# Excited-State Giant Dipole Resonances in $(p, \gamma)$: A New Probe of Single-Particle Strengths

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The $(p,\gamma)$ reaction populating highly excited states in $^{28}$Si is shown to be dominated by giant dipole resonances built upon one-particle, one-hole states. Each giant resonance is centered at $E_\gamma \approx 20$ MeV, with a width which increases with the energy of the one-particle, one-hole state, and with a strength that is simply related to the proton stripping strength to the same final state.

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We present here the results of a high-resolution study of the reaction $^{27}$Al$(p, \gamma)^{28}$Si at intermediate energies which provide new insight into the $(p, \gamma)$ reaction as well as the nature of giant dipole resonances (GDR's) built upon excited states. Our results demonstrate that the $(p, \gamma)$ reaction is highly selective, populating one-particle, one-hole (1p-1h) residual states of both $0\hbar\omega$ and $1\hbar\omega$ character, where $\hbar\omega$ is the usual shell-model oscillator energy. We observe a series of GDR's built on different final states and examine their properties. The integrated resonance strengths are found to be closely related to the spectroscopic factors for proton transfer to these same final states, suggesting that $(p, \gamma)$ may be a more useful tool than conventional stripping reactions for exploring single-proton strength distributions at high excitation energies.

Previous studies[1] of several radiative capture reactions at intermediate energies ($E_p = 24-80$ MeV), including primarily the reaction $^{11}$B$(p, \gamma)^{12}$C, have shown enhanced transitions corresponding to GDR decays[1,2] populating excited final states. These final states are thought to be primarily $1\hbar\omega$ 1p-1h states[3] although experimentally they are not resolved from neighboring levels of different structure.

Our $^{27}$Al$(p, \gamma)^{28}$Si measurements were made using the two-stage and three-stage tandem accelerators at the University of Washington (UW) for $E_p = 11$ to 24 MeV and at Brookhaven National Laboratory (BNL) for $E_p = 14$ to 39 MeV. $\gamma$ rays were detected at $\theta_\gamma = 90°$ in similar large NaI spectrometers with resolution 3.8% at UW and 2.3% at BNL for $E_\gamma = 20$ MeV. Most of the data were taken with a self-supporting Al foil of thickness 0.9 mg/cm$^2$ and dc proton beam currents of 50 to 1500 nA. The collected charge was typically 9 mC.

A selected $\gamma$-ray spectrum is shown in Fig. 1. The strong peaks observed in these spectra shift with $E_p$ according to $E_\gamma = (27/28)E_p + Q$ for fixed values of $Q$, indicating that they arise from radiative capture to final states in $^{28}$Si located at energies $E_x{}^f = 11.58$ MeV $- Q$. For $E_p \geq 19$ MeV all spectra show four strong peaks in the range $E_x{}^f = 10-15$ MeV, corresponding primarily to the population of the $E_x{}^f$ $(J^\pi, T) = 14.36$ MeV $(6^-, 1)$, 13.25 $(5^-, 1)$, 12.65 $(4^-, 1)$, and 11.58 $(6^-, 0)$ levels. These levels are known from proton-transfer studies[5,6] to have predominantly $1\hbar\omega$ 1p-1h $(1f_{7/2}, 1d_{5/2}{}^{-1})$ structure. Strong $(p, \gamma)$ transitions are apparent to other states which are also strongly populated in proton transfer,[5] as shown in Fig. 1. In fact *all* structures in our spectra may be correlated with states (or groups of states) with significant proton transfer strength. Accordingly, we fitted our spectra with a sum of line shapes of variable amplitudes, but with positions fixed (relative to $\gamma_0$) at the locations of states or groups of states with significant proton transfer strength, as shown in Fig. 1. This procedure provides good fits to all of our spectra in the region where structure is observed ($E_x{}^f < 15$ MeV). Pulse-pileup corrections of up to 20% were applied to our spectra in the region $E_\gamma = 16$

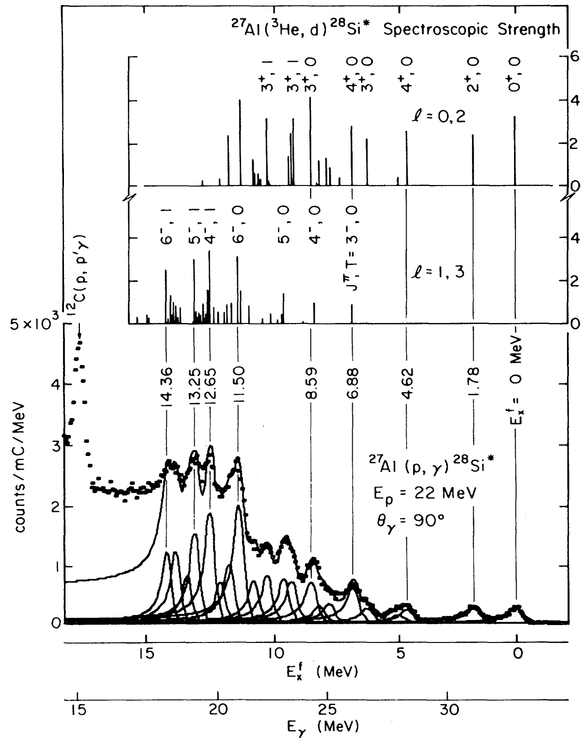


FIG. 1. Bottom: $^{27}$Al$+p$ BNL $\gamma$-ray spectrum with line-shape decomposition. Top: $^{27}$Al($^3$He, $d$)$^{28}$Si single-proton spectroscopic factor $(2J+1)C^2S$ (Ref. 4). Vertical lines indicate the correspondence of proton capture and proton stripping for some of the strong $\gamma$ transitions.

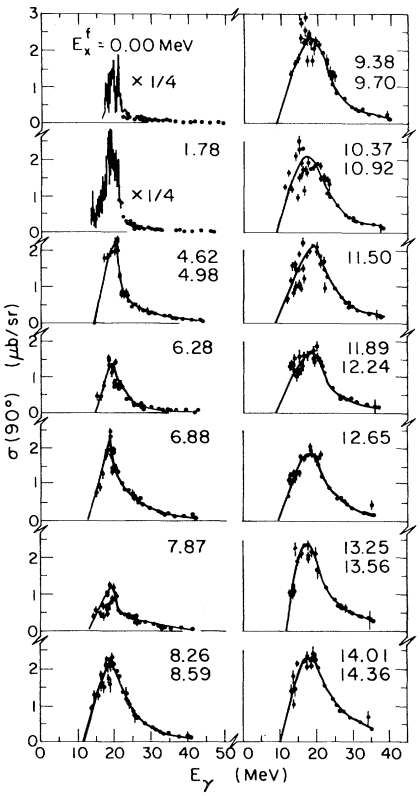


FIG. 2. $\sigma(90°)$ vs $E_\gamma$ for $^{27}$Al$(p,\gamma)^{28}$Si* transitions, labeled by $E_x{}^f$ (MeV) (several $E_x{}^f$ values indicate summed strength). The most important final-state $J^\pi$,$T$ values may be seen by comparison with Fig. 1. The hand-drawn curves were used for calculating the integrated strengths shown in Fig. 3.

to 19 MeV. Neutron backgrounds were negligible, as verified by pulsed-beam time-of-flight measurements.

The cross sections $\sigma(90°)$ obtained from these fits are shown in Fig. 2, labeled by the values of $E_x{}^f$ used in fitting the spectra. The $\gamma_0$ and $\gamma_1$ data for $E_p < 12$ MeV are taken from Singh *et al.*[4] All of the excitation functions show resonance shapes which peak at progressively higher $E_p$ for transitions to higher $E_x{}^f$. However, when plotted as a function of $E_\gamma$, the excitation energy above the final state, all resonances are centered at approximately $E_\gamma = 20$ MeV as shown in Fig. 2. The resonances all have strengths proportional to proton-stripping spectroscopic factors, as discussed below. The only plausible explanation for these resonances is that they are all due to a common mechanism; namely, giant dipole excitations of the different final states. The constancy of the $\gamma$-ray resonance energy for the various GDR's shown in Fig. 2 follows the "Brink-Axel" hypothesis.[7]

The observed resonance widths increase almost monotonically from $\Gamma \cong 4.5$ to 12 MeV as $E_x{}^f$ increases from 0.0 to 14.4 MeV (Fig. 3). Thus the resonance widths seem not to depend strongly on the nature of the final states, which include both positive-parity $0\hbar\omega$ 1p-1h excitations within the *sd* shell, and negative-parity $1\hbar\omega$ 1p-1h excitations from the *sd* to the *fp* shell, with isospins $T=0$ and 1.

A particularly interesting feature of our results is a quantitative relation between the proton capture and stripping strengths. In Fig. 3 (bottom) we compare the integrated inverse strengths[8] $I = \int (2J+1)\sigma(\gamma, p_0) dE_\gamma$ with the proton transfer spectroscopic strengths $\sum (2J+1)C^2S$, where the sum is over all $l = 0+1+2+3$ stripping strengths[5] in the energy intervals appropriate for the fitted $(p,\gamma)$ strengths. Here we use the relation

$$(2J+1)\sigma(\gamma, p_0) = 12(938 \text{ MeV})\,(27/28)^2 (E_p/E_\gamma{}^2)\sigma(p,\gamma)$$

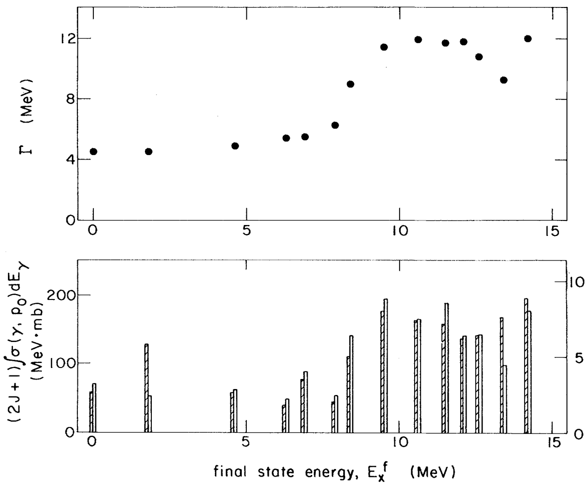


FIG. 3. Top: GDR width Γ vs final-state energy $E_x{}^f$ for $^{27}Al(p,\gamma)^{28}Si$. Bottom: hatched bars and left scale, integrated strengths $(2J+1)\int\sigma(\gamma,p_0)dE_\gamma$; open bars and right scale, single-proton spectroscopic strength $\Sigma(2J+1)C^2S$.

obtained from detailed balance. Figure 3 indicates the existence of a strong correlation of the form $I=K\sum(2J+1)C^2S$. A value for the proportionality constant, $K$, of $\approx 22$ MeV mb fits most[9] of the observed transitions within experimental error. We have repeated the same analysis using $^{28}Si(p,\gamma)^{29}P$ data of Lim *et al.*[10] for GDR capture to low-lying $\frac{1}{2}^+$, $\frac{3}{2}^+$, $\frac{7}{2}^-$ final states (predominantly $2s_{1/2}$, $1d_{3/2}$, and $1f_{7/2}$ single-proton states, respectively) as shown in Fig. 4. The integrated strengths[10] for these three transitions correspond[11] to a constant value of $K$ equal to that deduced from $^{27}Al(p,\gamma)^{28}Si$. The existence of such a simple relation between proton capture and stripping strengths is a remarkable quantitative demonstration of the simplicity of the capture process.

Both the magnitude of the proportionality constant $K$ and its approximate state independence can be understood in a simple manner.[10,12] Using harmonic-oscillator matrix elements in a direct-emission model, we calculate $K=25$, 25, and 30 MeV mb for $2s_{1/2}$, $1d_{3/2}$, and $1f_{7/2}$ single-proton states, respectively, in reasonably good agreement with experiment. Interestingly, these same $K$ values follow for GDR $p_0$ emission where the $p_0$ branching ratio is determined by the schematic model GDR amplitude for the valence proton. Thus the GDR collectively alters the energy distribution of the $(\gamma,p_0)$ cross sections but, to a good approximation, does not change the integrated $(\gamma,p_0)$ strengths.

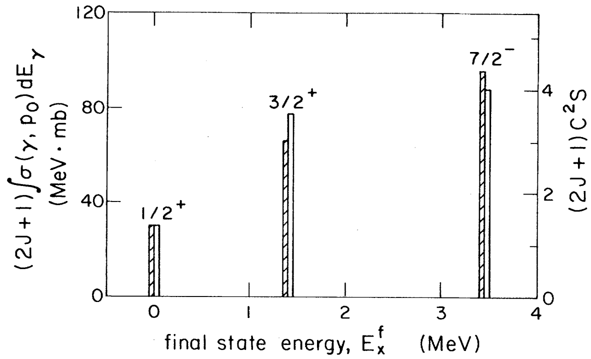


FIG. 4. Integrated $(\gamma,p_0)$ strengths from the reaction $^{28}Si(p,\gamma)^{29}P$ (Ref. 10) compared to single-proton spectroscopic strength, as in Fig. 3.

In conclusion, the $(p,\gamma)$ reaction is dominated by a doorway (nonstatistical) GDR capture process, in contrast to heavy-ion capture,[13] which is dominated by a statistical GDR reaction mechanism. The $(p,\gamma)$ reaction selects GDR's built upon final states which have a structure similar to the proton entrance channel; that is, one-particle, one-hole final states.[3] The integrated GDR strengths are, to a good approximation, directly proportional to the proton transfer spectroscopic factors, independent of the final-state configuration of the captured proton. One should contrast this simplicity with the well-known difficulties in the distorted-wave Born-approximation analysis of conventional stripping reactions populating highly excited, often overlapping levels in the continuum.

This suggests that the $(p,\gamma)$ reaction may be the best way to explore single-proton strength distributions at high excitation energies in the residual nucleus. Our $^{27}Al(p,\gamma)^{28}Si$ data for $E_p \gtrsim 30$ MeV indicate a great deal of capture strength to unresolved final states with $15 < E_x{}^f < 35$ MeV, corresponding to spectroscopic strength of magnitude comparable to that presented here for $E_x{}^f < 15$ MeV. This higher-energy strength along with a more detailed account of the present results will be discussed in a future publication.

We wish to thank the authors of Ref. 10 for permission to quote their results prior to publication.

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[8]We approximate our total cross sections by $\sigma(p,\gamma) \cong (4\pi/1.15)\sigma(90°)$. The $\gamma_0$ and $\gamma_1$ results are from Ref. 4.

[9]Exceptions are the 13.25 + 13.56-MeV group, for which the stripping strength is partially obscured by contaminants, and the $\gamma_1$ transition.

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