low-mass sub-bands than is found in the bulk. The satellite sub-bands can be populated by simply controlling the amount of inversion (position of the Fermi level) using the gate voltage. Experiments performed on IGFETS fabricated on such materials as n-GaAs and n-InP should provide a good measure of the satellite valley's effective mass anisotropy if the model for projecting the bulk mass tensor onto the surface[2] is indeed valid (and there is mounting evidence that it is valid[4]). Under strong inversion the effect of surface roughness on band structure should be measurable through this new effect.

In summary, a new transport effect in IGFETS has been predicted and holds promise of providing a new and powerful diagnostic tool in determining transport parameters and sub-band structure at the semiconductor surface.

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[1]The analysis has been made under the assumption that the current is confined by a channel to flow parallel to E_a.

[2]F. Stern, Phys. Rev. B 5, 4891 (1972).

[3]For convenience of calculation, the potential well was taken as triangular and the positions of the sub-bands were computed from the Airy function roots in the usual way. For example, see A. P. Gnadinger and H. T. Talley, Solid State Electron. 13, 1301 (1970). Ten sub-bands are sufficient to include essentially all of the carriers, as shown in Table II.

[4]For example, see R. G. Wheeler and R. W. Ralston, Phys. Rev. Lett. 27, 925 (1971); N. Kotera, Y. Katayama, and K. F. Komatsubara, Phys. Rev. B 5, 3065 (1972).

Evidence for a Giant Quadrupole Resonance in ^{16}O†

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Measurements on the polarized-proton capture reaction $^{15}N(p,\gamma_0)^{16}O$ indicate a broad $E2$ resonance which lies above the giant $E1$ resonance of ^{16}O. The measurements show that the $E2$ radiation for the (γ,p_0) channel of ^{16}O exhausts approximately 30% of the quadrupole sum rule.

The great concentration of $E1$ strength in the giant dipole resonance (GDR) of a nucleus has been a widely observed phenomenon in photonuclear and capture reactions. Extensive measurements of unpolarized angular distributions of (p,γ) reactions confirm the basic dipole nature of the GDR but show that $E2$ radiation is present as well. The evidence for $E2$ radiation comes from the appearance of Legendre polynomials of third and fourth degree in the angular distributions.[1] Of particular interest is the strength of this $E2$ radiation and the possibility that a giant quadrupole resonance (GQR) can be observed in a (p,γ) reaction (as well as the GDR). However, the unpolarized (p,γ) reaction by itself does not provide sufficient information to determine quantitatively the $E2$ strength. The purpose of this Letter is to report the finding of substantial $E2$ strength in the (γ,p_0) channel of ^{16}O from measurements on the polarized-proton capture reaction $^{15}N(p,\gamma_0)^{16}O$, which provide the additional information needed to determine the strength of the $E2$ radiation.

The ^{16}O nucleus is of particular interest since Wang and Shakin[2] suggested that the data for the (γ,n) reaction on ^{16}O could not be explained unless a large $E2$ amplitude was present in the region of the GDR of ^{16}O. Although we do report the presence of substantial $E2$ strength it should be emphasized that the $E2$ amplitudes we have determined are approximately a factor of 3 smaller than the $E2$ amplitudes suggested by Wang and Shakin. Furthermore, the phases of these $E2$ amplitudes show a quite different behavior with energy compared with the predictions of Wang and Shakin.

The $E2$ strength we have observed in the reaction $^{15}N(p,\gamma_0)^{16}O$ lies slightly above the center of the GDR of ^{16}O and is thus presumed to be mainly isovector in character. It is to be distinguished from the isoscalar $E2$ radiation reported in (p, p') experiments[3] at energies a few MeV below the GDR of nuclei and also from the lower lying isoscalar $E2$ radiation observed in (α,γ) reactions on even-even nuclei.[4]

The experimental procedure consisted in measuring the reaction yields $\sigma_u(\theta)$ and $\sigma_d(\theta)$, corresponding to the spin of the incident protons being "up" and "down" relative to the reaction plane. The polarized proton beam was obtained from an atomic-beam source[5] and the Stanford FN tandem accelerator. Reversal of the proton spin direction, after a specified integrated target current was reached, was carried out automatically by switching between two radio-frequency transitions induced in the polarized source. This operation does not affect either the position or size of the beam at the target. Instrumental asymmetries were minimized by switching between spin states about every 10 sec. The gamma rays were detected with the Stanford 24 cm×24 cm NaI spectrometer.[6] The target consisted of ^{15}N (98%) gas contained at 0.6 atm in a gas cell 5 cm in diameter fitted with tantalum entrance and exit windows 2.5×10^{-4} cm thick. After passing through the cell the beam was stopped 7 m downstream behind concrete shielding.

From the measured values of $\sigma_u(\theta)$ and $\sigma_d(\theta)$ the angular distribution coefficients a_k and b_k were extracted from the equations[7]

$$\sigma(\theta)=[\sigma_u(\theta)+\sigma_d(\theta)]/2 = A_0[1+\sum_{k=1} a_k P_k(\cos\theta)], \tag{1}$$

$$\sigma(\theta)A(\theta)=[\sigma_u(\theta)-\sigma_d(\theta)]/2P = A_0\sum_{k=1} b_k P_k^{\,1}(\theta), \tag{2}$$

where P_k and $P_k^{\,1}$ are the Legendre and associated Legendre polynomial functions, $\sigma(\theta)$ is the total cross section, $A(\theta)$ is the analyzing power, and P is the beam polarization. Precise measurements of $\sigma_u(\theta)$ and $\sigma_d(\theta)$ were made at nine energies in the range $E_p=8$ to 16 MeV. Typical results for $\sigma(\theta)$ and $\sigma(\theta)A(\theta)$ for three of the energies are shown in Fig. 1. The continuous curves drawn in Fig. 1 are best fits of Eqs. (1) and (2) above. The extracted coefficients a_k and b_k are listed in Table I. At each energy $\sigma_u(\theta)$ and $\sigma_d(\theta)$ were measured several times to investigate the importance of instrumental errors which were found to be of the same order as or smaller than the statistical errors. The errors assigned to a_k and b_k have been determined assuming only

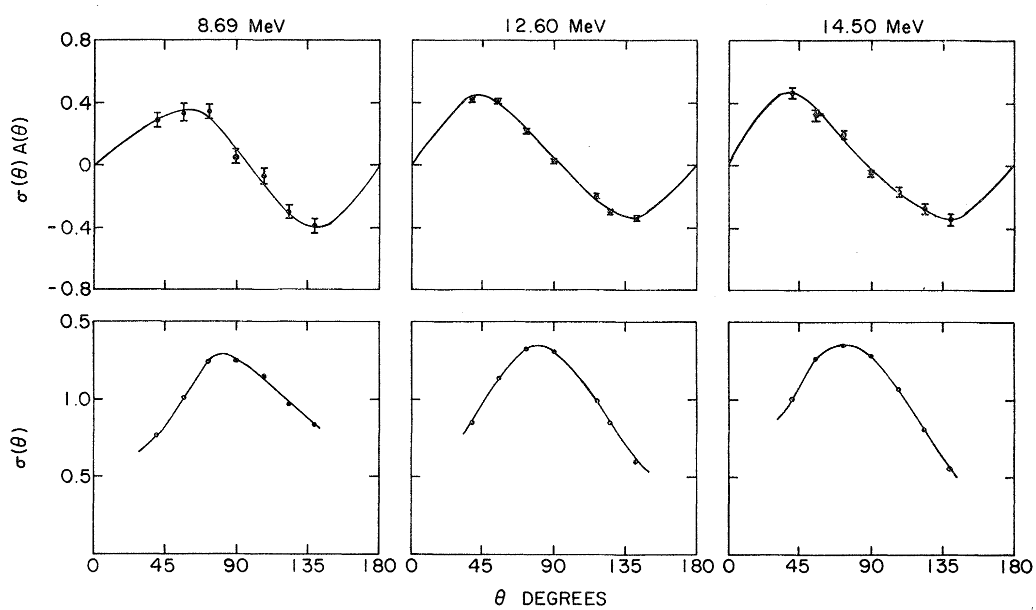

FIG. 1. Plots of $\sigma(\theta)$ and $\sigma(\theta)A(\theta)$ measured at three bombarding energies (listed at top) in the polarized-proton capture reaction ^{15}N$(p,\gamma)^{16}$O. Where error bars are not shown the errors are of the same order as or smaller than the dot size. The analysis of these and all the data is given in Table I.

TABLE I. Unpolarized and polarized angular-distribution coefficients.

E_p	a_1	a_2	a_3	a_4
8.69	-0.051 ± 0.013	-0.528 ± 0.030	-0.205 ± 0.026	-0.022 ± 0.037
9.50	0.078 ± 0.029	-0.248 ± 0.048	0.129 ± 0.033	-0.053 ± 0.035
10.10	0.051 ± 0.014	-0.537 ± 0.022	-0.161 ± 0.021	-0.017 ± 0.026
10.40	0.019 ± 0.005	-0.566 ± 0.007	-0.073 ± 0.009	-0.040 ± 0.010
11.50	0.203 ± 0.066	-0.403 ± 0.011	-0.111 ± 0.011	-0.072 ± 0.015
12.60	0.158 ± 0.007	-0.640 ± 0.015	-0.156 ± 0.015	-0.022 ± 0.023
13.00	0.208 ± 0.016	-0.607 ± 0.017	-0.178 ± 0.034	-0.073 ± 0.025
14.50	0.301 ± 0.017	-0.603 ± 0.034	-0.142 ± 0.030	-0.022 ± 0.027
15.70	0.324 ± 0.029	-0.543 ± 0.079	-0.127 ± 0.043	-0.075 ± 0.074
E_p	b_1	b_2	b_3	b_4
8.69	0.066 ± 0.014	0.233 ± 0.009	-0.045 ± 0.009	-0.003 ± 0.009
9.50	0.064 ± 0.018	0.326 ± 0.008	0.000 ± 0.009	-0.010 ± 0.009
10.10	0.046 ± 0.010	0.267 ± 0.008	-0.010 ± 0.009	-0.002 ± 0.006
10.40	0.022 ± 0.006	0.301 ± 0.004	-0.015 ± 0.004	0.003 ± 0.003
11.50	-0.006 ± 0.008	0.297 ± 0.006	0.043 ± 0.005	-0.002 ± 0.005
12.60	0.061 ± 0.013	0.248 ± 0.007	0.011 ± 0.009	0.015 ± 0.006
13.00	0.064 ± 0.013	0.281 ± 0.008	0.037 ± 0.008	-0.004 ± 0.007
14.50	0.017 ± 0.020	0.246 ± 0.010	0.032 ± 0.017	0.027 ± 0.010
15.70	0.017 ± 0.018	0.244 ± 0.020	0.062 ± 0.020	0.030 ± 0.012

the statistical counting errors.

By angular momentum and parity conservation only the following complex reaction amplitudes (jj scheme) can produce $E1$ and $E2$ radiation:

$$s_{1/2}\exp(i\varphi_s),\quad d_{3/2}\exp(i\varphi_d);\qquad (E1)$$

$$p_{3/2}\exp(i\varphi_p),\quad f_{5/2}\exp(i\varphi_f).\qquad (E2)$$

To the extent that the higher order multipoles $M2$, $E3$, etc. can be neglected and that $(M1)^2 \ll (E1)^2$ in the region of the GDR, the coefficients a_2, a_3, a_4 and b_2, b_3, b_4 depend only on the $E1$ and $E2$ amplitudes. Since one of the phases can be arbitrarily chosen (we chose $\varphi_s = 0$), seven quantities are needed to define the $E1$ and $E2$ radiation. The six coefficients $a_2, a_3, a_4, b_2, b_3, b_4$ and the overall normalization A_0 are sufficient for this purpose.

The results obtained for the extracted $E2$ cross section as well as the total cross section are shown in Fig. 2. Between 8.69 and 15.7 MeV the $E2$ cross section exhausts 30% of the isovector sum rule expressed by the equation[9]

$$\int\sigma(E2)\,dE/E^2 = 4\times10^{-4} ZN/A^{1/3}\text{ mb MeV}^{-1}.$$

A similar $E2$ strength might be expected for the neutron channel, in which case we have accounted for about 60% of the sum rule. This together with the resonant nature of the $E2$ cross section suggests the presence of a GQR in the (γ, p_0) channel of ^{16}O. Of special interest in this connection is the behavior of the $E2$ phases which, as shown in Fig. 2, fluctuate by as much as 90 to 180° at energies above and below the peak energy for the $E2$ cross section.

It should be mentioned that in extracting the $E1$ and $E2$ amplitudes two solutions were found, one (I) corresponding to a predominant $d_{3/2}$ amplitude and the other (II) to a predominant $s_{1/2}$ amplitude in the $E1$ part of the reaction. The results only for solution I are shown in Fig. 2. However, as it turns out, Solution II leads to nearly identical values for the $E2$ cross section.

It is interesting to note that the $E2$ and $E1$ am-

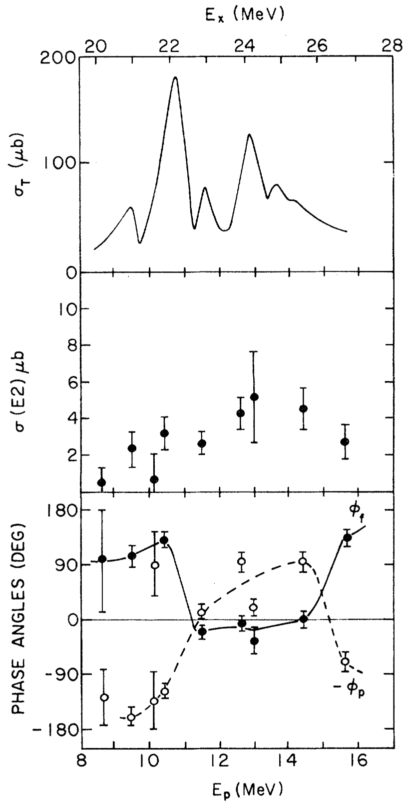

FIG. 2. Top: total cross section curve of $^{15}N(p,\gamma)^{16}O$ (Ref. 8). Middle: plot of total $E2$ cross sections derived from the analyses in Table I. Bottom: plot of the phases of the partial-wave amplitudes for proton capture leading to $E2$ radiation.

plitudes and phases extracted from the present data correctly reproduce the observed a_1 and b_1 coefficients (which were not used in the analysis) at all the energies investigated. Thus, recourse to $M1$ radiation is not required to account for the measured values for the a_1 and b_1 coefficients.

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[1]See, for example, R. G. Allas, S. S. Hanna, L. Meyer-Schützmeister, and R. E. Segel, Nucl. Phys. 58, 122 (1964).

[2]W. L. Wang and C. M. Shakin, Phys. Rev. Lett. 30, 301 (1973).

[3]M. B. Lewis and F. E. Bertrand, Nucl. Phys. A196, 337 (1972).

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

[5]H. F. Glavish, in *Proceedings of the Third International Symposium on Polarization Phenomena in Nuclear Reactions, Madison, Wisconsin, 1970,* edited by H. H. Barschall and W. Haeberli (Univ. of Wisconsin Press, Madison, Wis., 1971), p. 267.

[6]M. Suffert, W. Feldman, J. Mahieux, and S. S. Hanna, Nucl. Instrum. Methods 63, 1 (1968).

[7]H. F. Glavish, S. S. Hanna, R. Avida, R. N. Boyd, C. C. Chang, and E. Diener, Phys. Rev. Lett. 28, 766 (1972).

[8]W. J. O'Connell, Ph.D. thesis, Stanford University, 1969 (unpublished).

[9]M. Gell-Mann and V. L. Telegdi, Phys. Rev. 91, 169 (1953).