Fine structure of resonance at $E_x \sim$ 14 MeV in ^{40}Ca

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The inelastic scattering of protons by ^{40}Ca leading to a resonance at $E_x \sim 14$ MeV was studied at an incident energy of 65.1 MeV with an energy resolution of 23 keV. The resonance was found to consist of many discrete states, most of which were 2^+ states, and exhausted 8% of the energy-weighted sum rule. Octupole strength of 1.8% of the energy-weighted sum rule was found, 4 times smaller than that observed in electron scattering.

I. INTRODUCTION

The giant quadrupole resonance (GQR) is known to exist at an excitation energy $E_x \sim 63 A^{-1/3}$ MeV in a wide mass range of nuclei.[1,2] In heavy nuclei, the GQR is a compact resonance exhausting almost the full expected fraction of the energy-weighted sum rule (EWSR). In light nuclei, the GQR is highly fragmented.[2] On the other hand, in the medium mass nuclei from Ca to Ni, there are commonly two resonances in the GQR region.[3–23]

One resonance is the quadrupole resonance with a width of 3–4 MeV at $E_x \sim 16$–18 MeV, exhausting $\sim 50\%$ of the EWSR. The excitation energy of this resonance follows the systematics of those of the GQR observed in heavy nuclei.[1,2] The other resonance, the multipolarity of which is not well known, is observed with a width of ~ 1.5 MeV at $E_x \sim 13$–14 MeV. However, neither the splitting of the GQR nor the existence of such an additional resonance in this mass region are predicted theoretically.[24,25] Thus the assignment of the multipolarity of the lower excitation energy resonance has been of special interest. This lower excitation energy resonance has been investigated experimentally with various probes.[2–23] However, the results obtained have been contradictory. As a result, the multipolarity of this resonance has not yet been established. In the scattering of electrons[4–7] and high energy protons,[9,10] a 3^- assignment was favored. In the scattering of polarized protons,[11] ^{3}He, and α particles,[14,16–21] a 2^+ assignment was reported. In the (α,γ) reaction,[22] a 2^+ assignment was ruled out. The α-scattering study at forward angles indicated the predominance of isoscalar 1^- states.[23]

These contradictory results suggest that many states of various multipolarities coexist in this resonance. In the hope that a high resolution study of this resonance may finally resolve the problem, we have studied the fine structure of this lower excitation energy resonance in ^{40}Ca ($E_x \sim 14$ MeV), using inelastic proton scattering. Since the resonance is located below the neutron threshold, and the level density at excitation energies at the resonance is low in ^{40}Ca, the resonance is expected to consist of discrete states.

II. EXPERIMENT

The experiment was carried out using a 65.1 MeV proton beam from the AVF cyclotron of the Research Center for Nuclear Physics, Osaka University. The target was a self-supporting metallic foil of natural Ca, with a thickness of 1.4 mg/cm^2. Inelastically scattered protons were analyzed by the high resolution spectrograph "RAIDEN", and were detected by a 50 cm long position sensitive proportional counter backed by two ΔE proportional counters and a plastic E counter.[26,27] The energy span accepted by this counter system was about 2 MeV when the spectrograph was tuned to the excitation energy region around 14 MeV. This span was enough to cover

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the whole resonance region of present interest. The solid angle of the spectrograph was set to 3 msr. Overall energy resolution was 23 keV, which was mainly due to the target thickness. Peaks from carbon and oxygen contaminants were subtracted by using data with polyethylene and mylar targets. Angular distributions were measured in an angular range from $\theta_L = 10°$ to 54°. The absolute magnitude of the cross section was determined with a 30% uncertainty.

III. RESULTS AND ANALYSIS

Figure 1 shows a typical momentum spectrum of scattered protons taken at $\theta_L = 20°$ in the region of $E_x = 13.3-15.2$ MeV. The error in the absolute value of the excitation energy was estimated to be 40 keV from a comparison of the deduced excitation energies of low-lying states with the results of previous work.[28,29] The resonance was found to consist of at least eighteen prominent peaks. Although a search was made for narrow peaks above $E_x = 15.2$ MeV, none were found, within the present counting statistics.

We extracted differential cross sections of the prominent peaks after subtracting the underlying continuum as a background. We obtained the shape of the underlying continuum by smoothly connecting the minima between the peaks, which was possible with a straight line. In Fig. 1, the shape of the continuum thus obtained is shown by the dotted line. In Fig. 2, we show four typical angular distributions measured in the present work, and assigned to $L = 0$, 2, 3, and 4 transitions, respectively. Error bars in the figure are mainly due to the uncertainty in the assumed shape of the underlying continuum, and determine the uncertainty in the deduced EWSR fractions.

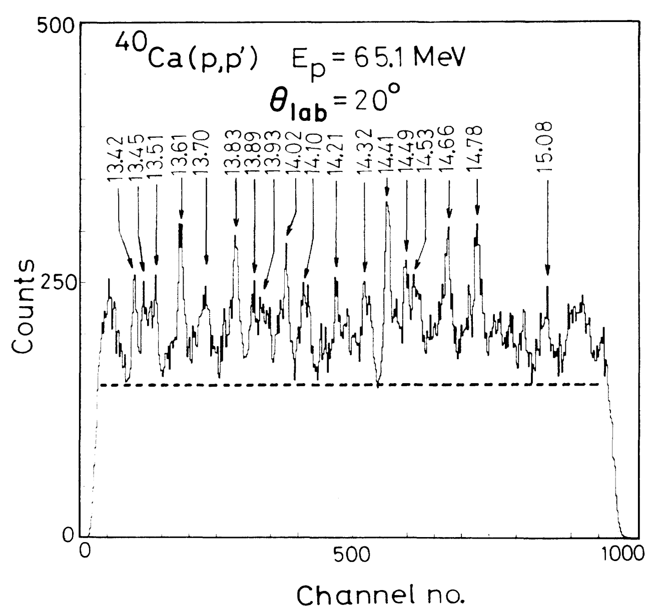

FIG. 1. Momentum spectrum of inelastically scattered protons at $\theta_L = 20°$. Excitation energies of prominent peaks are shown. Assumed shape of underlying continuum is shown by a dotted line.

Experimental angular distributions were compared with the results calculated by the distorted-wave Born approximation (DWBA), using the code, DWUCK-4.[30] Since angular distribution patterns of differential cross sections for natural parity transitions are not so sensitive to the choice of the form factors to be employed, we used the collective form factors for simplicity. Optical potential parameters were taken from Ref. 31. Assuming the observed transitions to be isoscalar ones, transferred L values and fractions of the EWSR were obtained.

As shown in Fig. 2, the shapes of each experimental angular distribution were reasonably well reproduced by the respective DWBA curves. However, at forward ($\theta_L < 15°$) and backward ($\theta_L > 50°$) angles, the experimental cross sections were larger than the calculated values, especially in the case of $L = 3$ and 4 transitions. This may be due to the presence of some unresolved weak peaks overlapping with the prominent ones. The reliability of the present analysis in deducing EWSR fractions was tested by analyzing our results for the 3^- state at $E_x = 3.736$ MeV. We obtained 15% of the EWSR which is in good agreement with other previously reported values[16–18] (10–22%). In Table I, excitation energies, spin-parity J^π, and deduced isoscalar EWSR fractions are summarized.

IV. DISCUSSION

The resonance at $E_x \sim 14$ MeV in ^{40}Ca is found to be composed of various states with different multipolarity.

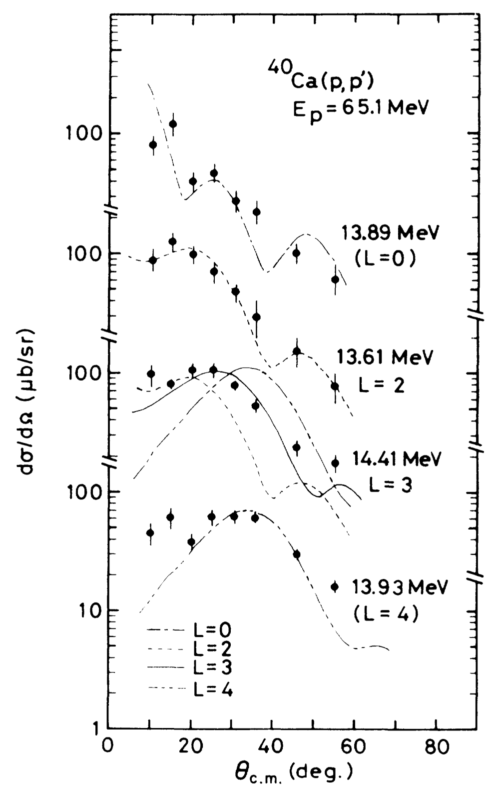

FIG. 2. Typical angular distributions of $L = 0$, 2, 3, and 4 transitions. Lines are results of DWBA calculations.

TABLE I. Excitation energies, J^π and EWSR fractions.

E_x (MeV)[a]	J^π	EWSR (%)[b]
13.42	(2^+)	0.6
13.45[c]		
13.51[c]		
13.61	2^+	0.8
13.70	2^+	1.1
13.83	(2^+)	1.1
13.89	(0^+)	3.3
13.93	(4^+)	0.3
14.02	(3^-)	0.5
14.10	2^+	0.7
14.21	(3^-)	0.2
14.32	(3^-)	0.5
14.41	3^-	0.6
14.49+14.53	2^+	1.3
14.66	2^+	1.0
14.78	2^+	1.0
15.08[c]		

[a]Errors are 40 keV.
[b]Isoscalar transitions are assumed.
[c]Probably a multiplet and L could not be assigned.

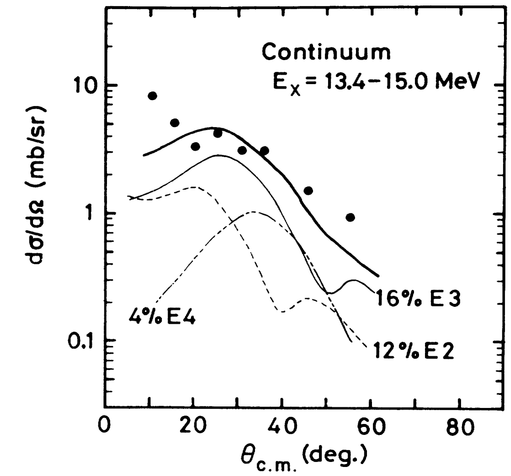

FIG. 3. The angular distribution of the underlying continuum. A bold solid line represents a fit by a combination of $L=2$, 3, and 4 DWBA curves. Each contribution is separately shown by lines.

The main components of this resonance are 2^+ states. The total strength observed for these 2^+ states is 8% of the EWSR. This value is in reasonable agreement with the α-scattering results of Youngblood *et al.*,[16,17] Lui *et al.*,[18] and Borg *et al.*,[19] who reported values of 7%, 2.4–7 %, and 12%, respectively. On the other hand, Zwarts *et al.*[20] reported from a decay study that no underlying continuum existed in this excitation energy region, and that only 2^+ and some 3^- states existed. As a result, they obtained an exceptionally large value of the EWSR ($\sim$40%). Their conclusion was quite different from those of previous studies,[16–19] in which the clear presence of an underlying continuum was claimed.

To solve the above problem we analyzed the cross section of the underlying continuum obtained in the present (p,p′) reaction. The deduced angular distribution of the underlying continuum in the excitation energy region of $E_x=13.4$–15.0 MeV is shown in Fig. 3. The slope of the angular distribution is less steep than that of any components in the resonance. In other words, the distribution does not show either an $L=2$ or an $L=3$ pattern. To examine the conclusion of Zwarts *et al.*[20] we tried to reproduce the angular distribution of the underlying continuum with a combination of $L=2$, 3 and 4 DWBA curves. The bold solid line in Fig. 3 shows the best fit obtained. From this analysis, 12% of $L=2$, 16% of $L=3$, and 4% of $L=4$ EWSR fractions are required. However, the fitting at both forward and backward angular regions is not satisfactory. To obtain a better fit, a mixture of lower and higher multipolarity components seems to be necessary, similar to the cases of the other previous studies.[16–19] However, we did not take this into account for simplicity. Thus, the 12% of the EWSR for $L=2$ deduced in our simplified analysis should be considered as an upper bound. Our result by no means supports the conclusion of Zwarts *et al.*

Four possible octupole states are observed in the present work at $E_x \sim 14$ MeV, with 1.8% of the EWSR. In electron scattering, Torizuka *et al.*[5] found isoscalar octupole strength of 8% of the EWSR at $E_x \sim 14$ MeV, 4 times larger than ours. In ^{56}Fe and ^{58,60}Ni, as in ^{40}Ca, considerable octupole strength (8–28 % of the EWSR) was reported in electron scattering.[4,6,7] This discrepancy can be understood if we assume that most of the octupole strength observed in electron scattering is due to not the isoscalar but the isovector resonance.[7,32] This is because electrons excite isovector octupole states in addition to isoscalar ones, although hadronic probes only weakly excite isovector octupole states.[32] Indeed, no appreciable octupole state has been observed in α scattering.[16–21] Nishimura *et al.*[32] recently predicted the location of isovector collective states in this excitation energy region and Nakayama *et al.*[33] observed an isovector octupole resonance at $E_x \sim 15$ MeV in ^{40}Ca by using a (^{7}Li, ^{7}Be) reaction. The 3^- assignment in proton scattering by Lewis[8] at 185 MeV, and the tentative 3^- assignment by Marty *et al.*[10] at 155 MeV may be due to a possible enhancement of isovector excitations in high energy proton scattering.

We observe no evidence of an isoscalar dipole transition in the present excitation energy region. On the other hand, Rost *et al.*[23] reported, from studying the (α,α') reaction, that the resonance observed at $E_x=14.3$ MeV in their study is dominated by isoscalar 1^- and 2^+ states. Our result contradicts their conclusion.

Only one possible 4^+ state is observed at $E_x=13.93$ MeV. The presence of the $2\hbar\omega$ component of the 4^+ strength has been predicted near 14 MeV excitation energy.[24,25] The presently observed 4^+ strength (0.3% of the EWSR) is much smaller than the predicted value. A possible 0^+ state is observed at $E_x=13.89$ MeV, which may correspond to the 0^+ state found by Yamagata *et al.* in ^{3}He scattering.[15]

In conclusion, we have clarified the structure of the resonance region in ^{40}Ca at $E_x \sim 14$ MeV by using proton inelastic scattering with a high resolution. The resonance is found to consist mainly of isoscalar 2^+ states with strength equal to 8% of the EWSR. The concentration of such 2^+ states at this excitation region has not yet been explained theoretically. To understand the quadrupole strength distribution in this mass region, improved theoretical calculations are needed. At this excitation energy, only 1.8% of the EWSR of octupole strength is observed. This value is 4 times smaller than that observed in electron scattering. This suggests that the octupole resonance observed at electron scattering corresponds to the isovector resonance.

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[1]F. E. Bertrand, Ann. Rev. Nucl. Sci. **26**, 457 (1976).

[2]J. Speth and A. van der Woude, Rep. Prog. Phys. **44**, 719 (1981).

[3]I. S. Gul'karov, N. G. Afanas'ev, V. M. Khvastunov, N. G. Shevchenko, V. D. Afanas'ev, G. A. Savitskii, and A. A. Khomich, Sov. J. Nucl. Phys. **9**, 274 (1969).

[4]Y. Torizuka, Y. Kojima, K. Itoh, A. Nakada, S. Mitsunobu, M. Nagao, K. Hosoyama, S. Fukuda, and H. Miura, in *Proceedings of the International Conference on Photonuclear Reactions and Applications, 1973,* edited by B. L. Berman (University of California Press, Livermore, 1973), p. 675.

[5]Y. Torizuka, K. Itoh, Y. M. Shin, Y. Kawazoe, H. Matsuzaki, and G. Takeda, Phys. Rev. C **11**, 1174 (1975).

[6]R. Pitthan, G. M. Bates, J. S. Beachy, F. B. Dally, D. H. Dubois, J. N. Dyer, S. J. Kowalick, and F. R. Buskirk, Phys. Rev. C **21**, 147 (1980).

[7]R. Klein, K. Kawazoe, P. Grabmayer, G. J. Wagner, J. Friedrich, and N. Voegler, Phys. Lett. **145B**, 25 (1984).

[8]M. B. Lewis, Phys. Rev. Lett. **29**, 1257 (1972).

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

[10]N. Marty, M. Morlet, A. Willis, V. Comparat, and R. Frascaria, Nucl. Phys. **A238**, 93 (1975).

[11]D. C. Kocher, F. E. Bertrand, E. E. Gross, and E. Newman, Phys. Rev. C **14**, 1392 (1976).

[12]C. C. Chang, F. E. Bertrand, and D. C. Kocher, Phys. Rev. Lett. **34**, 221 (1975).

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

[14]J. Arvieux, M. Buenerd, A. J. Cole, P. De Saintignon, G. Perrin, and D. J. Horen, Nucl. Phys. **A247**, 238 (1975).

[15]T. Yamagata, K. Iwamoto, S. Kishimoto, B. Saeki, K. Yuasa, M. Tanaka, T. Fukuda, K. Okada, I. Miura, M. Inoue, and H. Ogata, Phys. Rev. Lett. **40**, 1628 (1978).

[16]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).

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

[18]Y.-W. Lui, J. D. Bronson, C. M. Rozsa, D. H. Youngblood, P. Bogucki, and U. Garg, Phys. Rev. C **24**, 884 (1981).

[19]K. van der Borg, M. N. Harakeh, and A. van der Woude, Nucl. Phys. **A365**, 243 (1981).

[20]F. Zwarts, A. G. Drentje, M. N. Harakeh, and A. van der Woude, Phys. Lett. **125B**, 123 (1983); Nucl. Phys. **A439**, 117 (1985).

[21]B. Bonin, N. Alamonos, B. Berthier, G. Bruge, H. Faraggi, D. Legrand, J. C. Lugol, W. Mittig, L. Papineau, A. I. Yavin, D. K. Scott, M. Levine, J. Arvieux, L. Farvacque, and M. Buenerd, Nucl. Phys. **A430**, 349 (1984).

[22]L. Meyer-Schutzmeister, R. E. Segel, K. Raghunathan, P. T. Debevec, W. R. Wharton, L. L. Rutledge, and T. R. Ophel, Phys. Rev. C **17**, 56 (1978).

[23]H. Rost, W. Eyrich, A. Hofmann, U. Scheib, and F. Vogler, Phys. Lett. **88B**, 51 (1979).

[24]G. F. Bertsch and S. F. Tsai, Phys. Rep. C **18**, 125 (1975).

[25]K. F. Liu and G. E. Brown, Nucl. Phys. **A265**, 385 (1976).

[26]H. Ikegami, S. Morinobu, I. Katayama, M. Fujiwara, and S. Yamabe, Nucl. Instrum. Methods **175**, 335 (1980).

[27]Y. Fujita, K. Nagayama, S. Morinobu, M. Fujiwara, I. Katayama, T. Yamazaki, and H. Ikegami, Nucl. Instrum. Methods **173**, 265 (1980).

[28]C. R. Gruhn, T. Y. T. Kuo, C. J. Maggiore, H. McManus, F. Petrovich, and B. M. Preedom, Phys. Rev. C **3**, 915 (1972).

[29]J. A. Nolen, Jr. and R. J. Gleitsmann, Phys. Rev. C **11**, 1159 (1975).

[30]P. D. Kunz, private communication.

[31]W. T. H. von Oers, Phys. Rev. C **3**, 1550 (1971).

[32]M. Nishimura, M. Fujiwara, and S. Nishizaki, Phys. Lett. **190B**, 11 (1987).

[33]S. Nakayama, T. Yamagata, K. Yuasa, M. Tanaka, M. Inoue, T. Itahashi, and H. Ogata, Phys. Rev. C **34**, 366 (1986), and unpublished.