Inelastic electron scattering from ^{18}O at backward angles

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Discrete states in ^{18}O up to 25 MeV of excitation were studied by inelastic electron scattering. The measurements were performed at the Bates Linear Accelerator Center at 110° and 140°, and at momentum transfers ranging from about 1.2 to 2.5 fm^{-1}. A number of the states discussed here have not been observed previously. Form-factor measurements are presented for eight 4^- candidates and for two 6^- candidates. The strongest 4^- state has $T = 2$ and was observed at 22.40 MeV. Good $T = 2$ 4^- candidates were found at 18.68 and 20.36 MeV, and good $T = 1$ 4^- candidates were found at 8.52 and 12.99 MeV; the strongest 6^- candidate was found at 14.17 MeV. Form-factor measurements are also presented for several 2^- candidates. The $M2$ form factor for the lowest 2^- state at 5.53 MeV is similar in shape to that for the lowest 2^- state in ^{16}O, but is weaker in strength. Finally, form-factor measurements are presented for several high-lying normal-parity states, including strong excitations at 9.36, 9.71, 11.67, and 17.02 MeV.

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I. INTRODUCTION

This paper reports a study of $T = 1$ and 2 excitations in ^{18}O by high-resolution inelastic electron scattering. Differential cross sections were measured at the MIT–Bates Linear Accelerator Center in an experiment designed to search for candidate 4^- and 6^- excitations. The experiment was motivated in part by earlier exploratory measurements at 90° and 160° that revealed six narrow ($\Gamma < 100$ keV) peaks in ^{18}O at excitation energies of approximately 16.4, 17.0, 18.7, 19.2, 20.4, and 22.4 MeV [1]. These six levels were presumed to be $T = 2$ states because of their narrow widths (the threshold for neutron decay to the lowest $T = \frac{3}{2}$ state in ^{17}O opens at 19.12 MeV). It was speculated that the three states at 18.7, 20.4, and 22.4 MeV might be 4^- states based on the strength of their cross sections and on a Rosenbluth separation at $q = 1.7$ fm^{-1}, which indicated completely transverse form factors. The present experiment provided more complete measurements of the form factors for these states, and supports the earlier hypothesis.

In the ^{16}O(e,e') reaction, the strongest 4^- state is a narrow isovector excitation at 18.98 MeV, although at least four weaker excitations also have form factors consistent with 4^- assignments [2]. The form factor for the 18.98-MeV state is completely transverse, as required for an abnormal-parity excitation, and is well described by a harmonic-oscillator (HO) density with oscillator parameter $b = 1.58$ fm. In the nuclear shell model, this $T = 1$ 4^- state is excited primarily by the $1\hbar\omega$ "stretched" $1p_{3/2} \rightarrow 1d_{5/2}$ transition. Other single-particle $M4$ transitions require at least $3\hbar\omega$ of excitation. Because their one-body structure is simple, states excited by stretched magnetic transitions have been studied extensively using various different experimental reactions [3]. In ^{18}O, 4^- states with $T = 2$ should be excited primarily by the pure $1p_{3/2} \rightarrow 1d_{5/2}$ transition; however, because the ground state of ^{18}O has a significant occupancy of the $1d_{5/2}$ orbital, 4^- states with $T = 1$ may also be excited by nonstretched $1\hbar\omega$ $M4$ transitions, such as $1d_{5/2} \rightarrow 1f_{7/2}$ and $1d_{5/2} \rightarrow 2p_{3/2}$. Similarly, it should be possible to excite $T = 1$ 6^- states in ^{18}O by $1\hbar\omega$ stretched $1d_{5/2} \rightarrow 1f_{7/2}$ $M6$ transitions. Such states are essentially pure neutron excitations and are not expected to be excited strongly.

Several previous electron scattering experiments have investigated the structure of ^{18}O [4–12]. Early ^{18}O(e,e') measurements performed at the Stanford [4] and Saskatoon accelerators [5,6] were limited to low momentum transfers ($q < 1.0$ fm^{-1}) and were generally of low resolution. The first high-resolution measurements of electron scattering from ^{18}O concentrated on normal-parity levels below 10 MeV of excitation and were performed at the MIT–Bates Linear Accelerator in the momentum-

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transfer range $0.6 < q < 2.7$ fm^{-1} [7–10]. Additional high-resolution measurements were performed at the Darmstadt Electron Linear Accelerator at low momentum transfer ($q < 0.5$ fm^{-1}) for low-spin states with excitation energies between about 11 and 27 MeV [11,12].

The essential details of the experiment are described in Sec. II. A discussion of the data analysis that includes a description of how the form factors were parametrized is given in Sec. III. Examples of the fitted excitation-energy spectra are presented in Sec. IV, which also summarizes the levels observed in the present work. Form-factor data for individual levels are presented and discussed in Sec. V and Sec. VI. A comparison of the data for some of the states with nuclear-structure calculations is presented in Sec. VII, and the conclusions of the present work are summarized in Sec. VIII.

II. EXPERIMENTAL SETUP

The present ^{18}O(e,e') measurements were performed at the MIT–Bates Linear Accelerator Center using the Energy-Loss Spectrometer System (ELSSY), which has been described elsewhere [13,14], The ^{18}O target consisted of an isotopically enriched ^{9}Be^{18}O wafer of average thickness 47.3 mg/cm^2 and abundances of 90.8% ^{18}O, 7.2% ^{16}O, and 2.0% ^{17}O, relative to ^{9}Be. The ^{9}Be^{18}O target was the same as that used for previous (e,e') experiments at the Bates accelerator [7–10] and for a complementary (p,n) experiment at the Indiana University Cyclotron Facility [15]. Additional measurements were made using ^{9}Be and ^{9}Be^{16}O targets for the purpose of identifying background peaks and analyzing the ^{18}O spectra.

Since high-spin abnormal-parity excitations are excited strongly at backward angles and at relatively large momentum transfers, all of the present measurements were performed at a scattering angle of either 140° or 110°. The energy resolution of the measurements at 110° was typically about 90 keV full width at half maximum (FWHM) and varied from about 50 to 90 keV at 140°. The 140° measurements were performed with beam energies of (the corresponding approximate momentum transfer is given in parentheses) 140.3 MeV (1.25 fm^{-1}), 165.4 MeV (1.5 fm^{-1}), 220.4 MeV (2.0 fm^{-1}), 245.1 MeV (2.25 fm^{-1}), and 275.2 MeV (2.5 fm^{-1}). The 110° measurements were performed at beam energies of 220.2 MeV (1.75 fm^{-1}) and 250.3 MeV (2.0 fm^{-1}). Each set of spectra from these measurements extended to a maximum excitation energy between 23 and 29 MeV. In addition to the new measurements, older spectra [1] having a similar range of excitation energy were reanalyzed in a manner consistent with that used for the new measurements. The older spectra were measured at 90° and 248.4 MeV (1.75 fm^{-1}) and at 160° and 179.5 MeV (1.75 fm^{-1}).

III. DATA ANALYSIS

Differential cross sections were extracted from the measured spectra using the line-shape fitting code ALLFIT [16], which has been described previously [17]. Prior attempts to measure form factors for discrete states in ^{18}O were concerned mainly with excitations below about 10 MeV. In the present work, we were interested primarily in discrete states with excitation energies between about 10 and 25 MeV, which is a region relatively unexplored, particularly by electron scattering. Much effort was expended to fit the complete set of spectra in a tightly constrained, consistent fashion. By using an iterative approach, we succeeded in obtaining acceptable fits in which values of the excitation energy and width of each peak did not vary from spectrum to spectrum. The extracted form factors were renormalized relative to known cross sections for several low-lying normal-parity states in ^{18}O to compensate for uncertainties arising from beam monitoring, nonuniformities in the target thickness, etc. The average normalization factor required for about 70% of the fitted spectra at 110° and 140° varied between about 0.95 and 1.17 with typical uncertainties between about 3% and 6%. These uncertainties in the normalization factor are, in fact, typical for all of the fitted spectra, except those measured at 140° and 275 MeV, which had relatively low statistics.

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

$$\frac{d\sigma}{d\Omega} = Z^2 \, \sigma_{\mathrm{Mott}} \, \eta \, |F|^2 \, , \tag{1}$$

where Z is the nuclear charge and the Mott cross section for elastic scattering from a massive, unit point charge is given by

$$\sigma_{\mathrm{Mott}} = \left(\frac{\alpha}{2E}\right)^2 \frac{\cos^2\theta/2}{\sin^4\theta/2} \, . \tag{2}$$

Here α is the fine-structure constant, E is the incident electron energy, and θ is the laboratory scattering angle of the electron. The target recoil factor η is given by

$$\eta = \left(1 + \frac{2E}{M}\sin^2\theta/2\right)^{-1} \, , \tag{3}$$

where M is the target mass. In the PWBA, the square of the total form factor, $|F|^2$, is a function only of q, the three-momentum transfer, and θ. We may express $|F|^2$ as

$$|F|^2 = \frac{Q^4}{q^4}|F_L(q)|^2 + \left(\frac{Q^2}{2q^2} + \tan^2\theta/2\right)|F_T(q)|^2 \, , \tag{4}$$

where $F_L(q)$ and $F_T(q)$ are the longitudinal and transverse form factors, respectively. Here $Q^2 = q^2 - \omega^2$, where the energy transfer ω is related to the nuclear excitation energy E_x by $\omega = [(M + E_x)^2 + q^2]^{1/2} - M$. For a spin-0 target such as ^{18}O, only a single multipolarity contributes to the excitation of a given state. For a normal-parity excitation with spin J, we have $F_L = F_{CJ}$ (the Coulomb form factor) and $F_T = F_{EJ}$ (the transverse electric form factor); for an abnormal-parity excitation of spin J, the form factor is completely transverse and we have $F_T = F_{MJ}$ (the magnetic form factor). The form factors were corrected for Coulomb-distortion effects by transforming the experimental values of the momentum transfer q to values of the effective momentum transfer q_{eff}, with $q_{\text{eff}} = q[1 - V_C(r)/E]$. Here $V_C(r)$ is the Coulomb field of the target nucleus at distance r. We calculated $V_C(r)$ by approximating the nucleus as a uniformly charged sphere of radius $R = \sqrt{(5/3)}\, r_{\text{rms}}$, with $r_{\text{rms}} = 1.2\, A^{1/3}$ fm. For an excited state of spin J, the field was evaluated at $r = (J+1)/q$, which approximates the location of the innermost peak of the overlap between incident and scattered electron waves [18].

To facilitate comparisons with shell-model calculations that use HO wave functions, the multipole form factors were parametrized by polynomial-times-Gaussian expansions:

$$F_{CJ}(q) = \frac{\sqrt{4\pi}}{Z} \frac{q^J}{(2J+1)!!}\, f_{\text{c.m.}}(q)\, f_N(q) \times e^{-y} \sum_{n=0}^{N} A_n y^n \,, \tag{5a}$$

$$F_{EJ}(q) = \frac{\sqrt{4\pi}}{Z} \frac{q^J}{(2J+1)!!} \left(\frac{J+1}{J}\right)^{1/2} \frac{\omega}{q}\, f_{\text{c.m.}}(q)\, f_N(q) \times e^{-y} \sum_{n=0}^{N+1} B_n y^n \,, \tag{5b}$$

$$F_{MJ}(q) = \frac{\sqrt{4\pi}}{Z} \frac{q^J}{(2J+1)!!} \left(\frac{J+1}{J}\right)^{1/2} f_{\text{c.m.}}(q)\, f_N(q) \times e^{-y} \sum_{n=0}^{N'} C_n y^n \,. \tag{5c}$$

The coefficients A_n, B_n, and C_n were treated as variable parameters, and the $n = 0$ coefficients are related to the well-known reduced electromagnetic transition probabilities by $A_0 = B_0 \approx \sqrt{B(CJ)\!\uparrow}$ and $C_0 \approx \sqrt{B(MJ)\!\uparrow}$. The number of coefficients in the summations depends on the assumed model space. For a single-particle transition between major shells characterized by N_p and N_h oscillator quanta, the summation indices are $N = 0.5\,[(N_p + N_h)_{\max} - J]$ for normal-parity excitations and $N' = 0.5\,[(N_p + N_h)_{\max} - J + 1]$ for abnormal-parity excitations. In Eqs. (5), $y = (qb/2)^2$ is a dimensionless variable with b the oscillator parameter. The "center-of-mass" factor $f_{\text{c.m.}} = \exp(y/A)$, with A the mass number of the target nucleus, corrects for the lack of translational invariance in shell-model wave functions, and the dipole form factor $f_N(q) = (1 + q^2/\Lambda^2)^{-2}$, with $\Lambda = 4.33$ fm^{-1}, corrects for the finite size of the nucleon.

IV. LEVELS OBSERVED IN THE PRESENT WORK

Several of the low-lying normal-parity states observed in the present ^{18}O(e,e') experiment have well-established spins and parities, and have been discussed in previous papers on electron scattering [5,7–10]. These include the 0^+ states at 0.00, 3.63, and 5.34 MeV, the 2^+ states at 1.98, 3.92, 5.26, and 8.21 MeV, the 4^+ states at 3.55 and 7.12 MeV, the 1^- states at 4.46, 6.20, 7.62, and 8.04 MeV, the 3^- states at 5.10, 6.40, and 8.28 MeV, and the 5^- states at 7.86 and 8.13 MeV. New form-factor data are available from the Physics Auxiliary Publication Service (PAPS) [19] for these 18 states, as well as for 39 others observed in the present experiment. This paper discusses these 39 additional states.

Table I lists 27 states in ^{18}O observed in the present experiment with excitation energies below 16 MeV. All of these states necessarily have $T = 1$ since the lowest $T = 2$ state (the analog of the 1^- ground state in ^{18}N) is above 16 MeV. The states in Table I include 9 established levels [20] with excitation energies below 10 MeV and 18 *new* states between 10 and 16 MeV. Table II lists the 12 states observed above 16 MeV. No obvious structure due to discrete states was observed at excitation energies above about 23 MeV. Several of the states are presumed to have $T = 2$ based on their narrow widths. (As noted

TABLE I. Selected $T = 1$ ^{18}O levels observed in this work below 16 MeV. The excitation energies, widths, and most probable spins and parities are from the present work, except where noted. For states with no entry listed for Γ, the intrinsic widths are smaller than the minimum energy resolution (about 50 keV).

Peak No.	E_x (MeV)	J^π	Γ (keV)
1	5.53 ± 0.01	2^{-}[a]	
2	6.35 ± 0.01	(2^-)[a]	
3	7.77 ± 0.01	2^{-}[a]	
4	8.41 ± 0.01	(2^-)	
5	8.52 ± 0.01	(4^-)	
6	8.82 ± 0.01	(1^+)[b]	70 ± 12[a]
7	8.96 ± 0.01	(4^+)	43 ± 3[a]
8	9.36 ± 0.01	(2^+)[c]	
9	9.71 ± 0.01	(5^-)	
10	10.31 ± 0.02	(4^+)	
11	10.43 ± 0.04	(2^-)	
12	10.67 ± 0.02	(2^-)	
13	10.99 ± 0.02	(2^-)	
14	11.52 ± 0.05	(2^-)	
15	11.67 ± 0.02	(3^-)	112 ± 7
16	11.90 ± 0.03	(2^-)	
17	12.09 ± 0.02	$(1^-, 2^+)$	
18	12.41 ± 0.02	(3^-)	143 ± 24
19	12.52 ± 0.02		
20	12.66 ± 0.02	(2^-)	
21	12.99 ± 0.02	(4^-)	68 ± 18
22	13.40 ± 0.02	(2^-)	108 ± 26
23	13.85 ± 0.13	(6^-)	~ 200
24	14.17 ± 0.04	(6^-)	140 ± 50
25	14.45 ± 0.05		~ 1070
26	15.23 ± 0.04		~ 300
27	15.95 ± 0.03		

[a]Ref. [20].
[b]Ref. [20]. Present measurements are also consistent with a 2^- assignment.
[c]Ref. [9].

TABLE II. Observed $T = 1$ and $T = 2$ levels in ^{18}O above 16 MeV. The excitation energies, widths, and most probable spins and parities are from the present work, except where noted. For states with no entry listed for Γ, the intrinsic widths are smaller than the minimum energy resolution (about 50 keV).

Peak No.	E_x (MeV)	J^π	T	Γ (keV)
28	16.40 ± 0.02	2^{-a}	2	
29	16.88 ± 0.03	$(4^-,2^-)$	(1)	
30	17.02 ± 0.02	(3^-)	2	
31	17.46 ± 0.03	(4^-)	1	~ 600
32	18.45 ± 0.02	(3^-)	(1)	75 ± 27
33	18.68 ± 0.02	(4^-)	(2)	
34	19.22 ± 0.02	(3^-)	(2)	
35	20.36 ± 0.02	(4^-)	(2)	
36	20.86 ± 0.02			97 ± 41
37	21.42 ± 0.02	(4^-)	(2)	
38	22.40 ± 0.02	4^-	2	91 ± 8
39	23.10 ± 0.02			49 ± 24

[a]Ref. [12].

in Sec. I, the particle-decay threshold for $T = 2$ states opens at 19.12 MeV.)

Figures 1–5, which are discussed below, show representative ^{9}Be^{18}O(e,e') spectra measured in our experiment. The line shapes of individual peaks above a fitted polynomial background are shown only for the 39 ^{18}O states listed in Tables I and II. The peaks are numbered as indicated in the tables. In general, each of the 39 states will appear in a given spectrum, if it is within energy range, unless its cross section is too small to produce a visible peak.

Figure 1 displays a ^{9}Be^{18}O(e,e') spectrum measured for an incident beam of 250-MeV electrons scattered at 110°. These kinematics correspond to a momentum transfer ($q \approx 2.0$ fm^{-1}) at which high-spin states are excited preferentially, yet the scattering angle is sufficiently forward that states with normal parity are not suppressed. The fitted curves highlight contributions only from the ^{18}O peaks listed in Table I. The lowest 2^- state at 5.53 MeV is evident. Other levels of interest in this spectrum include the 2^+ candidate at 9.36 MeV, the 4^- candidate at 12.99 MeV, the 4^+ candidates at 8.96 MeV and 10.31 MeV, the 3^- candidates at 11.67 MeV and 12.41 MeV, the 4^- candidate at 8.52 MeV, the 5^- candidate at 9.71 MeV, and the 6^- candidates at 13.85 and 14.17 MeV. The continuum background in this figure opens at the neutron decay threshold for ^{9}Be. Figure 2 displays a spectrum measured at the same kinematics but covering a higher range of excitation energies. Here the fitted curves highlight contributions from the ^{18}O peaks listed in both Tables I and II. In this spectrum, the strong peaks are for the 3^- candidate at 17.02 MeV, the 4^- candidates at 12.99, 18.68, 20.36, and 22.40 MeV, and the 6^- candidates at 13.85 and 14.17 MeV.

Figure 3 displays a ^{9}Be^{18}O(e,e') spectrum measured for 275-MeV electrons scattered at 140°. These kinematics correspond to our *highest* momentum transfer ($q \approx 2.5$ fm^{-1}). At this backward angle, high-spin states with abnormal parity should be excited preferentially. The strongest peaks in this spectrum are for the 4^- candidate at 8.52 MeV and for the 6^- candidate at 14.17 MeV. Visible peaks also can be seen for the following less strongly excited states: the 2^- levels at 5.53 and 6.35 MeV and the 2^- candidates at 8.41, 10.43, and 10.99 MeV; the 3^- candidates at 11.67 and 17.02 MeV; the 4^- candidates at 12.99, 16.88, and 17.46 MeV; and the 5^- candidate at 9.71 MeV.

Figure 4 displays a ^{9}Be^{18}O(e,e') spectrum measured for 140-MeV electrons scattered at 140°. These kinematics correspond to our *lowest* momentum transfer ($q \approx 1.25$ fm^{-1}). In this spectrum, the strongest peaks are for the 3^- candidate at 11.67 MeV, the 2^- candidate at

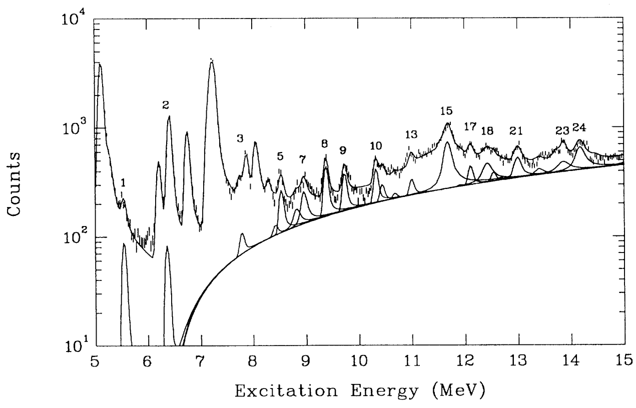

FIG. 1. Spectrum for 250-MeV incident electrons scattered at 110° from ^{9}Be^{18}O, corresponding to $q \approx 2.0$ fm^{-1}. Note the lowest 2^- state at 5.53 MeV (1), the 4^- candidate at 8.52 MeV (5), the 4^+ candidate at 8.96 MeV (7), the 2^+ candidate at 9.36 MeV (8), the 5^- candidate at 9.71 MeV (9), the 4^+ candidate at 10.31 MeV (10), the 3^- candidates at 11.67 MeV (15), 12.41 MeV (18), the 4^- candidate at 12.99 MeV (21), and the 6^- candidate at 14.17 MeV (24).

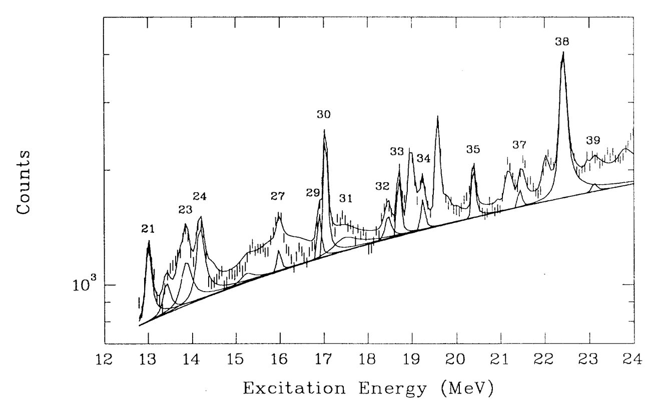

FIG. 2. Spectrum for 250-MeV incident electrons scattered at 110° from ^{9}Be^{18}O, corresponding to $q \approx 2.0$ fm^{-1}. Note the strong 4^- candidate at 12.99 MeV (21), the strong 6^- candidates at 13.85 MeV (23) and 14.17 MeV (24), the strong $T = 2$ 3^- candidate at 17.02 MeV (30), and the $T = 2$ 4^- candidates at 18.68 MeV (33), 20.36 MeV (35), and 22.40 MeV (38).

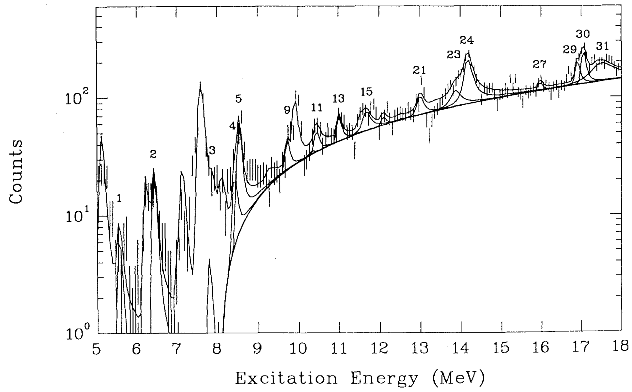

FIG. 3. Spectrum for 275-MeV incident electrons scattered at 140° from ^{9}Be^{18}O, corresponding to $q \approx 2.5$ fm^{-1}. Note the strong 4^- candidate at 8.52 MeV (5) and the strong 6^- candidate at 14.17 MeV (24).

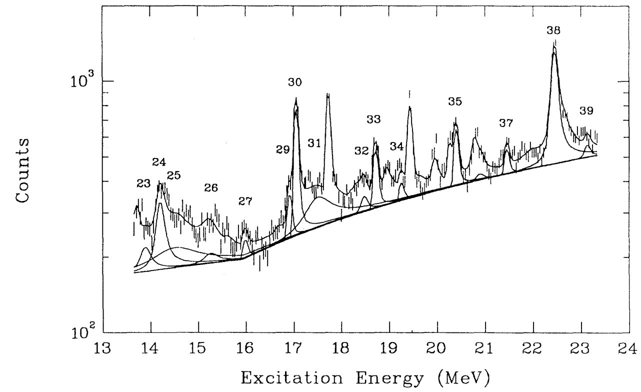

FIG. 5. Spectrum for 180-MeV incident electrons scattered at 160° from ^{9}Be^{18}O, corresponding to $q \approx 1.75$ fm^{-1}. Note the 6^- candidate at 14.17 MeV (24), the $T = 2$ 3^- candidate at 17.02 MeV (30), and the $T = 2$ 4^- candidates at 18.68 MeV (33), 20.36 MeV (35), and 22.40 MeV (38).

13.40 MeV, and the 3^- candidate at 17.02 MeV. Peaks are also clearly visible for the 1^- or 2^+ candidate at 12.09 MeV, the 3^- candidate at 12.41 MeV, and the 4^- candidate at 12.99 MeV. This is the only spectrum from the new measurements at 110° and 140° that clearly shows the $T = 2$ 2^- state at 16.40 MeV.

Finally, Fig. 5 displays a ^{9}Be^{18}O(e,e') spectrum measured for 180-MeV electrons scattered at 160°. These kinematics correspond to a momentum transfer of about 1.75 fm^{-1}. This spectrum was obtained from the exploratory measurements mentioned in the Introduction [1], although it was refitted based on the level scheme elucidated by our more recent measurements. Here, the strongest peaks are for the 4^- candidates at 18.68, 20.36, and 22.40 MeV, the $T = 2$ 3^- candidate at 17.02 MeV, and the newly proposed 6^- candidate at 14.17 MeV. We now discuss the measured form factors for the states shown in these spectra and listed in Tables I and II.

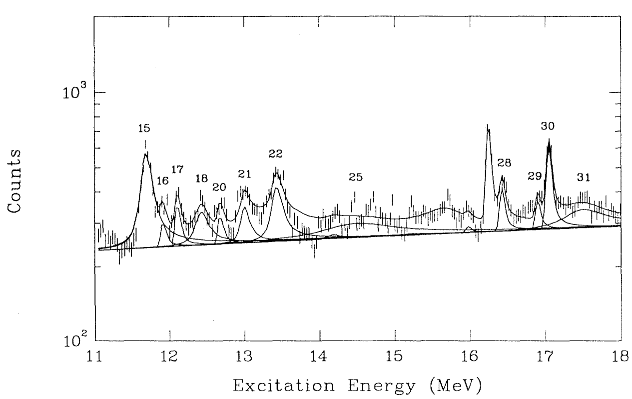

FIG. 4. Spectrum for 140-MeV incident electrons scattered at 140° from ^{9}Be^{18}O, corresponding to $q \approx 1.25$ fm^{-1}. Note the $T = 2$ states at 16.40 MeV (28) and 17.02 MeV (30), the strong 3^- candidate at 11.67 MeV (15), and the strong 2^- candidate at 13.40 MeV (22).

V. ABNORMAL-PARITY STATES

The form factor for a stretched excitation of multipolarity J is completely transverse and has a shape that can be described by a HO density with an oscillator parameter given by our empirical formula $b \approx (0.8671 - 0.0198J)\ A^{1/4}$ fm. For example, this formula predicts $b = 1.58$ fm for 4^- states in ^{16}O, $b = 1.72$ fm for 6^- states in ^{28}Si, $b = 1.92$ fm for 8^- states in ^{54}Fe, $b = 2.06$ fm for 10^- states in ^{90}Zr, and $b = 2.24$ fm for 14^- states in ^{208}Pb. The predicted values agree well with fitted values of b for the entire mass range from ^{12}C to ^{208}Pb [21].

A. Candidate 4^- states

Eight 4^- candidates were identified and are discussed below. The transverse form factors for these states are shown in Fig. 6, and the expansion coefficients for their transverse form factors (assuming 4^- assignments) are given in Table III. This table also includes the extrapolated $B(M4)\uparrow$ value for each state. The oscillator constant for describing the transverse form factors of 4^- candidates in ^{18}O was determined to be 1.632(18) fm from a simultaneous fit of the eight states at 8.52, 12.99, 16.88, 17.46, 18.68, 20.36, 21.42, and 22.40 MeV. By comparison, a simultaneous fit for five 4^- states in ^{16}O resulted in an oscillator parameter with the value 1.573(7) fm [22]. In principle, variations in the shape of the $M4$ form factor may occur for 4^- states with $T = 1$, due to nonstretched $M4$ transitions such as $1d_{5/2} \rightarrow 1f_{7/2}$.

The level observed in the present work at 8.52 MeV is probably the same as that observed initially at 8.48 ± 0.02 MeV in the ^{19}F$(t,\alpha)^{18}$O reaction [23]. This level was not observed in the ^{18}O(α,α') reaction, which suggests that this state may have abnormal parity [24]. This level also was not observed in the ^{14}C$(\alpha,n)^{17}$O reaction [25], which is consistent with that conclusion. This state

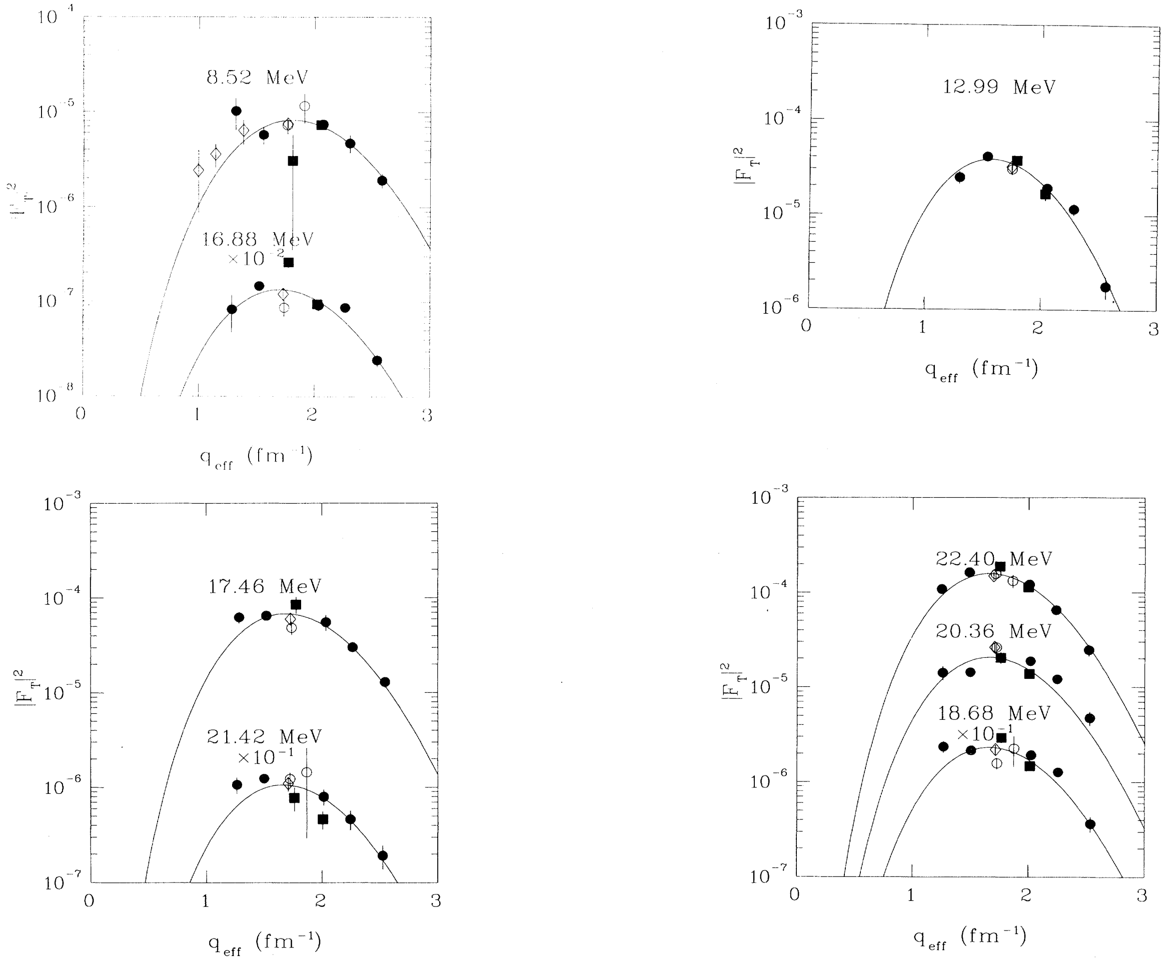

FIG. 6. Transverse form factors for the 4^- candidates at 8.52, 12.99, 16.88, 17.46, 18.68, 20.36, 21.42, and 22.40 MeV. The solid curves were obtained by fitting the data under the assumption that the first four states have $T = 1$ and the last four states have $T = 2$. Solid squares and solid circles indicate measurements from the present analysis at 110° and 140°, respectively; open circles and open diamonds indicate older measurements at 90° and 160°, respectively (see text).

is probably the same one observed as a weak peak at 8.521 ± 0.003 MeV in the $^{16}O(t,p)^{18}O$ reaction [26]. The present measurements for this state are consistent with a completely transverse form factor that has a maximum at $q \approx 1.7$ fm^{-1}. Based on the strength observed at large momentum transfers, we conclude that the state at 8.52 MeV probably has $J^\pi = 4^-$. Its analog in ^{18}F is expected at about 9.5 MeV; a 4^- candidate at 9.4 MeV was observed in the $^{18}O(p,n)^{18}F$ reaction [15].

A strongly excited state was observed in the present work at 12.99 MeV. The present measurements for this state are consistent with a completely transverse form factor. Its transverse form factor has a maximum at $q \approx 1.6$ fm^{-1}, and is almost exactly the same shape as that for the strong $T = 2$ 3^- candidate at 17.02 MeV (discussed in the next section). However, because abnormal parity is implied by the smallness of the longitudinal form factor, and because shell-model calculations predict a concentration of $T = 1$ 4^- strength near 12–13 MeV, we believe that the 12.99-MeV level is most likely a $T = 1$ 4^- state. The somewhat fast falloff of the form factor at high q compared with that for a $T = 2$ 4^- state, such as the 22.40-MeV level discussed below, could be due to small $(sd)(pf)$ admixtures in the wave function, which would permit the state to be excited by nonstretched $M4$ transitions. The analog of the 12.99-MeV state in ^{18}F is expected at about 14.0 MeV; the nearest 4^- candidate observed in the $^{18}O(p,n)^{18}F$ reaction at 135 MeV is at 14.4 MeV [15].

A narrow state was observed in the present work at 16.88 MeV. Our present measurements for this state are consistent with a completely transverse form factor. The shape of its transverse form factor is fairly well determined and is consistent with that expected for a 4^- state. The analog of this state in ^{18}F should be at about 17.9 MeV, which is near a $T = 1$ 4^- candidate that was observed in the $^{18}O(p,n)^{18}F$ reaction at 18.0 MeV [15].

A broad state ($\Gamma \approx 600$ keV) was observed in the present work at 17.46 ± 0.03 MeV. This width suggests that the state has $T = 1$ since we are below the particle decay threshold for $T = 2$ states. This level was observed at 17.35 ± 0.06 MeV with a width of 680 ± 250 keV in prior (e,e') measurements at 160° [1]. The shape of its transverse form factor is consistent with that expected for a 4^- state.

A narrow state was observed in the present work at 18.68 MeV. Its narrow width suggests that the state has $T = 2$ and our present measurements for this state are consistent with a completely transverse form factor. The shape of its transverse form factor is fairly well determined, and is consistent with that expected for a stretched 4^- state. Its analog in ^{18}F should be at about 19.7 MeV. A $T = 2$ 4^- candidate at that energy has been observed in the $^{18}O(p,n)^{18}F$ reaction [15].

Another narrow state was observed in the present work at 20.36 MeV. Its narrow width suggests that the state has $T = 2$ and our present measurements for this state are consistent with a completely transverse form factor. The shape of its transverse form factor is fairly well determined, and is consistent with that expected for a stretched 4^- state. Its analog in ^{18}F should be at about 21.4 MeV. A $T = 2$ 4^- candidate at that energy has been observed in the $^{18}O(p,n)^{18}F$ reaction [15].

The level that we observed at 21.42 MeV was observed in a previous (e,e') experiment as a weak state at 21.43 ± 0.02 MeV with a width of 49 ± 37 keV [1]. Present measurements for this state are consistent with a completely transverse form factor. The shape of its transverse form factor agrees well with that expected for a stretched 4^- state. The ^{18}F analog, which is expected at about 22.4 MeV, is not observed in the $^{18}O(p,n)^{18}F$ reaction [15], which suggests that this might be a normal-parity state. If so, it is most likely a 3^- state.

A strongly excited state was observed in the present work at 22.40 MeV. Our present measurements for this state are consistent with a completely transverse form factor. The shape of its transverse form factor is very well determined, and we unambiguously determine that this level is a $T = 2$ 4^- state. Its analog in ^{18}F should be at about 23.4 MeV; a $T = 2$ 4^- candidate at that energy has been observed in the $^{18}O(p,n)^{18}F$ reaction [15]. The isovector $M4$ strength of the level at 22.40 MeV is about one-third of that seen in ^{16}O, as expected by simple shell-model calculations [27].

B. Candidate 6^- states

In general, we expect the form factor for a stretched 6^- excitation in ^{18}O to be completely transverse and to peak at larger q than that for a stretched 4^- excitation. Two 6^- candidates at 13.85 and 14.17 MeV were identified and are discussed below. Their transverse form factors are shown in Fig. 7, and the expansion coefficients for their transverse form factors (assuming 6^- assignments) are given in Table III. This table also includes the extrapo-

TABLE III. Expansion coefficients (in e fm^J) and extrapolated reduced transition probabilities (in e^2 fm^{2J}) for the transverse form factors of 4^-, 6^-, and 2^- candidates in ^{18}O. (Uncertainties in the last significant figure are given in parentheses, and only the uncertainties due to fitting are represented.) The value of the oscillator constant b was determined to be 1.632 ± 0.018 fm for the 4^- candidates, 1.794 ± 0.021 fm for the 6^- candidates, and 1.767 ± 0.045 fm for the 2^- candidates.

E_x (MeV)	J^π	C_0	C_1	$B(MJ)\uparrow$
8.52	(4^-)	3.53(58)	0.91(25)	12(4)
12.99	(4^-)	14.43(83)	−1.63(37)	207(24)
16.88	(4^-)	6.2(14)	0.32(59)	38(17)
17.46	(4^-)	14.6(18)	0.45(80)	211(52)
18.68	(4^-)	8.99(66)		80(12)
20.36	(4^-)	8.47(65)		71(11)
21.42	(4^-)	6.09(42)		36(5)
22.40	4^-	23.56(92)		544(42)
13.85	(6^-)	507(45)		$26(5) \times 10^4$
14.17	(6^-)	764(71)		$58(11) \times 10^4$
5.53	2^-	0.027(21)	0.088(16)	$< 19 \times 10^{-4}$
6.35	(2^-)	0.024(29)	0.110(19)	$< 20 \times 10^{-4}$
7.77	2^-	0.301(53)	−0.195(26)	0.090(32)
8.41	(2^-)	0.335(44)	−0.062(39)	0.112(29)
10.43	(2^-)	0.020(25)	0.145(19)	$< 15 \times 10^{-4}$
10.67	(2^-)	0.017(64)	−0.132(32)	$< 23 \times 10^{-4}$
10.99	(2^-)	0.017(56)	0.145(35)	$< 23 \times 10^{-4}$
11.52	(2^-)	0.11(17)	−0.200(82)	$< 46 \times 10^{-3}$
11.90	(2^-)	0.085(88)	0.087(43)	$< 22 \times 10^{-3}$
12.66	(2^-)	0.19(13)	0.032(74)	$< 86 \times 10^{-3}$
13.40	(2^-)	0.31(11)	0.117(65)	0.094(66)
16.40	2^-	[0.80][a]	−0.349(19)	[0.63]

[a]Data for the $T = 2$ 2^- state at 16.40 MeV were fitted with the coefficient in square brackets constrained to give the quoted $B(M2)\uparrow$ value (see text).

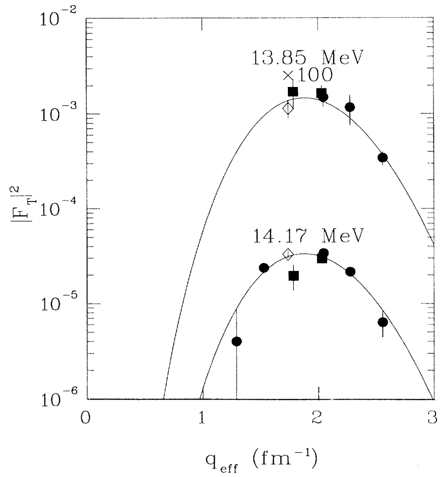

FIG. 7. Transverse form factors for the 6^- candidates at 13.85 and 14.17 MeV. Solid squares and solid circles indicate measurements from the present analysis at 110° and 140°, respectively; open diamonds indicate older measurements at 160° (see text).

lated $B(M6)\uparrow$ value for each state. (A preliminary report of possible 6^- states at 14.1 and 14.3 MeV is superseded by the results presented here [28].) The oscillator constant for describing the transverse form factors of 6^- candidates was determined to be 1.794(21) fm by performing a simultaneous fit of data for the two states. It should be noted that, in general, the sensitivity to a transverse form factor increases at extreme backward scattering angles (where the longitudinal form factors are suppressed). Since both 6^- candidates had relatively weak peaks except at the highest momentum transfers, the form factors for these states were fitted without the older data at 90°.

A fairly broad ($\Gamma \approx 200$ keV) excited state was observed in the present work at about 13.85 MeV. The data for this state are consistent with a completely transverse form factor that has a maximum at $q \approx 1.9$ fm^{-1}. The shape of its transverse form factor between 1.7 and 2.5 fm^{-1} is similar to that for a stronger nearby state at 14.17 MeV (see below); the proximity of this stronger state hindered our determination of the excitation energy and width of the state near 13.85 MeV. This state is a candidate 6^- state based on the same arguments presented below for the state at 14.17 MeV.

A fairly broad ($\Gamma = 140\pm50$ keV) strongly excited state was observed in the present work at about 14.17 MeV. The data for this state are consistent with a completely transverse form factor. The shape of its transverse form factor is consistent with that expected for a 5^+ state, which could be excited by the stretched $2\hbar\omega$ transition, $1p_{3/2} \rightarrow 1f_{7/2}$. A shell-model calculation predicts a 5^+ state at 13.20 MeV; this state is a member of the four-particle–two-hole (4p2h) $K^\pi = 2^+$ band headed by the 2^+ state at 9.36 MeV [9]. A better candidate for the predicted 5^+ state is, however, the 5^+ state observed at 13.3 MeV in the ^{14}C(^{6}Li,d)^{18}O reaction [29]. It is unlikely that the level we observe at 14.17 MeV is the 4^+ state observed at 14.2 MeV in the ^{14}C(^{6}Li,d)^{18}O reaction [29]. Another possibility is that the 14.17-MeV level might be a 4^- state since a 4^- candidate was observed [15] at 15.3 MeV in the ^{18}O$(p,n)^{18}$F reaction; the analog of that state is expected at about 14.3 MeV in ^{18}O. The most probable assignment, however, is that the 14.17-MeV level is a 6^- state since its transverse form factor peaks at larger q than expected for a stretched 4^- excitation. Evidence supporting this assignment comes from a recent spectroscopic study with the ^{17}O(α,^{3}He)^{18}O reaction, which found possible 6^- strength near 14.2 MeV [30]; however, no evidence was found in the present work for the possible 6^- state observed in that study at 11.06 MeV.

C. Candidate 2^- states

The form factor for a 2^- excitation in ^{18}O should be completely transverse and should peak at smaller q than that for a stretched 4^- excitation. (At momentum transfers below about 3 fm^{-1}, an $M2$ form factor may have up to two maxima. It is generally difficult to distinguish 2^- states from $T = 1$ 4^- states in ^{18}O on the basis of their form factors alone.) Twelve 2^- candidates (and one 1^+ candidate) were identified and are discussed below. The transverse form factors for these states are shown in Fig. 8, and the expansion coefficients for the transverse form factors of the 2^- candidates are given in Table III. This table also includes the extrapolated $B(M2)\uparrow$ value for each state. Since the sensitivity to the generally weak 2^- states is relatively small at forward angles, the form factors for these states were fitted without the data at 90° and 110°. The oscillator constant for describing the transverse form factors of 2^- states (including several 2^- candidates and a single 1^+ candidate) was determined to be 1.767(45) fm from a simultaneous fit of the 12 states at 5.53, 6.35, 7.77, 8.41, 8.82, 10.43, 10.67, 10.99, 11.52, 11.90, 12.66, and 13.40 MeV. (For the 2^- state at 16.40 MeV, the oscillator parameter was held fixed at this value.) By comparison, a simultaneous fit for six 2^- states in ^{16}O resulted in an oscillator parameter with the value 1.739(20) fm [22]. We expect the oscillator parameter for an excitation in ^{18}O to be slightly larger than that for a comparable excitation in ^{16}O. For example, our empirical formula for the oscillator constant (see beginning of Sec. V) suggests an enhancement factor of about $(18/16)^{1/4} = 1.03$. Thus, for 4^- states in ^{18}O, we expect $b \approx 1.03 \times 1.573$ fm or 1.62 fm, in excellent agreement with our fitted value (see above) 1.632(18) fm. Similarly, for 2^- states in ^{18}O, we expect $b \approx 1.03 \times 1.739$ fm or 1.79 fm, in excellent agreement with our fitted value 1.767(45) fm. This expectation also holds for normal-parity states; for example, for Coulomb excitations in ^{18}O, we expect (see below) $b \approx 1.03 \times 1.828$ fm or 1.88 fm, in excellent agreement with our fitted value 1.884(8) fm.

The three lowest 2^- levels in ^{18}O have excitation energies of 5.53, 6.35, and 7.77 MeV [20]. (The assignment of the 6.35-MeV level is not completely certain [31].) As required for abnormal-parity states, our measured form factors for these levels are completely transverse within experimental uncertainties. The $M2$ form factor of the lowest 2^- state is measured reasonably well, and has a

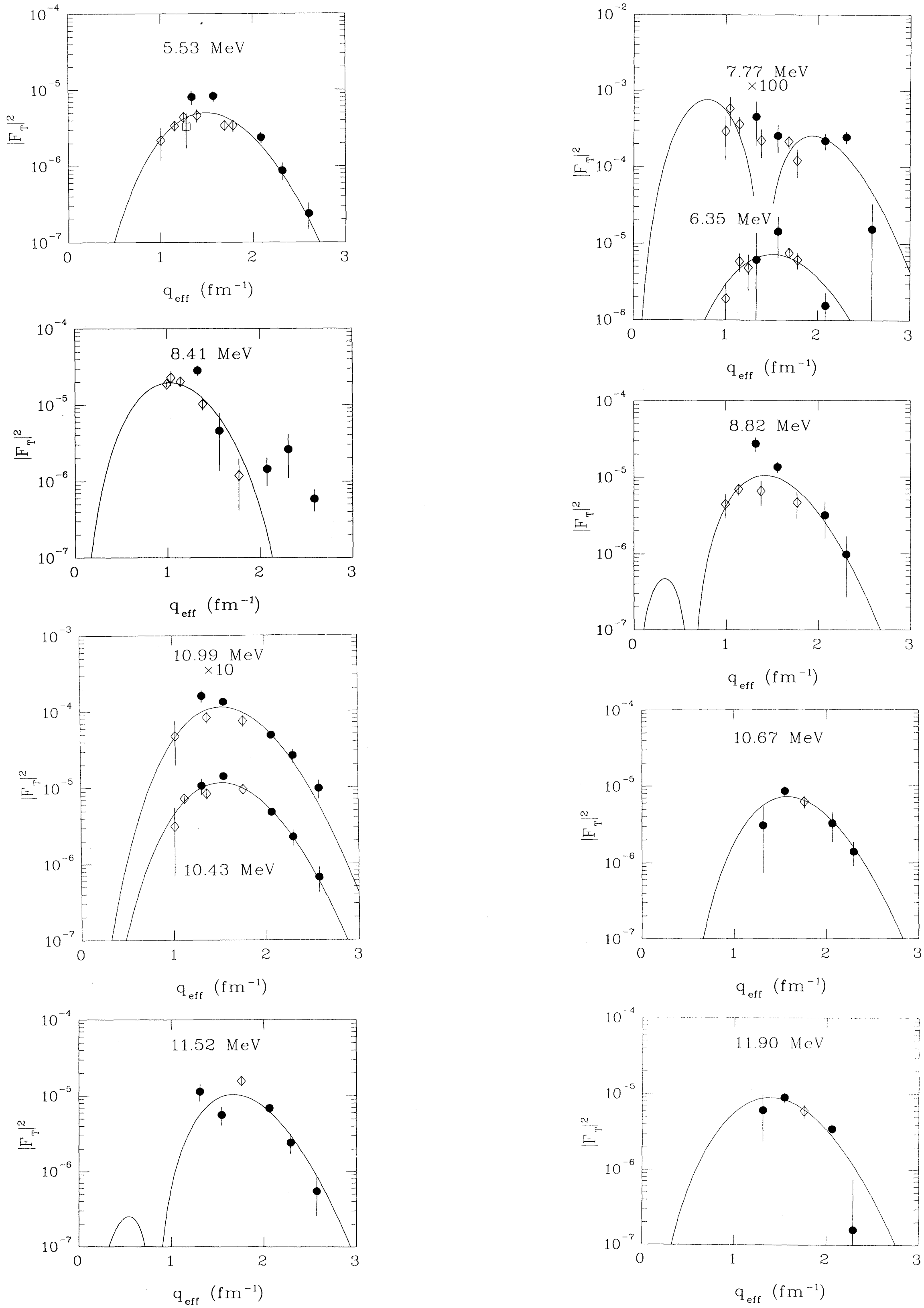

FIG. 8. Transverse form factors for the $T = 1$ 2^- states at 5.53, 6.35, and 7.77 MeV, and for the $T = 2$ 2^- state at 16.40 MeV. Also shown are the transverse form factors for a 1^+ candidate at 8.82 MeV and for $T = 1$ 2^- candidates at 8.41, 10.43, 10.67, 10.99, 11.52, 11.90, 12.66, and 13.40 MeV. Solid circles indicate measurements from the present analysis at 140°; open diamonds and open squares indicate older measurements at 160° and 140°, respectively (see text).

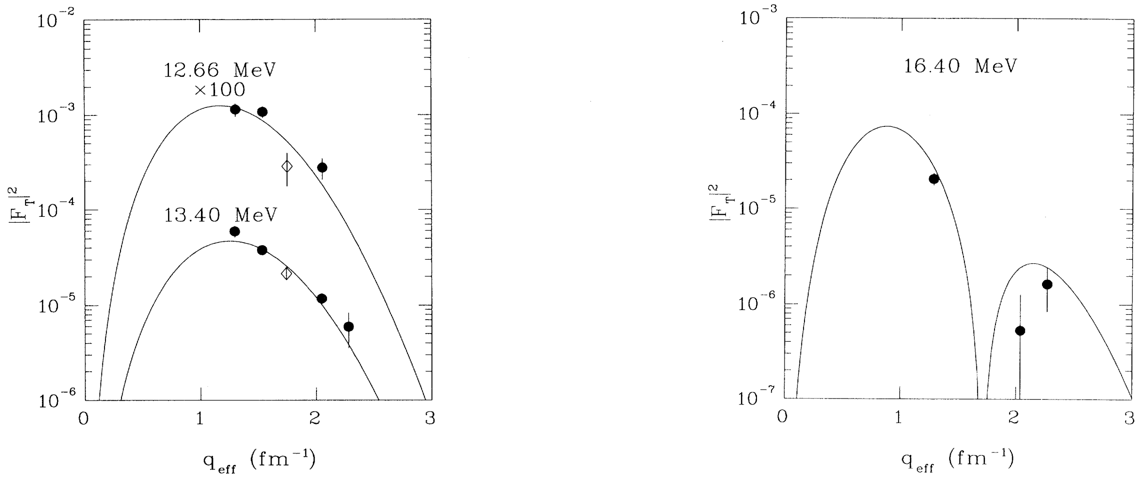

FIG. 8. (*Continued*).

peak magnitude of about 4.8×10^{-6} at $q \approx 1.5$ fm^{-1}. It is somewhat similar in shape to that for the lowest 2^- state in ^{16}O at 8.87 MeV, which has a peak magnitude of about 1.6×10^{-4} at $q \approx 1.3$ fm^{-1} [32,33].

A very weakly excited narrow peak at 8.41 MeV was observed in the $^{14}C(\alpha, n)^{17}O$ reaction [34,25] but *not* in the $^{14}C(\alpha,\alpha)^{14}C$ reaction [35]. (Note that in $^{14}C + \alpha$ reactions, a level can be assigned normal parity only if it is excited *strongly*.) This is probably the same level that was observed as a strong peak at 8.39 ± 0.02 MeV in the $^{19}F(t, \alpha)^{18}O$ reaction [23] and as a weak peak at 8.430 ± 0.012 MeV in the $^{16}O(t,p)^{18}O$ reaction [26]. The present measurements for this state at scattering angles of 110° and 140°, and at $q \approx 2.0$ fm^{-1}, are consistent with a completely transverse form factor. We tentatively conclude that this level has abnormal parity, and is most likely a 2^- state. The identification of this level as the fourth 2^- state is in good agreement with the predictions of shell-model calculations [31].

In studies of the $^{14}C(\alpha, n)^{17}O$ reaction, a weakly excited state was observed at 8.832 MeV with a width of 100 ± 20 keV by Sanders [34] and at 8.809 MeV with a width of 80 ± 20 keV by Bair, Ford, and Jones [25]. This state was not observed clearly in the $^{14}C(\alpha,\alpha)^{14}C$ reaction [35]. More recently, Djalali *et al.* [36] observed a narrow peak at 8.82 ± 0.01 MeV in the $^{18}O(p,p')$ reaction, which they identified as a 1^+ state. [The best energy resolution for the (p,p') measurements was about 75 keV (FWHM), obtained at forward angles.] The identification of a 1^+ state at 8.82 MeV is consistent with the $^{18}O(p,n)^{18}F$ measurements of Anderson *et al.* [37], who tentatively identified a $T = 1$ 1^+ state in ^{18}F at 9.9 MeV; the analog of this state is expected at about 8.8 MeV in ^{18}O. As noted in Ref. [9], the state at 8.82 MeV is a strong candidate for the lowest 4p2h 1^+ state in ^{18}O. The present measurements for the state at 8.82 MeV are consistent with a completely transverse form factor. The shape of the transverse form factor is consistent with that expected for a 1^+ state; however, the shape is also compatible with a 2^- assignment.

The data for a state observed at 10.43 MeV are consistent with a completely transverse form factor. The shape of its transverse form factor is consistent with that expected for either a 2^- or 3^+ state. Shell-model calculations [9] predict a 3^+ state at 10.47 MeV. The predicted 3^+ state is a member of the 4p2h $K^\pi = 2^+$ band headed by the 2^+ state at 9.36 MeV (see below).

The measured form factors for the observed levels at 10.67, 11.52, and 11.90 MeV appear to be mainly transverse, although the experimental uncertainties are large. In a recent study of the β-delayed neutron decay of ^{18}N, states in ^{18}O with $J^\pi = (0\text{–}2)^-$ were observed at 10.65 ± 0.03 and 11.49 ± 0.03 MeV [38]. These might be the 2^- candidates observed in the present work at 10.67 and 11.52 MeV.

The present measurements for a level observed at about 10.99 MeV are consistent with a completely transverse form factor. The shape of its transverse form factor is similar to that for the 2^- state at 5.53 MeV and for the state at 10.43 MeV; we tentatively assign the state at 10.99 MeV to have $J^\pi = 2^-$. In a recent study of the β-delayed neutron decay of ^{18}N, a state in ^{18}O with $J^\pi = (0\text{–}2)^-$ was observed at 10.99 ± 0.03 MeV [38]. This might be the 2^- candidate observed in the present work at 10.99 MeV.

The data for a level observed at 12.66 MeV are consistent, within experimental uncertainties, with a completely transverse form factor. The shape of its transverse form factor peaks at low q, which suggests a low-spin assignment. If this were a 1^+ state, we would expect to see its analog in ^{18}F at about 13.7 MeV, and no 1^+ candidate is observed near that energy in the $^{18}O(p,n)^{18}F$ reaction [37]. The state we observe at 12.66 MeV is possibly a 2^- state.

A fairly broad ($\Gamma = 108 \pm 26$ keV) excited state was observed in the present work at about 13.40 MeV. The data for this state are consistent with a completely transverse form factor. The shape of its transverse form factor is similar to that of the weaker state at 12.66 MeV, which suggests a low-spin assignment. If this were a 1^+ state, we would expect to see its analog in ^{18}F at about 14.4 MeV, and no 1^+ candidate is observed near that energy in the $^{18}O(p,n)^{18}F$ reaction [37]. The state we observe at 13.40 MeV is possibly a 2^- state.

A narrow state was observed in the present work at 16.40 MeV, but it was strong only for $q < 1.4$ fm^{-1}. The narrow width of this level suggests that it is a $T = 2$ state, and the fact that it is very weak except at low q suggests that it has spin $J \leq 2$. The first evidence for a $T = 2$ state at 16.40 MeV was presented in a short report about an ^{18}O(p,p') experiment [39], where it was also noted that this state is not seen in the ^{18}O(d,d') reaction (which is forbidden from populating $T = 2$ states). A narrow state at 16.399 ± 0.005 MeV was also observed in the high-resolution ^{18}O(e,e') experiment of Bender *et al.* [12]. (See also Ref. [11].) In that (e,e') experiment, which was performed at low momentum transfers ($q \leq 0.5$ fm^{-1}), the level at 16.40 MeV was unambiguously identified as a 2^- state. More recently, this state was observed in the ^{18}O(p,p') experiment of Djalali *et al.* [36], where its angular distribution at forward angles was characterized by $\Delta L = 1$, which is consistent with that expected for a 2^- state. Figure 8 shows the present form-factor measurements for this state. The fitted curve was obtained by a one-parameter fit; the oscillator parameter was held fixed at the value $b = 1.767$ fm obtained from the simultaneous fit of other 2^- candidates and the expansion coefficient C_0 was fixed at the value $\sqrt{B(M2)\uparrow} = 0.80\ e$ fm^2; this value corresponds to $B(M2)\uparrow = (58 \pm 7)\ \mu_N^2$ fm^2 ($= 0.64 \pm 0.08\ e^2$ fm^4), as determined by the low-q (e,e') measurements of Bender *et al.* [12]. The transition radius determined by our fit, 3.15 fm, is in good agreement with the value $R_{\rm tr} = 3.1 \pm 0.8$ fm, determined by Bender *et al.* Interestingly, the fitted $M2$ form factor for the state at 16.40 MeV is rather similar in shape and magnitude to that for the lowest $T = 1$ 2^- state in ^{16}O at 12.97 MeV [32].

VI. NORMAL-PARITY STATES

If the measured form factor of a state is inconsistent with $F_L(q) = 0$, then that state *must* have normal parity. Form-factor data for 27 normal-parity excited states in ^{18}O were fitted simultaneously to determine values of the oscillator parameter; the values for describing longitudinal and transverse form factors were 1.884(8) fm and 1.768(19) fm, respectively. By comparison, a simultaneous fit of form-factor data for 14 established normal-parity excited states in ^{16}O determined values of the oscillator parameter to be 1.828(11) fm and 1.668(16) fm, respectively, for describing longitudinal and transverse form factors [22].

The expansion coefficients for the form factors of most normal-parity states discussed in this section are given in Table IV. This table also includes extrapolated $B(CJ)\uparrow$ values.

A. Candidate 3^-, 4^+, and 5^- states

Five levels at 11.67, 12.41, 17.02, 18.45, and 19.22 MeV were identified as possible high-lying 3^- states (the last three have mainly transverse form factors, and so abnormal parity cannot be entirely ruled out for those states). Electron-scattering measurements for the three lowest 3^- states at 5.10, 6.40, and 8.28 MeV were discussed in a previous paper [10]. Except at very low momentum transfers, it is generally difficult to distinguish 3^- and 1^- states on the basis of their form factors. The spin assignments of these states could be established more reliably if additional data at forward angles were available.

Two normal-parity levels at 8.96 and 10.31 MeV, which have Coulomb form factors consistent with a 4^+ assignment, are discussed below. Electron scattering measurements for the two lowest 4^+ states at 3.55 and 7.12 MeV were discussed in previous papers [8–10].

One level at 9.71 MeV was identified as a candidate 5^- state. Electron-scattering measurements for the two lowest 5^- states at 7.86 and 8.13 MeV were discussed in a previous paper [10]. Weak states also were observed at 12.52, 14.45, 15.23, 15.95, 20.86, and 23.10 MeV. The form-factor measurements for these levels were generally inadequate for making spin and parity assignments. We note, however, that the 23.10-MeV state was most prominent in a spectrum measured for 165-MeV electrons scattered at 140° ($q \approx 1.25$ fm^{-1}). This state might be a 2^- level since it is strongest at relatively low q.

TABLE IV. Form-factor expansion coefficients (in e fm^J) and extrapolated reduced transition probabilities (in e^2 fm^{2J}) for selected normal-parity excited states in ^{18}O. (Uncertainties in the last significant figure are given in parentheses, and only the uncertainties due to fitting are represented.) The oscillator parameter b was determined to be 1.884 ± 0.008 fm for the longitudinal form factors and 1.768 ± 0.019 fm for the transverse form factors.

E_x (MeV)	J^π	A_0	A_1	B_1	$B(CJ)\uparrow$
9.36	(2^+)	1.805(92)	0.138(37)	1.68(42)	3.25(33)
11.67	(3^-)	16.1(14)	−0.77(52)	21.0(35)	257(44)
12.41	(3^-)	8.5(18)	−0.20(60)	12.6(48)	72(30)
17.02	(3^-)	−3.0(12)		32.9(10)	8.7 ± 7.3
18.45	(3^-)	3.1(15)		10.6(30)	9.3 ± 9.3
19.22	(3^-)	−1.2(18)		12.0(10)	< 6
8.96	(4^+)	30.6(68)	−1.7(27)	−59(32)	$9.3(41) \times 10^2$
10.31	(4^+)	13.6(76)	4.4(26)	21(32)	$< 4 \times 10^2$
9.71	(5^-)	178(10)		58(185)	$3.15(36) \times 10^4$

In studies of the ^{14}C(α,n)^{17}O reaction, a strongly excited state was observed at 8.966 MeV with a width of 54 ± 3 keV by Sanders [34] and at 8.956 MeV with a width of 65 ± 10 keV by Bair, Ford, and Jones [25]. Weinman and Silverstein [35] observed this state clearly in the ^{14}C(α,α)^{14}C reaction, and concluded that the state must have normal parity and $J \geq 2$. This state is probably part of the strongly excited complex observed at 9.030 ± 0.015 MeV in the ^{16}O(t,p)^{18}O reaction [26]. In a study of the ^{16}O(^{18}O,^{16}O)^{18}O reaction, Rae *et al.* [40]

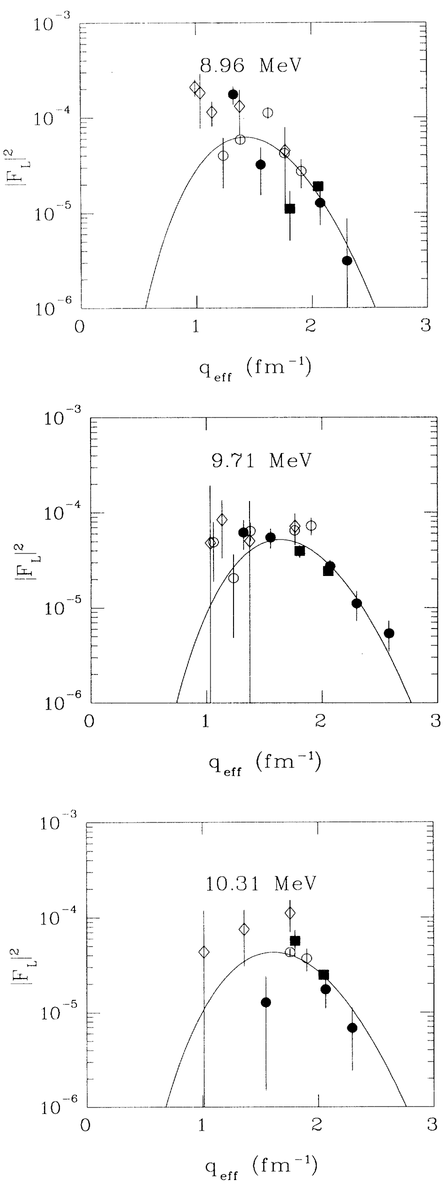

FIG. 9. Coulomb form factors for the normal-parity states at 8.96, 9.71, and 10.31 MeV. The solid curves were obtained by fitting the data under the assumption that the levels at 8.96 and 10.31 MeV are 4^+ states and that the level at 9.71 MeV is a 5^- state. Solid squares and solid circles indicate measurements from the present analysis at 110° and 140°, respectively; open circles and open diamonds indicate older measurements at 90° and 160°, respectively (see text).

also observed a strongly excited state at 9.0 MeV, which they identified as a 4^+ state. The identification of a state at 9.0 MeV as the 4^+ state having the dominant configuration $(1d_{5/2})(1d_{3/2})$ was confirmed by Fortune, Bland, and Rae in studies of the ^{16}O(t,p)^{18}O and ^{17}O(d,p)^{18}O reactions [41]. The present measurements for the 8.96-MeV state at scattering angles of 110° and 140°, and at $q \approx 2.0$ fm^{-1}, are consistent with a mainly longitudinal form factor, as shown in Fig. 9. The A_0 value for the 8.96-MeV state is 30.6 ± 6.8 (see Table IV), which agrees reasonably with the value 19.2 obtained by a shell-model calculation [9]. (The same calculation predicts A_0 values of 53.8 and 83.1 for the 4_1^+ and 4_2^+ states, respectively, whereas the experimental values are 31.12 ± 0.56 and 113.8 ± 1.5 for the 4^+ states at 3.55 and 7.12 MeV, respectively [10].) We conclude that the level at 8.96 MeV has normal parity, and it is consistent with being the 4^+ state having the dominant configuration $(1d_{5/2})(1d_{3/2})$.

A narrow normal-parity state was observed at 9.71 MeV. This state is probably the same one observed as a weak peak at 9.713 ± 0.007 MeV in the ^{16}O(t,p)^{18}O reaction [26]. The transverse form factor for the 9.71-MeV level is negligible within experimental uncertainties. The shape and strength of its longitudinal form factor, shown in Fig. 9, are consistent with that expected for a 5^- state. This may be the normal-parity state observed at 9.72 ± 0.03 MeV in the ^{18}O(α,α)^{18}O* reaction [24].

A 4^+ state was observed at 10.29 MeV in the ^{14}C(α,α)^{14}C reaction [42] and in the ^{14}C(^{7}Li,t)^{18}O reaction [43]. This is probably the normal-parity state observed at 10.29 MeV in the ^{18}O(α,α') reaction [24]. The 4^+ state has also been observed at 10.30 MeV in the ^{12}C(^{18}O,^{18}O* $\rightarrow$^{14}C+α)^{12}C reaction [44]. A weak state also was observed at 10.30 ± 0.02 MeV in the ^{16}O(t,p)^{18}O reaction [26]. The present measurements for the state at about 10.31 MeV are consistent with a mainly longitudinal form factor, as shown in Fig. 9. We conclude that this level has normal parity, and the data are consistent with a 4^+ assignment.

A strongly excited normal-parity state was observed in the present work at 11.67 MeV. The present measurements for this state indicate a mainly longitudinal form factor but also a measurable transverse form factor. Based on the shape and strength of the longitudinal form factor, which is well determined, as shown in Fig. 10, we conclude that this state probably has $J^\pi = 3^-$. [Note that a 6^+ state at 11.69 MeV was identified in the ^{14}C(α,α)^{14}C reaction [42]; however, this state is expected to be extremely weak in electron scattering since its excitation requires a $4\hbar\omega$ $1p \rightarrow 1h$ transition or a $2\hbar\omega$ $1d \rightarrow 1g$ transition.] The shape of the Coulomb form factor is not inconsistent with that expected for a 4^+ state; however, the strength of the 11.67-MeV state is comparable to that of the collective 4^+ state at 7.12 MeV and no known collective 4^+ state in ^{16}O or ^{18}O has a measurable transverse form factor. Hence, we believe that a 4^+ assignment for this state is rather unlikely. (A preliminary 4^+ assignment for this state is superseded by the present work [45].)

A state was observed in the present work at about 12.41 MeV. The present measurements for this state are consistent with a mainly longitudinal form factor, as shown in Fig. 10, but with a measurable transverse component. We conclude that this level has normal parity, and the data are consistent with either a 3^- or 4^+ assignment. Based on some of the arguments presented above for the 11.67-MeV state, however, the 3^- assignment is preferred.

A strongly excited narrow state was observed in the present work at 17.02 MeV. Its narrow width suggests that it is a $T = 2$ state. The present measurements for this state indicate a small (or possibly zero) longitudinal form factor. The shape of its transverse form factor, shown in Fig. 11, is well determined and is similar to that expected for a 4^- state. However, we believe strongly that this state is, in fact, the $T = 2$ analog of the 0.75-MeV 3^- state in ^{18}N, which is expected at about 17.03 MeV in ^{18}O [27]. By comparison, the lowest $T = 1$ 3^- state in ^{16}O at 13.26 MeV also has a large $E3$ form factor but a very small $C3$ form factor [32]. The first evidence for a $T = 2$ state at 17.02 MeV was presented in a short report on an $^{18}\mathrm{O}(p,p')$ experiment [39]. This report also noted that the 17.02-MeV state is *not seen* in the $^{18}\mathrm{O}(d,d')$ reaction, which should not excite $T = 2$ states. A narrow state at 17.025 ± 0.010 MeV was also reported in the high-resolution $^{18}\mathrm{O}(e,e')$ experiment of Bender *et al.* [12]. In that experiment, which was performed at low momentum transfers ($q \leq 0.5$ fm^{-1}), the state at 17.025 MeV was observed as a *weak* excitation, and was tentatively (and probably incorrectly) identified as a 1^- state.

A weak state with a width of 75 ± 27 keV was observed in the present work at 18.45 MeV. This width suggests that the state has $T = 1$ since we are below particle decay threshold for $T = 2$ states. This level was observed at 18.48 ± 0.02 MeV and with a width of 90 ± 34 keV in prior (e,e') measurements [1]. As shown in Fig. 11, its transverse form factor has a shape similar to that of the level at 17.02 MeV, which is believed to be a 3^- state; however, an assignment of abnormal parity cannot be ruled out for this state.

A narrow, relatively weak state was observed in the present work at 19.22 MeV. The narrow width of this level suggests that it is a $T = 2$ state. Present measurements for this state are consistent with a mainly transverse form factor. As shown in Fig. 11, its transverse form factor has a shape similar to that of the level at 17.02 MeV, which is believed to be a 3^- state. An assignment of normal parity is consistent with earlier electron-

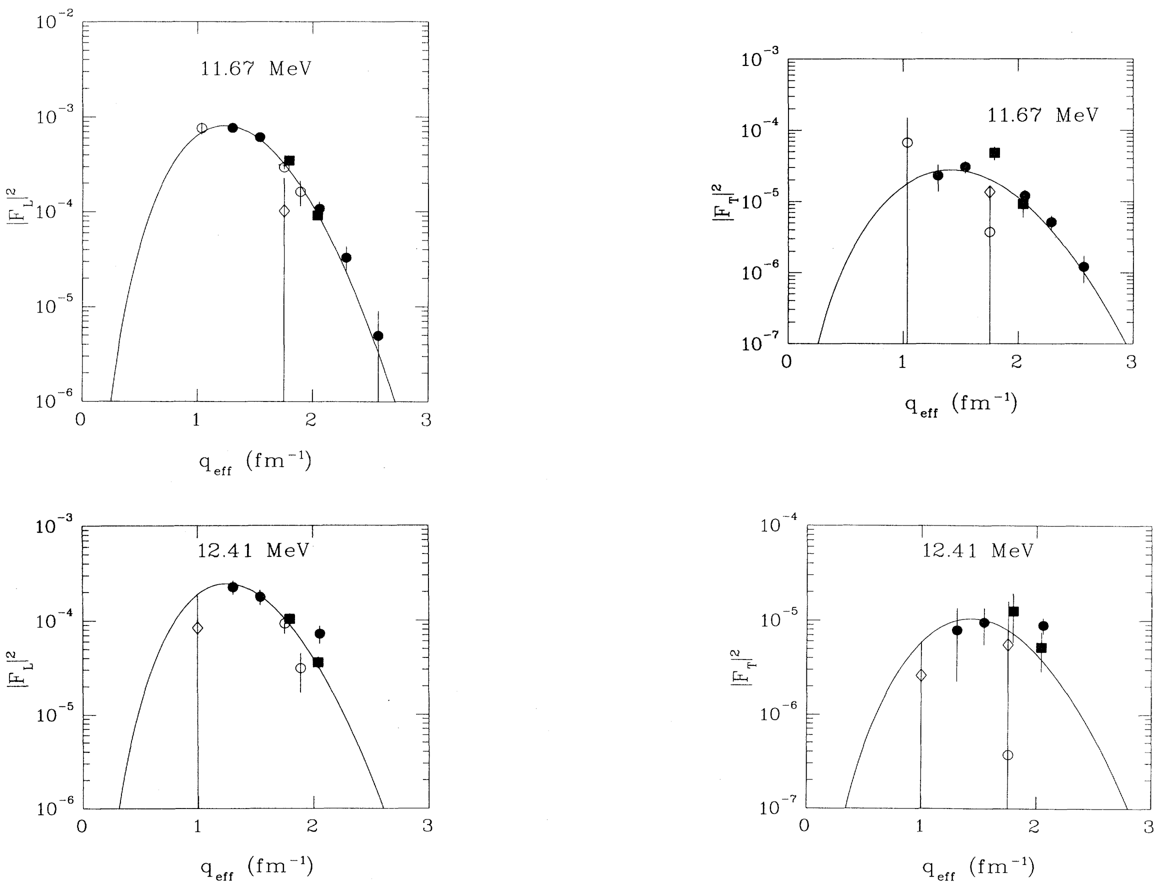

FIG. 10. Coulomb and transverse form factors for the normal-parity states at 11.67 and 12.41 MeV. The solid curves were obtained by fitting the data under the assumption that each level is a 3^- state. Solid squares and solid circles indicate measurements from the present analysis at 110° and 140°, respectively; open circles and open diamonds indicate older measurements at 90° and 160°, respectively (see text).

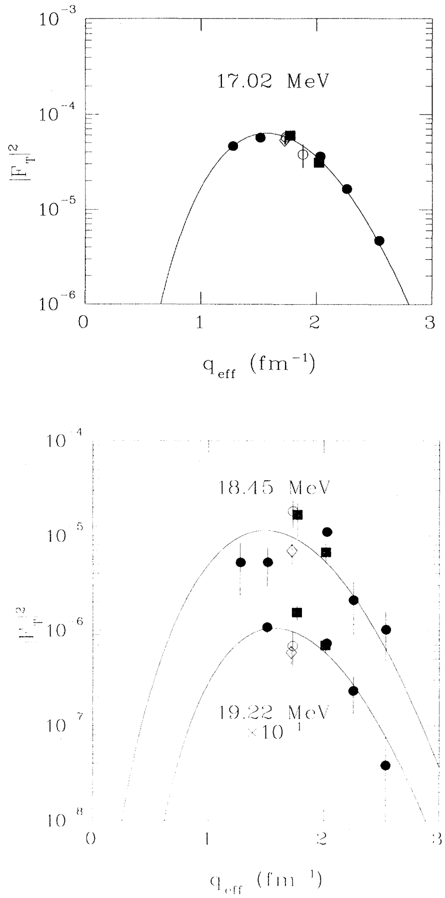

FIG. 11. Transverse form factors for the states at 17.02, 18.45, and 19.22 MeV. The solid curves were obtained by fitting the data under the assumption that each level is a 3^- state. (Abnormal parity cannot be ruled out for these states, based on the present measurements.) Solid squares and solid circles indicate measurements from the present analysis at 110° and 140°, respectively; open circles and open diamonds indicate older measurements at 90° and 160°, respectively (see text).

scattering measurements at $q \approx 1.75$ fm^{-1}, which suggested a significant longitudinal form factor for this state [1]; however, an assignment of abnormal parity cannot be ruled out, based on the present measurements. This might be the analog of the state at 2.9±0.2 MeV observed in the ^{18}O$(\pi^-,\gamma)^{18}$N reaction, which predominantly excites 1^- and 2^- states [46].

B. Candidate 1^- and 2^+ states

A strong normal-parity state at 9.36 MeV, previously suggested to be a 2^+ state [9], was observed in the present work and is discussed below. A normal-parity state at 12.09 MeV was also observed; the Coulomb form factor for this state peaks at low q and is consistent with either a 2^+ or 1^- assignment.

A strongly excited normal-parity state was observed in the present work at 9.36 MeV. This is probably the same level that was observed in the ^{14}C$(\alpha,n)^{17}$O reaction at 9.361 MeV with a width of 35 ± 20 keV [25]. A weak level at 9.362 ± 0.005 MeV also was observed in the ^{16}O$(t,p)^{18}$O reaction [26]. This level was discussed at length in Ref. [9], where it was argued that it is probably a 4p2h 2^+ state in which the four particles couple to $T = 0$. The state at 9.36 MeV is probably the head of a $K^\pi = 2^+$ band having large components of the $(\lambda\mu) = (82)$ representation of SU(3), which is the leading representation for four particles in the *sd* shell and two holes in the *p* shell. Shell-model calculations predict such a state to lie at 9.49 MeV, in good agreement with the measured excitation energy. The shape of its longitudinal form factor, shown in Fig. 12, is similar to that for the second 2^+ state at 9.84 MeV in ^{16}O [17], and suggests that this state is excited mainly by a $1p \to 1p$ transition. Its transverse form factor is negligible within experimental uncertainties. Present form-factor measurements for this state are consistent with earlier ones, and approximately double the available data for this state.

A narrow normal-parity state was observed in the present work at 12.09 MeV. This level has a longitudinal form factor that peaks at low q, which suggests that $J \leq 2$, and it has a significant transverse form factor, which implies that $J \neq 0$. Of the known low-lying 1^- and 2^+ states in ^{18}O, only 1^- states have a measureable transverse form factor [9,10]; hence, the most likely assignment for this state is 1^-. Its longitudinal and transverse form factors are shown in Fig. 13.

VII. COMPARISONS WITH NUCLEAR-STRUCTURE CALCULATIONS

All of the levels discussed in this paper have excitation energies greater than 5 MeV and most have energies greater than 10 MeV; consequently, many particle-hole configurations are possible for most of these states, which makes meaningful comparisons with shell-model

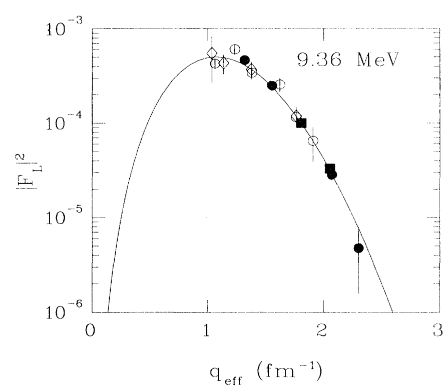

FIG. 12. Coulomb form factor for the normal-parity state at 9.36 MeV. The solid curve was obtained by fitting the data under the assumption that the level is a 2^+ state. Solid squares and solid circles indicate measurements from the present analysis at 110° and 140°, respectively; open circles and open diamonds indicate older measurements at 90° and 160°, respectively (see text).

calculations difficult. For that reason, the discussion here will be limited primarily to high-spin states ($J \geq 4$), for which the particle-hole structure is expected to be simpler. In addition, as noted in Sec. V and Sec. VI, a discussion of the structures of two states [the 2^+ candidate at 9.36 MeV and the 4^+ candidate at 8.96 MeV (tentatively identified here as the 4_3^+ state)] can be found in Ref. [9]. For these states, no further discussion will be presented here.

The excitation energy of a high-spin particle-hole state in ^{18}O can be estimated with the Bansal-French-Zamick formula for weak-coupling configurations [9,47],

$$E_x = E_B(16+m) + E_B(16-n) - E_B(^{16}\mathrm{O}) - E_B(^{18}\mathrm{O}) + Amn + B\langle \mathbf{T}_p \cdot \mathbf{T}_h \rangle \ . \quad (6)$$

Here E_x is the excitation energy of the state with the weak-coupling configuration $\{[(sd)^m J_p T_p \otimes p^{-n} J_h T_h] JT\}$; that is, m sd-shell particles with spin J_p and isospin T_p are coupled to n p-shell holes with spin J_h and isospin T_h to form a state with spin J and isospin T. The energy is a combination of binding energies E_B (including excitation energies) and the expectation value of the particle-hole interaction; the coefficients A and B in Eq. (6) were found [48] to have values of 0.23 and 5.02 MeV, respectively, by requiring approximate agreement between the calculated and experimental energies for the first $T = 0$ and $T = 2$ excited states in ^{16}O. Calculations with Eq. (6) used binding energies from the tables of Wapstra and Bos [49].

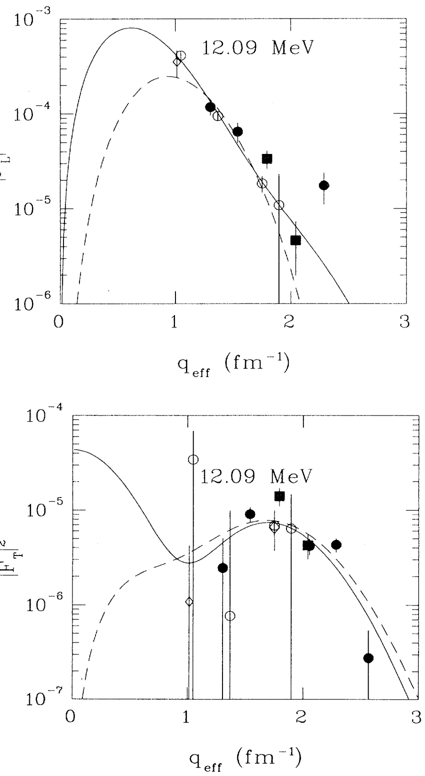

FIG. 13. Coulomb and transverse form factors for the normal-parity state at 12.09 MeV. The solid (dashed) curves were obtained by fitting the data under the assumption that the level is a 1^- (2^+) state. Solid squares and solid circles indicate measurements from the present analysis at 110° and 140°, respectively; open circles and open diamonds indicate older measurements at 90° and 160°, respectively (see text).

Consider, for example, the $T = 1$ 2^-,3^- doublet in ^{16}O with the weak-coupling configuration $[^{17}\mathrm{F}(\frac{5}{2}^+) \otimes {}^{15}\mathrm{N}(\frac{1}{2}^-) + {}^{17}\mathrm{O}(\frac{5}{2}^+) \otimes {}^{15}\mathrm{O}(\frac{1}{2}^-)]/\sqrt{2}$. Equation (6) predicts 13.01 MeV for the centroid energy of the doublet, in very good agreement with the measured energies, 12.97 MeV and 13.26 MeV for the 2^- and 3^- states, respectively. The analogous $T = 2$ doublet in ^{18}O has the weak-coupling configuration $[\sqrt{3}\ {}^{19}\mathrm{F}^*(\frac{5}{2}^+) \otimes {}^{15}\mathrm{N}(\frac{1}{2}^-) + {}^{19}\mathrm{O}(\frac{5}{2}^+) \otimes {}^{15}\mathrm{O}(\frac{1}{2}^-)]/2$, where the asterisk denotes a $T = \frac{3}{2}$ state. Equation (6) predicts 16.14 MeV for the centroid energy of the doublet, which is reasonable for a 2^- state at 16.40 MeV and a 3^- state at 17.02 MeV. Now consider the $T = 1$ $1^-, 2^-, 3^-, 4^-$ quartet in ^{16}O with the weak-coupling configuration $[^{17}\mathrm{F}(\frac{5}{2}^+) \otimes {}^{15}\mathrm{N}(\frac{3}{2}^-) + {}^{17}\mathrm{O}(\frac{5}{2}^+) \otimes {}^{15}\mathrm{O}(\frac{3}{2}^-)]/\sqrt{2}$. Equation (6) predicts 19.26 MeV for the centroid energy of the quartet, in good agreement with 18.98 MeV for the strong $T = 1$ 4^- state. The analogous $T = 2$ quartet in ^{18}O has the weak-coupling configuration $[\sqrt{3}\ {}^{19}\mathrm{F}^*(\frac{5}{2}^+) \otimes {}^{15}\mathrm{N}(\frac{3}{2}^-) + {}^{19}\mathrm{O}(\frac{5}{2}^+) \otimes {}^{15}\mathrm{O}(\frac{3}{2}^-)]/2$. Equation (6) predicts 22.42 MeV for the excitation energy of the quartet, in excellent agreement with 22.40 MeV for the $T = 2$ 4^- state discussed in this paper.

We use a shell-model calculation by Millener [50] to discuss the 4^- and 6^- states of ^{18}O. This calculation employs the full, nonspurious $1\hbar\omega$ basis of $p^{-1}(sd)^3$ and $(sd)(pf)$ configurations, in concert with the Chung-Wildenthal interaction [51] for the sd shell and the Millener-Kurath interaction [52] for all other two-body matrix elements. The resulting wave functions have been used previously in analyses of three-nucleon transfer on ^{15}N by Martz [53], the β decay of ^{18}N to ^{18}O by Olness *et al.* [31], inelastic pion scattering on ^{18}O by Chakravarti *et al.* [54], and, most recently, inelastic electron scattering to 1^-, 3^-, and 5^- states in ^{18}O by Manley *et al.* [10]. The predicted excitation energies were normalized so that the lowest $T = 1$ 1^- state is located at 4.46 MeV.

The two lowest predicted 4^- levels are at 7.70 and 8.39 MeV, to be compared with the experimental candidates at 7.98 MeV (not observed in this work) and at 8.52 MeV. The two lowest predicted 5^- states are at 7.24 and 7.72 MeV, to be compared with the experimental levels at 7.86 and 8.13 MeV. The two lowest 5^- levels and the second 4^- level, according to Millener's calculated three-nucleon spectroscopic factors, should be populated strongly in three-nucleon transfer on ^{15}N. These predictions agree well for states identified in a spectrum measured for the ^{15}N(^{6}Li,^{3}He)^{18}O reaction [53]. A strong state at ~11.10 MeV in that spectrum should be the first 7^- state.

In a shell-model picture with a HO potential, the $M4$ form factor for a stretched $1p_{3/2} \rightarrow 1d_{5/2}$ transition is given by [21]

$$F_{M4}(q) = f_{\mathrm{c.m.}}(q)\ f_N(q)\ \frac{1}{Z}\left(\frac{\hbar}{2mcb}\right)\frac{4\sqrt{2}}{3\sqrt{7}}\ \frac{\hat{J}_f}{\hat{J}_i} \times y^2 e^{-y}\ (Z_0\mu_0 + Z_1\mu_1) \ , \quad (7)$$

where $\hbar/(2mc) = 0.105$ fm, $\mu_0 = 0.880$, $\mu_1 = 4.706$, $\hat{J} = \sqrt{2J+1}$, and Z_0 and Z_1 are one-body density-matrix elements multiplied by the isospin Clebsch-Gordan coefficient $\langle T_i M_i 10 | T_f M_i \rangle$. The "$Z$ coefficients" in Eq. (7) have the value unity for a pure isoscalar or isovector particle-hole excitation from a closed shell. For $T = 2$ 4^- states in ^{18}O, we have $Z_0 = 0$ and the isovector Z coefficient is related to the fitting coefficient C_0 by $Z_1 = C_0/(15.74b^3)$. Using $b = 1.632$ fm and values of C_0 from Table III, we obtain $Z_1 = 0.131(10)$ for the state at 18.68 MeV, $Z_1 = 0.124(10)$ for the state at 20.36 MeV, $Z_1 = 0.089(6)$ for the state at 21.42 MeV, and $Z_1 = 0.344(13)$ for the state at 22.40 MeV. Clearly most of the isovector $M4$ strength is concentrated in the 22.40-MeV state. In comparison, for ^{16}O the isovector $M4$ strength is concentrated in the $T = 1$ 4^- state at 18.98 MeV, which has $Z_1 = 0.63(1)$ [2]. The extreme single-particle model (ESPM), which describes ^{16}O as a doubly magic nucleus, predicts that $Z_1^2 = 1$ for a $T = 1$ 4^- state. Similarly, this model predicts that $Z_1^2 = \frac{1}{3}$ for a $T = 2$ 4^- state in ^{18}O. Thus, if the isovector strength is quenched by the same amount in both nuclei, and if we ignore the fragmentation of strength into the weaker states, we would expect that the strongest $T = 2$ 4^- state in ^{18}O should have $Z_1 = 0.63/\sqrt{3} = 0.36$, which agrees very well with the measured value for the level at 22.40 MeV. The shell-model calculations of Millener predict the strongest $T = 2$ 4^- state to be at 21.43 MeV and to have $Z_1 = 0.4239$. (Note that this value includes an isospin Clebsch-Gordan coefficient of $1/\sqrt{2}$.) Thus, the strength of the observed state is quenched relative to the shell-model prediction by the factor $(0.344/0.4239)^2 = 0.66$; relative to the ESPM value, the strength is quenched by the factor $3 \times (0.344)^2 = 0.36$. These values are typical for the quenching of $M4$ strength in neighboring nuclei.

Figure 14 compares the shell-model $B(M4)\uparrow$ values for $T = 1$ and $T = 2$ 4^- states in ^{18}O with those listed for 4^- candidates in Table III. The calculated values use the same oscillator constant as determined by fitting the electron-scattering data. As noted above, the model predicts that the distribution of isovector $M4$ strength in $T = 2$ states should be concentrated in a single state at 21.43 MeV; this state is identified with the one we observe at 22.40 MeV. The model also predicts two weaker $T = 2$ 4^- states at 18.01 and 21.03 MeV with $Z_1 = 0.2380$ and $Z_1 = 0.2426$, respectively; these states can probably be identified with the observed levels at 18.68 and 20.36 MeV. For $T = 1$ 4^- states, there is no simple relationship between the Z coefficients and the fitting coefficients, C_0 and C_1, because several particle-hole transitions are allowed. Figure 14 shows that the predicted $M4$ strength is strongly fragmented for $T = 1$ 4^- states, with the four strongest model states at 11.95, 12.39, 13.18, and 16.54 MeV; the first two of these states are predicted to have large $(sd)(pf)$ admixtures (58.9% and 6.4%, respectively), which distorts the shape of their form factors from that associated with a typical $(d_{5/2}, p_{3/2}^{-1})$ transition. The remaining two model states at 13.18 and 16.54 MeV have smaller $(sd)(pf)$ admixtures (2.5% and 4.3%, respectively) and may be tentatively identified with the somewhat broad observed levels at 12.99 and 17.46 MeV. As noted earlier, an unambiguous identification of $T = 1$ 4^- states is difficult because their $M4$ form factors may have a variety of shapes. Some of the predicted $T = 1$ 4^- states may correspond to levels that we have identified as 2^- candidates.

In a similar shell-model picture, we can write the $M6$ form factor for a stretched $1d_{5/2} \to 1f_{7/2}$ transition as [21]

$$F_{M6}(q) = f_{\mathrm{c.m.}}(q)\; f_N(q)\; \frac{1}{Z}\left(\frac{\hbar}{2mcb}\right)\frac{16}{15\sqrt{39}}\,\frac{\hat{J}_f}{\hat{J}_i} \times y^3 e^{-y}\;(Z_0\mu_0 + Z_1\mu_1)\;. \quad (8)$$

Here it is convenient to introduce proton and neutron Z coefficients, which are given by $Z_p = (Z_0 + Z_1)/\sqrt{2}$ and $Z_n = (Z_0 - Z_1)/\sqrt{2}$, respectively. For $T = 1$ 6^- states in ^{18}O, we have $Z_p = 0$ and the neutron Z coefficient is related to the fitting coefficient C_0 by $Z_n = C_0/(193.24b^5)$. Using $b = 1.794$ fm and values of C_0 from Table III, we obtain $Z_n = 0.141(13)$ for the state at 13.85 MeV and $Z_n = 0.213(20)$ for the state at 14.17 MeV. Figure 14 compares the shell-model $B(M6)\uparrow$ values for $T = 1$ 6^- states in ^{18}O with those listed for the two 6^- candidates in Table III. The shell-model calculation predicts that the $M6$ strength should be fragmented into several states with the three strongest states occurring at 9.81 MeV (with $Z_n = 0.2121$), 11.30 MeV (with $Z_n = 0.2305$), and 14.27 MeV (with $Z_n = 0.2583$). Not surprisingly, these are also the three states with the largest percentages

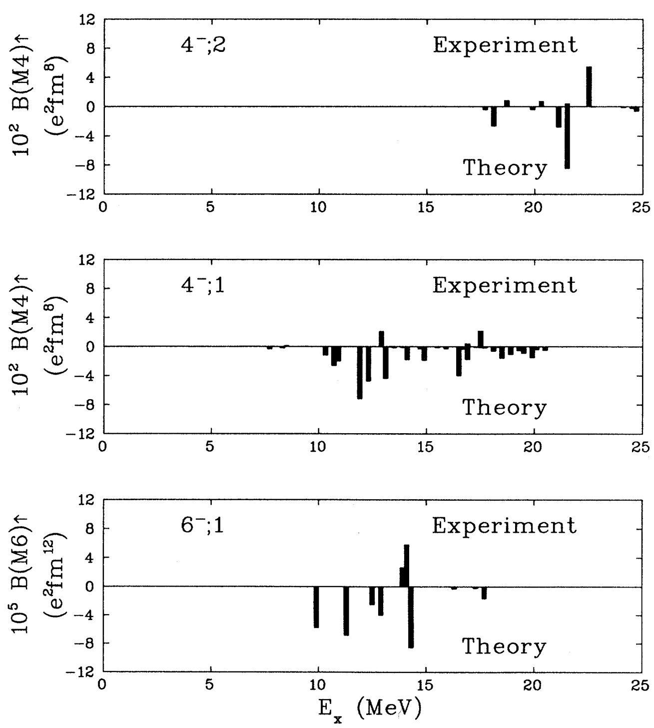

FIG. 14. Comparisons of the measured $B(M4)\uparrow$ and $B(M6)\uparrow$ values with predictions of a full $1\hbar\omega$ shell-model calculation (see text).

of $(sd)(pf)$ admixtures in their wave functions (18.0%, 21.3%, and 26.7%, respectively). Our experimental results indicate that the $M6$ strength in ^{18}O is much more concentrated than is predicted by the shell-model calculation. The ESPM predicts that $Z_n^2 = \frac{1}{6}$ for a $T = 1$ 6^- state in ^{18}O. Experimentally, we have $\sum Z_n^2 = 1/15.3$ for the two 6^- candidates at 13.85 and 14.17 MeV. Thus, the total strength of the observed states is quenched relative to the ESPM value by the factor $6/15.3 = 0.39$; as for the $M4$ strength, this amount of quenching is quite typical.

VIII. SUMMARY AND CONCLUSIONS

We have discussed form-factor measurements for 39 states in ^{18}O; most of these states have not been discussed in previous papers on electron scattering. New measurements at 110° and 140° were combined, when possible, with older data at 90° and 160° so that the form-factor measurements could be fitted with a polynomial-times-Gaussian parametrization suitable for comparisons with shell-model calculations using HO wave functions.

This paper presents the first form-factor measurements for the low-lying 2^- states in ^{18}O. The transverse form factor for the lowest 2^- state at 5.53 MeV is somewhat similar in shape to that of the lowest 2^- state in ^{16}O at 8.87 MeV [32,33], although the peak magnitude of the $M2$ form factor for the 5.53-MeV state is perhaps as small as 3% of that for the state in ^{16}O. This comparison suggests that the $M2$ strength is ^{18}O may be much more fragmented than in ^{16}O. The shapes of the $M2$ form factors for the 2^- states at 6.35 and 7.77 MeV were poorly determined by the present measurements. Several other states were identified as possible 2^- candidates. These include states at 8.41, 10.43, 10.67, 10.99, 11.52, 11.90, 12.66, and 13.40 MeV. We also measured a transverse form factor for the level at 8.82 MeV, which may be the lowest 4p2h 1^+ state in ^{18}O [9].

We observed a normal-parity state at 9.71 MeV that has a Coulomb form factor with the shape expected for a 5^- state. We also observed normal-parity states at 8.96 and 10.31 MeV with Coulomb form factors having shapes consistent with those expected for 4^+ states. The level at 8.96 MeV is probably the 4^+ state with a large $(d_{5/2})(d_{3/2})$ component in its wave function. Such a state was identified previously at about 9.0 MeV in low-resolution $^{16}O(t,p)^{18}O$ and $^{17}O(d,p)^{18}O$ experiments [40,41]. The state at 8.96 MeV is also excited strongly in the $^{14}C(\alpha,n)^{17}O$ reaction [34,25], which further supports this conclusion. The observed $C4$ strength of this state in the present work agrees reasonably well with shell-model predictions for the 4_3^+ state [9].

It is well established that the 0^+, 2^+, 4^+, and 6^+ states at 3.63, 5.26, 7.12, and 11.69 MeV, respectively, belong to the $K = 0$ rotational band contained in the (82) representation of SU(3). This is the leading (lowest) representation for low-lying positive-parity states in ^{18}O that can be described by four particles in the sd shell and two holes in the p shell. The (82) representation also contains a $K = 2$ band, which is probably headed by a strongly excited state at 9.36 MeV [9]. The present form-factor measurements for this state determine the shape of its Coulomb form factor above 1 fm^{-1}. The next member of the $K = 2$ band is a 3^+ state that is calculated to lie at 10.47 MeV [9]. We observe a state at 10.43 MeV that has a transverse form factor consistent in shape with that expected for a 3^+ state, although a 2^- assignment is perhaps more likely. The calculated excitation energy for the 4^+ member of the $K = 2$ band is 11.50 MeV [9]. This member might be the strong state we observe at 11.67 MeV; however, it is difficult to understand the strength of the observed state, and we believe a 3^- assignment is more likely.

Our limited measurements for the narrow $T = 2$ 2^- state at 16.40 MeV suggest that its form factor is probably similar in shape and strength to that for the $T = 1$ 2^- state in ^{16}O at 12.97 MeV. Our measurements for the strongly excited narrow $T = 2$ state at 17.02 MeV determine that its form factor is mainly transverse like that of the $T = 1$ 3^- state in ^{16}O at 13.26 MeV; the 17.02-MeV state probably also has $J^\pi = 3^-$ [27].

States at 8.52, 12.99, 16.88, 17.46, 18.68, 20.36, 21.42, and 22.40 MeV were identified as 4^- candidates. The strongest state, at 22.40 MeV, has $T = 2$ and about one-third of the isovector $M4$ strength seen in ^{16}O, as expected from the extreme single-particle model. The experimental distribution of $M4$ strength was compared with predictions of a shell-model calculation by Millener [50] that employs the full, nonspurious $1\hbar\omega$ basis of $p^{-1}(sd)^3$ and $(sd)(pf)$ configurations, in concert with the Chung-Wildenthal interaction [51] for the sd shell and the Millener-Kurath interaction [52] for all other two-body matrix elements. Qualitatively, the predictions for the energies and relative strengths of the $T = 2$ 4^- states agree with the measurements; however, the observed isovector $M4$ strength is quenched relative to the prediction by an amount comparable to that observed in other nuclei of similar mass. It is not simple to make comparisons between predictions and observations for $T = 1$ 4^- states because form factors for these states may have a variety of shapes, which makes definitive J^π assignments very difficult. In addition, the $M4$ strength for $T = 1$ levels is predicted to be highly fragmented; some of the levels we identify as 2^- candidates may, in fact, be $T = 1$ 4^- states.

States at 13.85 and 14.17 MeV were identified as 6^- candidates, based on the fact that their form factors are transverse and peak at larger q than those for the stretched 4^- excitations. Our measurements imply a concentration of probable $M6$ strength near 14 MeV with the total strength quenched by an amount comparable to that found in somewhat heavier nuclei. These observations, if confirmed, disagree with the shell-model prediction that the $M6$ strength should be fragmented over several levels between 10 and 15 MeV.

In summary, we have measured form factors for a wealth of states in ^{18}O, many of which were observed for the first time in our experiment. These data help to shed light on the rich spectrum of an important nucleus.

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