Alpha particle capture through the giant electric resonances in ^{90}Zr

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The $^{86}Sr(\alpha,\gamma_0)^{90}Zr$ reaction has been studied over the energy range $9.0 \leq E_\alpha \lesssim 12.5$ MeV; there was no detectable yield below 9 MeV. Data were taken at three angles, thus making it possible to decompose the radiation into its $E1$ and $E2$ components. The $E1$ yield, which is at least 85% of the total, shows a broad peak centered at an excitation energy of about 17 MeV. Utilizing Hauser-Feshbach calculations, the magnitude and shape of the $E1$ yield is shown to be consistent with the $E1$ capture proceeding entirely through the compound nucleus. The $E2$ yield is small at the lower bombarding energies, but appears to be significant above about $E(^{90}Zr^*) = 16.5$ MeV. Any observed $E2$ cross section is shown to be much too large for the reaction to proceed mainly through the compound nucleus.

[NUCLEAR REACTIONS $^{86}Sr(\alpha,\gamma_0)^{90}Zr$, $9 \leq E_\alpha \leq 12.5$ MeV; measured E_γ, $d\sigma/d\Omega(\theta, E_\alpha)$; deduced $\sigma_{E1}(\gamma,\alpha_0)$, $\sigma_{E2}(\gamma,\alpha_0)$.]

I. INTRODUCTION

Radiative capture measurements have proved to be a fruitful method for studying giant multipole resonances. While most of the previous work has utilized proton capture, some alpha particle capture studies have been published.[1-5] For alpha capture on an even-even nucleus, both the initial and final states are 0^+ (for the ground-state radiation), and the capture radiation is readily decomposed into its $E1$ and $E2$ components. Thus, alpha capture offers an opportunity to study the isoscalar $E2$ giant resonance, which has been observed in inelastic scattering.

In a previous publication, a study of the $^{54}Fe(\alpha,\gamma)^{58}Ni$ reaction was reported.[5] Both $E1$ and $E2$ radiation to the ground state were observed, with the ratio constant at about 10% $E2$ within rather wide experimental errors. The yield peaked at an excitation energy of about 15.7 MeV, which was close to the position of the isoscalar portion of both the $E1$ and $E2$ giant resonances. While the $E1$ capture appeared to take place mainly through the compound nucleus, the analysis indicated that the $E2$ capture was primarily direct and/or semidirect. In the present work, alpha capture into a heavier nucleus, ^{90}Zr, was studied. Here, too, the isoscalar $E2$ and $E1$ giant resonances have both been observed in other reactions[6-10] but in this case the $E2$ resonance is reported to be about 2.5 MeV lower than the $E1$ resonance.

II. EXPERIMENTAL RESULTS

Rolled strontium foils, enriched to 97.6% in ^{86}Sr, were bombarded by alpha particles from the ANL tandem Van de Graaff. The targets were about 1.7 mg/cm^2 thick, which corresponds to an energy loss of about 450 keV for 10-MeV alphas. Beam currents of up to 400 nA were used. The gamma rays were detected by the same 10 in. diameter ×12 in. thick NaI(Tl) spectrometer system that was used in previous radiative capture experiments done in this laboratory. A spectrum for $\bar{E}_\alpha = 10.3$ MeV, which is actually the sum of the data taken at 45° and at 135°, is shown in Fig. 1.

The largest cross section found in the present experiment was about 0.2 μb/sr, which is considerably smaller than that found in reactions previously studied. In fact, the cross sections in the present work are a factor of 5–10 lower than those

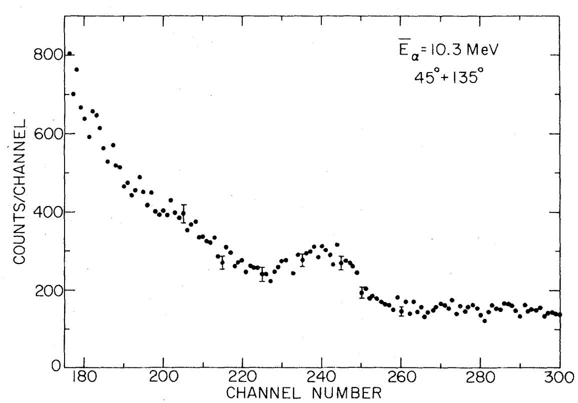

FIG. 1. Sum of the data taken at 45° and at 135° for 10.5 MeV alpha particles bombarding a 400 keV thick target. Before summing the spectra, a small shift was introduced in order to account for a reproducible variation of gain with angle.

observed in the $^{54}Fe(\alpha,\gamma_0)$ reaction.[5] In order to obtain satisfactory statistical accuracy, data were taken at each point for about 8 h, accumulating a total charge of about 10000 μC. As can be seen from Fig. 1, cosmic-ray background was significant and, furthermore, only the ground-state gamma ray γ_0 was separated from the low-energy background. The spectrum in the region of the γ_0 peak was therefore fitted as the sum of three components: cosmic rays, whose spectral shape was determined with the beam off; the γ_0 peak itself, whose shape was determined from stronger radiative capture reactions; and an exponential low-energy background. Tests have shown that at the counting rates at which the system was operated, there would be no significant degradation of the energy resolution and that pileup effects would be negligibly small. The γ_0 intensity was determined with the aid of a program which decomposed the spectrum into these three components. Varying the various parameters in the program, such as the number of channels used in obtaining the yield, the shape of the peak, or the way in which the low-energy background was determined, was found to have no material effect on the final results. The spectra in the vicinity of the peak at both 90° and (45°+135°) are shown together in Fig. 2. Any consistent analysis of the spectra at

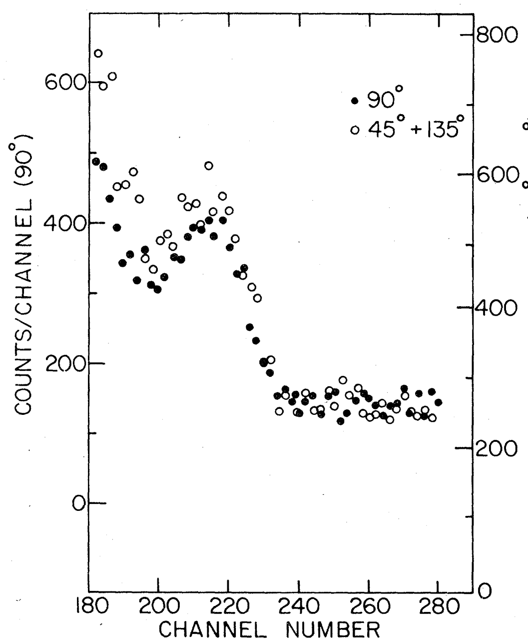

FIG. 2. Spectra taken at $\bar{E}_\alpha = 10.8$ MeV. The open circles indicate the spectrum taken at 45° added to that taken at 135°. The 90° spectrum is shown by solid points. The running time was approximately the same at all three angles, and the (45°+135°) spectrum has been shifted vertically so that its cosmic-ray background is equal to that of 90°.

$\bar{E}_\alpha = 10.3$ and 10.8 MeV yielded a significant $E2$ component in the capture radiation at these energies.

Absolute cross sections were determined by normalizing to the 14.2-MeV resonance in the $^{12}C(p,\gamma_0)^{13}N$ reaction, whose yield has been carefully determined.[11] As a check, the $^{59}Co(p,\gamma_0)^{60}Ni$ cross section was measured at a bombarding energy of 7.6 MeV and the result agreed to within 10% with that obtained by Diener *et al.*[12] Isotropy in the detecting system was carefully checked with a radioactive source.

For a 0^+ target and a 0^+ final state, alpha capture can only produce electric radiation, of which only dipole and quadrupole are likely to be present with detectable strengths. For pure $E1$ radiation, the angular distribution is

$$W(\theta)_{E1} = \frac{\sigma(E1)}{4}(1-P_2) = \frac{\sigma(E1)}{4\pi}\left(\tfrac{3}{2}\sin^2\theta\right), \quad (1)$$

while for pure $E2$,

$$W(\theta)_{E2} = \frac{\sigma(E2)}{4\pi}\left(1+\tfrac{5}{7}P_2 - \tfrac{12}{7}P_4\right) = \frac{\sigma(E2)}{4\pi}\left(\tfrac{15}{8}\sin^2 2\theta\right). \quad (2)$$

If both $E1$ and $E2$ capture occur, the angular distribution can be written

$$W(\theta) = \frac{1}{8\pi}\{3\sigma(E1)\sin^2\theta + \tfrac{15}{4}\sigma(E2)\sin^2 2\theta + 3\sqrt{5} \times [\sigma(E1)\sigma(E2)]^{1/2}\cos\theta_{12}\sin\theta\sin 2\theta\}, \quad (3)$$

where θ_{12} is the phase angle between the two components. Since there are but three unknowns, it suffices to take data at three angles and, for this experiment, 45°, 90°, and 135° were chosen. From (3), it follows that

$$\sigma(E1) = \frac{8\pi}{3}W(90), \quad (4)$$

$$\sigma(E2) = \frac{16\pi}{15}[W(45)+W(135)-W(90)], \quad (5)$$

and

$$\cos\theta_{12} = \frac{1}{2}\frac{W(45)-W(135)}{\{W(90)[W(45)+W(135)-W(90)]\}^{1/2}}. \quad (6)$$

Data were taken at all three angles in 500-keV steps from 9.0 to 12.0 MeV. In addition, a spectrum was taken at 12.5 MeV at 90°. On the low-energy side, a vanishingly small yield limited the energy range that could be profitably studied, while on the high-energy side, the range was restricted by a lower yield combined with a rising background.

The $E1$ yield curve, which is, when multiplied by a constant factor, the 90° yield curve, is shown in Fig. 3. Because of the thickness of the target, each point represents an average over 400–500 keV. The error bars are for the absolute cross sections and include such uncertainties as target thickness, beam integration, etc., which have little effect on the relative cross sections, particularly those taken at the same energy during the same run. Some points at 90° were taken two or three times, and some of these data were taken several months apart, yet, as can be seen from Fig. 3, the spread in these points is usually less than that implied by the error bars. The energy dependence of the cross section looks like that of a giant resonance peaking at an excitation energy of about 17 MeV with a width of about 2.5 MeV.

As expected, neutron emission is by far the leading decay mode of the ^{90}Zr giant dipole resonance (GDR)[9,10] and the neutron yield shows a peak at about 16.5 MeV, which is about 5 MeV wide. It should be noted that if isospin is conserved both the (γ, α) reaction and the (γ, n) reaction will proceed solely through the $T_<$ part of the giant resonance. Radiative proton capture through the giant resonance region has also been studied.[6] The yield curve for this reaction shows considerable sharp structure which is attributed to the $T_>$ component of the giant dipole resonance, superimposed on broader structure described as showing an ≈ 4-MeV wide giant resonance centered at an excitation energy of about 16.5 MeV, which would be

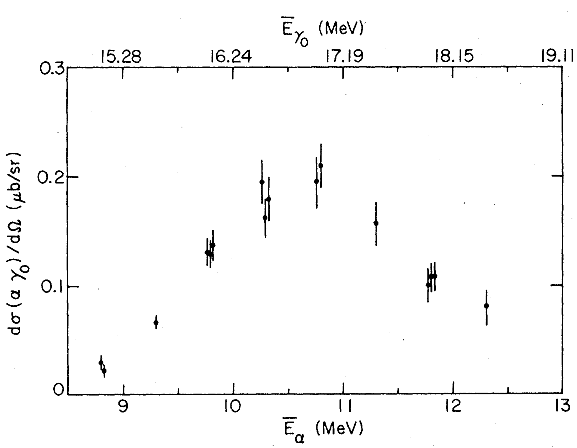

FIG. 3. Yield curve at 90°. The alpha energy is the mean energy in the target. Data are from different runs spread over about a year and the error bars indicate the estimated uncertainties in the absolute cross sections. The estimated errors in the relative cross sections, as far as angular distributions are concerned, are about one half of the absolute errors.

the main $T_<$ component. The photoproton spectrum has also been studied in some detail.[10] The summed proton yield curve shows two broad peaks—one centered at an energy of about 16.5 MeV, attributed to the $T_<$ component of the giant dipole resonance, the other one at about 21.5 MeV, identified with the $T_>$ component. The $E1$ yield in the present work, therefore, does appear to be concentrated in the region where other experiments also place the $T_<$ part of the GDR. However, Coulomb effects and the competition from other channels play major roles in shaping the yield curve and must be considered before definitive conclusions can be drawn. Using detailed balance to convert the radiative capture cross section to that of the inverse (γ, α_0) reaction, the integrated $E1$ yield is 0.47 MeV mb. This yield is 0.04% of the dipole classical sum $f \times 60NZ/A$, where $f = [T_0/(T_0+1)](1+\frac{3}{2}A^{-2/3})$ is the fraction of the strength in the $T_<$ part.

For pure $E1$ radiation the yield at both 45° and 135° would be exactly half that at 90°. However, as can be seen from Fig. 2, at $\bar{E}_\alpha = 10.8$ MeV the sum of the 45° and 135° spectra shows a γ_0 peak that is some 15% larger than the peak in the 90° spectrum. The finite solid angle of the crystal can only cause a 4% effect.[13] Statistically, the areas in the two peaks differ by five standard deviations. More important are systematic errors, of which the low-energy background is most likely the primary source. However, the peak shape is quite accurately known, as is the cosmic-ray background (virtually flat), and at both $E_\alpha = 10.3$ and 10.8 MeV it was found that for any reasonable shape of the low-energy background, the final extracted $E2$ intensity did not vary significantly. At $\bar{E}_\alpha = 11.3$ MeV, the background was much greater, and while there did seem to be an $E2$ component, its presence was not definitely established. At 11.8 MeV, the errors were too large, particularly at 45° and 135°, to permit much more than establishing an upper limit for the $E2$ radiation. On the other hand, the data below 10 MeV were quite clean and here the $E2$ was definitely significantly weaker than it was at 10.3 and 10.8 MeV. While more accurate determinations of the $E2$ yield would certainly be desirable, it is felt that the present experiment establishes the presence of an $E2$ component in the capture radiation, particularly in the $E_\alpha = 10$–11 MeV region, whose intensity is shown in Fig. 4. Inelastic alpha particle[8] and electron[7] scattering measurements have found the isoscalar giant $E2$ resonance at an energy of about 14 MeV, which is close to the expected energy of $63A^{-1/3}$ MeV. It is shown below that Coulomb effects may strongly distort the $E2$ capture yield curve.

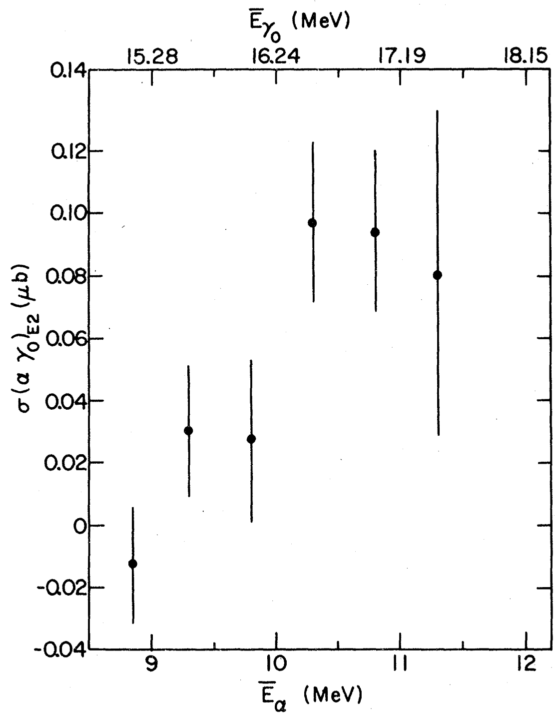

FIG. 4. Cross section for producing $E2$ radiation.

The phase angle, given by Eq. (6), was found to be indistinguishable from 90°. A small net interference could be attributed to the fact that each data point represents a summation over many compound nucleus levels. Using detailed balance to convert the $E2$ capture cross sections to that for the (γ, α_0) reaction, the energy weighted integral $\int \sigma dE/E^2 = 0.1$ μb/MeV is found to be about 0.12% of the isoscalar sum rule of $0.22Z^2/A^{1/3} = 79$ μb/MeV for ^{90}Zr.

III. DISCUSSION OF RESULTS

For a reaction proceeding only through a compound nucleus formation, transmission coefficients can be used to calculate the decay rate in each exit channel.[14] In the present case, then the (γ, α_0) cross section can be written

$$\sigma(\gamma, \alpha_0) = \sigma(\gamma, \text{tot}) \frac{T_{\alpha 0}}{\sum_i T_i}, \tag{7}$$

where T_i is the transmission in the ith channel and the summation is over all open channels.

It is, of course, not necessary that radiative capture in ^{90}Zr proceeds mainly through the compound nucleus. In fact, a previous study[5] in ^{58}Ni indicated that alpha capture through the $E1$ giant resonance does appear to be largely compund but that a portion of the $E2$ alpha capture cannot be accounted for by statistical processes. In the present work the total gamma-ray absorption cross section, $\sigma(\gamma, \text{tot})$, is calculated for the $E1$ component under the assumption that the reaction is purely compound. By comparing the results of such a calculation with the total resonance strength, the approximate portion of the capture that does go through the compound nucleus can be deduced.

Protons and neutrons, as well as alpha particles, can be emitted from ^{90}Zr over the region of excitation energy studied here. In calculating the transmission coefficients for the neutrons the optical-model potentials of Wilmore and Hodgson[15] were used. For the protons the parameters were calculated from the general optical-model parameters of Perey and Perey.[16] For the alphas, since elastic scattering data from ^{86}Sr were not available, the parameters were those for natural yttrium taken from the Perey compilation.[16] Table I lists the parameters that were used. For excitation energies in the final nuclei above the region where all of the levels were known, the level density formulas of Gilbert and Cameron[17] were used.

Under the assumption that the electric dipole portion of the (γ, α_0) reaction proceeds entirely through the compound nucleus, the compound $E1$ absorption cross section, $\sigma(\gamma, \text{tot})_{T_<}$, has been calculated using the methods outlined above. The results are shown in Fig. 5. The (γ, n), (γ, p), (γ, np), and $(\gamma, 2n)$ yield curves in ^{90}Zr have also been measured[10] and the sum of these, which can be considered the total gamma-ray absorption cross section, is also shown. The two curves are quite similar. From the cross sections thus calculated the integrated strength $\int_{15}^{18.5} (\lambda, \text{all}) dE = 780$ mb MeV is obtained which can be compared to the value of 1333 mb MeV for the classical dipole sum, of which 1226 mb MeV can be attributed to the $T_<$ portion of the giant dipole resonance. Thus the $E1$ yield curve is consistent with the entire $E1$ alpha capture proceeding through the compound nucleus.

The calculations for the $E2$ component were performed somewhat differently. If the $E2$ isoscalar GQR can be taken as having a Breit-Wigner shape the $E2$ gamma-ray absorption cross section can be written

$$\sigma_a = \frac{\lambda\!\!\!^{-2}\kappa}{(E - E_0)^2 + (\Gamma/2)^2}, \tag{8}$$

where κ is a constant and the $E2$ (γ, α_0) cross section

$$\sigma_{\gamma, \alpha_0} = \sigma_a \frac{\Gamma_{\alpha 0}}{\Gamma_{\text{tot}}}. \tag{9}$$

From the analysis of their inelastic alpha particle

TABLE I. Optical-model parameters used in calculating transmission coefficients.

Parameter	Alpha channel	Proton channel	Neutron channel
V (MeV)	146.1	$53.3-0.55E+\frac{27}{A}(A-2Z)-0.4\frac{Z}{A^{1/3}}$	$47.01-0.267E-0.0018E^2$
r (fm)	1.464	1.25	1.227
a (fm)	0.515	0.65	0.66
W (MeV)	18.25	0	0
W_D (MeV)	0	13.25	$9.52-0.053E^2$
r_i (fm)	1.47	1.25	1.246
a_i (fm)	0.449	0.47	0.48
V_{s_0} (MeV)	0	7.5	7.2
r_{s0} (fm)	0	1.25	1.25
a_{s0} (fm)	0	0.47	0.66
r_c (fm)	1.4	1.25	1.25

scattering data, Youngblood *et al.*[8] find $E_0=14.5$ MeV, $\Gamma=4$ MeV, and that the resonance exhausts 55% of the $E2$ isoscalar energy weighted sum rule, i.e.,

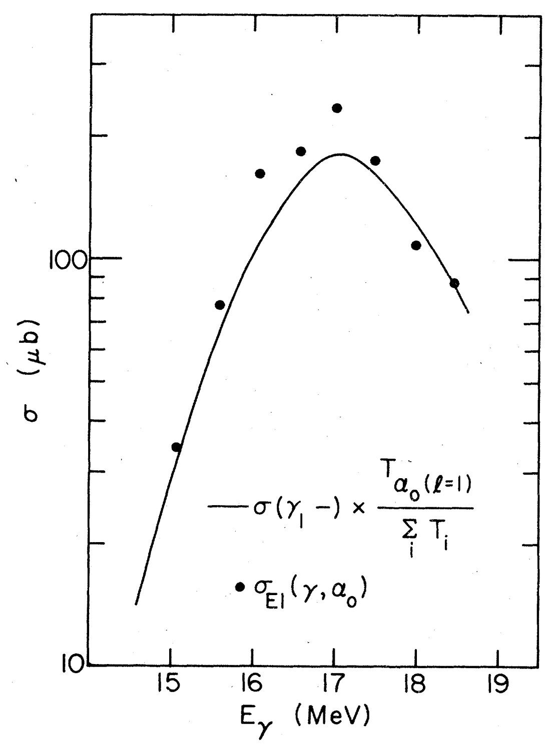

FIG. 5. Total $E1$ absorption cross section calculated from the measured $E1$ capture under the assumption that the entire reaction proceeds through the compound nucleus. Also shown is the measured total absorption given in Ref. 10.

$$\int_{\rm GQR}\frac{\sigma_\alpha dE}{E^2}=0.55\;S\,, \tag{10}$$

where

$$S=\frac{0.22Z^2}{A^{1/3}}\;\mu\text{b/MeV}\,.$$

Substituting (8) and (10) and performing the integration leads to

$$\lambda\!\!\!^{-}_0{}^2\kappa=5782\;\mu\text{b/MeV}^2\,. \tag{11}$$

In determining κ the approximations $\lambda^2\cong\lambda_0{}^2$ and $\int_{\rm GQR}\sigma_\alpha dE/E^2\cong(1/E_0{}^2)\int\sigma_\alpha dE$ have been made. These approximations were not really necessary but the error introduced by making them is negligible compared to the uncertainties in the calculation of the compound nucleus and direct components.

If the reaction proceeds through the compound nucleus, then

$$\frac{\Gamma_{\alpha_0}}{\Gamma_{\rm tot}}=\frac{T_{\alpha 0}}{\sum_i T_i}\,, \tag{12}$$

and the transmission coefficients can be calculated in the same way as for the $E1$ case. The results are shown in Fig. 6 as the solid curve which is labeled "compound nucleus." It is clear that α_0 capture through the compound nucleus is much too small to account for any $E2$ radiation observed here.

The direct (γ,α_0) reaction can be thought of as taking place because the GQ state formed by $E2$ gamma-ray absorption can decay directly by α_0 emission. The state can also mix into the other compound nucleus levels. Using the definitions

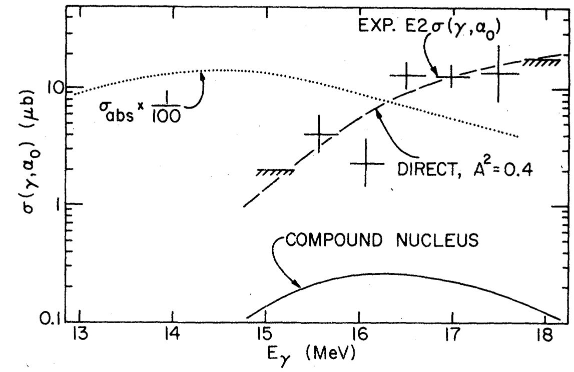

FIG. 6. Solid lines are the $E2$ (γ, α_0) cross section, obtained from the observed $E2$ capture by detailed balance. The cross hatching indicates an upper limit. Solid curve is the compound nucleus $E2$ (γ, α_0) expected from a 4-MeV wide resonance centered at 14.5 MeV. The broken curve is that calculated for a direct reaction proceeding through a giant quadrupole state that has a 40% ^{86}Sr + α component. Dotted curve is the gamma-ray absorption cross section, divided by 100, expected for a 4-MeV wide resonance centered at 14.5 MeV.

given by Lane and Thomas,[18] if Γ_{α_0} is small compared to the total width, a condition that is obviously fulfilled in the region studied here, the α_0 branching ratio can be written

$$\frac{\Gamma_{\alpha_0}}{\Gamma_{tot}} = \frac{2P_2\gamma_{\alpha_0}{}^2}{\Gamma}, \tag{13}$$

where $\gamma_{\alpha_0}{}^2$ = reduced width for α_0 emission from the isoscalar GQ state, and P_2 = penetrability for $l = 2$ alpha particles. In turn, $\gamma_{\alpha_0}{}^2$ can be written in terms of single particle units $\frac{3}{2}\hbar^2/mR^2$:

$$\gamma_{\alpha_0}{}^2 = A^2\left(\frac{3}{2}\frac{\hbar^2}{mR^2}\right), \tag{14}$$

where A^2 represents the fraction of the isoscalar GQ state that can be represented as ^{86}Sr + α. The penetrability was calculated using the formulas of Lane and Thomas[18] with the sum of the ^{86}Sr and ^{4}He radii taken to be 8.40×10^{-13} cm. The (γ, α_0) cross section was then calculated using (9) and (13). A fairly good fit to the observed $E2$ intensities was found with $A^2 = 0.4$. The results are shown as the dashed curve in Fig. 6, which is labeled "direct, $A^2 = 0.4$." This result would indicate that some significant fraction of the ^{90}Zr isoscalar GQ state can be represented by ^{86}Sr + α but, in view of the uncertainties in the data combined with the crudeness of the calculation, any quantitative conclusion must be regarded as very tentative. However, it is difficult to see how the present data could be consistent with $A^2 \lesssim 0.1$. It therefore appears that some significant fraction of the ^{90}Zr GQR can be represented as ^{86}Sr + α although this fraction could be considerably less than 50%. This conclusion is not known to be in conflict with any other study of the isoscalar GQR.

While it is shown here that Coulomb effects can explain the difference in shape between the $E2$ capture yield curve and the isoscalar GQR that is observed in other studies, there is also the possibility that the ≈ 17 MeV $E2$ radiation is not coming from this GQR. The GQR observed in alpha-particle inelastic scattering exhausts only about 50% of the energy weighted sum rule and so considerable other strength could be present. If it is assumed that the remainder of the strength is in a flat cross section form $E_\alpha = 10$ to 140 MeV (the upper limit does not matter much since the cross section is weighted by $1/E^2$) then the α_0 branch would have to be about 3% in the 17 MeV region in order to explain the present results. For decay through the compound nucleus, the α_0 branch in this region is calculated to be only about 4×10^{-4} and therefore the decay would have to be mainly direct. Taking the total decay rate to be that corresponding to a spreading width of 10 MeV, a direct α_0 decay proceeding at single particle speed is estimated to give a cross section about half of what is observed, which, in view of all of the uncertainties, cannot be considered as ruled out by the experiment.

There could, of course, be other distributions of the remaining $E2$ strength. However, even if one makes the extreme assumption that all of the remaining strength is concentrated in a 2 MeV wide state at 17 MeV, an assumption that is clearly inconsistent with the alpha-particle scattering results, the calculated compound nucleus (γ, α_0) cross section would still be only $\frac{1}{10}$ of what is observed. Using A^2 as defined by Eq. (14), such a state with $A^2 = 0.06$ would account for the present results. Put another way, a 2 MeV wide state on the high side of the previously observed GQR that contains 10% of the energy weighted sum rule $E2$ strength could account for the observed $E2$ capture if the decay rate into ^{86}Sr + α is 30% of single particle speed. Coulomb effects so strongly distort the α capture yield curve, particularly for direct capture but with $\Gamma_{\alpha_0} \ll \Gamma$, and the shape of the yield curve is so poorly determined, that the present experiment is rather insensitive to the shape of the underlying $E2$ strength. However, it appears that regardless of how the isoscalar $E2$ strength is distributed, and $E2$ strength that is observed here cannot be attributed mainly to statistical processes.

It is certainly an oversimplification to consider only the two extremes of a giant resonance decaying either directly or via the compound nucleus whose decay rate is governed solely by statistical and extranuclear factors. Rather, the excited nucleus is better described as passing from the giant resonance configuration to that of the compound nucleus through a series of steps with α_0 emission possible at each stage but becoming less likely as the statistical description becomes more valid. Thus, it is best to interpret the present experiment as indicating that to the degree that $E2$ alpha capture to the ground state in ^{90}Zr is observed in takes place largely through direct and/or semidirect components.

IV. CONCLUSIONS

Significant $E1$ strength is seen here in the $^{86}Sr(\alpha, \gamma_0)$ reaction in the energy region where the $E1$ giant resonance has been reported in other studies. An $E2$ capture yield 5–10% that of the $E1$ appears to be present with the evidence strongest at $\bar{E}_\alpha = 10.3$ and 10.8 MeV. The $E1$ yield peaks at about $E_\lambda = 17$ MeV which is close to the peak of the $E1$ giant resonance in ^{90}Zr seen in other reactions. Using the Hauser-Feshbach formalism[14] the expected $E1$ (γ, α_0) cross sections were calculated under the assumption that the reaction proceeds entirely through the compound nucleus using the previously reported $E1$ giant resonance parameters. The curve thus obtained agreed well with the observed $E1$ capture, and it is therefore concluded that $E1$ alpha capture takes place mainly through the compound nucleus. A similar calculation for the $E2$ component produces cross sections that are too small by as much as a factor of 100. To the limited extent that it can be determined, the shape of the measured $E2$ yield curve appears to be consistent with the isoscalar $E2$ giant resonance directly emitting an alpha particle to the ^{86}Sr ground state.

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