tively. In an extreme weak-coupling model, with an $f_{7/2}$ neutron coupled to the 3737-keV 3^- state and to the 0^+ ground state of ^{40}Ca to give, respectively, the ^{41}Ca 3369-keV level and the ^{41}Ca ground state, the predicted transition strength is 12/56 times that for the $E3$ core transition. From the measured strength of the ^{40}Ca transition, 31 W.u.,[11] we expect 6.6 W.u. for the $3369 \to 0$ transition. Since this should be a rough upper limit to the $\frac{11}{2}^+ \to \frac{7}{2}^-$ $E3$ rate, the solution $x = -(0.31 \pm 0.10)$ and $B(E3) = 4.1 \pm 2.3$ W.u. appears the most probable. The $M2$ strength is then 0.10 ± 0.01 W.u.

Results from heavy-ion–induced compound-nucleus reactions, exemplified here by data for ^{41}K and ^{41}Ca, will obviously be a powerful stimulus for detailed model predictions. For instance, the small $E2$ strengths encountered here are most intriguing (the average of the four values listed in Table I is only about 1 W.u.). It will be interesting to see how well these $E2$ strengths can be understood.

A limitation on the use of these reactions, for the present, is the difficulty of obtaining rigorous spin assignments without time-consuming γ-γ directional correlation measurements. Possibly one could obtain quite reliable assignments by coupling these studies with a theoretical or phenomenological description of the reaction mechanism. Thus, more information on the reaction mechanism is important, both for its own sake and for the aid it would provide to nuclear-spectroscopy studies.

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Excitation of Giant Resonances in ^{58}Ni via Inelastic Scattering of Polarized Protons*

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Measurements of the analyzing power and the differential cross section in the nuclear continuum for the reaction ^{58}Ni(p,p') initiated by 60-MeV polarized protons provide strong evidence for a quadrupole ($E2$) interpretation for the giant resonance at $E_x \approx 63/A^{1/3}$ MeV. A resonance approximately 3 MeV lower in excitation energy has also been observed.

Experiments on the inelastic scattering of electrons,[1-3] protons,[4-7] and ^{3}He particles[8,9] have established the existence of a giant resonance in the nuclear continuum, which is consistently 2–3 MeV lower in excitation energy than the well-known giant dipole ($E1$) resonance.[10] The observed excitation energy, $E_x \approx 63/A^{1/3}$ MeV, agrees well with predictions[11] for an isoscalar giant quadrupole ($E2$) resonance.

Angular distributions for the resonance from electron scattering are consistent with either an $E2$ excitation or an $E0$ giant monopole excitation.[1-3] Angular distributions from proton scattering were initially interpreted as evidence for an $E2$

excitation,[6,12] but a subsequent analysis[13] did not rule out an $E0$ assignment. A measurement of the relative cross section at two angles in ^{208}Pd(p, p') provides evidence for an $E2$ assignment.[7] In ^{3}He scattering an $E2$ assignment is suggested[8,9] by a comparison of the observed transition strength with predictions based on the linear energy-weighted sum rule (EWSR).[14] However, the assignment from the ^{3}He measurements is somewhat tenuous because of uncertainties in extracting the resonance cross section[9] and possible uncertainties in calculating the expected EWSR strength.[15]

In order to provide more conclusive evidence for the spin of the resonance, we have taken a new approach to the study of the giant resonance region. Since calculations by Satchler[13] suggested that the analyzing power of the resonance for incident polarized protons could distinguish between $E2$ and $E0$ excitations, we have studied the reaction ^{58}Ni(p,p') with 60-MeV polarized protons.

The measurements were made using the polarized proton beam[16] from the Oak Ridge isochronous cyclotron (ORIC) and a broad-range magnetic spectrograph with nuclear emulsions. The overall energy resolution was less than 200 keV. At each angle measurements were made with a spin-up proton beam ($\hat{s} \parallel \vec{k}_{\rm in} \times \vec{k}_{\rm out}$) and a spin-down beam. The number of incident protons was determined by integrating the unscattered beam in a Faraday cup. A measurement was also made with an unpolarized beam to provide additional cross section data and to check that false asymmetries were not extracted from the polarized-beam measurements.

The beam polarization p_y was measured between runs with a polarimeter employing p-^{12}C elastic scattering at $\theta_L = 60°$. The polarimeter analyzing power at this angle was determined to be $A_y = +0.95 \pm 0.05$ by comparing the left-right asymmetry at 60 MeV with the asymmetry at 49 MeV where the p-^{12}C analyzing power is known.[17]

The polarized-beam spectra in the continuum region at $\theta_L = 20°$ are shown in Fig. 1. The data are plotted in ≈ 400-keV wide bins to yield $\approx 3\%$ statistical uncertainty. The spectra above $E_x \approx 24$ MeV show little structure and a small asymmetry $\epsilon \equiv (\sigma_{\rm up} - \sigma_{\rm down})/(\sigma_{\rm up} + \sigma_{\rm down})$. At lower excitation energies a broad enhancement is observed with exhibits a pronounced asymmetry. In ^{58}Ni we observe the resonance at $E_x = 16.5 \pm 0.5$ MeV. The resonance width is about 4 MeV FWHM (full width at half-maximum).

The analyzing power for the 16.5-MeV resonance was obtained from the polarized-beam cross sections in the region $E_x \approx 14.6$–16.7 MeV. For each spin direction the resonance cross section was obtained from the measured cross section by subtracting contributions from the underlying continuum and the $E1$ resonance. The continuum contribution was estimated by a linear extrapolation of the observed cross sections above 24 MeV joined smoothly to the observed cross sections near the neutron separation energy. The assumed spectral shape for the continuum was based on our data at $\theta_L = 40°$, where the resonance cross sections are unobservably small, and on data for other nuclei in this mass region.[5] The $E1$ contribution was estimated by assuming a spectral shape obtained from the known total

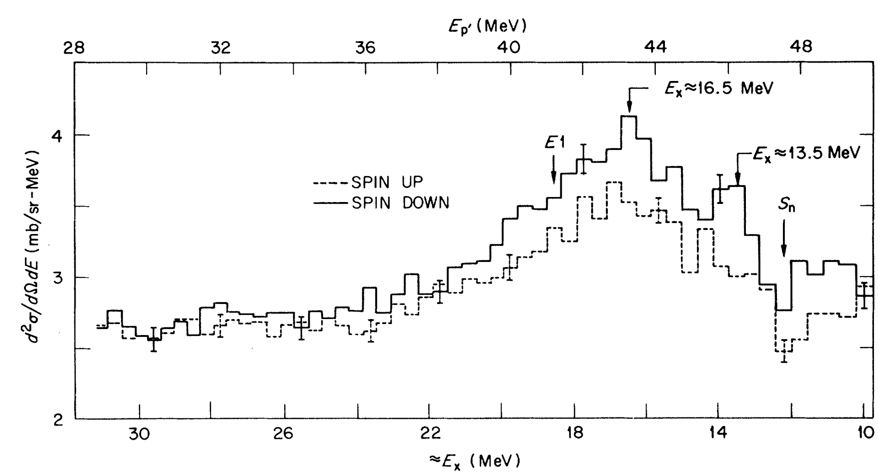

FIG. 1. Polarized-beam cross sections at $\theta_L = 20°$ versus outgoing proton energy ($E_{p'}$) and approximate excitation energy (E_x); S_n is the neutron separation energy; $E1$ is the known energy of giant dipole resonance.

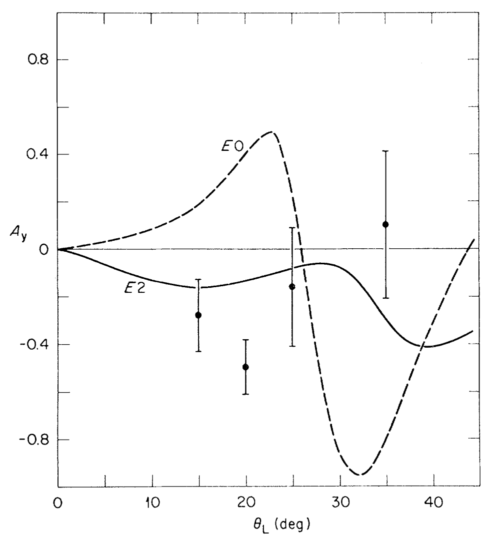

FIG. 2. Analyzing powers for resonance at $E_x \approx 16.5$ MeV compared with DWBA predictions.

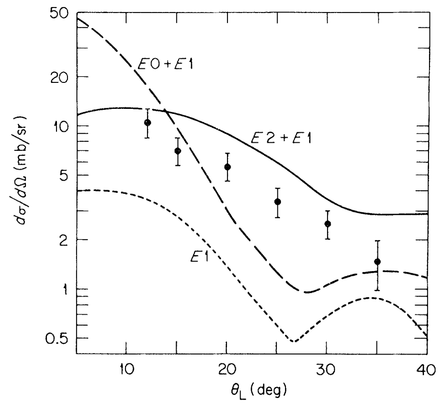

FIG. 3. Cross sections in giant resonance region ($E_x \approx 12.7$–23.7 MeV) compared with DWBA predictions.

photonuclear cross section for nickel[18] and normalizing the $E1$ shape to the observed cross sections in the region $E_x \approx 20.6$–23.0 MeV. The $E1$ contribution to the cross section for $E_x \approx 14.6$–16.7 MeV was always less than 10%.

The analyzing powers,[19] $A_y = \epsilon/p_y$, extracted for the 16.5-MeV resonance was shown in Fig. 2. The uncertainties with the data are purely statistical.[20] Comparison of the measurements with the distorted-wave Born-approximation (DWBA) predictions[13] shows a clear preference for an $E2$ assignment.

We have also extracted cross sections for the broad enhancement between $E_x \approx 12.7$ and 23.7 MeV, which is presumed to include the 16.5-MeV resonance and most of the $E1$ resonance. Small contributions from the peak at $E_x \approx 13.5$ MeV (see Fig. 1) were not included. The results are shown in Fig. 3. The estimated absolute uncertainty is $\pm 20\%$ except $\pm 33\%$ at $\theta_L = 35°$. The curves are obtained from DWBA predictions[12,13] for $E1$, $E2$, and $E0$ excitations. The normalization of the curves is based on the following percentage depletions of the predicted EWSR strengths: $E1 = 70\%$,[18] $E2 = 89\%$, and $E0 = 100\%$. The shape of the measured angular distribution shows a preference for the $E1 + E2$ curve. The discrepancy between the measured and predicted transition strength, which has been noted in other work,[1-3,15] may indicate that additional $E2$ strength occurs at other energies or that the predicted EWSR strengths are in error.

An additional feature in our spectra is a peak at $E_x \approx 13.5$ MeV (see Fig. 1) with a width of about 2 MeV FWHM. A resonance observed at this energy in ^{56}Fe(e, e') was given a tentative $E3$ assignment.[2] However, our cross sections shown in Fig. 4 are in poor agreement with an $E3$ DWBA prediction, but show better agreement with $E2$ or $E0$ predictions. The data also show good agreement with relative cross sections for the $E2$ resonance at $E_x = 16.5$ MeV.[21] The $E0$ possibility appears to be ruled out by the large negative asymmetry at $\theta_L = 20°$ (see Figs. 1 and 2). Measurements on other nuclei are needed to confirm the existence of the 13.5-MeV resonance and to determine its spin unambiguously.

We note from Fig. 4 that the cross section for the 16.5-MeV resonance shows an increase at forward angles which is not in agreement with

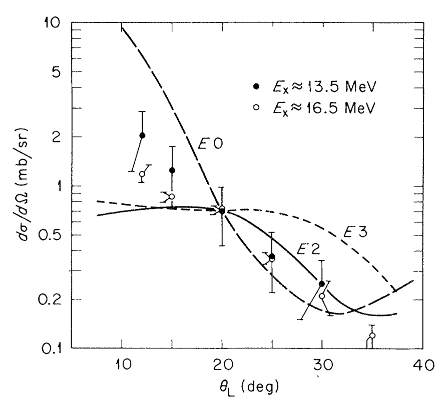

FIG. 4. Cross sections for resonance at $E_x \approx 13.5$ MeV (estimated absolute uncertainty is $\pm 40\%$), cross sections for $E2$ resonance at $E_x \approx 16.5$ MeV (Ref. 21), and DWBA predictions. The last two quantities are normalized to the cross section for the 13.5-MeV resonance at $\theta_L = 20°$.

the $E2$ calculation. A comparison of the data with the DWBA predictions suggests that some $E0$ strength may also occur at this excitation energy. An $E0$ contribution could affect the cross section at the forwardmost angles without noticeably influencing the analyzing power and the cross section at larger angles. Measurements at more forward angles would be useful in further investigating the possibility of an $E0$ contribution.

In conclusion, a comparison of the measured analyzing power and cross section for the reaction ^{58}Ni(p, p') with polarized protons at 60-MeV incident energy with DWBA predictions shows that the giant resonance at $E_x \approx 63/A^{1/3}$ MeV is predominantly $E2$ in character. The assumption that the DWBA provides a proper description of the reaction needs to be tested by studying the excitation of collective levels having known spin and parity with medium-energy polarized beams. It is noteworthy that the conclusion from the analyzing power measurement does not depend upon either calculated or measured transition strengths. The results of this experiment suggest that inelastic scattering studies with polarized beams may provide a unique and powerful method for investigating giant resonances and the nuclear continuum.

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[21]The cross sections for the $E2$ resonance are proportional to the average of the spin-up and spin-down resonance cross sections in the region $E_x \approx 14.6$–16.7 MeV, obtained as described previously in this paper. The uncertainties are purely statistical.