Angular Correlations for the $^{12}C(e,e'n)^{11}C$ Reaction in the Giant Resonance Region

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Angular correlations for the $^{12}C(e,e'n)^{11}C$ reaction in the giant resonance region have been measured for forward scattering at an effective momentum transfer of 0.35 fm^{-1}. The angular correlation for the ground-state transition indicates a strong forward-backward asymmetry at the peak of the giant dipole resonance ($\omega = 22.5$ MeV), which is different from the nearly symmetric angular correlations observed for the $^{12}C(e,e'p_0)^{11}B$ reaction. Recent random-phase approximation predictions fail to reproduce the experimental angular correlations for both $(e,e'n_0)$ and $(e,e'p_0)$, predicting the opposite patterns to those observed. [S0031-9007(97)02328-4]

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Although measurements of the $(e,e'n)$ reaction at intermediate energy are important, in the past, few such experiments [1–4] have been made by using continuous electron beams. This is because of experimental difficulties in detecting low energy neutrons in an environment with a huge γ-ray and neutron background.

Theoretical predictions for collective excitation in $(e,e'x)$ reactions are very useful as a means of extracting information on nuclear structure and dynamics from coincidence experiments. Recently, Cavinato *et al.* [5] have performed a self-consistent random-phase approximation (RPA) calculation with a Skyrme interaction for the $^{12}C(e,e'x)$ cross sections and angular correlations. The partial $^{12}C(e,e'p_0)$ and $^{12}C(e,e'n_0)$ cross sections for the monopole, dipole, and quadrupole modes have been calculated in RPA-SK3 for excitation energies between 15 and 30 MeV, at an incident electron energy of $\epsilon_i = 126$ MeV and a scattering angle of $\theta_e = 40°$. These calculations for finite nuclei and in the energy continuum, include a reaction mechanism where the final-state interaction and channel-coupling effects are treated self-consistently [6]. The dipole cross section has peaks at $\omega = 20$ MeV and $\omega = 27.2$ MeV. Both the proton and neutron decay channels exhibit similar dependence on energy and have much the same magnitude. On the other hand, the quadrupole cross section has a peak at $\omega = 23.8$ MeV and proton decay exceeds neutron decay.

Figure 1 shows the $(e,e'p_0)$ and $(e,e'n_0)$ angular correlations calculated in RPA-SK3 for an excitation energy of $\omega = 22.5$ MeV at $\epsilon_i = 126$ MeV, $\theta_e = 40°$, and an azimuthal angle of $\phi = 180°$ [5]. The angle $\phi = 180°$ indicates a nucleon emitted in the half-plane on the opposite side to the incident electron. The momentum transfer under these kinematics is $q = 0.41$ fm^{-1}. The calculation includes multipole modes of 0^+, 1^-, and 2^+. The $(e,e'p_0)$ angular correlation shows a strong forward-backward asymmetry. On the other hand, the $(e,e'n_0)$ angular correlation displays a behavior nearly symmetric about $\theta_n = 90°$, which indicates dominance of the dipole resonance. In both reactions a breaking of the symmetry about $\theta_x = 180°$ appears to be due to the presence of Coulomb-transverse interference.

The interference between the stronger 1^- mode and the weak 0^+ and 2^+ modes leads to a forward-peaked angular correlation in the calculation [5]. The relative contribution of the quadrupole mode to the total nucleon decay channels is greater than 36% for the proton case and only about 10% for the neutron case. Moreover, the proton monopole strength is 20 times stronger than that for neutrons. Cavinato *et al.* suggest that the sensitivity of

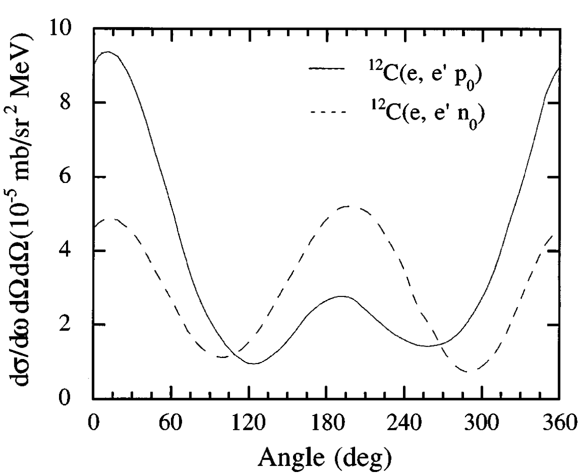

FIG. 1. Angular correlations for the $^{12}C(e,e'p_0)$ (solid curve) and $^{12}C(e,e'n_0)$ (dashed curve) reactions in the RPA-SK3 calculation at $\theta_e = 40°$, $\epsilon_i = 126$ MeV, $\omega = 22.5$ MeV, and $\phi = 180°$ from Ref. [5].

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^{12}C$(e, e'p_0)$ angular correlations in the forward direction to monopole excitations is particularly strong.

The ^{12}C$(e, e'p)$ angular correlation has been measured by Calarco *et al.* at Stanford [7], and subsequent measurements have been performed at Mainz [8], but no data for the ^{12}C$(e, e'n)$ reaction are available. The $(e, e'n)$ reaction is particularly interesting because it favors two-body correlations in the nuclear system. The contributions due to the quasielastic knockout process for $(e, e'n)$ is estimated to be about 2 orders of magnitude less than that for $(e, e'p)$. The present Letter reports a measurement of the angular correlations of the ^{12}C$(e, e'n_0)$ reaction in the giant resonance region and compares it with RPA predictions and the ^{12}C$(e, e'p_0)$ reaction.

The ^{12}C$(e, e'n)$ experiment was performed using the continuous electron beam from the 150-MeV Tohoku University pulse stretcher ring [9]. A natural carbon target of thickness 100 mg/cm^2 was bombarded with electrons of energy 129 MeV. Scattered electrons were detected at $\theta_e = 30°$ by a magnetic spectrometer which has a solid angle of 5 msr and a momentum resolution of 0.05% within the accepted momentum bite of 5.3%. Neutrons emitted from the target were measured using seven NE213 liquid scintillator neutron detectors.

These were placed in the electron scattering plane at $\theta_n = 7°$, 34°, 64°, 93°, 155°, 184°, and 214°, where θ_n is measured from the momentum-transfer direction. Each detector was placed 75 cm from the center of the scattering chamber allowing the neutron energy to be determined by the 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 [10].

The missing energy spectrum for the ^{12}C$(e, e'n)^{11}$C reaction is shown in Fig. 2 and indicates that the neutrons from the giant resonance decay primarily to the ground state. The ^{12}C$(e, e'n_0)$ angular correlations at 22.5, 23.5, 24.5, and 25.5 MeV are shown in Fig. 3(a). The solid lines are the Legendre polynomial fits described below. The angular correlation changes from a strong forward-backward asymmetry at 22.5 MeV to a weak forward-backward one at 25.5 MeV. Calarco *et al.* measured ^{12}C$(e, e'p_0)$ angular correlations [7,8], and Fig. 3(b) shows their angular correlations at the peak (22.5 MeV) and shoulder (25.5 MeV) of the giant resonance. These data were measured at an incident electron energy of 183 MeV and at $\theta_e = 22°$, and correspond to a momentum transfer of 0.34 fm^{-1}. In the figure, the lines indicate a similar fit using Legendre polynomials.

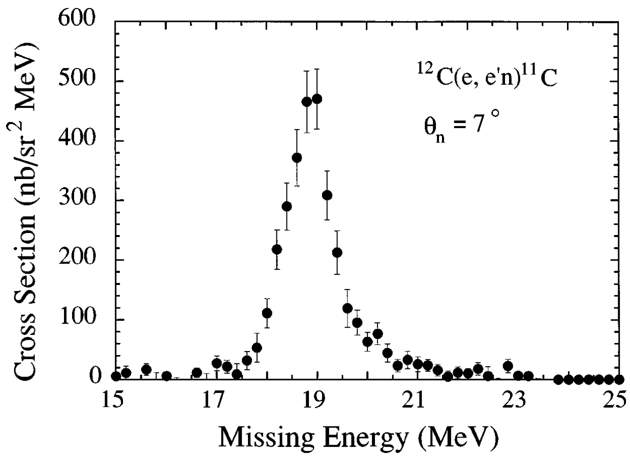

FIG. 2. Missing energy spectrum for the ^{12}C$(e, e'n_0)^{11}$C reaction at $\theta_n = 7°$.

The ^{12}C$(e, e'p_0)$ angular correlation indicates a forward-backward symmetry at $\omega = 22.5$ MeV, but changes to forward peaking at 25.5 MeV. The angular dependence of these angular correlations hardly changes for the momentum transfer range from 0.24 to 0.61 fm^{-1} measured.

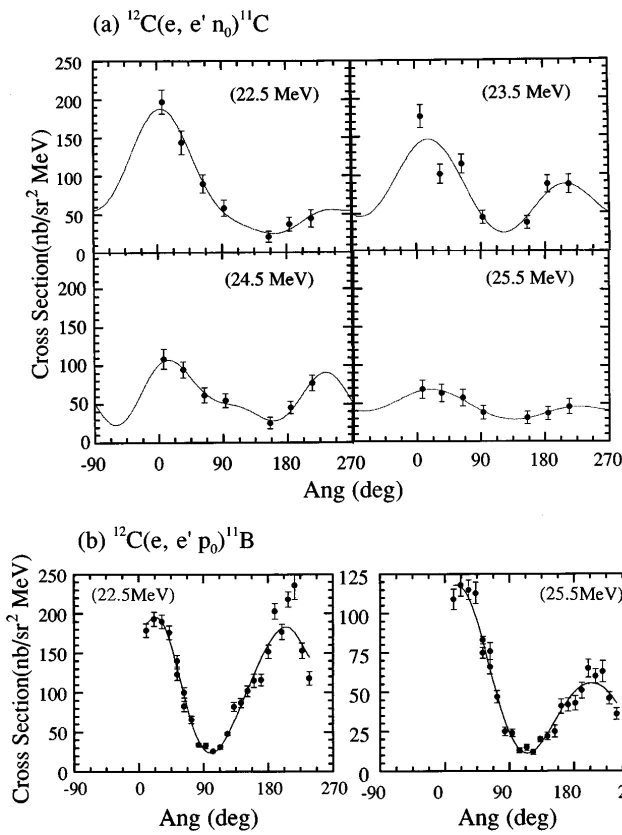

FIG. 3. (a) angular correlations at $\epsilon_i = 129$ MeV, $\theta_e = 30°$, and $\phi = 180°$. The momentum transfer is 0.34 fm^{-1}. The solid curves are Legendre polynomial fits. (b) ^{12}C$(e, e'p_0)$ angular correlations at $\omega = 22.5$ MeV and 25.5 MeV taken at the momentum transfer of $q = 0.34$ fm^{-1} from Ref. [8].

Figure 4 shows the $^{12}\mathrm{C}(e,e'n_0)$ and $^{12}\mathrm{C}(e,e'p_0)$ angular correlations for $\omega = 22.5$ MeV compared with the RPA predictions. The magnitude of the calculations are much greater than the measured cross sections and have been reduced on the plot by a factor of 0.4 [for the $^{12}\mathrm{C}(e,e'n_0)$] and 0.7 [for the $^{12}\mathrm{C}(e,e'p_0)$] so that the angular dependence might be compared. The experimental angular correlation for $^{12}\mathrm{C}(e,e'n_0)$ is remarkably different from the prediction, and the experimental $^{12}\mathrm{C}(e,e'p_0)$ data do not exhibit a clear indication of forward-backward asymmetry as predicted. Thus the observed shapes for both the $^{12}\mathrm{C}(e,e'n_0)$ and $^{12}\mathrm{C}(e,e'p_0)$ reactions are found to be poorly reproduced by the present RPA-SK3 predictions.

One of the principal reasons is the failure of the RPA to give the strength at the correct excitation energy. This is a problem for the $(e,e'p)$ reaction, but is even more severe for $(e,e'n)$, since the RPA predicts the peak of the GDR to be just above the threshold for n_0 emission. Thus the calculations possibly cannot get the correct partial wave. The different experimental behavior of the angular correlations for protons and neutrons may be a result of the isospin of the decay particles. The process also might include contributions from more complicated configurations than those used in the calculation.

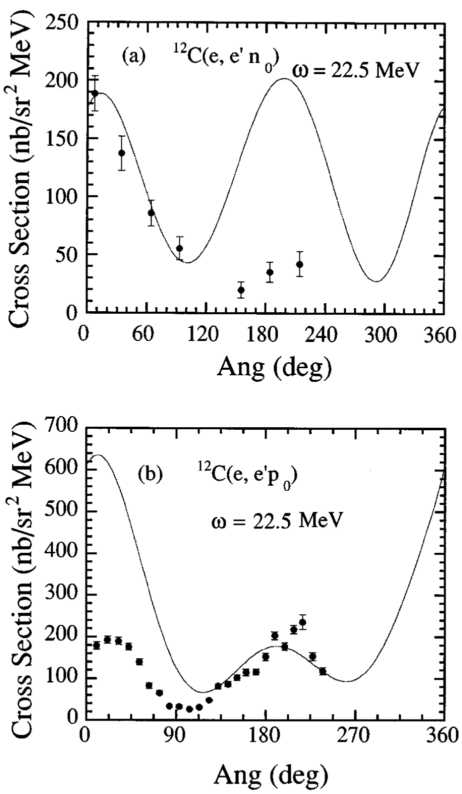

FIG. 4. Comparison of the $^{12}\mathrm{C}(e,e'n_0)$ and $^{12}\mathrm{C}(e,e'p_0)$ (Ref. [8]) angular correlations at $\omega = 22.5$ MeV with RPA-SK3 predictions. The calculated values for $^{12}\mathrm{C}(e,e'n_0)$ and $^{12}\mathrm{C}(e,e'p_0)$ are scaled down by factors of 0.4 and 0.7, respectively.

The theoretical $(e,e'x)$ cross sections can be expressed as [5,11]

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

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 W_i contain all the nuclear structure information. Under the present experimental conditions of forward scattering ($\theta_e = 30°$), $q_{\mathrm{eff}} = 0.35\ \mathrm{fm}^{-1}$, the giant dipole resonance is mainly excited through longitudinal interaction ($C1$); the transverse component ($T1$) and other multipoles ($C2$) may be weakly excited [12]. In this case, the longitudinal and transverse structure functions W_L and W_T can be expressed by $|C1|^2$, $C1^*C2$, and $|T1|^2$. The interference terms W_{LT} can be expressed by $C1^*T1$ and $C2^*T1$ and W_{TT} by $|T1|^2$. The present structure functions are approximated by Legendre polynomials up to third order:

$$\begin{aligned} V_L W_L + V_T W_T &= A_0[1 + b_1 P_1(x_n) + b_2 P_2(x_n) + b_3 P_3(x_n)], \\ V_{LT} W_{LT} &= C_2[c_1 P_1^1(x_n) + P_2^1(x_n) + c_3 P_3^1(x_n)], \\ V_{TT} W_{TT} &= D_2 P_2^2(x_n), \\ x_n &= \cos\theta_n. \end{aligned} \quad (2)$$

The $V_{TT}W_{TT}$ term was neglected in this analysis, since $V_{TT}W_{TT}$ is smaller than $V_T W_T$ in general [13,14]. The interference terms $c_1 P_1^1(x_n)$ and $c_3 P_3^1(x_n)$ were also neglected. These terms are assumed to be less than the main longitudinal-transverse interference term $C_2 P_2^1(x_n)$, because they involve interference between $E1$ and $E2$ in the longitudinal and transverse excitation modes. Five parameters, A_0, b_1, b_2, b_3, and C_2, were used in the fitting, and these are shown in Fig. 5.

The cross section ($4\pi A_0$) and angular coefficients (b_i) are compared with the (γ,n_0) results [15] extrapolated to the present value of q using the Kleppinger and Walecka formalism [4,13]. The shapes of the cross sections are similar, but the absolute cross section of $(e,e'n_0)$ is about 1.5 times larger than the (γ,n_0) extrapolated value at 22.5 MeV. The ratio of $(e,e'p_0)$ to $(e,e'n_0)$ at 22.5 MeV is about 1.1, which is not inconsistent with about 1.3 found in the (γ,n_0) and (γ,p_0) cross sections on ^{12}C and ^{16}O [16]. A large value of b_1 at $\omega = 22.5$ MeV indicates the existence of weak monopole and/or quadrupole strength interfering with the giant dipole resonance. The coefficient b_2 at $\omega = 22.5$ MeV roughly agrees with the (γ,n_0) angular coefficient extrapolated, which seems to be consistent with the fact that the $(e,e'p_0)$ angular coefficient b_2 agrees well at low q with photonuclear results. The longitudinal-transverse

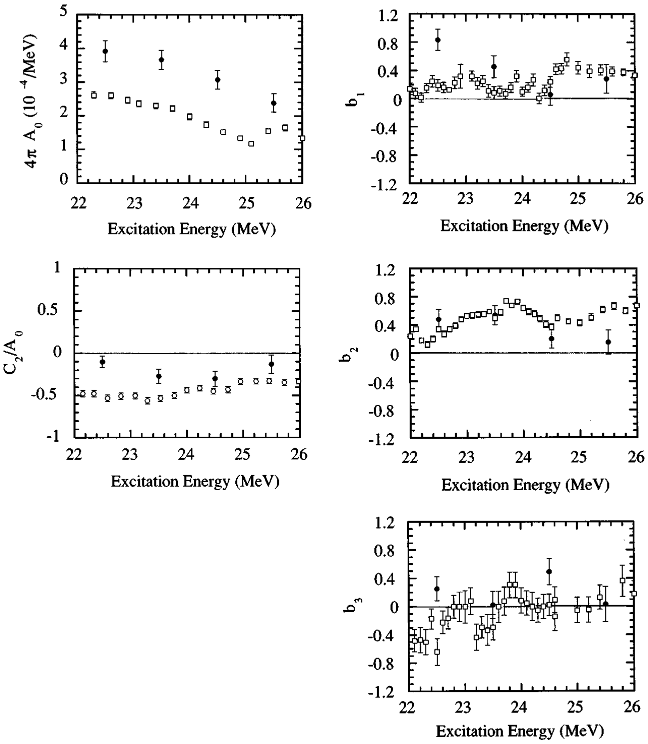

FIG. 5. Legendre fit parameters. The cross sections $4\pi A_0$ (divided by σ_M) and angular coefficients b_i for ^{12}C$(e,e'n_0)$ (filled circles) are compared with ^{12}C(γ,n_0) results (Ref. [15]) extrapolated to the present value of q (open squares). The interference parameters C_2 for ^{12}C$(e,e'n_0)$ (filled circles) are compared with the ^{12}C$(e,e'p_0)$ results from Ref. [8] (open circles).

interference parameter C_2 normalized by A_0 for $(e,e'n_0)$ is compared with that for $(e,e'p_0)$. If both $(e,e'p_0)$ and $(e,e'n_0)$ are proceeding through the same dipole resonance, then the electromagnetic contribution to W_{LT} should be the same. However, the parameter C_2 also depends on the neutron angular correlation. In fact, if one follows Kleppinger and Walecka, the ratio C_2/b_2 would be expected to be roughly constant. The present data show that C_2 appears to be weak where b_2 is strong, in contradiction to that expectation. This might be due to contributions from the interference of $E0$ and/or $E2$ multipoles with the dominant $E1$ multipole.

In summary, the angular correlations for the ^{12}C$(e,e'n_0)$ reaction in the giant resonance region has been measured in order to study the decay modes. The strong forward-backward asymmetry observed at $\omega = 22.5$ MeV is different from the symmetric distribution of the ^{12}C$(e,e'p_0)$ reaction. Those angular correlations are inconsistent with the predictions of recent RPA calculations. An improved theoretical approach is needed to resolve these discrepancies.

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