Giant electric resonances in ^{58}Ni studied by alpha particle capture*

L. Meyer-Schützmeister, R. E. Segel,† K. Raghunathan,† P. T. Debevec,‡ W. R. Wharton,§ L. L. Rutledge,† and T. R. Ophel¶
Argonne National Laboratory, Argonne, Illinois 60439

(Received 17 June 1977)

The reaction $^{54}Fe(\alpha,\gamma)^{58}Ni$ has been studied for $7.6 \geq E_\alpha \geq 12.8$ MeV. Seventeen angular distributions have been measured in this energy region making it possible to separate the $E2$ strength from the $E1$ strength. The $E1$ cross section reaches a maximum at about the expected energy. A compact $E2$ resonance was observed which agrees quite well with the one measured by inelastic α scattering, with a peak cross section at about 16 MeV and a width of ~ 3 MeV(half width at half maximum). The observed $E1$ strength equals 0.9% of the isospin allowed $E1$ sum rule. The measured $E2$ strength, however, equals 4.3% of the isoscalar $E2$ sum rule, which is about the same as the fraction of the total $E1$ strength in ^{58}Ni excited by proton capture. Assuming only statistical processes and applying the Hauser-Feshbach formula to calculate the total γ absorption from the measured particle-capture cross sections leads to the conclusion that the (α,γ) reaction exciting the isoscalar giant quadrupole resonance and the (p,γ) reaction exciting the giant dipole resonance must have direct components.

[NUCLEAR REACTIONS $^{54}Fe(\alpha,\gamma_0)^{58}Ni$ (g.s.). $d\sigma/d\Omega=f(E_\alpha,\theta)$ for $7.6 \leq E_\alpha \leq 12.8$ MeV. Target $\approx$1 mg rolled ^{54}Fe foil. Deduced $\sigma(\gamma,\alpha_0)$ for GDR and GQR in ^{58}Ni. Concluded from Hauser-Feshbach formalism $\sigma(\gamma,\alpha_0)$ into GQR of ^{58}Ni contains direct reaction components.]

I. INTRODUCTION

Recent investigations of inelastically scattered protons,[1] deuterons,[2] ^{3}He particles,[3] and α particles from ^{58}Ni have shown a resonance at about 16-MeV excitation energy which overlaps with the low-energy part of the giant electric dipole resonance (GDR).[5,6] However, for the study of the new resonance the (α,α') and (d,d') reactions seem to be of particular value since for both reactions the excitation of the interfering GDR should be strongly inhibited due to isospin selection rules. Measured angular distributions of the inelastically scattered α particles and deuterons together with distorted wave Born approximation (DWBA) calculations have indicated that this resonance is the giant electric guadrupole resonance (GQR) and that it contains about 50% of the isoscalar GQR sum rule.[5,6] Conservation of angular momentum and isospin permit observation of this resonance in α-particle capture. Although the α-capture process suffers from low cross sections and tends to be dominated by the GDR it has for a spin zero initial and final state the great advantage that the strengths of competing multipoles can be uniquely determined. Isospin selection rules permit the population of only the $T_<$ part of the $E1$ and $E2$ resonance and the objective of the present work was to measure both. The measured $E2$ strength should be directly comparable to the $E2$ resonance observed in inelastic α and d scattering. The measured $E1$ strength can be compared to the $E1$ resonance which is observed in photonuclear reactions in particular the $^{58}Ni(\gamma,p_0)$ reaction. This latter reaction excites the $T_<$ as well as the $T_>$ part of the GDR and while a comparison of proton and α capture is interesting it is questionable if it can be used to identify the two isospin components of the $E1$ resonance.

α capture through the giant resonance region has been studied earlier in a few cases[7-10]—mostly light nuclei. In all cases there was an appreciably larger cross section for the excitation of the GDR than for that of the GQR. This is even true for self-conjugate nuclei for which the α capture into the GDR is isospin forbidden.[7,8] However, usually only about 1% of the $E1$ sum rule is excited by the reaction (γ,α_0) while in the same reaction 4–14% of the isoscalar $E2$ sum rule is observed. In a few cases statistical analysis of yield curves have indicated[7,8,10] that the GDR is excited by α capture mainly through compound nuclear components. However, according to a recent observation[8] the α-particle capture into the GQR in ^{26}Mg might occur to a great extent via noncompound processes. These noncompound components of the reaction might make the α capture a valuable tool for the investigations of the GQR and the question of whether these direct components are also strong and observable in other, and particularly heavier, nuclei arises. In the present investigations an attempt is made to determine if indeed such direct processes are indicated for the ^{54}Fe(α, γ_0) reaction leading into the isoscalar GQR of ^{58}Ni.

II. EXPERIMENTAL PROCEDURES

The experimental technique was similar to the one used in earlier studies of proton[11] and α[7] capture. Self-supporting ^{54}Fe targets enriched to 97.7% in ^{54}Fe, were rolled to a thickness of 1.1 mg/cm^2 and bombarded by α particles with energies in the range of 7.6 to 12.8 MeV. The emerging γ rays were detected by a large NaI(Tl) crystal of 25-cm diam and 30-cm length. A γ-ray pulse-height spectrum obtained at an angle of 90° to the beam direction and at an α energy of 10 MeV is shown in Fig. 1. The γ rays populating the ground state and the first excited state of ^{58}Ni, γ_0 and γ_1, respectively, are observed but only the γ_0 transition is sufficiently well separated from the background to be measured with reasonable accuracy.

The γ_0 yield was extracted from the observed pulse height spectra.[7] The absolute cross sections were determined by measuring the efficiency of the detector system (see Table I) using the narrow 15.07-MeV resonance in ^{13}N excited in the bombardment of ^{12}C by 14.23-MeV protons. This resonance emits 15.07-MeV γ rays whose yield per proton has been carefully measured.[12] The efficiency is assumed to be energy independent over the range from 13.5–18.5 MeV since the mean free path of a 15-MeV γ ray equals about 6.7 cm in NaI and changes at most ±5% over the studied energy region.

As a check the γ-ray yield of the ^{59}Co$(p, \gamma_0)^{60}$Ni reaction at a proton energy of 7.6 MeV was measured at $\theta = 90°$ using a self-supporting 1.2-mg/cm^2 ^{59}Co target. According to Ref. 13 these γ rays are produced with an averaged differential cross section of $d\sigma/d\Omega = 0.58$ μb/sr. The ^{54}Fe$(\alpha, \gamma_0)^{58}$Ni cross section normalized to this value agrees very well with the one obtained by normalizing to the ^{12}C$(p, \gamma_0)^{13}$N reaction (see Table I), and it is believed that the absolute cross sections in the present work are accurate to ±20%. At $E_\alpha = 10$ MeV, $\theta = 90°$ the cross section for the ^{56}Fe$(\alpha, \gamma_0)^{60}$Ni reaction was found to be 0.56 ± 0.15 μb/sr (Table I) which is about a factor of 2 smaller than that previously reported.[10] The previous work was done with thin targets. The published 90° ^{56}Fe$(\alpha, \gamma_0)^{60}$Ni excitation function was averaged between 10 and 9.7 MeV from which a value of $d\sigma/d\Omega = 1.2$ μb/sr was obtained. While the reason for this discrepancy is not known, the cross checks that have been made here (Table I) gives confidence that the present values are correct.

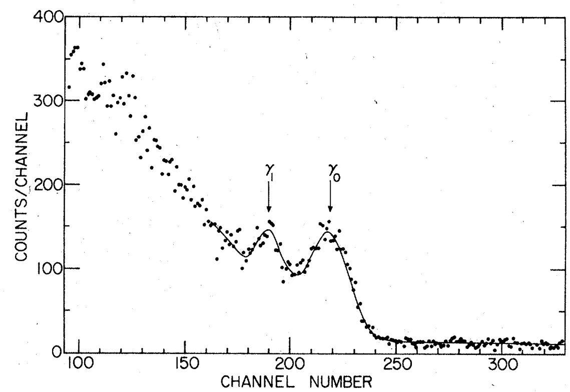

FIG. 1. The γ spectrum of the ^{54}Fe$(\alpha, \gamma_0)^{58}$Ni reaction for $E_\alpha = 10$ MeV and $\theta = 90°$.

III. EXPERIMENTAL RESULTS

A unique multipole decomposition of α particle capture into a $J^\pi = 0^+$ target nucleus populating a $J^\pi = 0^+$ final state by γ emission can be made by measuring angular distributions of the emitted γ rays. Assuming only $E1$ and $E2$ contributions, the angular distributions can be written as

$$W(\theta) = (1/4\pi)\{\sigma(E1) + \sigma(E2) - [\sigma(E1) - 0.71\sigma(E2)]P_2 - 1.71\sigma(E2)P_4 - 2.68[\sigma(E1)\sigma(E2)]^{1/2} \times \cos\theta_{12}(P_1 - P_3)\}, \quad (1)$$

where $\sigma(E1)$ and $\sigma(E2)$ are the cross sections for exciting the $E1$ and $E2$ resonances, respectively,

TABEL I. Determination of absolute cross sections of the ^{54,56}Fe$(\alpha, \gamma_0)^{58,60}$Ni reactions by using the known reactions ^{12}C$(p, \gamma_0)^{13}$N and ^{54}Co$(p, \gamma_0)^{60}$Ni for normalization (see text).

Reaction	E_α (MeV)	θ (deg)	Target thickness (mg/cm^2)	$d\sigma/d\Omega$ (μb/sr) normalized to ^{12}C$(p, \gamma_0)^{13}$N [a]	^{59}Co$(p, \gamma_0)^{60}$Ni [b]
^{54}Fe$(\alpha, \gamma_0)^{58}$Ni	10.0	90	1.1	1.3 ±0.2	1.2 ±0.2
^{56}Fe$(\alpha, \gamma_0)^{60}$Ni	10.0	90	1.0	0.56 ±0.15	0.53 ±0.15

[a] Reference 12.
[b] Reference 13.

and θ_{12} is defined as the phase difference between the two modes of excitation.

Twelve angular distributions of the $^{54}Fe(\alpha, \gamma_0)$ reaction have been obtained by measuring the differential cross section at either five or seven angles. According to Eq. (1) this allows us to deduce the ratio $R = \sigma(E2)/\sigma(E1)$ from the coefficients of P_2 as well as of P_4 independently. Five of the angular distributions, however, had been measured using only three angles 45°, 90°, and 135°. In this case the values for $\sigma(E1)$ and $\sigma(E2)$ are obtained by using another version of Eq. (1)

$$W(\theta) = A \sin^2\theta + B\sin^2 2\theta + C\sin\theta \sin 2\theta \qquad (2)$$

with $\sigma(E1) = 8\pi A/3$; $\sigma(E2) = 32\pi B/15$ and $\cos\theta_{12} = C/2(AB)^{1/2}$.

In Fig. 2 three of the measured angular distributions are shown. The open circles indicate the measured values, the solid lines Legendre polynomial fits. In all cases the maximum yield is at 90° indicating that $\sigma(E2)$ is much smaller than $\sigma(E1)$. Checks to verify that the observed deviation from the pure $E1$ angular distributions are real were made by performing two additional measurements. Firstly, asymmetries of the apparatus were checked by measuring an angular distribution for a radioactive γ source placed at the target position and, secondly, the effect of pileup was determined by measuring the yield of the (α, γ_0) reaction with different beam currents. In neither case was a significant error found.

The uncertainty in the determination of R can be estimated by comparing the results from different runs taken at the same energies or at energies whose spacing is substantially less than 300 keV, the target thickness. These results are shown in Fig. 3. From the observed fluctuations in the values of R for closely spaced energies the error in

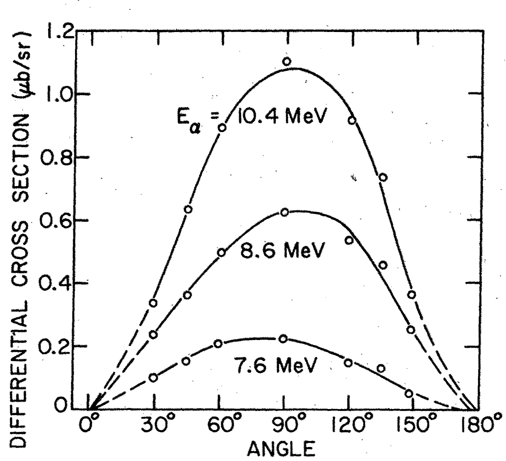

FIG. 2. Angular distributions of the $^{54}Fe(\alpha, \gamma)^{58}Ni$ reaction.

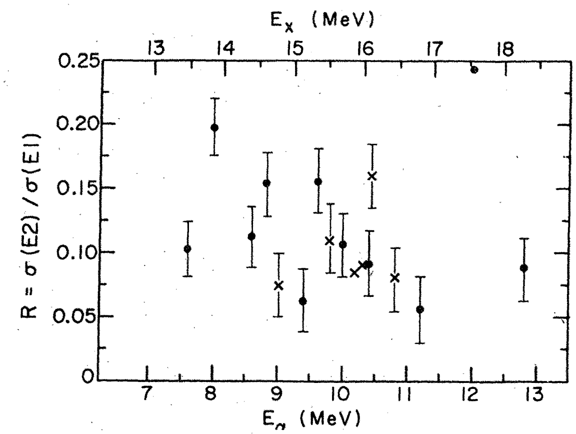

FIG. 3. The ratio $R = \sigma(E2):\sigma(E1)$ as function of energy. The estimated error is indicated. Crosses indicate angular distribution measurements with only three angles.

R is estimated to be $\Delta R = 0.025$. Within this error the ratio $R = \sigma(E1)/\sigma(E2)$ is energy independent and equals 0.11 ± 0.025.

Since the ratio of $E2$ to $E1$ strength in the $^{54}Fe(\alpha, \gamma_0)^{58}Ni$ reaction changes little over the energy range studied both cross sections $\sigma(E1)$ and $\sigma(E2)$ must follow the energy dependence of the yield curve. In Fig. 4 all 90° yield curves, measured at different times and with different targets, all about 1 mg/cm² thick, are shown. They all are normalized to 1.30 μb/sr at $E_\alpha = 10.0$ MeV. Since the yield curve was taken at 90° it contains $E1$ radiation only; the fluctuation in yield for closely spaced energies are an indication of the experimental errors. The solid line is a guide for the

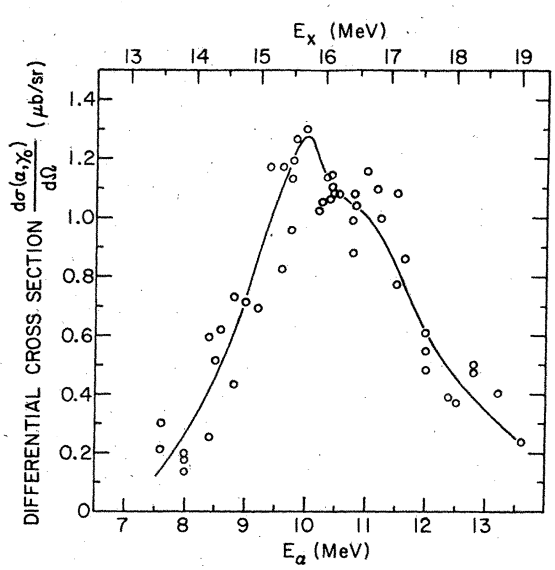

FIG. 4. Differential cross section of the $^{54}Fe(\alpha, \gamma_0)^{58}Ni$ reaction as function of energy. The measurements have been made at 90° for the incoming α beam.

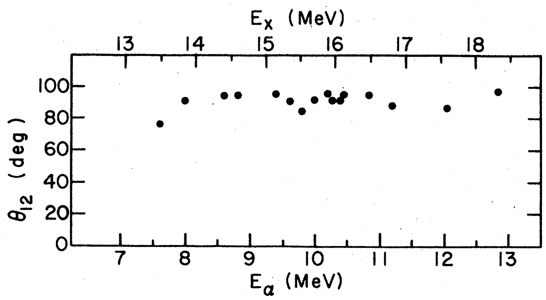

FIG. 5. The phase difference θ_{12}, defined in Eq. (1), and measured in the reaction ^{54}Fe$(\alpha,\gamma)^{58}$Ni as function of the energy.

eye and indicates a peaking of the measured cross section at about an α energy of 10 MeV or 15.7-MeV excitation energy in ^{58}Ni. Combining this result with the lack of variation in R leads to the result that over the measured energy range $E_x = 13.5-18.4$ MeV $\sigma(E1)$ as well as $\sigma(E2)$ have maximum cross sections at an excitation energy of about 15.7 MeV.

Finally, mention should be made of the phase differences θ_{12} which are deduced from the measured angular distribution [see Eqs. (1) and (2)] and plotted as function of the α-particle energy in Fig. 5. As in earlier (α,γ_0) experiments[7-10] they are close to 90° for the studied energy region. An interpretation of the vanishing interference term ($\cos\theta_{12}=0$) was given by Watson *et al.*[9] According to these authors at least one of the multipoles excited by the (α,γ) reaction consists of a great number of overlapping resonances, giving rise to so many interference terms that the average is close to zero when the target thickness is large compared to the width of individual resonances.

IV. DISCUSSION

The level scheme of ^{58}Ni is presented schematically in Fig. 6 as far as it is of interest to the present studies. The position of the GDR as measured by the reactions ^{58}Ni(γ,p) (Ref. 6) and ^{58}Ni(γ,n) (Ref. 5) is indicated. The expected, although experimentally not confirmed, isospin splitting into two components with $T_< = T_0 = 1$ and $T_> = T_0 + 1 = 2$ is also indicated. In addition, the isoscalar GQR as measured by inelastic α (Ref. 4) and d (Ref. 2) scattering is shown. Although the GQR and the GDR with $T=T_<$ overlap strongly, they can be studied separately in α capture.

A. Giant electric dipole resonance

The GDR has been studied by a number of photonuclear reactions—for detailed references see Ref. 5. Of these the ^{58}Ni(γ,p_0) reaction makes the

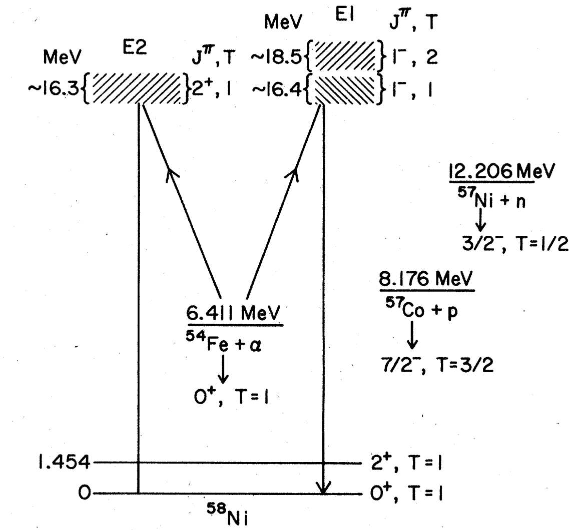

FIG. 6. Level scheme of ^{58}Ni. Indicated are the suggested GDR and GQR and the thresholds of the important open channels competing with the γ decay.

most interesting comparison. This reaction has been measured by the ^{58}Ni$(ee'p_0)$ process.[6] How well this method is able to measure the (γ,p_0) reaction can be tested in ^{60}Ni. In this nucleus both the ^{60}Ni$(ee'p_0)$ reaction[6] and the ^{59}Co(p,γ_0) reaction[13] have been studied. The results of the experiments agree quite well and seem to indicate that the $(e,e'p_0)$ reaction is equivalent to the (γ,p_0) reaction.

Both the ^{58}Ni(γ,p_0) and the ^{58}Ni(γ,α_0) cross sections are plotted in Fig. 7; the (γ,α_0) cross sections are obtained from the (α,γ_0) reaction by de-

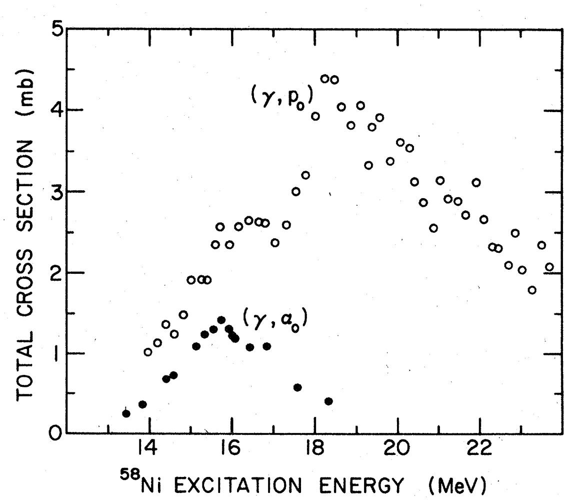

FIG. 7. The cross section of the ^{58}Ni(γ,α_0) is presented as function of the excitation energy in ^{58}Ni. The small contribution of the GQR is subtracted. For comparison the cross section of the ^{58}Ni(γ,p_0) (see Ref. 6) is shown.

TABLE II. Excitation of the GDR and of the isoscalar GQR by α and p capture.

	$E1$					$E2$	
	(γ,α_0)			(γ,p_0)		(γ,α_0)	
Nucleus	ΔE (MeV)	S^{E1} (%)	$S^{E1}(T_<)$ (%)	ΔE (MeV)	S^{E1} (%)	ΔE (MeV)	S^{E2}_{-2} (%)
^{24}Mg	14.6–20.6	0.33 [a]	Forbidden	15.5–23.0	3.3 [b]	12 –22.5	11.8 [a]
^{26}Mg	14.8–21.0	0.7 [a]	1.4			15.0–21.4	6.0 [a]
^{28}Si	14.5–21.5	1.2 [c]	Forbidden	14.5–23.0	13.9 [d]	14.5–21.5	14.5 [c]
^{30}Si	14.5–21.5	0.6 [c]	1.2				
^{58}Ni	13.5–18.3	0.45	0.9	14.0–23.7	4.0 [e]	13.5–18.3	4.3
^{60}Ni	13.8–22.7	0.9 [f]	1.35	14.3–23.0	2.5 [g]		

[a] Reference 8.
[b] Reference 14.
[c] Reference 7.
[d] Reference 15.
[e] Reference 6.
[f] Reference 10.
[g] Reference 13.

tailed balance. The comparison shows that the ^{58}Ni(γ,α_0) reaction excites a much smaller part the GDR than does the ^{58}Ni(γ,p_0) reaction and in particular that it sees only the low-energy part of the resonance. Since the (γ,α_0) reaction is isospin allowed only for the $T_<$ part of the GDR, it is tempting to assume that the measured (γ,α_0) cross section follows the distribution of the $T = T_< = 1$ component of the GDR in ^{58}Ni. However, this assumption is questionable since in several self-conjugate nuclei the isospin-forbidden (γ,α_0) reaction through the GDR has been found to be comparable in strength to what is observed in nearby nuclei where the reaction is isospin allowed (Table II). As mentioned earlier statistical analysis led to the conclusion that the (α,γ) reaction proceeds through the compound nucleus where the level spacing is small enough to allow strong isospin mixing. The observed decrease of $\sigma(\gamma,\alpha_0)$ with increased excitation energies above $E_x = 16$ MeV might well be due to the great number of open channels which become available (see Sec. IV C) and which compete with the (γ,α_0) channel.

In Table II the total strengths $\int \sigma dE$ of both the reaction (γ,α_0) and (γ,p_0) are compared for a number of nuclei with the classical sum rule for the GDR.

$$S^{E1} = \int \sigma(\gamma, -)dE = 60NZ/A\,(\text{mb MeV}) , \qquad (3)$$

where $\sigma(\gamma,-)$ represents the total γ absorption cross section leading into the GDR.

Isospin selection rules do not inhibit the (γ,p_0) reaction while the (γ,α_0) reaction is forbidden in self-conjugate nuclei. However, in non-self-conjugate nuclei the (γ,α_0) reaction is allowed to populate the $T = T_<$ component of the sum rule $S^{E1}(T_<)$, which is smaller than S^{E1} by the factor $T_0/(T_0+1)$. In Table II the energy integrated cross section of the (γ,p_0) and (γ,α_0) reactions in various nuclei are given in percentage of the sum rule S^{E1}; also shown are the cross sections in percentage of $S^{E1}(T_<)$, the isospin allowed part of the sum rule for the (γ,α_0) reaction in non-self-conjugate nuclei. Table II indicates that the cross sections for the (γ,α_0) reaction exciting the GDR in ^{24}Mg and ^{28}Si are comparable to those in neighboring non-self-conjugate nuclei suggesting isospin mixing in both nuclei with mixing being greater in ^{28}Si.

In all cases shown in Table II the (γ,p_0) reaction excites the GDR to a larger degree than does the (γ,α_0) reaction with the difference being the smallest in ^{60}Ni. However, the ^{60}Ni(γ,α_0) cross sections were taken from Ref. 10 and it is noted above that at 10 MeV the cross section for ^{56}Fe$(\alpha,\gamma_0)^{60}$Ni was found to be by a factor of 2 smaller than that given in Ref. 10.

The stronger excitation of the GDR by p capture than by α capture agrees well with earlier observations which show that the (p,γ_0) occurs largely through direct or semidirect processes.[11,15] These nonstatistical processes are expected to increase the cross section of the dipole excitation over that proceeding only through pure statistical reaction process.

B. Giant electric quadrupole resonance

The cross section of the $E2$ component of the ^{58}Ni(γ,α_0) reaction as function of the excitation energy is presented in Fig. 8. Although the experimental errors are large, about 20%, the data indicate a compact resonance with a width of about 3 MeV full width at half maximum and a maximum yield at an excitation energy of about 15.7 MeV. This agrees well with the energy of $E_x = 60/A^{1/3}$ (MeV) (see Fig. 8), which was predicted for an isoscalar quadrupole giant resonance.[16] However, no such well-defined resonance with a maximum cross section at an excitation energy of $60/A^{1/3}$

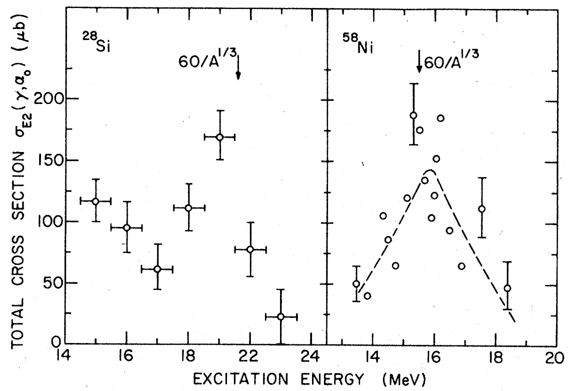

FIG. 8. The cross section of the ^{58}Ni(γ, α_0) reaction exciting only the GQR is shown as function of the energy. For comparison an older measurement of the reaction ^{28}Si(γ, α_0)^{24}Mg (Ref. 7) had been partially reanalyzed for a more detailed extraction of the $E2$ strength.

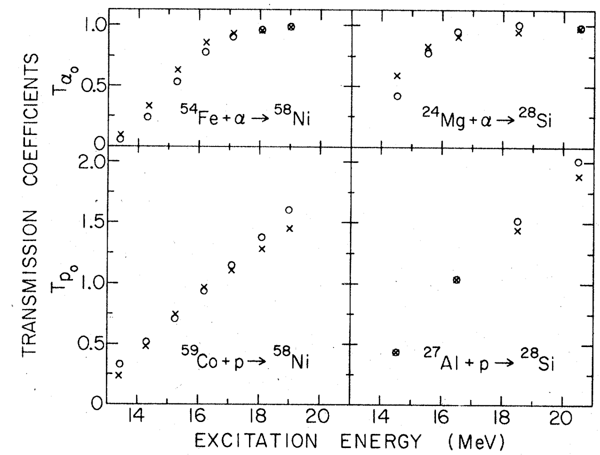

FIG. 9. Transmission coefficients for the emission of an α particle or a proton to the ground state of the final nucleus are shown as function of the excitation energy in ^{58}Ni or ^{28}Si. The crosses represent the decay of the GDR, the open circles that of the GQR.

MeV is observed in the other nuclei that have been studied by α capture, examples are ^{60}Ni (Ref. 10) and ^{40}Ca (Ref. 9). The $E2$ yield of the ^{28}Si(γ, α_0) reaction is also shown in Fig. 8 for comparison. While an enhanced cross section might be indicated at the expected energy but, different from ^{58}Ni, the $E2$ strength does not rapidly fall off with decreasing excitation energy. As illustrated in Fig. 9, the reason for this difference between ^{28}Si and ^{58}Ni might be partially due to different Coulomb barriers and thresholds in the two (γ, α_0) reactions.

In Fig. 9 the transmission coefficients T_{α_0} and T_{p_0} are shown as function of the excitation energy for the GQR and GDR states. They were obtained by DWBA calculations using the ABACUS code[17] with optical potentials shown in Table III. All possible l and s combinations are included. For the α emission only one such combination is possible: $s=0$ and $l=2$ for the GQR and $l=1$ for the GDR, but for proton emission several l-s combinations are allowed. For ^{58}Ni the T_{α_0} decreases steadily when the excitation energy in the GQR is changed from 16 to 14 MeV. Hence, the decrease of $\sigma_{E2}(\gamma,\alpha_0)$ in this energy region is not necessarily due to a falloff in the $E2$ strength but may also be due to Coulomb barrier effects. In contrast to ^{58}Ni the transmission coefficient T_{α_0} for the α capture into ^{28}Si does not show a strong energy dependence over the measured range of excitation energies 15 MeV$<E_x<$20 MeV (Fig. 9). Consequently in ^{28}Si the measured $E2$ strength should be rather unperturbed by Coulomb barrier effects.

It should be pointed out that the $E1$ strength in ^{58}Ni at excitation energies between 14 and 16 MeV displays a similar energy dependence in α and in proton capture (Fig. 7). Since the transmission coefficient T_{p_0} for the GDR in ^{58}Ni shows an energy dependence similar to T_{α_0} in the energy range from E_x= 14–16 MeV, the $E1$ strength measured by p capture might also be strongly perturbed by Coulomb effects. However, photonuclear measurements of the reaction ^{58}Ni(γ,n) indicate that indeed the $E1$ strength decreases rapidly from E_x= 16 to 14 MeV.

For a number of nuclei the total $E2$ strength is

TABLE III. Optical potentials used in the calculation of the transmission coefficients T_α, T_p, and T_n. The definition of the parameters are those of Ref. 20.

Reactions	V		a_0	W	r_W	a_W				Reference
^{54}Fe + α	183.7	1.4	0.564	26.6	1.4	0.564				18
^{24}Mg + α, ^{26}Mg + α	190.8	1.43	0.608	9.91	1.78	0.390				19
Reactions	V	r_0	a_0	W_D	r_D	a_D	V_{so}	r_{so}	a_{so}	
^{57}Co + p, ^{27}Al + p, ^{29}Al + p	53.3–0.55E	1.25	0.65	13.5	1.25	0.47	7.5	1.25	0.47	20
^{57}Ni + n, ^{27}Si + n, ^{29}Si + n	47.01–0.267E–0.0018E^2	1.322	0.66	9.52–0.053E	1.266	0.48	7.0	1.1	0.75	20

presented in Table II in comparison with the almost model independent energy weighted $E2$ sum rule

$$SR_{-2}^{E2} = \int \sigma(\gamma, -)dE/E^2 = 0.22Z^2/A^{1/3}(\mu\text{b MeV}^{-1}) , \quad (4)$$

where $\sigma(\gamma, -)$ represents the total γ absorption cross section into the isoscalar $E2$ resonance. Table II shows that in all cases the (γ, α_0) reaction is much more effective in exciting the GQR than the GDR and populates the GQR percentagewise as strongly as the (γ, p_0) reaction populates the GDR. This result may be taken as an indication that the (γ, α_0) reaction leading through the GQR has some direct or semidirect components as has been shown for proton capture into the GDR.

C. Statistical calculations

Statistical analysis has shown that α capture into the GDR is predominatly a statistical process.[7,8,10] Hence, this reaction is able to populate the resonance reasonably well in the energy region in which it can compete with only a few open reaction channels. However, with increasing energy the number of available channels increases strongly and, since they compete in a statistical manner with the α_0 channel, the cross section $\sigma(\gamma, \alpha_0)$ decreases rapidly and ceases to strongly populate the GDR. However, as mentioned earlier the p capture does not proceed only through statistical processes but has a direct-reaction component which competes only with the few open channels which have a strong overlap with the configuration of the GDR. To these few selected channels the GDR decays via a direct or semidirect process. In most cases the p_0 emission represents one of these preferred channels, and it is for this reason that the (γ, p_0) reaction has been so successful for the investigations of the GDR.

As noted above α capture seems to be a useful reaction for the study of the distribution of quadrupole strength just as proton capture studies have proved fruitful in investigations of the dipole strength. The fact that the $l = 2$ α capture contains substantial direct and/or semidirect components can be demonstrated by first assuming that all p and α captures leading into the GD and GQ resonances occur only through statistical reactions. The Hauser-Feshbach formula[21] is then applied to both reactions (γ, p_0) and (γ, α_0) leading through the GDR and GQR

$$\frac{\sigma(\gamma, -)}{\sum_{i,x} T_{x_i}} = \sigma(\gamma, \alpha_0)/T_{\alpha_0} \text{ or } \sigma(\gamma, p_0)/T_{p_0} , \quad (5)$$

where $\sigma(\gamma, -)$ represents the total γ absorption cross section leading into either the GDR or the GQR; T_x stands for the transmission coefficient of particle x, protons, neutrons, and α particles are considered, and i indicates the summation over all combinations of spins s and orbital-angular-momentum transfers l allowed for each of the open channels. The quantity $\sigma(\gamma, -)$ is evaluated by using measured cross sections $\sigma(\gamma, \alpha_0)$ and $\sigma(\gamma, p_0)$ and calculated transmission coefficients (see Table III). For the sum $\sum T_{x_i}$ not only the known levels of the different final nuclei were taken into account, but for the higher excitation energies the level density formula of Ref. 22 was used.

The evaluation of the total γ-ray absorption cross section $\sigma(\gamma, -)$ as function of the excitation energy permits a comparison with the sum rules [Eqs. (3) and (4)]. Such a comparison is presented in Table IV for some (γ, α_0) and (γ, p_0) reactions leading into either the GD or GQ resonances. The calculated values $\int_{E1} \sigma(\gamma, -)dE$ and $\int_{E2} \sigma(\gamma, -)dE/E^2$ were evaluated from the measured $\sigma(\gamma, \alpha_0)$ and $\sigma(\gamma, p_0)$ cross sections, and they are given in percentages of the sum rules S^{E1} and S_{-2}^{E2}. For the GDR in ^{58}Ni and ^{30}Si only the $T = T_<$ component is considered which is isospin allowed for α capture and which equals half of the full $E1$ strength for both nuclei.

If the assumption that both resonances decay only by statistical processes would be correct, it is expected that the integrals $\int_{E1} \sigma(\gamma, -)dE$ and $\int_{E2} \sigma(\gamma, -)dE/E^2$ would exhaust 100% of the re-

TABLE IV. Comparison of the sum rule S^{E1}, $S^{E1}(T_<)$, and S_{-2}^{E2} with the total γ absorption cross sections $\sigma(\gamma, -)$ calculated by using the Hauser-Feshbach formalism and the measured capture cross section: $\sigma(\gamma, \alpha_0)$ and $\sigma(\gamma, p_0)$.

		$E1$				$E2$
		(γ, α_0)		(γ, p_0)		(γ, α_0)
Nucleus	ΔE (MeV)	S^{E1} (%)	$S^{E1}(T_<)$ (%)	S^{E1} (%)	$S^{E1}(T_<)$ (%)	S_{-2}^{E2} (%)
^{28}Si	14.5–21.0	18	Forbidden	135		170
^{30}Si	14.5–20.5		40			
^{58}Ni	13.5–18.3		30		120	150

spective sum rules. As Table IV shows, this is not true for any of the six cases. Instead the integral for α capture into the GDR of ^{58}Ni, ^{30}Si, and ^{28}Si shows smaller values, while that for α capture into the GQR and p capture into the GDR exceeds the sum rules. In particular: (a) The α capture into the GDR of ^{28}Si indicates an exhaustion of only 15% of the sum rule. This is easily explained by noting that the reaction is isospin forbidden and is only observed because of some isospin mixing in the compound nucleus. (b) The α capture into the GDR of ^{58}Ni exhausts only 30% of the $T_<$ sum rule, although the α capture is fully isospin allowed for this component. The reduction from 100% to 30% must have other causes. Firstly, the $T=T_<$ component might not be fully contained in the studied energy region but instead might be spread to higher excitation energies as is possibly indicated by the ^{58}Ni(γ,n) experiments of Ref. 5. Secondly, the GDR might be excited by direct or semidirect processes (γ,x), where x is anything other than an α particle. In this case the calculated value $\sigma(\gamma,-)$ (Eq. 5) would be too low since T_x would underestimate the (γ,x) contribution. (c) Proton capture into the GDR of ^{58}Ni indicates that $\int_{E1}\sigma(\gamma,-)dE$ exceeds the sum rule [120% $S^{E1}(T_<)$]. Since p capture excites the $T_<$ as well as $T_>$ component of the GDR the choice of S^{E1} $(T_<)$ is arbitrary; one could have chosen that part of S^{E1} which is contained in the studied energy range from 13.5–18.3 MeV, about 25% of S^{E1} (see Ref. 5). Values larger than 100% seem to indicate that the original assumption, the occurrence of only statistical processes, is wrong. Indeed, it had been shown that p capture leads into the GDR predominantly through direct or semidirect processes (~70% for the ^{27}Al$(p,\gamma_0)^{28}$Si reaction).[15] Hence for the statistical evaluation of $\sigma(\gamma,-)$ [Eq. (5)] we would have to use only a fraction of the measured value $\sigma(\gamma,p_0)$, namely, only that part which presents the excitation of the resonance through the compound nucleus, through nondirect and nonsemidirect processes. (d) Similarly to (c) the p capture into the ^{28}Si GDR suggests again a too large value (135%) for the sum rule $\int_{E1}\sigma(\gamma,-)dE$. The studied energy range of 14.5–20.5 MeV does not contain the full strength of the GDR[15] in ^{28}Si hence the value of 135% is an underestimate. Similarly to the ^{58}Ni(γ,p_0) reaction this value deduced from the measured $\sigma(\gamma,p_0)$ cross sections implies a large fraction of nonstatistical processes which have to be excluded before applying Eq. (5). (e) Finally, the α capture into the giant quadrupole resonance of ^{58}Ni and ^{28}Si shows also a much too large value for the energy-weighted sum rule (150% S_{-2}^{E2} for ^{58}Ni and 170% S_{-2}^{E2} for ^{28}Si). It is concluded that similarly to (c) and (d) the α capture into the GQR has large components of direct or semidirect processes, a result which has been suggested earlier for the ^{22}Ne$(\alpha,\gamma)^{26}$Mg reaction.[8] These nonstatistical reaction components make the α capture as useful a tool for the study of the GQR as is the p capture is for the investigations of the GDR: It makes a measurement of the energy distribution of the $E2$ strength possible.

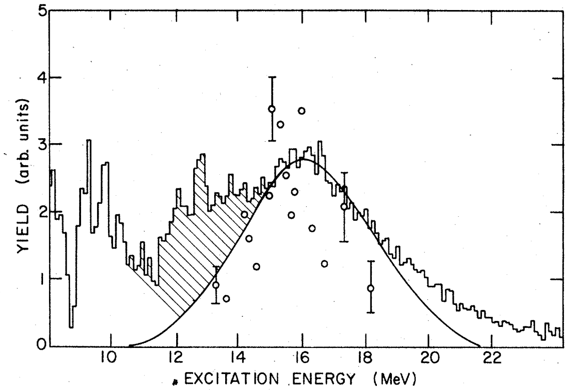

FIG. 10. The cross sections $\sigma(\gamma,\alpha_0)$ exciting the GQR in ^{58}Ni (open circles) are compared with those of inelastic α scattering in ^{58}Ni (Ref. 23). For a better comparison the continuous background observed in these α-scattering experiments is subtracted (Ref. 24). The histogram shows the differential cross section of the (α,α') reaction measured at 17° to the incoming α beam. The solid line indicates the $E2$ strength in ^{58}Ni taking all measurements at different angles into account. The shaded area represents an excitation in ^{58}Ni which does not contain $E2$ strength but seems to have components of mixed polarities.

The $E2$ strengths as measured by α capture can be compared with those obtained by inelastic α scattering. This is shown for ^{58}Ni in Fig. 10 using the (α,α') results of Ref. 23. For a better comparison the continuous background observed in these α-scattering experiments is subtracted.[24] The histogram indicates the (α,α') result at 17° using an α energy of 115 MeV. The solid line represents the $E2$ strength calculated from the many inelastically scattered α spectra taken at different angles. The shaded area is not believed to contain $E2$ strength. The open circles represent the $E2$ strength as measured by α capture with the ordinate chosen to facilitate comparison.

Figure 10 indicates that in both the α capture and the (α,α') reaction an $E2$ resonance is observed at about the same excitation energy. The width of this resonance, however, seems to be smaller in the α-capture experiment than in the (α,α') reaction. The same result is obtained by comparing the α-capture results with those of the (d,d') reaction.[2,25]

Kurath and Towner[26] have pointed out that in α-

transfer reactions from a 0^+ target nucleus into a 2^+ state of the final nucleus large direct components are to be expected when the wave functions of the target nucleus plus an α particle have a large overlap with those of the ground state of the final nucleus and in addition the excited 2^+ state can be described as an isoscalar particle-hole vibration of the ground state of the final nucleus. The strong direct components observed in the α capture into the GQR of ^{28}Si and ^{58}Ni might very well originate from such a transition. However, for (α,γ) reactions for which this overlap is not strong the direct processes should be weak and the value $\int_{E2}\sigma(\gamma,-)dE/E^2$ should be less than or equal to the S_{-2}^{E2} sum rule. It would therefore be interesting to search in a number of nuclei for a correlation of the $\sigma_{E2}(\gamma,\alpha_0)$ cross section with the spectroscopic factor for an α transfer from the ground state of the target nucleus to that one of the final nucleus.

CONCLUSIONS

α capture in ^{54}Fe targets has been studied in the energy range $7.6 \le E_\alpha \le 12.8$ MeV. Angular distributions made it possible to determine the energy distribution of the $E1$ and $E2$ strengths. At an excitation energy of 15.7 MeV an $E2$ resonance was observed in agreement with inelastic α- and d-scattering experiments. The width of the measured resonance, however, seems to be smaller in α capture than in inelastic scattering experiments.

The observed $E1$ strength equals 0.9% of the total isospin allowed $E1$ strength while about 4.3% of the total isoscalar $E2$ strength is observed. Thus the (γ,α_0) excitation of the GQR is as strong as the (γ,p_0) excitation of the GDR. This is also true for other nuclei which had been studied earlier (see Table II). Applying Hauser-Feshbach formalisms to calculate total γ absorption cross section through the measured $\sigma(\gamma,\alpha_0)$ and $\sigma(\gamma,p_0)$ cross sections and comparing the evaluated integrals $\int\sigma(\gamma,-)dE$ and $\int\sigma(\gamma,-)dE/E^2$ with existing sum rules suggests that α capture into the isoscalar GQR is not a purely statistical process but contains some direct components. This result might be due to a correlation between α transfer to and particle-hole excitation of the ground state of the final nucleus.[26] It makes the α capture a valuable tool for studying the isoscalar $E2$ strength.

We are grateful to Dr. D. Kurath and Dr. J. E. Monahan for many helpful discussions and contributions.

---

*Supported by U. S. ERDA, Division of Physical Research, and the NSF.

†Also at Northwestern University, Evanston, Illinois 60201.

‡Present address: Cyclotron Lab., Indiana University, Bloomington, Indiana 47401.

§Present address: Carnegie-Mellon Univ., Pittsburgh, Pennsylvania 15216.

¶Present address: Australian National Univ., Canberra, Australia.

[1]D. C. Kocher, F. E. Bertrand, E. E. Gross, R. S. Lord, and E. Newman, Phys. Rev. Lett. 31, 1070 (1973); Phys. Rev. Lett. 32, 264(E) (1976).

[2]C. C. Chang, F. E. Bertrand, and D. C. Kocher, Phys. Rev. Lett. 34, 221 (1975).

[3]A. Moalem, W. Benenson, and G. M. Crawley, Phys. Rev. Lett. 31, 482 (1973).

[4]D. H. Youngblood, J. M. Moss, C. M. Bozca, A. D. Bacher, D. R. Bacher, and D. R. Brown, Phys. Rev. C 13, 994 (1976).

[5]S. C. Fultz, R. A. Alvarez, B. L. Berman, and P. Meyer, Phys. Rev. C 10, 608 (1974).

[6]H. Miyase, S. Oikawa, A. Suzuki, J. Uegaki, T. Saito, M. Sugawara, and K. Shoda, in *Proceedings of the International Conference on Photonuclear Reactions and Applications, Asilomar, March* 1973, edited by B. L. Berman (Lawrence Livermore Laboratory, Livermore, 1973), Vol. 1, p. 553.

[7]L. Meyer-Schützmeister, Z. Vager, R. E. Segel, and P. P. Singh, Nucl. Phys. A108, 180 (1968).

[8]E. Kuhlmann, E. Ventura, J. R. Calarco, D. G. Maris, and S. S. Hanna, Phys. Rev. C 11, 1525 (1975).

[9]R. B. Watson, D. Branford, J. L. Black, and W. J. Caelli, Nucl. Phys. A203, 209 (1973).

[10]G. S. Foote, D. Branford, R. A. I. Bell, and R. B. Watson, Nucl. Phys. A220, 505 (1974).

[11]R. E. Segel, Z. Vager, L. Meyer-Schützmeister, P. P. Singh, and R. G. Allas, Nucl. Phys. 93, 31 (1967).

[12]F. S. Dietrich, M. Suffert, A. V. Nero, and S. S. Hanna, Phys. Rev. 168, 1169 (1968).

[13]E. M. Diener, J. F. Amann, P. Paul, and S. L. Blatt, Phys. Rev. C 3, 2303 (1971).

[14]R. C. Bearse, L. Meyer-Schützmeister, and R. E. Segel, Nucl. Phys. A116, 682 (1968).

[15]P. P. Singh, R. E. Segel, L. Meyer-Schützmeister, S. S. Hanna, and R. G. Allas, Nucl. Phys. 65, 577 (1965).

[16]A. Bohr and B. R. Mottelson, *Neutron Capture Gamma Ray Spectroscopy* (IAEA, Vienna, 1969); B. R. Mottelson, in Proceedings of the XV Solony Conference in Physics, Brussels, 1970 (unpublished).

[17]E. H. Auerbach, Brookhaven National Laboratory Report No. BNL-6562, 1962 (unpublished).

[18]R. Bock, P. David, H. H. Duhm, H. Hefele, U. Lynen, and R. Stock, Nucl. Phys. A92, 539 (1967).

[19]A. G. Drentje and G. D. A. Roeders, Phys. Lett. 32B, 356 (1970).

[20]L. C. Perey and F. G. Perey, At. Data Nucl. Data

Tables 13, 293 (1974).
[21]W. Hauser and H. Feshbach, Phys. Rev. 87, 366 (1952).
[22]A. Gilbert and A. G. W. Cameron, Can. J. Phys. 43, 1446 (1965).
[23]D. H. Youngblood, J. M. Moss, C. M. Rozsa, J. D. Bronson, A. D. Bacher, and D. R. Brown, Phys. Rev. C 13, 994 (1976).
[24]D. H. Youngblood (private communication).
[25]F. E. Bertrand, Annu. Rev. Nucl. Sci. 26, 457 (1976).
[26]D. Kurath and I. S. Towner, Nucl. Phys. A222, 1 (1974).