Charged particle decay from giant monopole resonance in $^{28}$Si

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Proton and alpha decay from the giant resonance region of $^{28}$Si excited with a 129 MeV alpha particle beam has been measured in coincidence with inelastic alpha particles detected at $0^\circ$. The angular correlation data show the presence of decay from both $E0$ and $E2$ giant resonances. The $E0$ giant resonance decays primarily through the $\alpha_0$, $\alpha_1$, $p_0$, and $p_1$ channels with the branching ratios $18\pm6\%$, $24\pm8\%$, $23\mp9\%$, and $18\pm8\%$, respectively. Substantial direct decay is observed.

**INTRODUCTION**

After first evidence for the isoscalar giant monopole resonance (GMR) was obtained,1 extensive studies were performed to identify the GMR in many nuclei over the periodic table and to extract the incompressibility of nuclear matter.2–4 Most of these studies were done with inelastic scattering of $^3$He ions and alpha particles with energies between 100 and 170 MeV. To identify the monopole, the experiments were performed at small angles, including $0^\circ$ where the monopole is most strongly excited. In medium and heavy nuclei (mass number $A > 64$), the GMR has been unambiguously identified at excitation energies $E_x = (70–80)A^{1/3}$ MeV with width $=2.5–4$ MeV and contains a large fraction of the energy-weighted sum rule (EWSR) strength.

For $A < 58$, the GMR has been elusive with only a few percent of the sum rule located in most nuclei. Lui et al.5 reported the identification of 66% of the $E0$ EWSR with a width of $4.8$ MeV centered at $17.9$ MeV in $^{28}$Si. $^{28}$Si was also investigated by Kaílas et al.,6 using 115 MeV proton inelastic scattering, who reported 34% EWSR $E0$ strength in the $E_x = 15.7–24.1$ MeV region, but with a large ambiguity due to the uncertainty in the strength of excitation of the isovector giant dipole resonance (GDR). Kihm et al.7 explored the giant resonance region of $^{28}$Si in an $(e,e')$ decay study and report that 20% of the $(e,e')$ cross section arises from $E0$ excitation. Lu et al.8 reported ~90% of the $E0$ EWSR between 11 and 20 MeV in $^{24}$Mg. Lebrun et al.9 investigated the nuclei $^{60,58}$Ni, $^{56}$Fe, $^{25}$Al, and $^{12}$C with inelastic scattering of $108.5$ MeV $^3$He and found monopole strength of less than 10% EWSR in each nucleus. Duhmal et al.10 report location of 23% of the $E0$ EWSR in $^{58}$Ni. In $^{40}$Ca, a $0^+$ state at $E_x = 14$ MeV containing 6% of the EWSR (Refs. 11 and 12) was identified. Brandenburg et al.13 have performed singles and coincidence measurements on $^{40}$Ca using 120 MeV alpha particles and report 30% of the $E0$ EWSR strength fragmented in the broad excitation energy region $10.5–20$ MeV.

The GMR lies in a continuum region and can decay by the emission of neutrons, protons, and alpha particles. Measurements of such decay particles in coincidence with inelastically scattered particles exciting the GMR should permit a more confident assignment of the multipolarity through angular correlations, and might provide information on the microscopic structure of the GMR. From the location of particle thresholds and experience with the decay of the giant quadrupole resonance,14 one would expect the GMR in heavier nuclei to decay primarily by neutron emission; thus we have chosen to investigate charged particle decay of the GMR in $^{28}$Si. Further, since the decay of the giant quadrupole resonance (GQR) in $^{28}$Si revealed interesting features of intermediate structure and predominance of the direct decay process,15 it is interesting to investigate whether the decay of the GMR shows a similar direct nature and provides information on the microscopic structure of GMR.

In this paper, we report measurements of charged particles decaying from the giant resonance region of $^{28}$Si in coincidence with alpha particles inelastically scattered at $0^\circ$. The $0^\circ$ measurement gives a maximum monopole cross section and an axial symmetry of the angular correlation which makes measurements in one plane sufficient for full determination of the correlation function. This removes one uncertainty in obtaining decay branches from such correlations and, correspondingly, enables a proper definition with fewer measurements.

**EXPERIMENTAL PROCEDURE**

A 129-MeV alpha particle beam from the Texas A&M University 88 Inch Cyclotron was used to bombard a Si target located in the scattering chamber of the Enge split-pole magnetic spectrograph. The experimental
configuration is illustrated in Fig. 1. The beam was focused on the target in a spot 1 mm high by 2 mm wide, brought into the spectrograph, and stopped by a Faraday cup located 1 m behind the focal plane. The target was a self-supporting natural Si foil with a thickness of 2.05 mg cm$^{-2}$. Inelastically scattered alpha particles were measured at 0° with a 40-cm long resistive wire proportional counter in the focal plane. The proportional counter was backed by an NE102 scintillator to provide total energy and time of flight signals. Energy-loss signals from both ends of the proportional counter were routed after amplification through two analog to digital converters (ADC's) to a PDP-15 computer, and software division was done to obtain position information.

A 2.0 cm × 2.0 cm collimator was used to define the solid angle of the spectrograph. The opening angle was 4.2°, corresponding to a solid angle of 5.3 msr. Considerable care was taken to minimize background contributions from spurious beam particles and from slit scattering. The experimental technique used for the inelastic measurements at 0°, including the electronics setup and precautions against slit scattering, etc., have been described previously.  

The decay products were detected by eight silicon detector telescopes located in the scattering chamber. Each telescope consisted of a 70 (or 75) μm (E1), a 500 μm (E2), and a 2000 μm (E3) silicon surface barrier detector. A collimator of 10.7 mm diameter, corresponding to an opening angle of 6.1° and defining a solid angle of 9.0 msr, was used for each detector telescope. The techniques used for particle identification and computer encoding were similar to those described in Ref. 15 and will be described only briefly here.

Linear signals from the three detectors in a telescope were summed together after preamplification; the total energy signal for each telescope was then amplified and routed to the computer through one ADC. In addition to the total energy, a logic signal corresponding to E1, E1•E2, or E1•E2•E3, where $E_i$ means that the $i$th detector fired, was supplied to the computer for each coincident event in addition to a tag identifying the telescope in which the event occurred.

In the giant resonance region ($E_x = 15–25$ MeV) of ²⁸Si, alpha and proton energies up to 14 MeV are of interest for the decays to the low-lying states of the residual nuclei. The maximum energies of alpha particles which stop in the detectors E1, E2, and E3 are 9.54 MeV, 34.9 MeV, and 82.9 MeV, respectively. For protons they are 2.52 MeV, 8.77 MeV, and 20.5 MeV, respectively.

For on-line spectral monitoring and during off-line data analysis, events of logic E1 or E1•E2 with a particle energy larger than 9 MeV were sorted as an alpha event and all others were sorted as a proton event. For particle energies below 2.52 MeV, alpha particles and protons were not separated. A time-to-amplitude (TAC) signal, generated by a start signal from the decay detectors and a stop signal from the scintillator, was also routed to the computer through an ADC to classify the event as a true or accidental coincidence. A fast coincidence between signals from the scintillator and any decay detector supplied a gate to the computer. Single data were taken simultaneously by supplying computer gates for a
fraction (typically 1 in 200) of the singles events. A pulser signal was fed through the single manipulation circuits to the computer during data acquisition and used for a dead-time correction for the entire system. The ADC values, and logic and tag information were stored in event mode on tape for further analysis. In addition, a number of singles and 2D spectra were accumulated live to monitor the experiment. The experiment was performed with beam currents of a 5–8 nA providing a coincidence event rate of 60–100 counts per second.

Three sets of data were taken with different angle settings for the decay stacks and data were obtained for 18 different angles between 25° and 155°. The actual angles at which data were taken for the different runs are given in Table I.

### EXPERIMENTAL RESULTS AND DATA ANALYSIS

#### General features of the data

Two-dimensional spectra from 28Si(α,α'α) and 28Si(α,α'p) reactions obtained at 55° (decay detector) are shown in Fig. 2 after subtraction of the accidental coincidences. Several loci which correspond to specific final states of the residual nuclei are apparent. The strong decay channels are alpha decay to the 0⁺ ground state (α₀) and to the 2⁺, 1.37 MeV state (α₁) of 24Mg, and proton decay to the 5/2⁻ ground state (p₀) and to the 1/2⁺, 0.84 MeV and 1/2⁺, 1.01 MeV state (p₁,2) of 23Al. The 0.84 MeV and 1.01 MeV levels were not resolved.

Projections of events lying along the loci for these states on the alpha axis are shown in Fig. 3 for decay angles of 25° and 155°. Resonant structures can be seen with very little continuum in the alpha and proton spectra taken at 155°. In the 25° proton decay spectra, however, there appears to be a significant continuum. The alpha decay spectra at 25° exhibit at most a small continuum. The continuum in the proton spectra may come from knockout where an incident alpha particle knocks out a proton in the nucleus, leaving it in a hole state, as discussed later.

A singles α' spectrum is shown in Fig. 4(a). An α' spectrum of events in coincidence with decay alpha particles or protons, obtained by summing the decay spectra (after subtraction of accidental coincidences) with the appropriate sinθ weighting factor and normalized by the solid angle subtended by the decay detector is shown in Fig. 4(b). The data in Figs. 4(a) and (b) were taken simultaneously, and the relative normalizations are dependent only on the singles step down ratio, not on charge, target thickness, or dead time. In the singles spectrum, there exists a broad, strong peak at an excitation energy around 17.5 MeV which was reported by Lui et al.5 to contain significant monopole and quadrupole strength. A relatively narrow component of this peak dominates the coincidence spectrum below £Eₓ£ = 20 MeV with a peak to continuum ratio > 3:1. The integrated cross section for the strong peak (primarily 0⁺) is about 87% of the cross section for the same peak in the singles spectrum. As the threshold for neutron decay is 17.2 MeV, the balance of decay of this state could be neutron decay. The continuum in Fig. 4(b) is considerably lower than that in Fig. 4(a), even below the neutron threshold, suggesting experimental (slit scattering) contributions to the spectrum. Below the neutron threshold the integrated cross section in the singles spectrum is about twice that which can be accounted for from the coincidence data. As partial confirmation of the origin of this discrepancy, in data taken on 24Mg during the same run period but with improved optics, the sum of the decay data did reproduce the singles spectrum below the neutron threshold. The fine structure in the individual decay spectra in Fig. 3 does not correspond well to that in the singles spectrum; however, that in the summed coincidence spectrum does correspond to the structure in the singles spectra.

To obtain angular correlation functions, the coincidence spectra were divided into several excitation energy bins roughly corresponding to the structure in the singles spectrum. In Figs. 5 and 6, the angular correlations for the α₀ and α₁ decay channels, respectively, are shown for each energy bin, and Fig. 7 shows the correlations for the entire region from 15.5 to 26 MeV. The error bars shown on the data points correspond to the statistical error after subtraction of accidental coincidences. The angular correlations for α₁ decay in the lowest excitation energy region (£Eₓ£ = 15.5–16.7 MeV) were not obtained because the kinematics locus of the α₁ decay in this region crosses the alpha particle threshold in the decay detectors.

The angular correlations for α₀ and α₁ decay summed over the entire region are almost symmetric about 90°. This suggests that contributions from quasi-free scattering are small. In the angular correlations for some of the individual energy bins, however, there is a small forward-backward asymmetry. If the finite solid angle of the decay detector is not taken into account, the angular correlation of the α₀ decay from the GQR [in plane-wave Born approximation (PBWA)] should be proportional to [P2(cosθ)]², where P2(cosθ) is the Legendre polynomial.

#### Table I. Angles at which the decay detector were located at each run.

<table>
<thead>
<tr>
<th>Run number</th>
<th>Decay angles (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25.5 40.5 55.5 70.5 109.5 124.5 139.5 154.5</td>
</tr>
<tr>
<td>2</td>
<td>48.0 63.0 78.0 93.0 87.0 102.0 117.0 132.0</td>
</tr>
<tr>
<td>3</td>
<td>33.0 48.0 63.0 78.0 102.0 117.0 132.0 147.0</td>
</tr>
</tbody>
</table>
The experimental angular correlations of the $\alpha_0$ decay show this $E2$-like pattern with a relatively large zero offset. This suggests that the main contributions to the $\alpha_0$ decay come from $E0$ and $E2$ (although, over the region covered, higher multipolarities cannot be ruled out—this is discussed later).

It is interesting to note that the individual correlations in fact do have some forward backward asymmetry and that the cross section around $90^\circ$ is sometimes higher and sometimes lower relative to the forward peak than would

![Graph](image)

FIG. 2. True coincidence spectra of $^{28}\text{Si}(\alpha, \alpha')^{24}\text{Mg}$ and $^{28}\text{Si}(\alpha, \alpha'p)^{27}\text{Al}$ reactions. In the low-energy part ($E_{\alpha} \leq 2.6$ MeV) of the $^{28}\text{Si}(\alpha, \alpha')$ spectrum, $\alpha$ and $p$ are not separated. Accidental coincidences have been subtracted.
be true for a pure \([P_2(\cos\theta)]^2\). The lower cross section at 90° suggests that there may exist interference between \(E0\) and \(E2\) decays in the overlapping resonance region as might be expected from the results of Lui et al.\(^5\) The forward-backward asymmetry may result from interference with a multipole of opposite parity.\(^15\)

The \(\alpha_1\) angular correlations also show the \(E2\)-like pattern except in the 16.7–17.2 MeV region, but with a larger offset than the \(\alpha_0\) decay. There are three components in alpha decay between two \(2^+\) states, corresponding to \(l=j=0, 2,\) and 4, where \(l\) and \(j\) are orbital and total angular momenta of the decaying alpha particle. The \(l=j=0\) component has the same isotropic correlation as for \(E0\) decay and cannot be distinguished from it. In a previous study\(^15\) of decay of the \(^{28}\)Si GQR, this component was found to be small. If that is true here, the large isotropic component of the correlation would imply a large \(E0\) strength in the \(\alpha_1\) channel.

At forward angles, the proton spectrum contains a significant continuum contribution which results in a strong forward-backward asymmetry in the angular correlations. Processes which would be forward peaked include pickup-breakup reactions (such as \(^{28}\)Si + \(\alpha\) \(\rightarrow\) \(^{27}\)Al + \(^6\)Li \(\rightarrow\) \(^{27}\)Al + \(\alpha\) + \(\gamma\)) (see Ref. 17) and quasifree knockout processes. From the kinematics of the proton pickup-breakup processes, such contributions would
scattering could be present in the proton spectra at forward angles. On the other hand, low-energy alpha particles from quasifree alpha-alpha scattering would be emitted near 90° with very low energy (≤200 keV for free scattering).

To estimate the proton knockout contribution, plane-wave Born approximation (PWBA) calculations have been performed. These are shown as solid lines in Fig. 3 for the p0 and p1,2 decay channels. It is apparent that the shapes of the calculated cross sections are a plausible representation of the continuum contribution. These results were obtained with a large radial cutoff (6 fm) in the integration, and the calculated cross sections were normalized to the data.

In Figs. 8 and 9, the angular correlations for the proton decay channels are shown after subtraction of the knockout contributions. The correlation for the entire region is shown in Fig. 7. In the lower excitation energy region (E = 18.4 MeV), the angular correlations are almost symmetrical about 90° in the p0 decay channel and do not show a strong forward-backward asymmetry in the p1,2 decay channels. In the higher excitation energy region, however, a strong enhancement of the cross section exists at forward angles (less than 40°–50°) and becomes larger as excitation energy increases. Thus, even with a knockout contribution subtracted, an enhancement of the cross sections at forward angles remains. It is unlikely that the remaining asymmetry is due to an incomplete model of the knockout (as can be seen from the proton spectrum in Fig. 3), but might be due to interference between the quasifree process and other processes or interference between states of odd and even parity. Other works looking only at GQR decay have explored the possible sources of such asymmetries at length, and this was not pursued further in this work.

In order to obtain the cross sections for alpha and proton decay into each channel, the angular correlation data were fitted with Legendre polynomials using a least-square fitting technique and integrated. A few data points at forward angles (less than 40°–50°) in the proton

<table>
<thead>
<tr>
<th>E (MeV)</th>
<th>E0 (%) EWSR</th>
<th>E2 (%) EWSR</th>
<th>(δ2 - δ0) (deg)</th>
<th>E3 (%) EWSR</th>
<th>χ²</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.5-16.0</td>
<td>0.99±0.20</td>
<td>0.45±0.19</td>
<td>90</td>
<td>0±0.014</td>
<td>1.3</td>
</tr>
<tr>
<td>16.0-16.7</td>
<td>0.79±0.21</td>
<td>0.65±0.31</td>
<td>88</td>
<td>0.015±0.064</td>
<td>3.4</td>
</tr>
<tr>
<td>16.7-17.2</td>
<td>0.74±0.18</td>
<td>0.25±0.21</td>
<td>102</td>
<td>0±0.072</td>
<td>1.6</td>
</tr>
<tr>
<td>17.2-18.4</td>
<td>2.5±0.2</td>
<td>0.72±0.51</td>
<td>98</td>
<td>0±0.019</td>
<td>2.2</td>
</tr>
<tr>
<td>18.4-19.1</td>
<td>0.89±0.21</td>
<td>0.49±0.08</td>
<td>92</td>
<td>0.095±0.001</td>
<td>1.6</td>
</tr>
<tr>
<td>19.1-20.1</td>
<td>1.4±0.2</td>
<td>0.54±0.11</td>
<td>70</td>
<td>0.035±0.020</td>
<td>1.5</td>
</tr>
<tr>
<td>20.1-21.2</td>
<td>1.2±0.2</td>
<td>0.03±0.03</td>
<td>85</td>
<td>0±0.004</td>
<td>2.3</td>
</tr>
<tr>
<td>21.2-22.5</td>
<td>0.74±0.22</td>
<td>0.13±0.06</td>
<td>90</td>
<td>0.12±0.02</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Total
15.5-22.5 | 9.2±1.6 | 3.3 ±1.5 | 0.27±0.22 |

15.5-22.5 | 10.3° | 3.6° | 88° | 2.9° |

*Fitting the angular correlation for the entire energy region.
angular correlations were omitted from the fits, because in that angular region, nonresonant components appear to exist. Decay particles with energies below 2.6 MeV were excluded because alpha and proton decay could not be distinguished in this energy region; this corresponded to 12% of the decay.

These decay cross sections are plotted as a fraction of the singles giant resonance cross section in Fig. 10(a). The singles giant resonance cross section was obtained from the spectrum in Fig. 4(a) by subtracting the empirical background indicated by the dashed line. Below the neutron threshold (17.2 MeV) where the decay should proceed predominantly through p and α decay, approximately 100% of the decay is accounted for in these experiments, about 60% α and 40% p decay, if the particles below 2.6 MeV are assumed to be α. In the region of the strongest concentration of GR strength (17–19 MeV), alpha particle decay decreases relative to the proton decay.

![Graph showing angular correlations](image)

**FIG. 5.** Angular correlations for α₀ decay from the indicated excitation energy regions of $^{28}$Si. Solid (dashed) lines are angular correlations calculated with coherent (incoherent) mixing of decay amplitudes with parameters as listed in Table II.
TABLE III. Decay strength obtained from the angular correlations for $\alpha_1$ decay. The two values given for the 17.2–18.4 MeV region (and the total) represent essentially equal quality fits.

<table>
<thead>
<tr>
<th>$E_x$ (MeV)</th>
<th>$L=0^a$ (%)</th>
<th>$L=2$ ($l=j=2$) (%)</th>
<th>$\delta_2-\delta_0$ (deg)</th>
<th>$L=2$ ($l=j=4$) (%)</th>
<th>$\delta_2-\delta_0$ (deg)</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.7–17.2</td>
<td>0.45±0.18</td>
<td>0.37±0.21</td>
<td>102</td>
<td>0.99±0.21</td>
<td>102</td>
<td>2.1</td>
</tr>
<tr>
<td>17.2–18.4</td>
<td>4.9±0.2</td>
<td>2.0±0.5</td>
<td>270</td>
<td>5.4±0.2</td>
<td>1.1±0.5</td>
<td>4.6</td>
</tr>
<tr>
<td>18.4–19.1</td>
<td>1.8±0.2</td>
<td></td>
<td></td>
<td>1.6±0.2</td>
<td>0.69±0.08</td>
<td>1.4</td>
</tr>
<tr>
<td>19.1–20.1</td>
<td>1.8±0.2</td>
<td></td>
<td></td>
<td>1.1±0.1</td>
<td>92</td>
<td>2.2</td>
</tr>
<tr>
<td>20.1–21.2</td>
<td>1.0±0.2</td>
<td></td>
<td></td>
<td>1.0±0.1</td>
<td>80</td>
<td>2.2</td>
</tr>
<tr>
<td>21.2–22.5</td>
<td>0.72±0.22</td>
<td></td>
<td></td>
<td>0.70±0.06</td>
<td>95</td>
<td>0.8</td>
</tr>
<tr>
<td>Total</td>
<td>10.7±1.2</td>
<td>2.4±0.7</td>
<td>4.5±0.6</td>
<td>0.37±0.21</td>
<td>5.6±1.1</td>
<td></td>
</tr>
</tbody>
</table>

$^{a}E2$ ($l=j=0$) strength is not distinguished, but negligible (see the text).

$^{b}$Fitting the angular correlation for the entire energy region.

FIG. 6. Angular correlations for $\alpha_1$ decay from the indicated excitation energy regions of $^{28}$Si. Solid lines are angular correlations calculated with coherent mixing of decay amplitudes with parameters as listed in Table III.
Above the GR peak (> 20 MeV), alpha and proton decays are comparable, and the sum considerably exceeds the singles GR yield, no doubt reflecting decay of the continuum. Unfortunately, the presence of slit scattering in the singles spectrum prevents extraction of meaningful absolute decay branches above the GR peak.

For comparison, the branching ratios of statistical decays, estimated with a Hauser-Feshbach calculation using the nuclear evaporation code (with parity conservation) CASCADE, are shown for the decay from the GMR and GQR in Figs. 10(b) and 10(c), respectively. If the giant resonances are assumed to decay statistically, the branching ratio of neutron decay is 10−15% at $E_x > 18$ MeV, as shown in Figs. 10(b) and 10(c). This is also approximate-

\[ \text{angular correlation analysis and sum rules} \]

In order to obtain the strength of the GMR, GQR, and other multipoles present, angular correlation functions were calculated and fit to the data. The angular correlation for a particle decay from an isolated resonant state with a spin $I$, and $z$ component $m_z$, can be written as

\[ W(\hat{p}_b) = \sum_{m_b, m_z} g(I, m_r \rightarrow I m_b) T_{m_z} \]

(1)

where,

\[ g(I, m_r \rightarrow I m_b) = \sum_{ij} \langle I m_i s_h m_b | j m_j \rangle \langle I m_j m_i | I m_r \rangle \]

\[ \times Y^{m_i}_l(\hat{p}_b) g(I, \rightarrow I l j) \]

(2)

and $g(I, \rightarrow I l j)$ is a decay amplitude which has a phase as the phase shift of the nonresonant scattering in the decay channel and $|g(I, \rightarrow I l j)|^2$ gives a partial decay width $G(l \rightarrow I l j)$. The spin and $z$ component of the decay particle (residual nucleus) are given by $s_h$ and $m_b$ ($I$ and $m_z$), respectively, and $I$ and $j$ ($m_i$ and $m_j$) are orbital and total angular momentum ($z$ component) of the decay particle, respectively. The decay particle is emitted to the direction $p_b$. $T_{m_z}$ is the $m$-substate population of the resonant state. For alpha inelastic scattering on a spin-zero target, $T_{m_z}$ is given by a transition matrix which can be calculated in the distorted-wave Born approximation (DWBA).

If resonances are overlapping, the decay from different resonant states can interfere coherently.

DWBA calculations to obtain the $m$-substate population were carried out with the computer code DWUCK4, the usual form factors were used (for a detailed discussion of form factors used for the $L=0$ mode and the optical model parameters, see Ref. 5). The finite solid angles of the spectrometer and the decay detectors were taken into account in the calculation of the angular correlation. The correction for the finite opening angle of the spectrometer detector was important, as the correlation was somewhat washed out because the recoil angle of the target nucleus is large even for a small $\alpha'$ angle. For example, the recoil angle is $28^\circ$ for $E_x = 15$ MeV and $\Theta(\alpha') = 2^\circ$. Therefore, the angular correlation pattern for $L \geq 2$ shifts considerably over the angular opening of the spectrometer, washing out the pattern somewhat.

\[ \alpha_0 \text{ decay} \]

The experimental angular correlations were fitted with a coherent mixture of $E_2$ and $E_0$. Where small asymmetries were present, some $E_3$ admixture was added to the calculation. In Fig. 5, the best-fit results of the calculations with the coherent mixing are shown as solid lines. Parameters obtained from the $\chi^2$ fitting are listed in Table II. $\delta_l$ is the phase of the complex coefficient
in Eq. (2), and the fraction of the EWSR is obtained from \(|g(I_r \rightarrow Il)|^2\) as explained above. The procedure followed in the fits is described below. As the angular correlation is not a linear function of the parameters [the strength and phase of \(g(I_r \rightarrow Il)\)], the angular correlations were calculated at many points in the parameter space, and the parameter set which minimized \(\chi^2\) was obtained. An example of the "fitting" procedure is shown for the 17.2–18.4 MeV data in Fig. 11. First, strengths of 2.7% of the \(E_0\) EWSR and 0.37% of the \(E_2\) EWSR were obtained from a calculation assuming incoherent mixing. Angular correlations were then calculated with the coherent mixing for a wide range of parameters around these values and wide range of phase parameters, with coarse steps of parameter values. In Fig. 11, \(\chi^2\) for the fits are shown, for example, for \(E_2\) strengths of 0.28%, 0.69%, and 1.25% of the EWSR, respectively, with several \(E_0\) strengths from 0.67% to

![Graph showing angular correlations for \(^{28}\text{Si}(\alpha, \alpha'p_0)\) decay from the indicated excitation energy regions of \(^{28}\text{Si}\). Solid lines are calculated angular correlations with incoherent mixing of decay amplitudes with parameters as listed in Table IV.](image-url)
4.66% of the EWSR and phase parameters ($\delta_2 - \delta_0$) from 0° to 350°. There are two minima in the $\chi^2$ curve (around 100° and 250°) with about the same value. This phase ambiguity is normal and either value can be used. The best fit parameters were then obtained by varying the parameters in fine steps around the values near one minimum.

The sensitivity of $\chi^2$ to each parameter is also shown in Fig. 11, while Fig. 12 shows the extent to which the angular correlation can be changed by varying the parameters. The uncertainty in each parameter has been estimated from these variations taking into account the statistical errors and variations which could be caused by differing gates for each decay channel ($\alpha_0$ vs $\alpha_1$, etc.).

The forward-backward asymmetry present in some of the correlations was reproduced well by including a small amount of $E3$ strength, consistent with the study of $^{28}$Si GQR decay. No contributions from $E4$ were necessary

FIG. 9. Angular correlations for $p_{1,2}$ decay from the indicated excitation energy regions of $^{28}$Si.
to fit the data, in contrast with the singles results. In general, fits from the coherent mixing calculations resulted in a $\chi^2$ lower by a factor of 2–3 than for incoherent calculations. In Figs. 13 and 14, respectively, the distributions of the $E0$ and $E2$ strength and the phase difference ($\delta_2 - \delta_0$) are shown. It is interesting to note that the strength distributions of the $E0$ and $E2$ and even the phase differences show a gross structure.

**Other decay channels**

Only the $\alpha_0$ channel, decay of a spin-zero particle to a spin-zero final state, has a unique $l$ wave in the decay of the $E2$. In the other channels, decay can proceed through at least two $l$ waves, and extraction of meaningful parameters is more ambiguous. Results of an analysis of these channels is described below. In general, the same fitting procedures were applied as in the $\alpha_0$ case; however, it must be recognized that a number of assumptions which may be plausible but not rigorously defensible must be made to draw significant conclusions.

In the $\alpha_1$ decay channel ($0^+, 2^- \rightarrow 2^+$), $l = j = 0, 2,$ and 4 can contribute to the decay. The $l = j = 0$ component of the $E2$ decay was neglected for simplicity because the GQR decay study of $^{28}$Si (Ref. 15) has shown that this contribution was very small. In Fig. 6, the results of the

<table>
<thead>
<tr>
<th>$E_x$ (MeV)</th>
<th>$E0^*$ (% EWSR)</th>
<th>$E2$ ($l = 2, j = \frac{1}{2}$) (% EWSR)</th>
<th>$E2$ ($l = 2, k = \frac{1}{2}$) (% EWSR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.5-16.0</td>
<td>0.45±0.10</td>
<td>0.34±0.23</td>
<td>0.09±0.20</td>
</tr>
<tr>
<td>16.0-16.7</td>
<td>0.47±0.13</td>
<td>0.61±0.28</td>
<td>0.41±0.24</td>
</tr>
<tr>
<td>16.7-17.2</td>
<td>0.39±0.12</td>
<td>1.2±0.3</td>
<td>0.48±0.26</td>
</tr>
<tr>
<td>17.2-18.4</td>
<td>3.6±0.6</td>
<td>2.6±0.8</td>
<td>0.26±0.51</td>
</tr>
<tr>
<td>18.4-19.1</td>
<td>1.4±0.3</td>
<td>0.02±0.20</td>
<td></td>
</tr>
<tr>
<td>19.1-20.1</td>
<td>1.4±0.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20.1-21.2</td>
<td>1.3±0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21.2-22.5</td>
<td>0.97±0.33</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>10.0±2.4</strong></td>
<td><strong>4.8±1.8</strong></td>
<td><strong>1.2±1.2</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$E_x$ (MeV)</th>
<th>$E0^*$ (% EWSR)</th>
<th>$E2$ ($l = 2, k = \frac{1}{2}$) (% EWSR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.5-22.5</td>
<td>11.4$^b$</td>
<td>2.8$^b$</td>
</tr>
</tbody>
</table>

$^a$ $E2$ ($l = 0, j = \frac{1}{2}$) strength was not distinguished (see the text).

$^b$ Fitting the angular correlation for the entire energy region.

**FIG. 10.** (a) Experimental alpha and proton decay branching ratios of $^{28}$Si excited to the indicated excitation energy by 129 MeV alpha particles detected at 0°. Below the $E_x = 17.2$ MeV neutron threshold, $\alpha_{tot} + P_{tot}$ was assumed to be 100% of the decay. Above 17.2 MeV, only relative branching ratios could be determined (see the text). (b) and (c) are alpha and proton branching ratios for the GMR and GQR, respectively, predicted for statistical decay with Hauser-Feshbach calculations.
FIG. 11. \( \chi^2 \) as a function of phase angle for fits to the \( \alpha_0 \) angular correlation data in the \( E_x = 17.2-18.4 \) MeV region using a coherent mixing calculation for different values of \( E0 \) strength (0.67-4.66\% EWSR). (a), (b), and (c) show the results for three values of \( E2 \) strength: 0.28\%, 0.69\%, and 1.25\% EWSR, respectively. (d), (e), and (f) show \( \chi^2 \) for fits as a function of the \( E0 \) strength, \( E2 \) strength and phase \( 82-80 \), respectively, around the best fit parameters.

### TABLE V. \( E2 \) decay strength and branching ratios from \( ^{28}\text{Si}(\alpha,\alpha c) \) experiments.

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>( E_x ) (MeV)</th>
<th>Present study(^a) (% EWSR)</th>
<th>( ^{28}\text{Si}(\alpha,\alpha c)(^b) BR)</th>
<th>( ^{28}\text{Si}(\alpha,\alpha c)(^b) (% EWSR)</th>
<th>( ^{28}\text{Si}(\alpha,\alpha c)(^b) (BR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha_0 )</td>
<td>15.5–18.4</td>
<td>2.1±1.2</td>
<td></td>
<td>3.4±1.1</td>
<td>11±2%</td>
</tr>
<tr>
<td></td>
<td>18.4–22.5</td>
<td>1.2±0.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>15.5–22.5</td>
<td>3.3±1.5</td>
<td>8.0±3.7%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>16.9–24.8</td>
<td></td>
<td></td>
<td>3.4±1.1</td>
<td>11±2%</td>
</tr>
<tr>
<td>( \alpha_1 )</td>
<td>16.7–22.5</td>
<td>6.5±1.4</td>
<td>18±4%(^c)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>16.9–24.8</td>
<td></td>
<td></td>
<td>8.7±1.4</td>
<td>28±3%</td>
</tr>
<tr>
<td>( \rho_0 )</td>
<td>15.5–22.5</td>
<td>(7.0±1.7)(^d)</td>
<td>d</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>16.9–24.8</td>
<td></td>
<td></td>
<td>6.8±1.0</td>
<td>22±3%</td>
</tr>
<tr>
<td>( \rho_{1,2} )</td>
<td>15.5–22.5</td>
<td>(6.4±1.5)(^d)</td>
<td>d</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>16.9–24.8</td>
<td></td>
<td></td>
<td>6.2±1.0</td>
<td>20±3%</td>
</tr>
</tbody>
</table>

\(^a\)Branching ratio was obtained assuming an \( E2 \) strength of 32±6\% EWSR in the excitation region 15.3–23.0 MeV (Ref. 5).

\(^b\)Branching ratio (BR) comes from Ref. 15 in which the 15.4–24.8 MeV excitation region was studied. Decay strength was obtained using 31±1\% EWSR in the 16.9–24.8 MeV region for GQR from Ref. 31 and the branching ratio 11±2\% for \( \alpha_0 \) decay, 28±3\% for \( \alpha_1 \) decay, 22±3\% for \( \rho_0 \) decay, and 20±3\% for \( \rho_{1,2} \) decay from Ref. 15.

\(^c\)\( E2 \) strength assumed to be 29±5\% EWSR in the \( E_x = 16.9–23.0 \) MeV region from Ref. 5.

\(^d\)The \( \rho_0 \) and \( \rho_{1,2} \) branching ratios in Ref. 15 were used to obtain % EWSR (see the text) assuming total \( E2 \) strength from Ref. 5.
angular correlation calculations for the $\alpha_1$ decay are shown as solid lines. In contrast with the $\alpha_0$ decay channel, the experimental $\alpha_1$ angular correlations did not show distinct asymmetries, and $E3$ was not included in the fit. The strengths and phases obtained are listed in Table III. Best fits were obtained from coherent mixing of the $E0$ and $E2$ strength with almost the same phase difference ($\delta_2 - \delta_0$) as in the $\alpha_0$ decay for each energy bin.

In the 17.2–18.4 MeV region, two different sets of parameters gave almost equally good fits, as listed in the table. One has an $l = j = 4$ component from the GQR decay with the same phase difference (98°) as in the $\alpha_0$ decay and the other an $l = j = 2$ component with an almost opposite phase difference of 270° ($=-90°$), which is physically possible if the wave function with $l = j = 2$ has the opposite sign. The shape of the angular correlation in the 16.7–17.2 MeV region is very different from that expected for $E2$ decay and could not be reproduced in the calculations by coherent mixing of $E0$ and either $l = j = 2$ or 4 in the $E2$. The $E0$ and $E2$ strength distributions are shown in Fig. 11.

The angular correlations of the $p_0$ and $p_{1,2}$ decays are even more complicated than $\alpha_1$ because many decay components may compete. For example, in the $p_0$ decay there are components $(l,j) = (2,\frac{1}{2})$ for the $E0$ and $(0,\frac{3}{2})$, $(2,\frac{3}{2})$, $(2,\frac{5}{2})$, $(4,\frac{3}{2})$, and $(4,\frac{5}{2})$ for the $E2$. In the measured $p_{1,2}$ decay, the situation is yet more complicated because experimentally the residual states are an unresolved $\frac{1}{2}^+$, $\frac{3}{2}^+$ doublet. Therefore, coherent mixing calculations were not carried out for the proton decay. Nevertheless, several conclusions can be drawn. The $p_0$ angular correlations show a pattern symmetrical about 90° in the 15.5–18.4 MeV region, which favor the $(l,j) = (2,\frac{1}{2})$ and $(2,\frac{3}{2})$ components for $E2$ as well as $E0$ decay. Angular correlation calculations assuming incoherent mixing of a few components are shown in Fig. 8, and the parameters obtained are listed in Table IV. In the 18.4–22.5 MeV region, except for several data points at forward angles with enhanced cross sections, the data are isotropic.

**DISCUSSION**

It is interesting to compare the coincidence spectra obtained in this study (Fig. 3) with those of the $^{28}$Si($\alpha,\alpha'\gamma$) coincidence experiment of Ref. 15, in which $\alpha'$ was measured at $\theta_{lab}=6.5°$ and therefore showed mainly $E2$ decay strength. The coincidence spectra at $\theta_{lab}=155°$ (opposite the recoil) of the present measurement have similar structure to the corresponding one of Ref. 15 (opposite the recoil), but the 17.5 MeV peak in the $\alpha_1$ and $p_0$ decay and the structure around 18 MeV in the $p_{1,2}$ decay are enhanced in the present work. From the correlations, these are attributed primarily to $E0$ decay. In Refs. 14 and 15, the fact that the $\alpha_0$ decay channel was weakly coupled to the GQR and did not reflect the strength distribution of the $E2$ in the singles spectrum, was attributed to the existence of a complicated doorway state rather than a doorway state, while a doorway state was suggested from the strong correlation of the strength distribution between the $p_{10}$, $p_{1,2}$, and $\alpha_1$ decay channel and the singles spectrum. In the present measurements also the $\alpha_0$ channel shows the least correspondence to the singles spectrum. The $p_{1,2}$ strength distribution is, however, a little different from the singles which shows a minimum near $E_\gamma=18$ MeV. On the other hand, as shown in Fig. 3, the coincidence spectrum at 25° differs more from the singles than does the 155° spectrum. There is different
TABLE VI. $\gamma_0$ decay strength and branching ratios from $^{28}\text{Si}(\alpha,\alpha\gamma)$ experiments.

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>$E_x$ (MeV)</th>
<th>Present study ($%$ EWSR)</th>
<th>BR$^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_0$</td>
<td>15.5–22.5</td>
<td>9.2±1.6</td>
<td>18±6</td>
</tr>
<tr>
<td>$\alpha_1$</td>
<td>16.7–22.5</td>
<td>10.7±1.2</td>
<td>24±8</td>
</tr>
<tr>
<td>$p_0$</td>
<td>15.5–22.5</td>
<td>12.2±3.3</td>
<td>23±9</td>
</tr>
<tr>
<td>$p_{1,2}$</td>
<td>15.5–22.5</td>
<td>9.5±3.3</td>
<td>18±8</td>
</tr>
</tbody>
</table>

$^a$Using 52±16% for $\gamma_0$ strength in the $E_x = 15.5–22.5$ MeV region obtained from Ref. 5.

$^b$Using 44±13% for $\gamma_0$ strength in the $E_x = 16.7–22.5$ MeV region obtained from Ref. 5.

enhancement for several peaks between these angles, especially in the $\alpha_0$, $p_0$, and $p_{1,2}$ decay and somewhat in the $\alpha_1$ decay spectra. This results in asymmetry in the angular correlation which was fit, for $\alpha_0$ decay, with coherent mixing of the $E3$ decay amplitude. In the proton decay channels, however, the knockout process probably contributes to the asymmetry.\textsuperscript{19,20}

The ratios between the forward/backward peak and the 90° peak in the $\alpha_0$ and $\alpha_1$ angular correlation data could be fit only with coherent mixing. The necessity of using a coherent mixing calculation for angular correlations was demonstrated previously in the $\alpha_0$ decay from the GQR of $^{16}\text{O}$ (Ref. 26), $^{24}\text{Mg}$ (Ref. 27), and $^{28}\text{Si}$ (Ref. 15) which showed forward-backward asymmetry and required mixing of opposite parity multipoles.

In the $p_0$ and $p_{1,2}$ decay, the fitting procedure for the angular correlation was complicated and the decay strength could not be obtained unambiguously. However, a rough estimate of the $\gamma_0$ and $E2$ decay strength of the $p_0$ and $p_{1,2}$ decay was obtained in the following way. The cross sections calculated with DWBA for $\gamma_0$ and $E2$ states each at $E_x = 18.7$ MeV with 100% of the EWSR, averaged over the finite solid angle of the spectrograph, are 81 mb/sr for $\gamma_0$ and 61 mb/sr for $E2$. From the singles experiment of Ref. 5, an $E2$ strength of 32±6% EWSR (with the same procedure used in the present study to extract the isoscalar transition strength) was found in the $E_x = 15.3–23.0$ MeV region. Using the $p_0$ decay

![FIG. 13. $\gamma_0$ and $E2$ strength distributions obtained for $\alpha_0$ and $\alpha_1$ decay channels (coherent mixing).](image-url)
branching ratio of $22\pm3\%$ reported for the $^{28}$Si GQR in Ref. 15, the cross section attributable to $E2$ decay is $4.3\pm1.1\text{ mb/sr}$. From the Legendre polynomial fits, a total $p_0$ decay cross section of $14.2\pm2.5\text{ mb/sr}$ was obtained, of which $9.9\pm2.7\text{ mb/sr}$ would then be $E0$ if only $E0$ and $E2$ contribute. These cross sections correspond to $7.0\pm1.7\%\text{ EWSR}$ for $E2$ and $12.2\pm3.3\%\text{ EWSR}$ for $E0$. In the same way, if the $p_{1,2}$ branching ratio $20\pm3\%$ for $E2$ (Ref. 15) is assumed and the cross section $11.6\pm2.4\text{ mb/sr}$ for the $p_{1,2}$ decay from the Legendre polynomial fits is used, the decay cross sections $3.9\pm1.0\text{ mb/sr}$ for $E2$ and $7.7\pm2.7\text{ mb/sr}$ for $E0$ are obtained, which correspond to $6.4\pm1.5\%\text{ EWSR}$ for $E2$ and $9.5\pm3.3\%\text{ EWSR}$ for $E0$.

The $E0$ and $E2$ strength and the branching ratio obtained in this study are summarized in Table V for $E2$ and in Table VI for $E0$, along with the results from the $^{24}$Mg($\alpha,\gamma$) reaction and the $^{28}$Si($\alpha,\alpha'$) GQR coincidence experiment. The present result for the $E2$ decay strength to the $a_0$ decay channel is in good agreement with both experiments. The $E2$ decay strength to the other decay channels is also in reasonable agreement with Ref. 15 within error, but the $a_1$ decay branch obtained is somewhat smaller than reported in Ref. 15. As shown in Table III, the decay strength of the $l=j=4$ component was strong in $a_1$ decay of the GQR. The dominance of $l=j=4$ component was also found in the alpha decay of the GQR in $^{28}$Si (Ref. 15) and $^{16}$O (Ref. 26) to the first excited state (2$^+$) of the residual nucleus and was explained by a strong overlap of the lp-1h configuration of the GQR with an alpha cluster $^{24}$Mg$+\alpha$ ($l=2$). The branching ratios into each of the observed channels for the $E0$ were obtained by comparing the absolute cross section of the observed $E0$ decay to the total $E0$ strength observed in the singles for the same energy region. They are summarized in Table VI. The total $E0$ decay observed to the $a_0$, $a_1$, $p_0$, and $p_{1,2}$ decay channels corresponds to $42\%$ of the $E0$ EWSR; $76\%$ of the monopole strength seen in singles. The $a_0$ and $p_0$ branching ratio for the $E0$ is larger than the corresponding ratio for the $E2$. This contrasts with the $^{28}$Si($e,e'c$) results of Kihm et al., where the $E0$ component of $a_0$ decay was found to be only $40\%$ of the $E2$ component. Their analysis is quite model dependent, however. Schmid reported a microscopic calculation of the structure of the GMR in $^{28}$Si, with angular momentum projected Hartree-Fock and the particle-hole model. Only $30\%$ of the EWSR strength, which was spread over a wide excitation energy region $E_x \sim 10$–$56\text{ MeV}$, was predicted in their model. The missing strength was attributed to the truncated configuration space employed in the calculation. From the large decay branches for the $p_0$ and $p_{1,2}$ channels (spin-parity for the residual states, $\frac{5}{2}^+, \frac{1}{2}^+$, and $\frac{3}{2}^-$) observed in the present experiment, large contributions to the transition strength may be expected from $2\hbar\omega$ lp-1h excitations into the 3s and 2d orbits, which were not included in Schmid’s calculation. There have been few experimental studies of the GMR decay, but the $30\%$ branch of the $a_0$ decay for the GMR in $^{40}$Ca, recently found by Brandenburg et al., is comparable to the $18\%$ branch obtained in the present work for $^{28}$Si. The large alpha decay branch suggests that alpha clustering could be important in the GMR in light nuclei.

The singles data obtained in this experiment are consistent with those of Ref. 5, with the same integrated giant resonance cross section and the same $E0$ strength; the DWBA calculations were done with the same transition potentials and optical parameters. Thus the branching ratios obtained in the present studies which rely on the singles data of Ref. 5 should be model independent, but the absolute strengths are model dependent. As an illustration of the model dependence of the strengths, the cross sections calculated with DWBA for both a GMR and a GQR located at 18.7 MeV in $^{28}$Si and excited with 129 MeV alpha inelastic scattering and detected at $0^\circ$, for differing models of the form factors and differing optical potentials are listed in Table VII. The first potential was used in the present study; the other was used in the GQR study of 120 MeV alpha inelastic scattering. Although the cross sections obtained for the $E2$ are not very sensitive to the parameters, there exist large differences in the predicted $E0$ cross sections. This problem is beyond the extent of the present study, and more experimental and theoretical efforts are needed to resolve these uncertainties.
CONCLUSIONS

Proton and alpha decay from the giant resonance region ($E_x = 15.5 - 22.5$ MeV) of $^{28}$Si was measured in coincidence with inelastic alpha particles at 0°. E0 and E2 states were selectively excited by inelastic scattering and decayed mainly to the low-lying states of the residual nuclei by emission of alpha particles and protons. The quasi-free knockout process did not contribute significantly to the $\alpha_0$ and $\alpha_1$ decay channels in the angular range $\theta_d = 25^\circ - 155^\circ$ of the decay detector, but did contribute in the $p_0$ and $p_{1,2}$ decay channels at forward angles, $\theta_d = 25^\circ - 50^\circ$. The coincidence spectrum showed fine structure and the angular correlation showed the interference of decay amplitudes from these overlapping resonances.

The E0 and E1 strengths and the branching ratios obtained for the main decay channels are summarized in Tables V and VI. The results for E2 decay are in good agreement with $\alpha$ capture

21 and a $^{28}$Si($\alpha,\alpha'$) coincidence GQR experiment. The E0 strength (% EWSR) obtained is $9.2 \pm 1.6 \%$ for $\alpha_0$, $12.2 \pm 3.3 \%$ for $p_0$, and $9.5 \pm 3.3 \%$ for $p_{1,2}$ in the 15.5 - 22.5 MeV excitation region and $10.7 \pm 1.2 \%$ for $\alpha_1$ in the 16.7 - 22.5 MeV region. The total (42% of E0 EWSR) represents 76% of the E0 strength found in the singles measurement.

These decay strengths correspond to branching ratios, $18 \pm 6 \%$ for $\alpha_0$, $24 \pm 8 \%$ for $\alpha_1$, $23 \pm 9 \%$ for $p_0$, and $18 \pm 8 \%$ for $p_{1,2}$. The branching ratios for $\alpha_0, \alpha_1$, and $p_0$ exceed the expected ratio from the statistical decay calculation. In the $p_0$ and $\alpha_1$ decay, the difference is a factor 2 - 4, strongly suggesting direct decay. In addition, the necessity of using a coherent treatment of the several contributions to fit the $\alpha$ angular correlation data also suggests the GMR in $^{28}$Si decays predominantly by a direct process. Similar direct contributions to decay have been observed in the GQR in $^{28}$Si (Ref. 15) and in $^{58}$Ni (Ref. 33).

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