Isovector Electric Monopole Resonance in ^{60}Ni

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The isovector electric monopole resonance (IVMR) was studied by the ^{60}Ni(^{7}Li, ^{7}Be)^{60}Co reaction at 65A MeV and at forward scattering angles including zero degrees. We confirmed the existence of the IVMR at an excitation energy of 20 ± 2 MeV with a width of 10 ± 2 MeV in ^{60}Co, which is an analog of the $T_0 + 1$ isospin component of the IVMR estimated at $E_x \approx 31$ MeV in ^{60}Ni. The result presently obtained is consistent with previous results using the pion charge-exchange reaction.

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Isovector resonances ($\Delta T = 1$) in nuclei are collective motions in which protons oscillate in opposite phase with respect to neutrons. These resonances are also characterized by the electric ($\Delta S = 0$) and magnetic ($\Delta S = 1$) modes which correspond to coherent motions of the spin-nonflip and spin-flip oscillations, respectively. Resonances with various multipolarities have been theoretically predicted [1]. Among them, the monopole resonances play a crucial role in astrophysics [2]. Concerning the isoscalar mode ($\Delta T = 0$), the electric monopole resonance (GMR; $\Delta T = 0$, $\Delta S = \Delta L = 0$) has been well established in various inelastic scatterings. The GMR was unambiguously identified due to a sharp enhancement at $\theta_L = 0°$ [3]. On the other hand, the existence of the isovector electric monopole resonance (IVMR; $\Delta T = 1$, $\Delta S = \Delta L = 0$) has been reported only by the pion charge-exchange reaction [4]. The IVMR has also been searched for by using other reaction probes such as electron scattering [5] and the (^{13}C, ^{13}N) reaction [6]. Confirmation of the IVMR is, however, still very desirable because of the inconclusive data from these reactions.

One of the major reasons for the inconclusive data is due to a difficulty in determining the multipolarity of the resonance. The resonance is, in general, observed as a broad bump riding on a large underlying background mainly caused by a quasielastic scattering. One meets another serious difficulty when one uses hadron reaction probes with spins like (p, n) and (^{3}He, t). These reactions allow simultaneous $\Delta S = 0$ and $\Delta S = 1$ excitations, differing from the case of the pion charge-exchange reaction which proceeds only via the $\Delta S = 0$ transition. There is no nuclear probe allowing only the $\Delta S = 0$ excitation. In this respect, the (^{13}C, ^{13}N) reaction is expected to be a promising probe for observing isovector electric resonances because of its large Fermi matrix element ($M_F/M_{GT} \sim 5$) [6]. In this reaction, a resonance has been observed at the relevant excitation energy, but its multipolarity is not consistent with the $\Delta L = 0$ assumption.

In the present work, we started with the following question: Can we observe the IVMR reported by the pion charge-exchange reaction? To answer this question, we employed the (^{7}Li, ^{7}Be) reaction at 65A MeV on a ^{60}Ni target which is the target studied by various other (n, p)-like reactions [4,6,7]. The (^{7}Li, ^{7}Be) reaction is chosen for the following two reasons. One is that the reaction predominantly proceeds via a one-step process at 65A MeV and at forward angles [8]. The other is that one can separate the $\Delta S = 0$ and $\Delta S = 1$ spectra by measuring the ^{7}Be ejectiles in coincidence with the ^{7}Be γ ray [9]. The quasifree scattering is expected to proceed in a similar way for the $\Delta S = 0$ and $\Delta S = 1$ excitations. Thus, such simultaneous observations of the $\Delta S = 0$ and $\Delta S = 1$ spectra may allow one to get evidence for isovector resonances with the $\Delta S = 0$ and $\Delta S = 1$ modes by distinguishing them from the underlying continuum. We investigated separately the singles, the $\Delta S = 0$, and the $\Delta S = 1$ spectra in the excitation energy [E_x(IVMR) = 23.1 MeV] region where the isovector resonances were theoretically predicted [1]. Their multipolarities were discussed by comparing the angular distributions of the differential cross sections with microscopic distorted-wave-approximation (DWBA) calculations. In this paper, we report on the IVMR excited by the (^{7}Li, ^{7}Be) reaction on ^{60}Ni.

A 65A MeV ^{7}Li^{3+} beam was provided from the Ring Cyclotron of the Research Center for Nuclear Physics, Osaka University. The target used was a self-supporting foil of a separated ^{60}Ni isotope (99.9%) with a thickness of 2.6 mg/cm^2. Details of the experimental setup have been described in Ref. [9]. The ^{7}Be ejectiles were analyzed using the spectrograph "Grand RAIDEN" [10] set at 0.3° and 1°. The aperture of the entrance slit of the Grand RAIDEN was ± 20 mrad horizontally and ± 15 mrad vertically. The

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scattering angles θ_L for the ^{7}Be ejectiles were determined by tracing back their positions and incident angles at the focal plane of the Grand RAIDEN. Energy spectra were obtained by gating with a width of 15 mrad horizontally. The 0.43-MeV γ ray from ^{7}Be ejectiles was measured with the γ detector system "NYMPHS" [9] surrounding the target chamber.

We investigated the singles spectra at $\theta_L = 0°$, 1°, and 2° where the angular momentum transfers of $\Delta L = 0$, $\Delta L = 1$, and $\Delta L = 2$ were, respectively, expected to be dominant in the ^{60}Ni(^{7}Li, ^{7}Be) reaction at 65*A* MeV [11]. Figure 1 shows the singles spectra at $\theta_L = 0°$, 1°, 2°, and the difference between the 0° and 1° singles spectra: $\sigma(0°) - \sigma(1°)$. This difference spectrum clearly indicates that two resonances are excited at the excitation energies, $E_x \approx 9$ and 20 MeV. Their excitation energies are roughly equal to the result of the (π^-, π^0) reaction [12]. The cross section of the 9-MeV resonance was found to be enhanced around $\theta_L = 1°$, and that of the 20-MeV one around $\theta_L = 0°$.

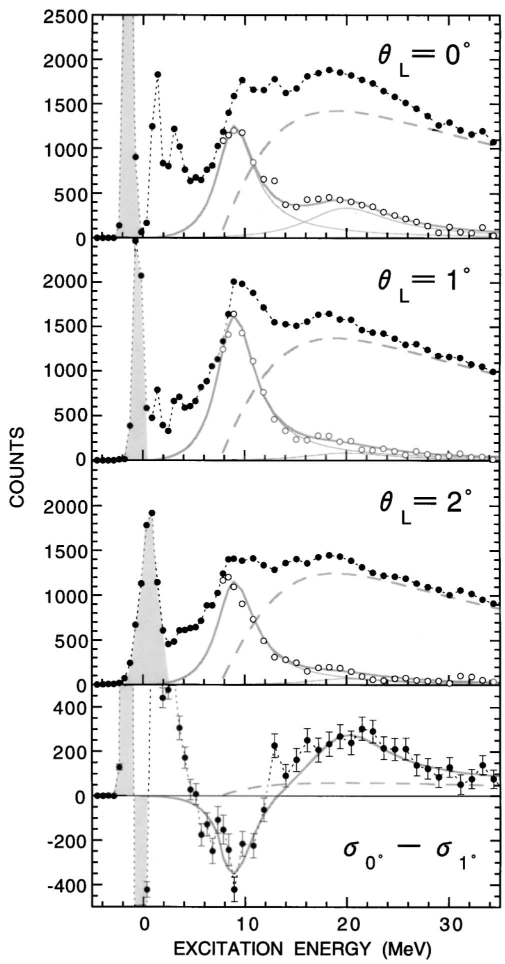

FIG. 1. Singles spectra at $\theta_L = 0°$, 1°, 2°, and the difference $\sigma(0°) - \sigma(1°)$ in the ^{60}Ni(^{7}Li, ^{7}Be)^{60}Co reaction at 65*A* MeV. Error bars indicated are from statistics. Shaded peaks are due to hydrogen contamination in the target. Dashed curves represent the assumed background due to the quasifree scattering. Open circles are the spectra with subtracted background. Solid lines represent two Lorentzian curves of $E_x = 9$ MeV, $\Gamma = 4.5$ MeV and $E_x = 20$ MeV, $\Gamma = 10$ MeV.

In these high excitation energy regions, an underlying continuum is observed as a background mainly due to the quasifree scattering. In order to subtract the underlying background, we investigated the nonresonant region around $E_x = 30$ MeV. The cross section at $E_x \approx 30$ MeV was found to decrease linearly as a function of the squared linear momentum transfer q^2. This behavior has also been observed in the $(\pi^\pm, \pi^0)$ reaction. Therefore, the shape of the background was estimated according to the prescription in the $(\pi^\pm, \pi^0)$ [12] and (^{3}He, t) [13] work. The quasifree scattering was described by using the parameters of the quasifree scattering energy E_{QF}, the cutoff energy E_0, the cutoff energy scale parameter T, and the width W_L, as given in Eq. (3.1) of Ref. [12]. The T value was fixed to the value of 100 MeV which was chosen in the previous work [13]. The W_L value was adjusted to be 12 MeV so as to reproduce the spectra above $E_x = 25$ MeV. The E_{QF} value was assumed to be $E_{\mathrm{free}} - S_n$, and the E_0 value to be $E_{\mathrm{g.s.}} - S_n$. Here the E_{free} and $E_{\mathrm{g.s.}}$ values are the ^{7}Be energy for the H(^{7}Li, ^{7}Be)n and ^{60}Ni(^{7}Li, ^{7}Be)^{60}Co(g.s.) reactions, respectively. The S_n value is the neutron separation energy in ^{60}Co. The result is shown by dashed lines in Fig. 1. The spectra with subtracted backgrounds are shown by open circles in Fig. 1. Besides a peak at $E_x \approx 9$ MeV, another peak at $E_x \approx 20$ MeV was clearly identified in the singles spectrum measured at $\theta_L = 0°$.

The two overlapping resonances were fitted assuming Lorentzian line shapes. The resulting widths and excitation energies are $\Gamma = 4.5$ MeV at $E_x = 9$ MeV and $\Gamma = 10$ MeV at $E_x = 20$ MeV. Fitting errors are given in Table I and are mainly due to uncertainty in evaluating the background. All singles spectra were found to be well reproduced by these two Lorentzian curves. The experimental angular distributions are shown in Fig. 2. The 9-MeV and 20-MeV resonances show quite different features from one another at forward scattering angles. The 9-MeV resonance has a maximum around $\theta_L = 1°$ (closed circles in Fig. 2), and the 20-MeV resonance steeply increases toward $\theta_L = 0°$ (open circles in Fig. 2). For comparison, an angular distribution of the cross section at $E_x \approx 30$ MeV is shown by triangles in Fig. 2 as an example of a distribution with a typical background. The result shows a monotonous decrease with increase of the scattering angle.

The angular distributions for the 9- and 20-MeV resonances were compared with microscopic DWBA calculations which have been successfully applied to heavy-ion charge exchange reactions [6,11,14]. The optical potential parameters for ^{60}Ni + ^{7}Li were assumed to be those obtained in ^{12}C + ^{7}Li at 19*A* MeV. Details of the calculation were given in Ref. [11]. The DWBA calculations were performed for the $\Delta L = 1$ transition to a pure particle-hole state of $1^-(2d_{5/2} \otimes 1f_{7/2}^{-1})$ and the $\Delta L = 0$ transition to one of $0^+(2f_{7/2} \otimes 1f_{7/2}^{-1})$. Here, the

TABLE I. Excitation energies and widths of isovector resonances studied by the ^{60}Ni(^{7}Li, ^{7}Be)^{60}Co reaction at 65A MeV.

	IVDR		IVMR
	GDR	SDR	
(π^-, π^0)[a]	$E_x = 10.7 \pm 1.6$ MeV $\Gamma = 4.2 \pm 2.0$ MeV		$E_x = 22.4 \pm 1.7$ MeV $\Gamma = 14.7 \pm 2.1$ MeV
(γ, n)[b]	$E_x = 5.5,\ 8.5$ MeV[c] $\Gamma = 4$ MeV		
(n, p)[d]		$E_x \sim 12$ MeV[e]	
(^{13}C, ^{13}N)[f]	$E_x = 9.1 \pm 0.3$ MeV $\Gamma = 2.2 \pm 0.4$ MeV		$E_x = 22.1 \pm 0.8$ MeV[g] $\Gamma = 8.1 \pm 1.0$ MeV
Present work	$E_x = 8.5 \pm 0.5$ MeV $\Gamma = 4.0 \pm 0.5$ MeV	$E_x = 9 \pm 1$ MeV $\Gamma = 7 \pm 1$ MeV	$E_x = 20 \pm 2$ MeV $\Gamma = 10 \pm 2$ MeV

[a] From Refs. [4,12]. [b] From Ref. [18]. [c] Data were fitted with two Lorentzian curves for the $T_<$ and $T_>$ components. [d] From Ref. [7]. [e] A $\Delta L = 1$ excitation was assigned by a multipole decomposition. [f] From Ref. [6]. [g] Angular distribution was not consistent with $\Delta L = 0$.

calculated cross sections were averaged over the solid angle of 15×30 (mrad)^2 used in sorting the data. The results were normalized to the cross section presently observed at $\theta_L = 0°$. They are shown by a solid curve for the $\Delta L = 1$ transition and a dashed curve for the $\Delta L = 0$ one in Fig. 2. The normalization factors N were about 1 for the 9-MeV resonance and 5 for the 20-MeV one. It should be noted that Bérat *et al.* found $N = 2$–3 for the former and $N = 10$–30 for the latter in the (^{13}C, ^{13}N) reaction [6], and the present N values are relatively consistent with the (^{13}C, ^{13}N) work. The DWBA calculations clearly show that the 20-MeV resonance has a more collective nature than the 9-MeV one, and the observed 9- and 20-MeV resonances are consistent with the dipole ($\Delta L = 1$) and monopole ($\Delta L = 0$) resonances, respectively.

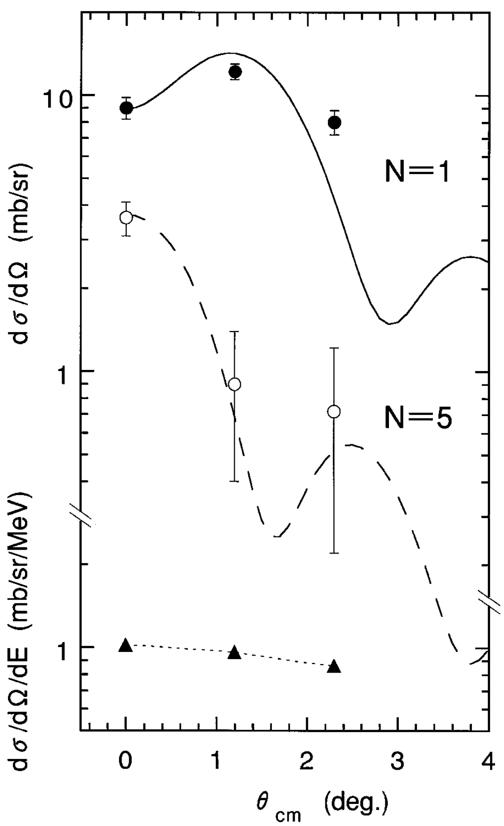

FIG. 2. Angular distributions of the differential cross sections for two isovector resonances at $E_x \approx 9$ MeV (closed circles) and 20 MeV (open circles). Triangles indicate the underlying continuum at $E_x = 30$ MeV. The DWBA calculations with $\Delta L = 1$ and 0 are denoted by solid and dashed curves, respectively (see text). The normalization factors N are obtained by fitting to the cross sections observed at $\theta_L = 0°$.

The experimental data discussed above were concerned with the singles spectra; that is, we did not distinguish the $\Delta S = 0$ and $\Delta S = 1$ excitations. In order to interpret whether the resonances were excited by $\Delta S = 0$ and/or $\Delta S = 1$ transitions, we compare the $\Delta S = 0$ and $\Delta S = 1$ spectra measured at $\theta_L < 1.5°$. The singles and coincident energy spectra of ^{7}Be were used to separate the $\Delta S = 0$ and $\Delta S = 1$ excitations according to the prescription in Ref. [15]. A peak due to hydrogen contamination in the target was used as a calibration for the relative contributions of the $\Delta S = 0$ and $\Delta S = 1$ spectra. Here, the $\Delta S = 0$ and $\Delta S = 1$ transition strengths used for the H(^{7}Li, ^{7}Be) reaction, $B_{\mathrm{F}} = 1$ and $B_{\mathrm{GT}} = 3$, are taken from the neutron β-decay data [16]. Together with the empirical relationship of $|V_{\sigma\tau}/V_\tau|^2 = |E_p(A\ \mathrm{MeV})/55|^2/3$ [17], the cross section ratio of $\sigma(\Delta S = 1)/\sigma(\Delta S = 0)$ was estimated to be 1.40 for the H(^{7}Li, ^{7}Be) reaction at 65A MeV. We adjusted the subtraction of singles and coincidence spectra to obtain the $\Delta S = 0$ and $\Delta S = 1$ spectra with this cross section ratio.

The $\Delta S = 0$ and $\Delta S = 1$ spectra thus obtained are shown in Fig. 3. The background was assumed to have the same shape as in the singles case and subtracted by adjusting its magnitude in the $\Delta S = 0$ and $\Delta S = 1$ spectra. The spectra with subtracted backgrounds are shown by open circles in Fig. 3. In the excitation energy region of 10 MeV, the isovector dipole resonance is clearly observed in both the $\Delta S = 0$ and $\Delta S = 1$ spectra. The spectra were fitted by a Lorentzian curve. The obtained excitation energies and widths are $E_x = 8.5$ MeV,

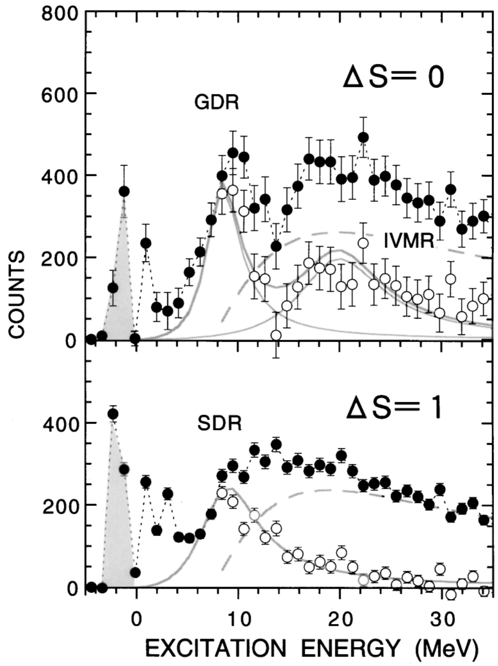

FIG. 3. Spin-nonflip and spin-flip spectra in ^{60}Ni(^{7}Li, ^{7}Be)^{60}Co reaction at 65*A* MeV and at $\theta_L < 1.5°$ (closed circles). Error bars indicated are included to represent the uncertainty of separating the $\Delta S = 0$ and $\Delta S = 1$ spectra. Open circles are the spectra with subtracted background which is denoted by dashed curves. Solid lines are obtained from the fitting procedure (see text).

$\Gamma = 4$ MeV in the $\Delta S = 0$ spectrum and $E_x = 9$ MeV, $\Gamma = 7$ MeV in the $\Delta S = 1$ one. The former is the giant dipole resonance (GDR; $\Delta S = 0$, $\Delta L = 1$) and the latter is the spin-dipole resonance (SDR; $\Delta S = 1$, $\Delta L = 1$). On the other hand, in a higher excitation energy region around $E_x = 20$ MeV, the $\Delta S = 0$ and $\Delta S = 1$ spectra are very different from each other. In the $\Delta S = 0$ spectrum, a resonance is clearly observed as it was in the singles spectrum at $\theta_L = 0°$. The $\Delta S = 0$ spectrum was found to be reproduced with a Lorentzian curve assuming $E_x = 20$ MeV, $\Gamma = 10$ MeV which were the same parameters as those fitting the singles spectra. No resonance was, however, identified in the $\Delta S = 1$ spectrum which was consistent with the (n, p) spin-flip reaction data at 198 MeV [7]. These results mean that the resonance observed at $E_x \approx 20$ MeV is due to the $\Delta S = 0$ transition and therefore the isovector electric monopole resonance.

The excitation energies and widths for the GDR, SDR, and IVMR are listed in Table I and compared with other work. The GDR presently observed is consistent with that observed in other reactions [4,6,12,18]. The SDR has rarely been investigated. With the multipole decomposition performed in the ^{60}Ni(n, p) reaction at 198 MeV [7], the $\Delta L = 1$ excitation has been identified to be distributed around $E_x = 12$ MeV and is considered to include the SDR presently observed. The SDR was observed to have a similar cross section to that for the GDR but distributed at a slightly higher excitation energy region and having a broader width than the GDR.

The excitation energy observed for the IVMR is approximately consistent with the theoretical prediction, i.e., $E_x = 23.1$ MeV [1]. Both the excitation energy and width for the IVMR presently observed are, within errors, consistent with the result observed in the pion charge-exchange reaction [4,12].

In the (^{13}C, ^{13}N) reaction at 50*A* MeV [6], a resonance has also been observed in a similar excitation energy region to our IVMR. But its angular distribution pattern was found to be inconsistent with one-step $\Delta L = 0$ calculations. This may be the result of a more complex reaction mechanism [14] involved in the (^{13}C, ^{13}N) reaction at 50*A* MeV. In fact, in this reaction, the differential cross section observed for the GDR has a maximum at $\theta_L = 0°$, which is not explained by the DWBA calculations.

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