PERIODIC STRUCTURES OF A KINETIC NATURE IN CONDUCTING MEDIA WITH A STATIONARY FLUX

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A conducting medium with a stationary flux due to an external electric field, light pressure, or a sound beam may, at a certain critical value of the flux, become unstable with respect to formation of a periodic distribution of the magnetic and electric fields, charge density, lattice displacements, and temperature. All the quantities mentioned depend periodically on the coordinates that are transverse to the flux direction. In this case two types of transitions to the inhomogeneous state are possible. For a "soft" transition the amplitude of the inhomogeneous part is proportional to the square root of the excess over critical. For a "hard" transition, which is similar to first-order phase transitions, the amplitude changes discontinuously from zero to a finite value. Some possibilities of observing the phenomena are mentioned.

1. INTRODUCTION

ASSUME that in a conducting medium (metal, semimetal, and in some cases, semiconductor) there is some stationary flux, for example a flux produced by radiation pressure or a sound flux. It can also be simply an electric current produced by an external electric field. The field producing the flux, and the flux itself, will be regarded as homogeneous in both the longitudinal and transverse directions. It then turns out that under a rather wide range of conditions, at fluxes exceeding a certain critical value, the conductor goes over into a new state, the character of which depends on the geometry of the conductor.

If the dimensions of the body in the flux direction exceed its transverse dimensions, then growing transverse oscillations are produced in the body. They were investigated in a number of papers: ferromagnetic waves in [1], acoustomagnetic in [2], optimagnetic in [3] and galvanomagnetic waves, which produce microwave radiation in semiconductors and radiation at lower frequencies in semimetals, in [4].

On the other hand, if the dimensions of the body in the flux direction are smaller than its transverse dimensions (the body is a plate or disk, and the flux is perpendicular to its plane), then the indicated fluxes produce in the body a different transition, which we shall consider in the present paper. A stationary magnetic field is produced in the body both in the longitudinal and in the transverse direction, and varies periodically in the direction transverse to the flux. The onset of a spatially-periodic magnetic field is accompanied by the appearance of an electric field, a charge distribution, a crystal-lattice displacement distribution and a temperature distribution, all of which are periodic in space. In a conductor of cylindrical form, in which the flux is directed along the axis, there may be produced an R structure, i.e., a radial distribution characterized by a Bessel function, and also a φ structure, i.e., a periodic azimuthal distribution of the indicated quantities.

The structures may be produced via phase transitions of either first or second order (i.e., either jumpwise or smoothly). In the latter case, near critical values of the flux, the amplitude of all the quantities forming the periodic or quasiperiodic structure is proportional to the square root of the excess above the critical value. A quasithermodynamic analysis of the transition to the structure, based on the principle that the derivative of the entropy be extremal with respect to time, also results in proportionality to the square root of the excess above critical value.

We consider transitions to the structure in four cases.

A. The crystal carries a flux of electromagnetic waves (we shall call this flux optical) or a flux of transverse acoustic oscillations, and a magnetic field whose direction, generally speaking, does not coincide with that of the flux. In this case the structure is produced via a second-order phase transition.

B. There is no external magnetic field, but account is taken of the temperature dependence of the coefficient of proportionality $\gamma = \gamma(T)$ between the flux density I and the electric field $E = \gamma I$ produced by the flux. In this case a first-order transition is produced if $\partial\gamma/\partial T > 0$.

C. The flux is an electric current and there is an external magnetic field. This case has a number of singularities connected with the fact that the current produces its own magnetic field. In this case a φ structure is impossible.

D. Electric current in an anisotropic medium in the absence of an external magnetic field. In an anisotropic medium, a structure is apparently possible in the presence of any flux, but the necessary parameters of the medium have not yet been determined experimentally, so that quantitative predictions are as yet impossible. The occurrence of a structure in this case is possible only in crystals of monoclinic and triclinic syngony.

In all the indicated cases, a common property of the geometries of the conductor is the fact that the flux must propagate in the direction of the smallest dimension.

At a certain critical flux I_c, a structure is produced formed with four telescopes[5] consisting of a front proportional counter and a rear NaI(Tl) scintillation counter. Particles with energies of 3–18 MeV emitted at 90° to the γ-ray beam were detected.

The target was gaseous nitrogen with 95% content of the isotope N^{15}.

In addition to protons, for $E_{\gamma\,max} \le 30$ MeV, deuterons and tritons were also detected. In the series of measurements at higher values of $E_{\gamma\,max}$, the resolution in the front counter was insufficient to distinguish the deuterons and tritons from protons, but their admixture to the protons did not exceed a few per cent.

The bremsstrahlung energy flux was measured by a quantameter[6] with an absolute calibration accuracy of 2% and a charge measurement accuracy of 0.1%.

The bremsstrahlung maximum energy scale of the synchrotron was calibrated by the method described by Denisov and Kul'chitskiĭ[7] with photoprotons from N^{15} and O^{16} with energies of 7–13 MeV. The calculations for the calibration were made in a computer with standard programs for proton energy intervals $\Delta E_p = 200$ keV. The accuracy of the calibration turned out to be better than 1%.

METHOD OF ANALYSIS OF EXPERIMENTAL DATA, AND RESULTS OF THE ANALYSIS

It is an extremely complex problem to determine in what states the final nucleus is produced as the result of a (γ, p) reaction and to obtain the cross sections for the individual branches of this reaction from data on the energy distributions of photoprotons obtained with bremsstrahlung. We will therefore discuss the analysis procedure. It can be broken down into three steps. In the first step the cross section for the (γ, p_0) reaction with formation of the final nucleus in the ground state was determined; in the second step, the group of protons corresponding to formation of C^{14} in excited states was identified, and the energies of these states were found; in the third step, the cross sections for the individual branches of the (γ, p) reaction with transitions to the observed excited states were calculated.

1. The (γ, p_0) cross section. Determination of the (γ, p_0) cross section is made easy in many ways by the fact that the first excited state of C^{14} has a rather high energy (6.09 MeV),[8] as a result of which the high-energy part of the photoproton spectrum has a broad region (about 6 MeV) consisting only of protons which have left the final nucleus in the ground state.

We will designate by $Y(E_p, E_{\gamma\,max})$ the yield of protons with average energy E_p for some proton energy interval ΔE_p. The yield is defined as the number of protons in the interval ΔE_p per unit energy flux of the radiation, measured by a quantameter. For protons which leave the final nucleus in the ground state, the yield $Y_0(E_p, E_{\gamma\,max})$ is proportional to the number of photons $P(E_{\gamma 0}, E_{\gamma\,max})$ in the interval $\Delta E_{\gamma 0} = {}^{15}/_{14}\,\Delta E_p$ of the bremsstrahlung spectrum, per unit quantameter reading:

$$Y_0(E_p, E_{\gamma\,max}) = \alpha_0 P(E_{\gamma 0}, E_{\gamma\,max}),$$

where the proton energy E_p is related to the energy $E_{\gamma 0}$ of the γ rays responsible for production of protons of energy of E_p by the equation $E_{\gamma 0} = {}^{15}/_{14}\,E_p + Q$; $Q = 10.2$ MeV is the threshold energy of the (γ, p_0) reaction. The desired cross section $d\sigma/d\Omega$ is proportional to the coefficient α_0, i.e., $d\sigma/d\Omega = k\alpha_0$, and the coefficient k is determined by the experimental geometry, the number of target nuclei, and the quantameter constant.

For each interval $\Delta E_p = 200$ keV the coefficient α_0 was found as the weighted mean value for various $E_{\gamma\,max}$ from the yields due only to transitions to the ground state.

2. Excited states of C^{14}. In order to determine in what excited states the C^{14} nucleus is formed, we found the spectrum of protons from transitions to the states for each value of $E_{\gamma\,max}$:

$$Y_e(E_p, E_{\gamma\,max}) = Y(E_p, E_{\gamma\,max}) - \alpha_0 P(E_{\gamma 0}, E_{\gamma\,max}).$$

Then for each two neighboring values of $E_{\gamma\,max}$ we calculated the difference spectra

$$\Delta Y_e^{(i)}(E_p) = Y_e(E_p, E_{\gamma\,max}^{(i+1)}) - Y_e(E_p, E_{\gamma\,max}^{(i)}),$$

where the index i enumerates a set of successive values of $E_{\gamma\,max}$ in which $E_{\gamma\,max}^{(i+1)} > E_{\gamma\,max}^{(i)}$.

It is evident that a spectrum shape such as that in the difference spectrum should be associated with protons produced by γ rays with the energy distribution $\Delta N_\gamma = P(E_\gamma, E_{\gamma\,max}^{(i+1)}) - P(E_\gamma, E_{\gamma\,max}^{(i)})$, shown schematically in Fig. 1. The center of gravity of the distribution ΔN_γ will be designated by ϵ_0.

If transitions are possible to levels of the final nucleus with energies $E_1 < E_2 < E_3$, then monochromatic γ rays with $E_\gamma = \epsilon_0$ should result in a line spectrum of protons, as shown in Fig. 1, where $E_p^{(S)} = [(A-1)/A] \times (\epsilon_0 - Q - E_S)$. In contrast to monochromatic γ rays, the γ rays of the bremsstrahlung difference spectrum give a spectrum of protons which consists of the superposition of curves similar to the curve of the bremsstrahlung difference spectrum, with the centers of gravity of the peaks at $E_p^{(1)}$, $E_p^{(2)}$, and $E_p^{(3)}$ (see Fig. 1). From the position of the peaks in the difference spectrum of protons it can be concluded which levels of the final nucleus are produced as the result of the (γ, p) reaction. In such an analysis it is convenient to plot the proton difference spectra as a function of the quantity $E = \epsilon_0 - Q - [A/(A-1)]\,E_p$, which characterizes the excitation energy of the final nucleus. The convenience lies in the fact that for any such difference spectra obtained for identical $\Delta E_{\gamma\,max} = E_{\gamma\,max}^{(i+1)} - E_{\gamma\,max}^{(i)}$, the locations of the peaks corresponding to a given level of the final nucleus should coincide. Since the shape of the bremsstrahlung difference spectra does not depend strongly on ϵ_0 for fixed $\Delta E_{\gamma\,max}$, it is possible to add the individual proton difference spectra in order to obtain the most distinct separation of the peaks.

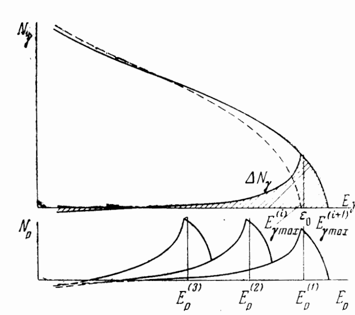

FIG. 1. Schematic representation of bremsstrahlung difference spectrum (crosshatched area) in the upper figure and proton difference spectrum in the lower figure.

Here the resolution function of the levels of the final nucleus will be similar to the bremsstrahlung difference spectrum with the given $\Delta E_{\gamma\,max}$.

In analysis of the data on N^{15} this summation was performed for two groups of proton difference spectra: with $\Delta E_{\gamma\,max} = 1$ MeV (21.7 – 20.7, 22.7 – 21.7, 23.8 – 22.7, 24.8 – 23.8, and 25.8 – 24.8 MeV) and with $\Delta E_{\gamma\,max} = 2.1$ MeV (27.9 – 25.8, 30.0 – 27.9, 32.1 – 30.0, and 34.2 – 32.1 MeV). Before summation, the proton difference spectra were reduced to the same number of γ rays in the peak of the corresponding bremsstrahlung difference spectra. Then the γ rays of the various bremsstrahlung difference spectra contribute to the various peaks of the proton difference spectrum in proportion to the cross section for excitation of a given level of the final nucleus by these γ rays.

The sum of these difference spectra is shown in Fig. 2, in which for $E_\gamma < 26$ MeV only one peak is visible in the C^{14} excitation-energy region near 7 MeV. For higher values of E_γ a peak appears also in the vicinity of 11 MeV. The first peak is well approximated by the resolution function with a center of gravity 7.0 ± 0.2 MeV, and we assigned this peak to the known level 7.01 MeV ($J^\pi = 2^+$), while the second peak was assigned to the 10.74-MeV level of C^{14}.[8]

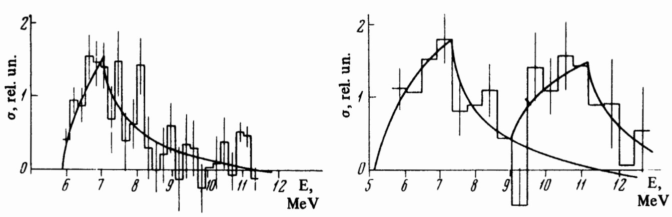

FIG. 2. Sum of reduced proton difference spectra corresponding to $\Delta E_{\gamma max} = 21.7 - 20.7, 22.7 - 21.7, 23.8 - 22.7, 24.8 - 23.8$, and $25.8 - 24.8$ MeV (upper figure) and $\Delta E_{\gamma max} = 27.9 - 25.8, 30.0 - 27.9, 32.1 - 30.0$, and $34.2 - 32.1$ MeV (lower figure); E and σ are respectively the energy and intensity of excitation of the final nucleus. The solid line is the resolution function for the final-nucleus level, similar to the bremsstrahlung difference spectrum curve.

3. (γ, p) cross section with formation of the final nucleus in excited states. If we know that in the $N^{15}(\gamma, p)C^{14}$ reaction the C^{14} final nucleus is produced in states with energy $E_1 = 7.01$ MeV and $E_2 = 10.74$ MeV, we can express the yields $Y_e(E_p, E_{\gamma\,max})$ in the following way:

$$Y_e(E_p, E_{\gamma\,max}) = \alpha_1(E_{\gamma 1})P(E_{\gamma 1}, E_{\gamma\,max}) + \alpha_2(E_{\gamma 2})P(E_{\gamma 2}, E_{\gamma\,max}),$$

where

$$E_{\gamma 1} = {}^{15}/_{14}E_p + Q + E_1, \quad E_{\gamma 2} = {}^{15}/_{14}E_p + Q + E_2.$$

The coefficients α_1 and α_2 are proportional to the cross sections of the (γ, p) reaction with production of C^{14} in the excited states indicated. These coefficients were found by the method of least squares from the values of $Y_e(E_p, E_{\gamma\,max})$ obtained for various $E_{\gamma\,max}$. The (γ, p) cross sections with formation of C^{14} in various states, obtained from the coefficients α_0, α_1, and α_2, are shown in Figs. 3–5.

Here the coefficient k relating the cross sections $d\sigma/d\Omega$ and the values of α was found by comparison of

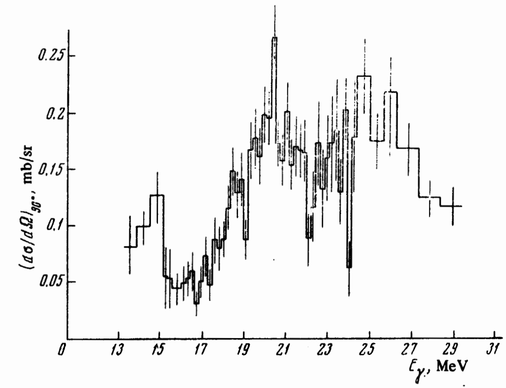

FIG. 3. Cross section $d\sigma/d\Omega$ for the reaction $N^{15}(\gamma, p_0)C^{14}$ with formation of the final nucleus in the ground state for protons emitted at an angle 90° with respect to the γ-ray beam direction.

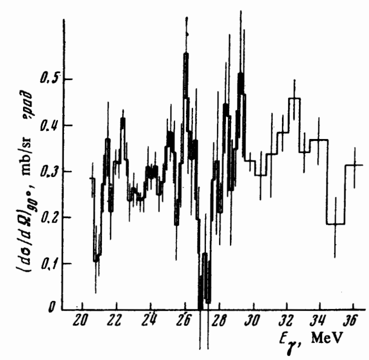

FIG. 4

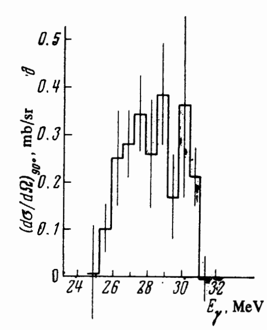

FIG. 5

FIG. 4. Cross section $d\sigma/d\Omega$ for the reaction $N^{15}(\gamma, p)C^{14}$ with formation of the final nucleus in a state with energy 7.01 MeV ($J^\pi = 2^+$) for protons emitted at an angle 90° with respect to the γ-ray beam direction.

FIG. 5. Cross section $d\sigma/d\Omega$ for the reaction $N^{15}(\gamma, p)C^{14}$ with formation of the final nucleus in a state with energy 10.74 MeV for protons emitted at an angle 90° with respect to the γ-ray beam direction.

the photoproton yields from N^{15} and O^{16} under the same conditions. The yields from O^{16} in a given experiment were normalized to the absolute yield measured previously[9] by us, and the absolute values of the $N^{15}(\gamma, p)C^{14}$ cross sections were calculated from these results. This is equivalent to measurement of the $N^{15}(\gamma, p)C^{14}$ cross sections under the same conditions in which the $O^{16}(\gamma, p)N^{15}$ cross sections were measured,[9] which increases the reliability of the comparisons made below of the cross sections for the two reactions.

Figures 6 and 7 show the total cross sections obtained from the differential cross sections given in Figs. 3–5.

Here the angular distribution for the (γ, p_0) reaction was taken from Rhodes and Stephens,[3] and in the other cases was assumed to be of the form $1 + 1.5 \sin^2\theta$. The cross section for the $N^{15}(\gamma, p)C^{14}$ reaction, as the sum of the cross sections of the individual branches of this reaction, is shown in Fig. 8.

DISCUSSION OF RESULTS

We will compare the results obtained with data from other studies of N^{15} photodisintegration. Those studies [3,4] give information only on the reaction $N^{15}(\gamma, p_0)C^{14}$.

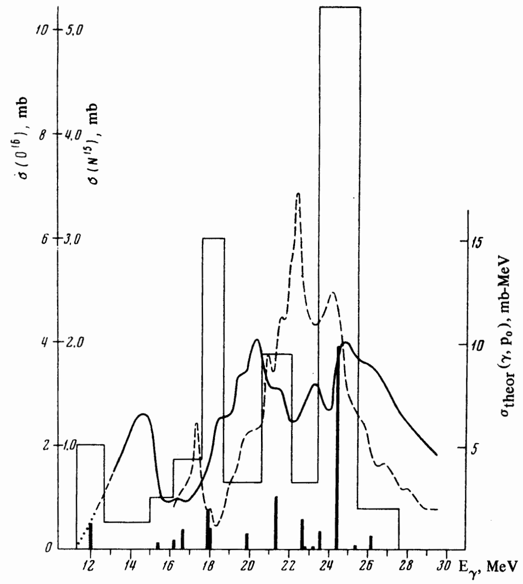

FIG. 6. Comparison of the $N^{15}(\gamma, p_0)C^{14}$ cross section (solid line) with the $O^{16}(\gamma, p_0)N^{15}$ cross section according to the data of ref. 9 (dashed line) and with the theoretical results of Zhusupov and Éramzhyan [2] for the $N^{15}(\gamma, p_0)C^{14}$ reaction. The initial portion of the cross-section curve for the reaction $N^{15}(\gamma, p_0)C^{14}$ was obtained from the data of Rhodes and Stephens. [3] The vertical lines give the theoretical energies of dipole states of N^{15} and the integrated cross sections for their excitation for the reaction channel (γ, p_0). The histogram shows the results of the same calculations of the cross section for the $N^{15}(\gamma, p_0)C^{14}$ reaction.

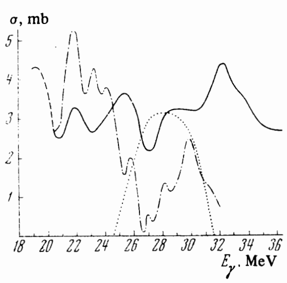

FIG. 7

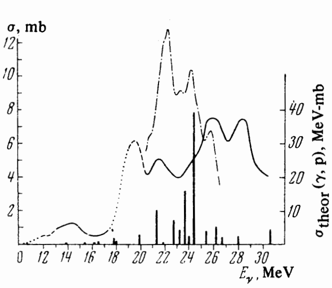

FIG. 8

FIG. 7. Comparison of the cross section for the reaction $N^{15}(\gamma, p)C^{14}$ with formation of the final nucleus C^{14} with formation of the final nucleus C^{14} in a state with energy 7.01 MeV (Solid line), and the data of ref. 9 on the cross section for the reaction $O^{16}(\gamma, p)N^{15}$ in which the N^{15} nucleus is left in the 6.33-MeV state (dot-dash line). The dotted curve is the cross section for the reaction $N^{15}(\gamma, p)C^{14}$ with formation of the C^{14} nucleus in the 10.74-MeV state. The initial portion of the solid curve was obtained from the data of Rhodes and Stephens. [3]

FIG. 8. Comparison of the total cross sections (the sum of all partial cross sections) of (γ, p) reactions in N^{15} (solid curve) and O^{16} (dot-dash curve) according to the data of ref. 9. The vertical lines represent the results of the calculation of Zhusupov and Éramzhyan [2] for the proton decay channel of N^{15} dipole states. The dotted part of the curve for N^{15} was obtained by extrapolation to the threshold of the (γ, p) reaction with formation of the C^{14} nucleus in the 7.01-MeV state.

Our curve for the (γ, p_0) cross section agrees with the corresponding curves in [3,4]. The integrated cross sections for the (γ, p_0) reaction are nearly the same in all studies. Thus, in the range $E_\gamma = 12.5-30.5$ MeV the integrated cross section according to our measurements is 21 ± 3 MeV-mb, and according to Kosiek[4] it is 22 ± 3 MeV-mb; in the range $E_\gamma = 12.5-24.7$ MeV we obtained 14 ± 2 MeV-mb, while Rhodes and Stephens[3] give 16 ± 2 MeV-mb.

It is interesting to compare the proton decay channels for O^{16} and N^{15}, in order to evaluate the effect of the hole in the $1p_{1/2}$ subshell on the properties of the giant resonance.

Previously[9] we obtained information on the various branches of the reaction $O^{16}(\gamma, p)N^{15}$. It turned out that as a result of this reaction the final nucleus is produced preferentially in states of the single-hole type—the ground state $(p_{1/2}^{-1})$ and the third excited state $(p_{3/2}^{-1})$. This corresponds to a mechanism in which on absorption of a γ ray a proton is emitted which has made a transition from the $1p_{1/2}$ or $1p_{3/2}$ subshell to the 2s or 1d shell, and the effect of the final-state interaction is not felt.

States arising in a similar process are produced also in the reaction $N^{15}(\gamma, p)C^{14}$. These states include the C^{14} ground state with $J^\pi = 0^+$, which is described by a configuration $p_{1/2}^{-2}$,[10] and also the state with energy 7.01 MeV ($J^\pi = 2^+$) with a configuration $p_{3/2}^{-1}p_{1/2}^{-1}$.[11] The states of the N^{15} final nucleus with configurations $p_{1/2}^{-1}$ and $p_{3/2}^{-1}$, like the states of the final nucleus C^{14} with configurations $p_{1/2}^{-2}$ and $p_{3/2}^{-1}p_{1/2}^{-1}$, can be considered to be formed as the result of emission of a proton in the (γ, p) reaction respectively from the subshells $1p_{1/2}$ and $1p_{3/2}$ of the nuclei O^{16} and N^{15}.

The integrated cross sections for (γ, p) reactions for O^{16} and N^{15} are listed in Table I, from which it follows that the intensity of proton transitions from the $p_{1/2}$ subshell in N^{15} is smaller by a factor of two than in O^{16}, i.e., as many times smaller as the number of protons in the $p_{1/2}$ subshell of N^{15}, while the intensity of the transitions from the $p_{3/2}$ subshell is the same for the two nuclei. This fact indicates that the hole in the $p_{1/2}$ subshell does not change the intensity of transitions from the closed $p_{3/2}$ subshell of N^{15} and O^{16}. In addition, as can be seen from Figs. 6–8, the existence of a hole in the $p_{1/2}$ subshell leads to a more smeared out giant resonance in N^{15} than in O^{16}.

Table I. Integrated cross sections for the different branches of the (γ, p) reaction in N^{15} and O^{16}

Integration limits, MeV	$N^{15}(\gamma, p)C^{14}$ reaction		$O^{16}(\gamma, p)N^{15}$ reaction, ref. 9	
	State of final nucleus C^{14}	Integrated cross section, MeV-mb	State of final nucleus N^{15}	Integrated cross section, MeV-mb
12.5 ÷ 30.0	Ground, $J^\pi = 0+$	21±3	Ground, $J^\pi = 1/2^-$	40.5±4.0
20.5 ÷ 32.0	7.01 MeV, $J^\pi = 2+$	32±5*	6.33 MeV, $J^\pi = 3/2^-$	27±3
12.5 ÷ 30.5	Sum over all states	72±10*	Sum over all states	84±8

*The errors take into account the uncertainty in the angular distributions.

Zhusupov and Éramzhyan[2] calculated the energies and dipole-transition intensities, and also the decay probabilities of dipole states by different channels. The calculation was carried out with the particle-hole approach usually used for nuclei with closed shells, where the dipole states are formed from single-particle transitions which are mixed by the residual interactions.[12] The decay of the quasistationary states was calculated by means of the reduced-width formalism.[13] According to the calculations of Zhusupov and Éramzhyan, as a result of the reaction $N^{15}(\gamma, p)C^{14}$, the C^{14} nucleus should be formed preferentially in the ground state and in the excited states with energy 7.01 MeV ($J^{\pi} = 2^{+}$) and about 11 MeV, which has been satisfactorily confirmed by our experiments. In Table II we have compared the theoretical[2] and experimental integrated cross sections of the various branches of the $N^{15}(\gamma, p)C^{14}$ reaction. It is evident that the theory gives values close to the experimental values for all observed channels of the (γ, p) reaction. This agreement with experiment in the case of N^{15} is opposite to the situation for light nuclei with closed shells, for which, as we have already said at the beginning of the article, the theoretical values of the integrated cross sections in the giant-resonance region are roughly a factor of two higher than the experimental cross sections.

Table II. Theoretical and experimental integrated cross sections for the different channels of the reaction $N^{15}(\gamma, p)C^{14}$

Integration limits, MeV	State of the final nucleus C^{14}	Integrated cross section, MeV-mb	
		Theory [2]	Experiment
0—30.5	Ground	22.4	22±3
0—36.4	7.01 MeV	67.8	52±7 *
0—36.4	10.7 MeV	26.5	15±3 *
0—30.5	Sum over all states	107.3	73±10 *

*The errors take into account the uncertainty in the angular distributions.

Apparently the richer set of single-particle states from which collective dipole states are formed in nuclei with unfilled shells is the principal factor determining the properties of the giant resonance of these nuclei. Thus, in N^{15} there are 61 such transitions,[2] while, for example, in O^{16} there are only 5.

In this way, in the case of the reaction $N^{15}(\gamma, p)C^{14}$, justification is found for the point of view[1] according to which the giant resonance of nonmagic nuclei should be much better described by the shell model than for magic nuclei, since the source of the spread of the giant-resonance excitation over a large number of states lies just in the shell approach to nuclei with unfilled shells, as the result of their rich genealogical structure. For magic nuclei the source of the spread must be sought outside the shell-model approach.

A certain disagreement of the theory of Zhusupov and Éramzhyan[2] with experiment in the distribution of intensity of dipole transitions over the giant-resonance region, as seen in Figs. 6 and 8, can apparently be reduced by choice of the model parameters.

In connection with the results of this work, it would be important to make calculations of the photodisintegration and carry out corresponding experiments for other nuclei near O^{16}, in order to establish whether the same agreement with theory is observed for them as for N^{15} in the ratio of the integrated cross sections. In addition, complete comparisons with theory for N^{15} require data not only on the proton decay channel but also on the neutron channel and on the total-absorption cross section.

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