Out of Plane Measurements of the Decay Neutron from the Giant Resonance in the ^{12}C$(e,e'n)^{11}$C Reaction

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Out of plane measurements of the angular correlations for the ^{12}C$(e,e'n)$ reaction have been performed for the first time in the giant resonance region. The cross sections were directly separated into the longitudinal and transverse, longitudinal-transverse, and transverse-transverse components. The cross section at the peak of the giant resonance ($\omega = 22.5$ MeV) has been found to be almost all longitudinal. It was reproduced by the multipole expansion with $E0$ and $E2$ components besides $E1$. The longitudinal-transverse component might have a maximum around 24 MeV. The transverse-transverse component is very small over the giant resonance.

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The giant resonances in ^{12}C have been studied by photoreactions, inclusive electron scattering, and inelastic hadron scattering. Recently, coincidence electron-scattering experiments such as $(e,e'p)$ and $(e,e'n)$ have become possible by using high duty factor electron beams. Such experiments can provide new insights into the decay mechanisms. The ^{12}C$(e,e'p)^{11}$C angular correlation has been measured by Calarco *et al.* [1]. It indicates a forward-backward symmetry at the peak (22.5 MeV) of the giant resonance. In the previous paper [2] we have pointed out that the measured ^{12}C$(e,e'n_0)^{11}$C angular correlation indicates a strong forward-backward asymmetry differently. Those angular correlations are inconsistent with the predictions of recent random-phase approximation [3]. In order to investigate this difference, we have tried separation of each structure function.

The coincidence cross section consists of four structure functions described below. Out of plane measurements provide a direct separation of the structure function. However, out of plane measurements in the $(e,e'n)$ reaction have not been carried out yet because of the difficulty in detecting low energy neutrons in an environment with a huge γ ray and neutron backgrounds. In this paper we report the first out of plane measurements for the angular correlations of the ^{12}C$(e,e'n)^{11}$C reaction in the giant resonance at a similar kinematics to the previous in-plane measurements [2]. In addition, we will discuss the separated structure functions.

The coincidence $(e,e'x)$ cross section can be expressed as [3,4]

$$d^3\sigma/d\Omega_e\, d\omega\, d\Omega_n = \sigma_M\{V_L W_L + V_T W_T + V_{LT} W_{LT}\cos\phi_n + V_{TT} W_{TT}\cos 2\phi_n\}, \qquad (1)$$

where σ_M is the Mott cross section for scattering on a point nucleus and V_i are the leptonic kinematic factors. The structure functions have four components: pure longitudinal (W_L), pure transverse (W_T), longitudinal-transverse interference (W_{LT}), and transverse-transverse interference (W_{TT}) terms. The terms $V_L W_L$ and $V_T W_T$ do not depend on the azimuthal angle ϕ, but the interference terms $V_{LT} W_{LT}$ and $V_{TT} W_{TT}$ depend on $\cos\phi$ and $\cos 2\phi$, respectively. From the measurements of at least three different values of ϕ, the noninterference, longitudinal-transverse, and transverse-transverse terms can be separated.

The experiment was performed using the continuous electron beam from the 150-MeV Tohoku University pulse stretcher ring [5]. A natural carbon target of thickness 105 mg/cm^2 was bombarded with electrons of energy 126 MeV. The scattered electrons were detected at $\theta_e = 40°$ by a magnetic spectrometer which has a solid angle of 5 msr and a momentum resolution of 0.05% within an accepted momentum bite of 5.3%. The emitted neutrons were detected using ten NE213 liquid scintillator neutron detectors.

Six detectors were placed in the electron scattering plane ($\phi = 180°$) at $\theta_n = 0°$, 30°, 60°, 90°, 150°, and 180°, three detectors were placed out of the scattering plane ($\phi = 135°$) at $\theta_n = 30°$, 60°, 90°, and one detector was

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placed out of plane ($\phi = 90°$) at $\theta_n = 30°$, where θ_n is measured from the momentum-transfer vector. Each detector was placed at 1.0 m from the center of the scattering chamber allowing the neutron energy to be determined by a time-of-flight method. The neutron detectors were shielded with lead, paraffin, and concrete, and lead collimators were placed in front of 4-cm-thick bismuth plates to absorb scattered electrons and soft γ rays from the target. The neutron detectors were calibrated using γ rays from ^{22}Na, ^{137}Cs, ^{60}Co, and Am-Be sources. The Compton edge of the ^{137}Cs γ ray was utilized to set the detection threshold. The neutron efficiency for the detectors was determined using a ^{252}Cf source and a MONTE CARLO code. The details of electronics, data acquisition, and detection efficiency are described elsewhere [6].

The angular correlations have been measured in the energy-transfer range 22–26 MeV at an effective momentum transfer of 0.41 fm^{-1} (for $\omega = 22.5$ MeV). The missing energy spectrum was similar to that obtained in the previous experiment [2], which indicates that the neutrons from the giant resonance decay primarily to the ground state. The angular correlations at 22.5, 23.5, 24.5, and 25.5 MeV are shown in Fig. 1. The angular correlation changes from a strong forward-backward asymmetry at 22.5 MeV to a weak forward-backward one at 25.5 MeV. This was also seen in the previous experiment. A large difference has been observed between the cross sections at $\phi = 180°$ and $\phi = 90°$ in the excitation energies of 23.5, 24.5, and 25.5 MeV, which indicates an existence of the longitudinal-transverse interference component.

Separation of the interference and noninterference terms has been done by the following method. If we express the noninterference, longitudinal-transverse, and transverse-transverse components with A, B, and C, respectively, the cross section can be written as

$$\sigma(\phi) = A + B\cos\phi + C\cos 2\phi\,. \tag{2}$$

From the measurements at $\phi = 180°$, 135°, and 90°, A, B, and C are obtained as

$$\begin{aligned} A &= [\sigma(180°) - \sqrt{2}\,\sigma(135°) + \sigma(90°)]/(2-\sqrt{2})\,,\\ B &= [\sigma(180°) - 2\sigma(135°) + \sigma(90°)]/(\sqrt{2}-1)\,,\\ C &= [\sigma(180°) - \sqrt{2}\,\sigma(135°)\\ &\qquad + (\sqrt{2}-1)\sigma(90°)]/(2-\sqrt{2})\,. \end{aligned} \tag{3}$$

The separated cross sections obtained from the measurements at $\theta_n = 30°$ are shown in Fig. 2. The noninterference component is seen to decrease with increasing the excitation energy. The longitudinal-transverse component is nearly zero at 22.5 MeV, and its maximum might be suggested to be around 24 MeV, although the data are low statistics. The transverse-transverse component is very small in the giant resonance region as predicted [3].

Because the transverse-transverse was found to be very small, the separation of the noninterference and interference components was done by neglecting the transverse-transverse. In Fig. 3, the angular correlations of the separated noninterference and longitudinal-transverse components at 22.5 MeV are compared with the predictions that have been calculated using a self-consistent random-phase approximation with a Skyrme interaction by Cavinato *et al.* [3]. The kinematical condition is the same between the experiment and calculations. In Fig. 3, the solid circles represent the separated noninterference components. The open circles at $\theta_n = 0°$, 150°, and 180° represent in-plane data, but the data at $\theta_n = 0°$ and 180° are only the noninterference components. The interference structure functions are zero for parallel kinematics in

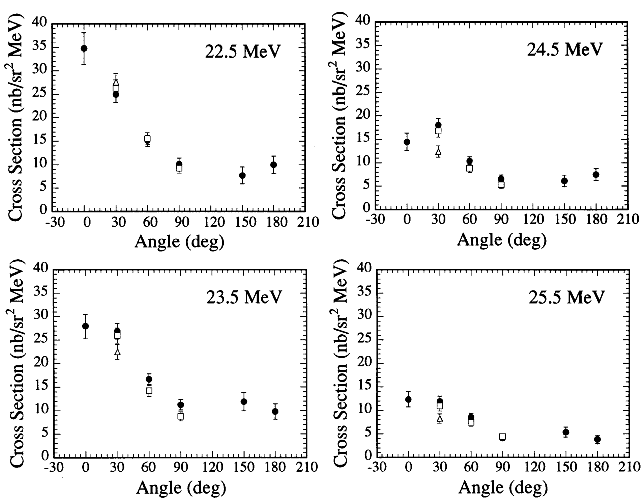

FIG. 1. Angular correlations for the ^{12}C$(e,e'n)^{11}$C reaction at $\theta_e = 40°$, $\epsilon_i = 126$ MeV, and $\omega = 22.5$, 23.5, 24.5, and 25.5 MeV. The solid circles, open squares, and open triangles represent in-plane ($\phi = 180°$), out of plane ($\phi = 135°$), and out of plane ($\phi = 90°$) measurements, respectively.

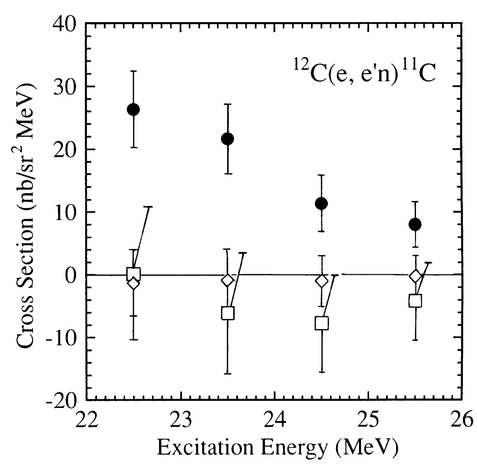

FIG. 2. Separated cross sections for the ^{12}C$(e,e'n)^{11}$C reaction at $\theta_e = 40°$, $\epsilon_i = 126$ MeV, and $\theta_n = 30°$. The solid circles, open squares, and open diamonds represent noninterference, longitudinal-transverse, and transverse-transverse components, respectively.

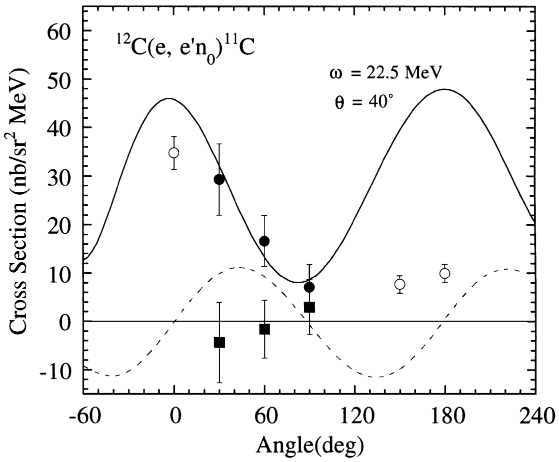

FIG. 3. Angular correlations for the separated components for the $^{12}C(e,e'n)^{11}C$ reaction at $\theta_e = 40°$, $\epsilon_i = 126$ MeV, and $\omega = 22.5$ MeV. The solid circles and solid squares are noninterference and longitudinal-transverse components deduced from two measurements at $\phi = 180°$ and $\phi = 135°$. The open circles are in-plane data. The solid and dashed lines are the noninterference and longitudinal-transverse predictions in RPA-SK3 [3].

which $\theta = 0°$ and $\theta = 180°$ because of a $\sin\theta$ dependence. Then five data values at $\theta_n = 0°$, 30°, 60°, 90°, and 180° are used as the noninterference component to compare with the calculations. The theoretical angular correlation for the noninterference component agrees with both the shape and absolute values of the present data at the forward angles. However, it shows remarkable difference between the calculation and experiment at the backward angles. The separated longitudinal-transverse component indicates nearly zero. The calculation for this predicts cross sections larger than the data.

A strong asymmetry of the angular correlation at 22.5 MeV is considered due to an interference of a transition with the opposite parity to $E1$. This angular correlation has been analyzed based on a channel spin formalism [7]. The multipole states of $J^\pi = 0^+$, 1^-, and 2^+ could be excited under the present conditions of forward scattering ($\theta_e = 40°$, $q_{\rm eff} = 0.41$ fm^{-1}). The decay channels from these states are classified as shown in Table I.

The decay from the 0^+ state is allowed only through the $^3P_0$ decay channel as is evident in Table I. For the 1^- state the $^3S_1$ or $^3D_1$ and $^5D_1$ decay channels are possible for the channel spins $S = 1$ and 2, respectively. As the strong asymmetry of the angular correlation is brought about by

TABLE I. Decay channels from the 0^+, 1^-, and 2^+ states are classified on the basis of the channel spin formalism.

	Channel spin	
J^π	$S = 1$	$S = 2$
0^+	$^3P_0$	
1^-	$^3S_1, {}^3D_1$	$^5D_1$
2^+	$^3P_2, {}^3F_2$	$^5P_2, {}^5F_2$

an interference of $E1$ with $E0$, the channel spin $S = 1$ is suggested. Also the angular distribution coefficient a_2 has a value of 0 (isotropic), -0.5, and $+0.5$ for the $^3S_1$, $^3D_1$, and $^5D_1$ decay channels, respectively. As the experimental a_2 value in the (γ, n) reaction is -0.2 [8], it favors the $^3D_1$ decay channel. Similarly from the comparison between the experimental a_1/a_3 ratio and theoretical one, the $^3F_2$ channel is favored [9]. As a result, we assume that the cross section at 22.5 MeV has only longitudinal component and the decay channels from the resonance are $^3P_0$, $^3D_1$, and $^3F_2$.

Following Kleppinger and Walecka [10], the cross section can be expanded by multipoles as follows:

$$d^3\sigma/d\Omega_e\, d\omega\, d\Omega_n = \sigma_M V_L W_L\,, \tag{4}$$

where

$$W_L = \sum_I A_I P_I(\cos\theta_n) \tag{5}$$

and

$$A_I = \sum_{JJ'LL'S} \alpha A_I(S;LJ;L'J')C(LS;J)^* C(L'S;J')\,. \tag{6}$$

Here, α and $A_I(S;LJ;L'J')$ are kinematical factor and products of $3j$ symbols, respectively. The Coulomb transition amplitude $C(LS;J)$ is defined as

$$C(LS;J) = \frac{(-i)^J}{\sqrt{(2J+1)}} \frac{\sqrt{\Gamma_J/2\pi}}{\omega - \omega_J + i\Gamma_J/2} \times (LS\,|\,J)\,(J\,\|\,\hat{M}_J\,\|\,0)\,. \tag{7}$$

The angular correlation was fitted with the parameters $C(11:0)$, $C(21:1)$, and $C(31:2)$ which are the transition amplitudes of the $^3P_0$, $^3D_1$, and $^3F_2$ channels. The result is shown in Fig. 4. Relative intensity ratios of $E0$, $E1$, and $E2$ components were obtained to be 0.34 ± 0.46, 1.0 ± 0.46, and 0.24 ± 0.44, respectively. This result is consistent with the calculated cross section around

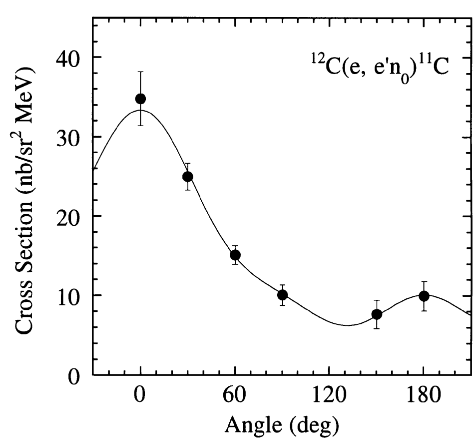

FIG. 4. Angular correlation in plane for the $^{12}C(e,e'n)^{11}C$ reaction at $\theta_e = 40°$, $\epsilon_i = 126$ MeV, and $\omega = 22.5$ MeV. The solid line represents a multipole expansion fit with $E0$, $E1$, and $E2$ components.

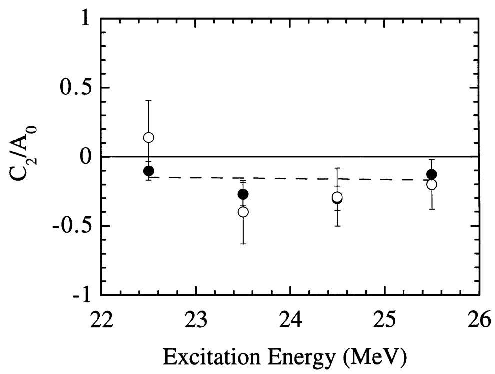

FIG. 5. Comparison of the longitudinal-transverse cross sections (open circles) obtained directly from out of plane measurements with those (solid circles) obtained from a Legendre polynomial fit of in-plane data [1]. The dashed line shows the prediction of the GT model [13].

22.5 MeV which is composed of the $E0$, $E1$, and $E2$ cross sections with the strength ratio of 0.13, 1.0, and 0.2, respectively [11]. It has been shown that the monopole and quadrupole modes besides $E1$ contribute the giant resonance in the $(e, e'n_0)$ reaction unlike predominant $E1$ in the $(e, e'p_0)$ reaction. It may be a result of the isospin of the decay particles as suggested by Saruis [12].

As described before, the transverse-transverse of the interference components is nearly zero in the giant resonance region. Therefore, the other longitudinal-transverse component obtained by neglecting the transverse-transverse is compared in Fig. 5 with that obtained by a Legendre expansion neglecting the transverse-transverse of the in-plane angular correlations taken at a close momentum transfer ($q_{\mathrm{eff}} = 0.33\ \mathrm{fm}^{-1}$) [1]. Both data are expressed in the ratio of the longitudinal-transverse to noninterference component. Both results agree well. This indicates that the Legendre expansion is a reliable method for the separation of the structure functions. The transverse component estimated from the Goldhaber and Teller (GT) model [13] is shown by a dashed line. A maximum might be suggested to be around 24 MeV although the data are low statistics, but the data are not inconsistent with the GT model estimate.

In summary, we have performed the first out of plane measurements of the angular correlations for the $^{12}\mathrm{C}(e, e'n)^{11}\mathrm{C}$ reaction in the giant resonance region at an effective momentum transfer of $0.41\ \mathrm{fm}^{-1}$. The angular correlations were separated into the longitudinal plus transverse, longitudinal-transverse, and transverse-transverse components. The prediction for the longitudinal plus transverse component agrees well with the separated data at the forward angles, but it shows a remarkable difference at the backward angles. The cross section at the peak of the giant resonance is found to be almost all longitudinal, which was reproduced by multipole expansion with $E0$ and $E2$ components besides $E1$. The longitudinal-transverse might have a maximum around 24 MeV, although the data are low statistics. The transverse-transverse is very small over the giant resonance region.

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