THE POSITION OF THE GIANT RESONANCE IN THE DIPOLE ABSORPTION OF GAMMA QUANTA BY ATOMIC NUCLEI

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The giant-resonance curves for a number of intermediate nuclei (Ca^{40}, V^{51}, Ni^{58}, and $Cu^{63,65}$) are calculated on the basis of the shell model. It is shown that if spectroscopic data on the lower nuclear levels are employed the shell theory calculations yield in a natural manner the correct position of the giant resonance.

WILKINSON'S[1] application of the shell theory to calculate the dipole absorption of gamma quanta has permitted a qualitative explanation of the width and area of the giant resonance. However, the energy of the giant resonance turned out to be approximately half as large as the experimental value. To obtain agreement with the experimental value, Wilkinson made use of the concept of "effective mass"; the correct position of the giant resonance is obtained for an effective mass equal to half the true mass of the nucleon. For such a value of the effective mass the distance between single-particle levels belonging to neighboring shells is increased by a factor of two and amounts to ~ 14 Mev for the usually accepted dimensions of the nucleus. However, the latest experimental data[2] show that the spacing between the above levels is, just as in the usual shell model, 6 — 7 Mev.

We wish to show that for nuclei with $A < 70$ account of the residual pair interactions in the calculations of the giant resonance according to the shell model, and a more accurate estimate of the nucleon binding energy in closed shells yield an energy value in agreement with experiment, so that the giant-resonance phenomenon can be understood within the framework of the usual shell theory without the introduction of an "effective mass." The effect of the residual interactions is apparent from empirical data on the lower states of nuclei without the introduction of any kind of explicit pair potential.

The method of taking account of these effects will be presented below by the example of a calculation of the dipole absorption curve for the Ca^{40} and V^{51} nuclei for which sufficient spectroscopic material is available.

For instance, in the E1 absorption of a gamma quantum by the V^{51} nucleus the following transition is possible:

$$(\nu f_{7/2})^8 (\pi f_{7/2})^3 \rightarrow (\nu f_{7/2})^8 (\nu d_{3/2}^{-1}) (\nu f_{5/2}) (\pi f_{7/2})^3. \quad (1)$$

We have no direct information on the energy of the final state, but we can calculate this energy by analyzing the data on the lower states of neighboring nuclei. The literature contains information on the position of the single-particle levels $1f_{7/2}$, $2p_{3/2}$, $2p_{1/2}$, $1f_{5/2}$, $1g_{9/2}$, and $2d_{5/2}$, in the Ca^{41} and Sc^{41} nuclei.[2] For the calculation we must, in addition, know the following:

a) the change in the binding energy of the $1f_{5/2}$, $2p_{3/2}$, $2p_{1/2}$, $1g_{9/2}$, and $2d_{5/2}$ nucleons in the transition from Ca^{41} and Sc^{41} to a heavier nucleus with a configuration of $(\pi\nu f_{7/2})^n f_{5/2}$, or $(\pi\nu f_{7/2})^n g_{9/2}$' etc;

b) the change in the binding energy of the whole nucleus in the transition from $(\pi\nu f_{7/2})^n$, for instance, to $(\nu d_{3/2}^{-1})(\pi\nu f_{7/2})^n$;

c) the value of the spin-orbit splitting constant of $d_{3/2}^{-1} - d_{5/2}^{-1}$ in Ca^{39}.

To obtain this information we make use of the following experimental data:

a) the energy $E(f_{5/2})$ of the single-particle level $f_{5/2}$ is equal to 2.0 Mev in Ca^{41} (reference 2), 7.8 Mev in Ni^{61} (references 3 and 4), 7.0 Mev in Cr^{53} (references 3, 5 and 6), and 4.1 Mev in Sc^{49} (reference 6), and must on the average depend linearly on the number of $f_{7/2}$ nucleons above Ca^{40} (cf., for example, reference 7), which is in approximate agreement with the values cited above. As a result $\Delta E(f_{5/2}) \approx (0.3 \text{ to } 0.4)n$ Mev (where n is the number of $f_{7/2}$ nucleons), i.e., there occurs, by comparison with Ca^{41}, a shift to lower energies. Analogously, we conclude from data on the Ca^{41} (reference 2), $Ca^{45,49}$ (reference 9), Ni^{57}, Cr^{53} (reference 3), and Fe^{55} (reference 8) nuclei that $\Delta E(2p_{3/2}) \approx (0.3 \text{ to } 0.4)n$ Mev. From the more scanty data on the Ca^{41}, Zn^{71}, and Ge^{73} (reference 3) nuclei we obtain $\Delta E(g_{9/2}) \sim 0.1\,n$ Mev.

b) In the K^{40} nucleus the neutron is bound more weakly than in Ca^{41}, on the average by 0.95 Mev [the $d^{-1}_{3/2}f_{7/2}$ states form a system consisting of four levels in an interval of 0.9 Mev (reference 9)]; in the K^{41} nucleus the two $f_{7/2}$ nucleons are bound more weakly than in the Ca^{42} nucleus by 1.95 Mev (reference 9), and in the K^{43} nucleus[4] the $f^4{}_{7/2}$ nucleons are bound more weakly than in Ca^{44} by 3.90 Mev, i.e., the energy change is, as was expected, approximately linear with the number of $f_{7/2}$ nucleons, and can be described by the formula $\Delta E\,(d^{-1}_{3/2}) \approx (0.9 \text{ to } 1.0)\,n$ Mev. When we deal with a "hole," the energy of the system no longer increases, but decreases instead. This last effect is thus the most important manifestation of residual interactions.

c) We take the spin-orbit splitting constant for $d^{-1}_{3/2} - d^{-1}_{5/2}$ in Ca^{39} to be the same as for $p^{-1}_{1/2} - p^{-1}_{3/2}$ in N^{15} (reference 10), so that $\Delta E\,(d^{-1}_{3/2} - d^{-1}_{5/2}) \sim 8$ to 10 Mev. In the following we will take the excitation energy of the $2s^{-1}_{1/2}$ state to be 3 – 4 Mev, corresponding to the position of the unsplit d level.

Now it is possible to estimate the energy of transition (1). We have $\Delta E = 15.8 - 6 + (9 \text{ to } 10) = 19$ to 20 Mev; this is one of the most intense transitions.

The calculation of the absorption cross sections is carried out according to the shell-theory formulas for mixed configurations with a summation over all the spins of the final states for a given final configuration, so that very simple expressions for the cross section are obtained:

a) in transitions from an unfilled shell

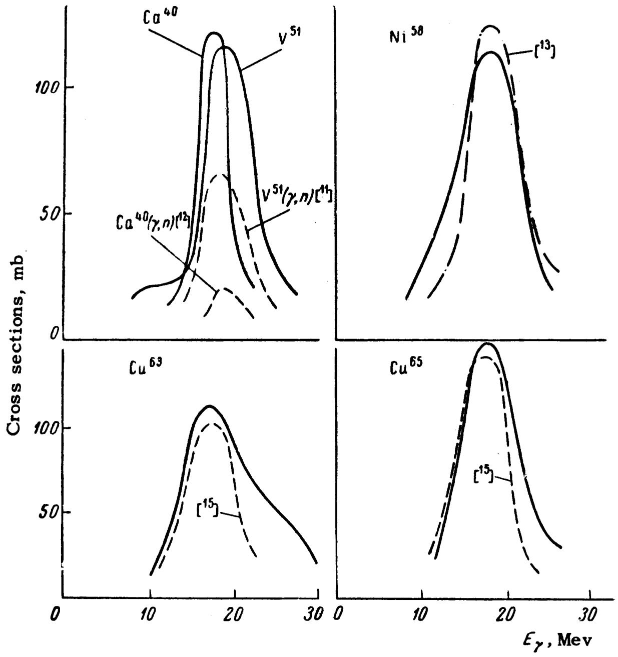
$$\int_\Delta \sigma(E)dE = \frac{4}{3}(\pi^2 e'^2/\hbar c)\, E_\gamma n_1 (2l_1+1)(2l_2+1)(2j_2+1) \times \begin{pmatrix} l_1 & 1 & l_2 \\ 0 & 0 & 0 \end{pmatrix}^2 \begin{Bmatrix} l_2 & j_2 & 1/2 \\ j_1 & l_1 & 1 \end{Bmatrix}^2 \langle l_2 | r | l_1 \rangle^2; \qquad \text{(a)}$$

b) for transitions from a filled shell

$$\int_\Delta \sigma(E)\,dE = \frac{4}{3}(\pi^2 e'^2/\hbar c)\, E_\gamma (2j_2+1-n_2)(2l_1+1)(2j_1+1) \times (2l_2+1) \begin{pmatrix} l_2 & 1 & l_1 \\ 0 & 0 & 0 \end{pmatrix}^2 \begin{Bmatrix} l_2 & j_2 & 1/2 \\ j_1 & l_1 & 1 \end{Bmatrix} \langle l_2 | r | l_1 \rangle^2. \qquad \text{(b)}$$

Here e' is the effective nucleon charge equal to Ne/A for a proton and $-Ze/A$ for a neutron, n_1 is the number of nucleons in the unfilled shell, n_2 is the number of nucleons in the shell into which the transition takes place (n_1 and n_2 refer to the initial state), l_1, j_1, l_2, j_2 are the orbital and total momenta of the nucleon in the initial and final state, respectively. The integration is over the region Δ in which the levels of the given configuration are located.

The results for V^{51} and Ca^{40} are presented in the figure. Without account of residual interactions the curve for V^{51} would have been shifted to the left by ~ 6 Mev. For Ca^{40}, for which additional account of residual interactions is naturally unnecessary, the maximum of the curve is in the region of 17 – 18 Mev, and not 14 Mev, owing to the fact that in Ca^{40} a decisive role is played by the high-energy $1d_{5/2} \to 1f_{7/2}$ transitions, while in V^{51}, in which the neutron $1f_{7/2}$ shell is filled, these transitions are less important than the sum of the $\pi\nu 1d_{3/2} \to 1f_{5/2}$ and $\pi\nu 2s_{1/2} \to 2p_{3/2}$ transitions which makes the main contribution to the giant-resonance maximum.



E1 absorption curves for various elements. The solid curves are calculated; the dot-dash curve is the experimental curve of the total absorption cross section for Ni^{58}; the dashed curves are the experimental curves for (γ, n) reactions.

For V^{51} and Ca^{40} only the excitation curves for the (γ, n) reactions have been measured.[11,12] A comparison of the integral cross sections of these reactions with the theoretical curves for the total absorption cross section shows that $\int \sigma(\gamma, p)\,dE$ should be somewhat larger than $\int \sigma(\gamma, n)\,dE$ for V^{51}, and considerably larger for Ca^{40}. Experiments to measure the total absorption cross section of gamma quanta by nuclei close to those considered [Ni^{58} and Ar^{40} (references 13 and 14)] confirm this conclusion.

In all substantial transitions with neutron excitation in nuclei in which N is close to Z the excited neutron is bound with respect to the framework in spite of the fact that the excitation energy is larger than the energy of the neutron threshold. Such excited states can emit nucleons but only on account of the mixing of configurations, i.e., the nucleon disintegration will, apparently, obey the laws of the statistical model of the nucleus. However, proton excitation, due to the fact that the Coulomb energy raises the proton levels, will, in the majority of cases, lead to the emission of "direct" protons with energies larger than those predicted by the statistical model. For instance, in the $\nu 1d_{3/2} \rightarrow \nu 1f_{5/2}$ transition the excited V^{51} nucleus cannot emit a $1f_{5/2}$ neutron (the direct photoeffect is forbidden), and in the $\pi 1d_{3/2} \rightarrow \pi 1f_{5/2}$ a $1f_{5/2}$ proton with an energy of ~ 3 Mev can be emitted. We note that although such terms as "neutron excitation" are not fully correct if the isotopic spin is considered a good quantum number, their use nevertheless has a certain intuitive advantage for the description of the disintegration of a state.

We have also calculated the dipole-absorption curves for Ni^{58}, Cu^{63}, and Cu^{65}. The figure shows a comparison of these curves with experimental data.[13,15] The agreement of the experimental data with the calculations is entirely satisfactory. It must be noted that for the calculations of Ni^{58}, Cu^{63}, and Cu^{65} the spectroscopic material is considerably scantier and the results are, therefore, of a more approximate nature.

In conclusion, we again emphasize that our analysis indicates good correspondence of the calculated giant-resonance position and the spectroscopic data on the lower states of nuclei in the investigated region. It seems important to us that extensive spectroscopic investigations be conducted in the same order in which they are needed for the analysis of photonuclear reactions. Until now such investigations have been carried out only for a small number of nuclei, and their absence hampers the analysis of photonuclear reactions in many portions of the periodic table.

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