[18]R. Giovanelli, Astron. J. 85, 1155 (1980).
[19]P. R. Shapiro and G. B. Field, Astrophys. J. 205, 762 (1977).
[20]F. B. Jenkins and E. J. Shaya, Astrophys. J. 231, 55 (1979).
[21]L. Spitzer, Astrophys. J. 124, 20 (1956).
[22]L. Spitzer, *Physical Processes in the Interstellar Medium* (Wiley, New York, 1978), p. 107.
[23]A. Songaila, Astrophys. J. Lett. 243, L19 (1981).
[24]N. G. Bochkarev and R. A. Syunyaev, Astron. Zh. 54, 957 (1977) [Sov. Astron. 21, 542 (1977)].
[25]G. B. Field, Astrophys. J. 142, 531 (1965).
[26]P. R. Shapiro and G. B. Field, Astrophys. J. 236, 577 (1980).
[27]J. N. Bregman, Astrophys. J. 236, 577 (1980).
[28]D. W. Sciama and A. L. Melott, to be published.

Direct Decays of the Isoscalar Giant Quadrupole Resonance in ^{28}Si

K. T. Knöpfle,[(a)] H. Riedesel,[(b)] K. Schindler, and G. J. Wagner
Max-Planck-Institut für Kernphysik, D-6900 Heidelberg, West Germany

and

C. Mayer-Böricke, W. Oelert, M. Rogge, and P. Turek
Institut für Kernphysik der Kernforschungsanlage Jülich, D-5170 Jülich, West Germany
(Received 20 March 1981)

The isoscalar giant quadrupole resonance in ^{28}Si, studied by ^{28}Si$(\alpha, \alpha' c)$ angular correlation experiments (in which the charged particle $c = \alpha_0$, α_1, p_0, $p_{1,2}$), constitutes the first obvious case of a dominant direct nucleon decay of a giant quadrupole resonance.

PACS numbers: 24.30.Cz, 23.90.+w, 25.60.Cy, 27.30.+t

The general question of the damping of high-frequency nuclear vibrations is of definite interest, but many important issues are not well understood theoretically or experimentally.[1] Does the initial coherent one-particle–one-hole (1p-1h) excitation decay in a "direct decay" by emitting the unbound nucleon, leaving the residual nucleus in specific hole states, or is the information on the 1p-1h configuration lost in a slower "statistical decay" through more complex np-nh degrees of freedom and the eventual evaporation? Random-phase approximation (RPA) continuum calculations predict direct decay to be unimportant in heavy nuclei for both the isoscalar giant quadrupole resonance (GQR) and the giant dipole resonance (GDR); for the GQR this prediction holds even for very light nuclei ($A \sim 16$).[1] Experimentally, the results of the few kinematically complete studies of the GQR decay have been found to be compatible with the assumption of statistical decay in the mass region $A \sim 40$–70.[2-4] On the other hand, a ^{16}O$(\alpha, \alpha' c)$ coincidence experiment[5] (in which $c = \alpha_0, \alpha_2, p_0, p_{1,2}$) gives the first evidence for a dominant direct decay of a GQR which surprisingly did not manifest itself in a nucleon but rather in the α-decay channel. Significantly, this observation was traced back later to the microscopic SU(3) structure of the GQR.[6] We briefly present here some results of an extensive study[7] of the GQR decay in ^{28}Si which exhibits for the first time the characteristics expected for direct decay, namely a resonant strength distribution in specific nucleon (proton) channels.

The charged-particle (c) decays from the GQR region in ^{28}Si were studied via the ^{28}Si$(\alpha, \alpha' c)$ reaction with use of the momentum-analyzed 155-MeV α-particle beam from the Jülich cyclotron. The α' particles were detected by two ΔE-E telescopes at fixed angles of $\theta_{\alpha'} = 6.5°$ and $13.5°$, corresponding to the second and third maximum of the $L = 2$ (α, α') angular distribution. As described previously,[4,5] decay products were measured in coincidence by four sets of ΔE-E_1-E_2 telescopes providing a unique particle identification for energies $E_c \geq 2.8$ MeV. The measured in-plane angular correlation functions (ACF's) cover the range of laboratory angles θ_c between $-40°$ and $-260°$ $(+100°)$ including both the direction parallel ($\theta_R = -56°$ for $E_x = 19$ MeV) and antiparallel to the recoiling excited ^{28}Si nucleus.

Figure 1 shows a singles α' energy spectrum taken during the coincidence runs at 6.5° with a resolution of 180 keV. The data agree well with those from previous (α, α') experiments[8,9] confirming both the deduced centroid energy ($\langle E_x \rangle = 19.7$ MeV) and width ($\Gamma_{\text{FWHM}} = 5.1$ MeV) of the GQR covering the range of excitation energy of

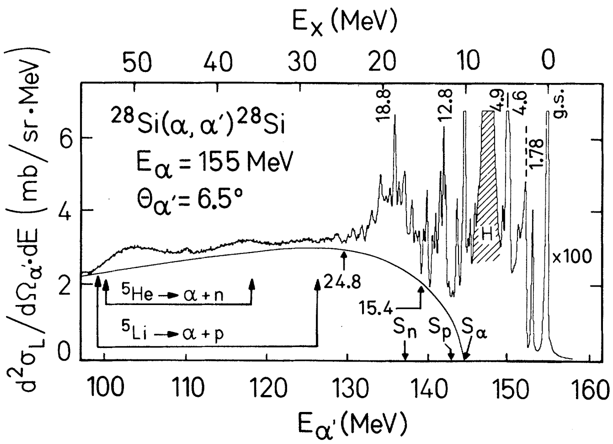

FIG. 1. The ^{28}Si(α,α') singles spectrum measured at 6.5°. An H_2 contaminant is marked by the shaded area; the particle (x) thresholds S_x and the kinematic limits for α particles from mass-5 breakup are indicated.

$15.4 \leq E_x \leq 24.8$ MeV. From the presence of fine structure which has been shown[10] to exhibit signatures[11] of intermediate structure we might already suspect an incomplete damping of the early doorway configurations into the compound levels. In an adjacent nucleus with a higher level density like ^{27}Al, the GQR shows much less dramatic amplitude modulations.[12]

Following a suggestion of Balashov *et al.*,[13] we present, in Figs. 2(b)–2(e), the (α, α') strength distributions of the relevant decay channels ($c = \alpha_0, \alpha_1, p_0, p_{1,2}$) as observed in "antiquasifree kinematics" demanding particle c to be detected opposite to the recoil direction ($\theta_R + 180°$). Nonsequential quasifree scattering (QFS) contributions to the measured $\alpha'c$ coincidence yields are thus minimized. As a unique feature we observe in the GQR region both in the α and p channels an impressive peak-to-background enhancement relative to the singles spectrum (Fig. 1). These resonant strength distributions indicate different modes of disintegration of the GQR and the underlying continuum, and thus our coincidence requirement enhances the decays of the GQR over the evaporation process; note that the decay energies in the displayed channels are all well above the Coulomb barrier.

Figures 2(b)–2(e) show that different parts of the GQR exhibit strongly different decay branches; at $E_x = 17.6$ MeV we observe, for example, a particularly strong α_1 decay. The correlation between the fine-structure peaks in the singles and coincident spectra is considered evidence[14,15]

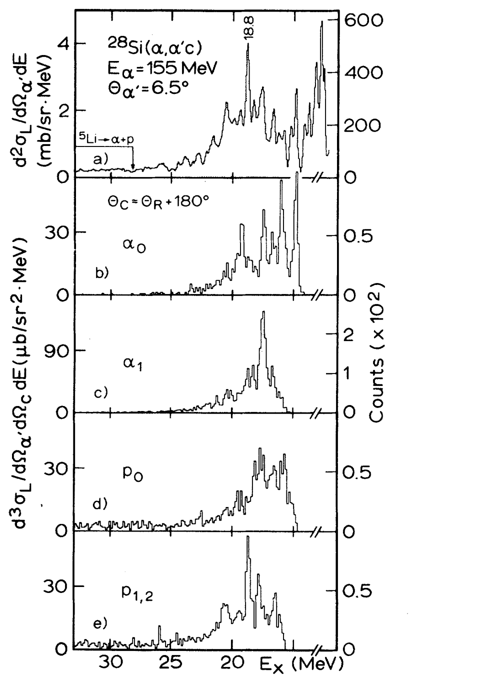

FIG. 2. (a) The enlarged part of the ^{28}Si(α,α') singles spectrum at 6.5° with the background (see Fig. 1) subtracted; (b)–(e) the ^{28}Si($\alpha,\alpha'c$) spectra measured in coincidence with α decay leading to the ground (α_0) and first excited (α_1) state in ^{24}Mg, and with protons decaying to the ground state (p_0) and first excited doublet ($p_{1,2}$) in ^{27}Al. The decay particles were detected at about the opposite ^{28}Si recoil direction.

for an intermediate structure phenomenon.[11] We note here the general similarity of the total $E2$ strength in the singles spectrum [Fig. 2(a)] with that in the $p_{0,1,2}$ decay channels. Since all these p channels lead to known[16] hole states in ^{27}Al, we observe a feature expected for a direct decay from the primary 1p-1h doorway states. This represents a nontrivial result when contrasted with the strikingly different behavior of the GQR in ^{16}O where the weak strength in the p channels has a flat nonresonant shape.[5]

ACF's for α_0, α_1, p_0, and $p_{1,2}$ decay from the GQR are given in Fig. 3. An incoherent background was subtracted in those (α, $\alpha'c$) spectra measured at decay angles close to the recoil axis; there the contributions from nonsequential QFS processes are known to take their maximum value. These (large) background corrections were estimated by comparing the (α, $\alpha'c$) yields in question with those measured in antiquasifree kinematics, and the deduced shapes of the QFS continuum turn out[7] to be surprisingly well de-

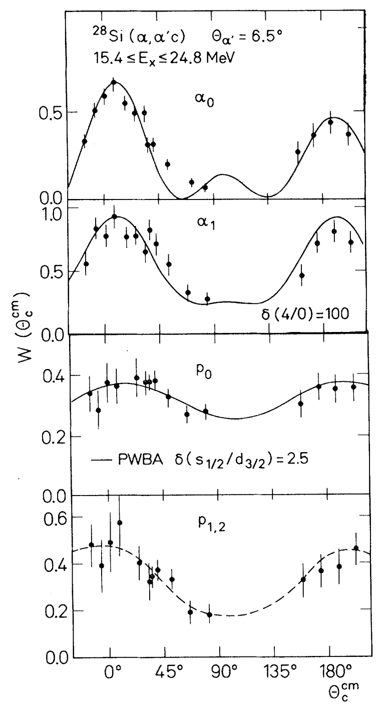

FIG. 3. The measured ACF's for α_0, α_1, p_0, and $p_{1,2}$ decay from the indicated GQR region in ^{28}Si; angles are measured with respect to the ^{28}Si recoil direction. The solid curves are PW fits that assume 98% $E2$ and 2% $E3$ cross section: deduced mixing parameters $\delta(L/L') = (\Gamma_L/\Gamma_{L'})^{1/2}$ are inserted. The dashed curve serves to guide the eye.

scribed in simple plane-wave (PW) impulse approximation. Even after substracting a maximum of incoherent background, the α_0 ACF still exhibits a strong forward-backward asymmetry indicating, according to Bohr's theorem,[17] the interference with additional overlapping multipole strength of opposite parity. The same interference phenomenon has also been observed[5] in ^{16}O and it proves[15] that the α_0 decay is a fast "direct decay" process. This result is obtained either from interference with fast QFS amplitudes, implying a short lifetime of the intermediate resonance in the sequential decay, or from interference with another resonance of opposite parity but before the compound stage is reached, else symmetry about $\theta_c = 90°$ would be restored from phase averaging. In fact, calculations based on the assumption of a dominant $E2$ strength interfering with a weak (2%) $E3$ amplitude and the PW Born approximation nicely reproduce the experimental α_0, α_1 and p_0 ACF's (solid curves in Fig. 3). No fit was attempted to the $p_{1,2}$ ACF since the final states could not be resolved.

TABLE I. Experimental branching ratios for the particle decay of the GQR in ^{28}Si into channel x and comparison with Hauser-Feshbach (HF) predictions. The quoted experimental values are an average of two measurements at $\theta_{\alpha'} = 6.5°$ and 13.5° which agree within 20%. The given errors include an estimate of the uncertainty in the background yield subtraction. Σ denotes summation over all open channels.

	Γ_x/Γ (%)	
x	Expt.	HF
α_0	11 ± 2	8
α_1	28 ± 3	18
$\alpha_{2,3}$	12 ± 2	9
$\Sigma\alpha_i$		39
p_0	22 ± 3	9.5
$p_{1,2}$	20 ± 3	10.5
p_{3-6}	9 ± 2	8
p_{7-10}	5 ± 2	7
Σp_i		54
Σn_i		7

The branching ratios of Table I were obtained by integrating the experimental in-plane ACF's and assuming axial symmetry (PW) about the recoil axis. The summed partial widths of all observed charged-particle decays account for the total decay width within the 20% estimated error. This is not surprising because of the high neutron threshold of 17.2 MeV in ^{28}Si. We find the dominant part (70%) of the total $E2$ strength in the α_1, p_0, and $p_{1,2}$ channels. As in ^{16}O,[5] the α_0 branch is weak but $\sum\Gamma_\alpha/\sum\Gamma_p$ changes from about 5 in ^{16}O to 1 in ^{28}Si, emphasizing the large p branches of the GQR in the latter nucleus. For comparison, Table I also lists the Hauser-Feshbach (HF) predictions for a statistical decay of the GQR. The HF calculations have been performed with the nuclear evaporation code CASCADE,[18] with use of the canonical average optical-model parameters[18] and the known level schemes of the residual nuclei as input. The excess of the measured branches in the dominant decay channels by 50% to 100% over the statistical model predictions provides a further independent piece of evidence for a predominant direct decay of the GQR in ^{28}Si. While the p decays immediately reflect the GQR's 1p-1h primary doorway configurations, it is not clear which stage of the early np-nh hierarchy is represented by the α decays. There are indications for attributing them to secondary doorways, e.g., cluster configurations.[14,15] On the other hand, SU(3)-model calculations predict for ^{28}Si still a sizable direct overlap of the $2\hbar\omega$ 1p-1h GQR excitation with α-cluster wave functions although it is about five times less than in ^{16}O.[19]

This work was supported in part by the Deutsche Forschungsgemeinschaft.

[a]Present address: High Energy Physics Laboratory, Stanford University, Stanford, Cal. 94305.

[b]Present address: Lawrence Berkeley Laboratory, Berkeley, Cal. 94720.

[1]G. F. Bertsch, Nature (London) 280, 639 (1979).

[2]D. H. Youngblood, A. D. Bacher, D. R. Brown, J. D. Bronson, J. M. Moss, and C. M. Rosza, Phys. Rev. C 15, 246 (1977).

[3]M. T. Collins, C. C. Chang, S. L. Tabor, G. J. Wagner, and J. R. Wu, Phys. Rev. Lett. 42, 1440 (1979).

[4]K. T. Knöpfle, H. Riedesel, K. Schindler, G. J. Wagner, C. Mayer-Böricke, W. Oelert, M. Rogge, and P. Turek, to be published.

[5]K. T. Knöpfle, G. J. Wagner, P. Paul, H. Breuer, C. Mayer-Böricke, M. Rogge, and P. Turek, Phys. Lett. 74B, 191 (1978).

[6]A. Faessler, D. J. Millener, P. Paul, and D. Strottman, Nucl. Phys. A330, 333 (1979).

[7]H. Riedesel, thesis, University of Heidelberg, 1979 (unpublished); H. Riedesel *et al.*, to be published.

[8]K. T. Knöpfle, G. J. Wagner, A. Kiss, M. Rogge, C. Mayer-Böricke, and Th. Bauer, Phys. Lett. 64B, 263 (1976).

[9]D. H. Youngblood, C. M. Rosza, J. M. Moss, D. R. Brown, and J. D. Bronson, Phys. Rev. C 15, 1644 (1977).

[10]K. T. Knöpfle, in *Nuclear Physics with Electromagnetic Interactions*, edited by H. Arenhobel and D. Vrechsel, Lecture Notes in Physics, Vol. 108 (Springer, Berlin, 1979), p. 311.

[11]C. Mahaux, in *Proceedings of the Europhysics Study Conference on Intermediate Processes in Nuclear Reactions*, edited by N. Cindro, P. Kulisic, T. Mayer-Kuckuk, Lecture Notes in Physics, Vol. 22 (Springer, Berlin, 1973), p. 1.

[12]A. Kiss, C. Mayer-Böricke, M. Rogge, P. Turek, and S. Wiktor, Phys. Rev. Lett. 37, 1188 (1976).

[13]V. V. Balashov, S. I. Grishanova, N. M. Kabachnik, V. M. Kulikov, and N. N. Titarenko, Nucl. Phys. A216, 574 (1973).

[14]K. T. Knöpfle, H. Riedesel, K. Schindler, G. J. Wagner, C. Mayer-Böricke, W. Oelert, M. Rogge, and P. Turek, in *Nuclear Interactions*, edited by B. A. Robson, Lecture Notes in Physics, Vol. 92 (Springer, Berlin, 1979), p. 443.

[15]G. J. Wagner, in *Giant Multipole Resonances*, edited by F. E. Bertrand (Harwood Academic, Chur, 1980), p. 251.

[16]H. Mackh, G. Mairle, and G. J. Wagner, Z. Phys. 269, 353 (1974).

[17]A. Bohr, Nucl. Phys. 10, 486 (1959).

[18]F. Pühlhofer, Nucl. Phys. A280, 267 (1977).

[19]K. T. Hecht and D. Braunschweig, Nucl. Phys. A295, 34 (1978).