Electroexcitation of $M4$ transitions in ^{17}O and ^{18}O

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We report the results of a study of high-resolution inelastic electron scattering from ^{17}O and ^{18}O at excitation energies between 15 and 23 MeV. Measurements were performed at 90° for momentum transfers of 1.4, 1.5, 1.7, and 1.9 fm^{-1} and at 160° for a momentum transfer of 1.7 fm^{-1}. Several prominent narrow peaks were observed in the spectra of both nuclei. The measured form factors for levels in ^{17}O at 15.78, 17.06, 20.14, and 20.70 MeV and in ^{18}O at 18.70, 20.36, and 22.39 MeV are, within experimental uncertainties, completely transverse. These strongly excited states are assumed to arise from isovector $M4$ transitions of the type $1p_{3/2}\rightarrow 1d_{5/2}$. A simple weak-coupling model is used to assign spins to the levels in ^{17}O. Finally, we also report measurements for several narrow states in both nuclei, for which the spins and parities have not yet been identified.

I. INTRODUCTION

"Stretched" high-spin states have received considerable attention in recent years because their one-body structure is simple. Isovector 4^- levels excited by $M4$ transitions that promote a single nucleon from the $1p_{3/2}$ orbital into the $1d_{5/2}$ orbital are known to exist in ^{12}C at 19.56 MeV and in ^{16}O at 18.98 MeV.[1] Several $M4$ excitations of similar structure have been studied in other p-shell nuclei.[2] Perhaps the clearest examples have been found in ^{14}C (Ref. 3) and ^{14}N (Ref. 4). The present work has uncovered evidence for $M4$ transitions in the lightest $(2s,1d)$-shell nuclei, ^{17}O and ^{18}O.

A recent analysis[5] of inelastic electron scattering from ^{16}O revealed that the isovector 4^- state at 18.98 MeV is very strongly excited between momentum transfers (q) of 1 and 2 fm^{-1}. Two previously established isoscalar 4^- states at 17.79 and 19.80 MeV are excited only weakly by electrons. These three stretched 4^- states must consist, to lowest order in $\hbar\omega$, of the single-particle, single-hole configuration $(1d_{5/2},1p_{3/2}^{-1})_{4^-}$. Evidence that these states have large multiparticle, multihole components includes the facts that at least two predominantly isoscalar 4^- states exist in ^{16}O and that their transition strengths are considerably less than expected for pure single-particle, single-hole configurations.[5] These states are, nonetheless, ideal for study by one-body nuclear probes, since cross sections for such diverse reactions as (e,e′), (π,π'), and (p,p′) depend upon the same magnetization density.

We have performed inelastic electron scattering from ^{17}O and ^{18}O at excitation energies (E_x) between 15 and 23 MeV. Form factors were measured at 90° for incident electron energies of 248 and 269 MeV ($q=1.7$ and 1.9 fm^{-1}) and at 160° for an incident energy of 179 MeV ($q=1.7$ fm^{-1}). Form factors for levels below 16 MeV were also measured at 90° for incident energies of 194 and 209 MeV ($q=1.4$ and 1.5 fm^{-1}).

Cognizant of the (e,e′) results for ^{16}O, we examined the prominent peaks near 20 MeV in the electroexcitation spectra of ^{17}O and ^{18}O that could arise from isovector $M4$ transitions of the type $1p_{3/2}\rightarrow 1d_{5/2}$. ^{17}O has a $J^\pi=\frac{5}{2}^+$ ground state, so that $M4$ strength in this nucleus can be distributed over $T=\frac{1}{2}$ and $\frac{3}{2}$ states with $J^\pi=\frac{3}{2}^-$ to $\frac{13}{2}^-$. The ground state of ^{18}O has $J^\pi=0^+$ and $T=1$; thus, $M4$ strength in ^{18}O can be distributed over $T=1$ and 2 states with $J^\pi=4^-$. In addition to having excitation energies in the expected range, experimental candidates for these states should satisfy two criteria: (1) they should have completely transverse form factors (or nearly so, in the case of ^{17}O), and (2) they should have form factors with shapes characteristic of a $1p_{3/2}\rightarrow 1d_{5/2}$ $M4$ transition. Finally, the $T_>$ states ($T=\frac{3}{2}$ in ^{17}O, $T=2$ in ^{18}O) should have relatively narrow intrinsic widths because of the limited number of possible hadronic decay channels. This property is necessary for the unambiguous identification of these states, since the level density of broad states is high in the energy range of interest.

Prominent narrow peaks were observed in ^{17}O at 15.78, 17.06, 20.14, and 20.70 MeV and in ^{18}O at 18.70, 20.36, and 22.39 MeV. Measurements at 90° and 160° for the same momentum transfer, $q=1.7$ fm^{-1}, confirmed that the form factors for these levels are transverse, within experimental uncertainties. The measured form factors are consistent with the assumption that these levels are excited primarily by $M4$ transitions; however, additional data are necessary to confirm this multipolarity assignment. The three peaks in ^{18}O are candidates for 4^- states, whereas the four peaks in ^{17}O are candidates, respectively, for $\frac{9}{2}^-$, $\frac{7}{2}^-$, $\frac{13}{2}^-$, and $\frac{11}{2}^-$ states, based upon calculations from a simple weak-coupling model.

II. EXPERIMENTAL DETAILS

The experiment was performed at the MIT-Bates Linear Accelerator using the high-resolution energy-loss spectrometer facility.[6] Measurements were made at 90° for incident electron energies of 194.3, 209.2, 248.4, and 268.8 MeV, which correspond to momentum transfers of approximately 1.4, 1.5, 1.7, and 1.9 fm^{-1}, respectively. The energy resolution for these measurements ranged from 20 to 30 keV. Measurements also were made at 159.8° for an incident energy of 179.5 MeV, which corresponds to a momentum transfer of about 1.7 fm^{-1}. These backward-angle measurements were performed with targets mounted in reflection geometry and had a somewhat poorer energy resolution of about 70 keV. Form factors were not measured under these conditions for all levels between 15 and 23 MeV because our primary objective was to study the mass-16, -17, and -18 isotopes of oxygen at excitation energies below about 10 MeV. Some results of these measurements already have been published.[7]

A single ^{17}O target, which consisted of an isotopically enriched BeO foil, was used for all measurements of electron scattering from ^{17}O. Its average thickness was 29.1 mg/cm^2. Isotopic abundances relative to ^{9}Be were accurately determined[7] to be 84.4% ^{17}O, 11.6% ^{16}O, and 4.0% ^{18}O. This target also contained ^{12}C and ^{14}N impurities with absolute abundances of about 3.5% and 1.0%, respectively. Two ^{18}O targets were used, which were also isotopically enriched BeO foils. The primary target had a thickness of 47.3 mg/cm^2 and had isotopic abundances relative to ^{9}Be of 90.8% ^{18}O, 7.2% ^{16}O, and 2.0% ^{17}O. The secondary target was used only for the measurement at 268.8 MeV. Its thickness was 21.6 mg/cm^2 and its isotopic abundances relative to ^{9}Be were 46.7% ^{18}O, 52.3% ^{16}O, and 1.0% ^{17}O. All three targets were manufactured at Lawrence Livermore National Laboratory (LLNL).[8] Inelastic electron-scattering measurements also were performed under the same kinematic conditions for target foils of pure ^{9}Be metal and of ^{9}Be^{16}O, which contained naturally occurring oxygen. Normalization of the ^{17}O and ^{18}O data was performed relative to the elastic cross sections for ^{16}O and ^{18}O and to the ^{9}Be cross sections measured with the ^{9}Be and ^{9}Be^{16}O targets.

III. DATA ANALYSIS

The differential cross section for electron scattering in the plane-wave Born approximation (PWBA) is given by[9]

$$\frac{d\sigma}{d\Omega}=Z^2\sigma_{\text{Mott}}\eta\left[\frac{q_\mu^4}{q^4}\,|F_L(q^2)|^2+\left[\frac{-q_\mu^2}{2q^2}+\tan^2\theta/2\right]|F_T(q^2)|^2\right], \tag{1}$$

where Z is the atomic number of the target nucleus,

$$\sigma_{\text{Mott}}=(\alpha/2E_0)^2(\cos^2\theta/2)/(\sin^4\theta/2) \tag{2}$$

is the Mott cross section for scattering from a unit point charge, α is the fine-structure constant, E_0 is the incident electron energy, θ is the scattering angle,

$$\eta=[1+2(E_0/M)\sin^2\theta/2]^{-1} \tag{3}$$

is the recoil factor, M is the mass of the target nucleus, $q_\mu^2=\omega^2-q^2$ is the square of the four-momentum transfer, ω is the energy loss of the scattered electron and hence the energy to which the target nucleus is excited, q is the three-momentum transfer, $F_L(q^2)$ is the longitudinal (or Coulomb) form factor, and $F_T(q^2)$ is the transverse form factor. The square of the total form factor, $|F(q^2,\theta)|^2$, is given by the quantity in large square brackets in Eq. (1).

To account for distortion of the electron waves by the Coulomb field of the target nucleus, we substituted the momentum transfer q with the effective momentum transfer q_{eff} given by

$$q_{\text{eff}}=q[1-V_C(r_e)/E_0], \tag{4}$$

where $V_C(r_e)$ is the Coulomb field observed by the electron at distance $r_e=1/q$ from the target nucleus. We approximated $V_c(r_e)$ by the field of a uniformly charged sphere of radius R:

$$\frac{-V_C(r_e)}{Z\alpha}=\begin{cases}3/(2R)-r_e^2/(2R^3), & r_e<R\\ 1/r_e, & r_e>R\end{cases} \tag{5}$$

where $R=\sqrt{5/3}(1.2A^{1/3})$.

The measured spectra for scattered electrons were fitted with the general line-shape-fitting routine ALLFIT (Ref. 10) developed at MIT and modified to run on a Cray X-MP computer at the National Magnetic Fusion Energy Computer Center at LLNL. Since a recent version of this code has been described by Buti *et al.*,[11] only its salient features will be discussed here. The spectrum to be fitted is described by a sum of peak-shape functions and a background term. The peak-shape function is a convolution of three terms: (1) an experimental resolution function, which was parameterized empirically by a hyper-Gaussian distribution with exponential tails; (2) an intrinsic line-shape function, which was parameterized by a Lorentzian distribution; and (3) a radiative response function, which was calculated according to the prescription of Mo and Tsai,[12] as implemented by Bergstrom[13] and Creswell.[14] The intrinsic line shape was described by a delta-function distribution for peaks with intrinsic widths less than about 10 keV. Parameters defining the empirical resolution function were determined simultaneously by fitting all peaks associated with a particular isotope in a given spectrum. Typically, a single resolution function was used for all oxygen isotopes and a different resolution function was used for the ^{9}Be peaks. The background term was taken to be a piecewise-continuous polynomial, which could have a discontinuous increase in slope at the threshold of a major hadronic decay channel. In this work, such a discontinuity was allowed for the neutron-decay threshold of ^{9}Be at 1.665 MeV.

Our fitting procedure was the method of maximum likelihood implemented for Poisson statistics. This method recognizes the fact that Poisson statistics, rather than Gaussian, are appropriate for describing data from counting experiments. The parameter space was searched for a best fit by a standard gradient-search technique based upon the algorithm CURFIT.[15] In each fit, the energy scale was calibrated using three reference peaks of known excitation energies. The reference peaks for this work usually were chosen from states in ^{16}O and always included the 4^- state at 18.98 MeV. Up to 75 peaks were included in fitting a single spectrum.

Some of the constraints imposed in fitting the spectra made use of our prior knowledge[1,16] of excitation energies and intrinsic widths for many of the levels. In such cases, widths and relative energy spacings of groups of peaks were held constant in the parameter search. Since many peaks resulted from target contaminants such as ^{16}O and ^{9}Be, relative cross sections for those levels were constrained by first fitting spectra for ^{9}Be and ^{9}Be^{16}O targets measured under the same kinematic conditions. The usual procedure was as follows. First, the ^{9}Be spectrum measured with the ^{9}Be target was fitted. Then, the ^{16}O spectrum measured with the ^{9}Be^{16}O target was fitted with constraints imposed to reproduce (up to an overall normalization factor) the major spectrum of ^{9}Be minus its background term. Since ^{17}O was almost negligible in the ^{18}O targets, we next fitted the ^{18}O spectrum with similar constraints imposed to reproduce contributions from both ^{9}Be and ^{16}O contaminants. Finally, we fitted the ^{17}O spectrum with constraints imposed for all three major contaminants, ^{9}Be, ^{16}O, and ^{18}O. In Fig. 1 we show a fitted ^{9}Be spectrum measured at $\theta=159.8°$ and $E_0=179.5$ MeV. For clarity, contributions of individual peaks and the background have been suppressed to show only the overall fit. Four sharp peaks, all of which probably are associated with $T=\frac{3}{2}$ levels, stand out from a complex background composed of several overlapping broad peaks. The corresponding fitted ^{17}O and ^{18}O spectra are shown in Fig. 2. In Fig. 3 we show comparative spectra measured for ^{16}O, ^{17}O, and ^{18}O at $\theta=90.0°$ and $E_0=248.4$ MeV. Prominent sharp peaks in Figs. 1—3 have been labeled by their excitation energies.

IV. RESULTS

A. Levels in ^{17}O

A total of six narrow peaks ($\Gamma \leq 100$ keV) are clearly observable in our electroexcitation spectra for ^{17}O between 15 and 23 MeV. The measured excitation energies and widths of these levels are presented in Table I. There also are indications of weakly excited narrow states ($\Gamma \leq 20$ keV) at 16.50 ± 0.02 and 18.83 ± 0.02 MeV and of a broad state ($\Gamma=530\pm150$ keV) at 19.85 ± 0.04 MeV. The present measurements are the first observations of all but two of these levels. The sharp levels recently observed by Blilie et al.[17] in the ^{17}O$(\pi^{\pm},\pi^{\pm\prime})^{17}$O* reactions at 15.7 and 17.1 MeV probably correspond to the states we observe at 15.78 and 17.06 MeV. The strongest level excited by electron scattering is at 20.14 MeV. This level was not

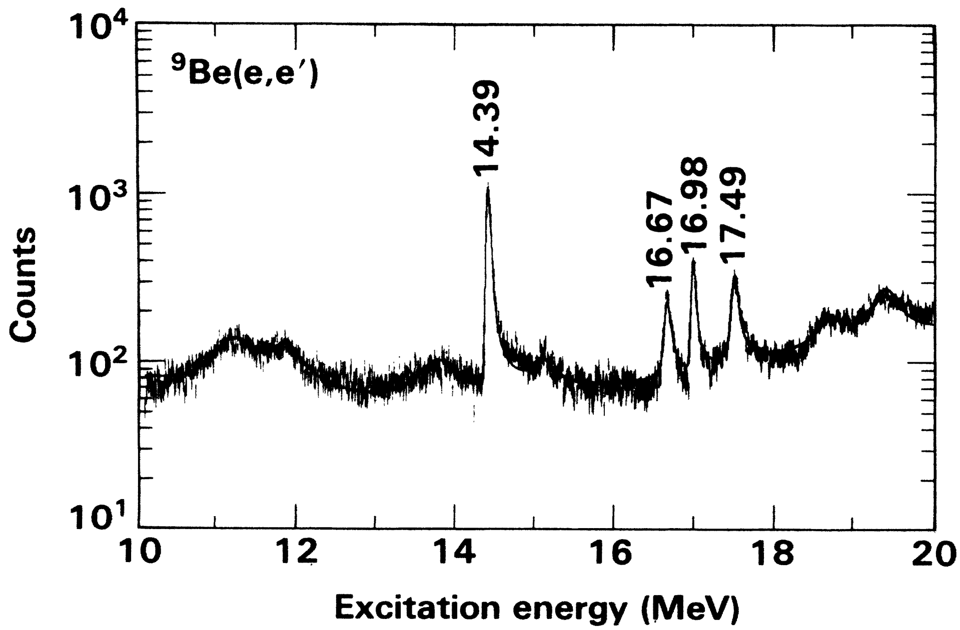

FIG. 1. Electron spectrum for ^{9}Be measured at $\theta=159.8°$ and $E_0=179.5$ MeV. The $\frac{3}{2}^-$ and $\frac{1}{2}^-$ states at 14.39 and 16.98 MeV, respectively, are both isovector excitations with $T=\frac{3}{2}$. The narrow levels at 16.67 and 17.49 MeV probably are $\frac{1}{2}^+$ and $\frac{5}{2}^+$ states, respectively, which also have $T=\frac{3}{2}$.

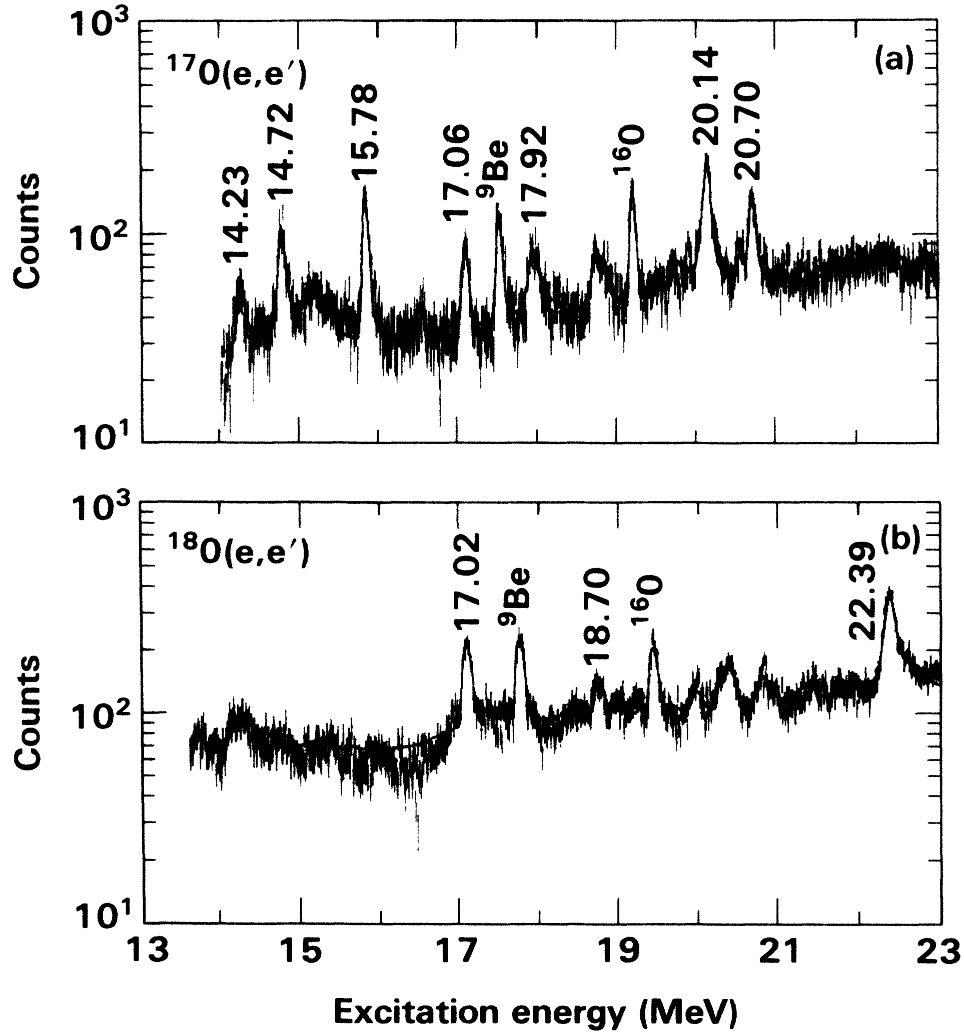

FIG. 2. Electron spectra for (a) ^{17}O and (b) ^{18}O measured at $\theta=159.8°$ and $E_0=179.5$ MeV. The peaks labeled ^{9}Be and ^{16}O refer, respectively, to the $\frac{3}{2}^-$ state in ^{9}Be at 14.39 MeV and the 4^- state in ^{16}O at 18.98 MeV.

observed in the pion-scattering experiment,[17] although it seems possible from inspecting the π^+ spectrum in Fig. 2 of Ref. 17 that this level was obscured by its proximity to the 4^- state in ^{16}O at 19.08 MeV, which is strongly excited by pions but weakly excited by electrons. It is interesting that our measurements reveal no obvious structure in the electroexcitation spectrum of ^{17}O between 21 and 23.5 MeV, the highest excitation energy to which our measurements extend.

Measured form factors for each of the six clearly observed levels are listed in Table II. The notation used here is the same as that used by Norum *et al.*[7] and the quoted error limits include both systematic and statistical uncertainties. It is possible to perform a Rosenbluth separation of the longitudinal and transverse form factors at $q=1.7$ fm^{-1}, since measurements were performed at this value of momentum transfer at two different angles. If the form factor were completely transverse, then our measurements at 90° and 160° should satisfy

$$\frac{|F|^2(\theta=160°)}{|F|^2(\theta=90°)} \simeq \frac{1+2\tan^2(80°)}{1+2\tan^2(45°)} \simeq 21.8 \ . \tag{6}$$

From Table II we see that this condition is satisfied, within experimental uncertainties, for the four levels at 15.78, 17.06, 20.14, and 20.70 MeV. We therefore tentatively conclude that these levels are excited primarily by $M4$ transitions from the ground state. If we consider the weak-coupling multiplet, $[1d_{5/2}\otimes{}^{16}\text{O}(18.98)4^-]$, then the form factors of these "hexadecapole states" with $J^\pi=\frac{3}{2}^-,\frac{5}{2}^-,\ldots,\frac{13}{2}^-$ should satisfy

$$|F[^{17}\text{O}(J^\pi)]|^2 = \frac{2J+1}{54}\,\frac{2T+1}{6}\,|F[^{16}\text{O}(4^-)]|^2 \ , \tag{7}$$

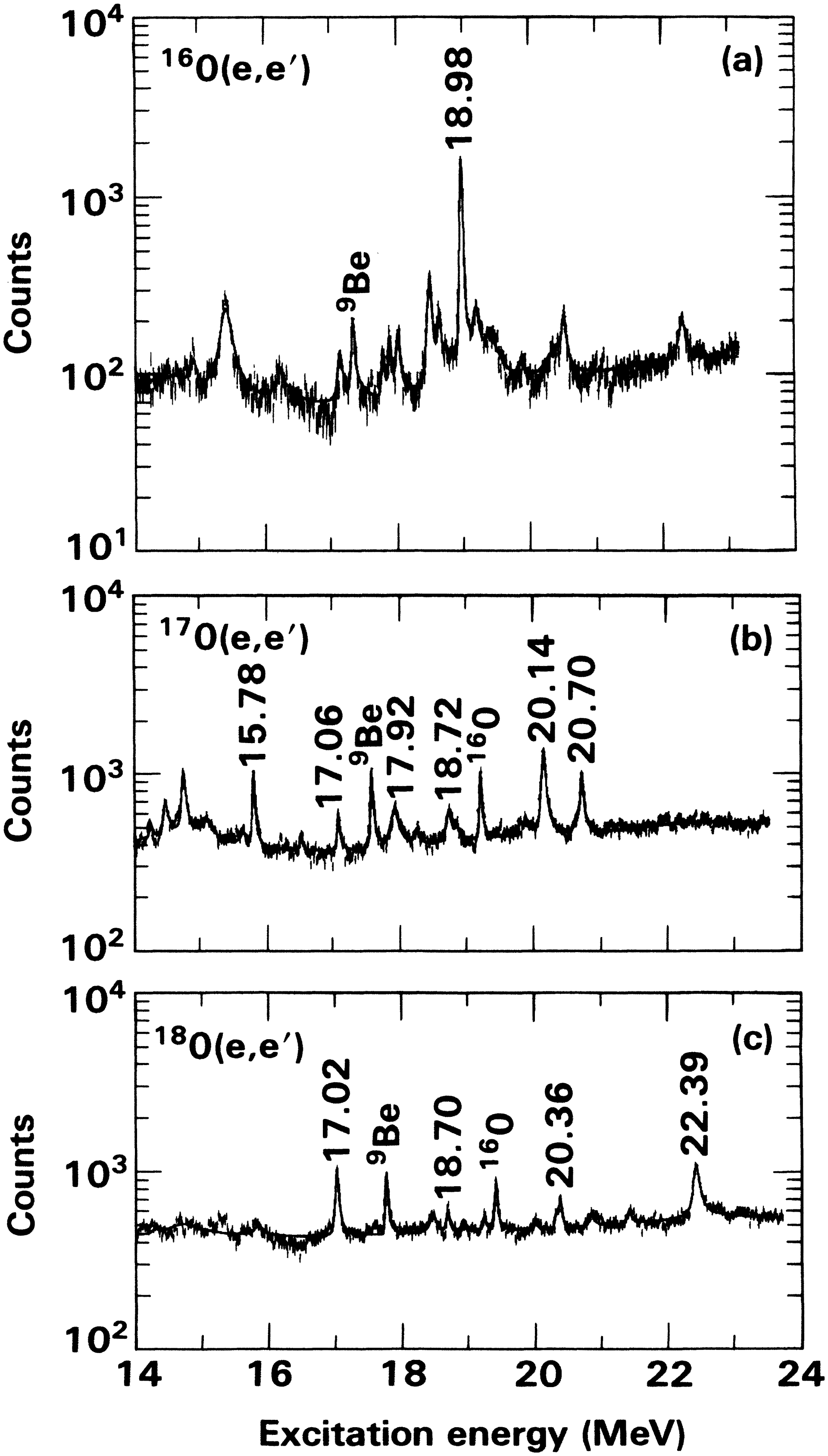

FIG. 3. Electron spectra for (a) ^{16}O, (b) ^{17}O, and (c) ^{18}O measured at $\theta=90.0°$ and $E_0=248.4$ MeV. The peaks labeled ^{9}Be and ^{16}O refer, respectively, to the $\frac{3}{2}^-$ state in ^{9}Be at 14.39 MeV and the 4^- state in ^{16}O at 18.98 MeV.

TABLE I. Levels in ^{17}O between 15 and 23 MeV excited by electron scattering.

E_x (MeV)	Γ (keV)
15.78±0.02	<30
17.06±0.02	<20
17.92±0.02	98±16
18.72±0.02	87±33
20.14±0.02	31±5
20.70±0.02	<20

TABLE III. Reduced transitions probabilities and inferred J^π and T assignments for levels in ^{17}O. The measured values were obtained assuming an oscillator constant $b=1.58$ fm. The calculated values are based upon $B(M4\uparrow)=1513\pm76\ e^2\,\text{fm}^8$ for the 4^- state in ^{16}O at 18.98 MeV (see text).

	$B(M4\uparrow)$ ($e^2\text{fm}^8$)		
E_x (MeV)	Measured	Calculated	$J^\pi;T$
15.78	177±17	187±9	$\frac{9}{2}^-;\frac{3}{2}$
17.06	76±6	149±8	$\frac{7}{2}^-;\frac{3}{2}$
20.14	349±18	392±20	$\frac{13}{2}^-;\frac{1}{2}$
20.70	177±10	224±11	$\frac{11}{2}^-;\frac{3}{2}$

where ^{16}O(4^-) refers to the isovector 4^- state in ^{16}O at 18.98 MeV. This model is undoubtedly too naive because the $M4$ strength is probably distributed over many more states than this simple model predicts. For example, if we consider states arising from two-particle, one-hole (2p-1h) configurations of the type $[(1d_{5/2})^2\otimes(1p_{3/2})^{-1}]$, then we obtain the following levels that can share the total $M4$ strength (the superscripts indicate the number of allowed levels for a given J^π):

$$T=\tfrac{1}{2}:\ (\tfrac{3}{2}^-)^4,\ (\tfrac{5}{2}^-)^4,\ (\tfrac{7}{2}^-)^4,\ (\tfrac{9}{2}^-)^3,\ (\tfrac{11}{2}^-)^2,\ (\tfrac{13}{2}^-)^1\ ,$$

$$T=\tfrac{3}{2}:\ (\tfrac{3}{2}^-)^2,\ (\tfrac{5}{2}^-)^2,\ (\tfrac{7}{2}^-)^2,\ (\tfrac{9}{2}^-)^1,\ (\tfrac{11}{2}^-)^1\ .$$

Since a $\frac{13}{2}^-$ level with $T=\frac{3}{2}$ is not allowed, we replace the isospin factor in Eq. (7) by unity for $J^\pi=\frac{13}{2}^-$. Equation (7) is expected to give reasonable predictions for the $\frac{9}{2}^-$ and $\frac{11}{2}^-$ levels with $T=\frac{3}{2}$, since these states are unique within the 2p-1h configurations described above. It should be noted, however, that the total wave functions for these states probably contain large multiparticle-multihole components, as do the 4^- states in ^{16}O.[5]

TABLE II. Form factors measured for levels in ^{17}O between 15 and 23 MeV.

E_x (MeV)	E_0 (MeV)	θ (deg)	q_{eff} (fm^{-1})	$\lvert F\rvert^2$	Uncertainty (%)
15.78	194.3	90.0	1.36	5.83(−5)	35
15.78	209.2	90.0	1.46	5.83(−5)	13
15.78	248.4	90.0	1.74	1.08(−4)	11
15.78	268.8	90.0	1.89	9.49(−5)	8
15.78	179.5	159.8	1.74	2.57(−3)	8
17.06	248.4	90.0	1.74	3.82(−5)	12
17.06	268.8	90.0	1.88	3.95(−5)	12
17.06	179.5	159.8	1.73	1.06(−3)	12
17.92	248.4	90.0	1.73	1.26(−4)	12
17.92	268.8	90.0	1.88	1.03(−4)	9
17.92	179.5	159.8	1.73	1.76(−3)	12
18.72	248.4	90.0	1.73	5.64(−5)	16
18.72	268.8	90.0	1.88	5.25(−5)	15
18.72	179.5	159.8	1.72	6.30(−4)	20
20.14	248.4	90.0	1.73	2.21(−4)	11
20.14	268.8	90.0	1.87	1.76(−4)	7
20.14	179.5	159.8	1.71	4.17(−3)	11
20.70	248.4	90.0	1.72	1.06(−4)	11
20.70	268.8	90.0	1.87	9.54(−5)	8
20.70	179.5	159.8	1.71	1.90(−3)	12

We fitted the experimental form factors for the levels at 15.78, 17.06, 20.14, and 20.70 MeV with the $M4$ form factors derived from harmonic-oscillator wave functions,

$$F_T(q)\propto f_{\text{c.m.}}(q)f_{\text{N}}(q)(qb)^4\exp[-(qb/2)^2)]\ , \tag{8}$$

where $f_{\text{c.m.}}(q)=\exp[(qb/2)^2/A]$ is the center-of-mass form factor, $f_{\text{N}}(q)=(1+q^2/\Lambda^2)^{-2}$ is the single-nucleon form factor, $b=1.58$ fm is the harmonic-oscillator constant, and $\Lambda=4.33\ \text{fm}^{-1}$. The value of the oscillator constant was determined by fitting form-factor measurements[5] for the isovector 4^- level in ^{16}O at 18.98 MeV. The reduced transition probability determined by this fit was $B(M4\uparrow)=1513\pm76\ e^2\,\text{fm}^8$. In Fig. 4 we show the fitted transverse form factors for the 18.98-MeV level in ^{16}O and the 15.78-MeV level in ^{17}O. Although the momentum-transfer dependence of this ^{17}O form factor was not well measured, it is consistent with the shape that characterizes a $1p_{3/2}\rightarrow 1d_{5/2}$ $M4$ transition.

In Table III we summarize the reduced transition probabilities obtained from single-parameter fits of the four levels in ^{17}O that have transverse form factors. Specifically, the $B(M4\uparrow)$ values were obtained by scaling the harmonic-oscillator form factor [Eq. (8)] to fit the available data. The oscillator constant was assumed to have the same value (1.58 fm) as determined for ^{16}O. Similar values describe $M4$ transitions in several p-shell nuclei; these values all lie within ±5% of the value we have asumed here.[18] If additional measurements were to require a 5% change in the oscillator constant, the extracted $B(M4\uparrow)$ values could change by as much as 40%.

To make comparisons with the predictions of the weak-coupling model [Eq. (7)], we assume that the observed levels correspond to the states that are expected to have the largest fractions of $M4$ strength: $\frac{13}{2}^-$ $(T=\frac{1}{2})$, $\frac{11}{2}^-$ $(T=\frac{3}{2})$, $\frac{9}{2}^-$ $(T=\frac{3}{2})$, and $\frac{7}{2}^-$ $(T=\frac{3}{2})$. Our inferred J^π and T assignments, based upon this comparison, are summarized in Table III as well. Of the four levels, only the one at 20.14 MeV has sufficient strength to correspond to the predicted $\frac{13}{2}^-$ state. The agreement be-

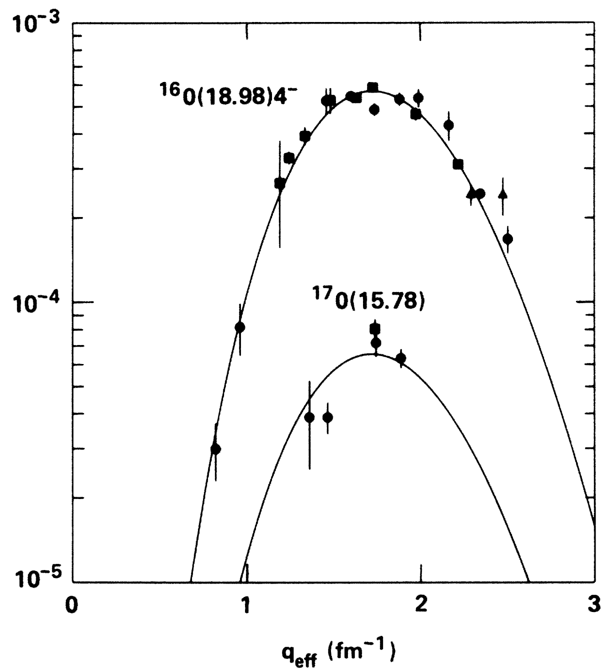

FIG. 4. Transverse form factors for the isovector 4^- state in ^{16}O at 18.98 MeV and the state in ^{17}O at 15.78 MeV. Measurements at 90°, 140°, and 160° are indicated by solid circles, triangles, and squares, respectively. The fitted curves are $M4$ form factors derived from harmonic-oscillator wave functions with the oscillator constant $b = 1.58$ fm. The measured values for the 4^- state in ^{16}O were taken from Ref. 5.

tween calculation and measurement is quite good for this state. Either of the two levels at 15.78 and 20.70 MeV could correspond to the predicted $T=\frac{3}{2}$ states with $J^{\pi}=\frac{9}{2}^-$ and $\frac{11}{2}^-$. We have assigned, somewhat arbitrarily, the higher spin to the state at higher energy. Finally, we assume the $\frac{7}{2}^-$ state to be the level at 17.06 MeV. The measured $B(M4\uparrow)$ is about half of the calculated value, which is not surprising, since two $\frac{7}{2}^-$ states with $T=\frac{3}{2}$ are expected from the 2p-1h configurations considered above. (Part of this strength may be shared by the first $\frac{7}{2}^-$ level with $T=\frac{3}{2}$ at 14.23 MeV, which is shown in Fig. 2.)

It is of interest to note that the levels assigned as $T=\frac{3}{2}$ states have narrower intrinsic widths than the level at 20.16 MeV assigned as a $T=\frac{1}{2}$ state. The even larger widths measured for the levels at 17.92 and 18.72 MeV suggest that these too are $T=\frac{1}{2}$ states. If indeed the three levels at 15.78, 17.06, and 20.70 MeV are $T=\frac{3}{2}$ states, then they should have analogs in ^{17}N at about 4.7, 6.0, and 9.6 MeV. Unfortunately, no correspondence with known levels in ^{17}N can be made at present because the spectrum of that nucleus is known only poorly[1] above about 3 or 4 MeV.

Although there have been shell-model calculations[17,19] for certain $T=\frac{3}{2}$ levels in $A=17$ nuclei, the validity of these models for describing the states we observe is questionable. For example, the $1p_{3/2}$ orbital is not active in the calculations of Reehal and Wildenthal,[19] so that their wave functions do not allow $M4$ transitions. Millener's calculations,[20] which use a complete, nonspurious $1\hbar\omega$ basis, do allow $M4$ transitions, but overestimate their transition strengths. This probably results because his wave functions exclude the multiparticle-multihole components that we expect to be important for these states.

B. Levels in ^{18}O

We clearly observe six narrow peaks between excitation energies of 15 and 23 MeV in our electroexcitation spectra for ^{18}O. The measured energies and widths of these levels are given in Table IV. There are some indications of weakly excited states at 18.48 ± 0.02 MeV ($\Gamma=90\pm34$ keV) and 21.43 ± 0.02 MeV ($\Gamma=49\pm37$ keV). The counting statistics for these states were too low to determine whether these were isolated peaks. There also are indications of a broad structure ($\Gamma=680\pm250$ keV) at 17.35 ± 0.06 MeV in the spectrum measured at 160°.

The levels we clearly observe at 16.42, 17.02, 18.70, 19.24, and 20.36 MeV presumably are $T=2$ states since they have widths of 20 keV or less. The strongly excited state at 22.39 MeV has a width of 74 ± 7 keV, which is more typical of a $T=1$ state. The states we observe at 16.42 and 17.02 MeV are probably the same levels as those at 16.40 ± 0.03 and 17.02 ± 0.03 MeV reported in an early inelastic proton-scattering experiment.[21] In a high-resolution, low-momentum-transfer ($q\leq0.5$ fm^{-1}) investigation[22] of the $^{18}O(e,e')^{18}O^*$ reaction at excitation energies above 15 MeV, two sharp states were observed, at 16.399 ± 0.005 and 18.871 ± 0.005 MeV, which were identified as 2^- and 1^+ states, respectively. The 16.40-MeV level is probably the one we observe at 16.42 MeV. A low-spin assignment is consistent with the present measurements, since it was not observed in spectra in which momentum transfers were greater than 1.4 fm^{-1}. We did not observe the state at 18.87 MeV, presumably for the same reason.

The measured form factors for the six levels that we observe clearly in ^{18}O are listed in Table V. A Rosenbluth separation was performed at $q=1.7$ fm^{-1} for all levels except the one at 16.42 MeV, which was observed in only one spectrum. Our measurements for the levels at 17.02 and 19.24 MeV suggest sizeable longitudinal form factors, which in turn imply that these levels have natural parity.

TABLE IV. Levels in ^{18}O between 15 and 23 MeV excited by electron scattering.

E_x (MeV)	Γ (keV)
16.42 ± 0.02	<20
17.02 ± 0.02	20 ± 6
18.70 ± 0.02	<20
19.24 ± 0.02	<20
20.36 ± 0.02	<20
22.39 ± 0.04	74 ± 7

TABLE V. Form factors measured for levels in ^{18}O between 15 and 23 MeV.

E_x (MeV)	E_0 (MeV)	θ (deg)	$q_{\rm eff}$ (fm^{-1})	$\|F\|^2$	Uncertainty (%)
16.42	194.3	90.0	1.36	8.82(−5)	17
17.02	248.4	90.0	1.74	1.39(−4)	13
17.02	268.8	90.0	1.88	6.59(−5)	22
17.02	179.5	159.8	1.73	1.75(−3)	11
18.70	248.4	90.0	1.73	3.09(−5)	55
18.70	268.8	90.0	1.88	3.38(−5)	36
18.70	179.5	159.8	1.72	7.35(−4)	13
19.24	248.4	90.0	1.73	1.61(−5)	20
19.24	179.5	159.8	1.72	1.13(−4)	42
20.36	248.4	90.0	1.73	3.81(−5)	15
20.36	179.5	159.8	1.71	7.59(−4)	13
22.39	248.4	90.0	1.72	2.22(−4)	13
22.39	268.8	90.0	1.86	1.99(−4)	17
22.39	179.5	159.8	1.70	4.86(−3)	13

Since their form factors are substantial at relatively large momentum transfers, they probably have $J>2$. These are possibly the 3^- states expected to arise by the weak coupling of a $p_{3/2}$ hole to the $\frac{5}{2}^+$ (g.s.) and $\frac{3}{2}^+$ (0.096 MeV) levels in ^{19}O. More complete measurements of their form factors are necessary to support this hypothesis. The measured data for the levels at 18.70, 20.36, and 22.39 MeV are consistent with a completely transverse form factor. If this were the case, then these would be likely candidates for 4^- states. The $B(M4\uparrow)$ values that result from fitting form factors for these states with $b=1.58$ fm [cf. Eq. (5)] are 63 ± 8, 66 ± 6, and 400 ± 32 $e^2 fm^8$, respectively. Thus, these levels account for only about a third of the $M4$ strength in the isovector 4^- state in ^{16}O. It is interesting to speculate as to whether or not the missing $M4$ strength might lie in 4^- states at slightly higher excitation energies than were measured in the present work. Additional measurements would be desirable to test this hypothesis as well.

If the five levels in ^{18}O at 16.42, 17.02, 18.70, 19.24, and 20.36 MeV are truly $T=2$ states, then there should be analog states in ^{18}N at about 0.1, 0.7, 2.4, 2.9, and 4.0 MeV. Shell-model calculations[23] for $T=2$ levels in $A=18$ nuclei have been limited to excitation energies below 1 MeV. Little is known experimentally about the spectrum of ^{18}N. Its ground state is known[23] to be a 1^- state and excited states have been observed at 0.12, 0.58, 0.75, 2.21, and 2.42 MeV in the $^{18}O(^7Li,^7Be)^{18}N$ reaction.[24] A few low-lying levels also have been suggested from prior studies[22,25] of analog levels in ^{18}O. Except for the cases discussed already, no correspondence can be made with levels observed in the present experiment, since previous works[22,25] were limited to the low-momentum-transfer region, where only states with small spins ($J\leq2$) can be seen clearly.

V. CONCLUSIONS

We have performed measurements of inelastic electron scattering from ^{17}O and ^{18}O for excitation energies between 15 and 23 MeV. These are the first high-resolution measurements for these nuclei in this excitation region at momentum transfers above 1 fm^{-1}. The form factors for several strongly excited levels in both nuclei were measured to be completely transverse, within experimental uncertainties. We describe the excitation of these levels from their respective ground states in terms of isovector $M4$ transitions. From comparisons with ^{16}O, such transitions are expected to be important at the momentum transfers and excitation energies of this work. The levels we have discussed are the first indications of $M4$ transitions in the lightest $(2s,1d)$-shell nuclei.

Our measurements should also furnish information regarding the level structures of ^{17}N and ^{18}N since the levels we observe in ^{17}O at 15.78, 17.06, and 20.70 MeV are presumed to be $T=\frac{3}{2}$ states, whereas the levels we observe in ^{18}O at 16.42, 17.02, 18.70, 19.24, and 20.36 MeV are presumed to be $T=2$ states. These tentative isospin assignments are based upon the narrow (≤20 keV) widths measured for these states. Additional studies of these states with isospin-sensitive probes are necessary to confirm these isospin assignments.

The arguments that we have presented to make spin and parity assignments for several narrow levels in ^{17}O and ^{18}O have been based upon a limited number of form-factor measurements between momentum transfers of 1.4 and 1.9 fm^{-1}. To make these assignments conclusive, it would be very desirable to perform a more ambitious experiment to measure the momentum-transfer dependence of these form factors more fully. This proposed experiment also should explore higher excitation energies in ^{18}O than the present work, since about two-thirds of the expected $M4$ strength in that nucleus is unaccounted for below 23 MeV. We hope as well that this work will stimulate theorists to perform more realistic shell-model calculations for the highly excited states in $A=17$ and 18 nuclei than have been available hitherto.

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