[15]P. A. Schmelzback, W. Gruebler, V. Konig, and P. Marmier, Nucl. Phys. A184, 193 (1972).

[16]W. D. Callender and C. P. Browne, Phys. Rev. C 2, 1 (1970).

[17]The partial widths for α decay of the 12.71- and 15.11-MeV levels are from F. D. Reisman, P. I. Connors, and J. B. Marion, Nucl. Phys. A153, 244 (1970); and D. P. Balamuth, R. W. Zurmühle, and S. L. Tabor, Phys. Rev. C 10, 975 (1974), respectively. The total width of the 12.71-MeV level is from F. E. Cecil, L. W. Fagg, W. L. Bendel, and E. C. Jones, Jr., Phys. Rev. C 9, 798 (1974).

[18]E. A. Silverstein, S. R. Salisbury, G. Hardie, and L. D. Oppliger, Phys. Rev. 124, 868 (1961).

[19]R. A. Lindgren, F. C. Young, and B. Cotton, Phys. Lett. 37B, 358 (1971).

[20]E. K. Warburton and J. Weneser, in *Isospin in Nuclear Physics*, edited by D. H. Wilkinson (North-Holland, Amsterdam, 1969).

[21]T. T. Gien, Nuovo Cimento 7A, 511, 532 (1972).

[22]See, for example, S. S. Hanna, in *Isospin in Nuclear Physics*, edited by D. H. Wilkinson (North-Holland, Amsterdam, 1969).

[23]R. K. Anderson, M. R. Wilson, and P. Goldhammer, Phys. Rev. C 6, 136 (1972).

[24]F. C. Barker and A. K. Mann, Phil. Mag. 2, 5 (1957).

Isolation of the Giant Quadrupole Resonance in ^{58}Ni via Deuteron Inelastic Scattering

C. C. Chang

Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742*

and

F. E. Bertrand and D. C. Kocher†

Oak Ridge National Laboratory,‡ Oak Ridge, Tennessee 37830

(Received 12 December 1974)

An investigation of the reaction ^{58}Ni(d,d') at $E_d = 46$ and 70 MeV has demonstrated significant advantages in studying isoscalar giant resonances with deuterons compared with other projectiles. The differential cross section at 70 MeV for the resonance at $E_x \approx 63A^{-1/3}$ MeV provides strong evidence for an $E2$ interpretation. A comparison of measurements in ^{58}Ni(d,d') and (p,p') provides evidence for excitation of the giant dipole resonance by protons.

The giant resonance region of the nuclear continuum has been extensively studied via inelastic scattering of electrons, protons, ^{3}He particles, and α particles.[1] The primary purpose of previous measurements has been to characterize the pronounced resonance structure at $E_x \approx 63A^{-1/3}$ MeV, which is 2–3 MeV below the well-known $E1$ giant dipole resonance.

The spin of this resonance is usually deduced by comparing measured differential cross sections with predictions of the distorted-wave Born approximation (DWBA) normalized to transition strengths based on depletion of the linear energy-weighted sum rule (EWSR).[1] Electron scattering and initial proton scattering results could not distinguish between excitation of an $E2$ giant quadrupole resonance and an $E0$ giant monopole resonance.[1] Later proton cross-section measurements[2,3] showed a preference for the $E2$ interpretation.[4] The angular distributions for 71-MeV ^{3}He ions could not distinguish between $E2$ and $E0$ excitations, but the $E2$ interpretation was preferred from the predicted EWSR strengths.[5,6] An angular distribution for 115-MeV α particles showed some preference for an $E2$ excitation, but an $E0$ excitation cannot be ruled out by the EWSR strengths.[7]

In this Letter, we report a study of the giant resonance region in ^{58}Ni using inelastic scattering of deuterons, a projectile not previously employed in such measurements. We find that three significant advantages are obtained with deuterons. (1) The cross section for the resonance structure relative to the cross section for the underlying, unstructured nuclear continuum is significantly increased compared with results for other projectiles. (2) Since, to a good approximation, the isovector $E1$ resonance is not excited by isoscalar projectiles, the resonance at $E_x \approx 63A^{-1/3}$ MeV can be isolated from the $E1$ resonance. (3) DWBA predictions suggest that the resonance differential cross section in deuteron inelastic scattering is sensitive to the transition multipolarity, particularly in distinguishing between $E2$ and $E0$ excitations.

Most of the measurements were made using a

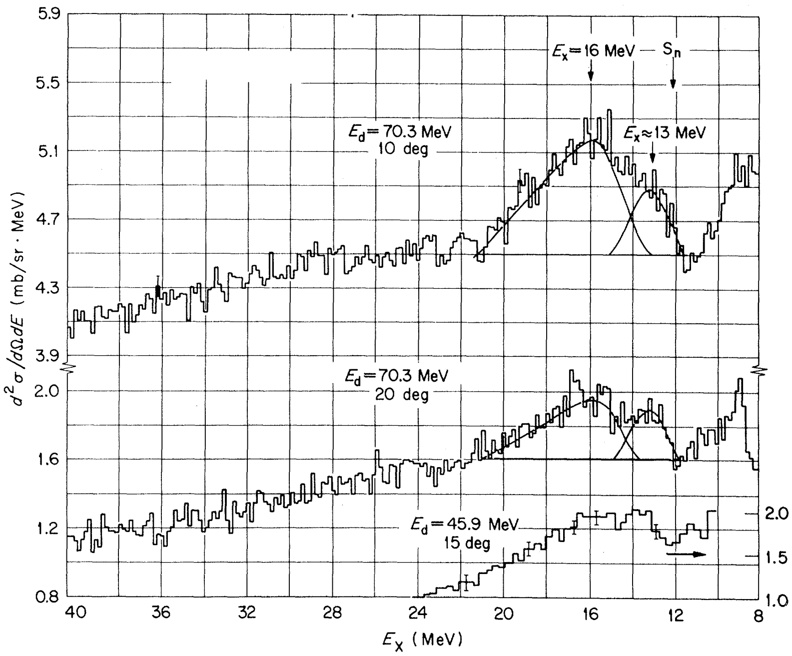

FIG. 1. Cross sections in the nuclear continuum for deuteron inelastic scattering from ^{58}Ni versus excitation energy; S_n is the neutron separation energy. The smooth curves with the 70-MeV spectra are described in the text.

70.3-MeV deuteron beam from the University of Maryland cyclotron. The scattered deuterons were detected in a ΔE-E counter telescope consisting of a 2-mm-thick silicon surface-barrier detector and a NaI(Tl) detector. Data were also taken at 45.9 MeV using the Oak Ridge isochronous cyclotron. The scattered deuterons were recorded on nuclear-emulsion plates placed in the focal plane of a broad-range magnetic spectrograph.

Deuteron spectra in the continuum region are shown in Fig. 1. The spectra show an enhancement centered at E_x =16.0± 0.5 MeV, an energy in agreement with a previous measurement[3] in

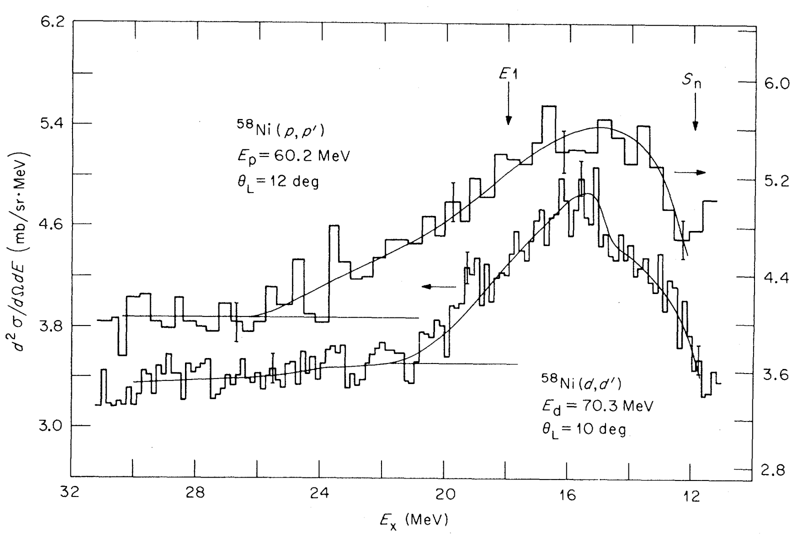

FIG. 2. Comparison of cross sections in the nuclear continuum for proton and deuteron inelastic scattering from ^{58}Ni; $E1$ is the known energy of the giant dipole resonance; S_n is the neutron separation energy. The uncertainties in the data are statistical only. The smooth curves indicate assumed separations into the resonance and the underlying continuum.

^{58}Ni(p,p'). The cross section in the region of the 16-MeV resonance results primarily from excitation of the relatively unstructured nuclear continuum. Comparison of the deuteron spectra at 20° with a spectrum at 20° for ^{58}Ni(p,p') at 60 MeV[3] shows that the continuum cross section just above the resonance is almost a factor of 2 less for 70-MeV deuterons and is further reduced for 46-MeV deuterons. The reduced deuteron continuum results in a greater enhancement of the resonance. A similar result is obtained from a comparison between deuteron and α-particle[7] spectra.

The excitation of the isovector $E1$ resonance by deuterons was investigated qualitatively by comparing inelastic deuteron and proton[3] spectra for ^{58}Ni, as shown in Fig. 2. It is known that the strength distribution for the $E1$ resonance is skewed toward energies above the $E1$ peak at $E_x \approx 18$ MeV.[8] In the region $E_x \approx 18-26$ MeV, we find that the resonance structure for protons extends several MeV beyond that for deuterons. This difference is consistent with the assumption that the $E1$ resonance is excited much less by isoscalar deuterons than by protons.

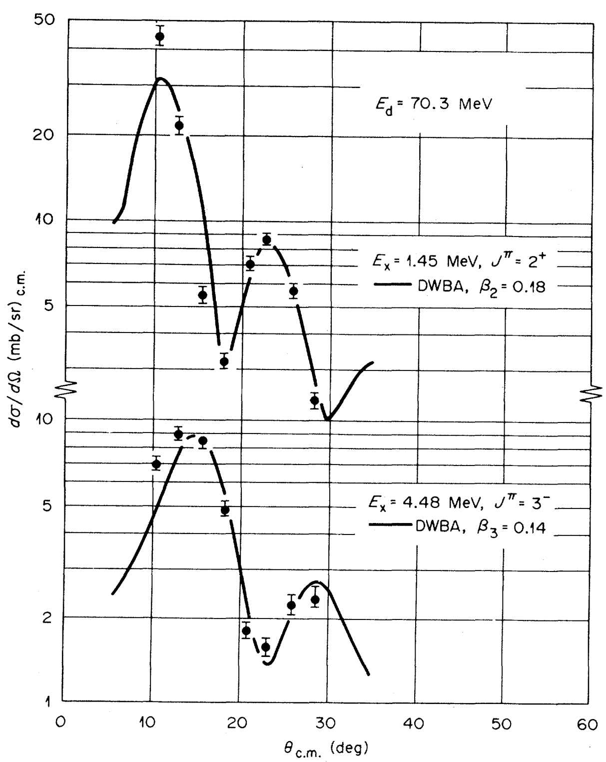

FIG. 3. Cross sections for deuteron inelastic scattering from the first 2^+ and 3^- states in ^{58}Ni compared with DWBA predictions.

The spectra in Fig. 1 provide clear evidence for a second resonance at $E_x \approx 13$ MeV.[1] To extract cross sections for the 16-MeV resonance, we decomposed the spectra for $E_x \approx 12-21$ MeV into contributions from the underlying continuum and the 16- and 13-MeV resonances. From isospin selection rules and the results of Fig. 2, the cross section for the $E1$ resonance was assumed to be negligible. Typical spectral decompositions at 70 MeV are shown by the smooth curves in Fig. 1. The 13-MeV resonance will be discussed in a later publication.

Cross-section angular distributions calculated in DWBA were compared with our measurements for the 16-MeV resonance. Deuteron optical-model parameters were taken from Table I and Eq. (3) of Duhamel *et al.*[9] The applicability of the DWBA to the excitation of collective states in ^{58}Ni by 70-MeV deuterons is demonstrated in Fig. 3. Excellent fits to our angular distributions for the first 2^+ and 3^- states are obtained, and the extracted deformation parameters agree well with previous results.[10]

The cross sections for the 16-MeV resonance are shown in Fig. 4. The absolute uncertainties result mainly from estimated uncertainties in the cross sections assumed for the continuum underlying the resonance. The $E2$ DWBA predic-

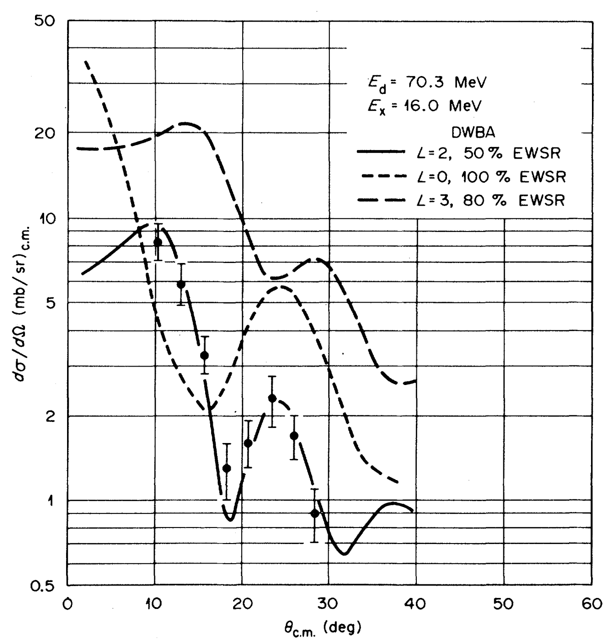

FIG. 4. Cross section for deuteron inelastic scattering from the 16-MeV resonance in ^{58}Ni compared with DWBA predictions. The normalization of the DWBA curves is described in the text.

tion is normalized to give a best overall fit to the data. The $E0$ and $E3$ predictions are normalized to the EWSR strengths not depleted by known bound states.[11] The $E2$ prediction provides an excellent fit to the data, while the $E0$ prediction gives poor agreement for any assumed normalization.[12] It is a weakness of our analysis, however, that no collective $E0$ excitations are known with which to test the DWBA predictions. The poor fit given by the $E3$ curve demonstrates the sensitivity of the DWBA to higher transition multipolarities. We conclude that multipolarities other than $E2$ can contribute only a small fraction of the total cross section for the 16-MeV resonance.

The normalization for the $E2$ calculation in Fig. 4 yields a deformation parameter $\beta_2^2 = 0.022$, which, with $R = 1.2A^{1/3}$ fm, corresponds to 50% depletion of the isoscalar $E2$ EWSR strength.[1] A similar analysis at 46 MeV gives 40% depletion. Therefore, our results are consistent with (45 $\pm$ 10)% depletion of the isoscalar $E2$ strength.

By subtracting calculated $E2$ cross sections based on 45% depletion of the EWSR strength from the measured ^{58}Ni(p,p') cross sections shown in Fig. 3 of Ref. 3, we obtain good agreement with the assumed $E1$ cross section shown in the same figure. This indicates that the $E1$ cross section can be calculated reliably with the DWBA and the $E1$ EWSR.[1] This result may help resolve inconsistencies in proton measurements on spherical and deformed Sm nuclei.[13]

In conclusion, an analysis of the cross section for the reaction ^{58}Ni(d,d') at $E_d = 70$ MeV shows clearly that the giant resonance at $E_x \approx 63A^{-1/3}$ MeV is predominantly $E2$ in character. We believe that the deuteron result provides the best evidence to date for the identification of the isoscalar giant quadrupole resonance. The significant reduction in the cross section for the nuclear continuum in the resonance region compared with other projectiles and the negligible contribution from the $E1$ resonance allow the cross section for the $E2$ resonance to be determined with increased accuracy, compared with previous measurements. Furthermore, the angular distributions predicted by the DWBA clearly distinguish between different transition multipolarities, so that a spin assignment can be made without reliance upon measured and calculated transition strengths. In view of our results, it would be interesting to investigate the $E2$ resonance in ^{58}Ni using vector-polarized deuterons in order to possibly understand the analyzing power results for the reaction ^{58}Ni(p_{pol},p').[3,4]

The authors thank E. E. Gross and E. Newman of Oak Ridge National Laboratory for their assistance in data taking and their constant support and encouragement; R. E. Berg, K. Kwiatkowski, and G. F. Burdzik of the University of Maryland for their assistance in data taking; the operating staffs at Oak Ridge isochronous cyclotron and the University of Maryland cyclotron; and V. Jones, R. Shelton, and M. P. Haydon for plate scanning.

---

*Research supported in part by the U. S. Atomic Energy Commission.

†Nuclear Information Research Associate prior to 1 May 1974; work was supported by the National Science Foundation through the National Academy of Sciences–National Research Council, Committee on Nuclear Science.

‡Research sponsored by the U. S. Atomic Energy Commission under contract with the Union Carbide Corporation.

[1]G. R. Satchler, Phys. Rep. 14C, 97 (1974), and references therein.

[2]M. B. Lewis, F. E. Bertrand, and D. J. Horen, Phys. Rev. C 8, 398 (1973); M. B. Lewis and D. J. Horen, Phys. Rev. C 10, 1099 (1974).

[3]D. C. Kocher, F. E. Bertrand, E. E. Gross, R. S. Lord, and E. Newman, Phys. Rev. Lett. 31, 1070 (1973), and 32, 264 (1974).

[4]The observation that the cross section for the reaction ^{58}Ni(p_{pol},p') (see Ref. 3) prefers the $E2$ interpretation, while the measured analyzing power agrees better with predictions for an $E0$ excitation, is not yet fully understood.

[5]A. Moalem, W. Benenson, and G. M. Crawley, Phys. Rev. Lett. 31, 482 (1973).

[6]For an $E2$ assignment from 80-MeV ^{3}He scattering, see J. Arvieux, M. Buenerd, J. Cole, D. J. Horen, P. de Saintignon, and G. Perrin, Communications of the Joint Meeting of the Belgian and French Physical Societies, University of Louvain, Louvain, Belgium, 27–29 May 1974 (unpublished), p. 10.

[7]L. L. Rutledge, Jr., and J. C. Hiebert, Phys. Rev. Lett. 32, 551 (1974).

[8]S. C. Fultz, R. A. Alvarez, B. L. Berman, and P. Meyer, Phys. Rev. C 10, 608 (1974).

[9]G. Duhamel, L. Marcus, H. Langevin-Joliot, J. P. Didilez, P. Narboni, and C. Stephan, Nucl. Phys. A174, 485 (1971).

[10]S. Raman, Nucl. Data, Sect. B 3, No. 3-4, 145 (1970).

[11]The $E3$ strength for bound states was taken from G. Bruge, A. Chaumeaux, R. De Vries, and G. C. Morrison, Phys. Rev. Lett. 29, 295 (1972).

[12]The monopole coupling potential given by Eq. (15) of G. R. Satchler, Particles Nucl. 5, 105 (1973), was used. A calculation using Eq. (8) gave similar results.

[13]D. J. Horen, F. E. Bertrand, and M. B. Lewis, Phys. Rev. C 9, 1607 (1974).