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# Radiative-Capture Studies of the Giant Dipole Resonance

## Gamma-ray yields from capture of protons and $\alpha$-particles give finer details than studies of $\gamma$-ray absorption.

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Emission of electromagnetic radiation (gamma rays) by nuclei was observed in the earliest days of radioactivity. For nuclei, as for other radiating systems, radiation and absorption are inverse processes: that is, if surrender of energy by emission of a gamma ray changes a nucleus from an excited state *A* to some state *B* in which it has less energy, and if this nucleus in state *B* regains the same amount of energy by absorbing a gamma ray, it returns to state *A*. This nuclear absorption of gamma rays was not observed until much later. The interaction between nuclei and electromagnetic radiation was first studied in "photonuclear reactions," in which absorption of a gamma-ray photon caused the nucleus to emit a particle. In the inverse experiments that I describe, however, gamma-ray emission results when a nucleus captures an energetic particle from an accelerator.

Most of the gross features of the nuclear absorption of gamma rays were established by experiments in many laboratories (*1–3*) during the late 1940's and early 1950's. The major result of these studies of photonuclear reactions was that the graph of gamma-ray absorption plotted against gamma-ray energy $E_\gamma$ for any particular nucleus invariably showed a single broad peak in the neighborhood of $E_\gamma = 20$ million electron volts (Mev). The properties of this peak, called a resonance because these are the energies to which the nucleus responds, are listed in Table 1.

The theoretical description of the electromagnetic radiation from some system of moving charges is an equation consisting of two infinite series of terms: the "electric" series corresponding to the vibrations of electric charges, and the "magnetic" series associated with changes in the magnetic moments of various configurations of current loops. In the electric series the first term corresponds to the radiation from an electric dipole consisting of two vibrating electric charges of opposite sign; the second term represents radiation from an electric quadrupole consisting of two positive and two negative charges vibrating relative to each other; and so on. The radiations associated with these successive terms are labeled $E1$, $E2$, $E3$, and so on. Other considerations being equal, the electric-dipole ($E1$) term dominates; indeed, detailed examination of the properties of the observed resonance in nuclear absorption shows that the radiation is described by the $E1$ term of the infinite series. (In the language of quantum mechanics, the $E1$ character of the radiation means that only one unit of angular momentum is transferred in the absorption process.) Hence the broad resonance is called the electric-dipole giant resonance, or "giant resonance" for short.

The bulk of the measurements that established this giant resonance were on photonuclear reactions induced by bremsstrahlung beams—beams of gamma rays produced when energetic electrons stop abruptly on striking a target. Even with the current refinement of these techniques, experiments with sources that produce a continuous spectrum of gamma rays cannot separate peaks that are less than a few hundred thousand electron volts apart. The best of the more nearly "monochromatic" (monoenergetic) sources of gamma rays now available gave no significant improvement in ability to resolve closely spaced peaks. Similarly, experiments with the inelastic scattering of electrons (which can be shown to be equivalent to gamma-ray absorption) cannot resolve peaks less than about 100 kev apart. Moreover, extensive measurements of the angular distributions of the outgoing particles were not feasible with any of these techniques. These difficulties notwithstanding, the giant resonance is an important bulk nuclear effect that merits study in greater detail. It is therefore fortunate that development of the tandem Van de Graaff accelerator (*4*) now permits study under much better experimental conditions; the machine provides beams of protons and other heavy charged particles having high enough energy that the giant resonance may be studied through the inverse reaction of radiative capture.

Absorption of a gamma ray in the giant resonance excites a nucleus to about 15 to 20 Mev; in most nuclei this excitation energy is 5 to 10 Mev above the threshold for emission of a neutron, proton, or alpha particle. For nuclei heavier than about mass 60, the Coulomb barrier effectively inhibits emission of charged particles, and neutron emission predominates; in lighter nuclei, proton emission competes successfully. In this region of the periodic table, the giant resonance can be studied through the inverse reaction where-

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in a proton is captured and a gamma ray is emitted. For reaching the upper part of the giant resonance, protons of up to at least 10 Mev are required; these are now available from tandems, which produce steady, steerable, well-collimated proton beams having continuously variable energy and energy spreads of less than 5 kev. With tandems, therefore, the giant resonance can be studied under the good experimental conditions under which detailed yield curves and angular distributions can be measured.

### Radiative-Capture Experiments

Figure 1 shows the experimental arrangement used in radiative-capture experiments at Argonne National Laboratory; similar setups are in use in other laboratories. The proton beam from the tandem impinges on a thin target—no thicker than about 300 micrograms per square centimeter. In a thicker target, the proton beam would lose more than a few thousand electron volts in passing through the target, and hence the $(p,\gamma)$ reactions in the back of the target would result from capture of appreciably slower protons than those in the front; that is, energy definition would be lost. Since target backings necessarily are a source of background, self-supporting targets are used whenever possible. When a backing is necessary (for example, when the target must be made by evaporation), it is made as thin as possible; carbon foils, which are commercially available as thin as 5 micrograms per square centimeter, make especially good backings. After passing through the target, the proton beam travels about 3 meters before being stopped.

Table 1. Approximate parameters of the giant dipole resonance. $A$, atomic weight; $N$, neutron number; $Z$, atomic number.

| | |
|---|---|
| Peak position | $82A^{-\frac{1}{3}}$ Mev* |
| Peak width | 3–8 Mev |
| Integrated cross section $\int \sigma dE$ | $0.08(NZ/A)$Mev•barns |

*Does not hold for $A$ less than about 20.

The proton-capture cross sections are small: 50 microbarns is typical (1 barn $= 10^{-24}$ square centimeter). Since, therefore, an efficient detector is necessary, the only practical detector is a thallium-activated sodium iodide crystal [NaI(Tl)]. (It is hoped that eventually one may use the lithium-drifted germanium diode, which has much better energy resolution. However, even the largest germanium detectors now available are too low in efficiency for the high-energy gamma rays we are studying.) Large NaI(Tl) crystals (such as the Argonne ones having linear dimensions of about 25 centimeters) have a reasonably high efficiency for the 15- to 20-Mev gamma rays. A lead jacket shields the crystal from stray background, and paraffin between crystal and target helps to filter out neutrons and lower-energy gamma rays. Without the shielding, these radiations could be troublesome because they are usually more numerous by several orders of magnitude than the capture gamma rays. The crystal is mounted on an arm that swings about the target. (The current practice at Argonne National Laboratory is to use two crystals in order to speed acquisition of the data.) When a gamma ray is absorbed in the crystal, the resultant electron produces a scintillation that is observed by one or more photomultiplier tubes optically coupled to the crystal. The amount of light in the scintillation, and hence the charge in the pulse from the photomultiplier, is proportional to the energy of the incident gamma ray. Thus the pulse-height spectrum, which is obtained when a multichannel analyzer sorts the pulses in order of size and displays the number of pulses in each narrow range of pulse heights, is equivalent to an energy spectrum of the gamma rays. The experiments, then, are for measurement of the yield of proton-capture radiation as a function of energy and angle.

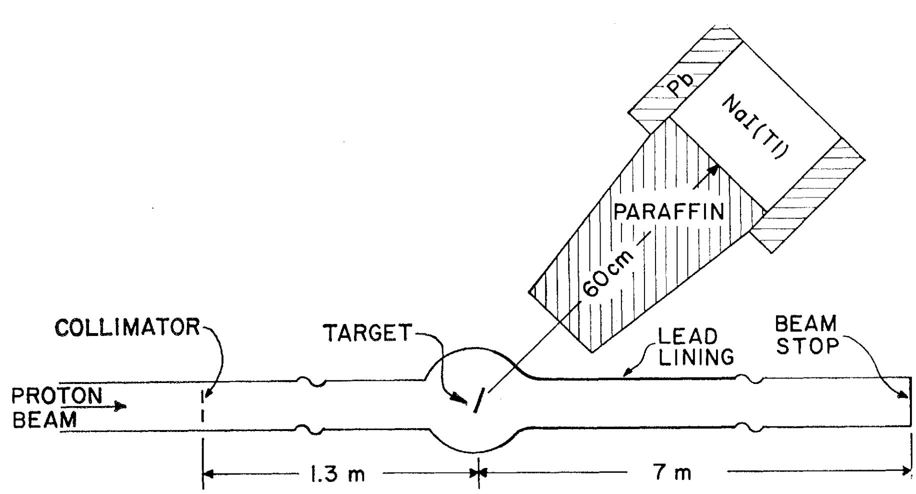



Fig. 1. Experimental arrangement for detecting the gamma rays from the radiative capture of protons accelerated by the tandem Van de Graaff accelerator at the Argonne National Laboratory.

The pulses from the crystal are passed through some special electronics to minimize the effect of pulse pileup; they are then amplified before being sorted by a multichannel analyzer whose output is punched on computer cards; Fig. 2 is typical. The pulses of highest energy are due to cosmic rays, which give rise to a continuum extending from the lowest energies all the way up to several hundred million electron volts. As one follows the graph toward lower energies, the first peaks encountered are due to the proton-capture gamma rays. This portion of the curve illustrates an important difference between the radiative capture and the experiments with gamma-ray absorption: the proton-capture radiation can arise from nuclear transitions to excited states as well as to the ground state of the nucleus (Fig. 3), whereas only the ground-state gamma ray is involved in absorption. On the other hand, gamma-ray absorption involves the entire giant resonance, while the capturing nuclei in $(p,\gamma)$ reactions always are initially in their ground states. In proton capture the strength of the gamma ray to the first excited state ($\gamma_1$) typically is comparable (Fig. 2) to that of the ground-state gamma ray ($\gamma_0$), while gamma rays to higher excited states are usually considerably weaker. Because of this, the bulk of the work has been concentrated on $\gamma_0$ and $\gamma_1$, although some information has been obtained on nuclear transitions to higher states.

At a pulse height corresponding to an energy of about 14 Mev, the spectrum rises sharply. This low-energy background is due to the very much more prolific nuclear reactions in which a proton, or neutron, or alpha particle is first emitted.

Since the aim is to study the yields of the individual gamma rays, the only nuclei suitable for study are those whose

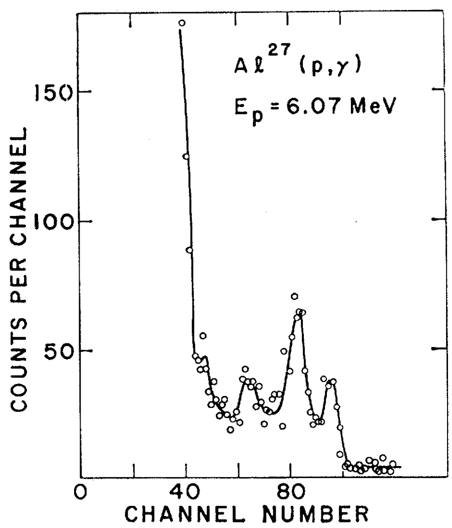



Fig. 2. Pulse-height spectrum observed in the NaI(Tl) crystal when an aluminum target with a thickness of 200 micrograms per square centimeter is bombarded with 6.07-Mev protons.

low-lying levels are separated so widely that the transitions to these levels can be at least partially resolved. For gamma-ray energies in the range from 15 to 20 Mev, the NaI(Tl) crystals give peaks whose widths at half the peak height are about 8 percent of the gamma-ray energy. Thus the gamma rays can be resolved only if the low-lying states of the nucleus are separated by at least 1.2 Mev. Although this restriction leaves many cases that can be studied, it has the effect of concentrating the effort on nuclei having even numbers of protons and neutrons, since it is almost exclusively in such even-even nuclei that the low-lying levels are widely spaced.

## Yield Curves

The yield curve for the $Al^{27}(p,\gamma_0)Si^{28}$ reaction, in which capture of a proton in $Al^{27}$ leads to emission of a gamma ray $\gamma_0$ that leaves the $Si^{28}$ nucleus in its ground state, is shown in Fig. 4; the data were obtained with a NaI(Tl) crystal fixed at 90 degrees to the direction of the beam; the target was an aluminum foil (200 micrograms per square centimeter), and data were taken in 15-kev steps (*5*). For comparison, Fig. 4 also shows the yield curve (*6*) for the photonuclear reaction $Si^{28}(\gamma,n)Si^{27}$, which was measured with a resolution width of 600 kev; the wealth of detail that is brought out in the high-resolution experiments is apparent. The $(p,\gamma)$ yield curve exhibits a fine structure with peaks about 100 kev apart; these are grouped into an intermediate structure with composite peaks several hundred thousand electron volts in width, and the whole is superimposed on a broad envelope about 5 Mev wide. The intermediate structure and broad envelope are also seen in the $(\gamma,n)$ work, in spite of its poorer resolution. (In nuclear physics, the word *structure* is used not only to refer to the arrangement of particles in the nucleus but also to denote the pattern of peaks in a curve, or merely the presence of peaks; the context indicates which meaning is intended.)

The fact that the fine structure appears in the yield curve (top curve in Fig. 4) indicates that the reaction proceeds at least partially through the compound nucleus; that is, at least part of the time the incident proton loses its identity, and its energy is shared among a number of nucleons. The compound nucleus usually decays by reconcentrating the energy on a single nucleon (because the electromagnetic interaction is comparatively weak, only occasionally is the decay by gamma-ray emission), but, since the energy has been shared among a number of nucleons, this reconcentration takes a long time. Then, by virtue of the Heisenberg uncertainty principle (which states that the product of the uncertainty in energy and the uncertainty in time is equal to a specified constant), this long time means that the states have sharply defined energy. Moreover, since there are very many ways in which the energy can be shared among a number of nucleons, a region of high excitation energy contains many nuclear states. In the contrasting case, known as the direct-interaction mode, the radiation occurs before the incident proton can share its energy; in this case, in which the incident proton retains all the energy, the nuclear state is simple, short-lived, and therefore broad.

Complex yield curves, such as those for the $Al^{27}(p,\gamma)$ reaction, can be analyzed statistically; to this end we compute the autocorrelation function, defined in the present case as

$$R(\epsilon) = \left\langle \left[ \frac{\sigma(E) - \langle\sigma(E)\rangle}{\langle\sigma(E)\rangle} \right] \times \left[ \frac{\sigma(E+\epsilon) - \langle\sigma(E+\epsilon)\rangle}{\langle\sigma(E+\epsilon)\rangle} \right] \right\rangle$$

where $\langle\square\rangle$ signifies an average over the energy. This use of the autocorrelation is a standard technique for discerning a characteristic width of peak in a curve that exhibits complicated fluctuations. The presence of such a

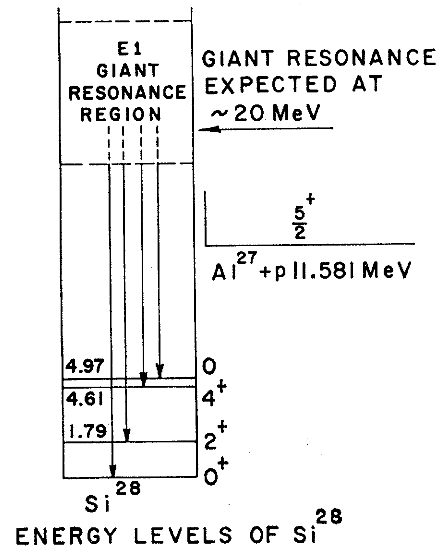



Fig. 3. Diagram showing the nuclear energy levels relevant to study of the giant resonance in $Si^{28}$ by the $Al^{27}(p,\gamma)$ reaction. Similar diagrams apply to the other nuclei that have been studied.

width is evidenced by a peak at $\epsilon = 0$ in the autocorrelation; the width of this peak is related to the characteristic width, and its height is related to the intensity of the component with which the characteristic width is associated. The exact form of the relation depends on the particular nature of the fluctuations. Ericson (*7*) has derived the autocorrelation function that is to be expected for a yield curve from a reaction that proceeds through strongly overlapping states in the compound nucleus so that interference between states of the compound nucleus produces strong fluctuations in the yield curve. The Ericson theory shows how the autocorrelation function, computed from the yield curve, depends on the widths of the states in the compound nucleus and on the fraction of the reaction that proceeds through the direct-interaction mode.

Analysis of the fine structure in the $Al^{27}(p,\gamma_0)Si^{28}$ yield curve indicates that the width of the states in the $Si^{28}$ compound nucleus is about 60 kev. Similar widths have been found for other reactions proceeding through $Si^{28}$ at the same excitation energy; an example is the $Al^{27}(p,\alpha)Mg^{24}$ reaction (*8*), in which absorption of the proton produces highly excited states of $Si^{28}$, which decay to $Mg^{24}$ by emitting an alpha particle. One should note that there is no statistically significant correlation between the structures observed in different reactions: that is, the peaks in the $Al^{27}(p,\gamma)$ yield do not coincide with the peaks in the $(p,\alpha)$

yield. The degree of correlation between two curves can be determined quantitatively by computation of the cross-correlation function, which is similar to the autocorrelation function. Thus the properties of the fine structure are determined by the properties of the compound nucleus $Si^{28}$ at a high excitation energy, and have little relation to the giant resonance as such; in fact quite different structure within the giant-resonance envelope is observed in other cases (Fig. 5).

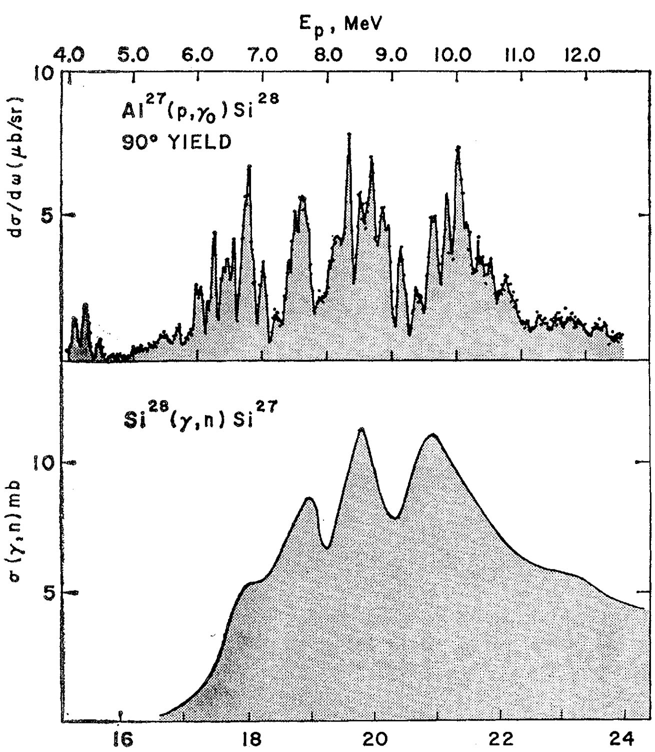
Analysis (*5*) of the $Al^{27}(p,\gamma)$ data showed that about 95 percent of the cross section is due to the direct-interaction component. In view of the violence of the fluctuations, this result is surprising until one remembers that there is interference between the compound-nucleus reaction and the direct interaction, and that a relatively small intensity (proportional to the square of the amplitude of the wave) can give rise to much greater interference effects (proportional to the amplitude and hence to the square root of the intensity). One should note that Ericson analyses of the yield curves of other nuclear reactions—such as the $Al^{27}(p,\alpha)$ reaction (*8*)—often indicate much smaller percentages of direct interaction; in such cases, the yield curves exhibit greater variation from peak to adjacent valley.

Table 2. Integrated $(\gamma_0,p_0)$ cross sections, expressed in units of the electric dipole sum $(2\pi^2e^2\hbar/Mc)$ $(NZ/A)$, for the series of nuclei having equal numbers of neutrons and protons and an even number of each. $N$, neutron number; $Z$, atomic number; $A$, atomic weight.

| Nucleus | $\int (\gamma_0, p_0)dE$ | $\int (\gamma_1, p_0)dE$ |
|---|---|---|
| $He^4$ | 0.17 | |
| $Be^8$ | .13 | 0.11 |
| $C^{12}$ | .29 | .09 |
| $O^{16}$ | .11 | |
| $Ne^{20}$ | .083 | .032 |
| $Mg^{24}$ | .033 | .032 |
| $Si^{28}$ | .14 | .06 |
| $Ca^{40}$ | .12 | |

The resonance structure in the giant resonance is much milder in lighter nuclei—as illustrated by Fig. 5, which shows the data (*9*) for proton capture by $B^{11}$; such a trend is expected since fewer nucleons are involved in the excitation of states in the lighter nuclei and thus the states may decay more quickly. Indeed, studies of level widths covering much of the periodic table (*10*) have determined that the characteristic widths of highly excited states continuously decrease with increase in atomic number.

There are so few peaks in the $B^{11}(p,\gamma)C^{12}$ yield curve that a statistical analysis would not be meaningful. Detailed yield curves have also been measured for proton capture (*11–14*) by $Li^7$, $N^{15}$, $F^{19}$, $Na^{23}$, and $P^{31}$; the measurements show that, as expected, the width of the fine-structure peaks decreases as the atomic number increases. In the $(p,\gamma)$ reactions on $B^{11}$, $Na^{23}$, and $Al^{27}$, we found no correlation between the $\gamma_0$ and the $\gamma_1$ yield curves. Where there is sufficient structure to permit statistical analysis, the degree of correlation has been computed formally through use of the cross-correlation function; such analysis of the $Al^{27}(p,\gamma)$ data showed no statistically significant cross correlation. On the other hand, the structure in the $\gamma_0$ and $\gamma_1$ curves from the $F^{19}(p,\gamma)$ reaction (*12*) appears to be strongly correlated, and this conclusion is supported by statistical analysis of the yield curves.



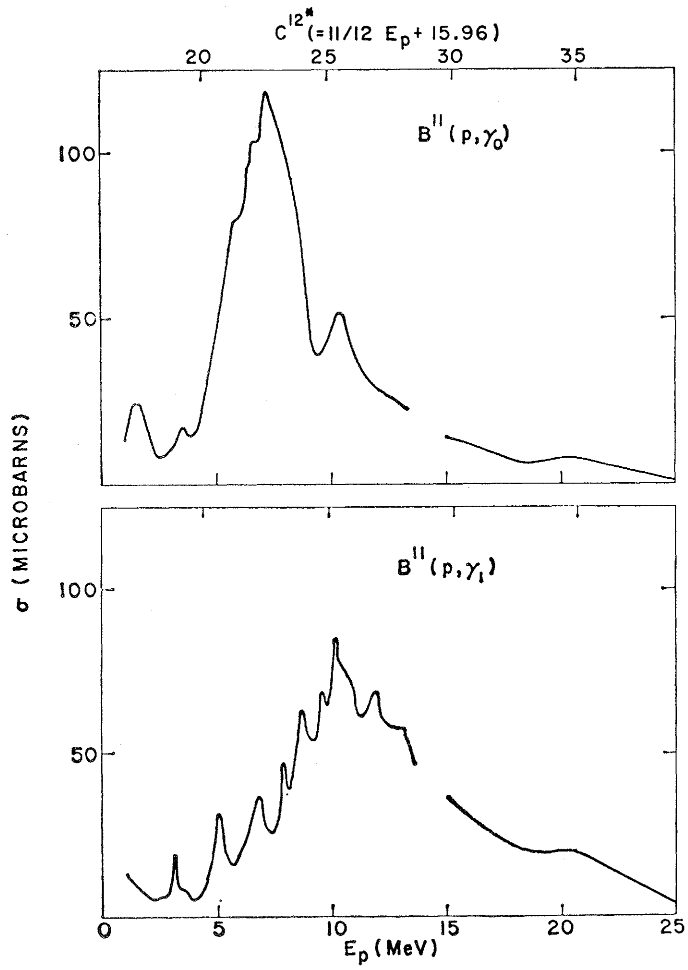




Fig. 4 (above). Giant resonance in $Si^{28}$. In the curve from the $Al^{27}(p,\gamma_0)Si^{28}$ reaction (*5*), features 15 kev apart could be resolved. In the study of the $Si^{28}(\gamma,n)Si^{27}$ reaction (*6*), however, the width of resolution of energy was 600 kev. Fig. 5 (right). Cross section as a function of energy for the gamma rays, to the ground state ($\gamma_0$) and to the 4.43-Mev first excited state ($\gamma_1$) in $C^{12}$, formed in the $B^{11}(p,\gamma)$ reaction.

The gamma ray $\gamma_1$, whose emission leaves the nucleus in the first excited state, has in each case a yield curve qualitatively similar to the corresponding $\gamma_0$ yield curve—that is, the curve is a giant-resonance envelope upon which some structure is imposed. In all cases, however, the envelope of the $\gamma_1$ yield curve peaks at a higher incident proton energy, the displacement from the $\gamma_0$ peak usually being about equal to the energy of the first excited state in the final nucleus. Thus it appears that giant resonances are associated with the excited states of nuclei, just as each nucleus has a giant resonance associated with its ground state. The ($\gamma$-ray) energy of the giant resonance is a slowly varying function of atomic number and appears to be independent of whether the giant resonance is associated with a ground state or with an excited state.

Nuclear theory leads to a quantity known as the electric-dipole sum, which represents the total expected gamma-ray absorption by any nuclear state: that is, it represents the absorption cross section integrated over all energies (*15*). In the experiments with gamma-ray absorption (*2, 3*) the integral over the giant resonance alone was found to almost equal the electric-dipole sum. By use of the principle of detailed balance, the yield to be observed in a $(\gamma,p_0)$ study can be calculated from the observed $(p,\gamma_0)$ yield; similarly, the $(p,\gamma_1)$ yield can be used to obtain the yield to be observed in a $(\gamma_1,p_0)$ study (even though the short life of the first excited state makes such a study virtually impossible).

From Table 2, showing various $(\gamma,p_0)$ integrated yields obtained from $(p,\gamma)$ studies, one sees that the fraction of the photonuclear reactions wherein a proton is emitted, leaving the final nucleus in its ground state, varies widely from one giant resonance to another. The hypothesis that the giant resonance is mainly associated with direct reactions enables one to explain many of the variations in terms of the shell-model configurations of the nuclear states that are involved. (In the shell model, also called the independent-particle model, each nucleon is thought of as moving in an orbit much as the electrons move about in an atom.) Individual cases are discussed (*5, 9, 12*) in reports of experiments on particular nuclei.

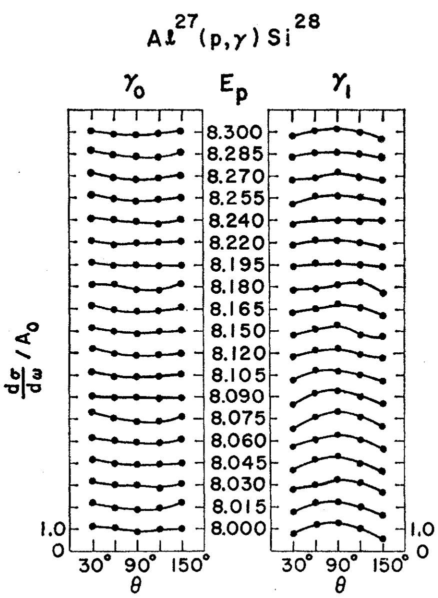



Fig. 6. Some angular distributions from the $Al^{27}(p,\gamma)Si^{28}$ reaction.

Some trends in the $(\gamma,p_0)$ yields are discernible in spite of the variations in the individual cases. One such trend is that the relative $(\gamma,p_0)$ yield decreases with increase in the atomic number. This effect may be attributed to the greater complexity of heavier nuclei, because of which the states excited in the giant resonance have a greater variety of possible modes of decay. With more decay modes available, any particular mode (in this case, the emission of a proton to leave the nucleus in its ground state) is less prominent. Another observed regularity is that the integrated $(\gamma_1,p_0)$ yield is almost always less than the corresponding integrated $(\gamma_0,p_0)$ yield. This effect can be explained on the basis of the simplest form of the independent-particle model, wherein a nucleus in its ground state is pictured as having all its nucleons in their lowest-energy orbits. In this model, the removal of a single nucleon from a nucleus in its ground state is likely to yield the next-lighter nucleus in its ground state. On the other hand, an excited state contains at least one nucleon in some higher orbit, and thus removal of a single nucleon is less likely to leave the residual nucleus in its ground state. These and other trends in the integrated yields are discussed in more detail elsewhere (*12*).

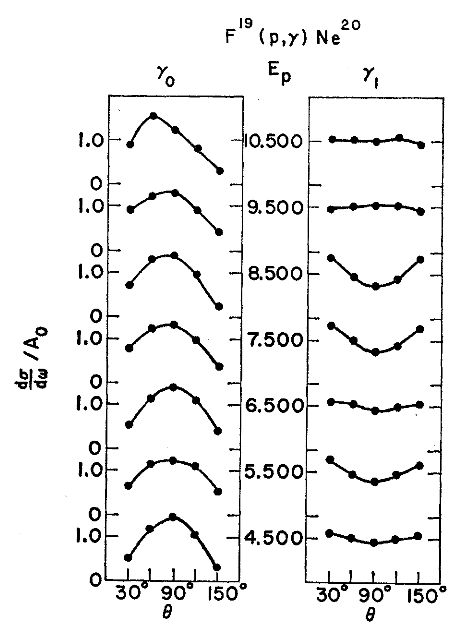



Fig. 7. Sample angular distributions from the $F^{19}(p,\gamma)Ne^{20}$ reaction.

Transitions to excited states higher than the first have been observed (*5, 12, 13*) in proton capture by $F^{19}$, $Na^{23}$, and $Al^{27}$; but the only case for which a giant resonance, associated with one of these higher states, has been indicated is capture by $Al^{27}$. At the upper end of the available range of proton energies (proton energies of about 12 Mev, corresponding to an excitation energy of 23 Mev in the compound nucleus $Si^{28}$) we observed what appeared to be the beginning of a giant resonance associated with the second or third excited states of $Al^{27}$, or with both. (These two states are only 360 kev apart, and therefore the gamma rays feeding them cannot be separated.) It is very possible that giant resonances, associated with the higher excited states of the other nuclides, are at too high an energy to have been observed in the proton-capture experiments; on the other hand, other factors (*12*) may be responsible for the failure to observe them in proton capture.

Since the fine structure observed in the $(p,\gamma)$ yield curves is primarily a reflection of the properties of the compound nucleus, similar structure would be expected if it were possible to measure gamma-ray absorption with similar energy resolution. However, the fluctuations would probably be less apparent because the energy of the absorbed gamma ray can be reemitted in several different ways (for example, by emission of a proton, which would leave the final nucleus in one or another of its excited states, or by neutron emission). Since these alternative decay modes are uncorrelated, their sum would show less-violent structure. In contrast, for gamma rays of each energy there is only a single mode of proton capture.

### Measurements of Angular Distributions

The angular distributions of $\gamma_0$ and $\gamma_1$ from proton capture by $B^{11}$, $F^{19}$, $Na^{23}$, and $Al^{27}$ have been measured at Argonne National Laboratory, (*5, 9, 12, 13*); those from proton capture by $H^3$, $N^{15}$, and $P^{31}$ have been measured elsewhere (*14, 16, 17*); some representative data appear in Fig. 6. The most striking result is that the angular distributions are nearly independent of the energies of the incident protons. In the study of the $Al^{27}(p,\gamma)$ reactions, angular distributions were taken at 15-kev intervals throughout each of several energy ranges scattered throughout the giant-resonance region; in all, 120 angular distributions were taken. Even at the energies marked by strong fluctuations in the yield curve, the angular distributions did not vary greatly.

The angular distribution of a nuclear reaction product can be expressed as a sum

$$W(\theta) = \sum_{n \geqslant 0} A_n \cos^n \theta \qquad (1)$$

where $\theta$ is the angle between the beam direction and the direction of the outgoing reaction product. The number of terms in the sum is greater by one than the smallest of three quantum numbers—the quantum number specifying (i) the angular momentum of the incident proton, (ii) the spin of the compound nucleus in its excited state, or (iii) the angular momentum carried off by the outgoing radiation. Odd-$n$ terms in the angular distribution are due to interference between states of opposite parity in the compound nucleus. If the reaction product is an electric-dipole gamma ray, the situation expected for

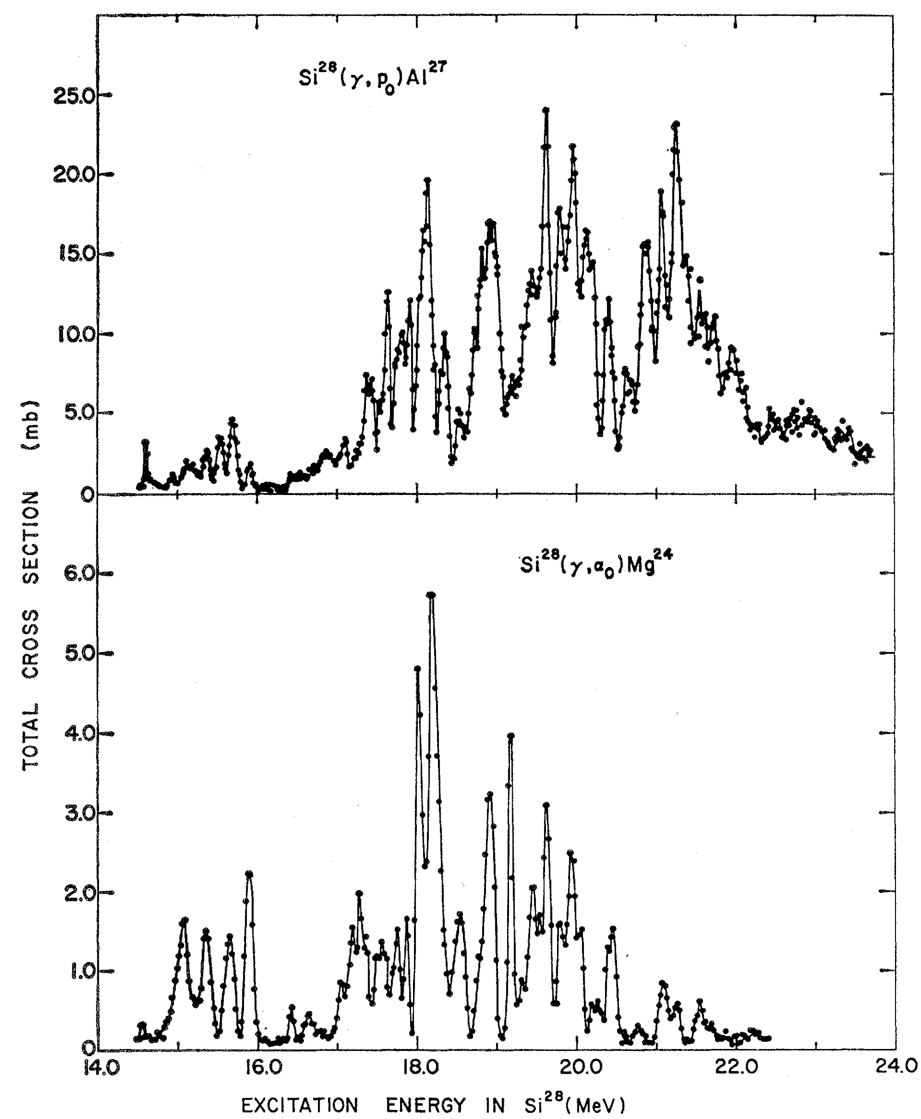



Fig. 8. Comparison of the $Si^{28}(\gamma,\alpha_0)$ and $(\gamma,p_0)$ cross sections. The data are from the radiative-capture experiments, but they have been converted to the inverse reactions by use of the principle of detailed balance.

capture through the giant resonance, the angular distribution can be written as

$$W(\theta) = 1 + A_2 \cos^2 \theta$$

In the $Al^{27}(p,\gamma)$ reaction, we found $A_2 \approx 0$ for $\gamma_0$ and $A_2 \approx -0.45$ for $\gamma_1$.

While the angular distributions show little variation with energy for any particular giant resonance, both the $\gamma_0$ and $\gamma_1$ angular distributions vary greatly from nucleus to nucleus. In Fig. 7, which shows some of the data from the $F^{19}(p,\gamma)$ reaction (*12*), one may see that the angular distributions are quite different from those observed in the $Al^{27}(p,\gamma)$ reaction. The $F^{19}(p,\gamma)$ angular distributions are not quite symmetric about 90 degrees, the yield usually being greater in the forward direction; this finding indicates the presence of odd-$n$ terms in the angular distributions.

The data are analyzed by use of a computer code that adjusts the coefficients $A_n$ in Eq. 1 to obtain a best fit to the data. The analysis of the $F^{19}(p,\gamma)$ angular distributions indicated that $A_1$ and $A_3$ were not zero and that their magnitude tended to increase with increase in energy. These odd-$n$ terms have been attributed to a small amount of electric quadrupole ($E2$) radiation interfering with the dominant $E1$ component. Since the interference term is proportional to the amplitude of the $E2$ component and the amplitude is proportional to the square root of the intensity, a small $E2$ intensity can give a sizable interference term: for example, if the $E2$ component constitutes 1 percent of the total intensity, the coefficients of the associated interference terms can be about 10 percent. The coefficient $A_4$, which is proportional to the $E_2$ intensity, has been indistinguishable from zero in all reactions yet studied.

The angular distribution is determined by the spins of the initial state, the compound-nucleus state, and the final state, by the angular momentum of the incident proton, and by the multipolarity ($E1$, $E2$, and so on) of the gamma radiation. Where the final state has zero spin, as for $\gamma_0$ here, the multipolarity of the radiation fixes the spin of the compound-nucleus state. Since the gamma radiation is primarily $E1$, the compound-nucleus states that radiate $\gamma_0$ must have spin and parity $1^-$, and thus the only variable is the angular momentum that is brought in by the incident proton. (The small $E2$ component is neglected; interference between $E1$ and $E2$ components cannot affect the even-$n$ terms in the angular distribution.)

The constancy of the angular distributions thus implies that the angular momentum of the incident proton remains nearly constant over the entire giant-resonance region; more formally, the angular momentum of the incident proton is in fact the vector sum of its orbital angular momentum relative to the target nucleus and its spin. Therefore, constant angular distributions require that the quantum numbers of the incident proton remain the same. The quantum numbers of the nucleons that compose the target nucleus are not, of course, affected by the energy of the incident proton. The conclusion therefore is that the configuration of the entire system, target nucleus and incident proton, changes little throughout the giant-resonance region, and one can say that this configuration describes the giant-resonance state.

No theory has yet successfully reproduced the constant angular distributions. In the generally accepted theoretical picture, the giant resonance is described (*18*) as the sum of a (small) number of particle-hole states (states in which a single nucleon is excited to the next-higher major nuclear shell, leaving a hole in one of the shells that was filled when the nucleus was in its ground state). Such a picture has very successfully explained the gross features of the giant resonance; in fact it accounts for the observation that proton radiative capture proceeds primarily by way of a direct interaction. However, this theoretical model indicates that the various particle-hole states have somewhat different energies; therefore the configuration of the giant resonance should change with energy, and consequently the angular distributions for the $(p,\gamma)$ reaction should vary with energy. This theoretical prediction is clearly contrary to the experimental result, and this discrepancy is still unresolved.

## Alpha-Capture Experiments

The giant resonances in some nuclei can also be studied with other reactions: in particular, alpha capture by $Mg^{24}$, $Mg^{26}$, and, to a lesser extent, $Si^{28}$ has been investigated (*19*). The $Mg^{24}$-$(\alpha,\gamma)$ reaction leads, of course, to the same nucleus that the $Al^{27}(p,\gamma)$ reaction leads to. The ground-state gamma rays for these two reactions are compared in Fig. 8. In order to present a more valid comparison, the principle of detailed balance has been used to convert each cross section to its inverse: that is, the yield curves for $Si^{28}(\gamma_0,p_0)$ and $Si^{28}(\gamma_0,\alpha_0)$ are shown. In this way statistical factors and other factors associated with phase space are eliminated, and the reactions are directly comparable. Although the $(\gamma,\alpha)$ yield does appear to follow a giant-resonance envelope, the envelope is somewhat distorted as compared to what is observed in the $(\gamma,p)$ reaction. The average $(\gamma,\alpha)$ cross section is much the smaller, and the fluctuations in the yield curve are correspondingly greater. Indeed, statistical analyses of the $(\alpha,\gamma)$ data have shown that this reaction proceeds mainly by way of the compound nucleus (*19*). Thus one may conclude that the direct interaction is suppressed in alpha capture, and it is this suppression that accounts for the reduced yield.

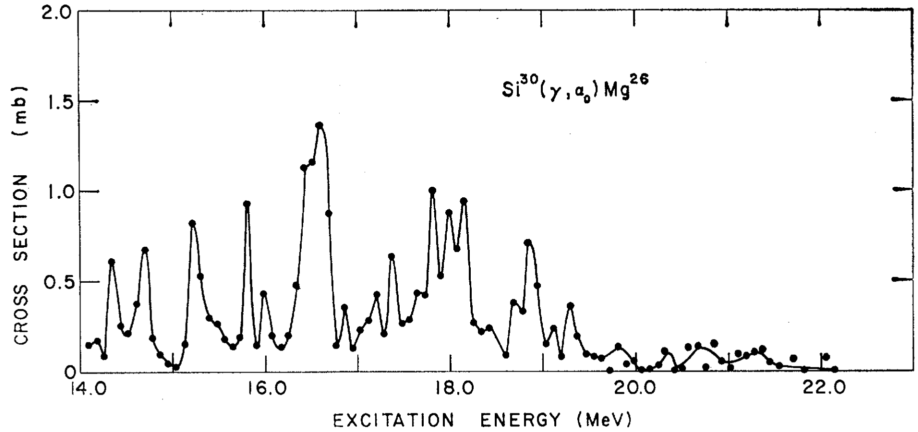



Fig. 9. Cross section as a function of energy for the $Si^{30}(\gamma,\alpha_0)Mg^{26}$ reaction, as deduced from data on radiative capture.

It may be argued that the smaller $(\gamma,\alpha)$ yield is due to the isotopic-spin selection rule. Space limitations prevent extensive discussion of isotopic spin here; suffice it to say that the notion arises because the nuclear forces have been shown to be independent of the charge—except for familiar electromagnetic effects. Thus the neutron and the proton can be considered to represent two states of a single kind of particle, the nucleon. The formalism developed around this idea introduces a vector called the isotopic spin. Each nucleon has an isotopic spin equal to ½; and, when these isotopic-spin vectors are projected on an axis of quantization, the neutron and proton are distinguished by having projections in opposite directions. The isotopic-spin vector is then treated like an angular momentum and, without my giving details, it follows that the states of a nucleus have a definite isotopic spin (designated $T$) which is in the range

$$\tfrac{1}{2}(A-2Z) \leqslant T \leqslant \tfrac{1}{2}A$$

Our knowledge of nuclear forces leads to the conclusion that states of lower isotopic spin are at lower energy; therefore the low-lying states in a self-conjugate nucleus (that is, in a nucleus having equal numbers of neutrons and protons) has $T = 0$. Moreover, an isotopic-spin selection rule states that, in a self-conjugate nucleus, $E1$ radiation takes place only between states differing by one unit of isotopic spin (*20*); the states that make up the giant resonance must therefore have $T = 1$. In particular, both the alpha particle and $Mg^{24}$ are self-conjugate nuclei, each with $T = 0$; thus, if electromagnetic effects are neglected, they could not combine to form the $T = 1$ giant resonance in $Si^{28}$. However, in a real nucleus the Coulomb effects spoil the charge independence, and therefore isotopic-spin selection rules are never completely obeyed. Thus, some alpha capture through the giant resonance in $Si^{28}$ is possible. In fact, current theory is inadequate for a direct estimate of how much of the hindrance of the $(\gamma,\alpha_0)$ yield can be attributed to the operation of the isotopic-spin selection rule.

This question has been answered experimentally, however, by study (*19*) of the $Mg^{26}(\alpha,\gamma)Si^{30}$ reaction. Neither $Si^{30}$ nor $Mg^{26}$ is self-conjugate, since each has two more neutrons than protons. Hence dipole radiation is permitted beween two states having the same isotopic spin. In fact, the giant resonance in a non-self-conjugate nucleus should split into two parts—one with the isotopic spin of the ground state (written $T_<$), the other with one unit more of isotopic spin ($T_>$). The part with $T_<$ can be fed by alpha capture, and thus the selection rules of isotopic spin permit observation of the giant resonance. However, as shown in Fig. 9, the yield from the $Si^{30}(\gamma,\alpha_0)Mg^{26}$ reaction, the inverse of the $Mg^{26}(\alpha,\gamma)$, is even less than for the isotopic-spin-forbidden $Si^{28}(\gamma,\alpha_0)Mg^{24}$ reaction. This fact shows that it is not the selection rules of isotopic spin that inhibit alpha capture through the giant resonance.

## Summary and Conclusions

The data on radiative capture through the giant resonance have led to a model in which the capture is pictured as proceeding through a single broad (and therefore short-lived) state that can be called the giant-resonance state. This state is the one formed directly upon capture of a proton, and hence most of the capture radiation is emitted quickly in the direct-interaction mode. Some of the energy that is contained in the giant-resonance state is shared with the more-complicated states of the compound nucleus (that is, with states having many excited nucleons). This sharing, in turn, gives rise to the fine structure that is observed within the giant-resonance envelope. The constant angular distributions that are observed throughout the giant-resonance region support the single-state picture of the giant resonance.

The simple model appears to account for the main features of the data, and at least qualitatively accounts for the variation in yield for proton capture through various giant resonances. Further information about the giant-resonance state is obtained from the alpha-capture data and from the characteristic angular distributions of the various gamma rays. However, there remains the difficulty that the shell-model picture predicts a varying angular distribution—contradicting the experimental result. Work in this field is being continued in the hope of resolving this difficulty and of extending the model to provide a more complete picture of this important nuclear phenomenon.

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# Population Policy: Will Current Programs Succeed?

Grounds for skepticism concerning the demographic effectiveness of family planning are considered.


Kingsley Davis


Throughout history the growth of population has been identified with prosperity and strength. If today an increasing number of nations are seeking to curb rapid population growth by reducing their birth rates, they must be driven to do so by an urgent crisis. My purpose here is not to discuss the crisis itself but rather to assess the present and prospective measures used to meet it. Most observers are surprised by the swiftness with which concern over the population problem has turned from intellectual analysis and debate to policy and action. Such action is a welcome relief from the long opposition, or timidity, which seemed to block forever any governmental attempt to restrain population growth, but relief that "at last something is being done" is no guarantee that what is being done is adequate. On the face of it, one could hardly expect such a fundamental reorientation to be quickly and successfully implemented. I therefore propose to review the nature and (as I see them) limitations of the present policies and to suggest lines of possible improvement.

## The Nature of Current Policies

With more than 30 nations now trying or planning to reduce population growth and with numerous private and international organizations helping, the degree of unanimity as to the kind of measures needed is impressive. The consensus can be summed up in the phrase "family planning." President Johnson declared in 1965 that the United States will "assist family planning programs in nations which request such help." The Prime Minister of India


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