Measurement and significance of Γ_γ/Γ for the 7117-keV 4^+ level of ^{18}O

B. Meltzow, E. K. Warburton,* Ch. Ender, J. Gerl,† D. Habs, U. Lauff, J. Schirmer, D. Schwalm, and P. Thirolf
Physikalisches Institut der Universitat Heidelberg, D69120 Heidelberg, Germany and Max-Planck-Institut-für-Kernphysik, D69117 Heidelberg, Germany
(Received 27 September 1993)

The excited 4^+ state at 7117 keV in ^{18}O is studied via the ^{12}C(^{7}Li,$p\gamma$)^{18}O reaction. We show that it is highly improbable that the state is energetically degenerate with a state of different decay properties and that its γ decay is consistent with previously reported values. We obtain a γ-branching fraction $\Gamma_\gamma/(\Gamma_\gamma+\Gamma_\alpha) = 0.561\pm0.013$ which together with recent results for other decay properties gives a $B(E2)$ value of 6.4±1.6 W.u. for the 4p-2h intraband transition 7117 $4_2^+ \rightarrow$ 5260 2_3^+. Shell-model calculations in a full $(0+2)\hbar\omega$ basis supplement a previous SU_3-truncated $(0+2)\hbar\omega$ calculation to the effect that the calculations result in a considerably more collective $B(E2)$ value of >15 W.u. for this transition leaving a rather puzzling discrepancy between experiment and theory.

PACS number(s): 21.60.Cs, 23.40.Hc, 23.20.Js, 27.20.+n

I. INTRODUCTION

In a recent ^{14}C$(\alpha,\gamma)^{18}$O experiment, Gai *et al.* [1,2] measured the γ-branching ratio for the $4_2^+ \rightarrow 2_3^+$ 7117 $\rightarrow$ 5260 transition of 1857 keV in ^{18}O (see Fig. 1). They combined this result with the then available information [3–6] on the radiative width of the 7117-keV level and obtained an $E2$ transition strength of 5.7 ± 1.9 Weisskopf units (W.u.) for this transition. This value is surprisingly small; the 4_2^+, 7117-keV level and the 2_3^+, 5260-keV level together with the 0_2^+, 3634-keV state have been convincingly assigned to the predominantly 4p-2h band [8] and due to its deformed nature, considerably larger intraband $B(E2)$ values are expected. In fact, the two "best" shell-model calculations result in considerably more collective $B(E2)$ values for the $4_2^+ \rightarrow 2_3^+$ transition, namely 21 W.u. as derived by Millener [9] using the semiempirical model of Lawson, Serduke, and Fortune [8] and 17 W.u. from the $(0+2)\hbar\omega$ SU_3-basis calculation of Hayes, Bromley, and Millener [10]. We consider the credentials of the latter prediction in Sec. III, for the time being we only state that it is very difficult to conceive of a mechanism to reduce these predictions by a significant amount. Thus, in seeking possible explanations for the disparity of ~3–4 between experiment and theory, we are led to a reconsideration of the experimental value for this transition strength.

There are three ingredients in the determination of the partial radiative width of the 7117 $\rightarrow$ 5260 transition. The 7117-keV level has two open channels, namely γ and α decay. Both of these are involved in the ^{14}C$(\alpha,\gamma)^{18}$O reaction and the cross section for its formation in this radiative capture process gives us a measure of the combination $\Gamma_\gamma\Gamma_\alpha/\Gamma$ where Γ_γ and Γ_α are the total γ- and α-decay widths, respectively, and Γ $(= \Gamma_\gamma + \Gamma_\alpha)$ is the total decay width of the state. The second ingredient is the partial radiative width for the specific decay 7117 $\rightarrow$

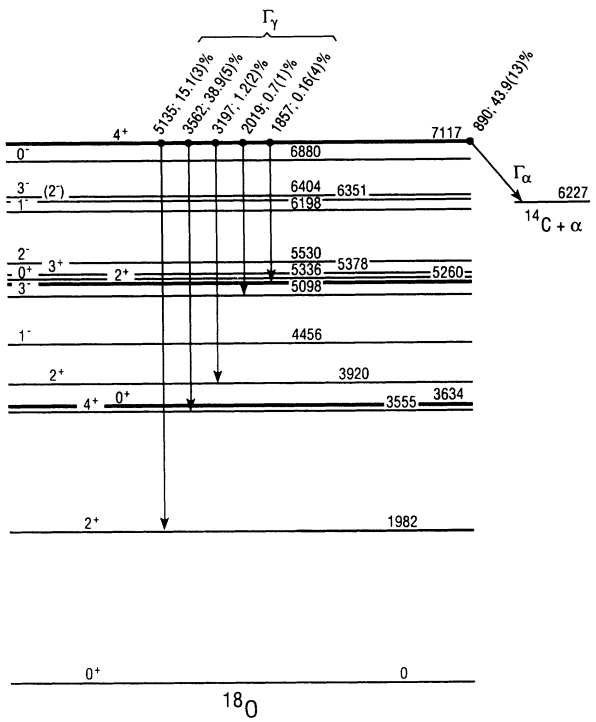

FIG. 1. Partial level scheme of ^{18}O showing the levels and decay modes of interest to the present study. The level energies (in keV) and spin-parity assignments are from Ref. [3]. The decay branches of the 7117-keV level are labeled by the transition energy (in keV) and the partial decay widths (in percent). The decay widths are taken from Refs. [1,2,7] using the Γ_γ/Γ value obtained in the present investigation. For both J^π and E_x, the 4p-2h band is shown to the right and the 2p-0h band next-to-right. The 4p-2h energy levels are of double thickness.

*Permanent address: Brookhaven National Laboratory, Upton, New York 11973. Internet: Warburton@bnlcl1.bnl.gov
†Present address: Gesellschaft für Schwerionenforschung, D64291 Darmstadt, Germany.

5260, $\Gamma_\gamma(7117 \rightarrow 5260)/\Gamma_\gamma$, which was measured by Gai *et al.* [1] and by Görres *et al.* [7] to be $(0.30 \pm 0.08) \times 10^{-2}$ and $(0.24 \pm 0.08) \times 10^{-2}$, respectively. The third ingredient is the relationship between the γ and α widths which can be expressed as Γ/Γ_α and which was measured by Becker *et al.* [6] using the $^{19}F(t,\alpha\gamma)^{18}O$ reaction to be 1.90 ± 0.10. The desired $\Gamma_\gamma(7117 \rightarrow 5260)$ is then the product of these three factors.

The factor $\Gamma_\gamma\Gamma_\alpha/\Gamma$ has been measured twice in recent years. Values of 50 meV [5] and 51 meV [7] with uncertainties of 20% and 17%, respectively, were obtained. These are in excellent agreement, and we adopt a value of (51 ± 7) meV. It is difficult to conceive of a reason why both measurements should have measured a too large value for this quantity. As for the γ-branching ratio for the $7117 \rightarrow 5260$ transition, the nature of the measurements is such that it is hard to conceive of their erring significantly on the low side. Indeed, the two measurements agree well within their errors, and we adopt a value of $\Gamma_\gamma(7117 \rightarrow 5260)/\Gamma_\gamma = (0.277 \pm 0.058) \times 10^{-2}$. The third factor, Γ/Γ_α, seems to us to be the weakest link in the determination of $\Gamma_\gamma(7117 \rightarrow 5260)$. There are two reasons for this: First, it has only been measured once and details of the measurement were not given [6]. Second, arguments were presented by Fortune *et al.* [11] to the effect that the 7117-keV level may be a doublet. Let us reconsider these arguments. Fortune *et al.* [11] observed the ^{18}O spectrum via the $^{12}C(^7Li,p)^{18}O$ reaction at 24 proton angles from 1.8° to 173° and at bombarding energies of 16 and 18 MeV. They found the angle-integrated yield to ^{18}O states followed a $(2J+1)$ dependence with a standard deviation <20% if two levels were excluded. One of the excluded levels was that at 7117 keV for which the cross section at both bombarding energies was twice that expected from this relationship. On this basis they suggested that the 7.1-MeV state was an unresolved doublet with one member being the 4_2^+ state and the other a state with $J = 3-5$ and—from other evidence—probably of negative parity. In order for the discrepancy with theory of the $7117 \rightarrow 5260$ $B(E2)$ value to be explainable on the basis of a doublet it is necessary that the 4_2^+ state has a significant γ-decay branch and that the second member of the doublet has $\Gamma_\alpha \gg \Gamma_\gamma$. Then the second member would show little or no effect in the $^{14}C(\alpha,\gamma)^{18}O$ reaction, but the value measured for Γ/Γ_α for the composite state would be smaller than the value for the 4_2^+ level and would depend on the details of formation. In a later study Fortune [12] proposed an alternative explanation for the deviations observed from a $(2J+1)$ dependence for the cross sections in the $^{12}C(^7Li,p)^{18}O$ reaction. He suggested involvement of the direct transfer of a six-nucleon cluster and gave a quantitative estimate showing that such a component could indeed explain the observed deviations. Nevertheless, this explanation seems somewhat *ad hoc* and the possibility of a doublet should be kept in mind.

We report herein a measurement of Γ_γ/Γ for the ^{18}O 7117-keV level—this is a more direct resultant of our measurement than Γ/Γ_α which is derived from it; the two are related by $\Gamma/\Gamma_\alpha = (1 - \Gamma_\gamma/\Gamma)^{-1}$. The same method is used as employed by Becker *et al.* [6] except that the $^{12}C(^7Li,p\gamma)^{18}O$ reaction is used instead of the $^{19}F(t,\alpha\gamma)^{18}O$ reaction. In addition, the measurement was designed to check on the possibility of a 7.1-MeV doublet. The experimental procedures and results are described in the next section.

II. EXPERIMENTAL PROCEDURES AND RESULTS

In view of the above discussion, the purpose of the present experiment was to measure Γ_γ/Γ for the ^{18}O 7117-keV level and simultaneously to check on the possibility that the 7117-keV level is actually a member of an unresolved energy doublet. Excited states of ^{18}O were formed via the $^{12}C(^7Li,p)^{18}O$ and $^{12}C(^7Li,p\gamma)^{18}O$ reactions at a bombarding energy of 18 MeV using a ^{12}C target isotopically enriched to 99.9%. Protons were selectively detected in a system of three silicon $\Delta E - E$ detector telescopes placed alternatively at 30°, 45°, 60° and 125°, 135°, 150° to the beam. Very high γ-ray detection efficiency was achieved using the Heidelberg-Darmstadt crystal ball, which is a modular 4π detector system consisting of 162 NaI(Tl) scintillation detectors with associated photomultipliers and electronics [13]. The proton-single (a) and the proton-γ-coincidence spectra (b) at detection angle $\vartheta_p = 150°$ are shown in Fig. 2. The

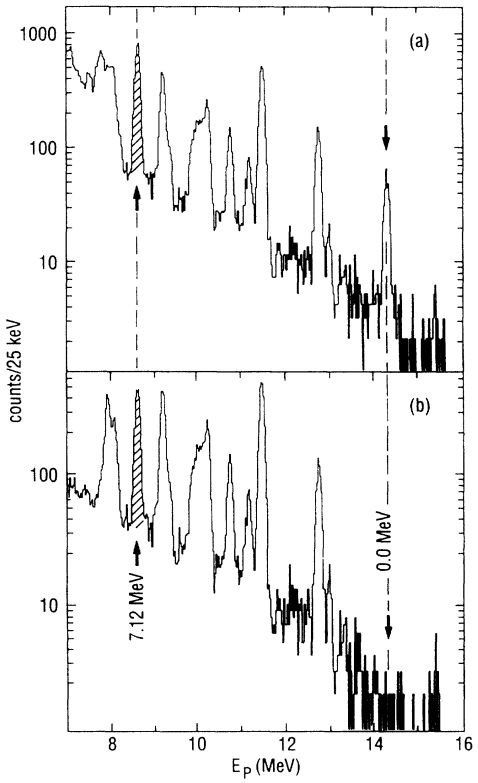

FIG. 2. Proton spectrum observed with the $^{12}C(^7Li,p)^{18}O$ reaction at $E_{^7Li} = 18$ MeV at detection angle $\vartheta_p = 150°$. The singles spectrum is shown in (a) while (b) displays the corresponding spectrum observed in coincidence with at least 1 γ ray. In both cases the proton peak corresponding to the 7117-keV level is crosshatched.

proton energies of the cross-hatched peaks correspond to the 7117-keV level. The levels below 6.23 MeV in ^{18}O are γ-emitting only so that comparison of the (^{7}Li,p) and (^{7}Li,$p\gamma$) spectra is a simple method to check the effective γ-ray detection efficiency $\langle\epsilon\rangle$ for states with different γ-decay patterns. Because of the 4π geometry (actually only 98.1% of 4π was covered by NaI modules because three of them were removed to let the beam in and out and to hold the target chamber) and the low γ-detection threshold (~100 keV), $\langle\epsilon\rangle$ is very high even for levels decaying with a multiplicity-one cascade—e.g., $\langle\epsilon\rangle_{1.98\ \mathrm{MeV}} = (89.3 \pm 3.2)\%$ is observed for the first-excited state at 1.98 MeV—and reaches already values >97% for γ multiplicities >2. The effective efficiencies $\langle\epsilon\rangle$ were actually evaluated from the known ϵ vs E_γ for the crystal ball and the known decay modes of the individual states [1,2]. In particular, for the 7117-keV state, $\langle\epsilon\rangle_{7.1\ \mathrm{MeV}}$ was calculated to be $(98.0 \pm 2.0)\%$.

In Fig. 3(a) we show as a function of proton detection angle the γ-branching fraction Γ_γ/Γ which is obtained from

$$\frac{\Gamma_\gamma}{\Gamma} = \frac{I_{p\gamma}}{I_p}\frac{1}{\langle\epsilon\rangle_{7.1\ \mathrm{MeV}}} \quad (1)$$

where $I_{p\gamma}$ and I_p are the areas under the proton peak corresponding to the 7117-keV level (the cross-hatched areas in Fig. 2) at a specific proton detection angle. Within the uncertainty of the measurements, we find that the γ-branching fraction Γ_γ/Γ is independent of proton angle. A dependence on the proton angle would be expected if the 7117-keV level is an unresolved doublet of two states with different decay properties. This is so because the proton angular distributions as measured by Fortune *et al.* [11] for various ^{18}O states are strongly structured and considerably different so that we view it as extremely improbable that the angular distributions for two unresolved levels would be closely identical. Thus Fig. 3(a) shows that it is extremely unlikely for the 7117-keV level to be an unresolved doublet. Further, albeit weaker [14], evidence against a doublet is supplied by the independence on proton angle found for the individual γ-decay modes as exemplified in Fig. 3(b) and by the agreement shown in Table I of the γ-branching ratios found in this measurement and those obtained in previous experiments using different reactions [1–3]. The mean value of the γ-branching fraction of the 7117-keV level resulting from the data of Fig. 3(a) is

$$\Gamma_\gamma/\Gamma = 0.561 \pm 0.013.$$

This is somewhat larger than the value of 0.474 ± 0.028 determined by Becker *et al.* [6] but not unduly so. The energy resolution of the crystal ball and the statistics of the measurement were not sufficient for the observation of the 7117 → 5260 transition but the upper limit of intensity (see Table I) independently excludes an underestimation of this γ-branching ratio as the main reason for the discrepancy between experiment and theory for its $B(E2)$ value.

The measured Γ_γ/Γ corresponds to $\Gamma/\Gamma_\alpha = 2.28 \pm 0.07$; thus we obtain a γ-decay strength for the 7117 → 5260 transition of

$$\begin{aligned}\Gamma_\gamma(7117 \to 5260) &= (51 \pm 7)\ \mathrm{meV} \times (0.00277 \pm 0.00058) \\ &\times (2.28 \pm 0.07) \\ &= 0.322 \pm 0.081\ \mathrm{meV}\ , \end{aligned} \quad (2)$$

which corresponds to 6.4 ± 1.6 W.u., very close to the value of 5.7 ± 1.9 W.u. originally derived by Gai *et al.* [1]. We are therefore convinced that the smallness of the 7117 → 5260 $B(E2)$ value is not an experimental problem but rather a theoretical one. In the next section we describe calculations designed to further explore possible reasons for this puzzling failure of what appears on the surface to be a straightforward calculation of a strongly collective intraband transition.

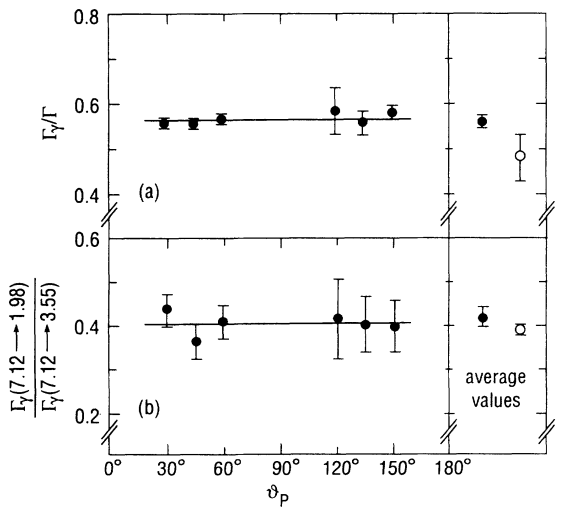

FIG. 3. (a) The γ-branching fraction Γ_γ/Γ of the 7117-keV level, and (b) the ratio of the two strongest γ branches in the decay of the 7117-keV level vs the proton detection angle ϑ_p. The values in both right panels are average values from the present measurement (black dots) or previous ones (open symbols)—(a) Ref. [6], (b) Refs. [1,2].

TABLE I. Comparison of the present γ-branching ratios for the 7117-keV level to those derived from Refs. [1,2,7].

Final state (keV)	γ-branching ratio (%) Present	Refs. [1,2,7]
1982	28.0(15)	26.9(5)
3555	68.0(11)	69.4(8)
3920	2.4(10)	2.16(24)
5098	≤2.0	1.27(17)
5260	≤0.5	0.277(58)

III. SHELL-MODEL CALCULATIONS

Mixed $(0+2)\hbar\omega$ shell-model calculations such as the present one are plagued by the problem of how to deal with the "truncation catastrophe" [15] which results from the omission of the $\geq 4\hbar\omega$ components of the $\hbar\omega$ expansion. The very strong interaction of the $SU_3(20)$ $0\hbar\omega$ and $2\hbar\omega$ components gives the $0\hbar\omega$ component a downward push of order 10 MeV. In nature this is compen-

sated for by a similar downward push on the $2\hbar\omega$ configuration by the $4\hbar\omega$ configuration, and so on. In a full $(0+2)\hbar\omega$ calculation the omission of $\geq 4\hbar\omega$ components leads to badly distorted wave functions as well as energy spectra. One of the very nice attributes of the Hayes-Bromley-Millener (HBM) SU_3 shell-model calculation [10] is that the $SU_3(20)$ component can be omitted (along with any others not considered significant) without incurring spurious center-of-mass problems and thus there is no sizable downward shift of the $0\hbar\omega$ states and a reasonable $(0+2)\hbar\omega$ energy spectrum can be obtained—i.e., the omission of $\geq 4\hbar\omega$ components can be approximately compensated for—with only a small ($\sim$1 MeV) decrease in the $0p-1s0d$ energy gap. As discussed recently [15] the effect of omitting the $SU_3(20)$ component (and the others as well) can in principle be compensated for by using effective operators. For the $B(E2)$ values of interest here this is a particularly simple procedure since the $E2$ effective charge can be simply adjusted such that the $B(E2)$ value of the $1982 \rightarrow 0$, $2_1^+ \rightarrow 0_1^+$ transition is in agreement with the experimental value of 3.4 W.u. However, the full consequences of this omission have not been explored and, more importantly, there is the chance that other SU_3 components neglected by HBM may have a bearing on the smallness of the $4_2^+ \rightarrow 2_3^+$ $B(E2)$ value in ^{18}O. Thus we felt it desirable to perform a $(0+2)\hbar\omega$ calculation with different strengths (and weaknesses) than the HBM calculation. The emphasis is on $B(E2)$ values for $4^+ \rightarrow 2^+$ and $2^+ \rightarrow 0^+$ transitions in ^{18}O, i.e., the transitions of interest to the present study.

Our starting point is the recent Warburton-Brown interaction for $A = 10-22$ nuclei [16]. The interaction is formed in almost an identical way to the oft-used Millener-Kurath (MK) interaction [17] and was developed to describe the same sort of nuclear states; namely unmixed $0\hbar\omega$, $1\hbar\omega$, $2\hbar\omega$, etc. states in $A = 6-22$ nuclei. Two important improvements over the MK interaction are that (1) the $0p-1s0d$ cross-shell part of the interaction used here was determined by a least-squares fit to a potential and (2) the potential contained monopole terms not present in the MK potential. Because of the "truncation catastrophe" the Warburton-Brown interaction [16] was not originally intended for the description of mixed $n\hbar\omega, (n+2)\hbar\omega$,... states. However, recent applications to $A = 11-16$ nuclei [15,18] have met with considerable success in this regard.

The first necessary step in the application of any cross-shell interaction to mixed $(0+2)\hbar\omega$ calculations is to adjust the energy gap between the major-oscillator shells or, better yet, between $0\hbar\omega$ and $2\hbar\omega$ components. This we do empirically with the energy spectrum providing the criterion for the adjustment.

In a recent study [18] it was found that considerable improvement over previous calculations in ^{16}O is obtained by changing that part of the interaction, $V^{2\hbar\omega}$, which mixes $n\hbar\omega$ and $(n+2)\hbar\omega$ components, from that of the Kuo bare G matrix (used in the MK interaction) or that of the original Warburton-Brown interaction (the WBP potential [16])—these two $V^{2\hbar\omega}$ give quite similar results—to the Bonn bare G matrix (scaled by a factor 0.8). For convenience, we refer to the Warburton-Brown interaction with this Bonn potential as the WBN interaction.

We present two calculations performed with the WBN interaction. In both, the $2\hbar\omega$ components are given a downward shift of $\Delta^{2\hbar\omega}$ relative to $0\hbar\omega$ components. These two calculations differ only in the composition of the $V^{2\hbar\omega}$ interaction. In the first calculation—referred to as WBN—the WBN interaction just described is used and it is found that $\Delta^{2\hbar\omega} = 12.34$ MeV gives a reasonable energy spectrum. (Our main criterion is that the 0_2^+ state closely matches the experimental excitation energy.) In the second calculation—referred to as WBN(T)—the $SU_3(20)$ component is removed from $V^{2\hbar\omega}$ (see Ref. [15]) with the result that a $\Delta^{2\hbar\omega}$ of only 2 MeV results in an even better energy spectrum.

The strengths of the present calculations relative to HBM are:

(1) A fuller $(0+2)\hbar\omega$ basis is used. A full $(0+2)\hbar\omega$ basis is used for the WBN calculation; while only the $SU_3(20)$ symmetry is omitted from $V^{2\hbar\omega}$ (but not the rest of the interaction) for the WBN(T) calculation.

(2) The Warburton-Brown interaction gives results for unmixed $0\hbar\omega$, $1\hbar\omega$, $2\hbar\omega$ spectra which are 2–3 times more accurate than the MK interaction used by HBM.

(3) The WBN interaction gives a significantly better description of $M1$ transitions and EL form factors connecting to the ^{16}O ground state [15] than any previously known realistic interaction.

The weaknesses are:

(1) In spite of its success in ^{16}O [15,19], the gap method of solving the "truncation catastrophe" is not fully consistent and its consequences have not been throughly explored.

(2) Another problem in dealing with calculations involving mixed $n\hbar\omega$ and $(n+2)\hbar\omega$ configurations is how to treat 1p-1h (one particle-one hole) excitations through two oscillator shells so as to satisfy the Hartree-Fock condition [15,20,21]. We follow Haxton and Johnson [19] in solving this problem technically by setting all $2\hbar\omega$ 1p-1h two-body matrix elements (TBME) equal to zero so that these matrix elements are only retained in order to remove spurious center-of-mass motion. It is expected that for $B(E2)$ values this omission can be adequately compensated for by an adjustment of the effective charge since the centroid of these 1p-1h excitations should be located at remotely high exitations. One piece of the $2\hbar\omega$ basis is not included in the present calculation; namely, that representing 1p–1h, $1s0d \rightarrow 2s1d0g$ excitations. Previous tests had indicated that this piece is insignificant for $A \leq 20$ nuclei [15]. The approximations just described are not so much a weakness relative to the HBM study—which has its own problems in dealing with the Hartree-Fock condition—but a general one which, however, we do not think is serious.

The dimensions $D(J^\pi)$ of the $J^\pi = 0^+$, 2^+, and 4^+ diagonalizations in the $(0+2)\hbar\omega$ calculation are $D(0^+) = 909$, $D(2^+) = 3570$, and $D(4^+) = 3103$. It might be remarked that these dimensions are small enough compared to present capabilities that there is no reason not to perform a complete $(0+2)\hbar\omega$ calculation if such is desired. In the present study we confine our attention to

the $B(E2)$ values connecting the low-lying J^π=0^+, 2^+, and 4^+ states.

In Fig. 4 the calculated level energies are compared to the experimental ones while the calculated $B(E2)$ values are confronted with the experimental values in Table II. For both calculations we assume neutron and proton incremental effective charges in the ratio of 1.75, as suggested by Alexander, Castel, and Towner [23] and in close agreement with the overall best-fitting values for the whole $(1s, 0d)$ shell of $e_n, (e_p - 1) = 0.49,0.29$ found by Brown and Wildenthal [24]. Adjusting the neutron effective charge so as to reproduce the 1982 $\rightarrow$ 0, $2_1^+ \rightarrow 0_1^+$ $B(E2)$ value of 3.4 W.u., the results for the effective charges are $e_n, (e_p - 1)$ =0.56, 0.32, and 0.72,0.41 for the WBN and WBN(T) calculations, respectively. For comparison we also show in Table II results for the WBN calculation obtained assuming $e_n = e_p - 1 = 0.53$. Note that the $B(E2)$ values of the $4_2^+ \rightarrow 2_3^+ \rightarrow 0_2^+$ cascade, i.e., for the transitions within the 4p-2h sequence, are somewhat smaller for the more realistic choice of $e_n/(e_p - 1)$ = 1.75 than for $e_n/(e_p - 1) = 1.00$. This is expected since there are more active protons in this cascade than in the $2_1^+ \rightarrow 0_1^+$ transition to which we normalize. We also note that the overall agreement between the three listed calculations and the experimental values is approximately the same and the WBN(T) effective charges are larger than the WBN ones. This supports the expectation that the omission of the $SU_3(20)$ term from $V^{2\hbar\omega}$ can be compensated for by an increase in the effective charges. Further, note that the incremental effective charges are even larger than the values found in Ref. [24] of 0.49,0.29 for the $(1s, 0d)$ shell as a whole in spite of the fact that the present calculation involves a much larger model space. This supports the theoretical expectation that the omitted $2\hbar\omega$ 1p-1h excitations play a major role in determining the effective charges and suggest that it would be worthwhile to explore other means of satisfying the Hartree-Fock condition such as the method used by Hoshino, Sagawa, and Arima [21].

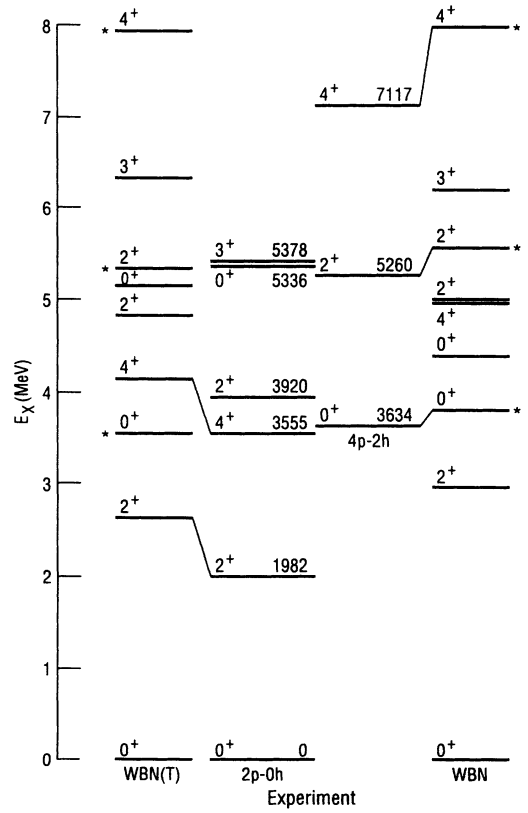

FIG. 4. Comparison of the experimental low-lying even-parity spectrum of ^{18}O to the predictions of the WBN and WBN(T) calculations. The * denotes theoretical levels belonging to the 4p-2h band. The experimental 4p-2h states are shown to the right and the 2p-0h states to the left.

TABLE II. Comparison of experimental (EXP) $B(E2)$ values connecting the low-lying even-parity states of ^{18}O with results from the present shell-model calculations.

J_i^π	J_f^π	$B(E2)$-(Weisskopf units) EXP[a]	WBN[b]	WBN(T)[c]	WBN[d]
2_1^+	0_1^+	3.4(1)	(3.40)	(3.40)	(3.40)
4_1^+	2_1^+	1.2(1)	2.12	2.45	2.10
0_2^+	2_1^+	17.1(20)	8.70	3.10	11.10
2_2^+	0_1^+	1.6(2)	0.16	0.52	0.20
	2_1^+	5.6(37)	1.83	4.00	2.00
2_3^+	0_1^+	2.0(1)	0.77	0.32	1.11
	2_1^+	0.9(5)	1.23	0.01	1.76
	4_1^+	20(11)	0.29	0.01	0.43
	0_2^+	23(14)	15.2	18.7	18.4
0_3^+	2_1^+	1.7(4)	0.05	0.10	0.10
	2_2^+	<15.0	1.45	2.20	1.20
4_2^+	2_1^+	3.9(5)	3.71	1.66	4.60
	4_1^+	<0.7	0.98	0.36	1.20
	2_2^+	3.3(6)	2.65	9.41	3.14
	2_3^+	6.4(16)	16.8	20.8	20.3

[a]Adopted from the compilation given in Ref. [2] with the exception of the 4_2^+ decay which is discussed in the present work (see Fig. 1 and Table I). The two standard deviation upper limit given for the $4_2^+ \rightarrow 4_1^+$ transition is obtained by using the $E2/M1$ mixing ratio $\delta = -0.014(42)$, which is the average of $\delta = -0.035(35)$ [22] and $\delta = 0.07(7)$ [6]. The number in parentheses is the uncertainty in the least significant figure.
[b]$e_n, (e_p - 1) = 0.56,0.32$.
[c]$e_n, (e_p - 1) = 0.72,0.41$.
[d]$e_n, (e_p - 1) = 0.53,0.53$.

There are several points of interest relative to a complete study of the structure of ^{18}O which can be gleaned from the comparison of the calculated level energies and $B(E2)$ values to experiment. From Fig. 4 we see that the energies of the 4p-2h band are reasonably well described by the calculations but the overall agreement is not impressive. We feel this indicates some difficulty in describing the mixing between 2p-0h and 4p-2h states. This difficulty is also indicated by the $B(E2)$ values for the interband transitions as well as for some of the transitions between 2p-0h states shown in Table II. As discussed also by HBM [10], the interband transitions depend critically on the detailed mixing of the basically different

configurations and, in any case, the corresponding $B(E2)$ values are small and the disagreements are not unduely large when judged on the overall agreement between theory and experiment reached in the present calculations [25]. On the other hand, the $4_2^+ \rightarrow 2_3^+$ and $2_3^+ \rightarrow 0_2^+$ transitions—of main interest in the present study—have very large $B(E2)$ values as expected for such a deformed band [8], and are not only stable against details of our calculation but also in agreement with the results of the HBM calculation. Any disagreement with experiment is certainly much more serious for them. The observed marked discrepancy between the calculated $B(E2)$ values for the $4_2^+ \rightarrow 2_3^+$ transition and the experimental value of about a factor of three is therefore of major concern. For this intraband transition we obtain 16.8 and 20.8 W.u. from the WBN and WBN(T) calculations, respectively, while the HBM calculations resulted in 17.3 W.u. [10]. A detailed examination of the single-particle contributions to the $E2$ matrix element reveals the expected coherence and no hint of any vagary in the calculation which might lead with some parameter adjustment to a reduced $B(E2)$ value near the experimental one of 6.4±1.6 W.u. The comparison of $B(E2)$ values for the $2_3^+ \rightarrow 0_2^+$ intraband transition is unfortunately hampered by the large experimental error; the experimental value is so poorly determined that it could just as well agree with the shell-model calculations or be as small as the experimental $4_2^+ \rightarrow 2_3^+$ $B(E2)$ value. A better determination of the experimental $2_3^+ \rightarrow 0_2^+$ $B(E2)$ value—and, likewise, of the $2_3^+ \rightarrow 4_1^+$ $B(E2)$ value, which could be extremely large—could certainly provide a valuable clue relevant to the present problem.

IV. CONCLUSIONS

Our conclusions can be stated as follows: The experimental $B(E2)$ value for the 7117 → 5060 transition in ^{18}O of 6.4 ± 1.6 W.u. is a firmly established number, which is very unlikely to be significantly in error. On the other hand, the mixed $(0+2)\hbar\omega$ calculations of HBM and of the present study indicate a stable deformed 4p-2h band for the 0_2^+-2_3^+-4_2^+ levels of ^{18}O with no hint that the calculation can yield a $4_2^+ \rightarrow 2_3^+$ $B(E2)$ significantly less than the expected large intraband value of >15 W.u.

We reiterate the importance of more accurate measurements for the $2_3^+ \rightarrow 0_2^+$ and $2_3^+ \rightarrow 4_1^+$ transitions, especially for the former. In fact, the nature of the disagreement between experiment and theory for the $4_2^+ \rightarrow 2_3^+$ transition depends critically on what is found for the experimental $2_3^+ \rightarrow 0_2^+$ $B(E2)$ value. If the latter turns out to be also considerably smaller than the predictions, we see no obvious explanation for the disagreement between experiment and theory for the the $4_2^+ \rightarrow 2_3^+ \rightarrow 0_2^+$ cascade. If, on the other hand, it turns out to be in agreement with the predictions, we would be lead to the conclusion that the difficulty in reconciling experiment and theory for the $4_2^+ \rightarrow 2_3^+$ transition lies with truncation to $(0+2)\hbar\omega$ and that the inclusion of (at least) $4\hbar\omega$ components is indicated. The question is not whether sizable $4\hbar\omega$ components are present in the low-lying states. By reference to ^{16}O [15,19] and because of the intrinsically favorable energetics of configurations built on a ^{12}C core, we expect them to be. Rather the question would be why the presence of these components is not representable by a simple change in the overall effective charge but could instead lead to the interference effects necessary to obtain the called-for decrease in the $B(E2)$ value of the $4_2^+ \rightarrow 2_3^+$ transition. Regardless of the size of the $2_3^+ \rightarrow 0_2^+$ $B(E2)$ value, an extension of the calculation to include $4\hbar\omega$ components is obviously desirable. A full $(0+2+4)\hbar\omega$ calculation is beyond present-day shell-model capabilities. However, it is conceivable that a meaningful SU_3-truncated calculation could be performed in a $(0+2+4)\hbar\omega$ model space.

ACKNOWLEDGMENTS

Research supported by the German BMFT under Contract No. 06HD133I and by the U.S. Department of Energy under Contract No. DE-AC02-79ER10493 with Brookhaven National Laboratory. One of us (E.K.W.) is grateful to the Alexander von Humboldt-Foundation for generous support during his stay in Germany. We thank D. J. Millener for valuable discussions.

[1] M. Gai, S. L. Rugari, R. H. France, B. J. Lund, Z. Zhao, D. A. Bromley, B. A. Lincoln, W. W. Smith, M. J. Zarcone, and Q. C. Kessel, Phys. Rev. Lett. **62**, 874 (1989).
[2] M. Gai, M. Ruscev, D. A. Bromley, and J. W. Olness, Phys. Rev. C **43**, 2127 (1991).
[3] F. Ajzenberg-Selove, Nucl. Phys. **A475**, 1 (1987).
[4] The Weisskopf estimate for this transition is 0.050 meV, the initial and final E_x from Ref. [3] are 7116.9 ± 1.2 and 5260.4 ± 1.2 keV.
[5] M. Gai, R. Keddy, D. A. Bromley, J. W. Olness, and E. K. Warburton, Phys. Rev. C **36**, 1256 (1987).
[6] J. A. Becker, L. F. Chase, D. Kohler, and R. E. McDonald, Phys. Rev. C **8**, 2007 (1973).
[7] J. Görres, S. Graf, M. Wiescher, R. E. Azuma, C. A. Barnes, and T. R. Wang, Nucl. Phys. **A548**, 414 (1992).
[8] R. D. Lawson, F. J. D. Serduke, and H. T. Fortune, Phys. Rev. C **14**, 1245 (1976).
[9] D. J. Millener (private communication).
[10] A. C. Hayes, D. A. Bromley, and D. J. Millener (unpublished); A. C. Hayes, Ph.D. Dissertation, Yale University, 1986.
[11] H. T. Fortune, L. R. Medsker, and J. N. Bishop, Nucl. Phys. **A309**, 221 (1978).
[12] H. T. Fortune, Phys. Rev. C **30**, 848 (1984).
[13] D. Schwalm, Ch. Ender, H. Gröger, D. Habs, U. v. Helmolt, W. Hennerici, H. J. Hennrich, H. W. Heyng, W. Korten, R. Kroth, M. Music, J. Schirmer, B. Schwarz, W. Wahl, R. S. Simon, W. Kühn, V. Metag, and C. Broude, in *Frontiers in Nuclear Dynamics,* Ettore Majorana International Conference Series, Vol. 25, edited by R. A. Broglia and C. H. Dasso (Plenum Press, New York and London, 1985), p. 33.
[14] If $\Gamma_\alpha \gg \Gamma_\gamma$ for the other member of the doublet then the

observed γ-decay modes of the unresolved doublet would be that associated with the 7117-keV level irregardless of the mode of formation. Thus the constancy of the relative γ-branching ratios is much weaker evidence against a doublet than the constancy of Γ_α/Γ.

[15] E. K. Warburton, B. A. Brown, and D. J. Millener, Phys. Lett. B **293**, 7 (1992).

[16] E. K. Warburton and B. A. Brown, Phys. Rev. C **46**, 923 (1992).

[17] D. J. Millener and D. Kurath, Nucl. Phys. **A255**, 315 (1975).

[18] E. K. Warburton, I. S. Towner, and B. A. Brown, Phys. Rev. C **49**, 820 (1994).

[19] W. C. Haxton and C. Johnson, Phys. Rev. Lett. **65**, 1325 (1990).

[20] D. J. Millener, A. C. Hayes, and D. D. Strottman, Phys. Rev. C **45**, 473 (1992).

[21] T. Hoshino, H. Sagawa, and A. Arima, Nucl. Phys. **A481**, 458 (1988).

[22] F. D. Lee, R. W. Krone, and F. W. Prosser Nucl. Phys. **A96**, 209 (1967).

[23] T. K. Alexander, B. Castel, and I. S. Towner, Nucl. Phys. **A445**, 189 (1985).

[24] B. A. Brown, in *Proceedings of the International Nuclear Physics Conference,* Harrogate, U.K., 1986, edited by J. L. Durell, J. M. Irvine, and G. C. Morrison (IOP, Bristol, 1987), Vol. 2, p. 119.

[25] From a least-squares fit of the calculated $B(E2)$ values of the listed transitions to the experimental values, it was estimated that the uncertainty in the predicted $B(E2)$ value for a $J_1 \rightarrow J_2$ transition with $J_1 \geq J_2$ is of the order of 1 W.u.