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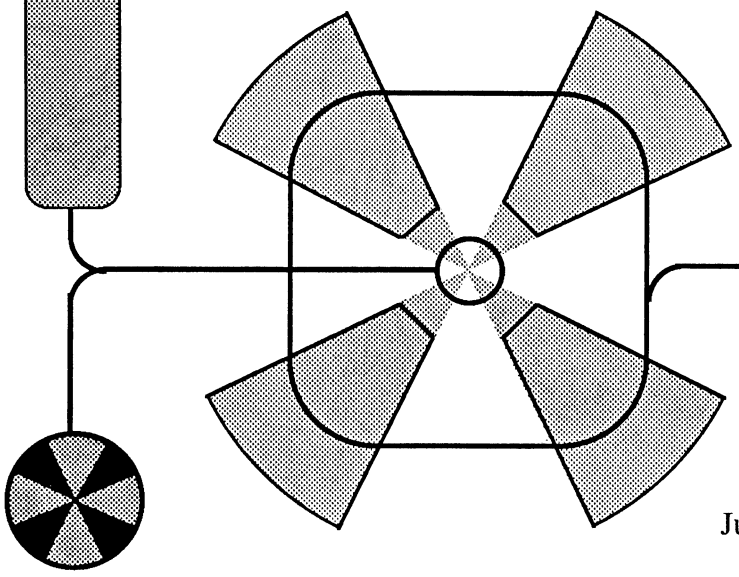

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Isovector Quadrupole Resonance observed in the ^{60}Ni(^{13}C,^{13}N)^{60}Co reaction at E/A = 100 MeV

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Abstract

Charge-exchange reaction ^{60}Ni(^{13}C,^{13}N)^{60}Co at E/A = 100 MeV has been studied to locate isovector (ΔT = 1) non-spin-flip (ΔS = 0) giant resonances Besides the giant dipole resonance at E_x = 8 7 MeV, another resonance has been observed at E_x = 20 MeV with a width of 9 MeV DWBA analysis on the angular distribution clearly indicated the L = 2 multipolarity, attributing the E_x = 20 MeV state to the giant isovector quadrupole resonance

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Giant resonances (GR) represent major modes of collective motion, which dictate the dynamical properties of nuclei For a nucleus as a many-body system of nucleons, various multipole modes exist reflecting isospin (T) and spin (S) degrees of freedom The isoscalar ($\Delta T = 0$) and isovector ($\Delta T = 1$) modes represent oscillations in which protons and neutrons move in phase and in opposite phase, respectively, while electric ($\Delta S = 0$) and magnetic ($\Delta S = 1$) modes correspond to non-spin-flip and spin-flip excitations, respectively Among the isovector non-spin-flip modes, the dipole resonance (IVGDR, $L = 1$) is a classical example of the giant resonance, which has been explored most extensively and is known to prevail over the nuclear chart On the other hand, only limited information has been so far obtained for the monopole (IVGMR; $L = 0$) and quadrupole resonances (IVGQR, $L = 2$) [1]

These two modes are supposed to be coherent states of $1p$-$1h$ excitations across two major shells ($2\hbar\omega$), while the IVGDR is related to excitations of one major shell ($1\hbar\omega$) Accordingly the IVGMR and IVGQR are expected to appear at similar excitation energies, which are considerably higher than 82 $A^{-1/3}$ MeV expected for the IVGDR At such higher energies, the excitation spectrum becomes progressively complex with mixed contributions from various excitation modes on top of the mounting continuum background The broader width of the resonance further increases the difficulty These features have hampered unambiguous identification of the high-lying resonances

In recent years, several attempts have been made to locate these high-lying resonances by employing charge-exchange reactions Among those studies, measurements with reactions of (π^-, π^0) at 165 MeV [2], and (^{7}Li, ^{7}Be) at $E/A = 65$ MeV [3] provided strong indications for the existence of the IVGMR On the other hand, clear observation of an IVGQR has been so far unsuccessful, while its occurrence was suggested from the forward-backward asymmetry due to the E1-E2 interference in (γ, n) and (n,γ) reactions [4], and by the multipole decomposition analysis of the inelastic electron scattering [5]

In this paper we report on the first clear identification of the IVGQR in the ^{60}Ni(^{13}C,^{13}N)^{60}Co reaction at $E/A = 100$ MeV For comparison, a measurement on the (^{12}C, ^{12}N) reaction was also performed These heavy ion reactions afford several advantages in probing the giant resonances of interest First of all, they exhibit strong selectivity for $\Delta T = 1$ and $\Delta T_z = 1$ excitations, uniquely populating the isovector $T+1$ resonances As for

the spin selectivity, the (^{13}C,^{13}N) reaction allows $\Delta S = 0, 1$ excitations while the (^{12}C,^{12}N) reaction only allows $\Delta S = 1$ excitations For the former reaction, it is also known that $\Delta S = 0$ components are much more favored than $\Delta S = 1$ components because of its large Fermi matrix element ($M_{\rm F}/M_{\rm GT} \sim 5$) [6] Hence the combination of these two reactions could provide a useful means to distinguish between spin-flip and non-spin-flip modes

There exist earlier measurements on the (^{13}C,^{13}N) reaction performed at $E/A = 50$ MeV [6] However the observed angular distributions turned out to be rather structureless, disallowing L determination for the resonances This is thought to be due to considerable contributions of multi-step processes at these energies In contrast, it has been shown for the (^{12}C,^{12}N) reaction that such contributions become almost negligible in the higher energy domain of $E/A \geq 100$ MeV [7, 8]

Given all these favorable features, the high-energy (^{13}C,^{13}N) reaction can be expected to make a powerful tool to locate the $\Delta S = 0$ and $\Delta T = 1$ resonances Indeed, the present measurement has revealed a clear $L = 2$ peak of ^{60}Co, which is uniquely attributed to the IVGQR

The measurements were performed using $E/A = 100$ MeV ^{13}C and $E/A = 135$ MeV ^{12}C beams from the K540 RIKEN Ring Cyclotron and spectrograph SMART [9] with a QQDQD-configuration The elastic scattering was also measured for the ^{13}C beam A self-supporting enriched ^{60}Ni target of 3 0 mg/cm^2 was used, resulting in an overall energy resolution of 1 MeV The spectrograph had a large angular acceptance of 200 mr for vertical and 50 mr for horizontal planes, which covered an angular range from -5 7° to 5 7° at a time by injecting the beam at 0° The spectrograph was equipped with a pair of cathode readout drift chambers (CRDC) [10], which were located at the focal plane and separated from each other by 50 cm Plastic scintillation counters placed behind the CRDC's provided ΔE and time of flight signals for particle identification The momentum as well as the vertical and horizontal scattering angles were obtained by reconstructing the trajectory through the two CRDC's The overall angular resolution achieved was estimated to be approximately 0 1° Thus differential cross sections were obtained for every 0 2° bin of the scattering angle (lab) for the charge-exchange reactions and for 0 1° bins for the elastic scattering of ^{60}Ni(^{13}C, ^{13}C)^{60}Ni

Figure 1 shows typical energy spectra of the ^{60}Ni(^{13}C, ^{13}N)^{60}Co reaction at $E/A = 100$ MeV Data at two angular bins, $\theta_{\rm lab}$ = 0°-0 2° and $\theta_{\rm lab}$ = 0 8°-1 0°, are shown together

with the difference spectrum between these two bins The excitation energies are given with respect to the ground state of ^{60}Co The difference spectrum is also shown for the ^{60}Ni(^{12}C, ^{12}N)^{60}Co reaction at E/A = 135 MeV for the sake of comparison

Besides the low-energy peak from the ^{1}H(^{13}C,^{13}N)n reaction, the energy spectra are dominated by resonance structures built on top of large continuum background The profiles of resonances are most clearly indicated in the difference spectra The difference spectrum for ^{60}Ni(^{13}C, ^{13}N)^{60}Co shows two resonances at E_x = 8 7 MeV and 20 MeV, while that for ^{60}Ni(^{12}C, ^{12}N)^{60}Co shows a resonance at E_x= 10 MeV The difference of the resonance structure between the two reactions can be attributed to the ΔS selectivity In the (^{12}C, ^{12}N) reaction only ΔS = 1 states will be excited Hence the resonance at E_x= 10 MeV can be assigned to a ΔS = 1 resonance Indeed this resonance is consistent with the assignment of the spin dipole resonance [3, 11] On the other hand, the (^{13}C, ^{13}N) reaction favors ΔS = 0 excitations over ΔS = 1 excitations [6] Thus the two resonances at E_x = 8 7 MeV and 20 MeV may be assigned to be ΔS = 0 states The absence of these peaks in the (^{12}C, ^{12}N) spectrum supports this conclusion

In order to extract yields of the observed resonances, subtraction of the continuum background is crucial The origin of the background may be mainly attributed to the quasi-free charge-exchange reactions In treating the continuum spectra, we followed the phenomenological expression developed by Erell *et al* [2] In this model, the functional form of the doubly differential cross section for the continuum background was given (Eq (3 1) of Ref [2]) as a product of a Lorentzian function of the ejectile energy E, which is centered at an energy $E_{\rm QF}$ and has a width W_L, and an energy cutoff function characterized by a maximum cutoff energy E_0 and a cutoff energy scale parameter T We have assumed $E_{\rm QF} = E_{\rm free} - S_n$, where $E_{\rm free}$ is the energy of ^{13}N for the p(^{13}C, ^{13}N)n reaction and S_n is the neutron separation energy of ^{60}Co The parameter E_0 was set at 0 MeV to accommodate the contributions from unresolved discrete levels as well as three-body continuum states

Peak fitting procedure has been performed for the 20 spectra of the ^{60}Ni(^{13}C, ^{13}N)^{60}Co reaction over the angular range from $\theta_{\rm lab}$ = 0° − 0 2° bin to $\theta_{\rm lab}$ = 3 8° − 4 0° bin Peak shapes for E_x = 8 7 MeV and E_x = 20 MeV states were assumed to be Gaussian The value of T was set to be same for the entire angular range while the angular dependence was introduced for W_L After a systematic search we found that the parameter set of W_L = 34(1 0 + 0 06$\theta_{\rm lab}$ + 0 06$\theta^2_{\rm lab}$) MeV and T = 15 5 MeV reproduces the continuum

TABLE I: Excitation energies and widths of the resonances observed in $\Delta T_z = 1$ charge-exchange reactions leading to ^{60}Co

	$(1\hbar\omega)$		$(2\hbar\omega)$		Ref
	E_x (MeV)	Γ (MeV)	E_x (MeV)	Γ (MeV)	
(π^-, π^0)	10 7 ± 1 6	4 2 ± 2 0	22 4 ± 1 7	14 7 ± 2 1	[2]
(^{7}Li, ^{7}Be)	8 5 ± 0 5	4 0 ± 0 5	20 ± 2	10 ± 2	[3]
(^{13}C,^{13}N)	9 1 ± 0 3	2 2 ± 0 4	22 1 ± 0 8	8 1 ± 1 0	[6]
Present work	8 7 ± 0 5	2 8 ± 0 8	20 ± 2	9 ± 2	

background consistently for all the angles involved ($\chi^2/f = 1\ 5$) For the sake of comparison, the peak fitting was also performed with a different E_0 value of 7 5 MeV, at which the three-body decay channel opens The extracted angular distribution was hardly changed for the 20 MeV resonance

Typical results from the fitting procedure are found in Fig 1 The dashed curves show the calculated continuum spectra, which reproduce a large portion of the high energy spectra and well represent the overall feature of the background The solid curves in Fig 1, obtained by superposing the two Gaussian peaks of the resonances, reproduce the experimental data very well

The energy and width (Γ) of the two resonances thus determined are listed in Table I together with the previous results on various (n,p) type exchange reactions on ^{60}Ni All the measurements exhibited two prominent peaks at excitation energies in the neighborhood of 9 and 20 MeV As for the lower-energy peak, the assignment of the IVGDR is consistently supported On the other hand, there exist different possibilities for the higher-energy peak While the works on the (π^-, π^0) [2], and (^{7}Li, ^{7}Be) [3] reactions claimed the $L = 0$ assignment, the work on the (^{13}C, ^{13}N) reaction at $E/A = 50$ MeV [6] was unable to confirm the $L = 0$ nature of the resonance A recent self-consistent random phase approximation (RPA) calculation, which employs the Skyrme force SGII, indicates that the IVGQR strength of ^{60}Co is peaked around 23 MeV and that of the IVGMR around 26 MeV [12] It is thus plausible that the IVGQR as well as the IVGMR gives rise to a high-energy peak as observed in the present work

The extracted angular distributions for $E_x = 8\ 7$ MeV and $E_x = 20$ MeV states are

TABLE II: Optical potential parameters deduced from the ^{60}Ni(^{13}C,^{13}C)^{60}Ni reaction at E/A = 100 MeV

V_r (MeV)	r (fm)	a (fm)	W_r (MeV)	r_w (fm)	a_w (fm)
52 8	1 09	0 79	35 0	0 87	1 78

plotted in Fig 2 They exhibit clear diffraction patterns, suggesting dominance of the one-step process at E/A = 100 MeV In contrast, the angular distribution of the background shown together exhibits a smooth fall-off behavior

In order to determine the multipolarity (L) of the resonances, microscopic DWBA calculations were performed using the code developed by Lenske [13] Optical-potential parameters were determined by fitting the present data on the ^{60}Ni(^{13}C,^{13}C)^{60}Ni elastic scattering with the code ECIS79 [14] They are summarized in Table II, and the calculated angular distribution is compared with the experiment in Fig 3 In the DWBA calculations, the form factors of L = 0, 1 and 2 were obtained by folding the transition densities of the projectile and the target with the effective interaction [15] The transition density of the projectile was obtained from the shell-model single-particle wave functions [7], while the transition density of the target was assumed to take a collective form of Tassie type [1, 16] with Wood-Saxon radial distribution of r_0 = 1 2 fm and a = 0 6 fm

The solid curves in Fig 2 represent the results of the DWBA calculations They are obtained after folding the calculated results with experimental angular resolutions and by normalizing the absolute magnitudes to the experimental data For the E_x = 8 7 MeV state, an IVGDR was assumed Hence the L = 1 form factor was taken Indeed, a very good fit has been obtained, justifying the validity of the DWBA analysis For the E_x = 20 MeV state, we have studied two cases, one with the L = 0 IVGMR form factor and the other with the L = 2 IVGQR form factor The calculated angular distribution for the L = 0 IVGMR (the dotted curve in Fig 2) exhibits a steep rise at 0° and the first minimum near the $\theta_{\rm cm}$ = 0 8° However, these distinctive features are hardly manifested in the observed angular distribution On the other hand, an excellent fit has been obtained with the calculated distribution for the L = 2 IVGQR excitation This result strongly indicates that the resonance state observed at E_x = 20 MeV is an IVGQR rather than an IVGMR

The present observation of the IVGQR raises a puzzling problem why the (^{13}C, ^{13}N) reaction favorably excites the IVGQR while other reactions such as (^{7}Li, ^{7}Be) reportedly populate only the IVGMR In this respect, we have examined the radial overlap of the form factor with the penetrability profile of the probe particles The insert of the Fig 3 shows a comparison of the penetrability profiles of the present (^{13}C, ^{13}N) reaction at $E/A = 100$ MeV and (^{7}Li, ^{7}Be) at $E/A = 65$ MeV [3] using the optical potentials as employed in the relevant analyses It was found that the former reaction is much more peripheral than the latter On the other hand, the form factor for the IVGMR is mostly distributed in the interior of the nucleus while that for the IVGQR is shifted towards the surface region Hence it is plausible that the excitation of the IVGQR is favored in the (^{13}C, ^{13}N) reaction while that of the IVGMR is favored in the (^{7}Li, ^{7}Be) reaction

In summary, we have studied the ^{60}Ni(^{13}C,^{13}N)^{60}Co reaction at $E/A = 100$ MeV to observe isovector non-spin-flip giant resonances Besides the IVGDR at $E_x = 8\ 7$ MeV, a significant peak was observed at $E_x = 20$ MeV with a width of 9 MeV DWBA analysis of the observed angular distribution clearly indicates $L = 2$ multipolarity, revealing the occurrence of the IVGQR No evidence of the IVGMR was observed by the present experiment

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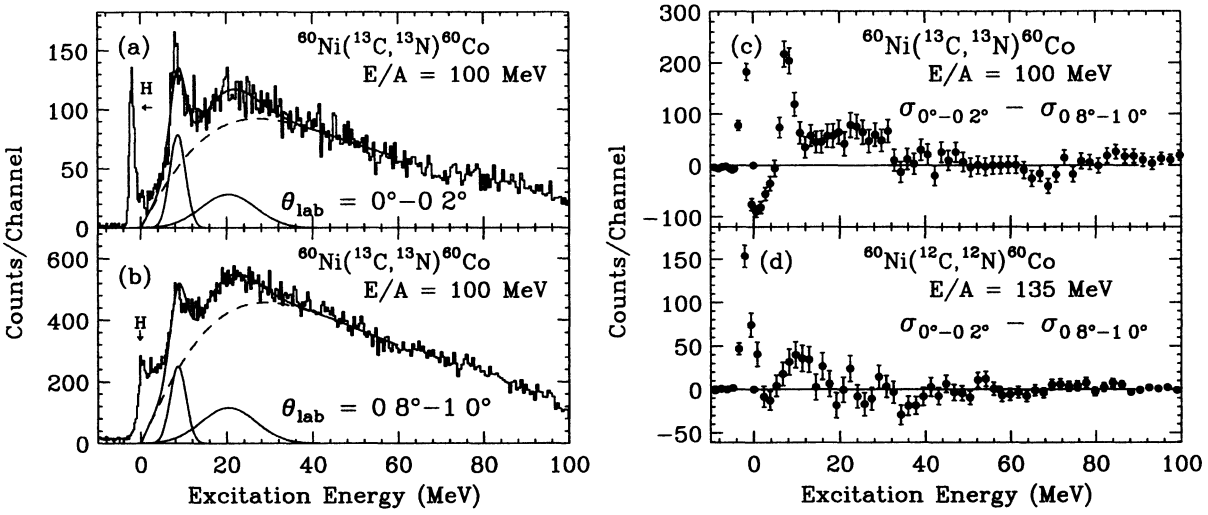

FIG 1: Energy spectra of the ^{60}Ni(^{13}C,^{13}N)^{60}Co reaction at E/A = 100 MeV for the angular bins of (a) θ_{lab} = 0°-0 2° and (b) θ_{lab} = 0 8°-1 0° The symbol H indicates the ^{1}H(^{13}C, ^{13}N)n reaction owing to the target contamination (c) represents the difference spectrum obtained by subtracting (b) from (a) after renormalization (every 4-channels are packed in a bin for better statistics) (d) represents the difference spectrum obtained for the ^{60}Ni(^{12}C,^{12}N)^{60}Co reaction at E/A = 135 MeV

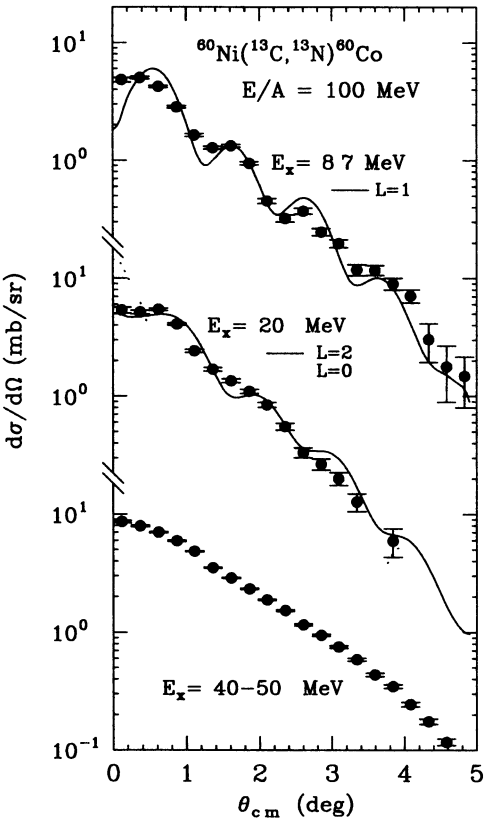

FIG 2: Differential cross sections for the E_x = 8 7 MeV and E_x = 20 MeV states and the background sum of E_x = 40-50 MeV of the ^{60}Ni(^{13}C,^{13}N)^{60}Co reaction at E/A = 100 MeV Error bars represent only statistical ones Curves are obtained from DWBA calculations The solid curve for E_x = 8 7 MeV is calculated assuming the IVGDR (L = 1) The solid and dotted curves for E_x = 20 MeV are calculated assuming the IVGQR (L = 2) and IVGMR (L = 0), respectively

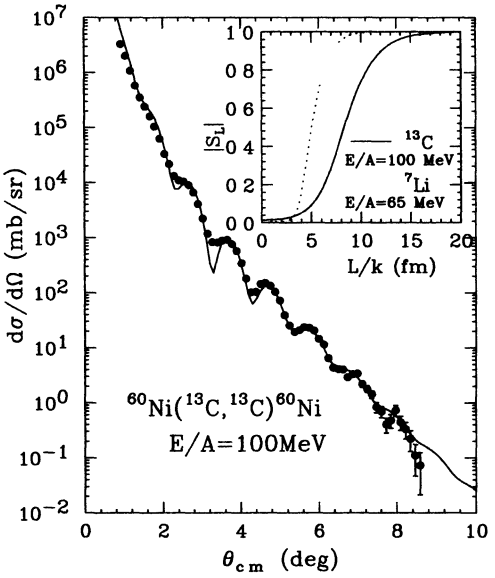

FIG 3: Measured differential cross sections for the elastic scattering of ^{13}C from ^{60}Ni at E/A = 100 MeV The solid curve is calculated with the optical parameters in Table II folded by the experimental angular resolution The solid and dotted curves of the insert show the absolute values of the S-matrix elements (S_L) calculated for the ^{60}Ni(^{13}C,^{13}C)^{60}Ni reaction at E/A = 100 MeV and ^{60}Ni(^{7}Li,^{7}Li)^{60}Ni reaction at E/A = 65 MeV (Ref [3]), respectively The horizontal axis is the orbital angular momentum (L) divided by the wave number (k) and given in units of fm