PHYSICAL REVIEW C VOLUME 34, NUMBER 1 JULY 1986

Excitation of isovector giant resonances in ^{27}Al by heavy ion charge exchange reaction

S. Nakayama
College of General Education, Tokushima University, Tokushima 770, Japan

T. Yamagata and K. Yuasa
Department of Physics, Konan University, Higashinada, Kobe 658, Japan

M. Tanaka
Kobe Tokiwa Junior College, Nagata, Kobe 653, Japan

M. Inoue,* T. Itahashi, and H. Ogata
Research Center for Nuclear Physics, Osaka University, Mihogaoka, Ibaraki, Osaka 567, Japan
(Received 31 March 1986)

Excitation of isovector giant resonances in ^{27}Al was studied by using the ^{27}Al(^{7}Li,^{7}Be)^{27}Mg reaction at incident energies of 100, 150, and 180 MeV. We observed the analog of the giant dipole resonance at $E_x = 14.3$ MeV in ^{27}Mg. From the observed excitation function, we suggest that a peak at $E_x = 9.5$ MeV is a resonance with a higher multipolarity than one. In the excitation energy region higher than the giant dipole resonance, no resonance was observed.

Studies of isovector giant resonances (IVGR's) in nuclei are one of the recent topics of interest.[1] Theoretical work predicts IVGR's with various multipolarities from both microscopic and macroscopic calculations.[2] Experimentally, on the other hand, only the isovector giant dipole resonance (GDR) has been observed in a wide mass range of nuclei.[3] Among high multipole resonances, excitation of the isovector giant quadrupole resonance (GQR) has been recently reported in medium and heavy mass nuclei.[5] In light mass nuclei, however, IVGR's with high multipolarities are not known until now.

So far, IVGR's have been studied by using photonuclear reactions,[3,4] electron scattering,[5] radiative capture reactions,[6] and charge exchange reactions.[7-9] Among other things, reactions such as (n,p) and (π^-,π^0) play a unique role in studying analogs of IVGR's because of their isospin selection rule.[10] Thus, in the (π^-,π^0) study,[9] excitation of the isovector giant monopole resonance (GMR) has been recently found in medium mass nuclei. Charge exchange reactions with heavy ions, such as the (^{7}Li,^{7}Be) reaction, would provide new information about IVGR's since they have the following advantages: (1) High multipole resonances may be preferentially excited due to the large angular momentum transfer. (2) As compared with the (n,p) and (π^-,π^0) studies where secondary beams are used, better energy resolution and better counting statistics may be possible.

In this paper, we present experimental results from a new charge exchange reaction, ^{27}Al(^{7}Li,^{7}Be)^{27}Mg. The IVGR known in ^{27}Al is only the GDR, and in the (n,p) study,[7] the GDR has been reported to split into two components, while the (γ,xn) study[4] has shown no evidence for such a splitting.

The experiment was carried out at three different incident energies of $E_L = 100$, 150, and 180 MeV. By changing the incident energy, we can distinguish resonance peaks from peaks due to multistep reaction processes. Further, we expect that excitation functions with different multipolarities behave in different ways due to angular momentum matching conditions. We determined transferred angular momenta for observed states from measurements of not only angular distributions but also excitation functions of differential cross sections.

Beams of ^{7}Li^{3+} were provided from the isochronous cyclotron of the Research Center for Nuclear Physics, Osaka University. A target was a self-supporting metallic foil of ^{27}Al with a thickness of 2.7 mg/cm^2. Emitted ^{7}Be particles in the forward angular region were detected by two sets of $\Delta E - E$ Si-detector telescopes. At $E_L = 150$ MeV, a $\Delta E - E$ position sensitive detector telescope was used for the measurement of angular distributions in an angular range of $\theta_L = 6°-17°$. The observed energy resolution was about 700 keV, which was not enough to distinguish the contribution from the first excited state of ^{7}Be at $E_x = 0.43$ MeV. Since this contribution is expected to be small, from the high resolution experiment,[11-13] it will be neglected hereafter. Contamination peaks due to ^{12}C and ^{16}O were estimated from measurements with Mylar and polyethylene targets to be negligible.

Typical energy spectra of ^{7}Be at $E_L = 100$, 150, and 180 MeV are shown in Fig. 1, where scattering angles are chosen so that the transferred momenta are nearly equal to each other. For comparison, the proton energy spectrum obtained in the (n,p) study at $E_n = 56.1$ MeV (Ref. 7) is also shown in the bottom of Fig. 1. Low-lying discrete states, i.e., the ground state ($\frac{1}{2}^+$) and the states at $E_x = 1.8$ MeV ($\frac{5}{2}^+$) and 3.8 MeV ($\frac{7}{2}^-$), are more conspicuous in any of the ^{7}Be spectra than in the proton spectrum. In the higher excitation energy region, two giant resonancelike structures at $E_x \sim 10$ and 14 MeV are visible on an underlying continuum. This continuum is observed as a very broad bump with a width of $\sim$40 MeV at peak position of $E_x \sim 30$ MeV in the case of $E_L = 180$ MeV. The location moves to lower excitation energy according to

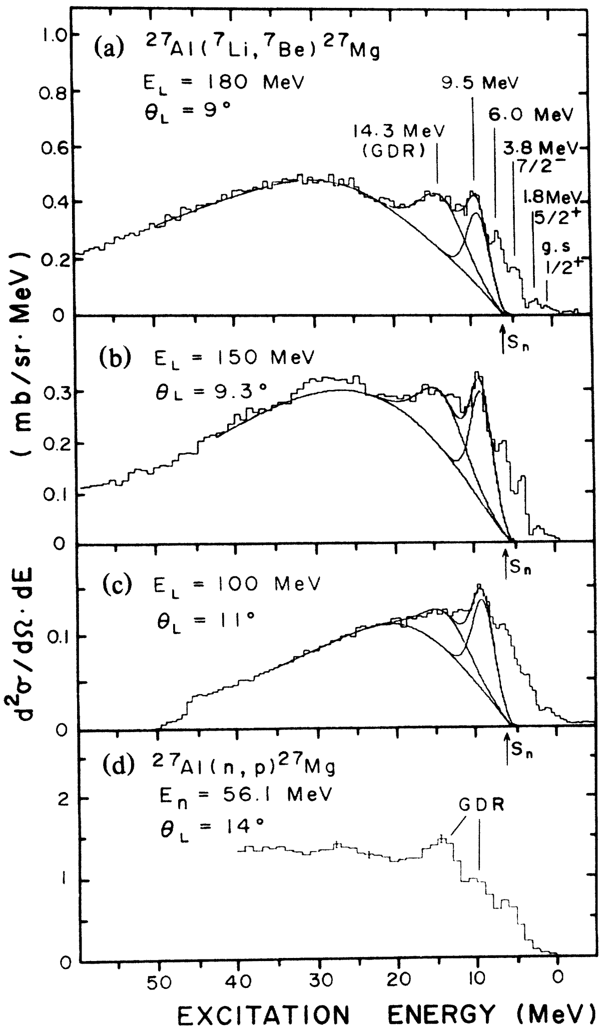

FIG. 1. (a)-(c) Typical energy spectra of ^{7}Be in the ^{27}Al(^{7}Li,^{7}Be)^{27}Mg reaction at different incident energies. (d) A proton spectrum of the (n,p) reaction taken from Ref. 7. Solid lines show assumed shapes of the underlying continua. S_n denotes the neutron separation energy. Fitted curves assuming Gaussian shape are also shown for the resonances at E_x =9.5 and 14.3 MeV.

decrease of incident energy as shown in Fig. 1; E_x~27 MeV at E_L=150 MeV and ~20 MeV at E_L=100 MeV. This continuum shape is very similar to the ^{6}Li spectrum in the ^{27}Al(^{7}Li,^{6}Li+x) reaction simultaneously measured in the present study. The underlying continuum seen in Fig. 1 is considered to originate mainly from the ^{7}Be in the (^{6}Li,^{7}Be) reaction after the breakup of ^{7}Li into ^{6}Li+n.

On the other hand, the locations of the peaks at E_x~10 and 14 MeV stay at fixed excitation energies irrespective of the incident energy. Therefore, these are resonance peaks in ^{27}Mg. Extracted values of the locations and widths of these resonances from the observed spectra are E_x=9.5 MeV, Γ=3.5 MeV and E_x=14.3 MeV, Γ=7 MeV, respectively. As mentioned already, in the (n,p) work, the GDR has been found to split into two parts at E_x=10 and 14.4 MeV as shown in Fig. 1(d). Presently observed values for excitation energies are very close to the (n,p) results. However, the 9.5-MeV resonance observed in the (^{7}Li,^{7}Be) reaction is more prominent than in the (n,p) reaction. In order to determine the multipolarities of these resonances, angular distributions of differential cross sections at E_L=150 MeV were compared with the DWBA calculations.

Differential cross sections were extracted by a peak fitting procedure with Gaussian shapes after subtraction of the underlying continuum as background. We assumed the underlying continuum to be linear around E_x=35–40 MeV and to be smoothly extended to E_x~5 MeV which is equal to the neutron separation energy as shown in Fig. 1, keeping in mind the resemblance of the underlying continuum shape to that of the ^{6}Li spectrum populated by the (^{7}Li,^{6}Li+x) reaction. Angular distributions of differential cross sections thus obtained, including that of the underlying continuum at E_x~14 MeV, are shown in Fig. 2. Here we could not obtain angular distributions at forward angles ($\theta_L \lesssim 7°$) due to a contribution from hydrogen contamination for the 9.5- and 14.3-MeV resonances. The angular distribution of the underlying continuum shows a monotonous decrease with increase of the scattering angle, whereas angular distributions of the 9.5- and 14.3-MeV resonances show oscillatory patterns. In this figure, angular distributions for low-lying states are also shown for comparison. Error bars result mainly from counting statistics for the low-lying states and from uncertainties in the underlying continuum subtraction and peak fitting procedure for the high-lying states.

The solid, dashed, and dotted-dashed lines in Fig. 2 are DWBA calculations for transitions of $0^+ \rightarrow 1^-(\Delta J^\pi = 1^-)$, $0^+ \rightarrow 2^+(\Delta J^\pi = 2^+)$, and $0^+ \rightarrow 3^-(\Delta J^\pi = 3^-)$, respectively. The DWBA curves were obtained by scaling the calculated results from the following authors: Cook *et al.* [11] (E_L=50 MeV on ^{16}O), Bang, Gareev, Goncharov, and Kasacha[12] (E_L=78 MeV on ^{12}C and ^{16}O), and Dodd *et al.*[13] (E_L=72 MeV on ^{28}Si). In these studies, the calculations for natural parity states have fitted the observed angular distributions reasonably well. It is found that the presently observed angular distributions for the low-lying states are also fairly well reproduced by the calculations with appropriate ΔJ^π values as shown in Fig. 2(a), i.e., $\Delta J^\pi = 2^+$ for the $\frac{1}{2}^+$ (g.s.) and the $\frac{5}{2}^+$ states (E_x=1.8 MeV) and $\Delta J^\pi = 1^-$ for the $\frac{7}{2}^-$ state (E_x=3.8 MeV). This fact encourages us to try to determine ΔJ^π values for the 9.5- and 14.3-MeV resonances. The observed angular distributions of the resonances are well reproduced by curves of $\Delta J^\pi = 1^-$ or 3^- as shown in Fig. 2(b). We cannot uniquely determine ΔJ^π values for these resonances since the calculated curves are similar to each other for $\Delta J^\pi = 1^-$ and 3^- in the presently observed angular range.

In order to obtain additional information about ΔJ^π values for these resonances ($\Delta J^\pi = 1^-$ or 3^-), we investigated excitation functions of the cross sections. In Fig. 3, the ratios of differential cross sections, $\sigma(\theta$,3.8 MeV, $\Delta J^\pi = 1^-)/\sigma(\theta$,14.3 MeV) and $\sigma(\theta$,9.5 MeV$)/\sigma(\theta$,14.3 MeV) are plotted as a function of the incident energy, where the scattering angles are chosen to have the same momentum transfer. As seen in this figure, the former ratio is almost constant. Therefore, we conclude that the ΔJ^π value for the 14.3-MeV resonance is the same as that

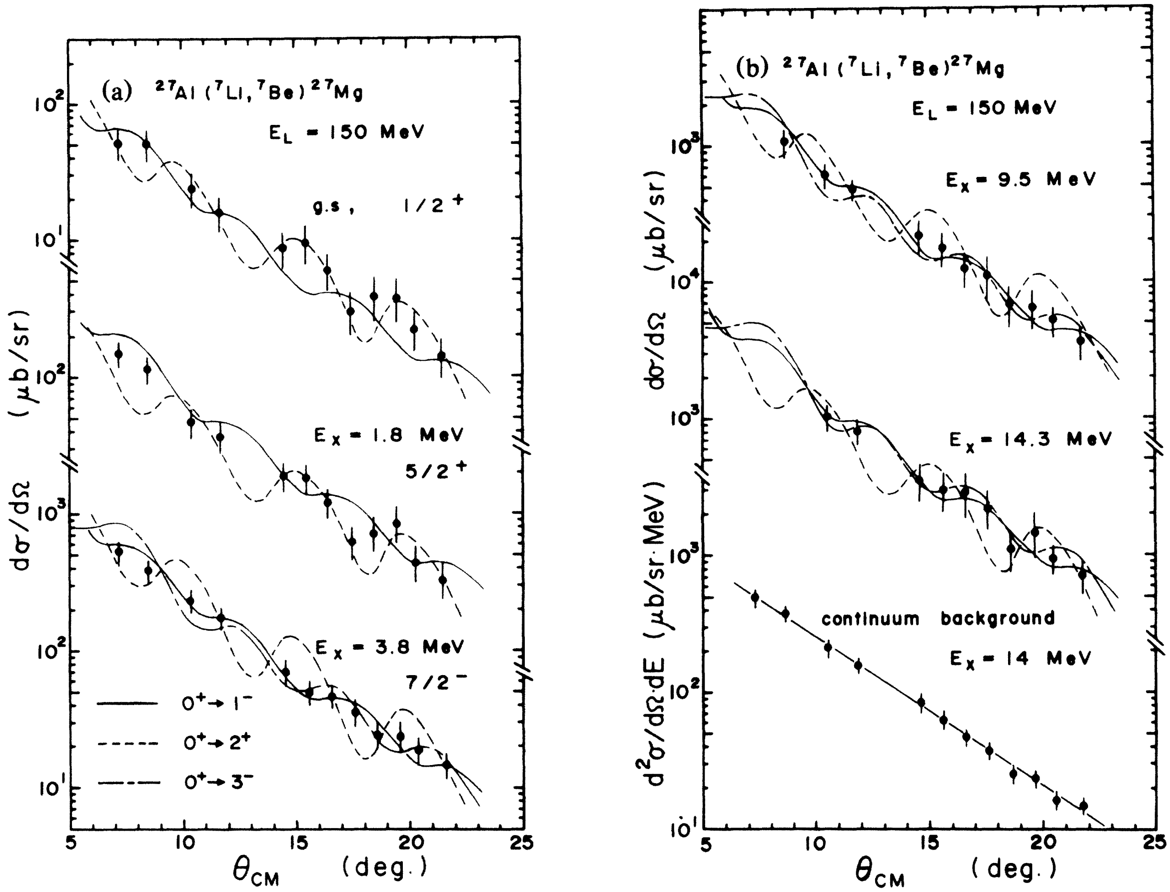

FIG. 2. Angular distributions of differential cross sections of (a) the ground state ($\frac{1}{2}^+$), the doublet at $E_x=1.8$ MeV ($\frac{5}{2}^+$), and the state at $E_x=3.8$ MeV ($\frac{7}{2}^-$), and (b) the 9.5- and 14.3-MeV resonances and the underlying continuum at $E_x\sim14$ MeV in the ^{27}Al(^{7}Li,^{7}Be)^{27}Mg reaction at $E_L=150$ MeV. Solid, dashed, and dotted-dashed lines correspond to angular distribution patterns of $\Delta J^\pi=1^-$, 2^+, and 3^- obtained by scaling DWBA calculations in Refs. 11–13.

for the 3.8-MeV state, namely, $\Delta J^\pi=1^-$, and the 14.3-MeV resonance is the analog of the GDR. It is noticed that this is the first observation of the IVGR in the (^{7}Li,^{7}Be) reaction.

On the other hand, the excitation function of the 9.5-MeV resonance is different from those of the 3.8-MeV state and the 14.3-MeV resonance ($\Delta J^\pi=1^-$). As shown in Fig. 3, the ratio of the differential cross section of the 9.5-MeV resonance to that of the GDR at $E_x=14.3$ MeV varies from 0.9 to 0.5 as the incident energy increases from 100 to 180 MeV. In addition, this ratio is larger than the (n,p) result, 0.39 ± 0.06 (shown by the hatched region in Fig. 3). These facts suggest that the 9.5-MeV resonance is not a component of the GDR but a resonance with a higher multipolarity than 1^-. Torizuka has observed the isovector giant octupole resonance in ^{197}Au at $E_x\sim9.7$ MeV by using electron scattering.[14] Assuming excitation energy systematics of $E_x\propto A^{-1/3}$, an estimated value of excitation energy is ~19 MeV in ^{27}Al, which corresponds to $E_x\sim12$ MeV in ^{27}Mg. Considering that the location of the giant resonances shifts lower than the values estimated from the $A^{-1/3}$ systematics in light mass nuclei, the 9.5-MeV resonance may be the analog of the isovector octupole resonance.

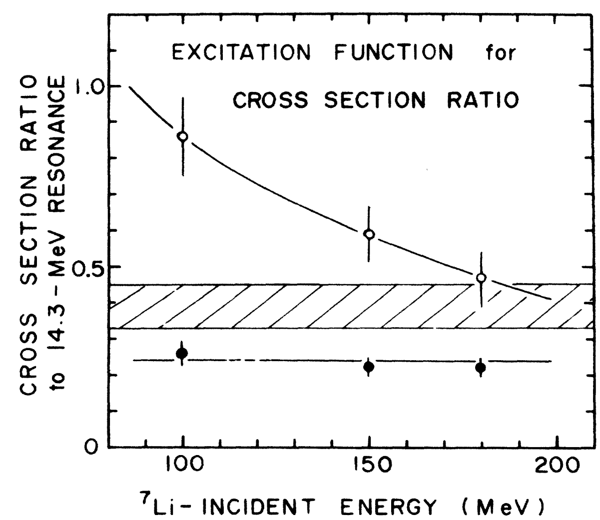

FIG. 3. Excitation functions of the cross section ratios; $\sigma(\theta$, 3.8 MeV, $\Delta J^\pi=1^-)/\sigma(\theta$, 14.3 MeV) (closed circles) and $\sigma(\theta$, 9.5 MeV)$/\sigma(\theta$, 14.3 MeV) (open circles). These ratios were reduced from the ^{7}Be spectra shown in Fig. 1. The hatched area shows the (n,p) result. Solid lines guide eyes.

Finally, we direct attention to the higher excitation energy region than the GDR. Recently, in medium and heavy mass nuclei, experimental evidence for the GQR[5] and GMR[9] has been reported at $E_x \sim 130A^{-1/3}$ and $150A^{-1/3}$ MeV, respectively. In the present work at $E_L = 150$ MeV [see Fig. 1(b)], an additional structure is seen at $E_x \sim 28$ MeV on the underlying continuum. However, such a structure is not discernible in spectra at $E_L = 100$ and 180 MeV, which suggests that the structure at $E_x \sim 28$ MeV is not an excited state in ^{27}Mg, but a peak due to sequential reaction processes.

This experiment was performed at the Research Center for Nuclear Physics, Osaka University, under Program No. 19A15.

---

*Present address: Keage Laboratory, Institute for Chemical Research, Kyoto University, Kyoto 606, Japan.

[1]H. W. Baer, R. Bolton, J. D. Bowman, M. D. Cooper, F. H. Cverna, N. S. P. King, M. Leitch, H. S. Matis, J. Alster, A. Doron, A. Erell, M. A. Moinester, E. Blackmore, and E. R. Siciliano, Nucl. Phys. **A386**, 437c (1983).

[2]A. Bohr and B. R. Mottelson, *Nuclear Structure* (Benjamin, New York, 1975), Vol. 2; N. Auerbach, Nucl. Phys. **A182**, 247 (1972); G. F. Bertsch and S. F. Tasi, Phys. Rep. **18C**, 125 (1975); K. F. Lin and G. E. Brown, Nucl. Phys. **A265**, 385 (1976); G. E. Brown, J. S. Dehesa, and J. Speth, *ibid.* **A330**, 290 (1979).

[3]B. L. Berman and S. C. Fultz, Rev. Mod. Phys. **47**, 713 (1975).

[4]J. Ahrens *et al.*, in *Proceedings of the International Conference Reactions and Applications, Pacific Grove, California, 1973*, edited by B. L. Berman (Lawrence Livermore Laboratory, Livermore, 1973), p. 23.

[5]S. Fukuda and Y. Torizuka, Phys. Rev. Lett. **29**, 1109 (1972); Phys. Lett. **62B**, 146 (1976); R. Pitthan, in *Proceedings of the International Conference on Giant Multipole Resonances, Oak Ridge, Tennessee, 1979*, edited by F. E. Bertrand (Harwood Academic, London, 1980), p. 161, and references therein.

[6]F. S. Dietrich, D. W. Heikkinen, K. A. Snover, and K. Ebisawa, Phys. Rev. Lett. **38**, 156 (1977); I. Bergqvist, R. Zorro, A. Hakansson, A. Lindholdm, L. Nilsson, N. Olsson, and A. Likar, Nucl. Phys. **A419**, 509 (1984).

[7]F. P. Brady, N. S. P. King, M. W. McNaughtor, and G. R. Satchler, Phys. Rev. Lett. **36**, 15 (1976).

[8]F. P. Brady, G. A. Needham, J. L. Nullmann, C. M. Castaneda, T. D. Ford, N. S. P. King, S. J. L. Romero, M. L. Webb, V. R. Brown, and C. H. Poppe, J. Phys. G **10**, 363 (1984).

[9]H. W. Baer, R. Bolton, J. D. Bowman, M. D. Cooper, F. Cverna, N. S. P. King, M. Leitch, and H. S. Matis, Phys. Rev. Lett. **49**, 1376 (1982).

[10]N. Auerbach, J. D. Bowman, M. A. Franey, and W. G. Love, Phys. Rev. C **28**, 280 (1983); N. Auerbach, J. Phys. (Paris) Colloq. **45**, C4-305 (1984).

[11]J. Cook, K. W. Kemper, P. V. Drumm, L. K. Fifield, M. A. C. Hotchkis, T. R. Ophel, and C. L. Woods, Phys. Rev. C **30**, 1538 (1984).

[12]J. Bang, F. A. Gareev, S. A. Goncharov, and G. S. Kasacha, Nucl. Phys. **A429**, 330 (1984).

[13]A. C. Dodd, N. M. Clarke, J. Coopersmith, R. J. Griffiths, K. I. Pearce, B. Stanley, and J. Cook, J. Phys. G **11**, 1035 (1985).

[14]Y. Torizuka, J. Phys. Soc. Jpn. Suppl. **44**, 397 (1978).