edited by K. Alder and A. Winther (Academic Press, Inc., New York, 1966), p. 303.
[14]O. Häusser and R. Y. Cusson, to be published.
[15]I. Ben Zvi, P. Gilad, M. Goldberg, G. Goldring, A. Schwarzschild, A. Sprinzak, and Z. Vager, Nucl. Phys. A121, 595 (1968).
[16]E. Matthias, S. S. Rosenblum, and D. A. Shirley, Phys. Rev. Letters 14, 46 (1965).
[17]D. Pelte, O. Häusser, T. K. Alexander, B. W. Hooten, and H. C. Evans, to be published.
[18]S. J. Skorka, J. Hertel, and T. W. Retz-Schmidt, Nucl. Data, Sec. A 2, 347 (1966).
[19]S. T. Lam, A. E. Litherland, and T. K. Alexander, to be published.
[20]S. Cohen, R. D. Lawson, M. H. McFarlane, S. P. Pandya, and M. Soga, Phys. Rev. 160, 903 (1967).
[21]N. Auerbach, Phys. Rev. 163, 1203 (1967).
[22]D. Cline, H. S. Gertzman, H. E. Gove, P. M. S. Lesser, and J. Schwartz, University of Rochester Report No. NSRL-15 (unpublished).
[23]P. H. Stelson and F. K. McGowan, Nucl. Phys. 32, 652 (1962).

POSSIBLE EVIDENCE FOR A QUADRUPOLE GIANT RESONANCE IN ^{16}O†

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Angular distributions for the reaction $^{16}O(\gamma,p)^{15}N$ are presented from 21 to 32.5 MeV. The asymmetry coefficients A_1 and A_3 increase to a maximum at 30 MeV and indicate a broad quadrupole state centered near 27 MeV.

Several authors[1-4] have discussed the possible existence of a giant quadrupole resonance in the nuclear photoeffect lying at a higher excitation than the dominant giant dipole state. Indeed, in some cases structure observed in photonuclear cross sections above the dipole resonance has been attributed to this effect.[5] In order to make a positive identification, however, angular distributions are needed to fix the multipolarity of the photon absorption. To date, very few such measurements have been made.[6]

The present measurement of photoproton angular distributions in ^{16}O extends the range of previous work[7,8] to well above the giant dipole resonance in order to examine the nature of the states in this region, and in particular, to search for suspected strong $E2$ absorption.

Photoproton spectra were recorded at five angles from 30° to 150°, using Si(Li) detectors 5 cm^2 in area and 4.3 mm deep. The oxygen-target gas, at a mean pressure of 934 mm Hg, was contained in a cylindrical Havar[9] cell of wall thickness 0.000 16 in. and placed in the collimated bremsstrahlung beam of the Iowa State University 70-MeV electron synchrotron. The bremsstrahlung endpoint energy was 33.1 MeV. Background from the Havar cell was determined from alternate evacuated cell runs. A measurement of the nonproton background from the target gas was made using $\Delta E\times E$ detector telescopes for particle identification. In the energy region $E_\gamma > 24$ MeV, the nonproton background subtracted was <3% at 30° and smaller than this at other angles. An energy-dependent correction was also made for charge collection losses in the detectors. The experimental apparatus and technique have been described in detail elsewhere.[10]

The background-subtracted spectra were converted to differential cross sections under the assumption of 100% ground-state transitions. Since the first excited state of ^{15}N is at 5.3 MeV, this assumption is completely justified above about 27 MeV. Below this energy the spectra contain a significant fraction (probably about 15% in the giant resonance[11,12]) of non-ground-state protons from levels above 27 MeV.

The angular distribution has been calculated as a function of energy in the form of a Legendre polynomial expansion:

$$\sigma(\theta)=A_0[1+\sum_{l=1}^{4}A_lP_l(\cos\theta)],$$

where A_0 is just the total cross section divided by 4π. The coefficients were transformed to the center-of-mass system by extending the method of Gove, Litherland, and Batchelor[13] and are shown in Fig. 1.

The continued presence of dipole radiation above the giant resonance is shown by the relative invariance of A_2, which remains close to the value expected for d-wave proton emission from a dipole state. However, the feature of the distributions we wish to emphasize in this note is the steady increase in magnitude of the asymmetry coefficients A_1 and A_3, which represent interference between states of opposite parity, to a broad maximum at about 30.5 MeV. While A_1 may result from either $E1$-$M1$ or $E1$-$E2$ interference, a nonzero value of A_3 requires $E1$-$E2$ interference; hence the most natural interpretation of the data is in terms of quadrupole excitation interfering with the tail of the giant dipole state. While not essential to the argument, it is also interesting to note the probable deviation of A_4 from zero near 30 MeV. A nonzero A_4 requires the presence of quadrupole excitation.

Unfortunately, the relationship between the interference coefficients and the $E2$ cross section responsible for these terms is extremely model dependent. However, Frederick and Sherick[10] were able to account for the magnitude of the odd coefficients observed in the reaction $C^{12}(\gamma,p)B^{11}$ by considering only one-particle, one-hole $E2$ excitations, and it is of interest to see if the same procedure will give plausible results in the present measurement. Considering only transitions to the ground state of N^{15}, and only single-particle excitation, the dominant configurations are then $(p_{1/2})^{-1}d_{3/2}$ and $(p_{1/2})^{-1}2s$ for $E1$ excitation, with $(1p_{1/2})^{-1}2p_{3/2}$ and $(1p_{1/2})^{-1}1f_{5/2}$ for $E2$ excitation, with transition amplitudes $\rho_{3/2,1}$, $\rho_{1/2,1}$, $\rho_{3/2,2}$, and $\rho_{5/2,2}$, respectively. If we assume that $\sigma_{E1}+\sigma_{E2}\approx\sigma_{E1}$, then the A_i's can be written in terms of the transition amplitudes and the phase shifts η as follows:

$$A_1=\frac{Qk}{5^{1/2}\alpha}\Big\{-6^{1/2}\rho_{3/2,2}\rho_{1/2,1}\cos(\eta_{3/2,2}-\eta_{1/2,1})+\frac{\sqrt{3}}{5}\rho_{3/2,2}\rho_{3/2,1}\cos(\eta_{3/2,2}-\eta_{3/2,1}) -(9/5)\sqrt{2}\rho_{5/2,2}\rho_{3/2,1}\cos(\eta_{5/2,2}-\eta_{3/2,1})\Big\}, \tag{1}$$

$$A_3=\frac{Qk}{5^{1/2}\alpha}\Big\{-\frac{2\sqrt{3}}{7}\rho_{5/2,2}\rho_{1/2,1}\cos(\eta_{5/2,2}-\eta_{1/2,1})-\frac{6}{5\sqrt{3}}\rho_{3/2,2}\rho_{3/2,1}\cos(\eta_{3/2,2}-\eta_{3/2,1}) +\tfrac{4}{5}\sqrt{2}\rho_{5/2,2}\rho_{3/2,1}\cos(\eta_{5/2,2}-\eta_{3/2,1})\Big\}, \tag{2}$$

and

$$A_4=\left(\frac{Qk}{5^{1/2}\alpha}\right)^2\{-(4/7)\rho_{5/2,2}^{\;2}+(8/7)(6^{1/2})\rho_{5/2,2}\rho_{3/2,2}\cos(\eta_{5/2,2}-\eta_{3/2,2})\}, \tag{3}$$

where Q is the ratio of effective electric quadrupole charge divided by the effective electric dipole charge, α^{-1} is the harmonic-oscillator range parameter, and $\hbar k$ is the photon momentum. For oxygen, $\alpha^{-1}=1.6$ F.

The $E1$ amplitudes are normalized, so that

$$\sum_{j'}\rho_{j'1}^{\;2}=\rho_{3/2,1}^{\;2}+\rho_{1/2,1}^{\;2}=1.$$

Since

$$\frac{\sigma(E1)}{\sigma(E1)}=\frac{Qk}{5^{1/2}\alpha}^2\sum_{j''}\rho_{j''2}^{\;2},$$

the simplifying assumption that $\cos(\eta_{j''\lambda''}-\eta_{j'\lambda'})\approx1$, together with Eqs. (1)-(3) and that for A_2 [cf. Eq. (18), Frederick[14]], lead to

$$\frac{\sigma(E2)}{\sigma(E1)}\approx\{[(28/5)\rho_{3/2,1}^{\;2}-2.96\rho_{1/2,1}\rho_{3/2,1}+(12/7)\rho_{1/2,1}^{\;2}]A_1^{\;2}+[6+\tfrac{3}{5}\rho_{3/2,1}^{\;2}-(6/5)\sqrt{2}\rho_{1/2,1}\rho_{3/2,1}]A_3^{\;2} +(36/5)(\rho_{3/2,1}^{\;2}-2.34\rho_{1/2,1}\rho_{3/2,1})A_1A_3\}/[6(2/7)^{1/2}-2.28A_2-9.23\rho_{3/2,1}^{\;2}].$$

The contributions of $E2$ excitations to the coefficient A_2 can be shown to have a magnitude of $\lesssim 0.03$. Since $A_2\approx-0.55$ over most of the energy region examined, the off-resonance assumption[15] that $\cos(\eta_{3/2,1}-\eta_{1/2,1})\approx1$ implies that $\rho_{3/2,1}^{\;2}\approx0.999$. As a result,

$$\frac{\sigma(E2)}{\sigma(E1)}\approx\frac{5.69A_1^{\;2}+6.65A_3^{\;2}+7.70A_1A_3}{22.9}. \tag{4}$$

The values of A_1 and A_3 shown in Fig. 1 and used in Eq. (4) yield cross-section ratios of 0.1% at 22 MeV, 1.5% at 26 MeV, and 5% at 30 MeV. The resulting $E2$ cross section, normalized to give a total $(\sigma_{E1}+\sigma_{E2})$ cross section of 8 mb at 24.3 MeV,[12] is shown in Fig. 2. The figure suggests a double-peaked behavior, with broad max-

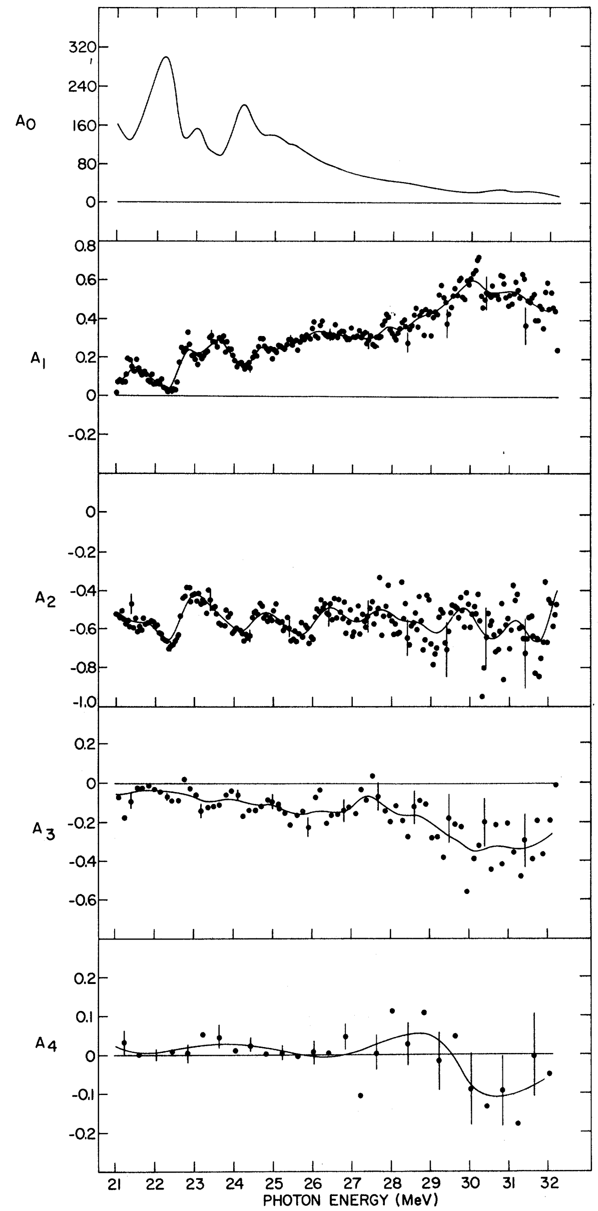

FIG. 1. The angular distribution coefficients A_1 through A_4. The total cross section (A_0) is also shown for comparison. Errors shown are statistical only. The solid lines are least-squares–smoothed fits to the data.

ima at 25.5 and 30 MeV. Despite the obvious oversimplification of assuming only one-particle, one-hole excitation and relative phase shifts of zero, it is felt that the cross section presented represents a valid reflection of nature and is not simply a result of the model used.

Although it is difficult to gauge the absolute strength of the $E2$ resonance since it may also decay through neutron and α-particle channels,

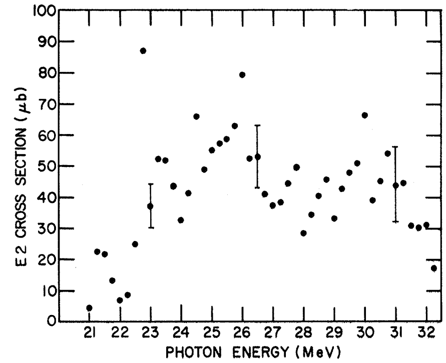

FIG. 2. The ground-state $E2$ cross section extracted from the data using Eq. (4). The errors shown reflect the statistical errors only of A_1 and A_3, with a 10% uncertainty assumed in Eq. (4) for $\sigma(E1)$.

as well as by non-ground-state proton transitions, an estimate can be made. Using the data of Fig. 2, one finds that the quadrupole strength in the ground-state proton channel alone accounts for ~13% of the Gell-Mann–Telegdi sum rule for $\Delta T = 0$ $E2$ transitions.[16] Hence we are dealing with a rather strong effect, which, when all channels are included, seems capable of accounting for a large fraction of the total $E2$ sum rule.[17] We conclude that the data appear to give direct evidence for a quadrupole giant resonance in ^{16}O.

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[1]M. Danos, W. Greiner, and C. B. Kohr, Phys. Rev. 151, 761 (1966).

[2]N. W. Tanner, Nucl. Phys. 63, 383 (1965).

[3]J. M. Eisenberg, B. M. Spicer, and M. E. Rose, Nucl. Phys. 71, 273 (1965).

[4]V. G. Shevchenko and N. Yudin, At. Energy Rev. 3, 3 (1965).

[5]R. Ligensa, W. Greiner, and M. Danos, Phys. Rev. Letters 16, 363 (1966).

[6]V. G. Shevchenko and B. A. Yur'ev, Zh. Eksperim i Teor. Fiz 43, 860 (1962) [translation: Soviet Phys. —JETP 16, 609 (1963)].

[7]E. D. Earle and N. W. Tanner, Nucl. Phys. A95, 241 (1967).

[8]R. J. J. Stewart, Australian J. Phys. 21, 107 (1968).

[9]Registered Trademark, Hamilton Watch Co., Lancaster, Pa.

[10]D. E. Frederick and A. D. Sherick, Phys. Rev. 176, 1177 (1968).

[11]J. T. Caldwell, S. C. Fultz, and R. L. Bramblett,

Phys. Rev. Letters 19, 447 (1967).

[12]R. C. Morrison, thesis, Yale University, 1965 (unpublished).

[13]H. E. Gove, A. E. Litherland, and R. Batchelor, Nucl. Phys. 26, 480 (1961).

[14]D. E. Frederick, Nucl. Phys. A101, 250 (1967).

[15]The assumption $\eta_{3/2,1}-\eta_{1/2,1}\simeq 0$ is not overly restrictive since a value as large as 75° would result in $\rho_{3/2,1}=0.98$, affecting the calculated ratio $\sigma(E2)/\sigma(E1)$ by less than 30%.

[16]M. Gell-Mann and V. L. Telegdi, Phys. Rev. 91, 169 (1953).

[17]A more complete report of this work will be published elsewhere.

EXPERIMENTAL SEARCH FOR SEMILEPTONIC NEUTRINO NEUTRAL CURRENTS*

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A search for the rare K^+ decay mode $K^+\to\pi^+\nu\bar{\nu}$ has been carried out using stopping K^+ mesons in a heavy-liquid bubble chamber. No events were found, and an upper limit on the branching ratio of this mode of 5×10^{-5} to all K^+ decays is obtained. Comparison is made with various theories which imply the existence of neutral neutrino currents.

A recurring question in the study of weak interactions is the possible existence of neutral leptonic currents. Although no theoretical model specifically predicts the absence of neutral currents, all present expermental data are consistent with the nonexistence of such currents, at least for first-order weak interactions.[1,2] However, up to the present, experimental searches for neutral-current processes have looked for decay modes of K mesons with either e^+e^- or $\mu^+\mu^-$ pairs in the final state, and the limits on these branching ratios are presently in most cases in the range 10^{-6}. No published limits exist for neutral-current modes with two neutrinos in the final state.[3]

Recently several investigations of possible mechanisms of CP nonconservation in weak interactions[4] and renormalizable theories of weak interactions[5-7] have suggested the possible existence of neutral leptonic currents coupled primarily to neutrinos

In this note we present the essential details of a search for the decay modes

$$K^+\to\pi^+\nu_\mu\bar{\nu}_\mu \text{ or } \pi^+\nu_e\bar{\nu}_e. \quad (1)$$

Examples of Reaction (1) were searched for using film from an exposure of the Argonne National Laboratory–Michigan bubble chamber to a stopping K^+ beam at the zero-gradient synchrotron.[8] The bubble chamber was filled with heavy Freon, and the magnetic field was run at 46 kG. An average of 3-4 K^+ were stopped in an appropriate fiducial volume for each picture. In this note we report on the search for decay modes (1) in a sample of 206 000 K^+ decays.

In order to separate decay mode (1) from all other K^+ decays, we make use of three characteristics of these decays: (a) detection of a stopping π^+ in the final state which is uniquely identified by the observation of a $\pi\to\mu\to e$ decay chain at the stopping point, (b) nonobservation of converted gamma rays coming from the K^+ decay point, and (c) a π^+ momentum measured by range in the bubble chamber that is different from that expected for $K_{\pi2}$ or $K_{\mu2}$ decays. Each of these characteristics is discussed below.

The unique identification of a π^+ as the charged decay product of a stopped K^+ is used to separate Reactions (1) from $K_{\mu3}$, $K_{\mu2}$, or $\mu\nu\gamma$ decays. There are a number of ways by which a stopping μ^+ track can appear to have a $\pi\to\mu\to e$ chain at the stopping point. In order to reduce the probability of such "fake π's," restrictive criteria for identification of the $\pi\to\mu\to e$ chain were used. By studying the $\pi\to\mu\to e$ chains on π^+ from τ decays, it was observed that 48% of stopping π^+ satisfy these criteria. In contrast only $\frac{3}{4}$% of μ's passed the $\pi\to\mu\to e$ chain test. It was also observed that slightly more rigid criteria for $\pi\to\mu\to e$ identification could easily reduce the $\frac{3}{4}$% by one half without changing the $\pi\to\mu\to e$ detection efficiency appreciably.

Excluding $K_{\mu2}$ and K_{e2} decays, all known decays of K^+ mesons with one charged particle in the final state result in one or more photons in the