$(e,e'\gamma)$ Measurements on the 4.439-MeV State of ^{12}C

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The relative phase of the longitudinal and transverse form factors of the 4.439-MeV $J^\pi = 2^+$ state of ^{12}C has been measured at $q_{\rm eff} = 0.36$ and 0.46 fm^{-1}. This phase was found to be negative, of the same sign given by Siegert's theorem in the long-wavelength limit. This measurement represents the first nuclear structure result derived through the $(e,e'\gamma)$ reaction.

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Electron scattering has proven to be the most precise probe available for the study of nuclear structure. This precision has been fully realized, however, only in the study of isolated excitations of a single multipolarity. In order to extend the power of the (e,e') reaction to the study of nuclei of nonzero spin, where more than one multipole can contribute, two techniques have been proposed: polarization of the target nucleus, and coincident detection of a nuclear decay product.

The $(e,e'\gamma)$ reaction channel is ideally suited for the study of bound-state excitations. Both the excitation and deexcitation mechanism are electromagnetic in nature and therefore well understood within the context of QED. The theory of the $(e,e'\gamma)$ reaction has been investigated repeatedly over the last twenty years.[1-7] Because of the formidable backgrounds associated with this reaction (primarily bremsstrahlung γ rays and thermal neutrons), it has not been practical to use this reaction until recently, when high-duty-factor electron beams became available. Its feasibility was first demonstrated by Williamson at Illinois.[8] We present here the first nuclear structure investigation based on the $(e,e'\gamma)$ probe.

The basic features of the $(e,e'\gamma)$ reaction can be understood with the aid of Fig. 1(a). An inelastically scattered electron deposits momentum, $\mathbf{q}$, and energy, ω, in the nucleus, exciting it from its ground state of spin-parity J_i^π to a state J_m^π which subsequently decays to a state J_f^π by emitting a photon of energy E_γ. This process is described to lowest order by the Feynman diagram shown in Fig. 1(b). For the case where the initial and final states are identical, the $(e,e'\gamma)$ process is coherent with the bremsstrahlung processes shown in Fig. 1(c) and 1(d), in which the electron emits a photon of energy E_γ, either before or after scattering elastically.

In the plane-wave Born approximation when a single multipolarity is involved, the $(e,e'\gamma)$ cross section is given by

$$\frac{d^4\sigma}{d\Omega_\gamma d\Omega_e\, d\omega\, dE_\gamma} = \sigma_{\rm Mott}\left(\frac{\Gamma_{\gamma f}}{\Gamma}\right)\Big\{V_L U_L |F_L(q)|^2 + V_T U_T |F_T(q)|^2 + V_I U_I \cos\phi_\gamma F_L(q) F_T(q) + V_S U_S \cos 2\phi_\gamma F_T(q) F_T(q)\Big\},$$

where $\sigma_{\rm Mott}$ is the Mott cross section and $\Gamma_{\gamma f}/\Gamma$ gives the probability that the state of interest will decay by emitting a photon of energy E_γ. The factors V_L, V_T, V_I, and V_S depend only on the electron kinematics, while U_L, U_T, U_I, and U_S are geometrical factors characteristic of the photon emission. If more than one multipolarity is involved in the transition, these geometrical factors allow the experimental separation of the different multipole contributions. This in turn permits the extraction of nuclear transition densities and currents for non-spin-zero nuclei in the same fashion that is done for inclusive measurements from spin-zero nuclei. All of the nuclear structure information is contained in the longitudinal and transverse form factors $F_L(q)$ and $F_T(q)$, which are Hankel transforms of the nuclear charge and current densities. Integration over the photon variables eliminates the last two terms because of their explicit dependence on ϕ_γ, the azimuthal angle of emission of the photon with respect to the momentum-transfer axis, yielding to the familiar expression for inclusive electron scattering.

The effect of the transverse-longitudinal interference term, $V_I U_I \cos\phi_\gamma F_L(q) F_T(q)$, is to rotate the decay radiation pattern through an angle that is a smooth function[2] of the ratio F_T/F_L. Measurement of this rotation provides an alternative to the Rosenbluth separation of $|F_T|^2$ and $|F_L|^2$. The sense of the rotation provides new nuclear structure information: the relative phase of these form factors. In this paper we present the results of the first experiment to demonstrate this technique by measuring this phase for the 4.439-MeV 2^+ state in ^{12}C.

Figure 2 displays our experimental geometry for $\theta_e = 80°$ together with a polar plot of the logarithm of the ^{12}C$(e,e'\gamma)$ coincidence cross section as predicted

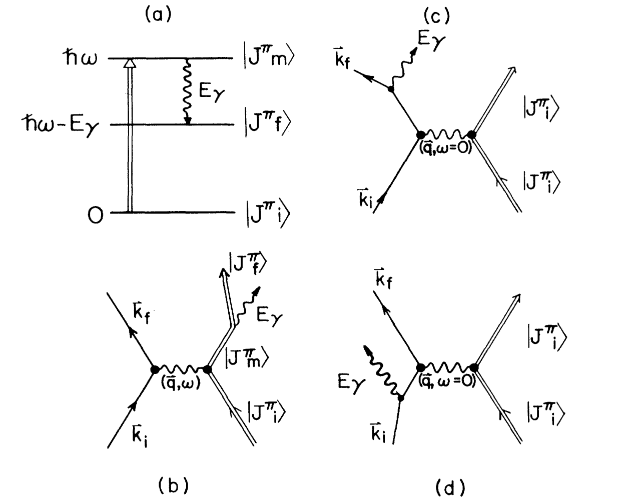

FIG. 1. (a) Energy level diagram and (b)–(d) Feynman diagrams relevant to the $(e,e'\gamma)$ reaction.

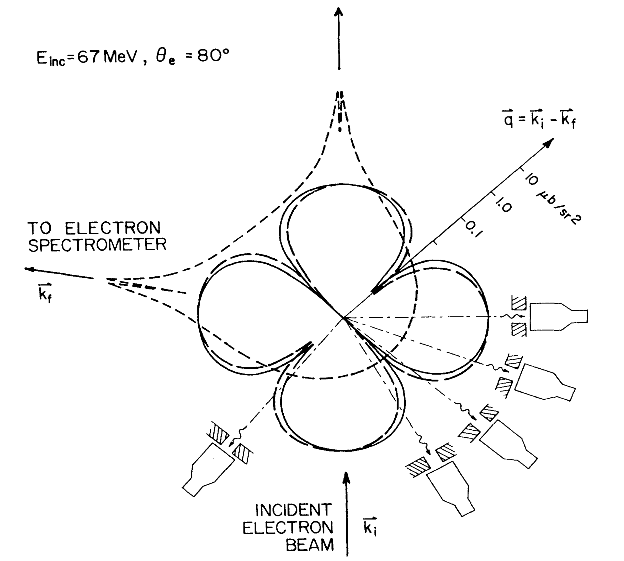

FIG. 2. Predicted angular distributions and the experimental geometry for the $^{12}C(e,e'\gamma)$ measurement.

by the theory of Acker and Rose.[2] The bremsstrahlung coincidence cross section is strongly peaked in the incident and scattered electron directions. The nuclear coincident cross section has been calculated with use of the measured value[9] of $|F_T|^2$ and $|F_L|^2$ extrapolated to our q values. If $|F_T|^2$ were zero, a simple quadrupole pattern relative to the $\mathbf{q}$ axis would result. For $|F_T|^2/|F_L|^2=5.8\times10^{-3}$ the pattern rotates by 2.3° with respect to the $\mathbf{q}$ axis; the sense of the rotation is clockwise (dashed curve) if F_T and F_L have the same sign, and counterclockwise (solid curve) if they have opposite signs. The nuclear-bremsstrahlung interference[2,4] is not observable in our experiment because the width of the 4.439-MeV state is much smaller than our energy resolution.

Our experiment used the 100%-duty-factor electron beam available from the University of Illinois MUSL-2 accelerator. The $(e,e'\gamma)$ coincidence cross section was measured at scattering angles, θ_e, of 60° and 80° for an electron beam energy, $E_{\rm inc}$, of 66.9 MeV, corresponding to effective momentum transfers, $q_{\rm eff}$, of 0.36 and 0.46 $\rm fm^{-1}$. Electron beams with intensities of up to 2 μA were scattered from carbon foils of 26 and 45 $\rm mg/cm^2$ and were detected in a magnetic spectrometer subtending 5 msr. Photons were detected in BGO and NaI crystals located at angles, θ_γ, relative to the beam axis of 140°, 210°, 230°, 250°, and 270° for $\theta_e=80°$ (see Fig. 2), and at $\theta_\gamma=140°$, 230°, and 270° for $\theta_e=60°$. These detectors typically subtended 25 msr and were always kept in the scattering plane ($\phi_\gamma=0$). The true-to-accidental ratios observed in the timing spectra ranged from 5:1 to 50:1 depending on the beam intensity and the position of the γ-ray detector. The relative efficiencies and solid angles of our γ-ray detectors were measured to an accuracy better than 1%. Event by event data recording was performed by use of our generalized coincidence electronics system,[10] which allowed simultaneous monitoring of all singles spectra and provided extensive diagnostic capabilities.

Systematic uncertainties were minimized by the use of the ratio technique.[11] As can be seen from Fig. 2 for $\theta_e=80°$, the ratio of the cross sections measured at appropriately chosen angles is quite sensitive to small rotations of the nuclear decay pattern. Matched pairs of photon detectors were placed at $\theta_\gamma=210°$ and 250°, and at $\theta_\gamma=230°$ and 270°. The $(e,e'\gamma)$ cross sections were then measured simultaneously at these angles. The detectors in each pair were interchanged frequently to cancel any efficiency differences. The resulting cross-section ratios are insensitive to most of the probable sources of systematic error, such as the target thickness, the beam intensity, the spectrometer solid angle, and efficiency. The remaining systematic error in the measured ratios is estimated to be 8%.

The electron spectra coincident with 4.4-MeV photons measured for the $\theta_\gamma=250°/210°$ pair for $\theta_e=80°$ are shown in Fig. 3. A line-shape fit to these data allows us to separate the nuclear $(e,e'\gamma)$ cross section, $d\sigma_N$, from the bremsstrahlung cross section. The ratio $R_N(250°/210°)=d\sigma_N(250°)/d\sigma_N(210°)$ was measured three times with use of different targets and beam intensities. All three measurements agree within their quoted uncertainties, supporting our claim that the systematic errors and backgrounds are understood.

Figure 4 illustrates the determination of the F_T/F_L relative phase at $q_{\rm eff}=0.36$ $\rm fm^{-1}$ for the $\theta_\gamma=270°/$

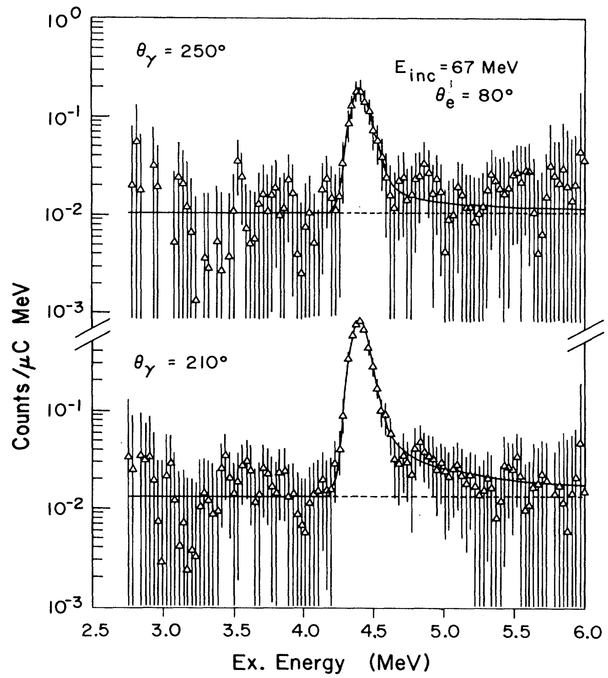

FIG. 3. Line-shape fits to $(e,e'\gamma)$ electron coincidence spectra allow the separation of the nuclear from the bremsstrahlung cross section.

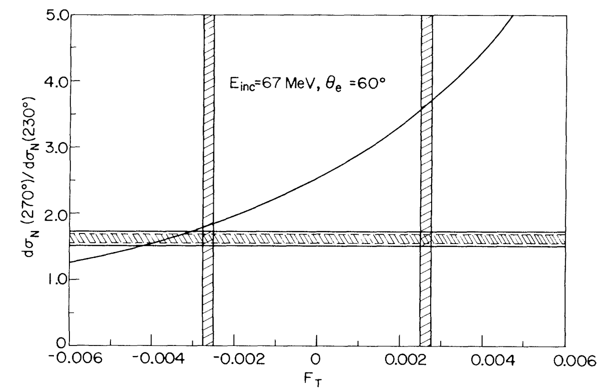

FIG. 4. Determination of the phase and the magnitude of the transverse form factor by use of the ratio technique.

230° detector pair. The ratio was measured to be 1.62 ± 0.11 and is shown in the figure by the horizontal shaded area. The vertical shaded bars indicate the two possible values (positive and negative) for F_T extrapolated from the measurements of Flanz *et al.*[9] Finally, the solid curve shows the ratio, R_N, calculated as a function of F_T for F_L fixed at the experimental value of 0.0269. The intersection of this curve with the measured ratio clearly prefers the negative sign for the relative phase of F_T and F_L at this q value. By use of the same technique for the ratios $R_N(250°/210°) = 4.80 \pm 0.30$ and $R_N(270°/230°) = 5.55 \pm 0.65$ obtained at $q_{\text{eff}} = 0.46\ \text{fm}^{-1}$, a negative relative phase for F_T/F_L is also obtained.

Our initial choice of phases also implies a negative relative phase at the real photon limit ($q \to \omega$) where F_T and F_L are related through Siegert's theorem:

$$F_T(q) = -\frac{\omega}{q}\left(\frac{\lambda+1}{\lambda}\right)^{1/2} F_L(q) \quad \text{for } q \to \omega.$$

The fact that, for our moderately low-q measurements the phase is still of the same sign as the Siegert limit strongly suggests that neither of the form factors has changed sign. Such behavior is to be expected if at these low momentum transfers the transverse form factor is dominated by the convection current as our current theoretical understanding of this state suggests.[12]

The cross-section ratios can be transformed into an angular distribution by accounting for the solid-angle–efficiency product of the photon detectors. The resulting angular distribution for the $q_{\text{eff}} = 0.46\text{-fm}^{-1}$ data is shown in Fig. 5. The solid and dashed curves correspond to the curves shown in Fig. 2 except that the amplitude of the total cross section has been adjusted to provide a minimum-χ^2 fit to the data for the two choices of the relative phase. The ability of the $(e,e'\gamma)$ reaction to determine the multipolarity of a transition is clearly evident in this figure, as is the decisive preference for the negative phase (solid line).

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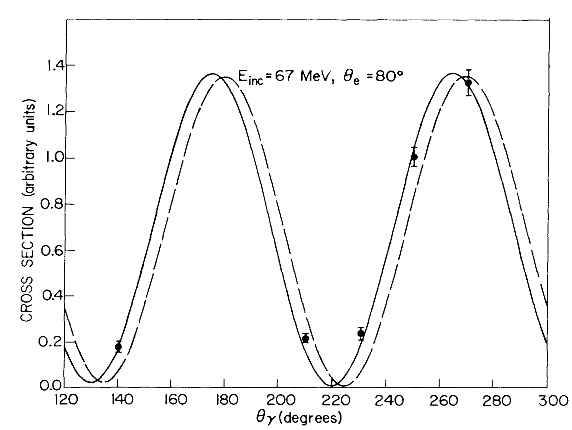

FIG. 5. The angular distribution of the $^{12}C(e,e'\gamma)$ coincidence cross section. The curves correspond to the two possible choices for the relative F_T/F_L phase. The preference for a negative phase is obvious.

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