PHYSICAL REVIEW C VOLUME 44, NUMBER 5 NOVEMBER 1991

Monopole strength in ^{58}Ni

D. H. Youngblood and Y.-W. Lui
Cyclotron Institute, Texas A&M University, College Station, Texas 77843

(Received 20 June 1991)

Differential cross-section data from 0° to 8° for inelastic scattering of 129 MeV alpha particles exciting ^{58}Ni in the region of 14–22 MeV have been analyzed to explore the existence of monopole strength at approximately $E_x = 17$ MeV. The angular distribution for a peak at $E_x = 17.0$ MeV with $\Gamma = 4.0$ MeV is consistent with an $E0$ transition exhausting $19 \pm 10\,\%$ of the $E0$ energy-weighted sum rule (EWSR). The angular distributions for peaks at $E_x = 16.1$ and 20.4 MeV with $\Gamma = 4.7$ and 4.4 MeV, respectively, were fit by $52 \pm 10\,\%$ of the $E2$ EWSR and a combination of $E2$ ($6.9 \pm 2.0\,\%$ EWSR) and $E0$ ($2.9^{+2.1}_{-2.9}\%$ EWSR).

The isoscalar giant monopole resonance (GMR) is well established [1,2] at an excitation energy several MeV above the giant quadrupole resonance in nuclei with $A \geq 90$. In lighter nuclei the monopole strength is located nearer the quadrupole (for ^{40}Ca [3] and ^{28}Si [4] at virtually the same energy). Only two reports of substantial strength in lighter nuclei are in the literature. Lui *et al.* [4] reported 66% of the $E0$ energy-weighted sum rule (EWSR) in ^{28}Si spread over an 8 MeV region, while Lu *et al.* [5] reported 90% of the $E0$ EWSR in ^{24}Mg between 11 and 20 MeV. Approximately 30% of the $E0$ EWSR was seen in ^{64,66}Zn by Youngblood *et al.* [1]. Duhamel *et al.* [6], using small-angle inelastic alpha scattering, report 23% of the $E0$ EWSR 900 keV above the quadrupole in ^{58}Ni, while in the small-angle inelastic scattering of Youngblood *et al.* [1] and further work of Garg *et al.* [7], the monopole component in ^{58}Ni was not identified. Bertrand *et al.* [8] using inelastic proton scattering had earlier reported monopole strength at 20 MeV, which was not seen in the small-angle alpha scattering most sensitive to $E0$ strength.

We have revisited the giant resonance region in ^{58}Ni to confirm the results of Ref. [6] and explore the nature of the component of the giant resonance peak at $E_x = 20$ MeV, reported in Ref. [6] to be required to fit the data. In the work described below we reanalyzed small angle inelastic alpha scattering data on ^{58}Ni reported in Refs. [1] and [7], supplemented by additional data taken at 0°, 4°, and 7°.

I. EXPERIMENTAL PROCEDURE

Spectra were measured for inelastically scattered 129 MeV alpha particles obtained from the Texas A & M University 88" Cyclotron. The experimental setup and beam preparation methods were similar to those discussed in detail in Refs. [1] and [9]. Considerable care was taken to minimize spurious contributions from the beam as well as slit scattering. Runs with blank-target frames were taken to ascertain that contributions from such processes were negligible in regions of interest. The thickness of the ^{58}Ni target was 4.18 mg/cm^2. The inelastically scattered alpha particles were detected in the focal plane of the Enge split-pole spectrograph with an 80-cm-long resistive wire proportional counter backed by an NE102 plastic scintillator. For the 0° measurement, the solid angle defining slits were open ±2.3° both horizontally and vertically, while for all nonzero angles they were ±0.3° horizontally and ±0.9° vertically. An active slit system was used to reduce slit scattering from the solid angle defining collimator. Details of the electronic setup, the data-acquisition system, and background subtraction techniques were discussed in Ref. [9]. The distorted-wave Born approximation (DWBA) calculations are discussed in Refs. [9] and [10]. Calculations were averaged over the finite angle opening of the detector. Optical parameters given in Ref. [11] for ^{58}Ni were used. For the $E0$ calculation, both Satchler [12] version 1 and version 2 form factors were used, giving essentially identical angular distributions. For ^{58}Ni, the version 2 form factor results in a theoretical cross section a factor of 3.3 smaller than version 1. A least-squares peak fitting program [9] using linearization techniques to fit multiple peaks in multiple spectra simultaneously has been ported to 80386-80486 class computers using Microsoft Fortran and a Grafmatic graphics package from Microcompatibles, Inc. The program has been modified for better convergence, convenient interactive input, and output compatibility with standard personal computer spreadsheets for manipulation, evaluation and display of results. A typical fit to nine spectra with three peaks (33 parameters) takes approximately 10 sec on a 25 MHz 80486.

II. RESULTS AND DISCUSSION

Inelastic alpha-scattering data on ^{58}Ni were available [1,7] at nine angles from 0° to 8°. Additional data were taken at the crucial angles of 0° (where the $E0$ strength is a maximum) and 4° (where $E0$ is a minimum) as well as at 7°, both to provide additional data for the fitting process and to increase confidence that the spectra were free from beam-related background. The spectra obtained are within statistics identical to our earlier data shown in Fig. 5 of Ref. [1].

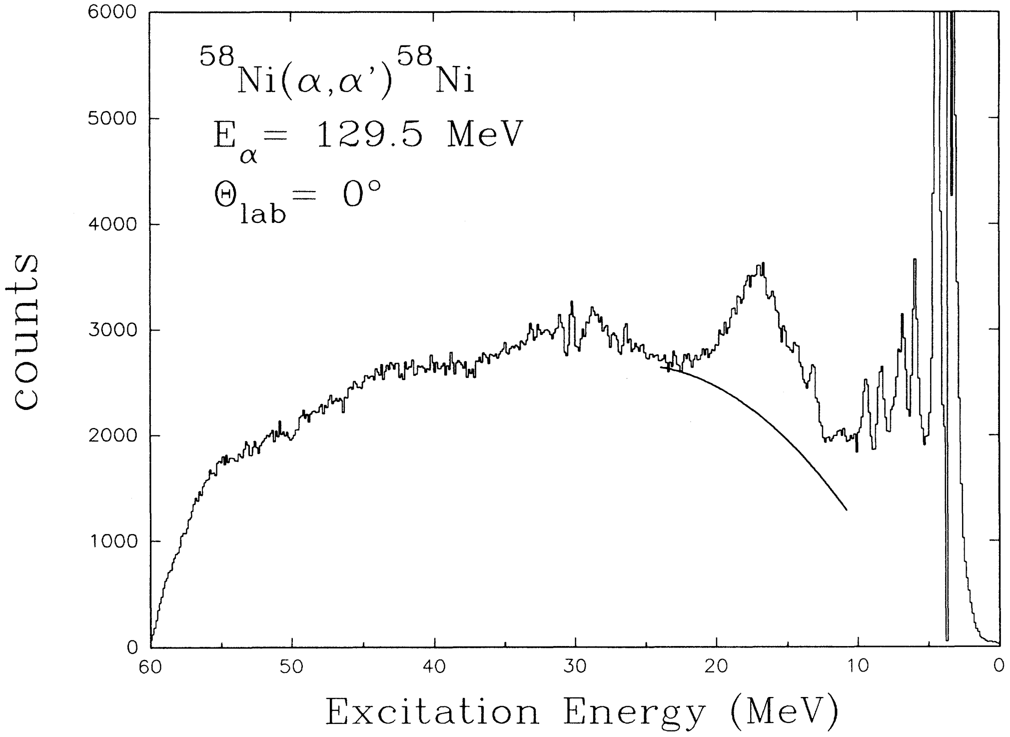

FIG. 1. Inelastic alpha spectrum taken at $\theta_{lab}=0°$. The solid line shows the continuum estimated as described in the text.

Data analysis proceeded somewhat differently than reported in Refs. [1] and [7]. In those works, the continuum under the giant resonance was estimated by connecting points on either side of the peak with a smooth curve. In this analysis the continuum was estimated as follows. On the low excitation energy side of the peak, the continuum was assumed to begin with a rapid rise at the neutron separation energy. On the high excitation side, the effects of the ^{5}Li-^{5}He breakup peaks were considered in arriving at a continuum level and slope. These two were joined with a smooth curve. The resultant continuum is illustrated in Fig. 1. The practical effect of this somewhat more realistic continuum was to increase the overall yield attributed to the giant resonance, particularly on the low excitation side. In addition, the multipeak fits to the subtracted data were carried out, including some restraints imposed by the physics as described below.

The giant resonance in ^{58}Ni has considerable fine structure on the low-excitation side, as can be seen in Fig. 1. Fitting only the region above the fine structure, Duhamel *et al.* [6] identified three broad peaks, one predominately quadrupole ($E_x=16.4$ MeV, $\Gamma=4.3$ MeV, 38% $E2$ EWSR), one predominately monopole ($E_x=17.3$ MeV, $\Gamma=3.1$ MeV, 23% $E0$ EWSR), and a third ($E_x=20.18$ MeV, $\Gamma=3.8$ MeV) for which no multipole assignment was given. Angular distributions of the data for the excitation regions between $E_x=15.5$ and 21.5 MeV in our previous reports [1] showed an increase in cross section at 0° characteristic of monopole strength, but a free fit to the data gave a comparable χ^2 assuming one, two, or three broad peaks in the region and revealed no predom-

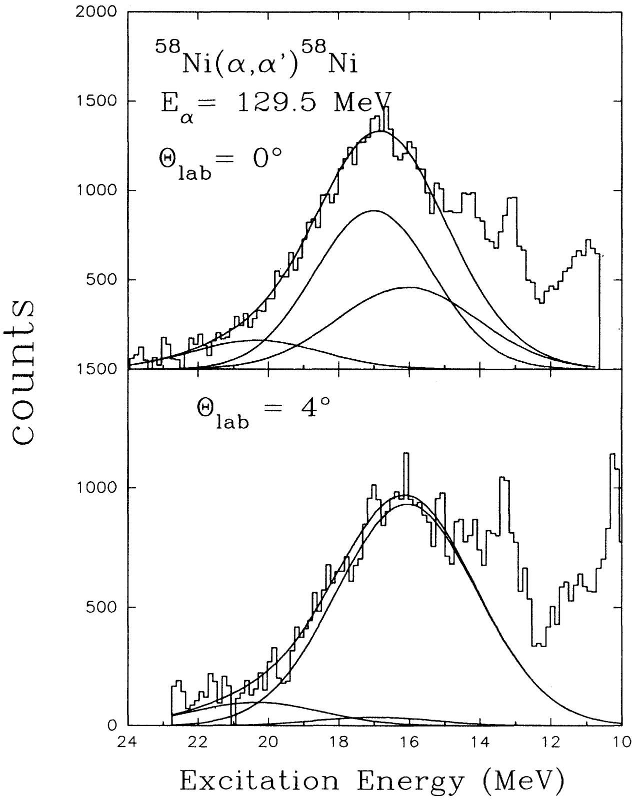

FIG. 2. Spectra of the giant resonance region $\theta_{lab}=0°$ and 4° after subtraction of the continuum. Three peak fits described in the text are shown superimposed.

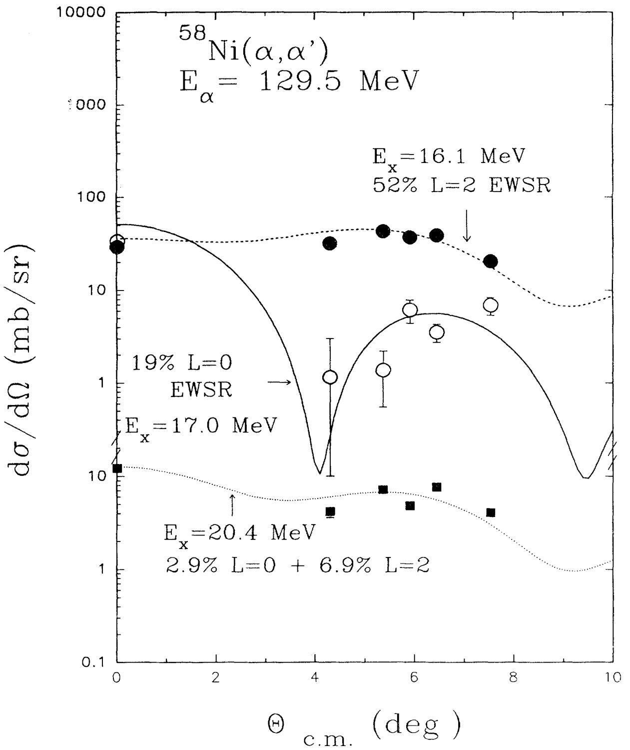

FIG. 3. Angular distributions of the three peaks. Error bars are shown where they exceed the point size. DWBA calculations are also shown for the angular momentum and strength indicated.

TABLE I. Parameters obtained for broad peaks in the giant resonance region.

E_x (MeV)	Γ (MeV)	Sum rule[a] (%)	Reference
16.1±0.2	4.7±0.2	$E2$ 52±8	This work
16.4±0.2	4.3±0.2	$E2$ 38±8	[6]
17.0±0.3	4.0±0.3	$E0$ 19±10	This work
17.3±0.2	3.1±0.2	$E0$ 23±5	[6]
20.4±0.3	4.4±0.2	$E0$ $2.9^{+2.1}_{-2.9}$ $E2$ 6.9±2.0	This work
20.2±0.2	3.8±0.75		[6]

[a] Satchler version 1 form factor for $E0$.

inantly monopole peak.

In this analysis, we began with the Duhamel *et al.* [6] premise of three broad peaks. All spectra were fitted simultaneously with the requirement that the peaks have the same excitation energy and width in each spectrum. The positions and widths reported in Ref. [6] were used as initial parameters. For the first fit, these were fixed and the amplitudes varied for best fit. This resulted in poor convergence of the fits and negative heights for the 17.3 MeV peak in the spectra near the minimum of the 0^+ yield. Then a bit of physics was inserted into the fitting process by using the 0° yield of the 17.3 MeV peak obtained with these fits to predict (assuming $E0$) the strength for the angles where the fitting process produced negative yields. New fits were generated with these heights fixed (for the data at three of the nine angles) at the predicted values and with positions and widths still fixed. Convergence was markedly improved and an overall reduced $\chi^2 \simeq 1.8$ was obtained. Starting with the latter parameters and leaving the heights for the 17.3 MeV peak fixed at the same three angles, a new fit was generated with all other parameters free. The peak positions and widths changed somewhat, but remained close to the Duhamel *et al.* [6] values. Then a final fit was carried out with all parameters free. Only small changes in parameters occurred and a final overall reduced $\chi^2 = 1.5$ was obtained. The resultant fits are shown at two angles in Fig. 2, and the angular distributions for the three peaks are shown in Fig. 3.

The angular distribution for the $E_x = 16.1$ MeV peak is fit well by a calculation for $L = 2$ transfer corresponding to 52±8 % of the $E2$ EWSR, while that for the 17.0 MeV peak is fit by a calculation for $L = 0$ transfer corresponding to 19±10% of the $E0$ EWSR (assuming Satchler [12] version 1 form factor). The angular distribution for the 20.4 MeV peak is fitted by a combination consisting of $2.9^{+2.1}_{-2.9}$% of the $E0$ EWSR and 6.9±2.0 % of the $E2$ EWSR. The energies, widths, and sum-rule fractions obtained are listed in Table I and compared to those of Duhamel *et al.* [6].

III. CONCLUSIONS

Except for the width of the 17 MeV peak, the parameters obtained for the peaks in ^{58}Ni in this work agree with those of Ref. [6] within the errors. While the overall χ^2 of the fit was virtually as good with a one peak or two peak fit to the data, the quality of fit to the 0° spectra was considerably better (χ^2 for the individual 0° spectra about a factor of 2 better) for the three-peak fit. This is clearly because the $E0$ is a significant portion of the peak in our data only at 0°. The angular distribution for the 20.4 MeV peak is not definitive over the angle range covered in this experiment. It is consistent with about 7% of the $E2$ EWSR and may contain up to 5% of the $E0$ EWSR.

The $E0$ strength observed corresponds at most to 32% of the $E0$ EWSR if Satchler version 1 is the appropriate model, but 100% of the $E0$ EWSR if version 2 is appropriate.

This work was supported in part by the Robert A. Welch Foundation and by the U.S. Department of Energy under Grant No. DE-FG05-86ER40256.

[1] D. H. Youngblood, P. Bogucki, J. D. Bronson, U. Garg, Y.-W. Lui, and C. M. Rozsa, Phys. Rev. C **23**, 1997 (1981).

[2] M. Buenerd, J. Phys. C **4**, 115 (1984).

[3] S. Brandenburg, R. de Leo, A. G. Drentje, M. N. Harakeh, H. Sakai, and A. van der Woude, Phys. Lett. **130B**, 9 (1983).

[4] Y.-W. Lui, J. D. Bronson, D. H. Youngblood, Y. Toba, and U. Garg, Phys. Rev. C **31**, 1643 (1985).

[5] H. J. Lu, S. Brandenburg, R. de Leo, M. N. Harakeh, T. D. Poelhekken, and A. van der Woude, Phys. Rev. C **33**, 1116 (1986).

[6] G. Duhamel, M. Buenerd, P. de Saintignon, J. Chauvin, D. Lebrun, Ph. Martin, and G. Perrin, Phys. Rev. C **38**, 2509 (1988).

[7] U. Garg, P. Bogucki, J. D. Bronson, Y.-W. Lui, C. M. Rozsa, and D. H. Youngblood, Phys. Rev. C **25**, 3204 (1982).

[8] F. E. Bertrand, G. R. Satchler, D. J. Horen, and A. van der Woude, Phys. Lett. **80B**, 198 (1979); F. E. Bertrand, G. R. Satchler, D. J. Horen, J. R. Wu, A. D. Bacher, G. T. Emery, W. P. Jones, D. W. Miller, and A. van der Woude, Phys. Rev. C **22**, 1832 (1980).

[9] C. M. Rozsa, D. H. Youngblood, J. D. Bronson, Y.-W. Lui, and U. Garg, Phys. Rev. C **21**, 1252 (1980).

[10] S. Shlomo, Y.-W. Lui, D. H. Youngblood, T. Udagawa, and T. Tamura, Phys. Rev. C **36**, 1317 (1987).

[11] D. H. Youngblood, J. M. Moss, C. M. Rozsa, J. D. Bronson, A. D. Bacher, and D. R. Brown, Phys. Rev. C **13**, 994 (1976).

[12] G. R. Satchler, Part. Nucl. **5**, 105 (1973); Nucl. Phys. **A195**, 1 (1972).