[8]K. Alder and A. Winther, *Electromagnetic Excitation* (North-Holland, Amsterdam-Oxford, 1975).
[9]A possible second-order contribution vanishes for a spin-3/2 projectile since the occurring $6j$ symbol is zero by accident [Eq. (34) of Ref. 2].
[10]P. Egelhof, thesis, University of Heidelberg, 1978 (unpublished).
[11]P. Zupranski *et al.*, to be published.
[12]O. Häusser, A. B. McDonald, T. K. Alexander, A. J. Ferguson, and R. E. Warner, Nucl. Phys. A212, 613 (1973).
[13]G. Baur, F. Roesel, and D. Trautmann, Nucl. Phys. A288, 113 (1977).
[14]O. Häusser, A. B. McDonald, T. K. Alexander, A. J. Ferguson, and R. E. Warner, Phys. Lett. 38B, 75 (1972).

Study of Strong Spin-Isospin Mode Analog States at 4.5 MeV in ^{12}B in $^{12}C(e,e'\pi^+)^{12}B$

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Strong spin-isospin mode, $T=1$, $T_z=1$ analog states at 4.5 MeV in ^{12}B were studied by the reaction $^{12}C(e, e'\pi^+)^{12}B$ at the electron energy $E_e=200$ MeV. The photoproduction cross sections at seven angles ranging from 30° to 150° were obtained with use of virtual-photon theory and an experimentally determined real-to-virtual photon ratio. The results are compared with theoretical calculations and also with the available data on inelastic scattering from the 19.5-MeV $T=1$, $T_z=0$ analog complex in ^{12}C.

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The photoproduction of pions near threshold and its inverse process, the radiative capture of stopped pions, preferentially excite spin-flip states in a nucleus through the dominant Kroll-Ruderman term, $\vec{\sigma}\cdot\vec{\epsilon}$ ($\vec{\sigma}$ is the nuclear spin and $\vec{\epsilon}$ is the photon polarization vector). Of special interest is the possibility of using these reactions to study the spin-flip states in the giant-resonances region—the so-called spin-isospin modes predicted by the generalized Goldhaber-Teller model.[1] In contrast to the well-known giant-resonance isospin modes[1] which have been extensively studied throughout the periodic table by photonuclear reactions and electron scattering, experimental studies of the spin-isospin modes are rather limited, most of the presently available data coming from the radiative capture of stopped pions.[2] However, this reaction has the serious limitation that the momentum transfer is restricted to a single value ($q\sim 0.6$ fm^{-1}), and therefore no information can be obtained about the multipolarities of the excited states. The inverse reaction, namely the photoproduction of charged pions, can be a more versatile tool to study the spin-flip giant resonance states since the momentum transfer can be varied to map out the form factors of the excited states.[3] The photoproduction of charged pions excites the $T=1$, $T_z=\pm 1$ spin-isospin analogs in the residual nucleus (for a $T=T_z=0$ target nucleus). The fact that the photopion reaction probes only the $T=1$ states is a unique feature which distinguishes it from other reactions such as electron scattering or pion inelastic scattering which are sensitive to both $T=0$ and $T=1$ states or their isospin-admixed states.

The purpose of this paper is to demonstrate the usefulness of photopion reactions with variable momentum transfer to obtain spectroscopic information about the spin-isospin analog states. We report here on angular distribution studies of emitted pions in the reaction $^{12}C(e,e'\pi^+)^{12}B^*$ leading to the 4.5-MeV $T=1$, $T_z=1$ analog complex in ^{12}B.

Strong excitation of these states was previously observed in (π^-,γ) (Ref. 2) and $(\gamma,\pi^\pm)$ experiments at a single fixed momentum transfer.[4] The $T_z=0$ analogs which correspond to these states are located at about 19.5 MeV in ^{12}C. Inelastic electron-scattering studies[5,6] together with particle-hole shell-model form-factor calculations[7] indicate that these states are dominantly $M2$ and $M4$.

In the present experiment a 200-MeV electron beam from the Tohoku University electron linac impinged on a graphite target of thickness 150 mg/cm^2. Energy spectra of the emitted pions were measured at seven angles ranging from 30° to 150° in steps of 20° using a double-focusing magnetic spectrometer with a 33-channel detector telescope array in its focal plane. Each channel consisted of three Si(Li) solid-state detectors operating in triple coincidence. System resolution was 0.6 MeV at all angles except 130° and 150° for which it was 1.0 MeV. The energy spectra at $\theta = 50°$ and 130° are shown in Fig. 1.

The absolute scale on the double-differential cross section was obtained by an auxiliary elastic electron-scattering measurement on the ^{12}C target. For each transition the pion spectrum reflects the virtual-photon spectrum shape, and the experimental data have been fitted with virtual spectra corresponding to transitions to the ground and 0.95-MeV states as well as the 4.5-MeV complex states in ^{12}B (see Fig. 1). At pion energies above the 4.5-MeV end point, the data are consistent in shape and strength with the experimental cross sections of Shoda *et al.*[3] for the transitions to the ground and 0.95-MeV states, thus implying that the contributions from other excited states below 4.5 MeV are small. In addition, the shapes of the spectra at pion energies below the 4.5-MeV end point are consistent with small contributions from transitions to states above 4.5 MeV. The pion contribution from the quasifree process ^{12}C $+\gamma \rightarrow {}^{12}$B $+ n + \pi^+$ was estimated using a Fermi-gas model[9] to be at about the 10% level.

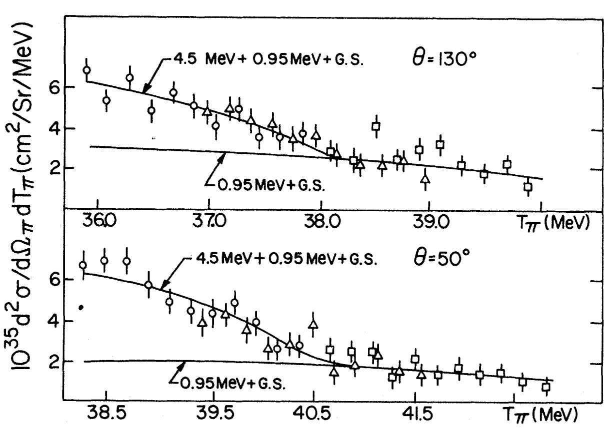

FIG. 1. The pion energy spectra from ^{12}C at $\theta = 50°$ and 130°. The solid curves are least-squares fits to the data using virtual-photon spectrum shapes (Ref. 8), with the lower lines representing the background due to transitions to the ground and 0.95-MeV states in ^{12}B.

The electroproduction results were converted to the equivalent photoproduction cross sections by use of a virtual-photon spectrum with shape given by Dalitz and Yennie[8] and intensity determined experimentally in separate measurements.[4]

The photopion cross sections thus obtained are shown in Figs. 2 and 3 where comparisons are made with the available theoretical calculations. The error bars are due to the propagation of counting statistics only. Systematic errors, including those associated with the absolute calibration, the virtual spectrum uncertainties, and the neglected contributions from other excited states, are estimated to be about 20%.

In Fig. 2, the experimental results are first compared with the shell-model calculations of Haxton.[10] These calculations employ nuclear wave functions derived from the work of Dubach and Haxton[10] (D-H) in which the ^{12}C positive-parity states are generated in a full $2\hbar\omega$ shell-model basis and the negative-parity states in a full $1\hbar\omega$ basis. Using the D-H wave functions, Haxton[10] finds that the calculated (e,e') form factors for the dominant $T=1$, $J=4^-$, 2^- states near 19.5 MeV in ^{12}C, when compared with the data of Flanz,[6] are too large in magnitude even though the correct shapes are reproduced. In order to reach agreement in magnitude, he finds that the 4^- and 2^- theoretical form factors must be reduced by factors of 0.7 and 0.5, respectively. Using these reduction factors, Haxton obtains the theoretical photopion cross sections shown in Fig. 2. For the photoproduction amplitude he uses the simple threshold partial conservation of axial-vector current operator proportional to the Kroll-Ruderman term $\vec{\sigma}\cdot\vec{\epsilon}$. The pion final-state interaction is included by means of a second-order optical-model potential employing π-nucleon phase shifts, two-nucleon absorption terms, and Pauli-blocking and Lorentz-Lorenz corrections.

The shell model calculations of Singham[11] with the same D-H wave functions but with the full Blomqvist-Laget (B-L) photopion production amplitude[12] are shown in Fig. 2 together with the Helm-model calculations of Nagl and Überall.[13] The nuclear structure input to the latter calculations is in the form of the transition charge density which is parametrized to the electron-scattering data of Yamaguchi *et al.*[5] for the 19.5-MeV complex in ^{12}C, and the full photopion production amplitude of Berends, Donnachie, and Weaver[14] is used. The pion final-state interaction is in-

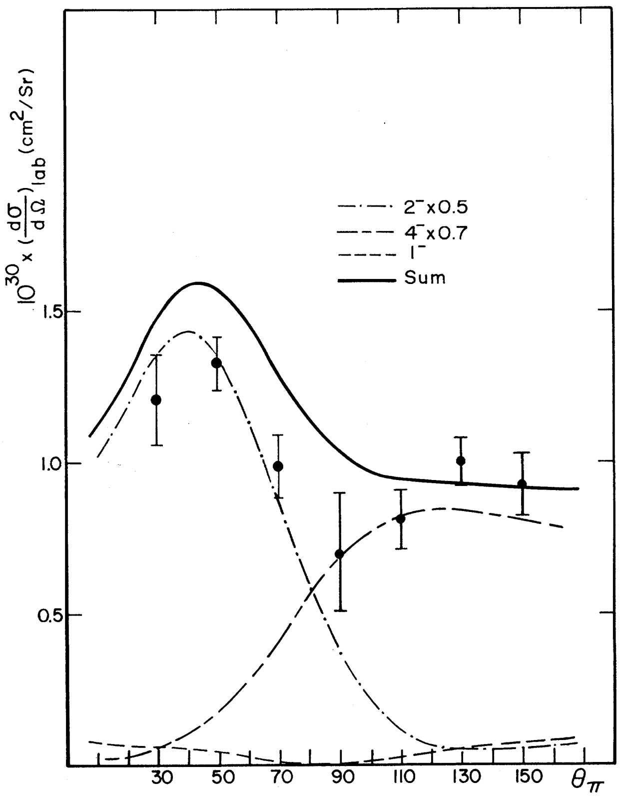

FIG. 2. Photopion cross sections compared with the shell-model calculations using the $\vec{\sigma} \cdot \vec{\epsilon}$ production amplitude (Ref. 10).

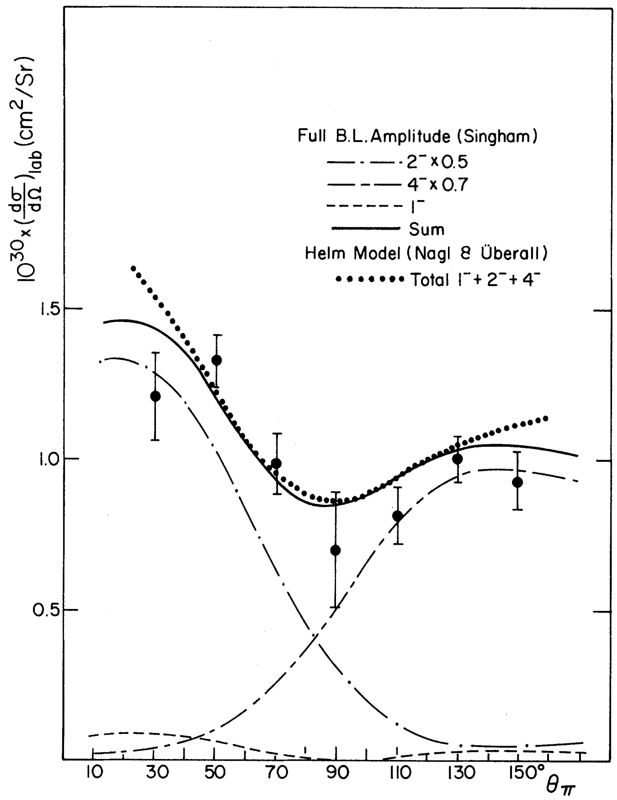

FIG. 3. Photopion cross sections compared with the shell-model calculations (Ref. 11) using the full Blomqvist-Laget amplitude (Ref. 12), and also with the Helm-model calculations (Ref. 13).

cluded by means of an optical potential with parameters determined to fit pion atomic and scattering data. The shapes of the differential cross sections predicted by the two models are in reasonable agreement with each other and with the experimental results, and they are consistent with the dominant presence of $M2$ and $M4$ states at the excitation energy of 4.5 MeV in ^{12}B.

Since the Helm-model calculations make explicit use of the electron scattering data, their agreement with the photopion data as shown in Fig. 3 indicates that the form factors of the $T_z = 1$ analog states as obtained in the present (γ, π^+) experiment and the form factors of the $T_z = 0$ states as obtained in inelastic scattering are consistent with each other. This conclusion is further supported by the fact that the same reduction factors in the shell-model calculations are needed to obtain agreement with both (e, e') and (γ, π^+) experiments. The relatively large magnitude of these reduction factors, on the other hand, clearly indicates that the D-H wave functions in their present form incompletely describe the negative-parity states in the 19.5-MeV region of ^{12}C and their analogs. It will be of interest to investigate whether the presence of more complicated configurations than those included in the D-H wave functions can explain the phenomenologically determined reduction factors.

The electron-scattering data on ^{12}C by Flanz[6] seem to indicate several 4^- states in the neighborhood of 19.5 MeV and there is evidence from pion inelastic-scattering[15] results showing isospin mixing among them. In our study of the analog states in ^{12}B with about 0.6 MeV resolution, we are unable to determine whether there are one or more $M2$ or $M4$ states. Their isospin character, however, is uniquely determined to be purely $T = 1$. For a full understanding of the relationship between the 4.5-MeV complex in ^{12}B studied here by the photopion reaction and the 19.5-MeV complex in ^{12}C studied by (e, e') and pion inelastic scattering, it will be interesting to investigate whether the strengths of the $T = 1$ components in the admixed states in ^{12}C sum up to the pure $T = 1$ strength in the analog in ^{12}B. This would serve as an additional verification of the isospin mixing in the 19.5-MeV complex in ^{12}C.

The present experiment has demonstrated the usefulness of photopion reactions as a spectroscopic tool to study the pure $T = 1$, $T_z = 1$ spin-isospin mode analogs, emphasizing the complementary nature of these reactions to inelastic electron-scattering experiments which probe the $T_z = 0$ analogs. The presence of strong $T = 1$, $T_z = 1$, $M2$ and $M4$ analogs at 4.5 MeV in ^{12}B observed in this experiment is consistent with the inelastic electron-scattering results[5,6] in the 19.5-MeV region in ^{12}C.

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[1]H. Überall, Nuovo Cimento Suppl. 4, 781 (1966). See also T. W. Donnelly and N. LoIudice, Nucl. Phys. A179, 569 (1972).

[2]J. P. Perroud, in *Photopion Nuclear Physics*, edited by P. Stoler (Plenum, New York, 1979), p. 86.

[3]F. Cannata, B. A. Lamers, C. W. Lucas, A. Nagl, H. Überall, C. Werntz, and F. J. Kelly, Can. J. Phys. 52, 1405 (1974). See also K. Shoda, H. Ohashi, and K. Nakahara, Phys. Rev. Lett. 39, 1131 (1977).

[4]N. Paras, A. M. Bernstein, K. I. Blomqvist, G. Franklin, M. Pauli, B. Schoch, J. LeRose, K. Min, D. Rowley, P. Stoler, E. J. Winhold, and P. F. Yergin, Phys. Rev. Lett. 42, 1455 (1979); P. Stoler *et al.*, to be published.

[5]A. Yamaguchi *et al.*, Phys. Rev. C 3, 1750 (1971).

[6]J. B. Flanz, Ph.D. thesis, University of Massachusetts, 1979 (unpublished).

[7]T. W. Donnelly, Phys. Rev. C 1, 833 (1970).

[8]R. H. Dalitz and D. R. Yennie, Phys. Rev. 105, 1598 (1957).

[9]W. M. MacDonald, E. T. Dressler, and J. S. O'Connell, Phys. Rev. C 19, 455 (1979).

[10]W. C. Haxton, private communication.

[11]M. K. Singham, private communication.

[12]I. Blomqvist and J. M. Laget, Nucl. Phys. A280, 405 (1977).

[13]A. Nagl and H. Überall, private communication.

[14]F. A. Berends, A. Donnachie, and D. L. Weaver, Nucl. Phys. B4, 1 (1967).

[15]W. Cottingame *et al.*, in Proceedings of the Eighth International Conference on High Energy Physics and Nuclear Structure, TRIUMF and University of British Columbia, Vancouver, British Columbia, Canada, 13–17 August 1979 (to be published).

Limits to the Fusion of 310-MeV ^{16}O with Ti

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Limits to the fusion of 310-MeV ^{16}O with Ti were probed with both singles and coincidence measurements of the heavy products and the emitted light particles. The upper limit to compound nucleus formation is found to be in accord with recent dynamic calculations, but the principal mechanism reducing the compound nucleus cross section below that predicted by critical distance models is not an increase in strongly damped processes, but the prompt emission of energetic light particles.

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Measurements of yields, energy distributions, and angular correlations for heavy ion-heavy ion and heavy ion-light particle coincidences have been used to probe the limits to fusion in the reactions of 310-MeV ^{16}O with Ti. The cross section for evaporation-residue-like products is found to be 1130 ± 80 mb in excellent agreement with the cross-section predictions of critical distance models with no saturation.[1-4] This result is in accord with previous measurements on similar systems.[5,6] However, the cross section for formation of equilibrated Zn compound nuclei is much lower, $\lesssim 314$ mb. Although this latter cross section is in reasonable agreement with recent

