigated very frequently during the past decade, but with inconsistent results. On the one hand, the "breaks" in the (γ, n) yield curve[6] and the peaks of photoproton and photoneutron spectra reported in[7-9] clearly indicate a fine structure of C^{12} giant resonance. Separate isolated resonances in the absorption cross section have been observed in[2,4]. On the other hand, data concerning the cross section for the inverse (p, γ_0) reaction[10,11] and later measurements of photoproton[12-14] and photoneutron[15] spectra do not support similar conclusions. The absence of any considerable contribution of isolated narrow resonances to the C^{12} absorption cross section (unlike the case of O^{16}) has also been indicated by an indirect method.[16]

In the present work we report measurements of the total γ-ray absorption cross section for C^{12} in the excitation region 13—27 MeV.

MEASUREMENT TECHNIQUE

Our measurements were performed at the 250-MeV synchrotron of the Lebedev Physics Institute by the absorption method using a pair magnetic spectrometer as the detector and a $10 \times 10 \times 100$ cm graphite block as the absorber. A detailed description of the apparatus and of the experimental geometry has been given in[5]. The spectrometer gap width was 4 mm; in[5] the gaps

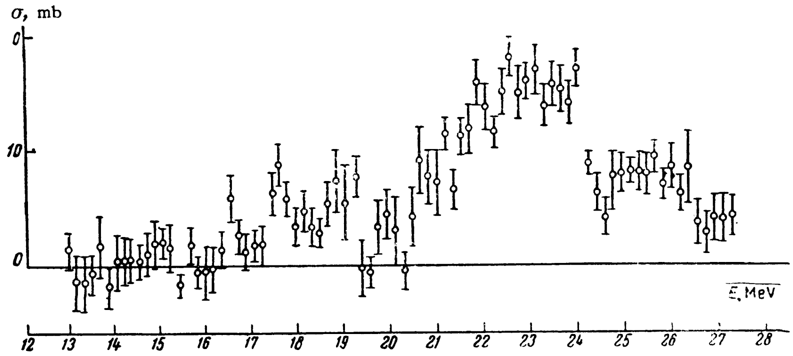

FIG. 1. C^{12} nuclear absorption cross section.

were 2 mm wide. The computed spectrometric resolving power under these conditions was 125 keV for 10-MeV γ rays, and 225 keV for 20-MeV γ rays. As a check the resolution was measured for a monochromatic γ line (9.716 MeV) from the Cr^{53} (n,γ) reaction; the resolving power was then found to be 120 keV.

The enhanced spectrometric efficiency brought about by the broader gaps enabled statistically accurate (~ 1%) measurements below the (γ, n) and (γ, p) reaction thresholds in the 13—16 MeV region. This permitted a more accurate normalization of the measured cross section and yielded a very reliable value of the absolute absorption cross section.

With constant maximum x-ray energy E_{max} = 220 MeV, the γ energy registered by the spectrometer varied by 175 keV in the 13—27 MeV region. For each given energy we measured the ratio of the number of γ quanta without the absorber (N_0) to the number (N) with the absorber in the photon beam, making at least 15 independent measurements at each energy. The statistical error was ~ 1% when the absorber was used.

RESULTS

The measured ratios N_0/N were used to calculate the total cross section σ_{tot} of γ absorption by carbon in the region 13—27 MeV. The cross sections for pair production and Compton scattering must be subtracted from σ_{tot} in order to obtain the nuclear absorption cross section.

As has been discussed in detail in [5], the large uncertainty in the cross section for pair production on electrons, which thus prevents a sufficiently accurate calculation of the absolute absorption cross section associated with such processes, and the small amount of cascade multiplication of high-energy photons that exists in the x-ray spectrum make it necessary to normalize the cross section curve for absorption associated with the electron interaction to the experimental curve. The nuclear part of the cross section was determined in the following manner.

The thresholds for C^{12} (γ, n) and C^{12} (γ, p), which are the principal reactions in the investigated energy region, are 18.7 and 15.96 MeV, respectively. In the interval 13—16 MeV below the thresholds of these reactions γ absorption by carbon nuclei can occur only in a (γ, α) reaction and through elastic and inelastic scattering. According to [17], the (γ, α) cross section in this energy region is smaller than 0.1 mb. For carbon Garwin has estimated [18] that the cross section for elastic and inelastic nuclear scattering of 13—16 MeV γ quanta also does not exceed 0.1 mb. Consequently, if the nuclear absorption cross section in the 13—16 MeV region is taken to be zero, the error will not exceed 0.2 mb.

In working with the pair magnetic spectrometer the position of each measured value E′ is displaced relative to the effective γ energy E by an amount approximately equal to the spectrometric resolving power. After making this correction the experimental total absorption cross section σ_{tot} was compared in the region 13—16 MeV with the calculated curve for the "non-nuclear" portion of the cross section.[19] The difference between the experimental points and the thus normalized "non-nuclear" cross section curve was the nuclear absorption cross section σ.

Figure 1 shows the cross sections for γ-ray absorption by C^{12}. The zero point of the nuclear absorption scale was determined with an error ± 0.4 mb from the experimental spread in the region 13—16 MeV.

Before analyzing the form of the nuclear absorption cross section, we shall discuss the conditions for observing peaks associated with separate nuclear levels when employing our present technique. We introduce the notation: σ_e for the cross section for absorption induced by Compton scattering and pair production, σ for the nuclear absorption cross section, Γ for the width of a nuclear level, d for the absorber thickness, n for the number of nuclei in unit volume, and $\Delta(E - E_0)$ for the function characterizing the instrumental resolution, which was normalized to unity:

$$\int_0^\infty \Delta(E - E_0)\,dE = 1.$$

The ratio of the counting rate with the absorber in the photon beam (N) and without the absorber (N_0) is

$$\frac{N}{N_0} = e^{-nd\sigma_e} \int_0^\infty e^{-nd\sigma(E)}\,\Delta(E - E_0)\,dE \qquad (1)$$

for which it is assumed that the γ-ray spectrum and σ_e are almost constant in an energy region, equal to twice the width δ of the energy resolution, where $\Delta(E - E_0)$ does not vanish. When $\Gamma \gg \delta$ the nuclear absorption cross section in the interval δ can also be regarded as approximately constant; then

$$\frac{N}{N_0} = e^{-nd(\sigma_e + \sigma)}.$$

Let the nuclear absorption cross section have the dispersive form

$$\sigma(E) = \sigma_0 \frac{(\Gamma/2)^2}{(E - E_r)^2 + (\Gamma/2)^2}. \qquad (2)$$

Equation (1) can be rewritten as

$$\frac{N}{N_0} = e^{-nd\sigma_e}\left[1 - \int_0^\infty (1 - e^{-nd\sigma(E)})\,\Delta(E - E_0)\,dE\right]. \qquad (3)$$

The integral here depends on the thickness of the absorber ($nd\sigma_0$), the level width Γ, and the form of the resolution function $\Delta(E - E_0)$. We shall assume that the latter is triangular, i.e.

$$\Delta(E - E_0) = 0 \qquad \text{for} \quad |E - E_0| \geqslant \delta/2,$$
$$\Delta(E - E_0) = 2\delta^{-1}[1 - 2\delta^{-1}|E - E_0|] \text{for} 0 < |E_0 - E| \leqslant \delta/2. \qquad (4)$$

If the sample is "thin" i.e., $nd\sigma \ll 1$ and $\Gamma \ll \delta$, we have, accurately to within the amount $(nd\sigma_0)^2(\Gamma/\delta)\exp\{-nd\sigma_e(E_0)\}$,

$$\frac{N}{N_0} = e^{-nd\sigma_e(E_0)}\left[1 - \frac{\pi\, nd\,\sigma_0\Gamma}{\delta}\left(1 - \frac{2}{\delta}|E_r - E_0|\right) + \ldots\right]$$
$$\text{for } |E_0 - E_r| \leqslant \frac{\delta}{2},$$

$$\frac{N}{N_0} = e^{-nd\sigma_e(E_0)} \qquad \text{for } |E_0 - E_r| \geqslant \frac{\delta}{2}. \qquad (5)$$

In the case of a "thick" sample, when $nd\sigma_0 \gg 1$ and $\Gamma/\delta \ll 1/\sqrt{nd\sigma_0}$, we obtain

$$\frac{N}{N_0} = e^{-nd\sigma_e(E_0)}\left[1 - \frac{2\sqrt{\pi}\,\Gamma\sqrt{nd\sigma_0}}{\delta}\left(1 - \frac{2}{\delta}|E_r - E_0|\right) + \ldots\right]$$
$$\text{for } |E_0 - E_r| \leqslant \frac{\delta}{2},$$

$$\frac{N}{N_0} = e^{-nd\sigma_e(E_0)} \qquad \text{for } |E_0 - E_r| \geqslant \frac{\delta}{2}. \qquad (6)$$

This result is correct to terms of the order

$$e^{-nd\sigma_e}\left(\frac{\Gamma\sqrt{nd\sigma_0}}{\delta}\right)^2 \ln\frac{\delta}{\Gamma\sqrt{\gamma nd\sigma_0}},$$

where γ is Euler's constant.

The foregoing equations show that when the level width Γ is much smaller than the resolution width δ we may fail to observe resonance in the nuclear absorption cross section even if σ_0 is relatively large. It follows from (6) that the well-known 15.11-MeV (1^+, T = 1) level of C^{12}, which has been observed in the elastic scattering of γ rays, will be practically unobservable in our present experiment if its parameters are those given by Garwin [18] (cross section at maximum 29.7 ± 1.1 b, width Γ = 64.5 ± 10.4 eV, and integral cross section 3.01 ± 0.60 MeV-mb).

DISCUSSION OF RESULTS

Figure 1 shows that the measured nuclear absorption cross section consists of several peaks having very different parameters. Most of the cross section for C^{12} giant resonance is located above 20 MeV. In this excitation region (up to 27 MeV) the absorption cross section exhibits two broad peaks having their centers of gravity at about 23 and 25.6 MeV. The integral cross sections of these peaks have the approximate ratio 3 : 1. It is evident that even relatively little worsening (by a factor 1.5—2) of the instrumental energy resolution by comparison with the resolution in our present experiment would result in quite symmetric giant resonance having its maximum at ~ 23 MeV, a width ~ 3.5 MeV, and a high-energy tail. This is confirmed by Ziegler's results.[1]

The major portion of the absorption cross section comprises a broad peak in the region 20—24 MeV with $\sigma_{max} \approx 16$ mb, half-width $\Gamma \approx 3$ MeV, and integral cross section 54 MeV-mb. The broad flat summit (~ 2 MeV), the sharp decline at 24 MeV, and the irregular shape of the curve suggest that this maximum consists of unresolved narrower peaks.

From earlier work[2] performed with the same apparatus but with better energy resolution we concluded that C^{12} has a well-resolved peak in its absorption cross section at 22.5 MeV with $\Gamma \leq 100$

Table I. C^{12} energy levels in the region 16–28 MeV obtained by different methods

From the nuclear absorption cross section: Present work	From the nuclear absorption cross section: [2,4]	From the yield curve of $C^{12}(\gamma,n)$ [6]*		From photoneutron spectrum [15]	From photoproton spectrum [13]	From cross section for inverse reaction B^{11} $(p, \gamma_0)C^{12}$ [11]	From cross section for reactions induced by charged particles[21]
16.5							16.58
							17.23
17.6							17,77
							18.40
							18.85
		18.90					
			(60)				
		18.96					
			(120)				
		19.08					
			(90)				
19.1		19.17				19.2	19.26
			(130)				
		19.30					19.42
			(160)				
		19.46					
			(110)				
		19.57					19.67
			(190)				
		19.76					19.88
			(160)				
		19.92					
			(210)				
	20.15	20.13					20.27
			(140)				
	20.46	20.27					20.49
			(350)				
		20.62					20.65
			(280)				
	20.92	20.90					
			(180)				
		21.08					
			(140)				
		21.22					21.34
			(360)				
		21.58					21,80
			(440)				
		22.02					
23.0	22.5			23.0	22.55	22.5	
25.6				26.0	25.5	25.5	
					27.5		

*Distances in keV between neighboring "breaks" are given in parentheses.

keV. Measurements performed with two absorbers of different thicknesses yielded identical results. The absence of a reliably resolved peak at 22.5 MeV on our present curve of the nuclear absorption cross section can be accounted for by the fact that the spectrometric resolving power was approximately only half as good as in [2]. The mean absorption cross section ~ 22 mb in the 22.2–23.5-MeV, obtained in [2], is approximately 1.5 times larger than in our present work. This is accounted for by the uncertainty in the theoretical cross section for "non-nuclear" absorption due to the cross section for "triplet" production [5] 1) and by the impossibility, when measurements are made in a narrow energy range, of normalizing this cross section to the portion of the experimental curve where the nuclear cross section is relatively very small.

The second peak, in the region ~ 24.5–26.5 MeV, has the parameters σ_{max} = 8 mb, $\Gamma \sim 2$ MeV, and an integral cross section 17 MeV-mb.

The cross section for nuclear absorption of γ rays by carbon which Ziegler [1] measured using a similar technique with inferior energy resolution (~ 400 keV) exhibits a smoother dependence on excitation energy in the region 24–27 MeV than in our present experiment. The absolute cross sections are in good mutual agreement. There are indications in [13,20] that both the first peak at 20–24 MeV and the second peak at 24.5–26.5 MeV have a

1)In [2] measurements were made using a 30-MeV synchrotron, and there was practically no cascade multiplication of photons.

more complex structure. Below 20 MeV three relatively narrow peaks are observed on the curve for the C^{12} nuclear absorption cross section, at 16.5, 17.6, and 19.1 MeV. The half-widths of these peaks, without corrections for the resolving power, are 250, 400, and 650 keV, respectively.

Table I gives the experimental data regarding excited C^{12} levels in the region 16—27 MeV. The peaks observed in the absorption cross section are compared with the investigation of breaks in the (γ, n) yield curves,[6] the latest most precise photoproton[13] and photoneutron[15] spectra, and the results from a study of the inverse reaction $B^{11}(p, \gamma_0)C^{12}$.[11] The last column gives the C^{12} levels discovered in reactions induced by charged particles[21] [except the (p, γ_0) reaction].

The table shows that the two absorption cross section peaks observed above 20 MeV in our present work agree with peaks of the (γ, n) and (γ, p) cross sections derived by analyzing photoproton and photoneutron spectra and the cross section for the (p, γ_0) inverse reaction [related by detailed balancing to the (γ, p_0) reaction].

The resonances in the absorption curve below 20 MeV (Fig. 1) were observed at the same excitation energies in the cross sections for reactions with charged particles.

The peak at 19.1 MeV was observed in the cross sections for the (p, γ_0), (p, p'), and (p, n) reactions.[11,21,22] The widths of the 450- and 500-keV levels given in[21,22] agree with our present results.

The 17.6-MeV peak can be associated either with a 17.23 MeV level (1^-, Γ = 1160 keV) or with a 17.77-MeV level (0^+, Γ = 140 keV) derived by investigating the (p, γ), (p, α), and (p, p') cross sections.[21] Since a $0 \rightarrow 0$ transition is forbidden, agreement with the 17.77-MeV level would require us to assume that the assignment 0^+ is incorrect.

The resonance observed with 16.5-MeV γ rays obviously corresponds to the 16.58-MeV level (2^-, Γ = 295 keV) derived by investigating the cross sections for $B^{10}(He^3, p)$, $B^{11}(p, \gamma)$, and $B^{11}(p, \alpha)$.[21] Although the probability of exciting a 2^- level must be small, the cross section for $C^{12}(\gamma, 3\alpha)$ indicates that this resonance occurs.[21]

The fact that a large number of the levels observed in reactions with charged particles do not appear in the cross section for γ-ray absorption could be accounted for by the small probability of their excitation in the course of photodisintegration. However, we are left with the problem of the peaks corresponding to the breaks in the (γ, n) yield curves measured by the methods of direct registration and induced activity (column 2).

Column 2 gives (in parentheses) in addition to the positions of the breaks, the energy separations of the neighboring breaks. With the exception of two breaks at 20.62 and 21.58 MeV all of these separations are in the range from 60 to 200 keV.

Since the spectrometric energy resolution in our measurements was about 200 keV, while the experimental points are separated by 175 keV, it

Table II. Parameters of C^{12} giant resonance obtained by different methods

	E_{max}, MeV, of cross section	Cross section at maximum σ_{max}, mb	Γ, MeV	$\int \sigma dE$, MeV-mb	Source
Absorption cross section	23	16	3.2	84(27)*	Present authors
	23	17	4	100(27)	[1]
Nuclear cross section of (γ,p) reaction	21.5	34	1.7	63(24)	[23]
	23	14.7**		46(24)	[7]
	22.1	8.1**	3.6		[24]
	22.5	24**			[10]
	22.5	12.7	3.3	57(27)	[12]
	22.5	12	3.1		[11]
	22.5	11	3.1	43(27)	[13]
Nuclear cross section of (γ,n) reaction	22.5	8.3	4.3	39(27)	[25]
	22.8	10.4	3.5	34(25)	[26]
	23.0	7.9	3.2	22(24)	[27]
	23.4	6.3	3.2	24(26)	[20]
	23.0	7.5	4	35(27)	[15]
	23	8	4.2	34(27)	[28]

*The upper integration limits (in MeV) are given in parentheses.
**The data given here are the values corrected in [12] for anisotropic distribution.

Table III. Energy levels and relative transition probabilities obtained in the present work, and theoretically calculated characteristics of C^{12} dipole transitions

Present work		Theoretical					
		[29]		[30]		[31]	
E, MeV	w, %	E, MeV	w, %	E, MeV	w, %	E, MeV	w, %
16.5	3			17.1	12		
17.6	6						
19.1	6.5	18.7	6.5	18.7	3		
		22.2	75			22.2	31
				22.5	54		
23	64					23.0	9
						23.7	9
		23.9	0.5				
				24.3	25		
25.6	20					26.3	11
						29.5	9
						31.9	30
		34.3	18				

is clear that, independently of their parameters, the corresponding resonances should not appear in the absorption cross section. The observed 19.1-MeV peak evidently represents the superposition of several close-lying levels. With regard to the two most isolated breaks the experimental points in Fig. 1 around 20.62 and 21.58 MeV seem to indicate the corresponding resonances. However, additional measurements are required for reliable confirmation.

The work in [4] was also performed by the absorption method, but with monochromatic γ radiation from the $T(p,\gamma)$ reaction. The energy resolution in the experimental region 20—21.2 MeV varied from 70 to 40 keV. The first two peaks at 20.15 and 20.46 MeV obviously correspond to breaks in the yield curve at 20.13 and 20.27 MeV. The sharp increase of the cross section beginning at ~ 20.6 MeV in the region of the third peak corresponds to the break at 20.62 MeV. However, the maximum of this peak at 20.92 MeV conflicts with the next break, which is observed at 20.90 MeV.

The first photoproton [7,8] and photoneutron [9] spectra from carbon, which were reported in earlier investigations, were regarded as a confirmation of the hypothesis that the absorption cross section represents a combination of isolated narrow resonances. However, later investigations, which appear to have used superior techniques, of photoproton [13] and photoneutron [15] spectra did not reveal a structure for carbon.

The cross section for the reaction $B^{11}(p,\gamma_0)C$ in the 21—26-MeV excitation region of C^{12} was very carefully investigated by Gove et al. [11] but no fine structure was detected; only relatively small irregularities (within 10%) of the cross section curve were found.

Further thorough experimental study will be required to determine whether the foregoing negative result can be attributed to inadequate energy resolution or to some other circumstance, and also to determine whether the partial reactions involving carbon possess a fine structure.

As already indicated, the (γ,p) and (γ,n) reactions are the principal processes occurring in the given energy region. It is therefore interesting to compare the observed absorption cross section with the sum of the cross sections for these reactions. Table II gives the available experimental parameters of C^{12} giant resonance.

The cross section for $C^{12}(\gamma,n)C^{11}$ was measured by several investigators using the residual activity method [25,27,28] and the direct registration method [20,26], while Fuchs et al [15] calculated the cross section from the photoneutron spectrum. The cross section for $C^{12}(\gamma,p)B^{11}$ has been determined by direct registration of protons, [23] from the cross section for the inverse (p,γ_0) reaction, [10,11] and from the photoproton spectrum. [7,12,13,24]

In calculating the (γ,n) and (γ,p) cross sections from the photoneutron and photoproton spectra, and also the (γ,p) cross section from the (p,γ_0) cross section, it was assumed that the ejected nucleons leave the product nucleus in its ground state. Penner and Leiss [24] have shown that this assumption is correct up to an excitation energy of 30 MeV. Further confirmation is found by comparing the absolute (γ,p_0) and (γ,p) cross sections.

Table II shows that the maxima of the (γ,p) and (γ,n) cross sections have average values of ~ 12 and ~ 8 mb, respectively. (The values of σ_{max} for the (γ,p) reaction obtained in [23,10] are obviously too high.) The sum of these cross

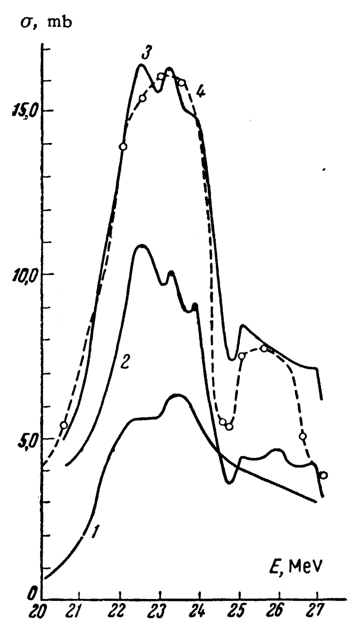

FIG. 2. Cross sections for the $C^{12}(\gamma,n)$ and $C^{12}(\gamma,p)$ reactions compared with the measured cross section for γ-ray absorption in carbon. 1—σ(γ,n),[20] with data above 25.5 MeV taken from [25]; 2—σ(γ,p); [13] 3—σ(γ,n) + σ(γ,p); 4—cross section for nuclear absorption in the 20—27MeV region.

sections is consistent within experimental error with the values 16 and 17 mb for the absorption cross section at the giant resonance maximum.

The sum of the mean values given in the table for the integral cross sections of the (γ, p) and (γ, n) reactions (~ 50 MeV-mb and ~ 30 MeV-mb, respectively) are in good agreement with the integral absorption cross section obtained in the present work.

Figure 2 compares, in the region 20—27 MeV, the absorption cross section shown in Fig. 1 and the sum of the (γ, p) and (γ, n) cross sections. The partial cross sections σ for the (γ, p) and (γ, n) reactions, which are also given in Fig. 2, were taken from the most recent literature.[13,20] Both the absolute values and the general behavior of the curves exhibit entirely satisfactory agreement.

Poorer agreement results when the (γ, n) cross sections σ given in[26,27] are used, because when these are added to the (γ, p) cross section the principal peak in the 20—24-MeV region becomes sharper. This appears to indicate that the maxima of the (γ, p) and (γ, n) reactions do not coincide.

Table III gives the energies and intensities of transitions involved in the dipole absorption of γ rays by C^{12} according to several theoretical conditions[29-31] and our present work. All the calculations were based on the shell model. A spherically symmetric potential was used in[29,30]; the difference between the results obtained in these two studies results mainly from the fact that different experimental values were used for the binding energies of nucleons in different shells. In[31] (the last column) a Nilsson deformed potential was used; in this case the C^{12} dipole resonance is split into two groups of transitions corresponding to the excitation of vibrations parallel and perpendicular to the nuclear axis of symmetry. These transition groups overlap partially because of strong spin-orbit interaction.

The table shows that the region of intense dipole transitions may extend above 30 MeV. It is therefore necessary when investigating the giant resonance to measure the nuclear absorption cross section up to 35—40 MeV. This also furnishes some information concerning the C^{12} quadrupole moment.

Below 30 MeV the levels making the principal contributions to the absorption cross section are located near 23 MeV, thus agreeing with the position of the principal maximum obtained in our work. The shape of the experimental curve above 20 MeV is in good agreement with the results of Nilsson et al.[31]

Below 20 MeV the calculations do not yield the required number of levels. This can be attributed to insufficient accuracy or to a different multipolarity of some transitions.

Calculations performed for other types of transitions[29] indicate the possibility that the 16.5- and 19.1-MeV levels obtained in our present work can be assigned to 2^+ and 2^- excitations. However, the probability of a 2^- excitation by γ-ray absorption within the given energy region must be relatively very small.

The integral cross section for nuclear absorption in the 13—27 MeV region, as calculated from the curve in Fig. 1, is 84 ± 10 MeV-mb. This agrees with the integral cross section 130 ± 20 MeV-mb obtained by a similar technique for the 10—30 MeV region.[1] Somewhat poorer agreement is found with the integral cross section 120 MeV-mb in the 10—27 MeV region, which was determined by the absorption method using a scintillation counter as the detector.[32]

The integral cross sections obtained in the present work and in[1,32] comprise about half of the integral absorption cross section 252 MeV-mb obtained theoretically from the "sum rule." This obviously shows that in the case of carbon (as for oxygen) the giant resonance region below 30 MeV includes only about half of the integral cross section for dipole transitions.

We wish to thank N. S. Kozhevnikov for much assistance with the measurements and treatment of the results, and B. A. Tulupov for numerous profitable discussions.

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Translated by I. Emin
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