Structure of proton resonances

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Experimental data are presented which attest to the nonstatistical nature of proton resonances for excitation energies 6–15 MeV in light and intermediate nuclei. The reduced proton widths and the absolute-width and amplitude correlations are analyzed. Special attention is devoted to the amplitude relative-phase correlations. At the end of the review a possible reason for the manifestation of the nonstatistical nature of proton resonances is discussed.

INTRODUCTION

Resonances in nuclear reactions induced by protons were first discovered in 1935.[1] Subsequent investigations of this area of nuclear physics have made and continue to make an important contribution to our understanding of the properties of nuclear states in a particular range of excitation energies. The lower limit of this region is the proton binding energy in the nucleus. There is also an upper limit. It is determined by the growth of the level width and the decrease of the level spacing. The level width grows with increasing incident-particle energy, owing to the increased penetrability of the Coulomb barrier and the increase of the number of channels via which the produced resonance state can decay. The growth of the density of nuclear states with increasing excitation energy is faster, the larger the nuclear mass number A.

The upper limit of the range of excitation energies where it is still possible to observe well-defined resonances in the case of bombardment by protons is 10–11 MeV in nuclei with $A \sim 60$, while in light nuclei, where the level density is small, the limit for resonance observation can reach excitation energies 15–17 MeV. In heavy nuclei ($A > 65$) up to now only analog resonances have been observed in the cross sections for reactions involving protons.

It is well known that these resonances are excited in proton elastic and inelastic scattering not only on light and intermediate nuclei, but also on heavy nuclei up to bismuth. Their widths range from about 1 keV up to several tens of keV.[2]

Analog resonances are a special type of compound-nucleus excitation—they are simple incoming states with isospin one unit larger than the isospin of the continuum states of the compound nucleus. If there were no mixing between the analog state and the other states in its vicinity, its width would be small. However, there is mixing. It leads to a broadening of the analog states and gives them a fine structure. It can therefore be said that analog resonances are structures similar to the giant resonance, which is produced as the result of the distribution of the force of a simple excitation over the levels of the compound nucleus.

The fine structure of analog states was first seen in the study of proton elastic scattering on isotopes of molybdenum.[3] Later on, experiments on resonances in proton reactions with very high energy resolution (250–300 eV) were carried out by the Bilpuch group, which studied a wide range of nuclei, $30 \leqslant A \leqslant 65$. In these experiments special attention was devoted to the properties of analog resonances. However, in the same excitation functions in the (pp), (pp'), and $(p\gamma)$ reactions for proton energies in the range 1–5 MeV a large number of other resonances was observed; these were not analog resonances and had width in the range from several tens to several hundreds of eV.

In addition to analog resonances, in nuclei at roughly the same energies there is yet another type of excitation, namely, the Gamow–Teller giant resonance. Until recently, this giant resonance has been observed only through certain indirect effects, such as the strong bremsstrahlung of Gamow–Teller β transitions to low-lying nuclear states. Systematic data on the population of the Gamow–Teller resonance in direct charge-exchange (pn) reactions in finite nuclei have appeared only in 1980–1982. It was found that the widths of the Gamow–Teller resonances are 2–4 MeV,[4] which is considerably greater than the analog widths.

The question arises of whether or not it is possible to observe the Gamow–Teller resonance in compound nucleus excitations in reactions induced by protons. When the strength of the Gamow–Teller resonance is distributed over the levels of a compound nucleus with complicated structure (leading to the creation of fine structure in the Gamow–Teller resonance) an intermediate structure must be produced in proton resonances, just as in the case of analog resonances. The difference is that this structure must be considerably more diffuse in energy, more "smeared out" than the analog structure, so that it is more difficult to detect experimentally.

It is possible that the above-mentioned nonanalog resonances observed in the (pp), (pp'), and $(p\gamma)$ reactions might appear when the Gamow–Teller giant resonance is distributed over the levels of the compound nucleus. Another possible interpretation of the structure of nonanalog resonances is that they are statistical resonances of the compound nucleus.

Until recently, most of the information on compound-nucleus levels in the energy range where the notion of levels is meaningful has been obtained by studying neutron reson-

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ances. A large amount of fairly complete experimental data for a wide range of nuclei has been obtained on these resonances. Analysis of these data[5] apparently leads to the conclusion that neutron resonances are statistical in nature, that is, in neutron capture levels of the compound nucleus are excited whose properties are described by the statistical model of the nucleus.

In recent years a large amount of experimental data has been obtained on the energies, quantum characteristics, and partial widths of nonanalog proton resonances. However, little was known about the structure of these resonances. By analogy with neutron resonances, it could be assumed that nonanalog proton resonances are also statistical in nature. However, there were certain indications that the properties of these resonances deviated from the statistical model.[6-8]

Direct evidence of the nonstatistical nature of nonanalog resonances would be the discovery of intermediate structure in cross sections for reactions with protons.[9]

The simplest manifestation of intermediate structure is the presence of a maximum in the distribution of the reduced widths of resonance decays as a function of excitation energy.

The reduced width γ_i^2, which characterizes the probability for the decay of a resonance with the emission of a particle i, is expressed as

$$\gamma_i^2 = \Gamma_i / \mathscr{P}_i,$$

where Γ_i is the partial width of the resonance corresponding to the probability of emission of the given particle and $\mathscr{P}_i$ is the transmission coefficient of the particle emission barrier. The quantity $\gamma_i = \sqrt{\Gamma_i/\mathscr{P}_i}$ is the amplitude for resonance decay with the emission of the given particle. In the literature the γ_i are often referred to as the amplitudes of the reduced widths.

Attempts to find maxima in the reduced width distribution for nonanalog proton resonances have been made in a number of studies. Here we shall review these studies and their results.

1. SEARCHES FOR INTERMEDIATE STRUCTURES USING THE RESONANCE REDUCED WIDTHS

In this review of the data we include those studies which were carried out using the high-resolution proton-beam technique and which contain a statistical analysis of the results for a large number of resonances.

Study of the resonances in proton elastic and inelastic scattering reactions has shown that anomalies are observed in the distribution of the resonance reduced width as a function of excitation energy only for analog resonances, although, as already noted, in addition to the analog resonances there is a large number of other resonances whose intensity is sometimes comparable to that of components of the analog fine structure.

The difference in the behavior of the reduced widths for analog and nonanalog resonances is shown in Fig. 1, taken from Ref. 10, where the reaction $^{48}Ti(pp)$ was studied. In the upper part of this figure we give the cumulative sums of the reduced widths for 40 resonances with $J^\pi = 3/2^-$ excited in this reaction. An anomaly is clearly seen at the proton energy 2.95 MeV, which corresponds to the position of the split $3/2^-$ analog resonance in ^{49}V. In the lower part of the curve we give the cumulative sums of the reduced widths for 112 resonances with $J^\pi = (5/2^+, 3/2^+)$ and 70 resonances with $J^\pi = 1/2^+$, which are not analogs. The energy dependence for these resonances proves to be monotonic.

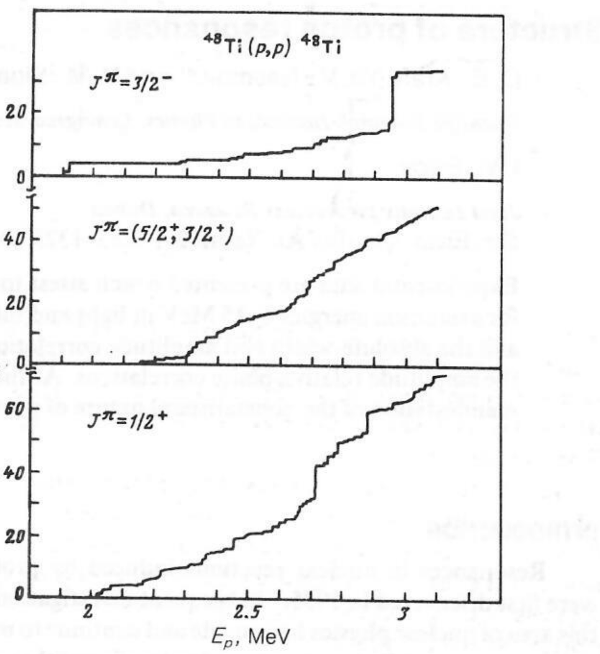


FIG. 1. Cumulative sums of the reduced widths for resonances in the $^{48}Ti(pp)$ reaction. The upper part of the figure is for the fragmented $p_{3/2}$ analog. The lower part is for nonanalog resonances with $J^\pi = (5/2^+, 3/2^+)$ and $J^\pi = 1/2^+$.[10]

In Ref. 11 the distribution of the reduced widths for these 70 resonances with $J^\pi = 1/2^+$ is compared to the Porter–Thomas distribution. The result is shown in Fig. 2. The histogram represents the experimental data, and the solid line is the Porter–Thomas distribution. The agreement between experiment and the calculation is good.

The reduced-width distribution for nonanalog resonances has been analyzed in a number of other studies, also. In Ref. 12 an analysis was carried out of 71 nonanalog reson-

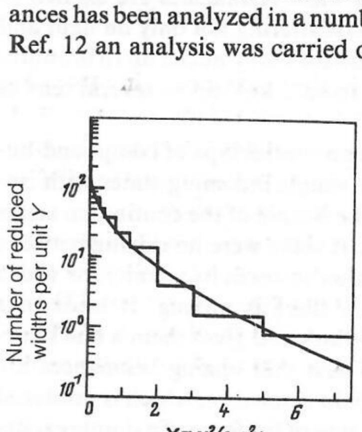


FIG. 2. Comparison of the reduced-width distributions for $1/2^+$ resonances in the $^{48}Ti(pp)$ reaction with the Porter–Thomas distribution (solid line; Ref. 11).

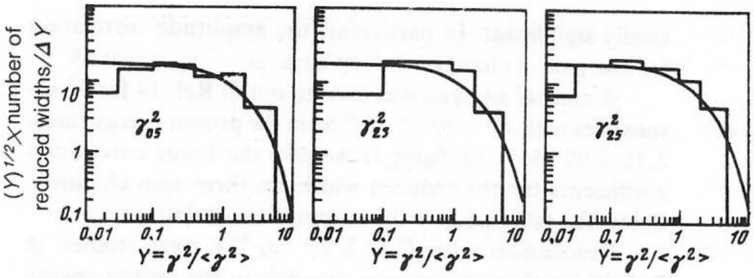


FIG. 3. Distribution of the inelastic reduced widths for three spin channels of the decay of $5/2^+$ resonances in ^{49}V. The histogram is from experiment, the solid lines correspond to the normalized Porter–Thomas distribution, and the subscripts on γ are the values of l', the orbital angular momentum of the inelastically scattered proton, and s', the spin of the outgoing channel.[13]

ances with $J^\pi = 3/2^-$ in ^{49}V for the case of inelastic proton scattering on ^{48}Ti in an energy range free from analogs. No anomalies were observed in the inelastic proton reduced widths; their behavior accurately coincided with the Porter–Thomas distribution.

In Ref. 13 a similar result was obtained for the inelastic reduced widths for 45 nonanalog resonances with $J^\pi = 5/2^+$ in the nucleus ^{49}V. In Fig. 3 we show the distribution of the inelastic reduced widths for three decay spin channels. We see that there is excellent agreement between experiment and calculation.

The inelastic widths for 53 resonances with $J^\pi = 5/2^+$ in ^{45}Sc were analyzed in Ref. 14. No deviations from the Porter–Thomas distribution were observed. The corresponding analysis for 37 nonanalog resonances with $J^\pi = 3/2^-$ in ^{45}Sc and 24 resonances with $J^\pi = 3/2^-$ in ^{51}Mn was carried out in Ref. 15. The reduced-width distributions in the two cases are in satisfactory agreement with the Porter–Thomas distribution. The statistical properties of 56 resonances with $J^\pi = 1/2^+$ in the reaction ^{60}Ni(pp) and 156 resonances with $J^\pi = 1/2^+$ in the reaction ^{62}Ni(pp) were studied in Ref. 16. No anomalies were observed in the elastic proton reduced widths.

On the basis of these examples we can conclude that no nonstatistical effects for nonanalog resonances are observed in the behavior of the proton reduced widths. Therefore, attempts to find an intermediate structure of nonanalog proton resonances by studying the reduced widths have not been successful.

2. SEARCHES FOR INTERMEDIATE STRUCTURES USING CORRELATIONS IN THE ABSOLUTE VALUES OF THE WIDTHS AND AMPLITUDES

According to Ref. 17, the presence of intermediate structure is manifested in the violation of the assumptions of the statistical model in a localized energy range. We have seen that such a violation is observed in the energy dependence of the reduced widths only for analogs.

Nonstatistical effects can be sought not only in the behavior of the reduced widths, but also in the correlations of both the widths and the amplitudes for various reaction channels. As a quantitative measure of the correlations between the quantities x_i and y_i we introduce the linear correlation coefficient, defined as

$$\rho(x,\ y)=\frac{\sum\limits_i (x_i-\bar{x})(y_i-\bar{y})}{[\sum\limits_i (x_i-\bar{x})^2]^{1/2}\,[\sum\limits_i (y_i-\bar{y})^2]^{1/2}}. \qquad (1)$$

If the distributions of x_i and y_i are statistically independent, there cannot be any correlations between them and the linear correlation coefficient must be equal to zero.

Correlation-analysis techniques were first used to search for intermediate structures in reactions involving neutrons.[9] They were later applied to analogs and made it possible to obtain interesting data on the structure of the $T_<$ component of the analog. As we have already pointed out, most analog resonances are split, fragmented into a series of fine structure components. The fine-structure appears as the result of mixing between the analog $T_>$ eigenstate and the compound-nucleus levels with isospin $T_<$. When analogs undergo γ decay, transitions into many low-lying states are observed. The strongest of these are determined by the $T_<$ component of the analog, while for weak transitions the probability for contribution of the $T_<$ component is large.[8]

The authors of Ref. 6 have calculated the linear correlation coefficient ρ_j for Γ_γ widths between transitions from the fine-structure components of the $p_{3/2}$ analog in ^{61}Cu to the ground state of this nucleus, determined by the $T_>$ component of the analog, and transitions to the states $p_{1/2}$ and $f_{5/2}$, determined by the $T_<$ component. The quantities ρ_j turned out to be negative and close to -1. In other words, clear anticorrelations were observed between transitions to the ground state and transitions to the $p_{1/2}$ and $f_{5/2}$ states. At the same time, correlations were observed for transitions from components of the analog fine structure to the $p_{1/2}$ and $f_{5/2}$ states. The authors of that study have interpreted this result as follows.

Although transitions to the $p_{1/2}$ and $f_{5/2}$ levels are determined by the $T_<$ states of the compound nucleus, these states do not have the complex structure characteristic of a compound nucleus. They possess a configuration as simple as that of the analog resonance. In other words, two incoming states are manifested in analog decay: one is the $T_>$ component of the analog and the other is the $T_<$ component with a structure as simple as that of the analog.

A multichannel study of the fine structure of the $p_{3/2}$ analog in ^{55}Mn was undertaken in Ref. 7. Elastic and inelastic proton scattering was measured with high resolution together with the γ decay of the eight components of the fine structure. As in the case of ^{61}Cu, anticorrelations were seen for transitions to excited levels relative to transitions to the ground state. The authors of that study also concluded that there exists a second incoming state in addition to the analog in the fine-structure components. A similar type of correlation analysis has been carried out in studies devoted to nonanalog proton resonances, which is what we are concerned with here. These studies have investigated proton inelastic

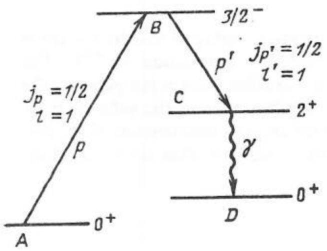


FIG. 4. Schematic diagram of inelastic proton scattering.

scattering on even–even targets corresponding to f-shell nuclei. Correlations between the widths and between the amplitudes were studied for various resonance-decay spin channels.

As an example, let us consider the inelastic scattering of protons from an even–even nucleus with $J^\pi = 0^+$ via a resonance of a compound nucleus with spin $J^\pi = 3/2^-$ on an excited state of the final nucleus with spin 2^+ (Fig. 4).

We restrict ourselves to the minimum value of the orbital angular momentum of the inelastically scattered proton, $l' = 1$. Then the spins of the incoming reaction channel can take the values $s' = \bar{J}_C + \bar{j}'_p$, i.e., for this case s', $= 3/2$ or $5/2$.

In the case of the resonance with $J^\pi = 5/2^+$, three spin channels are allowed for inelastically scattered protons: $s' = 5/2$ for $l' = 0$ and $s' = 3/2$ and $5/2$ for $l' = 2$ ($l' = 4$ gives a negligible contribution). Resonances with $J^\pi = 5/2^+$ in ^{49}V localized in an energy range of order 800 keV were studied in Ref. 13.

In Table I we give the linear correlation coefficients ρ_{ij} of the widths for various spin channels. The values of the ρ_{ij} are located in the position lying above the diagonal. The corresponding positions below the diagonal (the positions ji) contain numbers specifying the level of statistical reliability of the result. The quantities γ_p^2 are the reduced widths of elastic scattering, the quantities γ_{05}^2, γ_{23}^2, and γ_{25}^2 are the reduced widths of inelastic scattering for various decay spin channels with l' and s', respectively, equal to (0, 5/2), (2, 3/2), and (2, 5/2), and the quantity γ_p^2 is the reduced width for proton elastic scattering. Below the table we give the amplitude linear correlation coefficients defined as

$$p_{\text{ampl}} = \frac{\sum\limits_{\nu} \gamma_{\nu c}\gamma_{\nu c'}}{[(\sum\limits_{\nu} \gamma_{\nu c}^2)(\sum\limits_{\nu} \gamma_{\nu c'}^2)]^{1/2}} \qquad (2)$$

assuming that $\bar{\gamma}_{\nu c} = 0$.

We see from this table that many correlations are statistically significant. In particular, the amplitude correlation for one pair of channels is very large: $\rho(\gamma_{05}\gamma_{25}) = 0.88$.

A similar analysis was carried out in Ref. 14 for 53 resonances with $J^\pi = 5/2^+$ in ^{45}Sc in the proton energy range 2.31–2.99 MeV. In Table II we give the linear correlation coefficients for the reduced widths in three spin channels. Below the table we give the amplitude correlations.

Resonances with $J^\pi = 3/2^+$ in ^{49}V were studied in Ref. 18 for three decay spin channels in the proton energy range 2.42–3.08 MeV. The corresponding results are given in Table III.

Resonances with $J^\pi = 3/2^-$ in ^{45}Sc and ^{51}Mn were studied in Ref. 15 in energy ranges free from analogs. In Table IV we give the values of the linear correlation coefficients for the widths and amplitudes of two spin channels for 37 resonances in ^{45}Sc in the energy range $2.8 \leqslant E_p \leqslant 3.01$ MeV.

The data for 24 resonances with $J^\pi = 3/2^-$ in ^{51}Mn located in the energy range $3.03 \leqslant E_p \leqslant 4.30$ MeV are given in Table V.

Let us discuss some conclusions which follow from these studies. The data of the correlation analysis for nonanalog proton resonances indicate that there exist statistically significant correlations, observed for both the widths and the amplitudes, in proton inelastic scattering reactions. The presence of correlations points to the existence of nonstatistical effects characteristic of nonanalog resonances. The indirect data obtained from analysis of the γ decay of the analog fine-structure components lead to the same conclusion.

3. SEARCHES FOR INTERMEDIATE STRUCTURES USING CORRELATIONS IN THE AMPLITUDE PHASES

In the description of nuclear reactions involving compound-nucleus formation it is convenient to characterize the reaction by the channel spin mixing ratio δ_s, defined as the ratio of the amplitudes for decay via the corresponding channels. It is analogous to the multipole mixing ratios of the electromagnetic transitions which are well known in nuclear spectroscopy. For a number of compound-nucleus resonances (those with identical quantum characteristics), which are statistical, the quantities δ_s will not be correlated. The amplitudes and relative phases of the outgoing reaction channels must be random. This assumption of a statistical model can be expressed by the formula

$$\overline{\gamma_{\lambda c}\gamma_{\lambda c'}}^{\lambda} = \overline{\gamma^2_{\lambda c}}^{\lambda}\delta_{cc'}, \qquad (3)$$

where γ are the amplitudes, the averaging is carried out over λ resonances, and c and c' are the reaction spin channels.

TABLE I. Coefficients of the linear correlation for the reduced widths in proton resonances with spin $5/2^+$ in ^{49}V.

Reduced width	γ_p^2	γ_{05}^2	γ_{23}^2	γ_{25}^2
γ_p^2	1	0.59	0.08	0.41
γ_{05}^2	$>$99.9 %	1	0.46	0.71
γ_{23}^2	75 %	99.9 %	1	0.28
γ_{25}^2	99.5 %	$>$99.9 %	97.5 %	1

$\rho(\gamma_{05}\gamma_{25}) = 0.88$ $\rho(\gamma_{05}\gamma_{23}) = -0.06$ $\rho(\gamma_{23}\gamma_{25}) = 0.01$

TABLE II. Coefficients of the linear correlation for the reduced widths in proton resonances with spin $5/2^+$ in ^{45}Sc.

Reduced width	γ_p^2	γ_{05}^2	γ_{23}^2	γ_{25}^2
γ_p^2	1	0.26	0.10	0.28
γ_{05}^2	94 %	1	0.67	0.27
γ_{23}^2	50 %	> 99.9 %	1	−0.08
γ_{25}^2	95 %	95 %	40 %	1

$\rho(\gamma_{05}\gamma_{25}) = 0.72$ $\rho(\gamma_{05}\gamma_{23}) = 0.22$ $\rho(\gamma_{23}\gamma_{25}) = 0.06$

Violation of the relation (3) in a particular energy range would be an indication of the nonstatistical nature of the resonances.

To experimentally verify this relation it is necessary to determine δ_s.

A method of measuring the channel spin mixing ratio δ_s in proton inelastic scattering via a resonance was proposed in Refs. 19 and 20. It was shown that for determining the magnitude and sign of δ_s it is sufficient to measure the angular distributions of the inelastically scattered protons and the angular distributions of the photons following them.

In the example considered above, that of proton inelastic scattering on an even–even target with $J^\pi = 0$ via a compound-nucleus resonance with spin $3/2^-$ on an excited state of the final nucleus with spin 2^+ (see Fig. 4), the ratio of the mixture of the two outgoing spin channels δ_s is defined as the ratio of the amplitudes for the decay of the state B via these two spin channels:

$$\delta_s = \gamma_{s_{15}}/\gamma_{s_{13}}. \quad (4)$$

Here we have restricted ourselves to the minimum value of the orbital angular momentum of the inelastically scattered proton, $l' = 1$. The inelastic width $\Gamma_{p'}$ of the resonance will be proportional to the sum of the squares of the two amplitudes:

$$\Gamma_{p'} \approx (\gamma_{s_{13}})^2 + (\gamma_{s_{15}})^2. \quad (5)$$

In Refs. 19 and 20 it was shown that study of the angular distribution of inelastically scattered protons and the angular distribution of the following photons makes it possible to uniquely determine both the spin of the resonance state B and the value of δ_s. In particular, for the example under consideration the ratio of the mixture of spin channels δ_s is related to the parameters of the angular distribution of the inelastically scattered protons and photons, corresponding to the 2^+–0^+ transition, by the following expressions: for inelastically scattered protons

$$\delta_s(p') = \pm\sqrt{(4+5a_{2p'})/(1-5a_{2p'})}; \quad (6)$$

for photons of the 2^+–0^+ transition

$$\delta_s(\gamma) = \left(2 \pm \sqrt{2a_{2\gamma} - 4a_{2\gamma}^2}\right)/(4 - 10a_{2\gamma}). \quad (7)$$

Here a_2 is the coefficient of the Legendre polynomial P_2.

These equations are sufficient for determining both the magnitude and the sign of δ_s in the case under consideration. For resonances with other values of J^π there will be different relations between δ_s and the proton and photon angular distributions. In the case $J^{\pi +} = 5/2^+$ there are three possible spin channels for inelastically scattered protons[13,14]: $s' = 5/2$ for $l' = 0$ and $s = 3/2$ and $5/2$ for $l' = 2$; as noted above, $l' = 4$ gives a negligible contribution. Therefore, here there are three outgoing amplitudes, i.e., two independent ratios of the amplitudes:

$$\delta_1 = \gamma_{s_{23}}/\gamma_{s_{05}}, \quad \delta_2 = \gamma_{s_{25}}/\gamma_{s_{05}} \quad (8)$$

(the amplitude for $l' = 0$ is arbitrarily chosen to be positive).

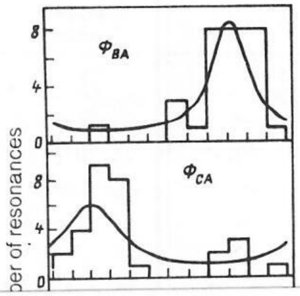
The angular distribution for inelastically scattered protons and photons in the case $J^\pi = 5/2^+$ is expressed in terms of the coefficients a_2 and a_4 of the Legendre polynomials P_2 and P_4. The parameters $a_{2p'}$, $a_{4p'}$, $a_{2\gamma}$, and $a_{4\gamma}$ are related to δ_1 and δ_2 as follows:

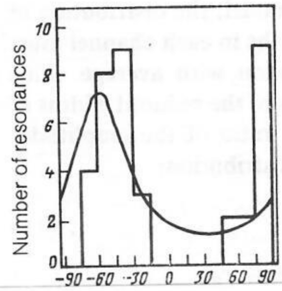
$$\left.\begin{aligned}
a_{2p'} &= \frac{(20/49)\,P\delta_1^2 - (20/49)\,P\delta_2^2 - \left(\frac{4\sqrt{14}}{7}\right) P^{1/2}\cos(\alpha_0-\alpha_2)\,\delta_2}{1+P\delta_1^2+P\delta_2^2};\\
a_{4p'} &= \frac{-(48/49)\,P\delta_1^2 + (27/49)\,P\delta_2^2}{1+P\delta_1^2+P\delta_2^2};\\
a_{2\gamma} &= \frac{(4/7) - (2/35)\,P\delta_1^2 + (2/35)\,P\delta_2^2 - (96/245)\,P\delta_1\delta_2}{1+P\delta_1^2+P\delta_2^2};\\
a_{4\gamma} &= \frac{-(4/7) + (2/7)\,P\delta_2^2 - (48/49)\,P\delta_1\delta_2}{1+P\delta_1^2+P\delta_2^2}.
\end{aligned}\right\} \quad (9)$$

TABLE III. Coefficients of the linear correlation for the reduced widths in proton resonances with spin $3/2^+$ in ^{49}V.

Reduced width	γ_p^2	γ_{03}^2	γ_{23}^2	γ_{25}^2
γ_p^2	1	0.02	−0.05	0.00
γ_{05}^2	8%	1	0.43	0.85
γ_{23}^2	19%	98%	1	0.15
γ_{25}^2	1%	>99.9%	56%	1

$\rho(\gamma_{03}\gamma_{23}) = 0.84$ $\rho(\gamma_{23}\gamma_{25}) = -0.65$ $\rho(\gamma_{03}\gamma_{25}) = -0.51$





a photon at an angle θ to the incident-particle direction can be written as an expansion in Legendre polynomials:

$$W(\theta)=\sum_k A_k P_k(\cos\theta).$$

If in the $(p\gamma)$ reaction a target with zero spin is used and the excited state is an isolated resonance with a definite value of the spin, the coefficients A_k for direct γ emission depend only on the resonance spin, the spin of the final state, and the mixture of multipole orders δ.[29] Here we list these dependences for the case of an expansion in Legendre polynomials of order no greater than four:

$\mathbf{J}_{\rm res}=\mathbf{1/2}$. All angular distributions are isotopic.

$\mathbf{J}_{\rm res}=\mathbf{3/2}$. $A_4=0$ for all distributions.

$$\mathbf{J}_{\rm lev}=1/2,\quad A_2=\frac{-0.5-1.732\delta+0.5\delta^2}{1+\delta^2};$$

$$\mathbf{J}_{\rm lev}=3/2,\quad A_2=\frac{0.4-1.55\delta}{1+\delta^2};$$

$$\mathbf{J}_{\rm lev}=5/2,\quad A_2=\frac{-0.10+1.18\delta-0.357\delta^2}{1+\delta^2};$$

$$\mathbf{J}_{\rm lev}=7/2,\quad A_2=+0.1428.$$

$$\mathbf{J}_{\rm res}=\mathbf{5/2}.$$

$$\mathbf{J}_{\rm lev}=1/2,\quad A_2=0.571,\quad A_4=-0.571;$$

$$\mathbf{J}_{\rm lev}=3/2,\quad A_2=\frac{-0.400-2.03\delta+0.204\delta^2}{1+\delta^2},\quad A_4=\frac{0.65\delta^2}{1+\delta^2};$$

$$\mathbf{J}_{\rm lev}=5/2,\quad A_2=\frac{0.457-1.084\delta-0.204\delta^2}{1+\delta^2},\quad A_4=\frac{-0.367\delta^2}{1+\delta^2};$$

$$\mathbf{J}_{\rm lev}=7/2,\quad A_2=\frac{-0.143+1.485\delta-0.347\delta^2}{1+\delta^2},\quad A_4=\frac{0.109\delta^2}{1+\delta^2}.$$

$$\mathbf{J}_{\rm res}=\mathbf{7/2}.$$

$$\mathbf{J}_{\rm lev}=3/2,\quad A_2=0.51,\quad A_4=-0.367;$$

$$\mathbf{J}_{\rm lev}=5/2,\quad A_2=\frac{-0.357-2.06\delta+0.085\delta^2}{1+\delta^2},\quad A_4=\frac{0.653\delta^2}{1+\delta^2};$$

$$\mathbf{J}_{\rm lev}=7/2,\quad A_2=\frac{0.476-0.825\delta-0.272\delta^2}{1+\delta^2},\quad A_4=\frac{-0.49\delta^2}{1+\delta^2}.$$

By comparing the experimentally determined angular distributions for γ transitions from a given resonance whose spin is unknown with the theoretical distributions under various assumptions about the spin, one can construct the function

$$\chi^2(\delta)=\sum_{i=1}^{N}\frac{(Y_i-W_i)^2}{\sigma_i^2},\qquad(15)$$

where Y_i is the relative intensity of the γ transition at the angle θ, W_i is the theoretical value of the transition probability at this angle, and σ_i is the error in the determination of the intensity.

The minimum value of χ^2 corresponds to the best set of values of the resonance spin and the mixture of multipole orders δ. The angular distribution for a single transition sometimes does not allow the unique determination of the resonance spin. A combined analysis of the angular distributions of several transitions from a given resonance can considerably simplify the determination of the resonance spin.

The equation for δ in terms of the coefficients A_2 is quadratic, so that its solution gives two values of δ. One of these is small and corresponds to the case when the $M1$ contribution to the transition intensity is dominant. The second value is large and is mainly related to the $E2$ contribution. The large value of δ can be discarded, since its use leads to unjustifiably large values of $B(E2)$, whereas it has been established experimentally that for resonance γ decays in *fp*-shell nuclei the characteristic transitions are strong $M1$ transitions with an $E2$ admixture only rarely exceeding 10%.[30]

Therefore, from the angular distributions we obtain a value of δ with a definite sign. We stress the fact that it is not the sign of δ itself that is meaningful, but rather the relative sign of δ for the decay of different resonances.

Intermediate structure of proton resonances in the nucleus ^{59}Cu

Resonances in ^{59}Cu were excited in the reaction ^{58}Ni$(p\gamma)^{59}$Cu. We studied the photon angular distributions for 28 proton resonances in the proton energy range from 2120 to 3460 keV, which corresponds to excitation energies from 5520 to 6815 keV. The ultimate aim of the study was to determine and analyze the values of δ for γ transitions from resonances to low-lying nuclear levels. To achieve this it was first of all necessary to determine the resonance spins.

In Table VI we list the resonance energies and spins

TABLE VI. Energies and spins of proton resonances in ^{59}Cu.

E_p, keV	J^π Our data	J^π Ref. 31	E_p, keV	J^π Our data	J^π Ref. 31
2136	5/2	5/2+	2668	3/2−	3/2−
2161	5/2, 3/2	5/2−	2704	3/2−	—

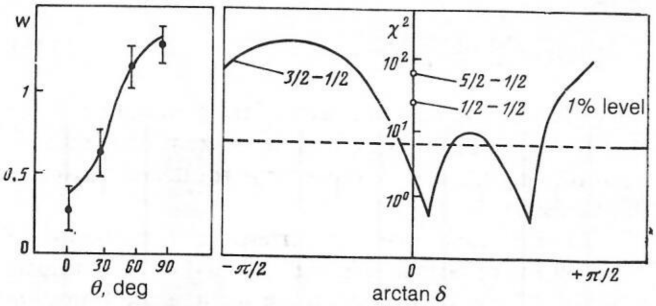


FIG. 12. Angular distribution and χ^2 analysis for γ radiation of the transition from the resonance $E_p = 2704$ keV to the level 491 keV ($1/2^-$) in ^{59}Cu.

obtained using our measurements together with the data of Ref. 31. The authors of that study obtained the values of the spins by measuring the anisotropy of the γ radiation assuming that all the γ transitions are purely dipole.

The method of measuring the spins in our case has already been discussed. For the nucleus of interest we studied the angular distributions of γ transitions from resonances to levels of ^{59}Cu with known quantum characteristics: 0, $3/2^-$; 491, $1/2^-$; 912, $5/2^-$; 1398, $7/2^-$; 1865, $5/2^-$, $7/2^-$; 1987, $5/2^-$; 2265, $3/2^-$; 2318, $1/2^-$; 2324, $3/2^-$; 2707, $5/2^-$; 2927, $5/2^-$; 3116, 5/2 (energies given in keV). The dependence of χ^2 on δ was constructed for each angular distribution. The γ transitions to levels with $J^\pi = 1/2^-$ proved to be very critical for choosing the resonance spin. In Figs. 12 and 13 we give examples of the angular distributions and the χ^2 analysis for γ transitions from resonances with $E_p = 2704$ keV and $E_p = 2869$ keV to the level 491 keV, $1/2^-$.

Both the spins and the parities are given for most of the resonances in Table VI. The parity is determined by analyzing the nature of the resonance γ decay and by using the experimental fact that no mixed transitions of the type $E1 + M2$ have been discovered in this range of excitation energies for the nuclei in question. Therefore, nonzero values of δ indicate the presence of a mixture of $M1$ and $E2$ transitions.

Intermediate structure was sought for resonances with $J^\pi = 3/2^-$ in the energy range under study. The analysis included resonances whose spins were not determined uniquely. In those cases where our measurements did not permit us to choose between the spins $3/2^-$ and $5/2^-$ we used the value $3/2^-$.

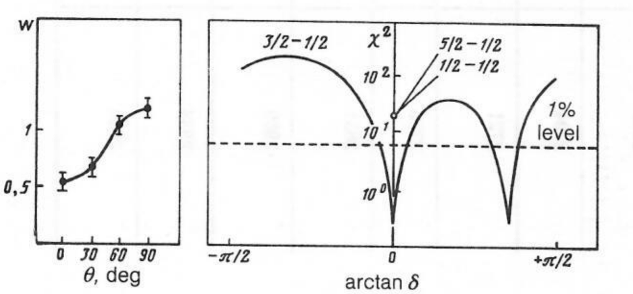


FIG. 13. Angular distribution and χ^2 analysis for γ radiation of the transition from the resonance $E_p = 2869$ keV to the level 491 keV in ^{59}Cu.

The values of A_2 and δ that we obtained are given in Table VII. The greatest amount of data was obtained for transitions of the type $3/2^-$–$3/2^-$. There were 25 of these. The quantity δ proved to be positive for all transitions of this type without exception. In Fig. 14 we give the distribution of the quantities $\Phi = \tan^{-1}(\delta/\alpha)$, where $1/\alpha = 1.42$ for 25 of the observed transitions. The dashed line corresponds to the uniform Φ distribution predicted by the statistical model. We see that there is a dramatic difference from this distribution, primarily owing to the absence of negative values of δ.

The following fact should be noted. According to the data of Ref. 32, the mixture of multipole orders δ for decays of resonances with $J^\pi = 3/2^-$ and energies $E_p = 1424$ and 1883 keV to the ground state of ^{59}Cu, $3/2^-$ has a different sign—it is negative. We carried out a test study of the γ decay of the resonance with $E_p = 1883$ keV. For the γ transition to the ground state we obtained the value $\delta = -0.25 \pm 0.07$, which within the error coincides with the value $\delta = -0.18 \pm 0.09$ from Ref. 32. From the viewpoint of associating the presence of intermediate structure with the violation of the assumptions of the statistical model in a localized energy range, this fact can be understood as pertaining to an energy range outside the one of interest.

For 13 transitions of the type $3/2^-$–$1/2^-$ the values of δ are close to zero; nine of them have positive sign, and the signs of the others are consistent with this within the error.

In 12 of the 15 transitions of the type $3/2^-$–$5/2^-$, δ has a negative sign. In the three cases for which δ is positive the errors of the measurements are very large, as can be seen from Table VII.

The data obtained for the mixture of multipole orders of γ transitions from resonances, in particular, for transitions of the type $3/2^-$–$3/2^-$, indicate the presence of a clearly expressed nonstatistical contribution to the structure of proton resonances in the nucleus ^{59}Cu. The correlations in the signs of δ can be attributed to an intermediate structure distributed over the range of excitation energies under study.

Intermediate structure of proton resonances in ^{61}Cu

Resonances in ^{61}Cu were excited in a ^{60}Ni$(p\gamma)$ reaction for proton energies from 1451 to 1850 keV, which corresponds to excitation energies in ^{61}Cu from 6200 to 6600 keV. The ^{60}Ni targets (95% enrichment) were 10–20 μg/cm^2 thick. This range of proton energies contains the analog states $p_{3/2}$, $f_{5/2}$, and $p_{1/2}$, the data on which were published in Ref. 27. In addition to these, this energy range contains many other resonances with smaller gamma width.[35] With few exceptions, the spins of these resonances have up to now not been determined. There have been no data on the multipole mixtures for γ transitions from these resonances.

The data that we obtained on the energies and spins of the observed resonances are given in Table VIII. The spins were determined from the angular distributions of γ transitions to low-lying levels of ^{61}Cu.

In Table IX we give the values of A_2 and δ for resonances with spin 3/2. As in the case of ^{59}Cu, here we have included resonances whose spins were not determined uniquely but for which the value 3/2 is possible. In this table

TABLE VII. Angular correlation coefficients and mixtures of multipole orders of photons emitted in the decay of resonances in ^{59}Cu.

E_p, keV \ E_{lev}, keV; J^{π}_{lev}		0, 3/2⁻	2265, 3/2⁻	2324, 3/2⁻	491, 1/2⁻	912, 5/2⁻	1987, 5/2⁻	2707, 5/2⁻	2927, 5/2⁻	3116, 5/2⁻
2161	A_2 δ	−0,13 (10) +0,35 (8)	—	—	—	—	—	—	—	—
2210	A_2 δ	−0,52 (10) $+0,81^{+44}_{-19}$	—	—	—	—	—	—	—	—
2338	A_2 δ	−0,20 (13) +0.41 (12)	—	−0,44 (11) $0,67^{+33}_{-11}$	—	—	—	−0,55 (12) -0.40^{+12}_{-17}	—	—
2512	A_2 δ	−0,25 (9) 0,45 (9)	—	−0,31 (40) $+0.51^{+75}_{-31}$	—	—	—	—	—	—
2574	A_2 δ	−0,49 (6) +0.77 (12)	−0,40 (23) $+0,62^{+58}_{-24}$	—	—	—	—	—	—	—
2668	A_2 δ	−0.41 (5) +0.63 (6)	−0,45 (34) $+0,70^{+59}_{-36}$		−0,69 (11) +0.12 (9)		+0,02 (38) $+0,11^{+79}_{-34}$	—	—	—
2704	A_2 δ		—	—	−0,66 (11) +0.10 (8)	—	—	—	—	—
2721	A_2 δ	−0.49 (5) $+0,76^{+13}_{-8}$	—	—	−0,39 (20) −0,06 (11)	—	—	—	—	—
2756	A_2 δ	+0,05 (13) +0,23 (9)	—	—	−0.39 (18) −0.06 (10)	—	—	—	—	—
2831	A_2 δ	+0,22 (12) +0,11 (8)	—	—	−0,64 (7) +0.08 (5)	—	−0,08 (11) $+0,02^{+4}_{-9}$	—	—	—
2869	A_2 δ	−0,63 (9) $+1.29^{+0}_{-39}$	—	—	−0,46 (7) −0,02 (4)	—	—	—	—	—
2938	A_2 δ	+0,10 (8) +0.19 (5)	−0.13 (25) +0,35 (17)	—	−0,64 (10) +0.09 (7)	—	−0,41 (11) −0,28 (11)	−0,39 (10) −0.25 (10)	−0.31 (18) −0.18 (9)	−0.47 (27) −0,33 (20)
2960	A_2 δ	−0,54 (10) $+0,88^{+41}_{-20}$	−0.43 (19) $+0,67^{+53}_{-22}$	—	−0.55 (14) +0.03 (9)	—	—	—	—	—

Continuation of TABLE VII.

E_p, keV \ E_{lev}, keV; J^{π}_{lev}	0, 3/2⁻	2265, 3/2⁻	2324, 3/2⁻	491, 1/2⁻	912, 5/2⁻	1987, 5/2⁻	2707, 5/2⁻	2927, 5/2⁻	3116, 5/2⁻
2978	$A_2 - 0.51$ (26) $\delta + 0.80^{+49}_{-35}$	−0,17 (19) $+0,38^{+32}_{-20}$	—	−0,60 (26) $+0,06^{+21}_{-14}$	−0,48 (12) $-0,34^{+11}_{-14}$	—	—	—	—
2999	$A_2 + 0,07$ (8) $\delta + 0.21$ (5)	—	—	−0.73 (5) +0,15 (4)	−0.30 (14) −0,17 (13)	—	—	—	—
3051	$A_2 - 0,39$ (7) $\delta - 0.61$ (9)	—	—	—	—	−0,33 (15) −0,20 (14)	—	—	—
3062	A_2 δ	−0.33 (20) $+0,54^{+45}_{-19}$	−0,24 (23) $+0.45^{+27}_{-19}$	−0,47 (14) −0.02 (7)	+0,03 (20) $+0.12^{+21}_{-18}$	—	−0,32 (25) −0.19 (23)	—	—
3106	A_2 δ	—	—	−0.74 (11) +0.16 (9)	−0,58 (17) −0,45 (9)	—	—	—	—
3453	$A_2 + 0.38$ (24) $\delta + 0.02^{+14}_{-25}$	—	—	−0.89 (12) $+0.30^{+25}_{-12}$	—	−0,69 (21) $+0.61^{+27}_{-44}$	—	−0,60 (11) -0.55^{+20}_{-9}	—

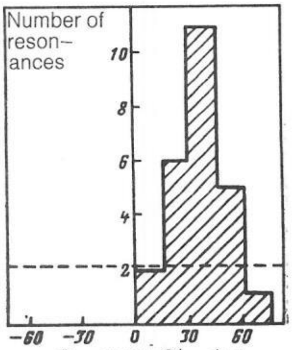


FIG. 14. Distribution of $\Phi = \tan^{-1}(\delta/\alpha)$ for transitions of the type $3/2^- - 3/2^-$ in ^{59}Cu.[28]

we also include the data on the four fine-structure components of the analog $p_{3/2}$ resonance obtained by us earlier in Ref. 27. It can be seen from the table that four transitions of the type $3/2^- - 3/2^-$ the signs of δ in the overwhelming majority of cases are identical for γ transitions from various resonances to a given level.

As a rule, the most intense transitions from resonances are those to the ground state of ^{61}Cu. For all of these δ has the same sign, that corresponding to the case of the analogs.

The distribution of $\Phi = \tan^{-1}(\delta/\alpha)$ is given in Fig. 15. We have included all transitions from resonances with spin $3/2^-$ to low-lying $3/2^-$ states (31 γ transitions: the value $1/\alpha = 1.96$).

We see from this figure that there a sharp deviation from the uniform distribution, essentially owing to the almost complete absence of negative values of δ. The sign of δ for the $3/2^- - 3/2^-$ transitions in ^{61}Cu under study is the same as the sign of δ for analog transitions in ^{59}Cu. We draw attention to this experimental fact, although its significance is not yet clear.

Analysis of the $3/2^- - 1/2^-$ and $3/2^- - 5/2^-$ transitions does not give sufficiently conclusive information. First of all there are relatively few of these transitions and, secondly, they are weak. As a rule, the values of δ for them are determined with large errors, so that the sign cannot be determined.

The experimental results obtained for resonances in ^{61}Cu lead to the following conclusions.

1. The relative phases of δ for the fine structure components of an analog are identical. A similar result has been obtained in experiments on proton inelastic scattering.[22]

2. The relative phases of δ for the γ decay of nonanalog resonances with spin 3/2 in the energy range under consideration (400 keV) are also identical, indicating the presence of intermediate structure.

Intermediate structure of proton resonances in ^{63}Cu

Resonances in the nucleus ^{63}Cu were excited in the ^{62}Ni$(p\gamma)$ reaction. The measurements were carried out in the range of proton energies from 1943 to 3175 keV, which corresponds to excitation energies in ^{63}Cu from 8040 to 9250 keV. The resonance spins and values of δ were determined by studying angular distributions of γ transitions from the resonances to the low-lying levels of ^{63}Cu with known quantum characteristics. The parity assigned to the resonances was chosen on the basis of the considerations discussed above.

The values of the resonance energies and spins that we obtained are listed in Table X. In many cases the analysis of the angular distributions of the γ transitions did not allow us to uniquely choose the value of the resonance spin, two values being equally possible.

The values of A_2 and δ for resonances with spin $3/2^-$ are given in Table XI. In this table, as in the preceding cases, we include resonances whose spins were not determined uniquely, but for which the value 3/2 is possible.

We obtained 63 values of δ for transitions of the type $3/2^- - 3/2^-$. The sign of δ is negative in only a single case—for the transition from the resonance at 1943 keV to the level 1547 keV. All of the other values of δ are positive. This clear correlation in the signs of δ implies the existence of an intermediate structure. The change of the sign of δ at low proton energies (1943 keV) apparently indicates, as in the case of ^{59}Cu, that the lower limit of the intermediate structure has been reached.

We obtained 19 values for γ transitions of the type $3/2^- - 1/2^-$ (all the transitions were to the level 668 keV, $1/2^-$). Of these, 15 values are negative and four are positive. However, of these positive values only one has error bars which do not overlap with a negative value.

TABLE VIII. Energies and spins of proton resonances in ^{61}Cu.

E_p, keV	$J^\pi_{\rm res}$	E_p, keV	$J^\pi_{\rm res}$
1451	1/2—5/2	1694	$3/2^-$ *
1461	1/2, 3/2	1698	3/2
1465	3/2	1711	3/2
1483	3/2, 5/2	1721	3/2, 5/2
1491	3/2, 5/2	1734	$3/2^-$
1515	$3/2^-$	1757	3/2
1519	3/2	1764	$3/2^-$, 5/2
1566	3/2	1770	$3/2^-$
1577	$3/2^-$	1793	$3/2^-$
1643	1/2—5/2	1815	$3/2^-$, 5/2
1649	3/2, 5/2	1835	$3/2^-$
1669	5/2	1850	$3/2^-$

*Spin first determined in Ref. 33; the errors in the determination of the proton energies are 3 keV.

TABLE IX. Angular correlation coefficients and mixtures of multipole orders of photons emitted in the decay of resonances in ^{61}Cu.

E_p, keV \ E_{lev}, keV; J^{π}_{lev}	0, 3/2⁻	1663, 3/2⁻	2357, 3/2⁻	2473, 3/2⁻	2687, 3/2⁻	476, 1/2⁻	2089, 1/2⁻	970, 5/2⁻	1395, 5/2⁻	2203, 5/2⁻
1491	A_2 +0,39 (15) δ $+0.00^{-9}_{+10}$	—	—	—	—	—	—	—	—	—
1515	A_2 +0,22 (11) δ $+0,12^{-8}_{+7}$	—	—	—	—	—	—	—	—	—
1577	A_2 −0,35 (9) δ +0,56 (10)	−0,37 (12) $+0,58^{+18}_{-12}$	—	—	—	−0,44 (8) $-0,03^{+4}_{-6}$	—	—	—	—
1588*	A_2 +0,18 (5) δ +0,14 (3)	—	−0,15 (21) $+0,37^{+20}_{-15}$	+0,12 (9) +0.18 (6)	+0.33 (22) +0.04 (14)	—	−0,59 (22) $+0,05^{+17}_{-13}$	−0,26 (14) −0.13 (11)	−0,31 (7) −0,17 (7)	—
1599*	A_2 +0,10 (6) δ $+0,20^{+3}_{-5}$	—	—	−0,29 (9) +0,50 (10)	−0,09 (15) $+0.32^{+12}_{-10}$	−0,80 (13) $+0.20^{+14}_{-9}$	−0,50 (8) 0,00 (4)	−0,30 (8) −0,17 (7)	−0,25 (6) −0,12 (4)	+0,05 (20) $+0,14^{+22}_{-18}$
1605*	A_2 +0,22 (6) δ +0,11 (4)	—	—	+0,09 (18) +0,20 (12)	—	—	−0,45 (2) −0,03 (1)	−0,13 (11) −0,03 (10)	−0,12 (6) −0,02 (5)	—
1620*	A_2 +0,14 (2) δ +0,16 (1)	—	+0,64 (13) −0,17 (10)	—	−0,16 (19) $+0,37^{+19}_{-13}$	—	−0.50 (16) 0.00 (10)	−0.09 (26) +0,01 (25)	−0,12 (14) −0.02 (10)	—
1649	A_2 −0,36 (15) δ $+0,57^{+23}_{-15}$	—	—	—	—	—	—	—	—	—
1694	A_2 +0,29 (4) δ +0,07 (2)	+0.14 (14) $+0.16^{+10}_{-9}$	—	—	—	−0.52 (7) +0.01 (4)	—	−0.19 (10) −0.07 (8)	—	—
1698	A_2 +0,26 (13) δ +0,09 (9)	—	—	—	—	—	—	—	—	—
1734	A_2 −0.31 (6) δ +0,51 (6)	−0,13 (22) $+0,35^{+22}_{-15}$	—	—	—	−0.58 (17) $+0.04^{+12}_{-9}$	—	+0.08 (17) $+0.17^{+19}_{-16}$	−0.04 (19) +0.05 (19)	—
1764	A_2 +0,09 (5) δ +0,19 (4)	+0,26 (11) $+0.08^{+8}_{-6}$	—	—	—	+0.23 (13) -0.39^{+6}_{-9}	—	—	−0,27 (10) −0.14 (8)	—

Continuation of TABLE IX.

E_p, keV \ E_{lev}, keV; J^{π}_{lev}	0, 3/2⁻	1663, 3/2⁻	2357, 3/2⁻	2473, 3/2⁻	2687, 3/2⁻	476, 1/2⁻	2089, 1/2⁻	970, 5/2⁻	1395, 5/2⁻	2203, 5/2⁻
1770	A_2 +0,37 (4) δ +0.02 (3)	−0.09 (9) +0,32 (7)	—	—	—	−0.62 (13) $+0.07^{+9}_{-8}$	—	—	—	—
1793	A_2 +0.05 (12) δ $+0.23^{+8}_{-10}$	—	—	—	—	−0.25 (13) −0.14 (7)	—	—	—	—
1815	A_2 δ	—	−0.14 (11) +0.36 (9)	—	—	—	—	—	—	—
1835	A_2 +0.10 (8) δ +0.19 (5)	—	+0.22 (13) +0.12 (8)	—	—	—	—	—	—	—
1850	A_2 −0.30 (3) δ +0.51 (3)	—	—	—	—	—	—	—	—	—

Fine structure components of the analog $p_{3/2}$ resonance.

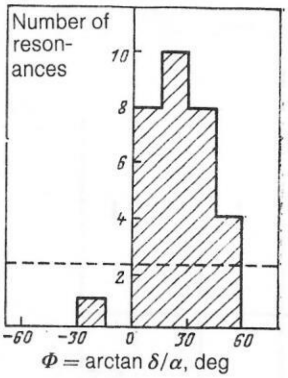


FIG. 15. Distribution of $\Phi = \tan^{-1}(\delta/\alpha)$ for transitions of the type $3/2^- - 3/2^-$ in ^{61}Cu.[26]

We obtained 22 values of δ for γ transitions of the type $3/2^- - 5/2^-$. In 17 cases δ is positive, and in five cases it is negative. For the negative values δ is significanly different from zero only in a single case, that of the transition from the resonance at 2696 keV to the $5/2^-$ level at 962 keV.

Therefore, a clear asymmetry is observed in the distribution of δ in the case of ^{63}Cu for γ transitions of the type $3/2^- - 1/2^-$ and $3/2^- - 5/2^-$, which confirms the assertion that an intermediate structure is present in this isotope.

4. INTERPRETATION OF THE INTERMEDIATE STRUCTURE

The data on the mixture of multipole orders of γ transitions from resonances, in particular, for transitions of the type $3/2^- - 3/2^-$, indicate the presence of a clearly expressed nonstatistical contribution to the structure of proton resonances for the odd isotopes of copper: ^{59,61,63}Cu. The fact that the signs of δ for these nuclei are the same apparently indicates that the intermediate structures in these nuclei are similar to each other. In Ref. 26 this effect was attributed to the presence of the Gamow–Teller resonance, to the manifestation of the fine structure of this resonance.

We shall show that the entire set of experimental data can be explained if it is assumed that the intermediate structure arises in the distribution of a configuration of the type of the Gamow–Teller giant resonance over resonances with a more complicated structure.

First of all, it is necessary to explain the dramatic difference between the structures of neutron and proton resonances. For simplicity, we shall assume that neutron resonances are statistical resonances in which no intermediate structure is manifested, whereas proton resonances are resonances with relatively simple configurations whose fundamental features are determined by intermediate structures.

This great difference between neutron and proton resonances can naturally be attributed to the existence of the neutron excess and the resulting particle–hole configurations. For example, the analog state which is observed among the proton resonances is an incoming state or an intermediate structure with a charge-exchange type of configuration, i.e., a proton-particle–neutron-hole bound in a state of angular momentum 0^+. There is no such charge-exchange excitation for neutrons. Therefore, the difference between the structure of proton and neutron resonances is naturally attributed to the existence of charge-exchange states. For protons this state corresponds to a proton-particle–neutron-hole bound in a state of angular momentum J, while for neutrons this state is a neutron-particle–proton-hole also bound in a state of angular momentum J.

Since we are interested in γ transitions of low multipole order, in particular, $M1$ transitions, we can restrict our consideration to particle–hole excitations with $J^\pi = 1^+$. The residual Gamow–Teller-type interactions mix these configurations and lead to the appearance of collective excitations like the Gamow–Teller resonance. The existence of the neutron excess leads to the dramatic difference between the properties of the incoming charge-exchange states for protons and neutrons.

TABLE X. Energies and spins of proton resonances in ^{63}Cu.

E_p^*	J^π_{res}	E_p^*	J^π_{res}
1943	3/2⁻	2642	3/2⁻
1953	3/2⁻	2675	3/2⁻
1958	3/2⁻, 7/2⁻	2682	3/2⁻, 5/2⁻
1976	3/2⁻ (5/2⁻)	2690	3/2⁻
1984	7/2⁻	2696	3/2⁻
2022	3/2⁻ (5/2)	2710	3/2⁻
2085	3/2 (5/2)	2722	3/2⁻, 5/2⁻
2113	3/2⁻	2730	3/2⁻
2169	3/2, 5/2	2765	3/2⁻
2231	3/2⁻, 5/2⁻	2783	3/2⁻ (1/2)
2238	3/2⁻	2811	3/2⁻ (1/2)
2251	3/2⁻, 5/2⁻	2818	3/2⁻, 5/2
2268	3/2⁻	2833	3/2⁻
2275	1/2⁻—5/2⁻	2839	3/2⁻, 5/2⁻
2285	1/2⁻—5/2⁻	2865	3/2, 5/2
2512	5/2⁻, 3/2⁻	2880	1/2—5/2
2584	3/2⁻, 5/2⁻	2933	3/2, 5/2
2613	3/2⁻, 5/2	2951	3/2, 5/2
2620	3/2, 5/2	3154	3/2, 5/2
2635	3/2⁻, 5/2⁻	3185	3/2, 1/2

*The error in the determination of the proton energies is ± 5 keV.

TABLE XI. Angular correlation coefficients and mixtures of multipole orders of photons emitted in the decay of resonances in ^{63}Cu.

E_p, keV \ E_{lev}; keV; J^{π}_{lev}	0, 3/2⁻	1547, 3/2⁻	2012, 3/2⁻	2497, 3/2⁻	668, 1/2⁻	962, 5/2⁻	1410, 5/2⁻
1943	A_2 −0.54 (18) δ +0,89$^{+40}_{-31}$	+0,73 (18) −0,25$^{+15}_{-10}$	—	—	−0,10 (10) −0,22 (6)	—	—
1953	A_2 −0.38 (13) δ +0.60$^{+20}_{-14}$	+0.22 (20) +0,11$^{+15}_{-13}$	—	—	−0,24 (15) −0,14 (8)	—	+0,06 (12) +0,15 (12)
1958	A_2 +0,003 (90) δ +0,26 (6)	—	—	−0,004 (160) +0,26 (12)	—	+0,13 (30) +0,22$^{+58}_{-28}$	—
1976	A_2 +0,014 (70) δ +0,25 (5)	−0,38 (15) +0.60$^{+24}_{-16}$	—	—	—	+0,58 (20) +0,80 (19)	—
2022	A_2 +0,31 (13) δ +0.06 (9)	—	—	+0,53 (32) −0.07$^{+19}_{-29}$	—	+0,34 (17) +0,57$^{+23}_{-31}$	—
2085	A_2 −0.11 (8) δ +0.34 (6)	+0.22 (17) +0.12 (11)	−0.18 (20) +0.39$^{+21}_{-15}$	—	+0.38 (19) −0,49$^{+12}_{-15}$	+0.22 (13) +0.32$^{+28}_{-14}$	+0,08 (11) +0,16$^{+13}_{-10}$
2113	A_2 −0,21 (10) δ +0.42 (9)	+0,08 (3) +0.20 (2)	—	—	−0,64 (14) +0.09 (10)	+0.17 (34) +0,26$^{+54}_{-32}$	+0,25 (15) +0,37$^{+43}_{-18}$
2169	A_2 −0,59 (15) δ 0.68−1,29	+0.16 (15) +0.15 (11)	—	+0,27 (40) +0.08 (28)	−0.46 (13) −0.03 (7)	−0,11 (9) −0.01 (8)	—
2231	A_2 −0,47 (9) δ +0.72$^{+22}_{-13}$	—	—	—	—	+0,045 (144) +0,13$^{+16}_{-13}$	—
2238	A_2 −0,25 (10) δ +0.46 (10)	−0,34 (12) +0.55$^{+16}_{-10}$	—	—	−0,38 (17) −0,07 (10)	+0,04 (19) +0.13$^{+21}_{-17}$	+0.11 (19) +0,19$^{+27}_{-20}$
2251	A_2 −0,43 (10) δ +0.69$^{+18}_{-9}$	—	—	—	—	—	—
2268	A_2 −0.34 (9) δ +0.55 (10)	—	—	—	—	—	—
2275	A_2 +0.063 (102) δ +0.21 (7)	—	—	—	—	−0,10 (16) 0,00 (14)	—

Continuation of TABLE XI.

E_p, keV \ E_{lev}; keV; J^{π}_{lev}	0, 3/2⁻	1547, 3/2⁻	2012, 3/2⁻	2497, 3/2⁻	668, 1/2⁻	962, 5/2⁻	1410, 5/2⁻
2285	A_2 −0,29 (13) $\delta +0,50^{+15}_{-12}$	—	—	—	—	—	—
2512	A_2 −0,37 (11) $\delta +0,58^{+15}_{-12}$	−0.25 (18) $+0,45^{+20}_{-14}$	—	—	−0,24 (21) −0,14 (11)	—	—
2584	A_2 −0,34 (16) $\delta +0,55^{+23}_{-16}$	−0,16 (32) $+0,37^{+37}_{-22}$	−0,23 (32) $+0,44^{+46}_{-24}$	—	+0,01 (22) −0,28 (12)	−0,01 (29) $+0,03^{+35}_{-20}$	—
2613	A_2 −0,54 (11) $\delta +0,89^{+40}_{-19}$	−0,10 (26) $+0,33^{+24}_{-18}$	—	—	—	—	−0,041 (21) $+0,05^{+21}_{-18}$
2620	A_2 −0,42 (9) $\delta +0,65^{+15}_{-11}$	+0,07 (22) +0,21 (14)	—	—	—	—	−0,23 (18) −0,11 (16)
2635	A_2 −0,29 (11) $\delta +0,49^{+13}_{-10}$	+0,07 (20) +0,21 (14)	—	—	—	—	—
2642	A_2 −0,36 (10) $\delta +0.57^{+14}_{-10}$	—	—	—	−0,70 (15) +0,13 (11)	—	—
2675	A_2 −0,49 (13) $\delta +0.76^{+59}_{-19}$	−0,71 (18) 0,82—1.29	—	—	−0,45 (12) −0,03 (7)	—	—
2682	A_2 −0.53 (9) $\delta +0,85^{+40}_{-17}$	—	—	—	—	—	—
2690	A_2 −0,21 (10) $\delta +0.42^{+10}_{-8}$	—	−0,28 (27) $+0,49^{+41}_{-23}$	—	−0,44 (18) −0,04 (8)	—	—
2696	A_2 −0,35 (12) $\delta +0,56^{+17}_{-12}$	—	—	—	−0,66 (18) +0,10 (12)	−0,47 (14) $-0,33^{+13}_{-16}$	−0,15 (18) −0,04 (15)
2710	A_2 −0.63 (12) δ 0,80—1.29	—	—	—	−0,38 (15) −0,07 (8)	—	—

Continuation of TABLE XI.

E_p, keV \ E_{lev}; keV; J^π_{lev}	0, 3/2⁻	1547, 3/2⁻	2012, 3/2⁻	2497, 3/2⁻	668, 1/2⁻	962, 5/2⁻	1410, 5/2⁻
2722	A_2 −0,70 (10) δ +1,29	—	—	—	—	—	−0,53 (25) $-0,39^{+24}_{-41}$
2730	A_2 −0,67 (10) δ 1,20−1,29	—	—	—	−0,44 (16) −0.04 (9)	—	—
2765	A_2 −0,16 (9) δ +0,38 (10)	—	—	—	−0,27 (12) -0.13^{+5}_{-8}	—	—
2783	A_2 +0,13 (11) δ +0,17 (9)	—	—	—	+0,16 (23) −0,35 (15)	—	—
2811	A_2 −0,28 (10) δ +0,48 (9)	−0,24 (31) $+0,40^{+50}_{-20}$	—	—	—	+0,19 (16) $+0.30^{+30}_{-15}$	—
2818	A_2 −0,22 (10) δ +0.43 (9)	+0,57 (35) 0,44−1,29	—	—	—	0,00 (16) +0,09 (10)	—
2833	A_2 −0,54 (13) $\delta+0,87^{+42}_{-20}$	—	—	—	−0,55 (14) +0.03 (12)	—	—
2839	A_2 −0,41 (9) δ +0,63 (13)	−0,20 (29) $+0.41^{+35}_{-20}$	—	—	−0,24 (26) −0,14 (14)	—	—
2865	A_2 −0,60 (12) δ 0,75−1,29	−0,59 (16) 0,44−1,29	—	—	—	—	—
2880	A_2 +0,05 (10) δ +0,30 (10)	−0,13 (23) +0,45 (20)	—	—	—	—	—
2933	A_2 δ	−0.76 (30) 0.49−1,29	—	—	−0.39 (24) -0.06^{+20}_{-14}	−0,29 (18) -0.16^{+16}_{-20}	—
2951	A_2 +0.10 (29) $\delta+0,17^{+23}_{-17}$	—	—	—	—	—	—
3154	A_2 −0.76 (12) $\delta \sim +1,29$	—	—	—	—	—	—
3185	A_2 −0.04 (23) $\delta+0,29^{+19}_{-16}$	—	—	—	—	—	—

The transition energies and strengths have been calculated for the case of a proton–neutron hole with $J^{\pi} = 1^{+}$ in Ref. 34 and for the case of a neutron–proton hole with $J^{\pi} = 1^{+}$ in Ref. 35.

As a rule, in the case of neutron resonances the charge-exchange incoming excitations are located below the neutron binding energy and the transition strengths are weakened by the existence of the neutron excess. The situation in the case of proton resonances is the reverse. The collective Gamow–Teller resonance is located near the analog state (in the range 1–2 MeV). It always exists in nuclei with a neutron excess, and the transition strengths increase with increasing neutron excess.

The calculations predict only the center of mass of the Gamow–Teller resonance. In real nuclei this configuration is distributed over states with more complicated structure. Since, as noted above, the widths of Gamow–Teller resonances are 2–4 MeV (Ref. 4), it can be concluded that the fine structure of this resonance is manifested in the excitation-energy ranges that we have investigated for copper isotopes.

The $p_{3/2}$ analog resonance in the isotope ^{59}Cu is located at the excitation energy 3900 keV. We have studied the energy range from 5500 to 6815 keV, i.e., the range at 1.6–2 MeV above the analog. The $p_{3/2}$ analog in ^{61}Cu is located at an excitation energy of about 6400 keV. We have studied the energy range from 6200 to 6600 keV, i.e., the range near the $p_{3/2}$ analog. In the case of ^{63}Cu the excitation energy corresponding to the $p_{3/2}$ analog is 8743 keV. We have studied the resonances in the energy range from 8040 to 9250 keV.

At present it is still difficult to quantitatively compare the energy position of the experimentally observed Gamow–Teller resonance with the presently available calculations of the positions of the maxima of this resonance in nuclei, since the energy ranges studied in the copper isotopes considered here—1300 keV in ^{59}Cu, 400 keV in ^{61}Cu, and 1200 keV in ^{63}Cu—far from exhaust the range in which the strength of the Gamow–Teller giant resonance is concentrated. However, the qualitative comparisons between experiment and calculation indicate that the agreement is satisfactory.

Calculations of the position of the Gamow–Teller resonance for a wide range of nuclei[36] using a schematic model which includes the isospin–isospin and spin–isospin residual interactions have shown that, using the analog state as the reference, the energy of the Gamow–Teller resonance varies smoothly with atomic number of the target nucleus from 4–5 MeV for light nuclei to 1 MeV for heavy nuclei. Our data on copper isotopes are consistent with these calculations.

A characteristic feature of the resonances which we have observed in copper isotopes is the strong $M1$ transition to the ground state. This result can be explained if it is assumed that these resonances are Gamow–Teller resonances. In fact, since the Gamow–Teller resonance is a coherent superposition of particle–hole excitations $\Sigma_i\, a_i p^n_{3/2}\, [pn^{-1}]_{i'}$, the ground state is an almost pure $p_{3/2}$ single-particle state, while in the $M1$-transition operator the isoscalar part is strongly suppressed relative to the isovector part, strong $M1$ transitions to the ground state must be observed.

According to the estimates made in Ref. 27 for ^{61}Cu, the quantity $B(M1)$ for the transition from the Gamow–Teller resonance to the analog state is $\sim 3\mu_0^2$. It can be expected that $B(M1)$ for the transition from the Gamow–Teller resonance to the ground state will be of the same order of magnitude. However, the configuration of this resonance is distributed over many resonances of the compound nucleus. We have observed nine resonances in the proton energy range 1577–1850 keV in ^{61}Cu. In the region roughly 2.5 MeV in extent in which the Gamow–Teller resonance is assumed to lie it is possible to find around 100 resonances which carry the strength of this giant resonance. Therefore, for each resonance it can be expected that $B(M1) \simeq 0.03\mu_0^2$ for a transition to the ground state. The experimentally determined average value of $B(M1)$ for transitions to the ground state of ^{61}Cu for these nine resonances is 0.027_0^2.

CONCLUSIONS

The set of experimental data that we have considered in this review leads to the conclusion that nonstatistical effects related to the presence of intermediate structure are observed in nonanalog proton resonances in nuclei of intermediate mass ($A \sim 45$–65) for proton energies in the range 1–5 MeV.

Intermediate structure in proton inelastic scattering is manifested in the correlation of the signs of the amplitudes for resonance decay.

In the $(p\gamma)$ reaction via a resonance, intermediate structure is manifested in the fact that the signs of the mixture of multipole orders of γ transitions from various resonances to a given nuclear level are identical.

Analysis of the features of the γ decay of nonanalog proton resonances together with the theoretical ideas about the Gamow–Teller resonance leads us to the conclusion that the observed intermediate structure is a consequence of the fine structure of the Gamow–Teller resonance. It is interpreted as a distribution of the strength of the Gamow–Teller giant resonance over resonance states of more complex structure.

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